

Chapter 4

Vortex Motion and Plasmoid Ejections in the Twisting Prominence

We analyze the characteristics of a quiescent polar prominence using the Atmospheric Imaging Assembly (AIA) onboard Solar Dynamic Observatory (SDO). Initially, small-scale barb-like structures are evident on the solar disk, which firstly grows vertically and thereafter move towards the southwest limb. Later on, a spine connects these barbs and we observe apparent rotating motions in the upper part of the prominence. These apparent rotating motions might play an important role in the evolution and growth of the filament by transferring cool plasma and magnetic twist. The large-scale vortex motion is evident in the upper part of the prominence. The large-scale vortex motion consists of a swirl-like structure within it. The slow-motion of the footpoint twist the legs of the prominence due to magnetic shear, causing two different kinds of magnetic reconnection. The internal reconnection is initiated by resistive tearing-mode instability, which leads to the formation of multiple plasmoids in the elongated current sheet. The estimated growth rate was found to be 0.02-0.05. The magnetic reconnection heats the current sheet for a small duration. However, most of the energy release due to magnetic reconnection is absorbed by the surrounding cool and dense plasma and used to accelerate the plasmoid ejection. The multiple plasmoid ejections destroy the current sheet. Therefore, the magnetic arcades collapse near the X-point. Oppositely directed magnetic arcades may reconnect with the southern segment of the prominence and an elongated thin current sheet is formed. This external reconnection drives prominence eruption.

4.1 Introduction

The Solar corona consists of large-scale sheared or twisted magnetic fields, which lie above the polarity inversion line. These sheared magnetic fields are sometimes associated with solar filaments (or called prominences). Solar prominences are comparatively cool and dense plasma structures suspended in the rarified and hotter million-degree corona with the help of magnetic field (Labrosse et al., 2010; Mackay et al., 2010; Parenti, 2014). On the basis of magnetic field strength and the location of the solar prominences, they may be classified as an active region, quiescent and, intermediate prominence (Mackay et al., 2010; Parenti, 2014; Tandberg-Hanssen, 1998). The prominence formation, stability, and lifetime have been governed by the magnetic field (Mackay et al., 2010; Priest, 1989). Various observational and theoretical models have been used to understand the magnetic structures of the solar prominences. The most recognized models are “sheared arcade model” (Antiochos et al., 1994; Aulanier and Schmieder, 2002; DeVore and Antiochos, 2000) and “flux rope model” (Dudík et al., 2008; Gibson and Fan, 2006; Kuperus and Raadu, 1974; Low and Hundhausen, 1995; Priest, 1989; van Ballegoijen and Cranmer, 2010; van Ballegoijen and Martens, 1989). It was found that 89% of filaments are supported by flux ropes, with the rest by sheared arcades (Ouyang et al., 2017). In the sheared arcade model, only sheared magnetic field lines are embedded in a much less sheared envelope field. In the flux rope model, the core magnetic field is twisted and in the form of helical configuration. Some additional models have also been introduced to discuss the stability of hedgerow and polar prominences. The most known models are “tangled field model” for hedgerow prominence (van Ballegoijen and Cranmer, 2010) and “flux linkage model” (Martens and Zwaan, 2001) for the development of polar prominence. A hedgerow prominence consists of multiple vertical threads and they are sustained by tangled magnetic fields (van Ballegoijen and Cranmer, 2010). According to the flux linkage model, two unconnected bipoles reconnect due to the flux convergence and reconnection near the

polarity inversion line, which creates longer magnetic loops with dips. Similar processes occur for multiple times, then it develops highly sheared longer structures (Martens and Zwaan, 2001).

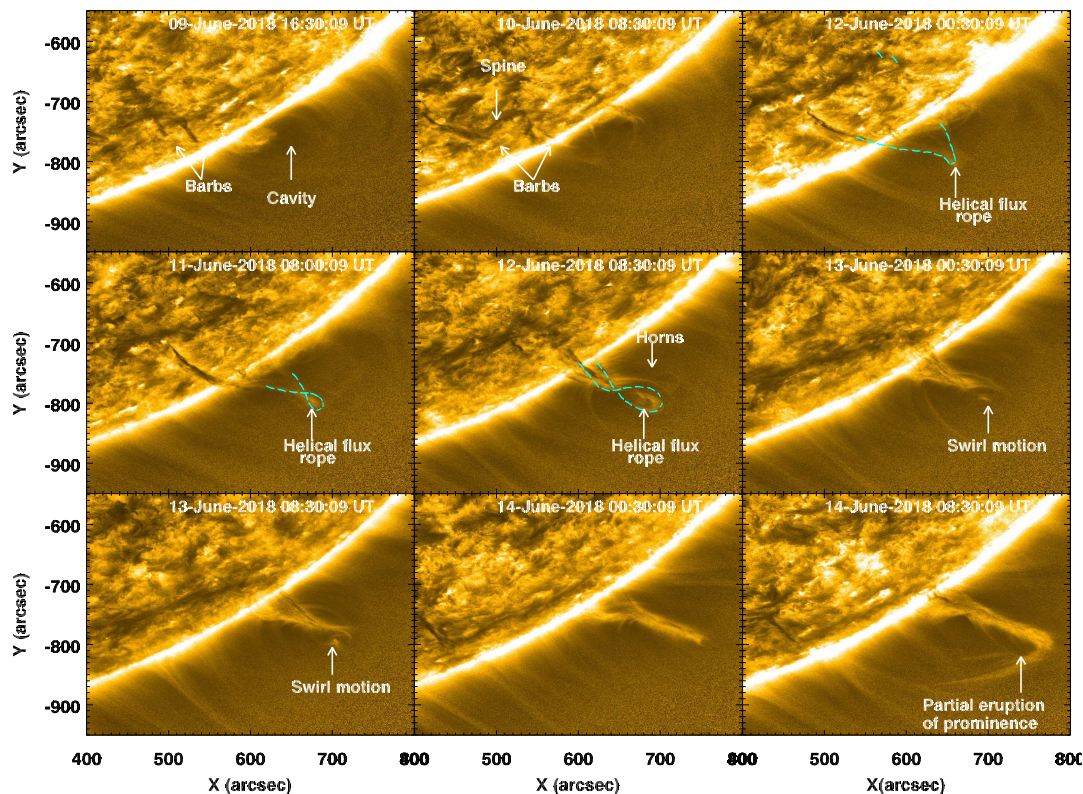


Figure 4.1: The normalized multi-gaussian fitted SDO/AIA 171 Å images showing the evolution of solar tornadoes-like motions related to the polar prominence during 9–14 June 2018. Two dark pillars indicate the prominence barbs and the horizontal structure that connects these barbs in the prominence spine. Several vertical threads and U-shaped horns-like structures have also evident (middle panel). Rotating plasma structure indicates that the growth of the prominence is related to the tornadoes-like motions. The evolution of a helical flux rope, apparent rotating plasma, swirling motion in the top part of the prominence is appeared.

Solar filaments have two main structures, a spine and several barbs. In the EUV emissions images of polar crown filaments, we mainly see barbs, which are known as filament legs observed as dark pillars. The evolution of multiple barbs in a polar prominence was observed by SDO (Li and Zhang, 2013). The kinematics of these barbs is highly

influenced by the photospheric magnetic field. The tornado-like structure is useful to support the prominence plasma (Luna et al., 2012). They found that the Lorentz force supports the barbs plasma if the magnetic field is sufficiently twisted. Solar tornadoes are magnetized plasma and their footpoints are rooted at the photosphere. They were sometimes suggested to be rotating vertical magnetized structures driven by the vortex-like motions in the photosphere (Su et al., 2012). These tornadoes act as the channels of energy and mass transfer into the corona (Wedemeyer-Böhm et al., 2012). Recent high-resolution observations taken from SDO suggest that the tornado-like prominences are associated with the apparent rotational motion of the helical structures (Li et al., 2012; Panesar et al., 2013; Su et al., 2012; Yang et al., 2018). In contrast, some authors suggest that the tornado-like motion of prominence is an illusion due to the line of sight projection effect. The apparent rotational motion can arise due to the counter-streaming flow or oscillations in the prominence spine and barbs in the plane of the sky (Panasenco et al., 2014). Anti-symmetric Doppler velocity pattern along the axis of prominence legs was found only in the coronal plasma with a temperature above 1 MK (Su et al., 2014). Doppler maps of Mg II k, which is formed in the frontmost layers of prominence plasma, do not show anti-symmetric or split patterns and do not support any of the rotating "tornado" models (Levens et al., 2016a). Instead, the horizontal counter-streaming of prominence threads connecting two prominence legs is observed in the Mg II k line (Levens et al., 2016b). The plasma behaviour associated with the internal magnetic field of tornado-like prominence was investigated and found that the quasi-vertical magnetic flux in which a tornado in a helical flux rope needs is not consistent with the totally horizontal magnetic field measured in prominence legs (Levens et al., 2016a,b).

