MAGNETIC STRUCTURE AND DYNAMICS OF THE ERUPTING SOLAR POLAR CROWN PROMINENCE ON 2012 MARCH 12

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ABSTRACT

We present an investigation of the polar crown prominence that erupted on 2012 March 12. This prominence is observed at the southeast limb by the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA; end-on view) and displays a quasi-vertical thread structure. A bright U-shaped or horn-like structure is observed surrounding the upper portion of the prominence at 171 Å before the eruption and becomes more prominent during the eruption. The disk view of STEREO-B shows that this long prominence is composed of a series of vertical threads and displays a half-loop-like structure during the eruption. We focus on the magnetic support of the prominence vertical threads by studying the structure and dynamics of the prominence before and during the eruption using observations from SDO and STEREO-B. We also construct a series of magnetic field models (sheared arcade model, twisted flux rope model, and unstable model with hyperbolic flux tube). Various observational characteristics appear to be in favor of the twisted flux rope model. We find that the flux rope supporting the prominence enters the regime of torus instability at the onset of the fast-rise phase, and signatures of reconnection (post-eruption arcade, new U-shaped structure, rising blobs) appear about one hour later. During the eruption, AIA observes dark ribbons seen in absorption at 171 Å corresponding to the bright ribbons shown at 304 Å, which might be caused by the erupting filament material falling back along the newly reconfigured magnetic fields. Brightenings at the inner edge of the erupting prominence arcade are also observed in all AIA EUV channels, which might be caused by the heating due to energy released from reconnection below the rising prominence.

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

Supporting material: animations

1. INTRODUCTION

The solar corona contains sheared or twisted magnetic fields overlying polarity inversion lines (PIL) on the photosphere. The sheared or twisted fields can be observed as filament channels on the disk and as coronal cavities in limb observations; solar prominences are located within these regions. These structures warrant investigation because of their role in prominence eruptions, coronal mass ejections (CMEs), and solar flares. Understanding the topology and evolution of the prominence/cavity magnetic field structure, as well as the thermodynamics of the plasma within and surrounding prominences prior to the eruption, is key to understanding the initiation of solar eruptions.

Solar prominences are relatively cool structures embedded in the million-degree corona. In Hα when viewed above the solar limb, prominences appear as bright structures against the dark background, but when viewed as “filaments” on the solar disk they are darker than their surroundings. We will use the terms “filament” and “prominence” interchangeably in general. For more detailed reviews on observations and modeling of solar prominences, see Hirayama (1985), Labrosse et al. (2010), Mackay et al. (2010), Parenti (2014), and van Ballegooijen & Su (2014). When observed on the solar disk with high spatial resolution, filaments show thin thread-like structures that continually evolve (Lin et al. 2008). Recent observations with the Solar Optical Telescope on the Hinode satellite and the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) have revolutionized our understanding of quiescent and intermediate prominences. When observed above the solar limb, such prominences always show many thin thread-like structures. In some cases the threads are mainly horizontal (e.g., Okamoto et al. 2007); in other cases they are mainly vertical (e.g., Berger et al. 2008; Su & van Ballegooijen 2012, and references therein). Hedgerow prominences consist of many thin vertical threads organized in a vertical sheet or curtain. Upward-moving plumes and bubbles have been observed in between the denser, downflowing threads (e.g., Berger et al. 2008). Other prominences consist of isolated dark columns standing vertically above the PIL, and such prominences often exhibit rotational motions reminiscent of “tornados” in the Earth’s atmosphere (e.g., Li et al. 2012; Su et al. 2012; Panesar et al. 2013). The rotational motions have been confirmed using Doppler shift measurements (e.g., Liggett & Zirin 1984; Orozco Suárez et al. 2012; Su et al. 2014). Many quiescent prominences have horn-like extensions that protrude from the top of the spine into the cavity above (e.g., Berger 2012; Su & van Ballegooijen 2012; Schmit & Gibson 2013). These horns may outline a flux rope located above the prominence (Berger 2012).

The cool prominence plasma must somehow be supported against gravity because without such support the plasma would fall to the chromosphere on a timescale of about 10 minutes. It has long been assumed that prominences are threaded by horizontal magnetic fields and electric currents, which provide the upward Lorentz force needed to counter gravity (e.g.,...
2. OBSERVATIONS

2.1. Data Sets and Instruments

A large polar crown prominence was observed to erupt on 2012 March 11–12 by the AIA (Lemen et al. 2012) on board the SDO, as well as the STEREOB (Behind)/Extreme Ultraviolet Imager EUVI; Wuelser et al. 2004; Howard et al. 2008). At the time of eruption, STEREOB was observing the Sun ahead of the Earth, and the separation angle with Earth was 118°. The photospheric magnetic field information is provided by the Helioseismic and Magnetic Imager (HMI, Schou et al. 2012) on board SDO.

