Kinematics and helicity evolution of a loop-like eruptive prominence

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Received date, accepted date

ABSTRACT

Aims. We aim at investigating the morphology, kinematic and helicity evolution of a loop-like prominence during its eruption.

Methods. We use multi-instrument observations from AIA/SDO, EUVI/STEREO and LASCO/SoHO. The kinematic, morphological, geometrical, and helicity evolution of a loop-like eruptive prominence are studied in the context of the magnetic flux rope model of solar prominences.

Results. The prominence eruption evolved as a height expanding twisted loop with both legs anchored in the chromosphere of a plage area. The eruption process consists of a prominence activation, acceleration, and a phase of constant velocity. The prominence body was composed of left-hand (counter-clockwise) twisted threads around the main prominence axis. The twist during the eruption was estimated at 6\(\pi\) (3 turns). The prominence reached a maximum height of 526 Mm before contracting to its primary location and partially reformed in the same place two days after the eruption. This ejection, however, triggered a CME seen in LASCO C2. The prominence was located in the northern periphery of the CME magnetic field configuration and, therefore, the background magnetic field was asymmetric with respect to the filament position. The physical conditions of the falling plasma blobs were analysed with respect to the prominence kinematics.

Conclusions. The same sign of the prominence body twist and writhe, as well as the amount of twisting above the critical value of 2\(\pi\) after the activation phase indicate that possibly conditions for kink instability were present. No signature of magnetic reconnection was observed anywhere in the prominence body and its surroundings. The filament/prominence descent following the eruption and its partial reformation at the same place two days later suggest a confined type of eruption. The asymmetric background magnetic field possibly played an important role in the failed eruption.

Key words. Sun: activity – Sun: prominences – Sun: magnetic fields

1. Introduction

Prominence eruptions are large-scale eruptive phenomena which occur in the low solar atmosphere. Observations show that prominences display a wide range of eruptive activity. There are three types of prominence (filament) eruptions according to the observational definitions of Gilbert et al. (2007) based on the relation between the filament mass and corresponding supporting magnetic structure: full, partial, and failed (confined), of which the partial ones are the most complex. A full eruption occurs when the entire magnetic structure and the pre-eruptive prominence material are expelled into the heliosphere. The case when neither the filament mass, nor the supporting magnetic structure escape the solar gravitational field is a failed eruption. Partial eruptions can be divided into two subcategories: i) when the entire magnetic structure erupts, with the eruption containing either part or none of its supported pre-eruptive prominence material, and ii) when the magnetic structure itself partially escapes with either some or none of the filament mass (Gilbert et al. 2007). One important observational consequence concerning partial and failed eruptions is the re-formation of the filament at the pre-eruptive location.

Sterling & Moore (2004a, b) unveiled a common pattern of prominence eruptions: an initial slow-rise phase (with a very small acceleration), during which the filament gradually ascends, followed by a sharp change to a phase of fast acceleration. There exist three types of prominence eruption after the fast rise phase: i) an eruptive prominence can continue to rise with acceleration, ii) the fast rise can be followed by a constant velocity phase, or iii) the constant velocity phase of an eruptive prominence can be followed by a deceleration phase (Vrsnak 1998).

Eruptive prominences (EPs) (or filaments if observed on the solar disk) are frequently associated and physically related to coronal mass ejections (CMEs) and flares (Tandberg-Hanssen 1993; Webb et al. 1978; Muir et al. 1979; Webb & Hundhausen 1987; St. Cyr & Webb 1991).
Usually, all three eruptive events occur in the same large-scale coronal magnetic field, in which the EP only occupies a limited volume at its base. Such an association suggests that possibly the same physical process drives these eruptive phenomena. Filament-CME relationship studies often do not take into account the relation between filament-related magnetic field configurations, like for instance, an empty filament channel, and a CME initiation (Alexander 2006). Therefore, the filament-CME relationship can be even stronger than is known so far. An EP and/or a CME are considered as the eruption of a pre-existing magnetic flux rope (MFR) or an initial magnetic arcade that evolves into a magnetic flux rope during the eruption process via magnetic reconnection (Chen et al. 2006; Antiochos et al. 1999). However, the question whether an MFR exists prior to the eruption or it is formed during the eruption remains controversial, with the MFR topology preceding the eruption being favoured in many studies during the last decade.