Tornado-like motions play an important role in supplying the mass and magnetic shear into the prominence. The rotating motion of barbs may transfer the shear and cool plasma into a prominence (Su et al., 2014). The sheared prominence legs may consist of oppositely

directed magnetic fields, which reconnect over the neutral line. The oppositely directed magnetic field of the filament legs leads to two-stage magnetic reconnection as we report observationally in the present work. The reversal of magnetic shear may lead to two-stage of magnetic reconnection (Kusano et al., 2004). The first stage of magnetic reconnection (internal reconnection) is governed by resistive tearing mode instability, which is dominated by multiple plasmoid ejections. The Yohkoh data provided the first observational evidence of X-ray plasmoid ejections. Long before the impulsive phase, the plasmoids may be ejected slowly and during the impulsive phase, they may accelerate rapidly (Ohyama and Shibata, 1997, 1998). The apparent rise velocity of the flares and reconnection rate is positively correlated (Shibata et al., 1995). The ejected $H\alpha$ plasmoids/filaments and thermal energy density of X-ray loop arcades are positively correlated. The ratio between the inflow speed and the plasmoid velocity is equivalent to the reconnection rate. Using the above results, (Shibata, 1996, 1997) suggested a new model for the magnetic reconnection i.e., plasmoid-induced reconnection, which is an extension of the standard CSHKP solar flare model. Inside the current sheet, the ejected plasmoids act as a resistance for the magnetic reconnection. Therefore, these plasmoids act as storage of magnetic energy. These plasmoids induce a strong inflow when they ejected from the current sheet. The current sheet in a solar flare consists of hot X-ray plasmoid ejection and cool $H\alpha$ plasmoid ejection (Ohyama and Shibata, 2008).

Solar filament reconnects with the nearby coronal loops and forms an elongated current sheet (Dai et al., 2018; Li et al., 2016; Xue et al., 2016). Magnetic reconnection can also happen in the lower solar atmosphere (photosphere and chromosphere), which is made of collision-dominant, partially ionized, dense and cool plasma. The energy released by reconnection is found to be absorbed by the cold plasma (Chen et al., 2001; Chen and Ding, 2006; Litvinenko, 1999; Litvinenko et al., 2007; Srivastava et al., 2019; Xue et al., 2018). Solar prominences have a similar type of physical properties (partially ionized,

collision dominant, dense, and cool plasma). Therefore, most of the energy released during the magnetic reconnection can be absorbed by the prominence as well (Srivastava et al., 2019). Murphy et al. (2012) investigated the asymmetric magnetic reconnection between solar flares and CME. The asymmetric inflows induce the ejected plasmoids to roll along the flux rope axis. In the elongated current sheet, fractional and turbulent magnetic reconnection was revealed (Cheng et al., 2018). Kusano et al. (2002) investigates the sheared magnetic arcade and suggests that the magnetic reconnection occurs at the shear inversion line. Footpoints of the magnetic arcades sheared in the opposite directions above the PIL. Magnetic shear above the polarity inversion line (PIL) may be responsible for two different kinds of magnetic reconnection (Kusano et al., 2004). The second stage of the magnetic reconnection (external reconnection) triggers the prominence eruption in the above-mentioned case.

In this chapter, we analyze the observational data to investigate the detailed process associated with magnetic reconnection between a prominence and the ambient corona. The present work is useful to understand the dynamics of the polar prominence, the association of tornado-like motion with the prominence growth and onset of the large-scale vortex motion. Observational data and analysis are presented in Section 4.2. Section 4.3 describes the observational results corresponding to development of the prominence, plasmoid enhanced reconnection, and the eruption of the prominence. In Section 4.4, discussion and conclusions are presented.

4.2 Observational Data and Analysis

We use high-resolution data of the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) onboard the Solar Dynamic Observatory (SDO; Pesnell et al., 2012). The AIA telescope provides full-disk images of the solar atmosphere (photosphere, chromosphere

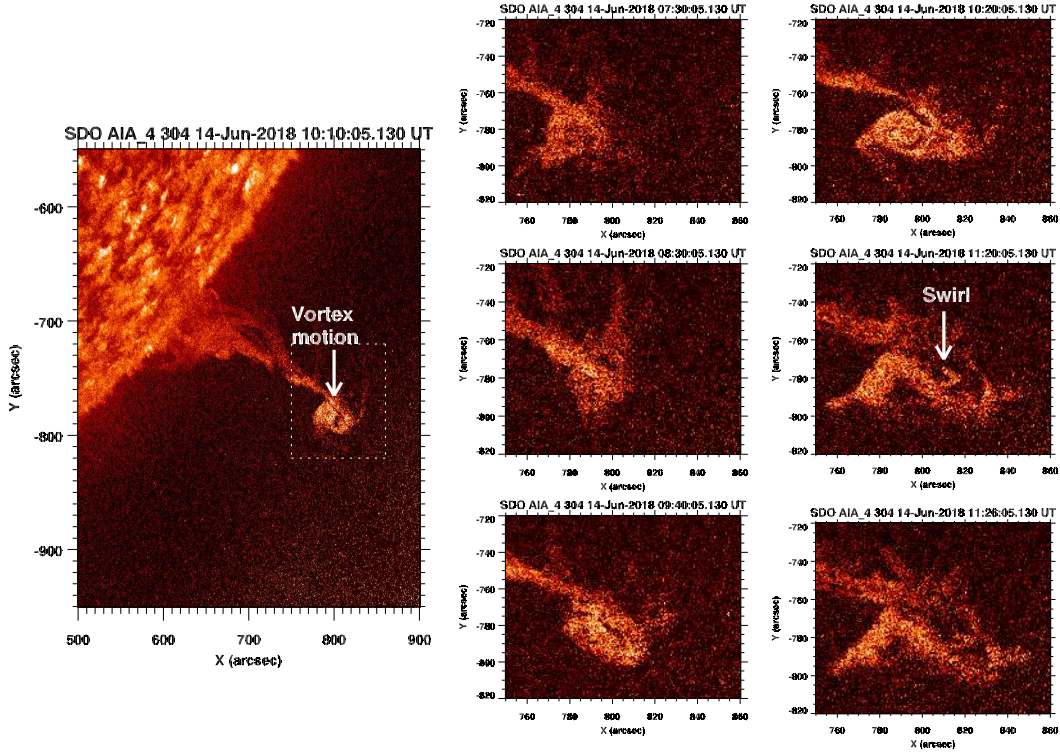


Figure 4.2: Left panel: Full Field of View (FOV) of a polar prominence observed by SDO/AIA 304 Å on 14 June 2018. The sub-region (white-box) consists of a large-scale vortex motion and a swirl-like structure. Right panel: The spatio-temporal evolution of the large-scale vortex motion. The cool plasma and photospheric vortices (large scale vortex) channeled through the prominence body.

and corona) in seven extreme ultraviolet channels (94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å, 335 Å), two ultraviolet channels (1600 Å, 1700 Å) and one visible imager channel (4500 Å). The AIA/EUV data have a 1.5 arcsec spatial resolution and 12 s temporal resolution. We use the AIA 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å, and 335 Å emission images for our observations. The basic calibration and analysis are performed by using the IDL routines `aia_prep.pro` and `aia_offlimb.pro`, which are available in the Solarsoft library.