The apparent slow rise of the large prominence begins around 17:00 UT on 2012 March 11. This prominence eruption is associated with a CME, which has a median velocity of 399 km s⁻¹, according to the CACTus Solar and Helioscropic Observatory (SOHO)/LASCO CME catalog. The first appearance of the associated CME in the LASCO/C2 field of view (FOV) is at 01:25 UT on 2012 March 12. Two bright ribbons and a post-eruption arcade are observed during the eruption, but no associated flare can be clearly identified. In the current paper, we study the structure and dynamics of the prominence before and during the eruption.

2.2. Structure and Dynamics of the Prominence/Cavity System before the Eruption

Figure 1 presents the multiwavelength SDO/AIA observations of the target polar crown prominence system at 17:01 UT on 2012 March 11 prior to the eruption. This figure shows that the prominence is composed of a series of vertical threads. In the 131, 94, and 304 Å images, the prominence displays dark absorption in the middle and bright emission in the surroundings. The extended bright emission surrounding the dark filament is best seen at 171 Å, which shows that a bright U-shaped or horn-like structure appears to be located above the dark vertical prominence threads. In the 335, 211, and 193 Å images, the prominence is seen in absorption, and the dark vertical threads are surrounded by a dark region, in contrast to the bright emission shown at 171 Å. In these three channels, we also see a cloud of bright emission (best seen in the 211 Å images) located above the vertical threads within the dark cavity. Some of the prominence vertical threads can be seen in emission at 1600 Å.

The AIA images at 304 Å (left), 171 Å (middle), and 193 Å (right) at 12:00 UT from 2012 March 6 to 11 are presented in Figures 2–3. These two figures show that in the prominence (304 Å) appears to increase with time, and the size of the cavity (193 Å) also appears to become bigger as time goes on. Due to the large time range, the prominence at the limb is a projection of different portions of the long prominence. Therefore, the apparent increase of the prominence height and cavity size may be due to two reasons: the heights of different parts of the prominence are different, or the whole prominence is rising with time. The end view of the prominence on March 6 shows that the vertical threads are located at the bottom of the dark cavity (Figure 2(c)). A series of nearly vertical horn-like structures appears to go through all of the vertical threads from bottom to top on the southern side of the prominence in the 171 Å image (Figure 2(b)). The side view of the prominence at 171 Å on March 7–8 shows a nearly horizontal bright horn-like structure protruding from the top of the vertical prominence threads. The cavity appears to become much bigger on March 8 (Figure 2(i)), although lots of bright loops along the line of sight (LOS) are projected within the cavity. As the Sun rotates from March 9 to 11, AIA observes the prominence from side view to end view (Figure 3). The vertical threads and horn-like structure are much wider on March 9 (Figures 3(a)–(b)), Figures 3(b)–(c) show that in the 193 Å image a bright U-shaped structure appears at both the top and bottom parts of the vertical threads, while at the other part a
bright U-shaped structure is shown at 171 Å. This suggests that the U-shaped structure goes through nearly all of the vertical threads when placing the two images together, and the same result can also be obtained from the observations on March 10–11. On March 11, the structure containing the vertical threads appears much narrower because the threads gradually align with each other along the LOS, and the horn-like structure becomes more like a narrow U-shaped structure. The size of the cavity outlined by the big bright loop is similar to that on March 8, though it is still filled with smaller bright loops projected along the LOS.

2.3. Structure and Dynamics of the Eruption

SDO/AIA and STEREO B/EUVI observations of the prominence eruption (before: top, during: middle, after: bottom) in three wavelengths (304 Å: left, 171 Å: middle, 193 Å: right) are presented in Figures 4–5, respectively. Details of the eruption process can be found in videos 1 and 2 (see Figures 4 and 5). The end view by AIA in Figure 4 shows that at 00:30 UT on March 12 the prominence rises much higher and becomes much wider with two dark columns on the two sides and fewer dark thin threads in between. Small posterosion loops are observed near the limb at 193 Å (Figure 4(f)). The prominence leaves the AIA FOV at 04:00 UT, the 193 Å image shows much brighter and larger posterosion loops (Figure 4(i)), and a helmet streamer structure appears in the 171 Å image (Figure 4(h)).

The top/side view by EUVI B in Figure 5 shows that this prominence is very long, and the part where the prominence erupts first is near the western end, which appears to be higher than the other part at 17:00 UT on March 11. This eruption appears to be an asymmetric eruption, during which only the western leg lifts off, while the eastern part remains attached to the surface, as shown in Figure 5(d) (also see video 2). After the eruption, a series of bright posterosion loops is observed in the 195 Å images (e.g., Figure 5(i)).

