The Acceleration Process of a Solar Quiescent Filament in the Inner Corona

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Abstract

Coronal mass ejections (CMEs) are frequently associated with filament eruptions. Theoretical studies propose that both magnetic reconnection and ideal magnetohydrodynamic instability of magnetic flux ropes can convert coronal magnetic energy into the filament/CME kinetic energy. Numerical simulations and analytical considerations demonstrate that both mechanisms can have significant contributions to the filament/CME acceleration. Many observational studies support that reconnection plays an important role during the acceleration, while it remains open how to resolve observationally the contribution of the ideal instability to the acceleration. On the other hand, it is difficult to separate and compare their contributions through observations as both mechanisms often work in a close time sequence. In this Letter, the above issues are addressed by analyzing the eruption process of a quiescent filament. The filament started to rise from ∼00:00 UT on 2011 December 25, 20 minutes earlier than the starting time of the flare impulsive phase (∼00:20 UT), and reached the maximum velocity at the flare peak time (∼00:50 UT). We divide the acceleration process into two stages, corresponding to the pre-flare and flare impulsive phases, respectively. The analysis indicates that an ideal flux-rope instability is dominant in the first stage, while reconnection below the flux rope becomes important during the second stage, and both mechanisms may have comparable contributions to the net acceleration of the filament.

Key words: instabilities – magnetic reconnection – Sun: coronal mass ejections (CMEs) – Sun: flares

Supporting material: animations

1. Introduction

Coronal mass ejections (CMEs) are the most energetic eruptive phenomenon in the solar system, and are frequently associated with filament eruptions (e.g., Webb & Hundhausen 1987). We use the term filament throughout the text, while it is dubbed as prominence when located near the solar limb. CMEs can arrive at the near-Earth space in several days with speeds ranging from several hundred to more than one thousand kilometers per second and subsequently cause geomagnetic activities (e.g., Gosling et al. 1991). Albeit the importance, our understanding of the physical initiation and acceleration mechanism of CMEs remains elusive (e.g., Chen 2011). The coronal magnetic field is regarded as the main energy source of CMEs (Forbes 2000), and two major mechanisms have been proposed to convert magnetic energy to the kinetic energy of CMEs: one is magnetic reconnection taking place along current sheets underneath CMEs (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976 the so-called CSHKP model), and the other is ideal magnetohydrodynamic (MHD) instability of large-scale magnetic flux ropes (van Tend & Kuperus 1978; Pneuman 1980; Priest & Forbes 1990; Vršnak 1990; Isenberg et al. 1993; Forbes & Priest 1995; Hu et al. 2003; Kliem & Török 2006; Chen et al. 2007a, 2007b; Fan & Gibson 2007; Olmedo & Zhang 2010). Magnetic reconnection below the flux rope on one hand reduces the tension of overlying magnetic loops and enhances the lifting force acting on the eruptive flux rope (e.g., Lin & Forbes 2000; Chen et al. 2006, 2007b); on the other hand, it also continuously supplies the poloidal flux to the rope (e.g., Vršnak 2008). Both factors can enhance and prolong the acceleration process (e.g., Schmieder et al. 2015; Vršnak 2016). The ideal flux-rope instability takes place in a catastrophic manner (see, e.g., Figure 4 in Vršnak 1990), and can accelerate CMEs through the unbalanced Lorentz force acting on the flux-rope structure (e.g., Chen et al. 2006, 2007b).

