A large polar-crown prominence composed of different segments spanning nearly the entire solar disk erupted on 2010 December 6. Prior to the eruption, the filament in the active region part split into two layers: a lower layer and an elevated layer. The eruption occurs in several episodes. Around 14:12 UT, the lower layer of the active region filament breaks apart: One part ejects toward the west, while the other part ejects toward the east, which leads to the explosive eruption of the eastern quiescent filament. During the early rise phase, part of the quiescent filament sheet displays strong rolling motion (observed by STEREO-B) in the clockwise direction (viewed from east to west) around the filament axis. This rolling motion appears to start from the border of the active region, then propagates toward the east. The Atmospheric Imaging Assembly (AIA) observes another type of rotating motion: In some other parts of the erupting quiescent prominence, the vertical threads turn horizontal, then turn upside down. The elevated active region filament does not erupt until 18:00 UT, when the erupting quiescent filament has already reached a very large height. We develop two simplified three-dimensional models that qualitatively reproduce the observed rolling and rotating motions. The prominence in the models is assumed to consist of a collection of discrete blobs that are tied to particular field lines of a helical flux rope. The observed rolling motion is reproduced by continuous twist injection into the flux rope in Model 1 from the active region side. Asymmetric reconnection induced by the asymmetric distribution of the magnetic fields on the two sides of the filament may cause the observed rolling motion. The rotating motion of the prominence threads observed by AIA is consistent with the removal of the field line dips in Model 2 from the top down during the eruption.

**Key words:** Sun: coronal mass ejections (CMEs) – Sun: filaments, prominences – Sun: magnetic topology – Sun: rotation – Sun: UV radiation – Sun: X-rays, gamma rays

**Online-only material:** animations, color figures

1. INTRODUCTION

Solar flares, filament eruptions, and coronal mass ejections (CMEs) are spectacular solar events and are the primary driver of “space weather” at Earth. It is well accepted that these three phenomena are different manifestations of a single physical process that involves a disruption of the coronal magnetic field (Harrison 1996; Forbes 2000), but it is unclear how the process that involves a disruption of the coronal magnetic field. Filaments or prominences are chromospheric material suspended in the corona by magnetic fields. We will use filament and prominence interchangeably throughout the text. Since the coronal magnetic field is difficult to observe, filaments can be useful tracers of the locations and movements of the erupting fields (Sterling & Moore 2005). Therefore, studying the evolution of the erupting filament may shed light on the trigger mechanism of a specific eruption.

Helical structures are frequently observed during prominence eruptions (Vrsnak et al. 1988; Rust & Kumar 1994; Koleva et al. 2012, and references therein). Helical-like structures are also observed in filaments before the eruption (e.g., Kurokawa et al. 1987) or in stable filaments (e.g., Rompolt 1975; Vrsnak et al. 1993). Sometimes helical structures are visible only in part of the prominence (internal/microscopic magnetic twist). In other cases, especially during eruptions, they are the most visible feature (external/macrosopic twist), such as in “helical prominences” where the prominence body is composed of a bundle of twisted threads (e.g., Rompolt 1975; Vrsnak et al. 1988, 1991; Srivastava et al. 1991).

The frequent exhibition of helical structures in erupting filaments is evidence of a twisted magnetic flux rope. There are two types of models regarding the formation of the twisted flux rope. Some models assume that a twisted flux rope is present in the region before the eruption. This flux rope becomes unstable as a result of footpoint motion, injection of magnetic helicity, and/or draining of heavy prominence material (Forbes & Isenberg 1991; Gibson & Low 1998; Krall et al. 2000; Wu et al. 1997; Roussev et al. 2003). Other models begin with an untwisted, but highly sheared magnetic field that becomes unstable as a result of reconnection, flux cancellation, or a similar process (Mikic et al. 1988; Mikic & Linker 1994; Antiochos et al. 1999; Amari et al. 2003; Manchester 2003).

According to the latter models, a twisted flux rope does not exist prior to eruption, but is formed during the eruption as a result of reconnection between the two sides of the sheared arcade. Therefore, in both types of models a twisted flux rope is present in the ejecta. The existence of such flux ropes is confirmed by in situ observations of magnetic fields in interplanetary magnetic clouds (Burlaga 1991). However, the question remains as to when and how such flux ropes are formed.

Erupting filaments are sometimes observed to undergo a rotation about the vertical direction as they rise (e.g., Kurokawa et al. 1987; Ji et al. 2003; Zhou et al. 2006; Green et al. 2007; Liu et al. 2007; Liu & Alexander 2009; Muglach et al. 2009; Bemporad et al. 2011; Joshi & Srivastava 2011; Thompson 2011). This filament rotation is interpreted as a conversion of twist into writhe in a kink-unstable flux rope. Therefore, MHD helical-kink instability is often taken to be the primary trigger of these eruptions (Fan & Gibson 2007; Török et al. 2010; Kliem et al. 2012). Consistent with this interpretation, the rotation is usually found to be clockwise (as viewed from
above) if the post-eruption arcade has right-handed helicity, but counterclockwise if it has left-handed helicity. Helicity is a quantitative, mathematical measure of chirality (Berger & Field 1984; Mughal et al. 2009; Ramporal et al. 2011). Magnetic reconnection with the ambient field can also cause filament rotation during eruption (Cohen et al. 2010; Thompson 2011). The aforementioned filament rotation should be distinguished from the rotation of the filament around its own axis, namely the “roll effect” (Martin 2003; Panasenko et al. 2011), i.e., the top of the prominence spine gradually bends to one side of the spine during the rise of the filament. This sideways rolling creates twist of opposite sign in the two prominence legs as the prominence continues to rise. Panasenko et al. (2011) interpreted this effect as consequence of force imbalances inside the filament arcade related to the adjacent large coronal holes. Murphy et al. (2012) hypothesize that this rolling motion is induced by an offset between the CME current sheet and the rising flux rope during some events.