The thermal properties of the elongated current sheet and plasmoids embedded in the dynamical prominence system are understood by estimating the differential emission measure (DEM). We map the DEM in the temperature range between $\log T=5.6-6.7$ using

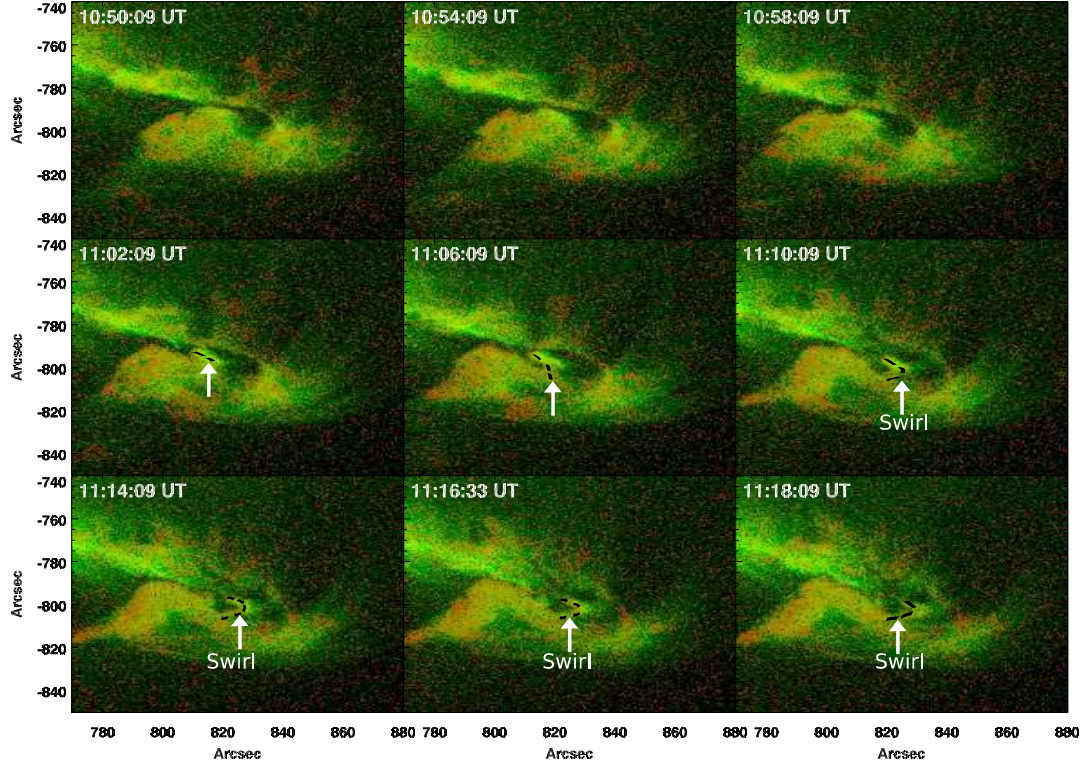


Figure 4.3: The region of interest (ROI; white box in Figure 4.2) is displayed in the SDO/AIA (171+304) Å composite images. The composite images display the large-scale vortex motion and swirl-like structure in the upper part of the prominence. We observed the spatio-temporal evolution of swirl indicated by white arrow within the prominence.

six AIA filters, i.e, 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å. The method developed by (Cheung et al., 2015) is adopted to calculate the DEM from the elongated current sheet and ejected plasmoids within the prominence system. This method adopts the concept of the sparse inversion, which uses the "simplex" function to minimize the total emission. The positive solution has been found by adopting the sparse inversion method, which lies between $\max(0, I - \text{tol})$ and $(I + \text{tol})$, where tol is the tolerance into the reconstructed intensities. For the sparse inversion, we divide the range of temperature between $\log T(\text{K}) = 5.0$ to 7.5 with 25 temperature bins at $\log T(\text{K}) = 0.1$ intervals. The AIA images are processed using the normalized multiscale Gaussian filter which is used to enhance the

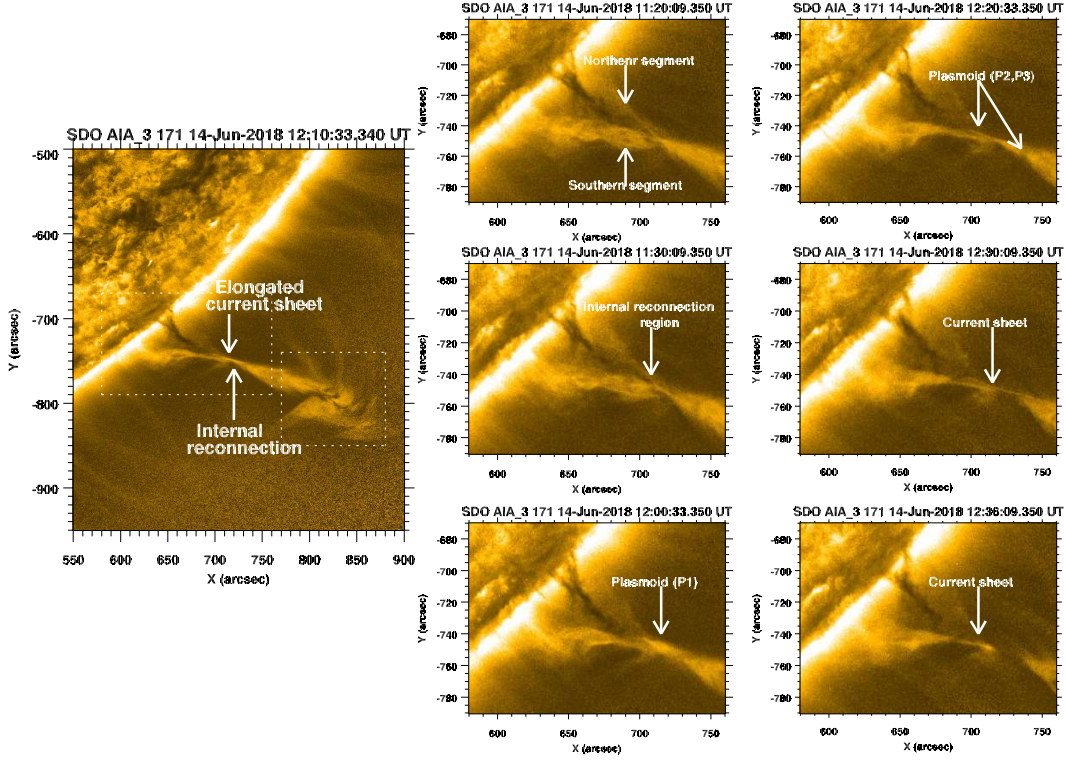


Figure 4.4: Left panel: The region of interest (ROI) of the polar prominence legs observed by SDO/AIA 171 Å on 14 June 2018. The oppositely directed prominence legs reconnect above the PIL. Right panel: Resistive tearing mode instability initiate the formation of multiple plasmoids within the current sheet. We observed three ejecting plasmoids and a bright cusp above the prominence legs (indicated by white arrows). The oppositely directed prominence legs reconnect over polarity inversion line (PIL) and initiate the plasmoid enhanced reconnection. We assume that the PIL is lying between the prominence legs.

fine structures of eruptive prominences and magnetic arcades (Morgan and Druckmüller, 2014).

Using the above observational data and different observational techniques, we analyze a polar prominence, which is associated with tornado-like motions in the solar corona. The small-scale dark pillars (barbs) interact with each other and form a large-scale prominence. This prominence shows various internal dynamics for more than four days at different spatio-temporal scales. We use nine-hour AIA emission data starting on 14 June 2018

at 09:20 UT. During the evolution of the prominence, we observed a large-scale vortex motion, plasmoid enhanced reconnection, and associated prominence eruption.

