A STUDY OF THE BUILD-UP, INITIATION, AND ACCELERATION OF 2008 APRIL 26 CORONAL MASS EJECTION OBSERVED BY STEREO

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\begin{abstract}
In this paper, we analyze the full evolution, from a few days prior to the eruption to the initiation, final acceleration, and propagation, of the coronal mass ejection (CME) that occurred on 2008 April 26 using the unprecedented high cadence and multi-wavelength observations by the Solar Terrestrial Relations Observatory. There existed frequent filament activities and EUV jets prior to the CME eruption for a few days. These activities were probably caused by the magnetic reconnection in the lower atmosphere driven by photospheric convergence motions, which were evident in the sequence of magnetogram images from the Michelson Doppler Imager on board the Solar and Heliospheric Observatory. The slow low-layer magnetic reconnection may be responsible for the storage of magnetic free energy in the corona and the formation of a sigmoidal core field or a flux rope leading to the eventual eruption. The occurrence of EUV brightenings in the sigmoidal core field prior to the rise of the flux rope implies that the eruption was triggered by the inner tether-cutting reconnection, but not the external breakout reconnection. During the period of impulsive acceleration, the time profile of the CME acceleration in the inner corona is found to be consistent with the time profile of the reconnection electric field inferred from the footpoint separation and the Reuven Ramaty High Energy Solar Spectroscopic Imager 15–25 keV hard X-ray flux curve of the associated flare. The full evolution of this CME can be described in four distinct phases: the build-up phase, initiation phase, main acceleration phase, and propagation phase. The physical properties and the transition between these phases are discussed, in an attempt to provide a global picture of CME dynamic evolution.

\textbf{Key words:} Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: magnetic topology
\end{abstract}

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\section*{1. INTRODUCTION}

Coronal mass ejections (CMEs) are large-scale activities releasing a vast amount of plasma and solar energetic particles (SEPs) into the outer space (Gosling 1993; Webb et al. 1994). These plasma and SEPs can propagate into the magnetosphere near the Earth and severely affect space-based modern technological systems, especially during the solar maximum (Smart & Shea 1989). Solar physicists have been pursuing what happens prior to the CME initiation and how CMEs are initiated. Various observational signatures, including magnetic cancellation, magnetic flux emergence, sigmoids, and filament activities are regarded as significant precursors of CME eruptions (Martin 1998; Canfield et al. 2000; Wang 2006; Gibson et al. 2006). The common nature of these signatures is magnetic free energy build-up in the corona. As a consequence of the energy build-up, the coronal magnetic fields may explosively erupt once a trigger leads to the loss of equilibrium (Forbes et al. 2006). However, there is no consensus so far on the exact trigger mechanism.

The MHD instability model suggests that the eruption of CMEs that have a flux rope morphology is probably caused by the kink and/or torus instability when the winding of the field lines exceeds a critical value (Sturrock et al. 2001; Linker et al. 2001; Fan et al. 2004; Rust & LaBonte 2005; Török & Kliem 2005; Gibson & Fan 2006). In the tether-cutting model, the magnetic reconnection that occurs close to the polarity inversion line (PIL) weakens the constraining tension force of the overlying field, and results in the rise of the sigmoid-shaped core field and subsequently the runaway eruption (Moore & Labonte 1980; Moore et al. 2001; Sturrock 1989; Liu et al. 2007; Sterling et al. 2007). The same tension reduction mechanism holds for the flux emergence model suggested by Chen & Shibata (2000) in which the magnetic reconnection occurs between the emerging field and the background field. In the breakout model proposed by Antiochos et al. (1999), the erupting magnetic field constraining the sheared core field is removed through external magnetic reconnection, which leads to the CME eruption. Other authors have proposed that the injection of poloidal magnetic flux (of sub-photospheric origin) in the flux rope can cause a CME to take off (Chen et al. 2000; Chen & Krall 2003; Krall et al. 2001). More details about CME initiation mechanisms can be found in the reviews of, e.g., Forbes (2000), Forbes et al. (2006), Gopalswamy (2003), Chen (2008), and Schrijver (2009).

