The Reversal of a Solar Prominence Rotation about Its Ascending Direction during a Failed Eruption

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Abstract

The magnetic orientation of solar coronal mass ejections (CMEs) near the Earth’s magnetosphere is one major parameter that influences the geoeffectiveness of CMEs. The orientation often varies during the eruption and propagation from the Sun to the Earth due to the deflection and/or rotation of CMEs. It is common to observe the counterclockwise (CCW) or clockwise (CW) rotation (viewed from above) of solar prominences in the corona, which can be used to predict the space weather effect of associated CMEs. In this Letter, we report an intriguing failed prominence eruption that occurred on 2010 December 10, exhibiting the CCW and CW rotations sequentially in the corona. The eruption is recorded by both the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory and the Extreme Ultraviolet Imager on board the Solar Terrestrial Relations Observatory. This stereoscopic combination allows us to reconstruct the three-dimensional structure and identify the rotation reversal without ambiguity. The prominence first rotates CCW about its ascending direction by ∼135° in ~26 minutes and then reverses to the CW rotation by ∼45° in ~15 minutes; i.e., the average CCW and CW rotation speeds are ∼5.2 and ∼3.0 deg minute⁻¹, respectively. The possible mechanisms leading to the rotation and reversal are discussed. The kinematics of the prominence is also analyzed, which indicates that an upward force acts on the prominence during the entire process.

Key words: instabilities – Sun: activity – Sun: coronal mass ejections (CMEs) – Sun: filaments, prominence

Supporting material: animations

1. Introduction

Coronal mass ejections (CMEs), being frequently associated with a prominence eruption (e.g., Webb & Hundhausen 1987; Gopalswamy et al. 2003), are an energetic eruptive phenomenon in the solar atmosphere. Usually, CMEs can arrive at the Earth space within several days after their occurrence and subsequently cause geomagnetic activities (e.g., Gosling et al. 1991; Zhang et al. 2003). The velocity and the magnetic orientation of CMEs near the Earth’s magnetosphere are the major parameters that determine their geoeffectiveness. The higher the CME velocity and the closer its magnetic field to the southward orientation, the more intense the geoeffectiveness will be. For the velocity, it is generally accepted that the magnetic reconnection taking place along current sheets underneath CMEs (e.g., Zhang et al. 2001; Qiu et al. 2004; Jing et al. 2005; Marić et al. 2007; Temmer et al. 2008) and the ideal magnetohydrodynamic (MHD) instability of large-scale magnetic flux ropes, including both kink (Török et al. 2004) and torus instability (Kliem & Török 2006), contribute to the CME acceleration process (e.g., Chen et al. 2007a, 2007b; Song et al. 2013, 2015, 2018). For the magnetic orientation, it is well known that the CME deflection and/or rotation during the eruption and propagation processes will significantly change its initial direction prior to eruption (see Manchester et al. 2017 and references therein). Understanding the physics that determine the CME orientation is crucial in space weather research.

CME deflection refers to the departure from a radial trajectory (e.g., Wang et al. 2004; Lugaz et al. 2011; Shen et al. 2011; Möstl et al. 2015; Capannolo et al. 2017; Liu et al. 2018). Isavnin et al. (2014) have reported a maximum total deflection of 49° in latitude and almost 30° in longitude. The deflections are caused by two primary factors: (1) magnetic forces produced by the background corona (e.g., MacQueen et al. 1986), and (2) the background solar wind flow pattern that can inhibit the latitudinal expansion of CMEs in the corona (e.g., Cremades et al. 2006) and interact with CMEs further in the interplanetary space (e.g., Wang et al. 2004). CME rotation refers to the magnetic axis of the magnetic flux rope in the CME rotates about its ascending direction. For example, the prominence often exhibits this kind of rotation in the corona and displays a characteristic “inverse γ” shape, resulting in a deviation from the original magnetic orientation near the solar surface. Rotations as large as 160° (with large uncertainties) have been reported (Démoulin 2008; Yurchyshyn 2008), demonstrating that the final orientation of the ejecta can differ largely from its initial orientation. Note that this rotation is different from the flux rope rotation about its own axis, which is known as the roll effect (Martin 2003; Panasenco et al. 2011) and will not be pursued in this Letter.