The kinematics of the erupting prominence is presented in Figure 6. We trace the leading edge of the prominence to infer its bulk motion by first selecting the linear slice (black) that best characterizes the overall trajectory. Two additional slices (blue and green) offset by 2° in either direction are processed identically for error estimation (Figure 6(a)). The emission along these lines at a given time is binned to 300 pixels and interpolated onto a uniform-distance grid, yielding a spatial resolution of ∼2″. Light curves are drawn from 10-frame (2 minute) averages to improve the signal-to-noise ratio and are stacked against subsequent observations to produce height–time images like the one shown in Figure 6(b) for the main slice (black). The height–time images are then further processed to improve contrast. Each row is multiplied by its height to boost signal far from the limb, and the image is thresholded above 1.5x its median value. The Canny edge-detection algorithm (Canny 1986) is then applied to extract the leading edge. Figure 6(c) shows the application of the Canny algorithm to the image in Figure 6(b), and the pixels highlighted in red are used as the individual height measurements. These points are extracted automatically, but their time range must be selected manually, which is particularly important for the start time because it effectively defines the onset of the slow-rise phase. This procedure is also used by Reeves et al. (2015) for IRIS observations of an eruptive prominence and by McCauley et al. (2015) for a statistical study that includes this event.

The height measurements are then fit with an analytic approximation presented by Cheng et al. (2013) for their study of an active region flux rope eruption:

\[ h(t) = c_0 e^{-(t-t_0)/\tau} + c_1(t-t_0) + c_2 \]  

where \( h(t) \) is height, \( t \) is time, and \( \tau, t_0, c_0, c_1, \) and \( c_2 \) are free parameters. This model combines a linear equation to treat the slow-rise phase and an exponential to treat the fast rise. The onset of the fast-rise phase can be defined as the point at which the exponential component of the velocity equals the linear

![Figure 1. Multiwavelength images taken by SDO/AIA at 17:00 UT on 2012 March 11 before the eruption.](image-url)
(i.e., the total velocity equals twice the initial), which occurs at
\[ t_{\text{onset}} = \tau \ln\left(c_{1}\tau/c_{0}\right) + t_{0}. \]

Fitting is accomplished using MPFIT, a nonlinear, least squares curve-fitting package for IDL (Markwardt 2009). Figures 6(d)–(f) show the fit result and its time derivatives. Based on this approximation, we find that the initial slow-rise velocity is \(2.6 \pm 0.2\) km s\(^{-1}\), and the maximum velocity in the AIA FOV is \(110 \pm 5\) km s\(^{-1}\). The onset of the fast-rise phase occurs at 22:57 UT \(\pm 7\) minutes at a height of \(97 \pm 5\) Mm. At the onset point, the acceleration is \(1.2 \pm 0.1\) m s\(^{-2}\), and the final acceleration is \(49 \pm 5\) m s\(^{-2}\).

Two strategies are employed to quantify uncertainty, and the errors quoted are the sum of both. The first is to identically process two adjacent slices offset by \(2^\circ\) on either side of the original. Standard deviations from these results account for \(\sim 55\%\) of the velocity, acceleration, and time uncertainties. The second strategy is to perform 100 Monte Carlo (MC) simulations to estimate uncertainties from the fit parameters by randomly varying our height measurements within some assumed error and refitting Equation (1), as was done by Cheng et al. (2013). Because there are no standard errors for the height measurements obtained by our edge-detection method, the assumed height errors are chosen to yield a reduced chi-squared \((\chi^2_r)\) of 1.0 for the fit. That gives us an uncertainty of \(4^\circ1\), which corresponds to about seven AIA pixels and about two pixels on the height–time image. This value is included in the onset height uncertainty, to which it contributes 65%, while uncertainties from the three separate slices and MC realizations account for 15% and 20%, respectively.

In order to test the accuracy of our computed trajectory, we calculate the expected arrival time of the CME in SOHO/LASCO/C2 using two different assumptions. If we assume a constant acceleration of \(49\) m s\(^{-2}\) after leaving the AIA FOV, the prominence would arrive at the LASCO/C2 FOV at around 02:14 UT on March 12 with a velocity of \(\sim 280\) km s\(^{-1}\). If, instead, the prominence continues along our height–time fit, it would appear in C2 at 02:05 UT with a velocity of \(\sim 420\) km s\(^{-1}\).

The actual arrival time of the prominence at \(2.5\ R_\odot\) is between

![Figure 2. SDO/AIA observations of the eruptive prominence before the eruption at 12:00 UT from 2012 March 6 to 8.](image)
02:00 and 02:12 UT, and the velocity listed in the CACTus CME catalog is $399 \pm 65$ km s$^{-1}$. The CACTus velocity is derived from linear fits to measurements across the entire CME from both the C2 and C3 detectors, which cover 2.5–30 $R_\odot$ (Robbrecht & Berghmans 2004; Robbrecht et al. 2009). The prominence may then have followed our projected trajectory until nearly 2.5 $R_\odot$, after which it transitioned to a constant velocity or decelerated somewhat at large heights, but this is speculative given the lack of observations between AIA and LASCO/C2.