One key aspect of understanding CME eruption is understanding the relationship between CMEs and flares, which itself has been a long-standing elusive issue for decades (Kahler 1992; Gosling 1993; Hundhausen 1999). Zhang et al. (2001, 2004) proposed three phases of CME kinematic evolution: the initiation phase, impulsive acceleration phase, and propagation phase, which are tightly associated with the three phases of the associated flare: the pre-flare phase, flare rise phase, and flare decay phase, respectively (see also Burkepile et al. 2004; Vršnak & Skender 2005). The temporal correlation between CME acceleration and flare hard X-ray (HXR) flux was studied by Qiu et al. (2004) and Temmer et al. (2008). In the standard CME–flare model, the flare ribbons separate in the chromosphere during the CME impulsive acceleration phase because of continuous magnetic field reconnection. The reconnection rate can be calculated in terms of flare ribbon separation speed and the line-of-sight (LOS) component of magnetic fields (Forbes & Priest 1984; 2007).\end{onlineonly}
Poletto & Kopp 1986; Forbes & Lin 2000; Qiu et al. 2002). Qiu et al. (2004) compared the reconnection rate with the acceleration of the filament/CME and found a similarity between them. It was also found that the total reconnection flux is proportional to the maximum speed of CMEs (e.g., Qiu & Yurchyshyn 2005).

In addition, Liu & Wang (2009) found that the spectral index of X-ray emission of flares is strongly anti-correlated with the reconnection electric field. All of these suggest that CMEs and the associated flares, during the impulsive energy-release phase in particular, are driven by the same physical process in the lower corona, presumably via magnetic reconnection (Lin & Forbes 2000; Priest & Forbes 2002; Vršnak et al. 2004; Zhang & Dere 2006; Marić et al. 2007; Temmer et al. 2008).

As a matter of fact, most previous studies concerning CMEs address only certain specific phases of CME evolution, while very few are for the full evolution cycle from the build-up phase (tens of hours prior to the CME initiation), throughout the initiation phase and acceleration phase, and to the propagation phase. Therefore, it is useful to make a complete observation to investigate the full CME evolution. It is also of particular interest to study the variation of magnetic topology involved in the different evolution phases, which shall shed light on possible initiation mechanisms of CMEs. The unique data of high cadence and full coverage acquired by Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) instruments on board the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008) spacecraft provide us with the opportunity to make such a study. In this paper, we investigate the full evolution of the CME on 2008 April 26, which was well observed by STEREO. In Section 2, we describe the instruments and the data. Our analysis and results are shown in Sections 3 and 4. In Section 5, a schematic model is proposed to explain the full evolution of the CME, followed by discussions and conclusions in Section 6.

2. INSTRUMENTS AND OBSERVATIONS

The STEREO spacecraft were designed to monitor solar activities from two different perspectives in space, which for the first time provide the stereoscopic measurement for understanding solar eruptions. STEREO A moves ahead of the Earth in its orbit and STEREO B trails behind. The separation between the two spacecraft has been continuously increasing. In particular, the separation angle was 49.5° on 2008 April 26 so that the CME studied in this paper was observed from two well-separated perspectives.

The SECCHI instrument suite on board STEREO is composed of five telescopes. Most of the data analyzed in this paper are from three of the telescopes: Extreme Ultraviolet Imager (EUV1), Inner Coronagraph (COR1), and Outer Coronagraph (COR2). EUVI observes the solar chromosphere and the lower corona at four passbands: 171 Å, 195 Å, 284 Å, and 304 Å, with a cadence higher than the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on board the Solar and Heliospheric Observatory (SOHO), especially at 171 Å passband. COR1 and COR2 are externally occulted white-light coronagraphs with fields of view (FOVs) of 1.4–4.0 $R_\odot$ and 2.5–15.6 $R_\odot$, respectively. Both of them have a cadence higher than Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board SOHO. Therefore, the SECCHI instruments can well observe CMEs from its birth place on the solar surface to its ultimate propagation in the outer corona.

In addition, GOES X-ray data reveal the temporal profile of the soft X-ray emission at 1–8 Å for solar flares, which are often associated with CMEs. The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) spacecraft provides the HXR light curve of the flares. The location of flares can be found in the Solar Geophysics Data Reports.4 The Michelson Doppler Imager (MDI; Scherrer et al. 1995) images provide the longitudinal magnetic field at the surface of the Sun.

More than 300 CMEs have been observed by STEREO since the launch in 2006 December.5 The CME that occurred on 2008 April 26 was associated with a GOES B3.8 class flare. It appeared near the solar limb as seen from the perspective of STEREO A, while near the disk center, it appeared as a halo CME as seen from the perspective of STEREO B. From the running difference images, the leading edge (LE) of the CME that appeared in the FOVs of COR1 and COR2 was evidently sharp, thus in favor of the height measurement. From the height measurement, we can further infer the CME’s kinematical evolution. Recently, Ternisien et al. (2009) obtained its three-dimensional velocity and average acceleration by a forward modeling method using only the SECCHI/COR2 observations. Here, we study this event using multi-wavelength data with a focus on its full evolution, including the magnetic topology in different phases.