During activation, the slow rise motion of an EP is usually accompanied by a gradual morphological evolution from an initially intricate structure into an apparently toroidal shape, exposing sometimes a twisted pattern, that is most often prominent in the legs of the prominence (Vršnak et al. 1991). EPs very often develop a clearly helical shape in the course of the eruption, which is the characteristic signature of a MagnetohydroDyanmic (MHD) kink instability of a twisted MFR (e.g. Rust & Labonte 2005). A MFR becomes kink-unstable if the twist exceeds a critical value of $2\pi$ (e.g. Hood & Priest 1981; Fan 2005). The axis of an MFR then undergoes writhing (kinking) motions and part of the twist of the field is transformed into helical writhe of the axis, since the magnetic helicity is conserved (Rust & Labonte 2005). The conservation of helicity in ideal MHD (Berger 1984) requires the resulting writhe to be of the same sign as the transformed twist. The kink instability has long been investigated as a possible triggering mechanism for solar eruptive phenomena, especially in flux rope models (Liu & Alexander 2009).

Kink and torus instabilities are suggested to be two mechanisms for triggering solar flares and coronal mass ejections (Sakurai 1976; Kliem & Török 2003; Kliem & Török 2006; Schrøver et al. 2008). Kink instability was first suggested as the trigger of prominence eruptions (confined and ejective) by Sakurai (1976) but has been generally regarded as a possible explanation only for confined events (e.g. Gerrard & Hood 2003; Török & Kliem 2005, and Fan 2005) succeeded in modelling full ejection of a coronal flux rope from the Sun driven by kink instability. A kinking may be an important factor in the erupting process, but the type of eruption may strongly depend on the role played by magnetic reconnection and its location with regards to the prominence body (Antiochos et al. 1999). As discussed in Gilbert et al. (2007, and the references therein) the kink instability as a main trigger of prominence destabilization and eruption is challenging to be proven observationally because the helicity can force a flux rope to writhe, without any instability occurring.

Kliem & Török (2006) studied the expansion instability of a toroidal current ring embedded in a low-beta magnetised plasma. Schrøver et al. (2008) analysed two near-limb filament destabilisations involved in CMEs. Numerical simulation of a torus instability showed a relatively close quantitative match of the observations, implying that these two cases are likely to be torus instability eruptions.

Observations of filament eruptions that strongly suggest a helical kink occurring in flux rope topology were presented by Williams et al. (2005) for a full eruption, by Zhou et al. (2006) and by Liu et al. (2007) for partial eruptions, and Ji et al. (2003) and Alexander et al. (2006) for confined (failed) eruption. An observational definition of kinking related to the different types of filament eruptions is given by Gilbert et al. (2007) and Green et al. (2007).

In this paper, we investigate the phenomenology of an eruptive loop-shaped helically twisted prominence with fixed footpoints using state-of-art observations from the Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamics Observatory (SDO) in the 304 A EUV passband. We have the unique opportunity to combine limb with on-disk observations of an eruptive prominence thanks to the EUVI/STEREO B observations which at the time of the observations was at an angular distance of 71 degrees with the Earth. We aim at investigating the morphology, kinematic and helicity evolution of a loop-like prominence during its eruption. In Section 2 we describe the set of observations used in this study. In Section 3 we present the main results, which are discussed in Section 4. The conclusions are drawn in Section 5.

2. Observations and data analysis

The prominence eruption occurred at the North-East solar limb between 17:30 UT and 19:30 UT on 2010 March 30. The EP was centered at mean heliographic co-ordinates N22.63°; E78.80° and mean position angle 66°.

For the present study we used images taken with 1 min cadence in the He ii 304 Å passband of AIA/SDO (AIA; Lemen et al. 2011). The AIA consists of seven Extreme Ultra-Violet (EUV) and three Ultra-Violet (UV) channels which provide an unprecedented view of the solar corona.