2.4. Signature of Reconnection: U Shapes and Blobs

Figure 7 shows rotated views of AIA images from 19:00 UT on March 11 to 00:39 UT March 12, and details can be found in the corresponding online video 3. The first and second rows show radial-filtered and running-difference images at 171 Å, and following the same format, AIA images at 193 Å are presented in the third and fourth rows. The prominence gradually rises up from 19:00 UT to 23:00 UT on March 11. A posteruption arcade (blue arrow) begins to appear around 23:50 UT on March 11. A newly formed U-shaped structure (green arrow) begins to show up at the lower part of the rising vertical threads around 00:10 UT on March 12.

Similar to Figure 7, Figure 8 shows rotated AIA images from 00:43 UT to 01:19 UT on March 12. Small bright blobs (white arrow) begin to appear at the bottom of the erupting prominence vertical threads around 00:51 UT. The blobs are best observed at 171 Å, and the bigger and brighter blobs can also be seen at 193 Å. These bright blobs then rise up into the less-dense prominence region located between the two dark, dense vertical threads. The blobs appear to rise faster than the bulk motion of the erupting prominence (see video 3).

A detailed kinematics study of the rising blobs is presented in Figure 9. Figure 9(a) shows the AIA 171 Å running-difference image at 01:20 UT on 2012 March 12. Distance–time plots of emission at 171, 193, and 211 Å along the white slice marked in Figure 9(a) are presented in Figures 9(b)–(d), respectively. We perform linear fits (marked as red lines) to
three of the rising blobs for each channel, and the velocity for each rising blob is presented in the figure. This figure confirms that the speed of these bright rising blobs is larger than that of the leading edge and bulk motion of the prominence. The rising blobs that appear earlier ($95 \text{ km s}^{-1}$) are slower than those that appear later ($259 \text{ km s}^{-1}$). The appearance height of these blobs is increasing with time, as shown in Figures 9(b)–(d). In addition, bright falling features are also observed starting around 01:10 UT (at 171 Å) on March 12, as shown in Figure 9(b).

The concave-upward U-shaped structure, rising blobs, and posteruption arcade are all signatures of reconnection. The aforementioned observations suggest that magnetic reconnection begins around 23:50 UT on March 11 near the bottom of the vertical threads. The increase of the appearance height of bright blobs may be due to the increase in height of the reconnection point. Intermittent plasmoids or blobs are generally explained by the tearing-mode instability of the thin current sheet, where a series of magnetic islands are recurrently created during reconnections (Furth et al. 1963; Drake et al. 2006). Small plasmoids or magnetic islands have been found to flow along the current sheet either sunward or antisunward in both observations (Savage et al. 2010; Liu 2013; Liu et al. 2013, and references therein) and simulations (Shen et al. 2011; Karpen et al. 2012, and references therein). The speed of rising blobs in our eruption is at the lower end of the antisunward blobs’ speed in the literature ($100$–$1400 \text{ km s}^{-1}$). This is not surprising because our event is a slow eruption that occurred at the polar crown.

2.5. Darkenings and Brightenings during the Eruption

Figure 10 shows AIA observations of bright and dark ribbons during the eruption. In the 304 Å (Figure 10(a)) image, we can see two bright ribbons located at the footpoints of the posteruption arcade, which can be seen most clearly at 193 Å (Figure 10(c)). Corresponding to these bright ribbons, two dark ribbons are seen in absorption at 171 Å (Figure 10(b)). Distributions of intensity versus time along a slice (from
Figure 5. STEREO_B/EUVI observations of the prominence eruption on 2012 March 12. (An animation of this figure is available.)

Figure 6. (a) Trajectories used for tracking. The black slice is selected manually, and the others are offset by 2° in either direction. (b) Height-time image for the black slice in panel (a). The dashed line indicates the time shown in panel (a), and the asterisk indicates the fast-rise onset point. (c) Output of the Canny edge-detection algorithm applied to panel (b). The red pixels are used as individual height measurements. (d) Fit to the red pixels in panel (c). The dotted lines indicate the onset of the fast-rise phase, and the colors correspond to results from the different slices in panel (a). (e) Velocity and (f) acceleration profiles for the height profile in panel (d).
southwest to northeast) nearly perpendicular to the ribbons (white line in the top left corner image) at 304 and 171 Å are presented in Figures 10(d)–(e). Figure 10(d) shows that the two bright ribbons first appear around 01:30 UT, and the two ribbons then gradually move away from each other. The slope of the outer edge of the ribbons, that is, the newly formed ribbons, shows that the southern ribbon appears to move faster. The southern dark ribbon seen in absorption at 171 Å first appears around 01:10 UT, and the appearance of the full northern dark ribbon is around 01:30 UT. At 171 Å, the ribbons are only seen in absorption initially, but later on the bright emission also shows up. Most of the northern ribbons are seen in absorption, while only the outer edge of the southern ribbon, that is, the newly formed ribbons, are dark.