Observational evidence should be found to tell which mechanism plays a dominant role in the CME energetics. There are some detectable signatures indicating the occurrence of magnetic reconnection during the CME acceleration, such as the enhancement of X-ray and EUV emissions and the appearance of flare ribbons. Researchers have studied the relationship between the kinematics of filaments/CMEs and the energy release of associated flares, and found that good temporal correlations exist between CME speed and the soft X-ray profiles of flares (Zhang et al. 2001; Maričić et al. 2007). It was also revealed that the velocity of CMEs is proportional to the total reconnection flux estimated from flare ribbon observations (Qiu & Yurchyshyn 2005; Miklenic et al. 2009). Further, some observations demonstrated that the acceleration of eruptive filaments/CMEs is temporally correlated with the hard X-ray flux and magnetic reconnection rate (Wang et al. 2003; Qiu et al. 2004; Jing et al. 2005; Temmer et al. 2008, 2010). All of these results support that the magnetic reconnection may dominantly contribute to the acceleration of filaments/CMEs. On the other hand, it is not trivial to find
observational support that the flux-rope instability contributes to the acceleration, because the energy-release process induced by the ideal instability does not produce strong electromagnetic emissions (such as X-rays or EUVs) to indicate its action.

It has been suggested that the flux-rope instability triggers and accelerates the filament/CME first, and the magnetic reconnection is induced subsequently and provides further acceleration (Priest & Forbes 2002; Lin et al. 2003; Temmer et al. 2010; Vršnak 2016). Numerical simulations demonstrate that the instability and reconnection can have comparable contributions to the acceleration process (Chen et al. 2007a), whereas analytical considerations by Vršnak (2016) showed that reconnection is dominant in the most impulsively accelerated events. It is difficult to separate and compare their contributions through observations, as both mechanisms often work in a close time sequence with their contributions being mixed and unresolved (Maričić et al. 2007; Temmer et al. 2010). Song et al. (2015) conducted a comparison of the contributions from the two mechanisms by analyzing the eruptive process of an active region filament that is associated with an M5.9 class flare. Its acceleration process had two apparently separated fast acceleration phases. Inspecting the temporal correlations between the velocity and soft X-ray flux, as well as the acceleration and hard X-ray flux, they inferred that the flux-rope instability made a major contribution to the first acceleration phase, whereas reconnection was dominant in the second phase. Their quantitative analysis further demonstrated that both mechanisms have comparable contributions to the total acceleration of the filament. This is consistent with the results of early axisymmetric MHD simulations of the flux-rope eruption (Chen et al. 2007a).

The magnetic field environment of the quiet-Sun region is significantly different from that of the active region, and the quiescent filament eruptions are usually associated with weak X-ray flares, or even without X-ray flares (Song et al. 2013). It remains unclear whether one can resolve the contribution of the flux-rope instability to the filament acceleration, and compare it with that of reconnection during a particular filament eruption in the quiet-Sun region. This is our motivation for conducting the present study.

2. Observations and Results

2.1. Instruments

The Extreme Ultraviolet Imager (EUVI) on board Solar Terrestrial Relations Observatory (STEREO) provides solar EUV images at four wavelengths with a field of view (FOV) of 1.7 R⊙, which partially overlaps with that of COR1 (1.4–4 R⊙) and allows us to observe the filament continuously in the inner corona (Howard et al. 2008). The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board Solar Dynamic Observatory (SDO) observes the solar atmosphere with an FOV of 1.3 R⊙ through 10 narrow UV and EUV passbands. The Helioseismic and Magnetic Imager (HMI; Hoeksema et al. 2014) on board SDO provides the line-of-sight magnetic fields on the photosphere. The soft X-ray flux is provided by Geostationary Operational Environment Satellite (GOES) and the X-ray telescope (XRT; Golub et al. 2007) on board HINODE. GOES provides the soft X-ray flux integrated from the full solar disk, while the XRT can spatially resolve the X-ray flux.

2.2. Overview of the Filament Eruption

The eruption of a quiescent filament was observed by the AIA and EUVI on 2011 December 25 when STEREO A (B) was ∼107° (∼110°) west (east) of SDO as shown in the left panel of Figure 1. See the animation to examine the complete eruption process. The right panel presents one image recorded by AIA 304 Â prior to the eruption. The filament, as denoted with the white dotted line, is located close to the disk center and exhibited the inverse sigmoidal morphology. The white dashed (solid) curve depicts the solar limb when observed from the STEREO A (B) perspective. It is a limb (backside) event for
Figure 2. Filament eruption presented by the composite images of EUVI 304 Å and COR1 on board STEREO B (left) and A (right).