Fig. 1. Mauna Loa Hα images before and during the start of the prominence activation. The arrow points at the region revealing twisted structure.
Fig. 2. He II 304 Å AIA images (in reversed colour table) showing the morphology and, in particular, the helicity evolution of the erupting prominence. AIA He II 304 Å image animation of the prominence eruption can be seen online.

with an average cadence of $\sim12$ s. The AIA image field-of-view reaches 1.3 solar radii with a spatial resolution of $\sim1.5''$. We used level 1 reduced data, i.e. with the dark current removed and the flat-field correction applied. The images were further stabilised for the satellite movements by applying intensity cross-correlation analysis using the SolarSoftware procedure getcorrel offsets.pro. For the purpose of our analysis we defined the visible limb from the AIA He II 304 Å images. Note that the jitter correction was only needed this early in the mission as the image stabilisation was still subject to calibration in the commissioning phase when these observations were taken.

We also analysed observations from the Extreme Ultraviolet Imager (EUVI) aboard STEREO Behind (B) spacecraft. EUVI has a field-of-view of $1.7R_\odot$ and observes in four spectral channels (He II 304 Å, Fe IX/X 171 Å, Fe XII 195 Å and Fe XIV 284 Å) that cover the 0.1 to 20 MK temperature range (Wuelser et al. 2004). The EUVI detector has $2048 \times 2048$ pixels$^2$ size and a pixel size of 1.6''. In the present study we used images in the He II 304 Å channel with an average cadence of 10 minutes. Images obtained by the Large Angle and Spectrometric Coronagraph (LASCO)/C2 on board SOHO, whose field-of-view extends from 2 to 6 solar radii (Brueckner et al. 1995) were also analysed in the present study.

3. Results

3.1. Morphology and helicity evolution

The prominence eruption evolved as a height expanding twisted loop with both legs anchored in the chromosphere of a plage area. The prominence before the activation can already be seen in Hα at 17:19 UT (Fig. 1). It shows as a few bright clouds above the limb with no distinguishable fine structure. In the AIA He II 304 Å images at 17:32 UT and 17:40 UT in Fig. 2 (see also the online material), the fine structure of the prominence appears very dense, the prominence lies very close to the limb and, therefore, it is impossible to distinguish its small-scale structure. Note that in Hα we see the cold core of the prominence, while in He II 304 Å it is the envelope at higher temperatures (Labrosse et al. 2010). The Hα image at 17:49 UT shows
the first signature of a twisted prominence fine structure. From part of the prominence where the fine structure is visible, we could estimate a $2\pi$ twist, i.e., one turn of the prominence rope around its main axis. This time coincides with the beginning of the prominence slow rise during the activation phase. The full amount of prominence twist is first seen at around 18:20 UT (Fig. 2) in the AIA He $\text{ii}$ 304 Å images. We estimated from the AIA 304 Å images at 18:20 UT, 18:26 UT and 18:32 UT, a total twist of about $6\pi$ (3 turns) of the eruptive prominence body.

We also searched for a signature of magnetic reconnection in all available data including AIA and EUVI He $\text{ii}$ 304 Å and Fe $\text{xii}$ 195 Å. Both the off-limb AIA and on-disk EUVI data do not show any brightening in the footpoints of the prominence, their surroundings as well as along the prominence body. This suggests that magnetic reconnection may not have had contributed to the prominence destabilization and eruption.

After 18:25 UT the eruption can also be followed on the EUVI/STEREO image differences shown in Fig. 3 (see also the online material). Here, thanks to the different viewpoint (see the AIA view translated on the EUVI B image in Fig. 3) we could see that the filament upper body underwent a right-hand writhe. The deformation of the prominence is still not visible in the AIA images at this time (Fig. 2) due to the line-of-sight effect. At 18:56 UT the crossing of the prominence body axis due to the writhe as seen in projection on the disk, in the STEREO difference images (Fig. 3) is visible at approximately half of the rising filament height. At 19:06 UT, this crossing is visible at approximately one third from the feet of the prominence. The writhe increased with time, reaching $\pi/2$ at 19:26 UT (Fig. 3).