In the present work, we identify two other types of filament rotation that occurred during the filament eruption on 2010 December 6. Thompson (2012a) presents STEREO/EUVI observations of this filament and divides this filament into three branches. The main eruption occurred in the middle branch around 14:16 UT on December 6, while the right part of the filament erupted at 2:06 UT on December 7. Thompson (2012a) studied the magnetic twist in the erupting prominence using triangulation of prominence threads with primary focus on the second eruption. The structure and dynamics of this prominence before the eruptions are presented in our previous paper (Su & van Ballegooijen 2012, hereafter Paper I). In this paper, we focus on plasma dynamics during the first eruption, which will be referred as filament eruption or main eruption on December 6 in the following sections.

2. OBSERVATIONS

A polar-crown filament spanning nearly the entire solar disk erupted around 14:16 UT on 2010 December 6. This filament eruption is associated with a CME, and a corresponding long-duration B2 (GOES class) flare is identified. The Solar and Heliospheric Observatory (SOHO) LASCO CME catalog1 shows that the CME first appears in the LASCO/C2 field of view at 17:24 UT, and the linear speed is 538 km s\(^{-1}\) projected onto the plane of sky. According to the CACTus CME catalog,2 the CME first appears at LASCO/C2 at 18:00 UT, and the CME median velocity is 523 km s\(^{-1}\).

The prominence eruption under study is well observed near the east limb by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO). Extreme Ultraviolet Imaging (EUVI) Telescopes on board the Solar Terrestrial Relations Observatory (STEREO; Wuelser et al. 2004; Howard et al. 2008) also observed this eruption. The separation angle between the twin STEREO spacecraft was about 171°. STEREO-B (Behind) viewed this event on the solar disk, while this event is visible at the east limb in the view of STEREO-A (Ahead). Synoptic observations by the X-Ray Telescope (XRT; Golub et al. 2007; Kano et al. 2008) on board Hinode (Kosugi et al. 2007) and Hα observations by Kanzelhöhe Solar Observatory (KSO) are also included. The photospheric magnetic field information is provided by the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board SDO.

The large polar-crown filament is composed of active region parts and quiet-Sun parts on the eastern and western sides of the active region. AIA and STEREO-B images of the prominence at 304 Å prior to the eruption are shown in Figure 1. According to the eruption behavior, the prominence is divided into seven different segments, which are marked using white arrows in Figure 1. Prior to the eruption, the filament in the active region splits into two layers. One layer lies at the core of the active region (AR1), while the other layer is elevated (AR2). This type of double-decker filament has also been studied by Liu et al. (2012). The quiescent prominence on the eastern side of the active region is composed of four segments. The segment closest to the active region is named Q1, and the other segments are named Q2, Q3, and Q4 sequentially based on the distance away from the active region (see Figure 1). The Q2 and Q3 prominences appear to be divided by the dense column (DC) structure (black arrow in Figure 1), which is similar to the solar “tornado” studied by Su et al. (2012). The non-erupting segment Q4 and the quiescent filament on the western side of the active region (Q5) correspond to the left and right filament branches as named by Thompson (2012a). Thompson (2012a) presented that the eruption occurs in the middle branch of the filament, which corresponds to the AR1, AR2, Q1, Q2, and Q3 filaments in this paper.

Figures 2–4 show AIA, STEREO-B/EUVI, and STEREO-A/EUVI observations of the prominence at the onset of (top row), during (middle row), and after (bottom row) the eruption at 304 Å (left column) and 193/195 Å (right column) on December 6. The eruption originates from brightenings and ejections of AR1 filament material in two opposite directions (east and west). This ejection leads to the eruption of the eastern quiescent filament (Q1, Q2, Q3) on December 6 (Figures 2(c), 3(c), and 4(c)), which is followed by a slow rise of the western quiescent filament (Q5) that erupted on December 7 (Figures 2(e), 3(e), and 4(e)). In the present study, we focus on the eruption on December 6. The nearest eastern quiescent prominence (Q1) erupts first and appears to be the strongest. The further the prominence is away from the active region, the later and weaker the eruption is. At the early stage of the eruption, the Q1 and Q2 prominences display a rolling motion while rising up as observed at 195 Å by STEREO-B. The Q1 prominence erupts like a jet or surge with a more inclined path rather than a radial path. It appears to be the first part to leave the AIA field of view. Prominence Q2 evolves into an arch-like structure (Figures 2(c), 3(c), and 4(c)) before its successful eruption. AIA has a better view of the Q3 prominence, which rises up then drags back to the Q4 prominence, which shows no eruption at all (Figures 2(c) and (e)). The arch-like structure (Q2) remains separate from the vertical threads (Q3) during the entire eruption process (Figure 2(c)). The overlying active region filament (AR2) rises up and erupts when the eastern quiescent filament has already risen to a much larger height. A timeline of various activities during the eruption is shown in Table 1.

Corresponding to Figures 2–4, three animations (animations 1–3) of this eruption are available in the online version of the journal. The cadence of the AIA video is 2 minutes, which is reduced from the original 12 s observations. The cadence of STEREO observations at 195 Å is generally 5 minutes with an exception of 2–3 minutes between 16:10 UT and 20:00 UT for STEREO-A. STEREO generally took images every 10 minutes at 304 Å with an exception of 2–3 minutes between 17:16 UT and 21:56 UT for STEREO-A. Structure and dynamics of different prominence segments during the eruption are better viewed in

1 http://cdaw.gsfc.nasa.gov/CME_list/
2 http://sidc.oma.be/cactus/catalog.php
Table 1
Activity Timeline during the Eruption

| Time (UT)        | Activity                                      |
|-----------------|-----------------------------------------------|
| 2010 Dec 6 14:16| Brightenings in active region                 |
| 2010 Dec 6 14:21| Clear rise of AR1                             |
| 2010 Dec 6 14:26| Rolling motion of Q1 and Q2 begins            |
| 2010 Dec 6 14:46| AR1 filament ejection in two directions       |
| 2010 Dec 6 15:30| Clear Eruption of Q1 and Q2 begins            |
| 2010 Dec 6 16:00| Rise of Q3 begins                             |
| 2010 Dec 6 16:00| Bright curved features on the eastern quiet Sun begin to fade out |
| 2010 Dec 6 18:00| AR2 eruption begins                           |
| 2010 Dec 6 18:30| Bright ribbons in active region appear        |
| 2010 Dec 6 19:30| First post-eruption loops appear              |
| 2010 Dec 7 2:06 | Eruption of Q5                                |

Although the eruption originates from the active region part, the elevated filament in the active region does not erupt until 18:00 UT or so. The eruption of the elevated active region filament is associated with the expansion or disappearance of the overlying loops as observed at 195 Å by STEREO (white arrows in the right columns of Figures 3 and 4). Following the eruption of the active region filament, bright ribbons appeared on the two sides of the filament channel around 18:30 UT as observed at 304 Å by AIA (Figure 2(e)). Highly sheared post-eruption loops (Figure 2(f)) first appear at 193 Å by AIA around 19:30 UT. These loops show that the filament channel has sinistral orientation of the axial field (see Paper I).