3. PRECURSORS, INITIATION, AND ERUPTION OF THE CME

3.1. Magnetic Cancellation in the Active Region

Inspecting the surface source region in magnetogram images, we found a continuous flux cancellation occurring for several days prior to the eruption. We plotted in Figure 1 the LOS magnetic field of the active region in which the CME originated. The three magnetograms in Figure 1 were taken in three consecutive days prior to the CME eruption; they had been rotated to the same time in order to have a better comparative view. The cancellation of magnetic flux mainly occurred near the PIL. We showed in Figure 2 the changes of the magnetic fluxes in both the whole region (left panel) and the central region (indicated by the white rectangle in Figure 1). Both the positive flux and the negative flux decreased slowly, as well as the unsigned magnetic flux in the whole region. For the central region near the PIL, the positive magnetic flux decreased sharply from about $5.8 \times 10^{20}$ to $2.2 \times 10^{20}$ Mx during the 3 days before the eruption. Note that the increase of the negative magnetic flux for about 1 day prior to the onset of the CME/flare (denoted by the vertical solid line in Figure 2) was due to the motion of the negative patch toward the northeast; the change was caused by flux transportation instead of flux emergence. Therefore, the slow converging motion between the two opposite polarities, driven probably by photospheric flows, resulted in the continuous magnetic cancellation. We believe that this photospheric flux cancellation process lead to subsequent filament activities and ultimately to the CME that we will be discussing. The magnetic cancellation has been considered as one of the primary magnetic signatures leading to major solar activities (e.g., Wang 2006).

3.2. Disappearance of the Associated Filaments

We carefully examined what occurred in the corona of the source active region in the 2 days prior to the CME eruption. As shown in the left and middle panels of Figure 3, a filament

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4 http://www.ngdc.noaa.gov/stp/SOLAR
5 http://cor1.gsfc.nasa.gov/
existed over the active region. It was initially visible for several hours on April 24, during which several jets occurred, indicated by the white arrow in the left panel. The filament was also visible on April 25 during which some mass flew down slowly along the field lines. Eventually, the filament rose impulsively on April 26 (indicated by the white arrow in the right panel of Figure 3). Note that such active behaviors of filaments before their final eruption have been well observed before (see the review by Pick et al. 2006). Nevertheless, the final eruption of filaments is closely associated with that of CMEs.

3.3. Sigmoid Configuration and EUV Brightening

The CME of interest also had the sigmoid signature prior to the eruption. Figure 4 showed some sampling EUV images of the active region prior to the CME eruption; the sigmoid was particularly obvious in the 284 Å (lower-middle panel) and 195 Å (lower-right) passband images. The 171 Å passband images, on the other hand, did not show the sigmoid well, but revealed better the morphology of the overlying magnetic loop arcade (upper panels). The sigmoid seemed to be consistent with two co-existing J-shaped bundles of low-lying loops forming a reversed-S shape in projection; the two ends were in opposite sides of the PIL and anti-parallel to each other. Similar sigmoid structures comprising of many individual loops have been identified by McKenzie & Canfield (2008). Such structures are preferentially observed in eruption regions and thus have been regarded as a precursor of CMEs (Canfield et al. 2000; Gibson et al. 2006). Note that the 195 Å image at 9:06 UT on April 25 (lower-left panel) showed the coronal configuration prior to the formation of the coronal sigmoid.

Another noticeable feature was the EUV brightening in the sigmoid core field, most clearly seen in the 171 Å passband images, denoted by the two small squares in Figure 4 (upper panels). The brightening can also be seen in the 284 and 195 Å passband images. Such brightening, first appearing at ∼12:40 UT, implies that magnetic reconnection occurred at this site about 1 hr before the eruption. We also note that some twisted field lines in the sigmoid started to rise slowly from ∼13:36 UT. These observations help understand the triggering or initiation mechanism of the CME. They seem to favor the tether-cutting model proposed by Moore et al. (2001) and further elaborated by Liu et al. (2007), but not the breakout model proposed by Antiochos et al. (1999). First, the active region on the photosphere appeared as a simple bipolar magnetic field, and the corona magnetic field could be characterized by a sigmoidal core field constrained by an overlying bipolar arcade field. Second, the pre-eruption EUV brightenings only occurred within the core field; we do not find any remote brightenings surrounding the active region as expected from the breakout model (Moore & Sterling 2006). The breakout model usually requires a quadrupole magnetic configuration and an initiation magnetic reconnection at the null point above the central core.
field. Therefore, the observational features of this event are well consistent with the tether-cutting model, in which the magnetic reconnection occurs within the low-lying core field lines (Moore et al. 2001). We believe that the initial reconnection, as indicated by the EUV brightenings, caused the slow rise of the sigmoidal magnetic structure.