Figure 3. XRT observations of the solar disk before the flare onset (top left) and near the flare peak time (top right), with the white rectangles depicting the filament source region. The GOES and XRT X-ray fluxes are plotted in the bottom panel.
STEREO A (B). This stereoscopic combination allows us to analyze the change of the reconnection flux through the disk observations of SDO, and at the same time reveal the kinematics of eruption through the limb observations of STEREO.

The left (right) panel of Figure 2 presents the COR1 B (A) observation, overlaid with EUVI 304 Å data. We show images with the best filament observations. The eruption of the filament was recorded well in the EUVI FOV at \( \sim 00:36:15 \) UT, and then in the COR1 FOV 30 minutes later. The filament exhibits a writhing morphology in both EUVI and COR1 observations. This indicates that the eruption might be triggered by the kink (Török et al. 2004) or torus instability (Török et al. 2010). We will analyze the filament kinematic process using STEREO A observations as it is a limb event from this perspective with a minimal projection effect. The asterisk and diamond symbols in the right panel denote the filament apex when observed with EUVI and COR1, respectively. This will be used to trace the movement of the filament.

GOES recorded a C1.1 class X-ray flare during the eruption of the filament, as shown in the bottom panel of Figure 3 (red curve). To make sure whether this flare was relevant, we examined the observations of the XRT on board HINODE. The XRT observed the corona continuously during the eruption with a large FOV, as shown in the top panels of Figure 3. The top left (top right) panel shows the XRT Ti_poly image taken before (during) the eruption. The FOV contains the filament region as depicted with the white rectangle, over which we obtain the integrated soft X-ray flux. The obtained flux profile is plotted in the bottom panel (black curve), which is similar to that given by GOES, especially in the flare impulsive phase. This unambiguously confirms that the C1.1 class flare is associated with the filament eruption, and can be used to analyze the relationship between the filament kinematics and magnetic reconnection process.

Besides the X-ray flux, another parameter that can be used to characterize the magnetic reconnection is the amount of magnetic flux that was reconnected during the eruption. So far, it is impossible to measure the reconnected flux directly through coronal observations. The standard two-ribbon flare CSHKP model implies that a quantitative relationship exists between the coronal reconnection flux and the magnetic flux swept by the flare ribbons (Forbes & Priest 1984; Miklenic et al. 2007, 2009; Qiu et al. 2007). This can be expressed as

\[
\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial t} \int B_n dS = \frac{\partial}{\partial t} \int B_n dS_{\text{ribbon}},
\]

(1)

where \( \frac{\partial}{\partial t} \) denotes the coronal magnetic reconnection rate, i.e., the reconnection flux per unit time, defined by the integration of the inflow coronal magnetic field (\( B_0 \)) over the reconnection area (\( dS \); Kazachenko et al. 2017). \( B_n \) is the normal component of the magnetic field in the flare ribbons, and \( dS_{\text{ribbon}} \) is the newly brightened area swept by the ribbons. The total amount of magnetic flux reconnected in the corona can be obtained by summing the normal flux swept by the ribbons (Miklenic et al. 2007, 2009).

Figure 4 shows the temporal evolution of the AIA 304 Å flare ribbons superimposed on the co-aligned HMI magnetogram. The blue and red colors correspond to the flare ribbons at early and late stages, respectively. See the animation to examine the separating motion of the flare ribbons. With the flare ribbon motion and the magnetogram data, we can infer the evolutions of both the total reconnection flux (including positive and negative polarities) and the magnetic flux change rate (or the reconnection rate) during the flare, which are shown in Figure 5 (this will be discussed later).