2.2. Rolling Motion of Prominence Q1 and Q2 Observed by STEREO-B

After 14:21 UT, STEREO-B/EUVI detects a clear rise of the elevated filament in the active region part at 195 Å. Following this rise, the dark quiescent filament (Q1 and Q2) sheet adjacent to the active region begins to rise up as well and displays a rotating motion around the filament axis. This rolling motion is along the clockwise direction when viewing the filament from the east to the west (see animation 2). Note that this rolling motion is well observed by STEREO-B, while no clear corresponding motion is identified in the SDO/AIA and STEREO-A observations. A series of STEREO-B images at 195 Å of the early stages of the rolling motion are shown in Figure 6. The bottom and top of the filament sheet are marked using the solid and dashed white lines, respectively. At 195 Å, the filament is observed in optically thick absorption, which makes it easier for us to qualitatively identify the relative heights of different layers. This figure shows that the western end of the bottom of the Q1 filament begins to rise upward, passing in front of the top of the sheet, which rotates downward gradually. Figure 6(c) shows that the western Q1 filament is turned around, i.e., the bottom of the sheet becomes the top and vice versa.
Figure 2. SDO/AIA observations of the prominence eruption on 2010 December 6. The images in the left and right columns are taken at 304 Å and 193 Å, respectively. Different segments of the prominence are marked with white arrows. The black arrows refer to the straight features on the two sides of the active region filament channel.

This rolling motion (illustrated with black arrow in Figure 6) is associated with a slow rise of the filament. Around 14:51 UT, the projection of the filament sheet reaches the limb as shown by Figure 6(d). STEREO-B observations (animation 2) show that this rolling motion begins from the border of the active region and quiet Sun, then propagates toward the quiescent filament on the east. This clear rolling motion appears mainly in the Q1 and Q2 filament segments. It lasts until 17:00 UT or so, after which the rising motion of the filament becomes dominant.

Initially, the bright curved features (black arrow in Figure 3(b); Su et al. 2010, 2012) on the northern side of the quiescent filament channel remain undisturbed. These bright features are interpreted as the lower legs of the field lines that turn into the flux rope in Paper I. The bright features fades out starting from the eastern end (near the dense column structure),
then spreads to the western part gradually. This process starts around 16:00 UT, and most of the bright curved features fade out by 19:00 UT.

2.3. Rotating Motion of the Q3 Prominence Observed by SDO

The previous section shows the rolling motion of the Q1 and Q2 filament segments as observed by STEREO-B. The Q3 prominence displays another type of rotating motion, which is clearly identified in the SDO observations at 304 Å as shown in Figure 7. The curved black arrows in Figure 7(c) represent the path of the prominence motion. This figure shows that Q3 contains mainly thin threads, which are initially crinkled and more vertical (Figure 7(a)), then turn horizontal and become more straight with time (Figure 7(d)). There is a lower edge for these threads. The southern end of this lower edge rises much faster than the northern end. Eventually, these initially vertical threads make a half turn while draining back to the Q4 filament (see Figure 7 and animations 1 and 2). The northern leg of the
Figure 4. STEREO-A/EUVI observations of the prominence eruption on 2010 December 6. The left and right columns show images taken at 304 Å and 195 Å, respectively. The white arrows in the left and right columns refer to different segments of the prominence and overlying loops in the active region, respectively. (An animation (animation 3) and a color version of this figure are available in the online journal.)
arch of the Q2 filament also shows the same rotating behavior, though not as clearly as that shown in the Q3 filament.

Not all of the filament material successfully escaped from the Sun even for the Q1 filament. Most Q3 filament material appears to fall back to the Sun as observed at 304 Å by AIA. The northern leg of the Q2 filament displays very similar behavior as the Q3 filament, although the Q2 filament rises much higher. The falling motion starts from the Q2 filament and is followed by the Q3 filament. Around 17:30 UT, a portion of materials in the Q1 filament starts to fall back toward the Sun. Around 18:20 UT, the southern leg of the Q2 filament arch shows sign of material falling that is associated with an untwisting motion, since all the falling material became straight in the end.

2.4. Post-eruption Arcades after the Eruption

After the filament eruption on December 6, cusp-shaped arcades are observed by both SDO/AIA and Hinode/XRT, as shown in Figure 8. The top three rows present AIA images at 211 Å (first row), 335 Å (second row), and 94 Å (third row) taken around 01:00 UT (left column) and 06:00 UT (right column) on 2010 December 7. In AIA, the cusp-shaped arcades are best observed at 94 Å (Figures 8(e) and (f)), and they first appear around 20:00 UT on December 6. Cusp-shaped structures are also visible at 335 Å (Figures 8(c) and (d)) after 1:00 UT on December 7. More rounded loop-like structures are observed in most of the other EUV channels (e.g., Figures 8(a) and (b)). AIA observations suggest that the cusp-shaped arcades show clear evidence of field-line shrinkage as that found by Reeves et al. (2008). The bottom row of Figure 8 shows two XRT images taken with Al-mesh and Ti-poly filters at 06:03 UT on December 7, respectively. This figure suggests that the cusp-shaped arcades are best viewed in the soft X-ray images taken by XRT. Moreover, XRT can see the more outer part of the cusp, i.e., the part that just goes through reconnection.