3.4. Eruption of the CME

From inspecting the EUVI movies, we found that the overlying field lines were relatively stable for days before the eruption at about 13:44 UT, at which the whole system became unstable and erupted impulsively. The CME first appeared in the FOV of the COR1 A image at 14:15 UT at a height of 1.91 \( R_\odot \) from the disk center. From the COR1 A movie, one can clearly see that a sharp semicircular front expanded outward. On the other hand, the CME first appeared in the FOV of the COR1 B image at 14:25 UT as a halo shape at a height of 1.72 \( R_\odot \). At 14:55 UT, another inner halo structure appeared. The two halos may correspond to the CME disturbance front and the expanding flux rope, respectively (see also Wood & Howard 2009). Selected snapshots of the CME are shown in Figure 5. Note that during the CME eruption, a streamer disturbance was triggered at the southern side as indicated by the black arrow in Figure 5.

4. KINEMATICS OF THE CME

We can well track the LE of the CME using the running difference images at 171 Å and in white light images, as shown in Figure 5. The white arrows in the figure pointed to the position angle of the measurement, at which we measured the height—
time variation of the CME. The height–time measurement was then used to derive the velocity profile through the piecewise numerical derivative method, i.e., the Lagrangian interpolation of three neighboring points (Zhang et al. 2001, 2004). From the velocity profile, the CME acceleration can be further derived through a similar method but having a larger uncertainty. We thus obtained the full kinematic evolution of the event from the solar surface continuously to the outer corona as indicated in the middle panels of Figure 7. Note that the uncertainty in the height measurements was estimated to be 0.026, 0.12, and 0.24 \( R_\odot \) for EUVI, COR1, and COR2, respectively. This is the main factor causing the uncertainty in the calculation of speed and acceleration of a CME (Zhang et al. 2004).

The reconnection electric field can be calculated using the separation speed of the \( \text{H} \alpha \) ribbons, serving as a proxy of the magnetic reconnection rate. Here, we revisit this issue using EUVI observations. For the event here, the flare ribbons were well shaped and thus can be easily traced. We chose five directions, marked by the white lines in Figure 6, to measure the separation speed of the ribbons. The final separation speed was obtained by averaging the speeds along the five lines. The magnetic field was taken from the MDI magnetogram image just prior to the CME eruption. Since the event occurred near the disk center as seen from \textit{SOHO}, the observed LOS magnetic field should be close to the radial component of the fields needed for the calculation. The reconnection electric field can then be
inferred as $E_{\text{rec}} = V B_n$, which was plotted as the green lines in the bottom panels of Figure 7.

The relationship between the acceleration phase of the CME and the impulsive phase of the associated flare had been investigated in many papers (e.g., Zhang et al. 2001, 2004; Temmer et al. 2008). Qiu et al. (2004) and Jing et al. (2005) compared in detail the acceleration of the CME, the reconnection rate, and the HXR emission of the associated flare. In the two studies, they used the filament acceleration as the proxy of CME acceleration because of the lack of CME observations in the inner corona. However, thanks to the STEREO observations, we were able to study the event on 2008 April 26 with better continuity in space and time. We derived the CME’s acceleration from two well-separated viewing angles and tracked the CME continuously from the solar surface to the outer corona. We then compared the CME’s acceleration with the reconnection rate and the HXR flux of the associated flare, as shown in the bottom panels of Figure 7. The acceleration of the CME peaked at 13:51 UT, while the reconnection electric field and the RHESSI 15–25 keV HXR flux peaked at 13:54 UT. This time difference
was relatively small and was within the time resolution of the CME acceleration curve. In general, the profile of the CME acceleration was co-incident with the profile of the reconnection electric field and the HXR flux curve.