Except for the space weather research as mentioned, it is also important to investigate the CME rotation during eruptions for other two reasons (see Török et al. 2010): (1) it implies that the ejecta has the magnetic structure of a freely moving flux rope,
line-tied only at its two ends, at the onset of the helical deformation (e.g., Rust 2003); and (2) the deformations correspond to the evolution of the helical kink instability of the current channel in the core of a flux rope and are taken as a strong indication for the occurrence of the kink instability (Török et al. 2004; Török & Kliem 2005; Zhou et al. 2006; Gilbert et al. 2007; Yan et al. 2014). This instability can transform the twist of the flux rope field lines into the writhe of the axis, rotating the flux rope’s upper part into the direction of the overlying field and facilitating the rope passage through the overlying field to form a CME (Sturrock et al. 2001; Fan 2005).

Many observations of the prominence rotation about its ascending direction have been reported during both failed and successful eruptions (e.g., Ji et al. 2003; Williams et al. 2005; Zhou et al. 2006; Thompson 2011). In the meantime, some numerical simulations are conducted to analyze the rotation phenomenon (Török et al. 2004; Török & Kliem 2005; Cohen et al. 2010; Török et al. 2010; Kliem et al. 2012). So far almost all of the prominences show a rotation with unique direction, i.e., either counterclockwise (CCW) or clockwise (CW) viewed from above throughout the whole eruption process. Only in the famous “Cartwheel CME” event that occurred on 2008 April 9, did the prominence first rotate CCW by ~115° up to a heliocentric height of 2.5 $R_e$ and then displayed a possible slight CW rotation by ~15° in the height range up to 3.3 $R_e$. (Thompson et al. 2012). In this Letter, we report an intriguing prominence eruption that exhibits both CCW and CW rotations sequentially without ambiguity. The detailed observations and results are presented in Section 2, followed by the discussion and summary in Section 3.

2. Observations and Results

2.1. Instruments

The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamic Observatory (SDO) images the chromosphere, transition region, and corona in 10 narrow ultraviolet (UV) and extreme-UV (EUV) passbands with high cadence (12 s), high spatial resolution ($0″.6$ per pixel), and large field of view (FOV; $1.3 R_e$). The Extreme Ultraviolet Imager (EUVI) on board the Solar Terrestrial Relations Observatory (STEREO) provides solar EUV images at four wavelength with an FOV of $1.7 R_e$ (Howard et al. 2008). Both SDO and STEREO provide solar remote-sensing images at ~1 au, while STEREO consists of two spacecraft in orbits around the Sun, one ahead (A) and the other behind (B) the Earth. Both A and B separate from the Earth by ~22° each year in heliocentric longitude and provide solar observations from different perspectives.

2.2. Rotations of the Prominence

A failed prominence eruption was observed by the AIA and EUVI-A on 2010 December 10 when STEREO-A was ~85° west of the Earth as shown in Figure 1. The source region is located at the heliographic coordinates of ~N35W15 as seen from the STEREO-A perspective and indicated by a red dot on the Sun. The source near the surface is invisible completely for the AIA and EUVI-B. However, AIA can image the prominence ascending motion during the eruption (from 05:54 UT to 06:41 UT) as the source region is close to the solar limb when observed from the Earth perspective.

Figure 1. Positions of the STEREO-AB, Earth (SDO), Venus, and Mercury in the ecliptic plane on 2010 December 10. The red dot on the Sun marks the prominence source region, which appears on the solar disk when viewed from STEREO-A, on the limb from SDO, and on the backside of the Sun from STEREO-B.

