**ABSTRACT**

We report an observation of a partially erupting prominence and its associated dynamical plasma processes based on observations recorded by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory. The prominence first went through a slow rise (SR) phase followed by a fast rise (FR) phase. The SR phase began after a couple of small brightenings were seen toward the footpoints. When the prominence had transitioned from SR to FR, it had already become kinked. The prominence shows strong brightening at the central kink location during the start of FR. We interpret this as an internal magnetic reconnection occurring at a vertical current sheet forming between the two legs of the erupting prominence (flux rope). The brightening at the central kink location is seen in all EUV channels of AIA. The contributions of differential emission at higher temperatures are larger compared to that for typical coronal temperatures supporting a reconnection scenario at the central kink location. The plasma above the brightening location is ejected as a hot plasmoid-like structure embedded in a coronal mass ejection, and those below the brightening move down in the form of blobs moving toward the Sun’s surface. The unique time resolution of the AIA has allowed these eruptive aspects, including SR-to-FR, kinking, central current sheet formation, plasmoid-like eruption, and filament “splitting,” to be observed in a single event, providing strong and comprehensive evidence in favor of the model of partially erupting flux ropes.

**Key words:** Sun: activity – Sun: atmosphere – Sun: corona – Sun: coronal mass ejections – Sun: filaments, prominences – Sun: magnetic fields – Sun: UV radiation

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

1. INTRODUCTION

Prominence eruptions are one of the best proxies for coronal mass ejections (CMEs). Therefore, understanding the initiation and evolution of the erupting prominences provides a crucial physical understanding of the dynamical processes involved in CME initiation and evolution, with broader implications for space weather and geospace climate.

Prominence eruptions show a range of observational characteristics including complete eruption, partial eruption, and failed or sympathetic eruption. Partial eruption of prominences is a relatively new phenomenon which was first described by Gilbert et al. (2000). Partial eruptions were observed in the form of downflows from the erupting prominences. Gilbert et al. (2000, 2001) found that a majority of the erupting prominences observed with the Hα coronagraph located at the Mauna Loa Solar Observatory (MLSO) were associated with downflows. Based on these observations, Gilbert et al. (2001) hypothesized that during the process of eruption the prominence breaks into two parts, an X-type neutral point and internal magnetic reconnection. Depending on the location of the internal magnetic reconnection, the prominence would show a complete, partial, or failed eruption (Gilbert et al. 2001).

Gibson & Fan (2006a, 2006b) studied the evolution of a flux rope from the Sun’s surface out to 6 solar radii, where a flux rope with enough twist erupts due to loss of equilibrium. In this simulation, a flux rope undergoes a kink instability, leading to the formation of a vertical current sheet between the two legs of the flux rope (see also Birn et al. 2006). Based on these simulations, Gibson & Fan (2006a, 2006b) demonstrated that multiple internal reconnections (inside the flux rope) take place at the vertical current sheet. This leads to the bifurcation of the flux rope. In this process, the part of the flux rope above the reconnection point escapes as the core of the CME and the part of the flux rope below the reconnection point falls back toward the Sun’s surface. Srivastava et al. (2010) found observational evidence of kink instability in a highly twisted loop system and the formation of a horizontal current sheet below the double fragmented loop-top.

Based on the above-mentioned simulations, Gibson & Fan (2006b) predicted some observables that could be directly compared with observations. Tripathi et al. (2009) studied six CMEs events associated with erupting prominences/filaments and concluded that the model of Gibson & Fan (2006a, 2006b) involving the partial eruption of the flux rope during the CME eruption was capable of producing almost all of the observed signatures in different CME events. Thus, the general behavior described by the model is broadly applicable to partial eruptions, assisting in the interpretation of CME evolution and its interplanetary consequences.

Alexander et al. (2006) reported a prominence eruption using Transition Region and Coronal Explorer (Handy et al. 1999) observations together with RHESSI (Lin et al. 2002) observations. They identified two coronal hard X-ray sources, which were located above the filament before the main activation phase (see also Ji et al. 2003) and directly beneath the apex of the filament when the filament was strongly kinked. Alexander et al. (2006) attributed this second brightening to an internal magnetic reconnection occurring at the vertical current sheet formed under the apex of the kinked filament slightly above the projected crosspoint of its two legs. This event was classified as a failed eruption because no associated CME was observed. Liu et al. (2007) reported an observation of partial eruption where the filament/cavity structure bifurcated into two parts, with the
upper part ejected as a CME and the lower part along with the bulk of the filament material remaining on the Sun’s surface. This event was classified as a partially erupting prominence. However, no clear evidence of reconnection was observed related to this event.