5. A FOUR-PHASE CME EVOLUTION MODEL

In this section, we attempt to use a schematic model to explain the full evolution of the CME from early development to the ultimate eruption (Figure 8). We piece together many components proposed by other researchers that we believe are relevant to CME evolution and put them into a coherent scenario. For the sake of clarity of discussion, we suggest that the full evolution of the CME should be divided into four phases: (1) the build-up phase, (2) the initiation phase, (3) the main acceleration phase, and (4) the propagation phase.

The build-up phase was the phase of preparation that lasted for days before the CME. As discussed earlier, it is characterized by many pre-cursor signatures: flux cancellation, filament activity, sigmoid and EUV brightening, even though these signatures are neither necessary nor sufficient for an eruption. Formation and evolution of filaments had been extensively studied for many years. Martens & Zwaan (2001) proposed a head-to-tail model to explain the formation of filaments through flux convergence and cancellation. Subsequently, Welsch et al. (2005) simulated the filament formation using two flux systems driven by the convergence of opposite polarities along PILs. Chae et al. (2001) proposed that slow magnetic reconnection driven by converging motions may occur at all times in the chromospheres. The continuous reconnection can result in both the overlying field lines straddling the neutral line and the low-lying core field lines (Chae et al. 2001; Welsch et al. 2005).

Further, some EUV jets and small eruptions took place at the site of magnetic cancellation. As the positive and negative fluxes moved close to each other near the PIL, the anti-parallel inner ends of the two bundles of the loops reconnected slowly and continuously in the lower atmosphere (i.e., the chromosphere). That resulted in the formation of the overlying M-shaped field lines that are almost perpendicular to the PIL. At the same time, it also produced the low-lying field lines that are nearly parallel with the PIL. The active filaments condensed at the dip of the M-shaped field lines, as indicated in the upper right panel of Figure 8. As the filament mass flew down along the M-shaped field lines, more field lines rose and served as the overlying loops. These loops were heated slowly and remained invisible at 171 Å until about tens of hours prior to the CME eruption. Note that as long as some open field lines exist at the reconnection site, part of the filament mass may erupt as EUV jets. However, although part of the filament mass flew down slowly or erupted, the rest of the filament appeared to be quite stable in the dip of the field lines all the time prior to the CME eruption (Figure 8(c)). As time progresses, the lower field lines in the eastern part and the pre-existing field lines in the western part, being both J-shaped, moved closer to each other, driven by the continuous convergence motion along the PIL and formed a reversed-S sigmoid structure in the projection plane. Then, the ends of the two bundles of the J-shaped loops, on the opposite sides of the PIL, reconnected as tether cutting and formed the little twisted field lines, while the energy released through the reconnection heated the plasma in the middle part of the reversed-S sigmoid configuration and thus producing the observed EUV brightenings. The shortest field lines submerged into the sub-photosphere after the slow reconnection, which was manifested by the magnetic cancellation in the photosphere.
The initiation phase occurred when the upward force within the sigmoid was able to overcome the tension force of the overlying field lines. As more and more J-shaped loops reconnected by tether cutting, the twisted field lines in the reversed-S sigmoid configuration beneath the overlying loops moved up due to an increased upward magnetic hoop force and a decreased downward magnetic stress (Moore et al. 2001; Liu et al. 2007; Sterling et al. 2007). The rising twisted field lines pushed the overlying loops upward. When the overlying loops were stretched to a certain extent due to the tether-cutting reconnection, a current sheet between the legs of the distorted overlying field line was formed under the loops so that a fast runaway reconnection was subsequently initiated, leading to the main energy release phase and the impulsive acceleration of the CME; this is the standard model of eruptive flares (Hirayama 1974). Another possibility leading to the main eruption is the triggering of MHD instability of the flux rope formed from the tether-cutting reconnection, through kink and/or torus instability (Török & Kliem 2005; Kliem & Török 2006).