Figure 2 presents eight snapshots of the AIA images at 304 Å that display the failed eruption process. The prominence initially rotates CCW (as viewed from above) from 06:00 UT to 06:26 UT (top panels); i.e., the north leg moves toward the observer, and the south leg moves away from the observer. We trace the angle between the tangent vector at the prominence apex (direction from the south to north leg) and the longitudinal line (north direction), which is called the angle of prominence apex hereafter. At 06:00 UT, this angle is close to 0° as shown in Figure 2(a), which can be readily demonstrated in the EUVI-A image (Figure 3(a)). The angle increases to an acute angle at 06:06 UT (Figure 2(b)) due to the CCW rotation, a right angle at 06:16 UT as the tangent vector is nearly parallel to the line of sight or latitudinal line (Figure 2(c)), and then an obtuse angle at 06:26 UT (Figure 2(d)). After that, the prominence starts the reverse rotation, or CW rotation from 06:27 UT onward (bottom panels) and the angle decreases to a right angle before fading away at 06:41 UT (Figure 2(h)).

To display the reversal unambiguously, we show the EUVI-A images in Figure 3, which presents one image at 195 Å (Figure 3(a)) and four images at 304 Å with the cadence of 10 minutes (Figures 3(b)–(e)). White dotted lines are used to show the prominence spine clearly, and the white solid curve depicts the solar limb when observed from the AIA perspective. Figure 3(a) shows that the spine of the prominence (note that the prominence is dubbed as filament when located on the solar disk) is almost along the longitude (i.e., the angle of the prominence apex is close to 0°). Figures 3(b)–(d) present the situations when it is acute, right, and obtuse angle, respectively. As mentioned, the angle of prominence apex is close to 90° at 06:41 UT. It would be around 270° if the reversal did not occur, which means that the angle is likely larger than 180° at 06:36 UT. If so, the upper part of the north leg would project to the right side of the south leg when observed from the EUVI-A perspective, thus a crossing of the two legs should be expected in the EUVI-A image due to the projection effect. Furthermore, the magnetic reconnection between the two legs would probably take place in this situation. However, no crossing (i.e., no “inverse γ” characteristic) and reconnection signatures between
the two legs are observed by the EUVI-A, and the south leg keeps at the right side all the time. This supports the theory that the rotation reversal did occur during the eruption.

To demonstrate the rotation and reversal intuitively, the three-dimensional (3D) topology of the prominence spine is reconstructed with the AIA and EUVI-A observations. We use the solar software routine scc_measure to acquire the 3D information of the prominence. The program acts as follows (see e.g., Thompson et al. 2012): two side-by-side images from both telescopes are selected and presented. The user selects one point on the AIA image with the cursor, and the program calculates the 3D line of sight represented by the selected point and overplots the projection of the line onto the EUVI-A image. Then the user identifies the same point at this line on the EUVI-A image. The 3D coordinates of the selected point, including the heliographic longitude, latitude, and radial distance in solar radii, are then determined. With this technique, we get the 3D locations of multiple points along the prominence spine and reconstruct the 3D structure.

The 3D results at four times are acquired and presented in Figure 4, including both the side and top views. The red, green, blue, and white lines correspond to Figures 2(b), (c), (d), and (g), respectively. The bottom part of the north leg is invisible in the EUVI-A image at 06:36 UT (see Figure 3(e)), so the reconstructed spine is not complete for this time (see Figure 4(a)). As the points in both AIA and EUVI images are not guaranteed to represent exactly the same point, the 3D results should be regarded as an approximation, but good enough to trace out the spine of the prominence. Figure 4(a) demonstrates that the prominence reverses its rotation direction from the side view. The relative relations of the prominence spine at 06:16 UT, 06:26 UT, and 06:36 UT shows the CCW and CW rotations. This is unambiguously confirmed from the top view as shown in Figure 4(b). The yellow arrow depicts the CCW rotation from 06:16 UT (green) to 06:26 UT (blue), and the red arrow presents the CW rotation from 06:26 UT (blue) to 06:36 UT (white). Furthermore, we know that the angle of prominence apex at 06:26 UT is around 135° through the 3D reconstruction result. This means that the prominence first rotates CCW about 135° in ~26 minutes, and then CW about 45° in ~15 minutes. Due to the limited time points, the validated variation trend of the rotation speed is not available. The average CCW and CW rotation speeds are 5.2 and 3.0 deg minute⁻¹, respectively. Note that the rotation from 05:54 to 06:00 UT is neglected as no clear observations are available. Therefore, the CCW rotation of ~135° should be the lower limit.