As mentioned earlier, the post-eruption loops first appear around 19:30 UT on December 6. Cusp structure is still visible 10 hours later (as shown in Figure 8), which indicates a slow and gradual reconnection event. The post-eruption arcades (Figure 8) appear to be a characteristic skewed candle flame shape. The skewed arch is a signature of asymmetric reconnection, as suggested by Murphy et al. (2012). The post-eruption arcades appear to be located at the quiet-Sun
Figure 6. STEREO-B/EUVI 195 Å observations of the rotating motion of the Q1 and Q2 prominences. The white solid and dashed lines refer to the initial bottom and top border of the filament. The rotating direction of the filament is represented by the black arrow. The white arrows mark different segments of the filament as well as the dense column (DC) structure.

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

region where the eruption of prominence Q1 and Q2 occurs. No clear post-eruption arcades are observed in the active region part. Moreover, a comparison of Figure 2 and Figure 8 shows that the straight features (i.e., lower legs of the large scale overlying loops, see yellow arrows in Figure 8) located on the two sides of the active region filament remain unchanged through the eruption. AIA and STEREO observations also show that the active region filament escapes toward the quiet-Sun part on the east then erupts. These observations suggest that this eruption is a sideways eruption, because initially the filament did not erupt radially by opening up the overlying loops in the active region. A possible interpretation of the sideways or non-radial eruption is that the confining magnetic pressure decreases much faster horizontally than upward (Sun et al. 2012).

3. MODEL FOR THE ERUPTING PROMINENCE

In this section, two simple models for the dynamics of the erupting prominence on December 6 are presented. The main goal is to understand the nature of the rotating motions described in Section 2. The prominence is assumed to consist of a collection of discrete blobs that are tied to particular field lines. The time-varying magnetic field is described by a simple analytical model of a helical flux rope, and the motion of the blobs is determined by solving their equations of motion along the field lines, taking into account the effects of gravity and friction with the surrounding corona. At the top of the erupting flux rope the plasma is forced to move radially outward, but in the legs the plasma falls back down to the photosphere.

3.1. Assumptions and Methodology

The prominence is assumed to be driven outward by an expanding magnetic flux rope (e.g., Chen et al. 1997). We assume that the flux rope was already present prior to the eruption, and that the two legs of the expanding flux rope remain attached to the photosphere. The magnetic field is assumed to evolve according to ideal MHD; i.e., we neglect the effects of magnetic reconnection in the wake of the erupting flux rope. However, we do take into account the writhing of the flux tube (e.g., Kliem et al. 2012). The shapes of the magnetic field lines are described by an analytic function \( r(p, q, \xi, t) \), where \( p \) and \( q \) are labels of the field lines, \( \xi \) is the coordinate along a field line, and \( t \) is the time. The coordinate \( \xi \) varies from \(-1\) at one endpoint of the field lines to \(+1\) at the other end. A detailed
Figure 7. SDO/AIA 304 Å observations of the rotating motion of the Q3 prominence. The white arrows refer to different segments of the filament. The rotating direction of the filament is represented by the black arrow.

The prominence plasma is described as a collection of discrete blobs ($i = 1, 2, \ldots$) located on different field lines characterized by labels $p_i$ and $q_i$. The blobs are treated as point masses that are tied to the particular field lines on which they are initially located, i.e., a blob can slide along its field line, but cannot move from one field line to another (consistent with our assumption of ideal MHD). We simulate the dynamics of the blobs by solving their equations of motion along the field lines, including the effects of field-line motion, gravity, and a hypothetical frictional force. The magnetic field is assumed to be relatively strong, so that the weight of the prominence blobs does not significantly affect the shapes of the field lines. In the initial state just before the start of the eruption, the flux rope is assumed to be at rest in the low corona, and the blobs are located at the dips of the helical windings. The expansion of the flux rope causes some blobs to be carried outward by the expanding field, while others fall back down to the photosphere.

Let $\xi_i(t)$ be the dimensionless coordinate of a blob along its field line, then its position in the corona is $r_i(t) = r[p_i, q_i, \xi_i(t), t]$. Each blob is carried along by the motion of the field line on which it is located, so its velocity is

$$v_i(t) = \frac{\partial r}{\partial \xi} \dot{\xi}_i + \frac{\partial r}{\partial t},$$  \hspace{1cm} \text{(1)}$$

and its acceleration is

$$\ddot{r}_i = \frac{\partial^2 r}{\partial \xi^2} (\dot{\xi}_i)^2 + 2 \frac{\partial^2 r}{\partial \xi \partial t} \dot{\xi}_i + \frac{\partial^2 r}{\partial t^2},$$  \hspace{1cm} \text{(2)}$$

where the dot denotes a total derivative with respect to time. The coronal plasma surrounding the blob is assumed to move with the expanding flux rope ($\xi_{cor} = \text{constant}$), so the coronal plasma velocity is

$$v_{cor}(r_i) = \frac{\partial r}{\partial t}. $$  \hspace{1cm} \text{(3)}$$

Therefore, the blob moves relative to its local surroundings and may experience a “frictional” force due to its motion along the field line (as described by $\dot{\xi}_i$). Then the equation of motion of a blob along its field line is given by

$$\ddot{r}_i \cdot \mathbf{s}_i = \mathbf{g}(r_i) \cdot \mathbf{s}_i - \beta [v_i - v_{cor}(r_i)] \cdot \mathbf{s}_i, \hspace{1cm} \text{(4)}$$

where $\mathbf{s}_i$ is the unit vector along the field line, $\mathbf{g}(r)$ is the acceleration of gravity, $\beta$ is a friction coefficient, and we neglect
Figure 8. SDO/AIA and Hinode/XRT observations of the post-eruption arcades. The first (211 Å), second (335 Å), and third (94 Å) rows show AIA images taken around 01:00 (left column) and 06:02 UT (right column) on 2010 December 7. The two images in the last row are taken with Al-mesh and Ti-poly filters by XRT at 06:03 UT on December 7. The AIA images at 335 Å and 94 Å are summed then averaged over 20 images. The cusp structure is marked with white arrows. The yellow arrows refer to the straight features on the two side of the active region filament channel.