The subsequent main acceleration phase is believed to be caused by the runaway magnetic reconnection, coupled with the explosive poloidal flux injection into the rising flux rope. The reconnection rapidly injected a large amount of poloidal flux into the twisted field lines, thus supplying a stronger upward driving force so as to impulsively accelerate the CME flux rope. On the other hand, the CME eruption led to a decrease in the magnetic pressure below the flux rope, which caused a faster inflow toward the current sheet and enhanced the runaway reconnection. This positive feedback process effectively released the magnetic free energy stored in the lower corona, which was converted into the kinetic energy of the CME and also produced the enhanced soft X-ray and HXR emissions (Li et al. 1993). Moreover, the CME eruption led to a depletion of mass in the lower atmosphere near the active region and formed coronal dimming (Thompson et al. 1998). As the magnetic reconnection progressed, the reconnection site rose gradually. The upward moving reconnection site induced the flare ribbons to separate horizontally at the base of the corona, as evidently seen in the EUV and Hα channels. Beneath the reconnection site, the newly reconnected magnetic loops were filled by the plasma that evaporated from the chromosphere and the sigmoid magnetic structure changed to post-flare loop arcades (see also Liu et al. 2007), as shown in Figure 8(f). Note that the magnetic configuration before the eruption (Figure 8(c)) had been unambiguously confirmed by the extrapolated coronal magnetic field obtained from a linear force-free field (LFFF) model using the MDI magnetogram as the input.

After the main phase which lasted about 10 minutes, the runaway reconnection came to a stop. The CME now entered into the simple propagation phase: the CME was propagating with either a nearly constant speed or with a small residual acceleration in the outer corona.

6. DISCUSSIONS AND CONCLUSIONS

The STEREO observations provide an unprecedented opportunity to investigate solar eruptions. In this paper, we presented multi-wavelength observations of the flare-associated CME that occurred on 2008 April 26. We have studied its evolution for a long period and discussed the full evolution in a four-phase scenario: the build-up phase, initiation phase, main acceleration phase, and propagation phase. During the build-up phase, the active filaments, instantaneous EUV jets, and a reversed-S sigmoid structure were observed. All the features were physically related to the persistent slow magnetic reconnection in the solar lower atmosphere, which was manifested as photospheric magnetic cancellation. Before the eruption, there was a long period of reconnection occurring in the lower layers, resulting in the transferring and accumulation of magnetic free energy, as well as the formation of a magnetic structure favorable for eruption, i.e., the sigmoid structure in this event. Different from the process of flux cancellation, the emerging of magnetic flux may also play an important role in transferring magnetic free energy from the sub-photosphere into the corona (Tian et al. 2008; Archontis et al. 2009). MacNeice et al. (2004) showed that as the magnetic field shear increases, the magnetic free energy continuously accumulates. They also proposed that such a quasi-static energy accumulation phase is necessary for any fast CME eruption. The magnetic field shear can be caused by the convergence motion of opposite magnetic fluxes (Titov et al. 2008). Using a non-LFFF extrapolation, it was recently found that the accumulated magnetic free energy increases with time prior to the eruption (Thalmann & Wiegelmann 2008; Guo et al. 2008; Jing et al. 2009). Therefore, the build-up phase accumulates sufficient magnetic free energy for the eventual initiation and the final eruption.

In general, the initiation phase of a CME eruption is characterized by a slow rise of the CME flux rope. In the present event, the EUV emission started to brighten in the core part of the reversed-S sigmoid configuration, which implied that slow magnetic reconnection was taking place there. As the field lines in the reversed-S sigmoid configuration continually reconnected, the CME flux rope rose slowly for about 20 minutes. This inner core magnetic reconnection prior to the eruption, combined with the bipolar magnetic structure in the active region and the absence of remote brightenings, seems to rule out the breakout model as the triggering mechanism of this event. Instead, we think that this eruption is well consistent with the tether-cutting initiation model. We also investigated the kinematics of this CME and found that its acceleration was well correlated with the HXR flux of the associated flare and the magnetic reconnection rate (see also Zhang et al. 2004; Qiu et al. 2004; Temmer et al. 2008). It suggests that the main acceleration phase of the CME in the inner corona is likely caused by the fast runaway magnetic reconnection. Later on, the CME propagated with an almost constant velocity in the outer corona (see also Zhang et al. 2001; Gallagher et al. 2003). However, for CMEs associated with a long decay flare, even though the fast magnetic reconnection ceases, a positive post-impulsive-phase acceleration may continue to exist after the impulsive acceleration phase (Cheng et al. 2009). In general, these observational results are consistent with the standard CME–flare model.

We think that the schematic model comprised of the four phases proposed in this paper can be applied to most CME events. However, owing to different physical circumstances under which CMEs occur, individual events may have their own characteristics. In particular, there may be various manifestations for the build-up phase and the initiation phase, as mentioned above. We look forward to more observations in the coming years to study a variety of CME events in order to
fully understand the full evolution cycle of CMEs, including energy build-up, initiation, impulsive acceleration, and subsequent propagation in the interplanetary space.

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