Using multi-wavelength observations recorded by the Extreme-ultraviolet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory, the Soft X-Ray Telescope (SXT) on board Yohkoh, and Hα and white light coronagraphic observations from the MLSO, Tripathi et al. (2006, 2007) reported observations of a coronal downflow in the wake of a prominence eruption which was bright in EIT and XRT observations. The speed of the downflow measured using the white light coronagraphic data was equivalent to the local Alfvén speed. Furthermore, a cusped-shaped structure was observed in SXT images. The downflow began at the location of the X-ray cusp and base difference images showed an increase in the area of the dimming region at the cusp. All of these observed features were interpreted as signatures of magnetic reconnection occurring at the location of the cusp. However, due to different observational limitations, the complete evolution of the prominence eruption was not observed. For instance, the time resolution of EIT or SXT was not enough to determine if the prominence exhibited kinking motions. In addition, neither EIT nor SXT observed the apex of the cusp because of a limited field of view. On the other hand, Hα and white light observations at MLSO showed the apex and location of the bifurcation of the erupting prominence, but were not available for the early phase evolution, and, since white light observations are temperature-independent, they could not provide information about the thermal properties of the plasma.

The six events studied by Tripathi et al. (2009) showed many characteristics predicted by the model of Gibson & Fan (2006b). These events individually showed different predicted observables, but none of the events showed all of the predicted observables. In addition, due to limited temporal and spatial resolution, some of the predicted characteristics could not be studied, in particular, a transition from slow rise (SR) to fast rise (FR), kinking, central current sheet formation, and filament “splitting.”

In the present paper, we report an observation of a partially erupting prominence and the associated dynamics of the hot, plasmoid-like structure using observations recorded by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). The spatial and temporal resolution of AIA observations and broad temperature coverage is ideal for such observations. In particular, we are able to study the complete evolution and dynamics of an erupting prominence and detect eruptive aspects indicative of a partially ejected flux rope in the observations. The remainder of the paper is organized as follows. We describe the observations in Section 2, followed by a presentation of data analysis and results in Section 3. We summarize and discuss our results in Section 4.

2. INSTRUMENTATION AND OBSERVATIONS

A small erupting prominence was observed on 2011 September 12 by AIA at the east limb of the Sun in a region later called NOAA AR 11295 on September 13. AIA provides observations of the Sun in eight different wavelength channels simultaneously with a typical cadence of 12 s and a pixel size of 0.6 arcsec. The primary contributing ion and the temperature response for each of these channels can vary depending on the features on the Sun’s surface being observed. For more details, see O’Dwyer et al. (2011) and Del Zanna et al. (2011). In this paper, we have investigated all of the EUV channels with particular emphasis on 304 Å, 193 Å, and 211 Å, and have focused on the early phase evolution of the prominence and plasma heating.

Since this is an event occurring on the limb of the Sun, we have also used observations recorded using the Sun Earth Connection and Heliospheric Investigation (SECCHI; Howard et al. 2008) on board the Solar Terrestrial Relations Observatory (STEREO-B), which, due to a specific orbit, provides complementary on-disk information for the same event. At the time of the observations presented here, the location of the STEREO-B spacecraft was such that the features which were seen by SDO at the east solar limb, were seen by STEREO-B nearly at the disk center. Therefore, it provides a complementary vantage point for observations.

3. DATA ANALYSIS AND RESULTS

Figure 1 and its accompanying animation in the online journal show a sequence of images taken in the 304 Å passbands of AIA. Note that the images are displayed in negative intensity. The prominence stays relatively quiet until 20:28:44 UT, when two distinct brightenings are seen, which are marked by two arrows in the top left panel, one near the upper leg of the prominence and the other near the middle. We scrutinized the observations taken in the other bands of AIA and found a similar morphology. The two brightenings (marked by arrows) are strongest in the 304 Å channel but are also seen mildly in 193 Å and to a lesser extent in 211 Å.