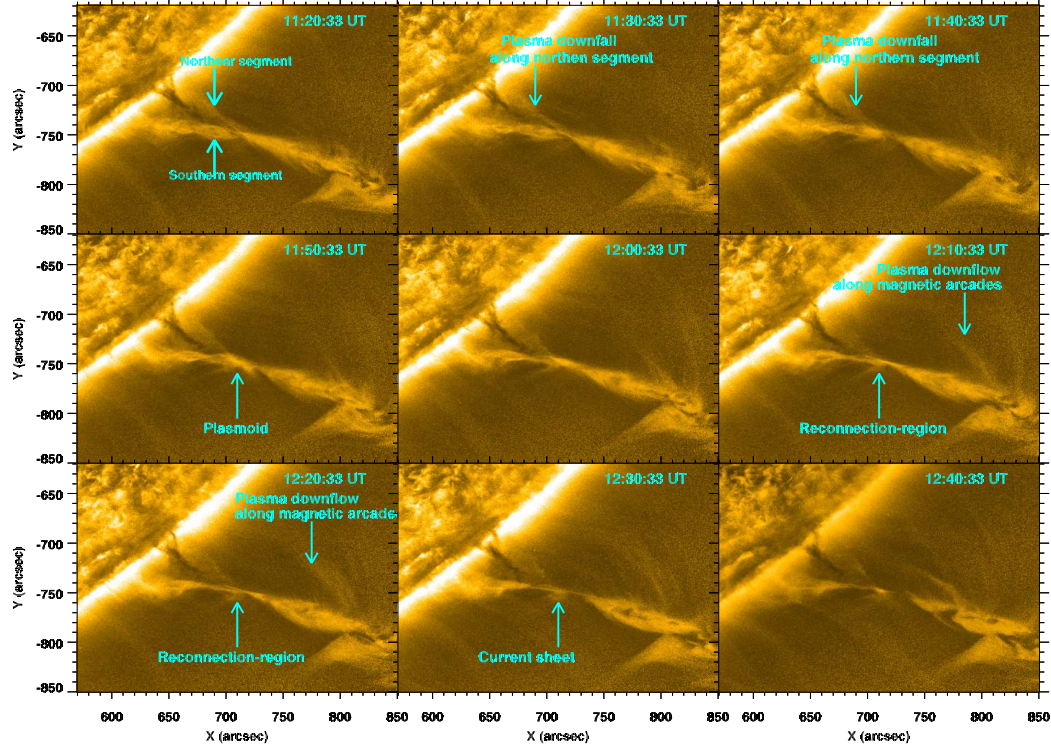


Figure 4.5: The normalized multi-gaussian fitted SDO/AIA 171 Å images display the FOV of polar prominence. Upper panel: Southern segment of the prominence is rising while northern segment is falling along prominence legs. The oppositely directed prominence legs reconnect above the PIL. Multiple plasmoid ejection also observed during the reconnection. These plasmoid passes through the main body of the prominence. Simultaneously, plasma downfall has also evident along the magnetic arcades.

4.3 Observational Results

As mentioned above, we observed a polar crown prominence that erupted on 14 June 2018 at 13:35 UT, as indicated by different AIA wavebands. Before the eruption of this prominence, several internal dynamics are observed. The polar prominence initially appeared on 9 June 2018. We use high-cadence and high-resolution AIA 171 Å emission images

to investigate the internal dynamics of prominence and its associated thread-like structures. The subsection below outlines the step-wise development of the eruptive prominence.

4.3.1 Evolution of the Prominence

Before the filament eruption, several types of internal dynamics (prominence barbs, spine, vertical threads, swirl motion, horn-like structure, plasmoid-enhanced reconnection, and associated inflows and outflows) are observed. The prominence consists of three structural components, i.e., barbs, spine, and prominence legs. The barbs and the spines are vertical and horizontal parts of the prominence. Plasma flows and the development of the prominence are governed by barbs, which may be rooted in the network boundaries (Lin et al., 2005c). Vortex motion is also evident at the network boundaries. We observe here the step-wise evolution of the tornado-like prominence and its dynamics (Figure 4.1). However, in this chapter, we are not interested in understanding the development of the tornado and its internal dynamics. Instead, we are interested in the later phase of this prominence when it is in an eruptive stage. Two barbs appear on 9 June 2014 (Figure 4.1, top panel). These structures grow horizontally and vertically and one day later on 10 June 2018, a spine connects these barbs. In the later stage of the development, we observe that vertical threads appeared in the upper part of the prominence (Figure 4.1, middle panel). These vertical threads are associated with the quiet-region of the Sun. Horn-like structures are also observed on the top of these vertical threads (Figure 4.1, lower middle panel). The horns connect cooler and denser prominence plasma with the rarefied and hotter corona. The morphology of the horns indicates that they are field-aligned structures, therefore, they may be used to understand the magnetic configuration of the prominence-corona transition region (Liu et al., 2012; Luna et al., 2012; Schmit and Gibson, 2013; Schmit et al., 2013; Wang et al., 2016). A cavity lies above the prominence vertical thread (Figure 4.1, middle

panel). Initially, a thin helical structure starts to rise in the cavity (Figure 4.1, top panel). Some plasma material falls along with the horns and the helical field lines. The falling plasma material follows the path of the helical field lines, which causes the swirling motion on the top of the prominence (Figure 4.1, middle panel). Cool prominence associated plasma shows shearing or rotational motions on the top of the vertical threads. The plasma flow occurs via the horns, which acts as a channel to transfer mass and shearing to the prominence. Several types of internal dynamics and the partial eruptions are observed during the growth of this prominence (Figure 4.1, bottom panel). We do not aim to understand these dynamics and partial eruptions. On the contrary, we focus on the dynamics of the prominence on 14 June 2018, before and after its eruption and the associated plasma outflows.

4.3.2 Large-Scale Vortex Motion

The eruptive prominence is associated with twisting/swirling motions. This twisting/swirling motions may act as a channel to transport the cool and dense plasma and twist into the prominence spine. On 14 June 2018 at 09:30 UT, sheared prominence legs transport the large-scale vortices (swirls) to the upper part of the prominence. A large-scale vortex motion is evident in the top part of prominence (Figure 4.2). The evolution of this vortex flow is observed by using SDO/AIA 304 Å images at different times. The large-scale vortex flows consists of swirl motions inside (Figures 4.2–4.3). We use an array of composite images of 171+304 Å to observe the spatio-temporal evolution of the swirl motion (Figure 4.3). Initially, a linear structure is moving at the prominence-corona interface (Figure 4.3, middle panel). It further changes into a fragmented ring-like structure at the interface (Figure 4.3, bottom panel). It further merges into the southern upper part of the prominence. The typical lifetime is ≈ 30 minutes. The large-scale vortex motion is seen for more than 2 hours starting at 09:00 UT on 14 June 2018 (Figures 4.2–4.3). The