2.3. Kinematics of the Filament

The kinematics of the filament is obtained by analyzing both EUVI A 304 Å and COR1 A white-light images. The evolution of the filament height with time is plotted in the top panel of Figure 5. Based on these measurements, the velocity is calculated from the numerical differentiation using the three-point Lagrangian interpolation method (e.g., Hong et al. 2015). The uncertainty of the height measurement, which is estimated to be \( \sim 4 \) (\( \sim 10 \)) Mm in the EUVI (COR1) FOV, is used to calculate the velocity errors in the standard way. The velocities with the error bars (in black) are plotted in the middle panel, along with the GOES X-ray flux (in red) and inferred total reconnection magnetic flux (in blue).

The filament started to show an appreciable velocity increase after \( \sim 00:00 \) UT, as marked with the vertical solid line in Figure 5, indicating the onset of the eruption. The vertical dotted line depicts the starting time of the flare impulsive phase (\( \sim 00:20 \) UT). The acceleration process ceased near the flare peak time (\( \sim 00:50 \) UT) as shown with the vertical dashed line. We divide the acceleration interval into two stages, separated by the starting time of the flare impulsive phase, i.e., the two stages of acceleration are coincident with the pre-flare and impulsive phases, respectively. The filament velocity reached \( 150 \) km s\(^{-1}\) in the first stage, and further increased to \( 420 \) km s\(^{-1}\) at the end of the second stage. The average acceleration of the first (second) stage is \( 0.13 \) (\( 0.15 \)) km s\(^{-2}\).

According to the bottom panel of Figure 5, the reconnection rate estimated during the first stage is \( \sim 4 \times 10^{16} \) Mx s\(^{-1}\), lower than that of the second stage (\( \sim 4 \times 10^{17} \) Mx s\(^{-1}\)) by one order of magnitude, while both stages present similar amounts of accelerations. This implies that the magnetic reconnection process was likely not important to the filament acceleration during the first stage, and the other mechanism, i.e., an ideal MHD instability had a major contribution in this stage. The velocity and soft X-ray flux reached their peaks at \( \sim 00:50 \) UT synchronously in the second stage, which is similar to earlier reports (e.g., Zhang et al. 2001), and indicates that the magnetic reconnection may play a major role during the second stage. According to the above analysis, it is likely that the flux-rope instability and magnetic reconnection dominated during the first and second acceleration stages, respectively, and both stages lasted for comparable durations with similar amounts of average accelerations. Therefore, we suggest that the two energy-release mechanisms have comparable contributions to the net filament acceleration.

To further demonstrate that the flux-rope instability contributes to the acceleration during the first stage, we plot the temporal profiles of the acceleration (in black), along with the GOES X-ray derivative (in red) that can be used as the proxy of hard X-ray according to the Neupert effect (Neupert 1968) in the bottom panel of Figure 5. The reconnection rate (i.e., magnetic flux change rate, in blue) is also plotted. Though the error bars of the acceleration are large (not shown here), we can identify its variation trend that has been marked with the green solid line. The acceleration increases gradually during the first stage, and decreases along
with the descent of both the reconnection rate and the derivative of soft X-ray flux during the second stage. Finally, it approaches 0 km s\(^{-2}\) when both the reconnection rate and derivative become low in the decay phase. The relationship between the variation trends of the acceleration and reconnection rate as well as the derivative of the soft X-ray flux is in general consistent with earlier reports (Qiu et al. 2004; Jing et al. 2005; Miklenic et al. 2009). However, the amounts of acceleration during the pre-flare phase (the first stage) are large, not proportional to the corresponding reconnection rate. The acceleration profile would be similar to the green dashed line as plotted in the panel, if magnetic reconnection was the major contributor to the acceleration during the pre-flare phase. The discrepancy between the green solid and dashed lines indicates that an ideal MHD instability plays a major role during the first stage. Again, the temporal correlation between the acceleration and reconnection rate during the flare impulsive and decay phases support magnetic reconnection and is likely important to the acceleration during the second stage.