**Table 1.** The kinematics of the eruptive prominence derived from the AIA images.

| Phase          | Time (UT) | Height (Mm) | Velocity (km s$^{-1}$) | Acceleration (m s$^{-2}$) |
|----------------|-----------|-------------|------------------------|---------------------------|
| Activation     | 17:33 – 18:00 | 18 - 34     | 10                     | 0                         |
| Acceleration   | 18:00 – 18:12 | 34 - 121    | 15 – 166               | 46 – 430                  |
| Constant velocity | 18:12 – 18:44 | 121 – 295   | 91                     | 0                         |

**Fig. 3.** Running difference images from EUVI B in the He $\text{ii}$ 304 Å channel. EUVI/STEREO B He $\text{ii}$ 304 Å image difference animation of the prominence eruption on 2010 March 30 can be seen online.
The AIA He\textsc{ii} 304 Å images after 18:26 UT reveal best the helical twist of the prominence and its evolution in time (last row of Fig. 2). We can clearly see that during the prominence uplift the twist transfers from the lower (legs) to the upper prominence body causing the prominence to evolve from a loop-shaped into a ribbon-like structure. With the help of the EUVI B difference images (Fig. 3), we established the footpoint location noted with black circles in Fig. 4 (top left). The so defined foot positions are also shown on the EUVI image at 18:36 UT (Fig. 4, top right). A feature above the northern leg is also encircled and labelled with ‘R’. This feature is used as a reference for the translation of the AIA images into the STEREO B view. In Fig. 4 (bottom right) we show the AIA 304 Å image at 18:32 UT with the expanding loop-like prominence. This image was transformed to the STEREO B view and the legs of prominence identified in the EUVI B images were transposed (shown with black circles) as well as the reference feature. We paid special attention to the localisation of the feet of the EP in order to determine the type of twist and writhe, and their evolution in time. Based on the magnetic field polarity configuration obtained from the magnetograms, the Hα images and the prominence drawings (Fig. 5), we could determine in which magnetic polarity the southern and the northern legs of the prominence were located. From all the above information we established that the prominence underwent a writhe as a result of counter-clockwise rotation with respect to the two polarity fluxes.

3.2. Kinematics

The prominence height was determined as the height of the main axis of the prominence above the visible limb as observed in the He\textsc{ii} 304 Å channel of the AIA/SDO images (Fig. 6). The time evolution of the height reveals three distinctive phases of the prominence eruption: a prominence activation, an eruption with acceleration, and an eruption with a constant velocity (Fig. 7). From the first and second derivatives of the polynomial fit of the height-time curve, we defined the speed and the acceleration of the prominence eruption. The prominence activation is already in progress at the beginning of the AIA observations around 17:33 UT. It is defined as the time period of a slow rise of the loop system with a velocity of 10 km s\textsuperscript{−1}. Until 18:00 UT the height of the prominence changed from 18 Mm to 34 Mm. The eruption onset was registered at 18:00 UT and it was determined from the AIA images as a sudden increase of the prominence height. It lasted until around 18:12 UT (Fig. 7). During this phase the prominence height increased from 34 Mm to 121 Mm and the speed of the prominence rise increased from 15 km s\textsuperscript{−1} to a maximum of 166 km s\textsuperscript{−2}. The constant velocity phase was measured until 18:44 UT. After this time the top of the looped prominence is outside the AIA field-of-view. The kinematics of the different phases of the eruptive process is summarised in Table 1.

It took 80 min the prominence to reach its maximum height (Fig. 5) at 19:16 UT as seen in the EUVI B im-
ages (note that the top of the prominence quits the AIA FOV after 18:44 UT). We were able to measure a descent of the prominence body with a velocity of \( \sim 50 \text{ km s}^{-1} \) using three EUVI images in which the prominence is clearly visible above the limb, i.e. at 19:16 UT, 19:26 UT and 19:36 UT (last row of Fig. 3).