The complete prominence brightens up at around 20:30 UT, about two minutes after the first two brightenings, as seen in the 304 images. These images clearly show that the prominence is comprised of many different threads (strands). The brightening in the northern footpoint increases and the prominence goes through morphological evolution as revealed by the high time resolution of AIA images. During this time, the prominence shows an SR phase. Similar features have been reported previously by Chifor et al. (2006, 2007) and Isobe & Tripathi (2006). At 20:40:08 UT (after about 12 minutes), when the prominence has attained some height, a large part of the prominence brightens up. At 20:43:20 UT, the morphology of the prominence resembles that of a kinked flux rope (slinky) with two footpoints attached to the surface. A similar kind of morphological behavior is seen in the other EUV passbands of AIA. The kinked prominence continues to rise. The prominence appears to go through heating and cooling, as manifested by many localized brightenings that again indicate thermally independent strands comprising the prominence. By 20:46:08 UT (after about three minutes of the kink), most of the plasma located above the kink location becomes much brighter than the two legs of the prominence which are still connected to the surface (see the middle right panel in Figure 1).

At around 20:46:32 UT (see the animation in the online journal) and 20:46:44 UT (shown by an arrow in bottom left panel in Figure 1), brightenings took place exactly at the location of the kink. Figure 2 shows near simultaneous observations taken using all six EUV bandpasses of AIA. The brightening shown in the bottom left panel in Figure 1 are indicated by an arrow in all EUV channels of AIA in Figure 2. This sudden brightening at the kinked location, which is seen in the cooler as well hotter channels of AIA, strongly suggests that magnetic reconnection is occurring at the kink location at the current sheet which may have formed between the two legs of the erupting flux rope.
Figure 1. Sequence of AIA images showing the erupting prominence taken in the 304 Å passband. The two arrows in the top left image point to the first two brightenings. “P” designates the feature that was tracked to obtain the height–time diagram shown in Figure 3. The arrow in the bottom left panel shows the intense brightening at the location of the kink.

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

Figure 3 displays the height–time plot for the erupting prominence measured using the observations recorded in the 304 Å channel. The plot was obtained by tracking the tip of the erupting prominence. The error bars are due to the standard deviation of three simultaneous measurements of the same features. The plot clearly demonstrates that the prominence goes through an SR phase until $\sim$20:47 UT before it is accelerated. A linear fit to the data point from the beginning until 20:47 UT yields a speed of about 16 km s$^{-1}$ and a separate linear fit to the data from 20:47 UT onward yields a speed of $\sim$98 km s$^{-1}$. The height-time plot shows a clear “knee” at around 20:47 UT, which matches the time at which the prominence kinks.

We note that the SR to FR change occurs around 20:47 UT, while the kinking becomes evident somewhat earlier around 20:44 UT. Instead of the sharp turning point, there is a knee (cf. Figure 3) observed which indicates that the kinked prominence
threads involved in a bulk reconnection between 20:44 and 20:47 UT and thereafter rise abruptly. The plasma above the location of the kink is ejected outward and the plasma below drains toward the surface, similar to the observations reported previously (Tripathi et al. 2006, 2007; see also Gilbert et al. 2001). The associated CME seen in LASCO/C2 field of view (not shown) first appear at 20:12 UT and disappear quickly within a few frames of LASCO/C2 observations. This supports the scenario of reconnection at a central kink location and the splitting of the prominence in a partial eruption. Unfortunately, because we do not have hard X-ray (HXR) observations from RHESSI in a similar time domain of the event, we therefore cannot examine the formation of the HXR at the central kink location, as previously observed in various studies (Török et al. 2004; Alexander et al. 2006; Liu & Alexander 2009).

In addition, there are signatures of interaction between the eruptive filament system and the overlying loops, as reflected in the form of de-acceleration in the height-time diagram shown in Figure 3. We also note that the overlying fields play an important role in prominence eruptions as shown by, e.g., Török & Kliem (2005), Fan & Gibson (2007), and Kliem (2012).

In order to understand the thermal structure of the erupting prominence and possibly the associated flux rope, we have derived emission measure (EM) maps in different temperature bins (see Figure 4) using the six AIA channels. EMs were calculated using the xrt_dem_iterative2.pro routine (Weber et al. 2004; Golub et al. 2004), modified for use with the AIA passbands. The validation of this method can be found in the Appendix of Cheng et al. (2012). The EM was derived at a slightly later time than the images shown in Figure 2 as some of the images were saturated at this time. The emission measure maps were created by calculating a EM in every pixel using the six AIA EUV filters, and then integrating the EM over the indicated temperature bins in order to obtain the emission measure in that temperature range. Errors in the EM calculations are estimated by calculating Monte Carlo runs on the data using intensity values varied normally by the sigma error. This sigma error is estimated by using an empirical formula that approximates Poisson statistics for low count rates, but approaches Gaussian statistics for high count rates (see, e.g., Gehrels 1986). Examining the Monte Carlo runs shows that the errors in the EMs are higher where the signal in several of the passbands is very low, and where the temperatures are outside the range covered well by the AIA passbands (i.e., <1 MK and >20 MK).