(A color version of this figure is available in the online journal.)
the effects of plasma pressure. Using $\dot{\mathbf{s}}_i = (\partial \mathbf{r}/\partial \xi)/|\partial \mathbf{r}/\partial \xi|$, we obtain the following second-order differential equation for the coordinate $\xi_i(t)$:

$$\dot{\xi}_i + a_i(\dot{\xi}_i)^2 + 2b_i \dot{\xi}_i + c_i = -\beta \dot{\xi}_i,$$  \hspace{1cm} (5)

where

$$a_i \equiv \left( \frac{\partial \mathbf{r}}{\partial \xi} \cdot \frac{\partial^2 \mathbf{r}}{\partial \xi^2} \right) / \left| \frac{\partial \mathbf{r}}{\partial \xi} \right|^2,$$  \hspace{1cm} (6)

$$b_i \equiv \left( \frac{\partial \mathbf{r}}{\partial \xi} \cdot \frac{\partial^2 \mathbf{r}}{\partial \xi^2 \partial t} \right) / \left| \frac{\partial \mathbf{r}}{\partial \xi} \right|^2,$$  \hspace{1cm} (7)

$$c_i \equiv \left[ \frac{\partial \mathbf{r}}{\partial \xi} \cdot \left( \frac{\partial^2 \mathbf{r}}{\partial t^2} - \mathbf{g} \right) \right] / \left| \frac{\partial \mathbf{r}}{\partial \xi} \right|^2.$$  \hspace{1cm} (8)

We assume that the blobs are initially at rest in the dips of the helical field lines, $\xi_i(0) = 0$ and $\mathbf{g}(\mathbf{r}_i) \perp \mathbf{s}_i$. The later condition determines the values of $p_i$ and $q_i$, describing the field lines on which the blobs are located. Using these values, Equation (5) is numerically integrated to obtain $\xi_i(t)$ for each blob. The positions $\mathbf{r}_i(t)$ and velocities $\mathbf{v}_i(t)$ can then be computed.

One of the free parameters of the flux rope is the number of helical windings. In our modeling for Section 3.3, we find that the ability of the flux rope to carry matter outward depends strongly on the degree of twist of the flux rope. The number of turns is chosen such that at least half of the blobs are ejected. This required about three turns. Unfortunately, the observations do not put strong constraints on this number. For the model of Section 3.2 we use fewer turns because (1) only a short section of the flux rope is modeled and (2) the starting time is earlier, so fewer turns have built up.

We find that in order to slow down the speed of falling blobs we have to introduce a friction between the blobs and the surrounding corona. Also, in the model of the rolling motion (Section 3.2), we need friction to prevent the blobs from sliding along the field lines. The nature of this friction is unclear. One possibility is that the pressure of the coronal plasma on either side of a blob provides a net force on the blob as it moves along its field line (Antolin & Rouppe van der Voort 2012). Another possibility is that the motion of the blob causes the emission of MHD waves that propagate out into the surrounding medium. These waves carry energy away from the blob, so the kinetic energy of the blob must be reduced.

### 3.2. Modeling of the Rolling Motion of Q1 and Q2 Observed by STEREO-B

In the early phase of the event, the prominence Q1 and Q2 rises slowly and displays a clockwise rotating motion around its own axis as discussed in Section 2.2 and shown in Figure 6. Here we present a numerical model for the observed motions.

We assume that the twist is continuously injected into the magnetic flux rope as a result of asymmetric reconnection occurring within the active region (see Section 4). Theoretical modeling of magnetic reconnection in non-symmetric configurations has shown that asymmetries can lead to rotating motions of the ejected plasma (Murphy et al. 2012). The twist is assumed to propagate along the flux rope in the eastern direction, and gives rise to the observed rolling motion. The present model is an empirical description of the observed motions, and does not depend on the details of the process by which the twist is generated.

Model 1 describes the dynamics of the filament flux rope during the period from 14:00 UT to 16:00 UT. The parameters of this model are listed in Table 2, and a detailed description of the meaning of these parameters is given in the Appendix. In the initial state, a right-helical flux rope lies horizontally above the solar surface. Its total length corresponds to a heliocentric angle of about 44°. The axis of the flux rope lies at a height $c_0 = 0.05R_\odot$, equal to the radius of cross section ($R_0 = 0.05R_\odot$), hence the lower edge of the flux rope touches the photosphere. The flux rope is centered at latitude $-35^\circ$ and longitude $-40^\circ$ as seen from Earth. The axis of the flux rope is tilted with respect to a line of constant latitude by an angle of $-35^\circ$. Initially, the helical field lines make one full turn around the axis.

Figure 9(a) shows the initial state of the flux rope and filament projected onto the plane of the sky as seen from STEREO-B at 14:00 UT. The circular arc indicates the southwest quadrant of the solar limb, and the black curves show three field lines at the outer edge of the flux rope. The colored line segments simulate prominence threads located in the lower half of the flux rope. The threads are radially oriented, and each thread consists of 80 blobs that are too close to be distinguished in this figure. Initially, each blob is located at a dip in its field line.

Figure 9(b) shows the magnetic configuration at 16:00 UT after additional twist has been injected into the flux rope from the western side (right-hand side of the figure). The number of helical windings has increased from 1.0 to 1.8. The field lines are held fixed on the left-hand side ($\xi_0 = -1$), therefore, as more twist is injected from the right the field-line dips move to the left in the figure. We simulated the dynamics of the prominence blobs for different values of the parameter $\beta$ describing the frictional coupling between the blobs and their surroundings. We found that in the case without frictional coupling ($\beta = 0$), the blobs have a strong tendency to slide...
down along the magnetic field lines and remain close to the field line dips. However, when the coupling constant $\beta$ is large, the motions of the blobs along the field lines are suppressed, and the blobs tend to follow the rotating motion of the flux rope. The latter leads to better agreement with the STEREO-B observations. Figure 9(b) shows the results for $\beta = 0.01$ \,s$^{-1}$, which corresponds to a frictional time scale of only 100 \,s, much shorter than that for blobs to slide down along the field lines. Note that the threads on the western end of the filament have rotated in the clockwise direction, consistent with the field lines. However, in the legs the dips soon disappear from the top down. Therefore, as they fall the simulated threads start to fall first, followed later by the blobs at the bottom of that thread. This is due to the fact that the dips are removed from the top down. Thus, the model provides only a very crude fit to the observations, so the value of $\beta$ is highly uncertain.