After 18:47 UT (Fig. 2), the prominence legs are no longer twisted and we can clearly observe the downflow of individual plasma blobs thanks to the high AIA cadence of 1 min as well as its excellent spatial resolution. From the measurements of four blobs we found an average downflow speed of 31.8 km s\(^{-1}\) with a minimum of 13.7 km s\(^{-1}\) and maximum of 60 km s\(^{-1}\). Because of the continuous draining of the plasma towards the chromosphere, the prominence plasma density becomes lower and the prominence fainter in the AIA and EUVI B He \( \text{II} \) 304 Å images.

3.3. A CME association

At 18:30 UT C2/LASCO registered a CME at the eastern limb which was associated with the eruptive prominence. The width of the CME was 64° and the position angle was 74°. The prominence is located at the northern periphery of the CME magnetic system, at 19° to the north of the position angle of the highest part of the CME. The CME propagated in the C2/LASCO field-of-view with a velocity decreasing from 853 km s\(^{-1}\) to 599 km s\(^{-1}\), implying a deceleration of 16.4 m s\(^{-2}\). The average linear velocity was 724 km s\(^{-1}\). At the location of the prominence eruption an expanding loop with an empty cavity underneath which is part of the CME system is well seen in the C2/LASCO images (indicated with an arrow in Fig. 3). Assuming a constant velocity of 91 km s\(^{-1}\) for the prominence eruption, at 18:54 UT, the prominence had reached a height of 390 Mm while at 19:16 UT, when it reached its maximum height, it was at 526 Mm (less than one solar radius). This strongly supports the observation that no prominence material is seen in the C2/LASCO FOV.

3.4. Prominence reformation

The prominence partially reformed in the same place two days after its eruption. In Fig. 5, the re-formation of the filament is presented from March 31 to April 2. On March 31, one day after its eruption, the filament can be traced only above and below the plage area on the Coimbra Solar Observatory \( H_\alpha \) (Fig. 5a). The magnetic field of the plage...
4. Discussion

Although the velocity evolution profile of the prominence/filament analysed here is similar to torus-ring eruptions, a very clear twist of the prominence body above a critical value of 2π which evolves into a writhe does favour the kink instability scenario. However, a kink instability may not have been the only trigger for this eruption but, for instance, the data do not reveal any indication of magnetic reconnection. A clear signature of the VERY triggering of destabilization based on the present observations is, therefore, difficult to establish. Conclusive observations on the onset of prominence eruptions would require magnetic field measurements in the footpoints of eruptive prominences, combined with imaging and spectroscopic observations.

We examined the possible role of kink instability in the eruption of the prominence discussed here. A magnetic flux rope becomes kink-unstable if the twist of the magnetic field \( T_w \), a measure of the number of turns of the magnetic field lines about the prominence main axis, exceeds a critical value of 2π \( (\text{Hood & Priest 1981}) \). During the instability a flux tube would helically untwist reducing the magnetic stress due to this instability. The magnetic helicity, \( H_m \), can be expressed as the combination of twist and writhe, i.e. \( H_m = \Phi^2 (T_w + W_r) \), where \( \Phi \) is the axial magnetic flux in the flux rope and \( W_r \) is the measure of the twist of the rope around itself. Because of the conservation of magnetic helicity \( (\text{Berger 1984}) \), the twist will transfer into a writhe, \( W_r \), i.e. forming a ribbon-like structure. \( \text{Vršnak et al. 1991} \) found that non-eruptive prominences have a total twist less than 2π (less than one complete turn) and, on the contrary, all eruptive prominences that had a total twist \( \geq 2.5\pi \) (one and a quarter turns) erupted. On theoretical grounds \( \text{Mikić et al. 1999} \) found that a purely axial loop which is twisted by its footpoints becomes kink unstable when the twist exceeds 4.8π.