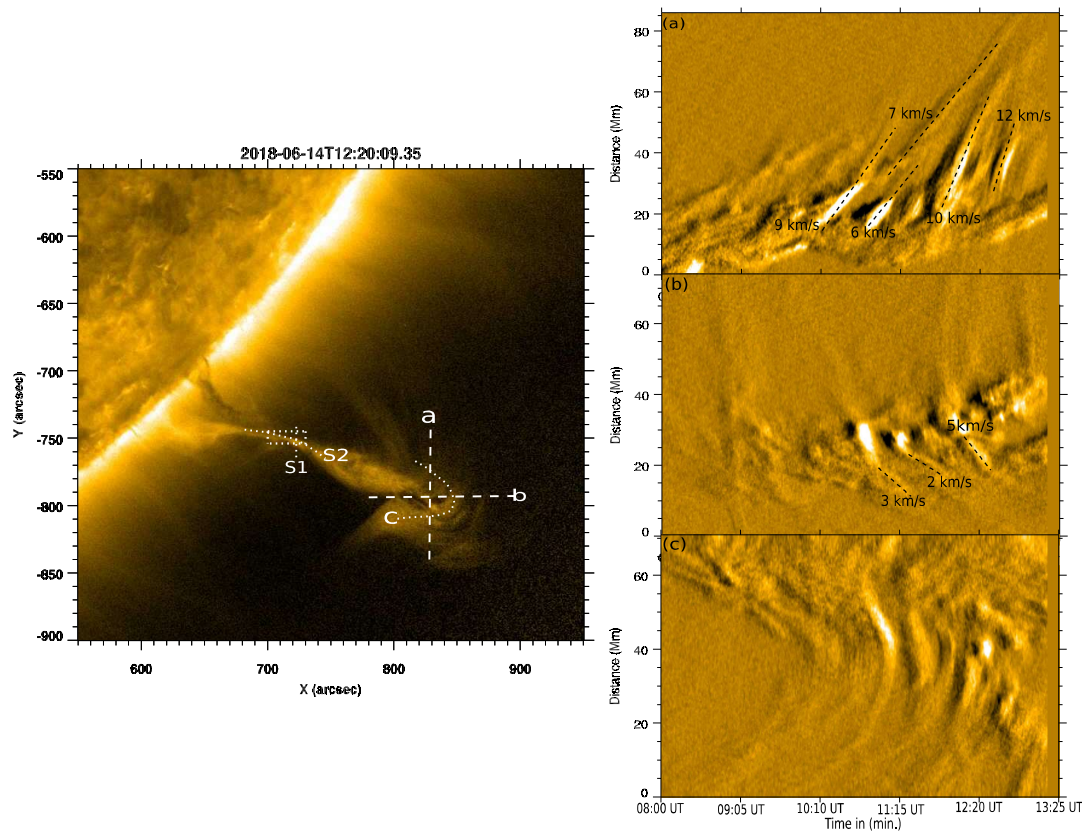


Figure 4.6: The Full FOV of the polar prominence in AIA 171 Å emission imager to analyses the inflow, outflow and nature of EUV intensity pattern at the reconnection site. We have estimated the EUV emission from the selected white box region. Two path (slit S1 and S2) has taken across the X-point to estimate the inflow and outflow velocity. Running difference images of spacetime maps from slits "a", "b", and "c" is used to understand the magnetic field structuring and swirl motion on the top of the prominence.

condensation process of prominence has been simulated with the helical field lines in the cavity (Xia et al., 2014). We observe that during the evolution of the prominence, it exhibits a helical structure along the spine of the prominence and plasma falls along the legs of the prominence and horns (Figures 4.4–4.5). We choose two linear slits namely "a" and "b" along and perpendicular to the swirling motion and a curved slit "c" along the outer edge of the prominence (Figure 4.6). Ten-minutes running difference images at AIA 171 Å are used to understand the dynamical behaviour of the plasma and possible

magnetic field structuring. During the swirling motion of the prominence, there are two types of magnetic field lines. The twisted central core, lying below the magnetic field arcades. It consists of large-scale vortex motions and swirling motion within it. The bright features with a positive slope indicate the clockwise swirling motion on the top of the prominence (Figure 4.6, top and middle panels). Sheared magnetic arcades, lying above the prominence in the concave shape (Figure 4.6, bottom panel along slit "c"). Therefore, the present observation is consistent with the numerical model of the condensation process of prominence with the helical field lines in the cavity (Fan, 2018; Xia et al., 2014). During the vortex motion, the sheared legs of the prominence reconnect over the neutral line, which is discussed in detail in the next subsection.

4.3.3 Plasmoid Enhanced reconnection

Magnetic reconnection is a fundamental process that occurs in the astrophysical plasmas, where magnetic field lines with anti-parallel components reconfigure. Due to magnetic reconnection, the stored magnetic energy is released in the form of kinetic energy and radiation. The footpoints of the tornadoes, which is associated with the barbs/prominence legs, is associated with photospheric vortices. Due to shear motion at the footpoints, the legs of the prominence possess opposite magnetic field configuration above the polarity inversion line (PIL; Figures 4.4–4.5). We observe that the southern segment of the prominence leg is rising and the northern segment is falling between 11:15 UT to 11:40 UT (Figure 4.5). We observe here two different kinds of magnetic reconnection. The first type of magnetic reconnection (internal reconnection) is governed by plasmoid-enhanced reconnection, which consists of an elongated current sheet (Figures 4.4–4.8). In the second stage (external reconnection), thin coronal magnetic arcades reconnect with the southern part of the overlying prominence and may be responsible for the eruption and

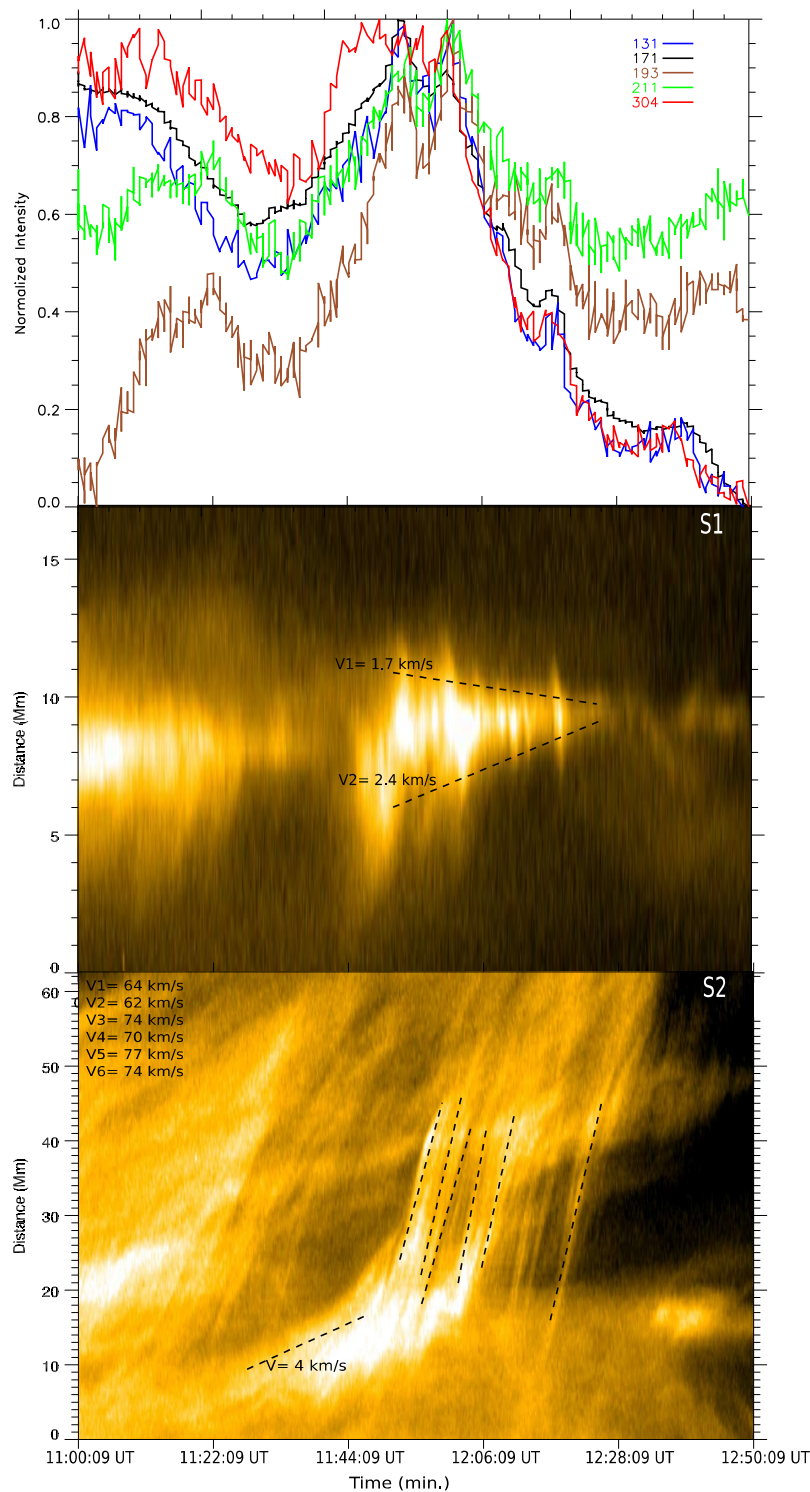


Figure 4.7: Top panel: The nature of EUV emission from six different SDO/AIA filters measure from white box of Figure 4.6. The temporal variation of EUV plasma intensity (131 Å, 171 Å, 193 Å, 211 Å, 304 Å and 335 Å) has estimated to understand the thermal behaviour at the reconnection site. We have analysed the inflow (rate of the thinning of the current sheet along slit S1) and outflow velocity (ejected plasmoids along slit S2) at the reconnection site. Middle panel: The thinning of current sheet after reconnection gives the inflow speed at the X-point. Bottom panel: We track the of plasmoids in H-T diagram to measure the outflow velocity.

plasma outflows. In the external magnetic reconnection, an elongated thin current sheet is seen, which is mostly visible in AIA 211 Å Figure 4.11. The internal reconnection is probably triggered by the resistive tearing mode instability, which grows in the magnetically sheared legs of the prominence. The sheared field lines are destroyed above the polarity inversion line. As a result, multiple plasmoids are ejected along height of the prominence (Figures 4.4–4.8).