Figure 10 (and the associated animations) shows that for a given thread in the leg of the flux rope the blobs at the top start to fall first, followed later by the blobs at the bottom of that thread. This is due to the fact that the dips are removed from the top down. Therefore, as they fall the simulated threads are turned upside down. This rotating motion of the threads (left leg in Figure 10(d)) is consistent with the observations (black arrows in Figure 7(c)) discussed in Section 2.3. We conclude that the observed motions of the threads are consistent with the existence of dips in the field lines in the pre-eruption state, and the subsequent removal of those dips from the top down during the eruption.

A comparison of Figures 10(d)–(f) and Figures 2(c), 3(c), and 4(c) suggests that the modeled overall shape of the erupting prominence matches the observations. However, there are some differences in the evolution of the right leg between observations.

Figure 9. Model for the rotating motion of the filament observed by STEREO-B early in 2010 December 6 eruption event. (a) Initial state at 14:00 UT. The black curves indicate helical field lines at the outer edge of the flux rope, and the magenta line segments simulate nearly vertical threads located in the lower half of the helical flux rope. (b) Configuration at 16:00 UT after the prominence has been rotated in the clockwise direction by about half a turn. The colors of the blobs indicate the LOS velocity ($\pm 10$ km s$^{-1}$). (An animation (animation 4) of this figure is available in the online journal.)
Figure 10. Flux rope model for the 2010 December 6 prominence eruption from the view of AIA (left column), STEREO-B (middle column), and STEREO-A (right column). (a–c) Initial state at 16:00 UT: the black curves indicate helical field lines at the outer edge of the flux rope, and the red line segments simulate nearly vertical threads located in the lower half of the helical flux rope. (d–f) Configuration at 17:36 UT when some of the prominence blobs have been carried outward by the erupting flux rope, while others are falling back down to the photosphere. The colors of the blobs indicate the LOS velocity (±30 km s\(^{-1}\)).

(Animations (animations 5, 6, and 7) of this figure are available in the online journal.)

and the model. In observations, the right prominence leg erupts much later than the other part of the prominence, which is possibly due to the strong overlying magnetic field in the active region. In the model, the entire flux rope erupts radially outward at the same time.

4. ORIGIN OF THE ROLLING MOTION OF PROMINENCES Q1 AND Q2

In Section 3.2, we presented a rolling motion of prominences Q1 and Q2 that occur at the early phase of the eruption on December 6 from 14:21 UT to 17:00 UT. STEREO-B 195 Å observations show that the filament sheet is rotating around its own axis in the clockwise direction as viewed from the east to west. The motion starts from the active region, then propagates toward the east. This motion is similar to the roll effect identified by Panasenco & Martin (2008) in the sense that it is a rotation around the axis of the filament. In all cases of the roll effect recognized to date, there has been a one-to-one relationship between the chirality of the filament and the direction of rotation of the roll with dextral filaments always rolling toward the positive photospheric magnetic field side of the prominence and sinistral filaments rolling in the opposite direction (Martin 2003; Panasenco & Martin 2008; Panasenko et al. 2011). However, the filament studied in the current paper is sinistral (also see Paper I) and displays rolling motion toward the positive photospheric magnetic field side of the prominence.

There are several candidate mechanisms for the observed rolling motions: (1) untwisting of the magnetic field in the rising flux rope during expansion and relaxation; (2) local magnetic force imbalance caused by the presence of a coronal hole near the filament channel (Panasenko et al. 2011); (3) increase of twist due to reconnection below a flux rope or sheared arcade; and (4) asymmetric reconnection due to an offset between the CME current sheet and the rising flux rope (Murphy et al. 2012). In the present case, the erupting filament has a sinistral orientation of its axial field and has right-helical (positive) twist. The observed clockwise rolling motion indicates an increase of twist rather than untwisting of the magnetic field, which rules out the first mechanism. Moreover, our simulation suggests that a continuous increase of twist in the flux rope is consistent with the observed rolling motion. The second mechanism cannot be ruled out because there is indeed a coronal hole to the north of the active region. However, it seems unlikely that the weak fields of the coronal hole can affect the flux rope in the active region at the early slow rising phase of the eruption.

The third mechanism can lead to twist increase in the existing flux rope or sheared arcade. There are two alternatives. First, reconnection (beneath the flux rope) of weakly sheared flux that is rooted immediately outside the filament channel would yield a highly twisted layer surrounding the existing, weakly twisted flux rope. Second, reconnection beneath a sheared arcade will convert shear into twist, yielding a flux rope in which the number of twists is dictated by the shear length and the filament channel...
length. However, it is difficult to imagine how this twist increase will affect the preexisting filament material located near the center of the flux rope or sheared arcade. In particular, it is unclear whether such reconnection can cause rolling motion of the existing filament. In the following, we focus on the fourth mechanism, i.e., we suggest that the observed rolling motion may be due to asymmetric reconnection.

Figure 11 shows cross sections of the distribution of field-aligned electric currents along different parts of the flux rope at the active region from one non-linear force-free field model (NLFFF, Model 1) presented in Paper I. The background images in the top row are the maps of the radial component of the photospheric magnetic field observed by SDO/HMI. The zero point of the longitude corresponds to the central meridian on 2010 December 10 at 14:00 UT. The blue curve refers to the path where the flux rope is inserted. The bottom row shows vertical slices of $\alpha$ distribution along different parts of the flux rope (as indicated by the yellow line in the corresponding top-row image) from the NLFFF model.