The observational characteristics of dark ribbons at 171 Å suggest that they might be caused by the erupting filament material falling back along the newly reconfigured magnetic fields. The cospatial brightenings at 304 Å might be partially caused by heating of the plasma due to the kinetic energy of falling filament material compressing the plasma (Gilbert et al. 2013). In addition, thermal or nonthermal energy released from reconnection impacting the chromosphere might also contribute to the observed brightenings, as suggested by the lateral appearance of brightenings at 171 Å.

Figure 11 shows brightenings of prominence material observed by AIA (left: 211 Å, middle: 304 Å) and EUVI_B (right: 304 Å) during eruption. The top row shows images before the appearance of the brightenings, and the brightenings are shown in the bottom row. Brightening B1 first appears around 01:15 UT, and brightening B2 shows up (01:19 UT) immediately after. Both brightenings are observed in all EUV channels, and B1 appears to be brighter than B2, especially in
the hotter channels (e.g., 94, 335 Å). The change of the prominence seen from absorption to emission (B1 in Figures 11(a) and (d)) suggests that the brightenings might be caused by heating. The EUVI_B observation shows that these brightenings occur at the inner edge of the erupting prominence. Therefore, the observed prominence brightenings are likely to be caused by heating due to energy released from reconnection below the rising prominence.

3. MODELING

3.1. Flux Rope Insertion Method

Our magnetic field models are constructed using the flux rope insertion method developed by van Ballegooijen (2004). A detailed description of the methodology can be found in the literature (Bobra et al. 2008; Su et al. 2011; Su & van Ballegooijen 2012), and we describe the method briefly below.

First, the potential field is computed from the high-resolution (HIRES) and global magnetic maps. Then, by appropriate modifications of the vector potentials, a “cavity” is created above the selected path, and a thin flux bundle (representing the axial flux of the flux rope ($\Phi_{ax}$)) is inserted into the cavity. Circular loops are added around the flux bundle to represent the poloidal flux of the flux rope ($F_{pol}$). The above field configuration is not in force-free equilibrium, so our next step is to use magnetofrictional relaxation to evolve the field toward a force-free state. This method is an iterative relaxation method (van Ballegooijen et al. 2000) specifically designed for use with vector potentials. Specifically, we solve the following equation:

$$
\frac{\partial \mathbf{A}}{\partial t} = \eta_0 \mathbf{v} \times \mathbf{B} - \eta_2 \nabla \times \mathbf{B}
+ \frac{B}{B^2} \nabla \cdot \left( \eta_3 B^2 \nabla \mathbf{A} \right) + \nabla \left( \eta_4 \nabla \cdot \mathbf{A} \right),
$$

(3)
where $v$ is the plasma velocity, $\eta_0$, $\eta_2$, $\eta_4$, and $\eta_d$ are constants in space, and $\alpha \equiv j \cdot B/B^2$, where $j = \nabla \times B$. The velocity is given by

$$v = \left( f \cdot j - v_1 \hat{r} \times B \right) \times B/B^2,$$

where $f$ is the coefficient of magnetofriction, and $v_1$ describes the effects of buoyancy and pressure gradients in the photosphere (Bobra et al. 2008). Magnetofriction has the effect of expanding the flux rope until its magnetic pressure balances the magnetic tension applied by the surrounding potential arcade. Significant magnetic reconnection between the inserted flux rope and the ambient flux may occur during the relaxation process. Therefore, the end points of the flux rope in the relaxed model may be different from that in the original model.

The lower boundary condition for the HIRES region is derived from LOS photospheric magnetograms obtained with the SDO/HMI. Because the prominence is observed near the east limb, we use magnetograms that are taken several days after the prominence eruption on March 12. We combine four magnetograms taken on 2012 March 16–19 (each at 18:11 UT) to construct a high-resolution map of the radial component $B_r$ of the magnetic field as a function of longitude and latitude at the lower boundary of the HIRES region. We also use a SDO/HMI synoptic map of $B_r$ to compute a low-resolution global potential field, which provides the side boundary conditions for the HIRES domain and also allows us to trace field lines that pass through the side boundaries of the HIRES region.

The HIRES magnetic map is shown in Figure 12. Note that this region is at the polar crown, and the field has mixed polarity with dominantly positive polarity on the south side of the PIL and negative polarity on the north side. Based on this map alone, it is difficult to recognize exactly where the PIL is located. Therefore, we used the filament channel observed by STEREOB to locate the base of the prominence/filament on the magnetic map. The blue curve is the path along which the flux rope will be inserted into the model. At the two ends of the path.