3. Discussion

The acceleration mechanism of filaments/CMEs is an important issue in solar physics. Previous studies showed that several mechanisms, including the ideal MHD instability, flare reconnection, mass drainage, and CME–CME collision, can accelerate filaments/CMEs (e.g., Reva et al. 2017). In this event, the filament erupted from the quiet-Sun region without observable mass drainage and adjacent eruptions, and finished its acceleration in the inner corona. Hence, the flux-rope instability and magnetic reconnection are the main potential acceleration mechanisms. Besides, it is essential to analyze the kinematics of the filament and the associated reconnection process, which were well conducted in this event as it was observed clearly as both a limb and disk event. Therefore, the filament eruption provided us with an excellent opportunity to study the acceleration contributions of the flux-rope instability and magnetic reconnection.

As mentioned, it is not straightforward to find observational support that the ideal instability contributes to the acceleration, and it is also difficult to compare its contribution with that of the reconnection on the basis of present observations. To disentangle their contributions, Chen et al. (2007a) constructed a flux-rope model and calculated different cases in which they either prohibited or allowed magnetic reconnection to take place across the growing current sheets in the wake of CMEs. They found that CMEs, even fast ones, can be produced when taking the ideal instability as the only process to convert magnetic energy. Nevertheless, the CME speed can be enhanced significantly after magnetic reconnection sets in. Their quantitative calculation showed that the two magnetic energy-release processes could have comparable contributions to the CME accelerations, which are supported by our observational studies of filament eruptions from both the active region (Song et al. 2015) and the quiet-Sun region (this study). However, the situation might be very different from event to event. It seems that only one mechanism has the major contribution to the filament/CME acceleration in some particular events. For instance, when the specific physical quantities of filaments/CMEs and flares exhibit the evolutionary similarity and synchronization in the whole process (Zhang et al. 2001; Qiu et al. 2004; Jing et al. 2005; Maričić et al. 2007), it is likely that the magnetic reconnection is important to the acceleration. On the other hand, when no good temporal correlations exist at all between the filament/CME kinematics and reconnection characteristics (including fast flareless CMEs; see Song et al. 2013), the reconnection may not be important to the acceleration, and the flux-rope instability may play a major role in the acceleration process.
4. Summary

The eruption of a quiescent filament, associated with a C1.1 class flare, was well observed by the AIA and HMI on board SDO, and EUVI and COR1 on board STEREO on 2011 December 25. The source region was located close to the solar disk center from the perspective of SDO. AIA recorded the separating motion of the flare ribbons clearly, which allowed us
to analyze the magnetic reconnection flux with the HMI data. On the other hand, the source located at the limb as viewed from the perspective of STEREO A was very suitable for measuring its heights and velocities with a minor projection effect. The filament erupted from \(\sim 00:00\) UT onward, 20 minutes earlier than the starting time of the flare impulsive phase (\(\sim 00:20\) UT), and reached its maximum velocity near the flare peak time (\(\sim 00:50\) UT). We divided its acceleration process into two stages, corresponding to the pre-flare and impulsive phases, respectively. Both stages had similar values of average acceleration, but the reconnection rate \((\sim 4 \times 10^{16} \text{ Mx s}^{-1})\) in the first stage was significantly lower than that \((\sim 4 \times 10^{17} \text{ Mx s}^{-1})\) in the second stage. This strongly indicates that the flux-rope instability played a major role in the first stage. According to the observations that the filament velocity and soft X-ray flux reached their peaks at \(\sim 00:50\) UT synchronously, and the reconnection rate was large in the second stage, it is more likely that the reconnection process was important to the acceleration in this later stage. Based on the above analysis, we suggest that both the flux-rope instability and magnetic reconnection have comparable contributions to the net filament acceleration in this event.

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