Figure 11 suggests the existence of an offset between the vertical current sheet and the slowly rising flux rope as shown in Figure 12(b). The asymmetric reconnection induced by this offset may result in the rolling motions, as shown by the dashed arrows in Figures 12(a) and (b). Note that the directions of the rolling motions are predicted to be opposite in the eastern and western sides of the active region. The filament in the active region should not roll since the underlying current sheet is not offset. Here we assume that the flux rope is held fixed at the two ends. However, the different rolling motions will lead to the twist increase on the two sides of the active region, while reducing the twist or even reversing the sign of the twist in the active region.

One possible result is the formation of magnetic twist that varies along the flux rope, as shown in Figure 12(c). This scenario provides a natural explanation on the observed rolling motion on the eastern side of the active region. This alternate twist along the flux rope exists as long as the “driving force” caused by asymmetric reconnection exists. Once the “driving force” stops, the twist will propagate until it is uniform throughout the flux rope.

Thompson (2012a, 2012b) determines magnetic twists of the filament during the eruption on December 6 using triangulations of prominence threads observed by STEREO. Thompson (2012a) finds that the prominence threads display negative twist in the active region (his Figure 11), while positive twist is identified for the eastern and western sides of the filament (his Figures 9 and 10). This result is consistent with our observed rolling motion and interpretation, as shown in Figure 12 in this paper.
5. CONCLUSIONS

We present observations and modeling of the eruption of a large polar-crown prominence on 2010 December 6. This complex prominence is composed of different segments. The middle part of the prominence is located in the active region remnant. Observations suggest that this middle part contains two layers: one layer is elevated above the active region and the other layer is located low at the core of the region. The majority of the prominence is located on the eastern (left) side of the active region, while a small part of the filament is located on the western (right) side of the region. The primary focus of the current study is the eastern side of the quiescent filament, which is divided into four parts according to the different behavior during the eruption. The Q1 filament is located right next to the active region, while the Q2, Q3, and Q4 filament segments are located sequentially further away from the active region.

The eruption begins with appearance of brightenings immediately surrounding the active region filament at 14:16 UT on December 6 as observed by AIA. STEREO-B observes that the filament in the core of the active region breaks apart around 14:21 UT. Part of the filament ejects toward the east, which leads to the explosive eruption of the eastern (left) part of the quiescent prominence, which is the focus of the present paper. The other part of the filament material ejects to the west, which leads to a clear rise of the western (right) end of the filament followed by an eruption at 2:06 UT on December 7. Although the instability appears to begin in the core of the active region, the elevated filament above the active region remains stable until the eastern quiescent filament rises to a much larger height. The prominence eruption on December 6 appears to be a sideways/non-radial eruption in which the filament material escapes from the weaker field region first.

Thanks to the three views of the Sun by STEREO and SDO, we have identified two types of rotating motions during the prominence eruption on 2010 December 6. To understand the observed rotating motions from different points of view, we develop a simplified three-dimensional model. The prominence is assumed to consist of a collection of discrete blobs that are tied to particular field lines. The time-varying magnetic field is described by a simple analytical model of a helical flux rope, and the motion of the blobs is determined by solving the equations of motion along the field lines, taking into account the effects of gravity and friction with the surrounding corona.

The first rotating motion occurs at the early phase of the (from 14:21 UT to 17:00 UT) eruption of the eastern quiescent filament (Q1 and Q2). STEREO-B 195 Å observations show that the filament sheet is rotating around its own axis in the clockwise direction as viewed from the east to west. This rotating motion is not clearly visible in SDO and STEREO-A observations. The motion starts from the active region and then propagates toward the east. The observed rotating motion is reproduced by continuous twist injection into the flux rope in Model 1 from the active region side. We suggest that the observed rolling motion is most likely caused by asymmetric reconnection induced by the asymmetric distribution of the magnetic fields on the two
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sides of the filament. The second type of rotating motion is observed by SDO, but is not visible in STEREO observations. AIA 304 Å observations suggest that the Q3 filament makes a half turn during its process of rising and draining back toward the Sun. The northern leg of the Q2 filament also displays a similar rotating motion, though not as remarkable as the Q3 filament. This rotating motion is very well reproduced by our Model 2. Our model suggests that this rotating motion of prominence threads is consistent with the existence of dips in the field lines in the pre-eruption state, and the removal of those dips from the top down during the eruption.

Our results suggest the following scenario for the event: (1) Reconnection in the active region leads to twist increase in the existing flux rope (or enabled the formation of a flux rope). (2) The twist on the quiet Sun reached a critical threshold for kink instability, leading to an eruption of the eastern quiescent filament. (3) Later on the elevated layer of the active region filament is pulled out as well. Both our model result and the observational result by Thompson (2012a) indicate that there is no strong writhing motion during the eruption.

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APPENDIX

ANALYTIC MODEL FOR AN ERUPTING FLUX ROPE

The prominence plasma is assumed to be located in a curved, helical flux rope that expands with time. Here we describe the time-dependent shapes of the field lines inside the flux rope. Each field line follows a curved path \( \mathbf{r}(\xi, t) \), where \( \xi \) measures position along the field line, and \( t \) is the time as measured from the start of the eruption. The parameter \( \xi \) varies from \(-1\) at one endpoint of the flux rope to \(+1\) at the other end. Positions are described in terms of a Cartesian coordinate system \((x, y, z)\) with the origin located at Sun center and the \(+z\) axis along the direction of flux-rope expansion. All lengths are given in units of the solar radius.