2.3. Kinematics of the Prominence

The kinematics of the prominence is obtained by analyzing the AIA 304Å images. We carefully inspect the images and identify the prominence leading edges along the ascending direction as marked with the white dotted line in Figure 2(e). The height refers to the projected distance of the leading edge from the solar surface. The measurements are performed 30 times and all of the results are plotted in Figure 5(a) with different colors, which show that the difference among the measurements is not significant. The mean of the 30 measurement values at each time is adopted as the final height value at that time, and the corresponding standard deviation is taken to be the error. The final height with error bars is plotted in Figure 5(b). The velocity is calculated from a numerical differentiation that employs the three-point Lagrangian interpolation method (e.g., Song et al. 2015, 2018). The height errors are used to derive the velocity errors in the
Figure 3. EUVI-A observations of the prominence morphology during the eruption in 195 Å (a) and 304 Å (b)–(e) passbands. The white dotted lines depict the prominence spine. Panels (b)–(e) of this figure are available online as an animation that displays the eruption process in 304 Å passband. The animation starts at 06:06 UT and ends at 06:36 UT. The duration of the video is four seconds.

(An animation of this figure is available.)

Figure 4. Side (a) and top (b) views of the reconstructed 3D topology. The side one displays the spine of the erupting prominence at different times as viewed from the AIA perspective. The yellow and red arrows in panel (b) depict the CCW (from green to blue) and CW (from blue to white) rotations, respectively. Please pay attention to the top part of the reconstructed prominence and follow the arrows to inspect the rotation directions, reducing influence from the prominence legs. This figure is available online as an animation that displays the observations from different views continuously. The duration of the video is 27 seconds.

(An animation of this figure is available.)
acceleration about approached to zero around 06:32 UT with an average

Figure 5

Figure 5. Height-time (a), (b) and velocity-time (c) plots of the prominence during the failed eruption. See the text for details.

standard way. The velocity with the error bars is plotted in Figure 5(c).

As mentioned, the prominence started to rise after 05:54 UT according to the AIA observations. Its velocity increased from almost zero to the maximum (~170 km s\(^{-1}\)) around 06:14 UT in about 20 minutes with an average acceleration ~141.7 m s\(^{-2}\). Then it began to decelerate and the velocity approached to zero around 06:32 UT with an average acceleration about -157.4 m s\(^{-2}\), which is smaller than the solar gravitational constant (g = 274 m s\(^{-2}\)). This indicates that the force, pushing the prominence upward, even existed during the deceleration process.

3. Discussion and Summary

The mechanism of prominence rotation is still elusive. Numerical simulations (Kliem et al. 2012) demonstrated the conversion of twist into writhe in a kink-unstable magnetic flux rope acting as a rotation mechanism. The dynamical evolution process of the kink instability has shown good quantitative agreement with many well-observed events (e.g., Török & Kliem 2005; Williams et al. 2005; Kliem et al. 2012).