During the development of the prominence, oppositely-directed magnetic fields associated with the prominence threads reconnect above the PIL. The southern rising segment of the prominence leg reconnects with the oppositely-directed northern leg of prominence between 11:30 UT to 11:40 UT. An elongated current sheet is observed in the main body of this prominence. The ejection and acceleration of plasmoids are related to magnetic reconnection. We observe that an elongated current-sheet is formed that lies above certain part of the polarity-inversion line of the quiet-Sun (Figure 4.4). Plasma downfall is also observed along the thin coronal arcades (Figure 4.5). The current sheet consists of multiple plasmoid (P1, P2, P3; Figure 4.4) ejections from the tip of the current sheet. This current sheet follows the fractional structure by the following the path: Plasmoid ejection $\Rightarrow$ thinning of current sheet $\Rightarrow$ reconnection $\Rightarrow$ plasmoid ejection $\Rightarrow$ thinning of current sheet and repetition of the same process. The magnetic reconnection may create a jet, which hits and accelerate the plasmoids along the current sheet (Figures 4.4–4.8). The reconnection rate is a fundamental parameter for magnetic reconnection, which can be calculated by (Priest and Forbes, 2000; Shibata and Tanuma, 2001),

$$M = \frac{V_{inflow}}{V_{outflow}} \quad (4.1)$$

where " M " is the reconnection rate, V_{inflow} is the inflow velocity, and $V_{outflow}$ is the outflow velocity. The inflow velocity may be estimated as the thinning of the current sheet (Figure 4.7, middle panel) and the outflow velocity is related to the plasmoid velocity

(Figure 4.7, bottom panel). The inflow velocity is related to the apparent velocity of the reconnecting loops, which are descending so that its width is decreasing with such apparent velocity. We estimate the inflow velocity (thinning of the current sheet along slit S1, Figure 4.6) to be $\approx 1.7 - 2.4 \text{ km s}^{-1}$ and the outflow velocity (plasmoid velocity along slit S2, Figure 4.6) is lying in the range of $62 - 77 \text{ km s}^{-1}$ (Figure 4.7). Correspondingly, the reconnection rate is lying between $0.02 - 0.05$. (Shibata et al., 1995; Shibata and Tanuma, 2001) studied the relationship between the apparent growth of the flaring loop and the velocity of the plasmoids and found that they are correlated as (Shibata et al., 1995)

$$V_{plasmoid} \simeq (8 - 20) \times V_{loop} \quad (4.2)$$

where $V_{plasmoid}$ and V_{loop} are the apparent velocities of the plasmoid and the flare loop, respectively. We estimate the velocity of the rising prominence and plasmoids. The prominence is rising with an apparent velocity (V) of $\approx 4 \text{ km s}^{-1}$ and apparent velocity of plasmoids are lying in the range of $62 - 77 \text{ km s}^{-1}$ (Figure 4.7, bottom panel). We conjecture that the rising velocities of the prominence and the plasmoids are positively related as well.

We measure the temporal evolution (11:00 UT to 12:50 UT) of the emission from five different SDO/AIA filters near the reconnection X-point. The intensity at the X-point for the cool AIA 304 Å ($\log T=4.7$), AIA 171 Å ($\log T=5.8$) and AIA 131 Å ($\log T=5.6$) filters are higher compared to the hotter filters of AIA 193 Å and AIA 211 Å at 11:50 UT (Figure 4.7). The sheared legs of the prominence come closer and may reconnect around 11:50 UT. Oppositely-directed prominence legs (the southern leg is rising and the northern segment is falling between 11:20 UT to 11:40 UT, Figure 4.5) reconnect above PIL. During the magnetic reconnection emissions from different filters are minimum (11:25 UT to 11:40 UT, Figure 4.7). The decrement in the emission is related to the coronal dimming, which may be caused by density depletion due to the lifting of eruptions in

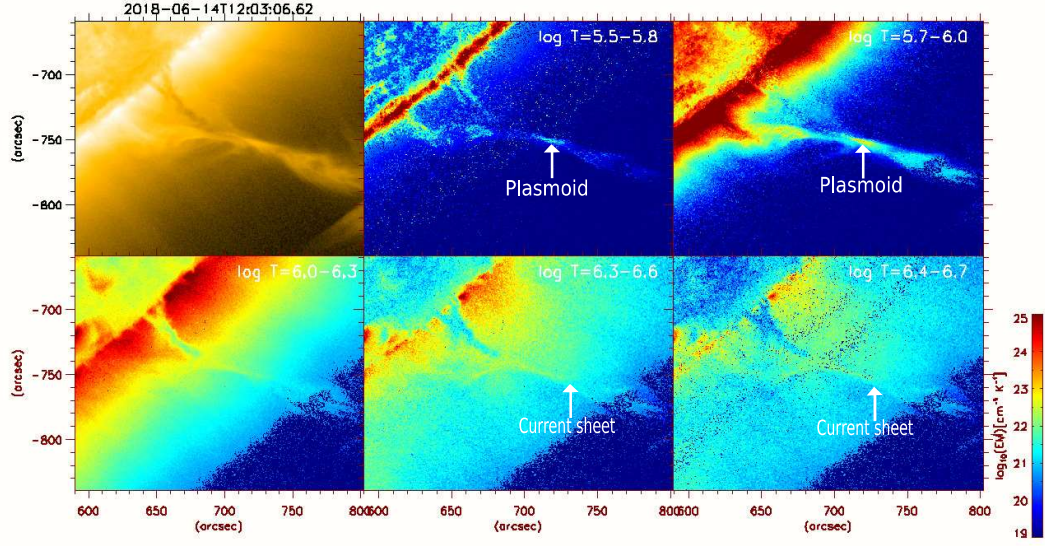


Figure 4.8: The Differential Emission Measure (DEM) of the sub-region to observe thermal structure of the plasmoids and current sheet. The DEM (Cheung et al., 2015) map the temperature bins from $\log T=5.6$ to $\log T=6.7$ shows that plasmoid are best visible temperature range $\log T=5.8-6.1$ and an elongated current sheet observed between $\log T=5.8-6.7$.

the solar corona (Reeves et al., 2010; Sterling and Hudson, 1997; Zhu et al., 2016). The decrement in the intensity is related to the depletion of the density. As the reconnection initiated, the prominence starts to rise and evacuate the corona. After reconnection, the first bigger plasmoid is ejected from the top of the reconnecting cusp. The intensity is maximal for the cool AIA 304 Å filter and it peaks between 11:50 UT to 12:05 UT. As the reconnection begins, the other high temperature AIA filters e.g., AIA 131 Å ($\log T=5.6$), AIA 171 Å ($\log T=5.8$), AIA 193 Å ($\log T=6.2$) and AIA 211 Å ($\log T=6.3$), peak between 11:55 UT to 12:05 UT. The intensities are maximal near the X-point at $\approx 11:55$ UT, which indicates that the spontaneous energy release occurs after the reconnection. After 12:20 UT, at some locations, higher emission is seen. These higher emissions are associated with other plasmoids, which propagate along the current sheet. We use the (Cheung et al., 2015) DEM method to derive the thermal properties of the prominence