We first consider the shape of the flux-rope axis, which is a special field line at the center of the flux rope. Its non-circular shape \( \mathbf{r}_{\text{axis}}(\xi, t) \) is given by the following expressions:

\[
x_{\text{axis}}(\xi, t) = r_0 \sin(\theta_0 \xi) / \cos^n(a_0 \theta_0 \xi),
\]

\[
y_{\text{axis}}(\xi, t) = u_0 \sin(\pi \xi),
\]

\[
z_{\text{axis}}(\xi, t) = r_0 \cos(\theta_0 \xi) / \cos^n(a_0 \theta_0 \xi) + z_0,
\]

where \( \theta(t) \) is the “angular width” of the curved path, \( r_0(t) \) is the radius of curvature at the top of the path, \( z_0(t) \) is the position of the curvature center, and \( w_0(t) \) describes the writhe of flux-rope axis. The parameter \( a_0 \) is a constant that determines the width-to-height ratio of the expanding flux rope \((0 < a_0 < 1/2)\), and the exponent \( n \equiv 1/a_0 \). During the eruption, the middle part of the flux rope rises, but the endpoints are assumed to remain at fixed positions in the low corona: \( x_{\text{axis}}(\pm 1, t) = \pm d_0 \) and \( z_{\text{axis}}(\pm 1, t) = h_0 \), where \( d_0 \) and \( h_0 \) are constants. It follows that the functions \( r_0(t) \) and \( z_0(t) \) are given by

\[
r_0(t) = d_0 \cos^n(a_0 \theta(t)) / \sin \theta(t),
\]

\[
z_0(t) = h_0 - d_0 / \tan \theta(t).
\]

The constant \( h_0 \) is chosen such that the endpoints lie at a fixed height \( R_0 \) above the solar surface:

\[
h_0 = \sqrt{(1 + R_0)^2 - d_0^2},
\]

where \( R_0 \) is the radius of the cross section of the flux rope at the two endpoints. The unit vector \( \mathbf{s}(\xi, t) \) along the flux-rope axis can be found by differentiating expressions \((A1), (A2), and (A3)):

\[
\mathbf{s}_0 = \hat{\mathbf{r}}_{\text{axis}} / |\hat{\mathbf{r}}_{\text{axis}}| = \cos(a_0 \theta_0 \xi) \mathbf{x} + \sin a_0 \theta_0 \xi \mathbf{y} - \sin a_0 \theta_0 \xi \cos \gamma \mathbf{z},
\]

where \( a_0 \equiv 1 - a_0 \) and the angle \( \gamma(\xi, t) \) is defined by

\[
\tan \gamma = \pi u_0 / r_0 \cos^n(a_0 \theta_0 \xi) \cos(\pi \xi).
\]

The outward motion of the flux-rope axis is given by

\[
z_{\text{tot}}(t) = z_{\text{axis}}(t, 0) = 1 + c_0 + v_{\text{max}}[t - \tau_{\text{acc}}(1 - e^{-t/\tau_{\text{acc}}})],
\]

where \( \tau_{\text{acc}} \) is the timescale of the initial outward acceleration of the flux rope, \( v_{\text{max}} \) is its terminal velocity, and \( c_0 \) is the initial height of the flux-rope axis above the solar surface \((z_{\text{tot}}(0) = 1 + c_0)\). The function \( \theta(t) \) is computed by inverting the equation \( z_{\text{tot}}(t) = d_0 f(\theta(t)) + h_0 \), where \( f(\theta) \equiv [\cos^n(a_0 \theta) - \cos \theta] / \sin \theta \), which follows from Equation \((A3)\). The out-of-plane motion of the axis is described by

\[
w_0(t) = w_{\text{writhe}}[t - \tau_{\text{writhe}}(1 - e^{-t/\tau_{\text{writhe}}})],
\]

where \( \tau_{\text{writhe}} \) is the timescale for the onset of the writhe motion and \( w_{\text{writhe}} \) is its terminal velocity.

The flux rope is assumed to have a circular cross section. The radius \( R(\xi, t) \) of the cross section varies with time \( t \) and with position \( \xi \) along the flux rope:

\[
R(\xi, t) = R_0 \left[ 1 - \frac{\xi^2}{\cos[\theta(t)/2]^2 + \xi^2} \right].
\]

For the model describing the main eruption (Section 3.3), we use \( a_0 = 0.28 \), \( d_0 = 0.55 R_0 \), and \( c_0 = 0.16R_0 \), which yields \( \theta(0) = 1.153 \) rad. Therefore, in the initial state \( \cos[\theta(0)/2] = 0.838 \), and the radius of the flux rope is approximately constant along the flux rope, \( R(\xi, 0) \approx R_0 \). However, as time progresses the radius \( R(0, t) \) at the top of the flux rope increases significantly.

The shape of the helical field lines can now be approximated as follows

\[
\mathbf{r}(p, q, \xi, t) = \mathbf{r}_{\text{axis}}(\xi, t) + R(\xi, t) \left[ p \cos \phi(\xi, t) \right.
\]

\[
- q \sin \phi(\xi, t) \left| S_1(\xi, t) \right. + \cdots + R(\xi, t) \left[ p \sin \phi(\xi, t) + q \cos \phi(\xi, t) \right] S_2(\xi, t). \]

(A12)
where \( p \) and \( q \) are constants along a given field line, and are also constants of motion; they can be used as labels of the field lines. The interior region of the flux rope is given by \( p^2 + q^2 \leq 1 \). The vectors \( \hat{s}_1(\xi,t) \) and \( \hat{s}_2(\xi,t) \) are defined by

\[
\hat{s}_1(\xi,t) = \sin(a_1 \theta \xi) \hat{x} + \cos(a_1 \theta \xi) \hat{z},
\]

(A13)

\[
\hat{s}_2(\xi,t) = \cos(a_1 \theta \xi) \sin \gamma \hat{x} - \cos \gamma(\xi,t) \hat{y} - \sin(a_1 \theta \xi) \sin \gamma \hat{z},
\]

(A14)

so that the vectors \( \hat{s}_0, \hat{s}_1, \) and \( \hat{s}_2 \) are mutually orthogonal. Hence, the helical displacement of the field lines is perpendicular to the flux rope axis. The phase angle \( \phi(\xi,t) \) is given by

\[
\phi(\xi,t) = \pi N(t)(\xi - \xi_0),
\]

(A15)

where \( N(t) \) is the number of helical windings along the length of the flux rope, i.e., the number of full turns as we follow a field line from \( \xi = -1 \) to \( \xi = +1 \). The number of windings \( N(t) \) is the same for all field lines within the flux rope, and does not vary with radial distance from the flux rope axis. Equation (A15) determines the position along the flux rope where there is no rotating motion. In this paper, we use \( \xi_0 = -1 \) to keep the field lines fixed at one of the endpoints of the flux rope.

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