**Figure 9.** Height–time analysis of the rising blobs from 00:00 UT to 02:00 UT on 2012 March 12. AIA image at 171 Å at 01:20 UT on 2012 March 12. (b)–(d) refer to position–time plots of emission along the white stripe shown in (a) at 171, 193, and 211 Å. Velocities are derived from linear fits to height–time plots of several blobs marked with red lines.
Because this region is very close to the south pole, strong numerical artifacts begin to appear at the side near the south pole during the magnetofrictional relaxation process. To reduce the artifacts, we adopt a special relaxation procedure. During the first 70,000-iteration relaxation, we move the HIRES region close to the disk center by setting the latitude of the center of the HIRES box to zero. According to our previous experience, we find that it normally takes an about 70,000-iteration relaxation for the magnetic fields in the quiescent polar crown filament system to approach a force-free state. Then we move the HIRES region back to the original location and then run 10,000 more iterations to make the fields interact and merge with the real global polar magnetic fields. After this extra 10,000-iteration relaxation, the magnetic fields in the HIRES region become adjusted to the real global polar fields in the surrounding low-resolution region. If we continue to relax the magnetic fields, numerical artifacts begin to appear. The two criteria that we use to choose the specific iteration numbers are (1) minimizing numerical artifacts and (2) keeping the HIRES region adjusted to the original surrounding polar magnetic fields. The parameters used during the relaxation process are presented in Table 1.

### 3.2. Models versus Observations

We construct five models with different combinations of axial and poloidal fluxes of the inserted flux rope. In all cases, the inserted flux ropes have a sinistral orientation of the axial field.

Table 2 shows the model parameters of the five models. The initial inserted flux bundles of Models 1 and 2 are straight (untwisted) bundles, while for Models 3–5 the initial inserted flux bundles are twisted flux ropes with nonzero poloidal flux ($F_{pol}$). As mentioned in Su et al. (2011), one constraint on the stability of the models is that the magnetic energy of the field after the relaxation should be less than that of the open field. To estimate the energy of the open field, we change the negative polarity fields of the HIRES region to positive polarity and then compute a potential field. The resulting open-field model has a magnetic energy of $E_{open} = 9.77 \times 10^{31}$ erg, whereas the standard potential field has an energy of $E_{pot} = 1.15 \times 10^{31}$ erg. Therefore, the free energy of the open field is about $8.62 \times 10^{31}$ erg. This requires that the free energy of the flux rope models be less than $8.62 \times 10^{31}$ erg. Note that these energies refer to the HIRES part of the computational domain only (not the whole Sun). All five models presented in this paper meet this criterion.

Figure 13 presents the current distribution in a vertical plane, indicated by the yellow line (nearly perpendicular to the PIL) in Figure 12 for Models 1–4 after relaxing for 80,000 iterations. The strong current is concentrated in the white region. The black and white vectors refer to the magnetic vectors. This figure shows that Model 1 is close to a normal sheared arcade, while Model 2 appears to be a flux rope configuration with an
X-point/HFT and sheared arcade located below. Model 3 and Model 4 display an elevated twisted flux rope configuration.

Figure 14 shows comparisons of Models 1–4 with SDO/AIA and STEREO-B observations. The colored curves in Figure 14 show field lines selected by clicking different points in the two-dimensional plots shown in Figure 13 from the four models. The blue features indicate dips in the field lines (depth of color increases with height). The red and green contours refer to the HMI photospheric flux distribution in the HIRES region. The background images in row 1, row 2, and row 3 are taken at 171, at 193 Å by SDO/AIA, and at 171 Å by STEREO-B, respectively. We can see that the dips of the field lines in Model 1 are lower than the prominence observed by both SDO/AIA and STEREO-B/EUVI. Moreover, the cavity in the model is much smaller than observed, and the model cannot reproduce the observed U-shaped or horn-like structure. Therefore, we think that the sheared arcade topology does not match the observations. For Model 2, the height of the dips of the field lines matches the AIA observations well, but it is much lower than the height of the prominence seen in the STEREO-B.
observations, especially the part where it erupts first. This model exhibits an X-point topology, as suggested by the simulation in Fan (2012), and the location and height of the U-shaped structure in the model match the SDO/AIA observations well, but not the STEREOB observation. Moreover, the size of the “U” in the model is much smaller than that of the observation. The height of the dips of the field lines in Models 3 and 4 correspond very well with the height of the observed prominence by AIA and EUVI, though a small offset toward the south in the models is identified when compared with AIA observations. There appears to be different sizes of cavities in the observations because the prominence is very long. The size of the flux rope in Model 3 appears to match the foreground cavity, while for Model 4 it appears to match the background larger cavity better.