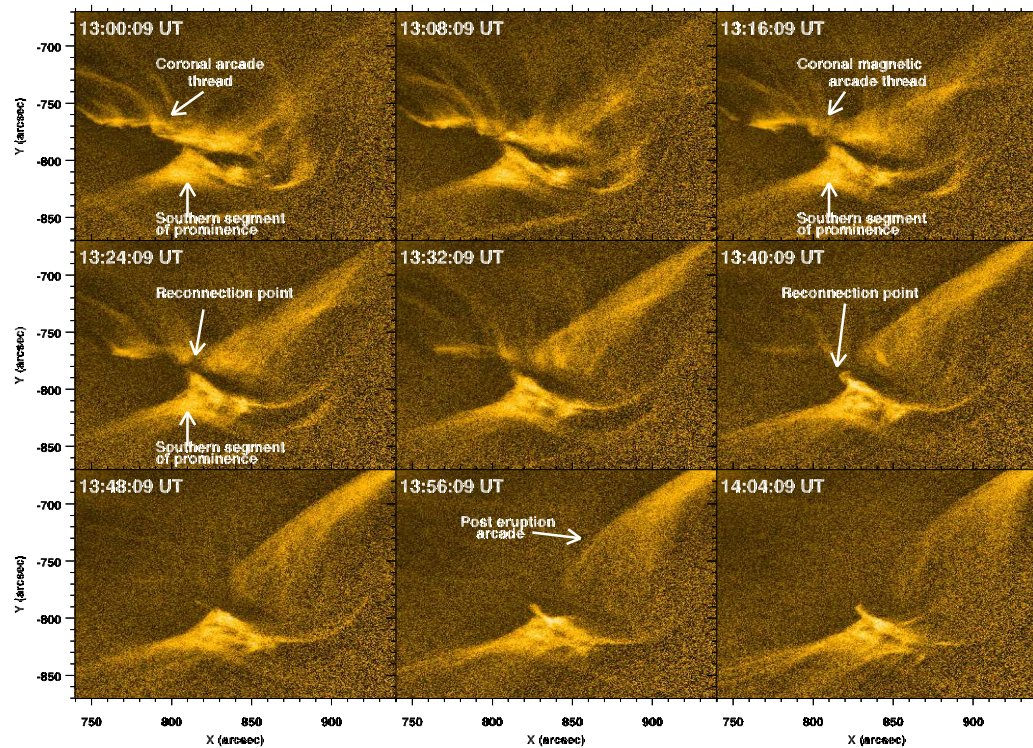


Figure 4.9: The sub-region of eruptive prominence after applying normalized multi-Gaussian filter on AIA 171 Å imager. Several sheared magnetic arcades are evident and they collapse near the reconnection site. A sheared coronal arcade thread reconnect with the southern segment of the overlying prominence. This external reconnection may trigger to erupt the prominence. The eruptive prominence consists of the post-eruption arcade and flux rope, which are indicated by arrows.

and the elongated current sheet. The DEM analysis indicates that plasmoids are most visible in the temperature range of $\log T(K)=5.8-6.1$. A major part of the emission in this temperature range, which is lying at the million-degree corona is also observed by the SDO/AIA 171 Å filter. The current sheet is best observable in the temperature range of $\log T(k)=5.8-6.7$. After reconnection, local heating occurs and accelerated plasmoid ejection is observed (Figure 4.8). This magnetic reconnection occurs within the prominence legs, which are partially ionized, cool, and, dense plasma regions. The spontaneous energy release after the reconnection may be absorbed by the surrounding plasma and may be used to accelerate the plasmoids.

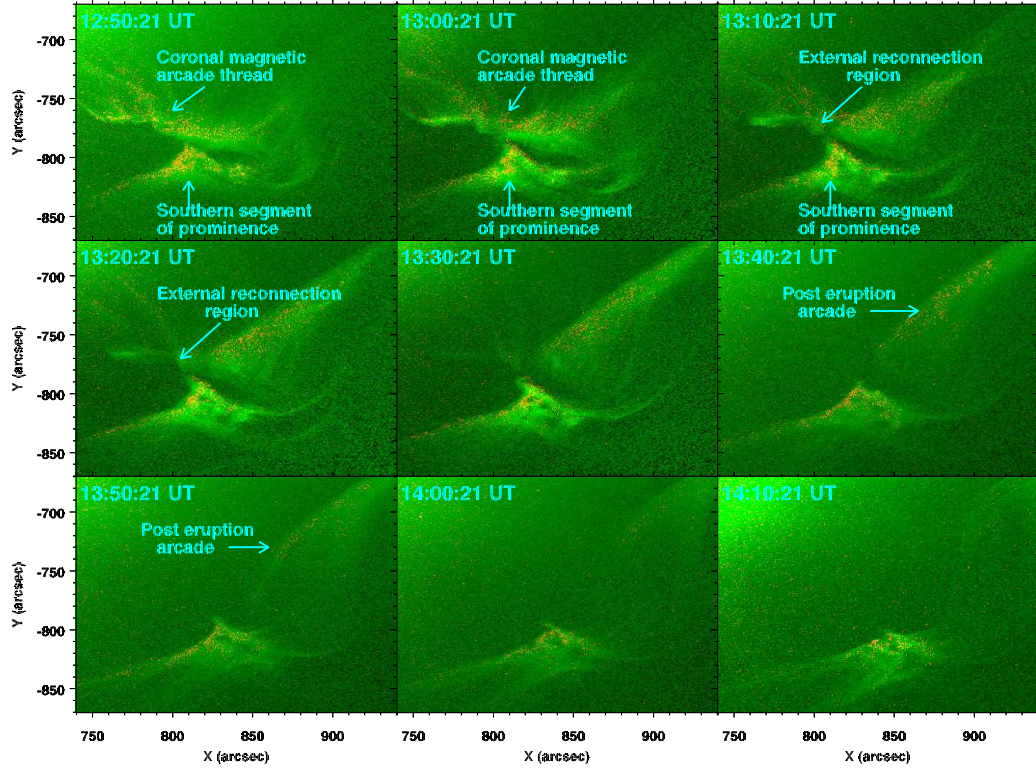


Figure 4.10: The sub-region of eruptive prominence as observe by the composite images of AIA 171+304 Å. The composite images observed the characteristics of hot magnetic arcades (AIA 171 Å, green color) and cool prominence associated plasma (AIA 304 Å, red color). A sheared coronal arcade thread reconnects with the southern segment of the overlying prominence.

As discussed above, plasmoid-enhanced reconnection and an elongated current sheet are observed in a prominence. The reconnection takes place between the sheared legs of the prominence above the neutral line. The resistive tearing mode most likely destroyed the sheared flux rope and multiple plasmoids are ejected (Figures 4.4–4.7). As a result, multiple magnetic arcades collapse near reconnection point. The magnetic arcades and their collapse are observed near reconnection-point (Figures 4.9–4.10, top panel). The magnetic arcade may reconnect with the southern segment of the overlying prominence (Figures 4.9–4.11). These magnetic arcades are very thin and diffuse. Therefore, the external magnetic reconnection is not clearly observable. However, the interaction between

the magnetic arcade associated field lines and the southern segment of the prominence is observed. After the reconnection, the magnetic arcade associated field lines move opposite to the temporary X-point and the northern segment of the prominence erupts. An elongated thin current sheet is evident above the PIL. This current sheet is associated with the external magnetic reconnection and it is best visible in the composite image of AIA 171+211 Å (Figure 4.11). This current sheet is situated between the prominence legs and its southern segment. The reconnection rate for this external reconnection may be near the lower end of fast reconnection. Therefore, we do not observe significant inflow and heating in the current sheet. This external reconnection is responsible for the southern segment of the prominence eruption. The eruption of this prominence follows the prominence/cavity flux rope model (Berger et al., 2012; van Ballegooijen and Cranmer, 2010). This eruptive prominence mainly consists of two parts, a core of the cool prominence plasma and hot post-eruption arcades (Figures 4.9–4.11, bottom panel).

4.4 Discussion and Conclusion

A quiescent polar prominence erupts on 14 June 2018 at 13:35 UT. Before the eruption, the polar prominence showed several types of dynamics for more than five days. In the present chapter, we observe the development of prominence with twisting/swirling motions. The sheared prominence legs reconnect and trigger most likely the resistive tearing mode instability. The resistive tearing mode instability is governed by the multiple plasmoid ejection within the elongated current sheet. An external magnetic reconnection takes place between the magnetic arcade and overlying prominence, which triggers the prominence eruption.