Therefore, the rotation is taken as a strong indication of the kink instability as mentioned. However, there may exist an alternative rotation mechanism for the line-tied magnetic flux ropes, which relies on the presence of an external shear-field component (Isenberg & Forbes 2007). For a given chirality of the erupting field, the latter mechanism yields the same rotation direction as the kink instability (e.g., Kliem et al. 2012). In addition, some other mechanisms, e.g., magnetic reconnection with the surrounding field (Cohen et al. 2010; Thompson 2011), the straightening from an initial S or inverse-S shape (Török et al. 2010), and any asymmetric deflection of the rising flux rope from radial ascent induced by adjacent coronal holes (Panasenco et al. 2011) and/or the heliospheric current sheet (HCS; Yurchyshyn 2008), can contribute to the rotation. Each of the above rotation mechanisms is usually controlled by more than one parameter. Therefore, it is not a trivial task to confirm which mechanisms are responsible for the rotation in the observational study.

The rotation direction of prominences is determined by the helicity sign of the source region, though some exceptions exist (Muglach et al. 2009). Prominences erupting from source regions with positive/negative helicity, i.e., dextral/sinistral chirality, usually exhibit CW/CCW rotation as viewed from above (Green et al. 2007; Liu et al. 2018). In this event, the post-eruptive arcades are left-skewed as shown in Figure 3(d), which implies the sinistral chirality (e.g., Ouyang et al. 2017) and the CCW rotation. However, the prominence exhibited both CCW and CW rotations during the eruption, which adds complexity to the explanation of the prominence rotation. One simulation has showed some backward rotation (see Figure 7 in Kliem et al. 2012), while it is not straightforward to clarify the mechanism responsible for the reversal.

Here we provide a tentative explanation of the observed reversal of rotation. It is suggested that the Lorentz forces, due to both the twisted field lines of the flux rope and the shear-field component in the ambient field, can cause the prominence rotation away from the polarity inversion line (PIL) in the photosphere during the early eruption stage. The currents and Lorentz forces in the erupting prominence decrease at larger heights, while the influence of the pressure gradient force increases with the increasing plasma beta in the ambient environment. Then the alignment with the HCS (or the PIL of the radial field component above the source region) becomes more important in the dynamics of the prominence eruption (Kliem et al. 2012; Thompson et al. 2012). This may reverse the prominence rotation direction to make its orientation along the PIL at a higher height. As the source region was behind the west limb when the event took place, we conduct the potential field extrapolation based on the magnetogram on 2010 December 5, five days earlier than the event, when the source region was located on the solar disk. The extrapolation result shows that the PIL of the radial field component around 260 Mm above the source region (where the reversal occurs) is roughly parallel with the original prominence orientation (not shown), which implies that the reversal is rotating the prominence back to alignment with the PIL at this height. This indicates that the discussed mechanisms above are possibly responsible for the rotation reversal. Unfortunately, the prominence faded away during the rotation, and we cannot conclude whether its orientation is ultimately in alignment with the PIL.
In this Letter, an intriguing failed prominence eruption that occurred on 2010 December 10, was analyzed with both the AIA on board the SDO and EUVI on board the STEREO-A when the two spacecraft were separated by ~85°. It is a limb (disk) event from the AIA (EUVI-A) perspective. The prominence exhibited both CCW and CW rotations about its ascending direction sequentially during the eruption process, and the reversal was demonstrated unambiguously through the 3D reconstruction results. The prominence first rotated CCW by ~135° in about 26 minutes, and then reversed to rotate CW by ~45° in around 15 minutes. The average CCW (CW) rotation speed is ∼5.2 (3.0) deg minute⁻¹. Our observational results complicate the effort to predict the space weather effects of CMEs, as the rotation reversal can take place during both successful (Thompson et al. 2012) and failed (this event) prominence eruptions. The prominence usually escapes into the interplanetary space quickly during the successful eruption, resulting in a difficulty in observing the reversal process. Conversely, it is relatively easy to image the rotation reversal in the corona during a failed eruption, which provides us with the observational characteristics of this phenomenon. More detailed theoretical considerations and numerical simulations are necessary to identify the reversal mechanisms. The kinematical process indicated the force pushing the prominence upward existed during the deceleration process.

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