Figure 15 shows comparisons of the “U” structure in Model 3 (right column) and Model 5 (left column) with that in observations. The color curves in this figure are selected field lines that go through a vertical plane near the location of the “U” structure where the prominence first erupts (white arrows in Figures 15(a)–(b)). The bright “U” structures in both AIA and EUVI observations are indicated with the solid white arrows. The corresponding U-shaped structures in the models are marked with dashed white arrows (light blue and pink lines). This figure shows that the location, size, and height of the U-shaped structure in Model 4 match the observations well, but for Model 5, the “U” structure is much lower than that in the observations.

Table 2

| Model No. | $\Phi_{pol}$ ($10^{20}$ Mx) | $F_{pol}$ ($10^{10}$ Mx cm$^{-1}$) | $E_{free}$ ($10^{30}$ erg) | $E_{free}/E_{poten}$ (%) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| 1         | 2               | 0               | 1.98            | 17              |
| 2         | 3               | 0               | 2.98            | 26              |
| 3         | 2               | 2               | 8.14            | 71              |
| 4         | 3               | 3               | 16.2            | 141             |
| 5         | 3               | 1               | 5.76            | 50              |

Note. The potential field energy is 1.1531 erg.
4. DISCUSSIONS

4.1. Onset of Fast Rise: Torus Instability

In Section 2.3, we found that the prominence eruption begins with a slow rise and then evolves to a fast rise, as is often seen in solar filament eruptions (Sterling & Moore 2005; Cheng et al. 2013). The important question is what causes the transition from slow rise to fast rise? In other words, what causes the onset of the explosive fast-rise phase? In this section, we investigate two possibilities: torus instability and magnetic reconnection.

The threshold of torus instability is given in terms of the decay index of the external poloidal field at the position of the current channel, \( n = -\frac{\partial \ln B}{\partial \ln z} > n_{cr} \). The canonical values of the critical decay index are 1.5 for a toroidal current channel (Bateman 1978) and 1.0 for a straight current channel (van Tend & Kuperus 1978). The critical index \( n_{cr} \) for torus instability ranges from 1.0 to 2.0 in theoretical calculations and numerical simulations (Kliem & Török 2006; Fan & Gibson 2007; Aulanier et al. 2010; Démoulin & Aulanier 2010). On the other hand, from the measurement of the height of a set of quiescent prominences, combined with potential field extrapolations, Filippov & Den (2001) found \( n_{ct} \approx 1 \).

Figure 16 shows the distributions of the magnitude of horizontal components of the potential field (top) and the decay index (bottom) of the horizontal components with height over the main PIL at two locations marked with a yellow line (middle) and a star symbol (right) in Figure 12. The dashed and solid vertical lines refer to the height of the outer edge of the prominence and the center of the dark cavity at the onset of the fast-rise phase, respectively. Because of the variety of the supporting magnetic configurations, we take the first (used by Filippov & Den 2001) and second heights as the lower and upper limits of the apex of the flux rope magnetic axis, respectively. We find that at the onset of the fast-rise phase, the decay index \( n \) is \( 1 \pm 0.2 \), which is very close to the critical value of a straight current channel for torus instability.STEREO observations suggest that this prominence begins to erupt near the west end rather than the middle. Figures 16 shows that the lower limit of the decay index near the west end is slightly larger than that in the middle at the onset of the fast rise. We should note that the potential field model is based on the magnetograms taken several days later, which is only a close approximation. The magnetic fields at the time of the eruption may be different due to a disturbance from a prominence eruption nearby several hour earlier. Therefore, we cannot exclude the possibility that the overlying field
actually falls off more quickly with height as the reason that the western portion of the filament erupts first.

4.2. Magnetic Structure Supporting the Vertical Threads

The aforementioned comparisons between models and observations suggest that the twisted flux rope model (Model 4) best matches the observations, whereas the sheared arcade model (Model 1) shows the worst match in comparison to observations. Xia et al. (2014) presents a simulation of the in situ condensation process of solar prominences. In this simulation, the vertical prominence resides in the horizontal fields of concave-upward field regions of a flux rope. The synthetic SDO/AIA views at 304 and 211 Å in Figure 4 by Xia et al. (2014) match our observations (Figure 1) very well, but not for the other two channels, 171 and 193 Å. The synthetic SDO/AIA views show a horn and cavity structure located above the vertical prominence threads at 193 Å and 211 Å, while in observations, the “U” structure is shown at 171 Å. This prominence is similar to the tornado-like prominences that are often observed to show rotational motion along the vertical axis (Li et al. 2012; Su et al. 2012). It is unclear how horizontal fields of the flux rope can survive in the presence of rotational motions of the vertical structure.

Model 2 is closest to the “tangled-field model” proposed by van Ballegooijen & Cranmer (2010), in which the vertical prominence threads are supported by the tangled fields in a vertical current sheet below a twisted flux rope, and the “U” structure corresponds to the central, vertical current layer in the MHD simulation by Fan (2012). Because of limitations in the magnetofrictional method, we are not able to reproduce the vertical current sheet as suggested in the “tangled-field model”; instead we obtain a configuration with a newly reconnected arcade located below an X point. Moreover, the magnetic configuration can be strongly distorted by the weight of the prominence because the magnetic field at the polar crown is very weak. Therefore, although Model 2 does not match the observations well, we cannot rule out the “tangled-field model” for the target prominence because, unlike the twisted flux rope model, the “tangled-field model” can explain the rotational motions of the tornado-like vertical structure.