The EM maps shown in Figure 4 suggest that the erupting prominence is highly multi-thermal and fairly dense at all temperatures. It should also be noted that the EM is high in
the higher temperature bands (e.g., 10–13 MK; the higher red colors at the log EM scale), while comparatively low at typical coronal temperatures (e.g., 1–2 MK; the moderate yellow color at the log EM scale) at the central kink location. This supports our premises of reconnection-generated heating, which appears in the form of EM in various temperature bands.

The EM maps also reveal a hot overlying arched structure, which might be representative of an erupting flux rope. Such hot erupting structures have been seen previously by Reeves & Golub (2011) and Cheng et al. (2011, 2012, 2013) where they were interpreted as a heated erupting flux rope. However, we do not see any signature of the twist or writhe in this hot, overlying flux rope as previously observed by Liu et al. (2010) and Zhang et al. (2012). Therefore, it may be plausible that this overlying structure is caused by the heating at the current sheet between the kinked flux rope and the overlying field (Török et al. 2004). Observations of such a rare heating scenario are possible, most likely due to the narrow EUV passbands of SDO/AIA and the availability of the hot channels.

As shown in Figures 1 and 2, the observation reported here is above the limb from the vantage point of SDO. In order to get an on-disk perspective, we have used the observations recorded by STEREO-B. Figure 5 displays images recorded by SECCHI using its 195 Å passband. The spatial and temporal resolution of SECCHI images are not as good as that of AIA. However, the images shown in Figure 5 capture the essential dynamics of the erupting prominence. The arrow in the top right panel shows the filament in question, which is rising. The two arrows in the bottom right panel show that the filament has broken into two parts (shown by the two arrows). The bottom part of the filament shows a cusp-shaped structure. The top of the cusp corresponds to the location of the reconnection and enhanced heating, which is captured in the multi-wavelength observations by AIA filters (see Figure 2). Observation of the cusp-shaped structure is one of the most important signatures of magnetic reconnections (see, e.g., Forbes & Acton 1996).

4. SUMMARY AND DISCUSSION

We have studied the complete evolution of a prominence (from early phase evolution to eruption) that shows partial eruption using the excellent observations recorded by AIA on board SDO. The prominence shows the SR phase during the early phase, followed by FR. The start of the SR phase coincided with two small brightenings located near the foot points. The prominence shows a kinking motion almost at the time when it transitions from SR to FR. The enhanced brightening was seen at the location of the kink, which is seen in all wavelengths, and is suggestive of the presence of multi-thermal structures, a premise borne out by the emission measure analysis. The material above the kink location has been observed to be ejected outward (see Figure 3 and the animation in the online journal) and the plasma below drains down toward the surface.

To the best of our knowledge, this is the first observation where all of the predicted characteristics of partial ejection, including the transition from SR to FR, kinking, the formation of the central vertical current sheet, and the splitting of a filament preceded by magnetic reconnection has been detected in a single
Figure 4. Emission measure maps obtained using the six channels of AIA at 20:46:59 UT.
(A color version of this figure is available in the online journal.)

Figure 5. Sequence of SECCHI 195 images showing the on disk evolution of the erupting filament.
(A color version of this figure is available in the online journal.)

event due to the unique time and spatial resolution of AIA. The multi-temperature coverage of AIA allows us to study the temperature structure of the erupting prominences and the heating and cooling of plasma during erupting prominences.

These observations provide strong and comprehensive evidence in favor of the model of partially erupting flux ropes. Gibson & Fan (2008) found that the magnetic connectivity, twist, orientation, and topology of the ejected portion of a partially erupting flux rope differs significantly from its pre-eruption state. While this idealized simulation cannot capture the details of the observations presented in this paper, the fact that the observations follow the predicted characteristics of that simulation argues that a significant part of the magnetic twist remains in the lower portion of a rope that does not erupt; therefore, this region is likely to experience further eruptions. It should also be noted that the observed kink is a configuration of the magnetic flux rope that enables the reconnection but does not necessarily manifest the evolution of the kink instability (Isenberg & Forbes 2007; Török et al. 2010; Liu et al. 2012).

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