Several internal dynamics (barbs, spine, horns, swirl motion, and partial eruptions) are observed during the growth of this prominence and before the eruption. We investigated in details the dynamics of the prominence before and after the eruption. Cool plasma and

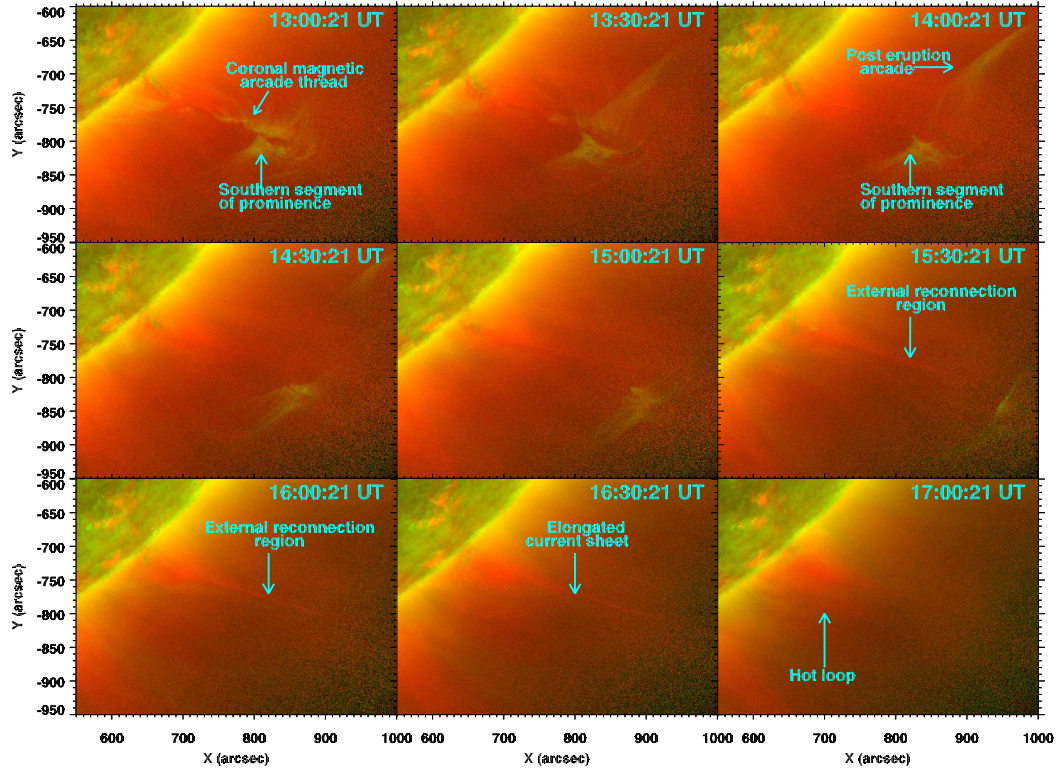


Figure 4.11: The eruptive prominence observed as composite image of AIA 171+211 Å. Southern segment of the overlying prominence reconnects with the collapsing magnetic arcades and lead to the external magnetic reconnection. A thin elongated current sheet is evident, which is best visible in AIA 211 Å (red color) waveband. The prominence associated hot plasma, magnetic arcades and post-eruption arcades are best visible in the AIA 171 Å (green color) waveband. This external magnetic reconnection trigger the prominence eruption.

large-scale shear) are transferred by the helical magnetic fields and horn-like structures into prominence during its evolution (Figure 4.1, middle and bottom panel). We observed large-scale vortex motions in the upper part of the prominence (Figures 4.2–4.4)). Twisted prominence legs transfer shear into the prominence barbs, which leads to two different kinds of magnetic reconnection above the polarity inversion line (PIL, Figures 4.4–4.9). The internal magnetic reconnection is initiated when two oppositely directed magnetically sheared prominence legs reconnect above the PIL (Figures 4.4–4.6). The resistive tearing mode instability most likely is initiated and grows above the magnetic sheared layer,

which destroys the sheared flux ropes. An elongated current sheet is developed above PIL (Figures 4.6–4.8). The resistive tearing mode instability leads to the formation of several plasmoids (Figures 4.4–4.8). These plasmoids act as an obstacle for the reconnection into the current sheet. As the plasmoids are ejected, reconnection inflow occurs. We analyzed the inflow and outflow plasma dynamics near the reconnection site (Figure 4.6). The velocity of the ejected plasmoids corresponds to reconnection outflow velocity and the thinning rate of the current sheet gives the inflow velocity near the X-point (Figures 4.6–4.7). We estimated the reconnection rate, which is found to be 0.02–0.05.

We measured the emission of five AIA filters (131 Å, 171 Å, 193 Å, 211 Å, and 304 Å) inside a box along the current sheet to observe the intensity pattern at the reconnection site (Figure 4.7, top panel). The intensity map indicates that cool AIA 304 Å filter ($\log T=4.7$) peaks at $\approx 11:50$ UT. Once reconnection begins, the intensity of the higher temperature filters, i.e., AIA 131 ($\log T=5.6, 7.0$), AIA 171 ($\log T=5.8$), AIA 193 ($\log T=6.2$), AIA 211 ($\log T=6.3$) and AIA 335 ($\log T=6.4$), peak between $\approx 11:55$ –12:15 UT. The DEM analysis shows that the plasmoids are best visible at the coronal temperatures ($\log T=5.8$ –6.1). The elongated current sheet could be observed in the wide temperature range ($\log T=5.8$ –6.7; Figure 4.8). The emission measure and the DEM analysis indicate that the quick energy release occurred inside the current sheet in 10 minutes (Figures 4.7–4.8). However, this energy release does not produce strong local heating. The reason is probably that the magnetic reconnection occurs within the prominence leg (partially ionized, dense and cool plasma). Therefore, the energy released during the reconnection may be absorbed by the cool and dense prominence. The reconnection also triggers the overlying body of the prominence to erupt. Due to this reconnection, multiple plasmoids ejection appeared in the current sheet. The magnetic arcades start to collapse near the reconnection-point (Figure 4.9, upper panel). The second kind of magnetic reconnection develops between the southern segment of the prominence and collapsing magnetic arcades.

A very thin, elongate, and cool ($\log T=6.3$) secondary current sheet evolves, which leads to the prominence eruption (Figure 4.10). This current sheet is thin and cool due to a very slow reconnection-rate. The eruptive prominence consists of hot post-eruption arcades and prominence associated flux rope. It disrupts the overlying coronal magnetic field. The alignment of the magnetic field and hot coronal loops are observed after this eruption (Figure 4.10). After the eruption, the northern segment consists of a post-eruption arcade and the southern part consists of cool prominence plasma. This eruptive prominence is associated with a CME.

In this chapter, we discussed the evolution and growth of a polar prominence related to solar tornadoes-like motions. During the evolution of the prominence partial eruption was observed (Figure 4.1), but other tornadoes-like motions may connect to the prominence and supply cool plasma (Su et al., 2012, 2014; Wedemeyer-Böhm et al., 2012). We observed large-scale vortex motions and swirl-like structures transferred into the overlying prominence. The swirling motion appears due to the falling plasma along the helical field lines. Pant et al. (2018) reported the tornado-like swirl motions near the footpoint of the eruptive prominence. The slow-motion at the footpoint may shear the prominence legs and two-stage reconnection takes place (Kusano et al., 2002, 2004; Nemati et al., 2015). The similar dynamics observed in this prominence, in which sheared and oppositely directed prominence legs reconnect over a PIL (Figures 4.4–4.6) and multiple plasmoids ejection are observed (Figures 4.4–4.6). The estimated magnetic reconnection rate initiated by plasmoid enhanced reconnection is consistent with the Petscheck-type reconnection (Priest and Forbes, 2000; Shibata and Tanuma, 2001). The external reconnection may be responsible for prominence eruption (Figure 4.11). The eruptive quiescent prominence consists of hot post-eruption arcades and a flux rope associated cool plasma structure (Figures 4.9–4.11), which is consistent with the previous coronal cavity/prominence flux rope model (Berger et al., 2012; van Ballegooijen and Cranmer, 2010).

The present work to the best of our knowledge provides a relation between tornadoes-like motions, formation, and an eruption of prominence through plasmoid enhanced reconnection. The tornadoes transport the cool plasma and sheared magnetic fields in prominence, and may be responsible for the generation of tearing mode instability, thinning of current sheet, and ejection of plasmoids. The prominence system is also subjected to the two-stage magnetic reconnection during these whole physical processes. Later, the external magnetic reconnection in the upper part of the prominence system leads to its eruption and the associated plasma outflows. These physical processes develop at different spatio-temporal scales in a sequential manner. Therefore, overall they provide the complete scenario of the formation of polar prominences, the associated large-scale vortex motions, and the formation of elongated current-sheet through a series of reconnection.