5. SUMMARY AND CONCLUSIONS

In this work, we study the magnetic structure and dynamics of a tornado-like eruptive polar crown prominence using observations by both SDO and STEREO-B and magnetic field modeling. Our main findings are summarized below:

1. STEREO-B observes that the prominence is a very long structure consisting of a series of vertical threads. AIA observes the prominence at the southeast limb. Prior to the eruption, the prominence gradually becomes much higher and the cavity becomes much bigger as the Sun rotates from 2012 March 6 to 11. A horn-like or U-shaped structure appears to go through nearly all of the vertical threads from top (171 Å) to bottom (193 Å).

2. The slow rise of the prominence begins around 17:00 UT on March 11, and it then evolves to a fast rise around
22:57 (±7) UT on March 11, when the height of the prominence’s leading edge is 97 ± 5 Mm. In the AIA FOV, the maximum velocity is 110 ± 5 km s\(^{-1}\), and the final acceleration is 49 ± 5 m s\(^{-2}\). Comparing with SOHO/LASCO CME observations, we find that the prominence may have followed our height–time fit (i.e., with increasing acceleration) after leaving the AIA field of view until nearly 2.5 \(R_\odot\).

(3) A posteruption arcade begins to appear around 23:50 UT on March 11. A newly formed U-shaped structure begins to show up at the lower part of the rising prominence threads around 00:10 UT on March 12. Around 00:51 UT, we start to see small bright blobs at the bottom of the rising vertical threads. The speed of the rising blobs is faster than the leading edge and bulk motion of the erupting prominence. The blobs that appear earlier (95 km s\(^{-1}\)) are slower than those that appear later (259 km s\(^{-1}\)). These blobs can be explained by the tearing-mode instability of a thin current sheet, where a series of magnetic islands are recurrently created during magnetic reconnection.

(4) During the eruption, AIA observes dark ribbons seen in absorption at 171 Å, corresponding to the bright ribbons shown at 304 Å. The observational characteristics of dark ribbons at 171 Å suggest that they might be caused by the erupting filament material falling back along the newly reconfigured magnetic fields. Dark ribbons are also reported by Xiao et al. (2015), who interpret it as a void region with a smaller magnetic field strength and lower plasma density caused by magnetic field deflection during magnetic reconnection. The cospatial brightenings at 304 Å might be partially caused by heating of the plasma due to the kinetic energy of falling filament material compressing the plasma (Gilbert et al. 2013).

(5) Brightenings at the inner edge of the erupting prominence arcade are observed in all AIA EUV channels during the eruption. These brightenings might be caused by the heating due to energy released from reconnection below the rising prominence.

(6) Using the flux rope insertion method, we construct a series of magnetic field models (sheared arcade model, twisted flux rope model, and unstable model with HFT) and then compare them with both SDO and STEREO observations. Various observational characteristics appear to be in favor of the twisted flux rope model. However, the “tangled-field model” cannot be ruled out because it can explain the rotational motions of the tornado-like vertical structure that the twisted flux rope model cannot.

(7) We find that the flux rope supporting the prominence enters the regime of torus instability at the onset of the fast-rise phase, and the signature of reconnection (posteruption arcade, new U-shaped structure, rising blobs) appears about one hour later. This result suggests that the transition from the slow-rise to the fast-rise phase of this prominence eruption is likely to be caused by the torus instability.

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REFERENCES

Alexander, D., Liu, R., &Gilbert, H. R. 2006, ApJ, 653, 719

Aulanier, G., DeVore, C. R., &Antiochos, S. K. 2002, ApJL, 567, L97

Aulanier, G., Torok, T., Démoulin, P., &DeLuca, E. E. 2010, ApJ, 708, 314

Antiochos, S. K., Dahlburg, R. B., &Klimchuk, J. A. 1994, ApJL, 420, L41

Antiochos, S. K., DeVore, C. R., &Klimchuk, J. A. 1999, ApJL, 510, 485

Bateman, G. 1978, MHD Instabilities (Cambridge, MA: MIT Press), 270

Berger, T. 2012, in Second ATST-EAST Meeting: Magnetic Fields from the Photosphere to the Corona 463, ed. T. Rimmele et al. (San Francisco, CA: ASP), 147

Berger, T. E., Shine, R. A., Slater, G. L., et al. 2008, ApJL, 676, L89

Bobra, M. G., van Ballegooijen, A. A., &DeLuca, E. E. 2008, ApJ, 672, 1209

Su et al.