In the present case the prominence shows a left-hand twist of 6π which during the eruption transfers from the prominence legs to its upper body forming a counterclockwise writhe. The left-hand twist of the prominence body can be clearly seen on the AIA He ii 304 Å images while the writhe of the eruptive filament is evident from the images of EUVI/STEREO B (Fig. 3). A flux rope helical twisting and writhe of the same sign is a basic condition for kink instability to work \( (\text{Hood and Priest 1979}) \). That makes us to suggest that the eruptive prominence analysed here was possibly submitted to a kink instability, although other instabilities may also have played some role.

The eruptive prominence was located in the northern periphery of a large-scale CME magnetic configuration. Therefore, the background magnetic field is asymmetric with respect to the filament position. There are several observational \( (\text{e.g. Li et al. 2003; Alexander et al. 2006; Green et al. 2007; Liu et al. 2009; Shen et al. 2011}) \) and theoretical \( (\text{Török & Kliem 2005; Kliem & Török 2006; Fan & Gibson 2007; Liu 2008}) \) studies suggesting a confining role of the overlying magnetic field during failed filament eruptions due to a slowly decreasing gradient of the magnetic field and a strong field intensity at low altitude. Recently, \( \text{Liu et al. 2009} \) investigated a failed filament eruption in which two filaments are asymmetrically located in coronal loops. The authors compared the confinement ability of symmetric and asymmetric fields and found that the magnetic confinement of an asymmetric field is stronger.
than that of a symmetric one. [Shen et al.] (2011) made such calculations for six EPs, from which five represented failed eruptions and one a successful eruption. They suggested that an asymmetric background field is an important factor leading to failed filament eruptions.

5. Conclusions

We examined the kinematic and helicity pattern together with the morphological and geometrical evolution of an EP, based on He η 304 A AIA/SDO and EUVI/STEREO B observations. The unique combination of high-resolution limb observations of the EP in AIA and a central meridian position in EUVI B permitted a detailed analysis of the prominence eruption on 2010 March 30. The obtained results can be summarised as follow:

- The EP appeared as a helically twisted MFR with fixed footpoints. The prominence body was composed of left-hand twisted threads around the main prominence axis. The twist during the eruption was estimated at 6π (3 turns).

- The EP twist progressively converted into a left-hand writh that is well traced in the EUVI/STEREO B images. The position of the crossing-point of the writhed prominence body descended while the eruption was progressing. Co-temporally the drain of prominence plasma towards the chromosphere can be followed in the AIA/SDO images.

- The height-time profile of the EP revealed three distinctive phases of prominence eruption: a prominence activation phase, accelerating phase, and eruptive phase, the last one with constant velocity. Consequently the prominence contracted to its primary location after reaching a maximum height of 526 Mm. The prominence/filament partially reformed suggesting that either part of the material returned to its primary temperature.

- The draining plasm blobs at low altitudes were found to have high temperatures which could result from the encounter of the downflowing plasma with the static plasma in the legs and the resulting heating compression.

- The EP was associated with a narrow expanding loop and an empty cavity underneath located in the northern periphery of a CME which appeared at the eastern limb and was triggered by the prominence eruption.

Acknowledgements. The authors thank the anonymous referee for the helpful suggestions and comments. The AIA data are courtesy of SDO (NASA) and the AIA consortium. Research at Armagh Observatory is grant-aided by the N. Ireland Department of Culture, Arts and Leisure. This work is grant-aided by the Bulgarian Academy of Sciences via the Institute of Astronomy. The authors thank the STEREO/SECCHI consortium for providing the data. The SECCHI data used here were produced by an international consortium of the Naval Research Laboratory (USA), Lockheed Martin Solar and Astrophysics Lab (USA), NASA Goddard Space Flight Center (USA), Rutherford Appleton Laboratory (UK), UK, Max-Planck-Institut for Solar System Research (Germany), Centre Spatial de Liège (Belgium), Institut d’Optique Theorique et Appliquée (France), Institut d’Astrophysique Spatiale (France). JCV and EB acknowledge the support of C.N.R.S. in the frame of the CNRS/BAS agreement (28 April 2010, # 66459). They also acknowledge the support of C.N.E.S. (Space French Agency) for easing the access to AIA/SDO data. They thank Claude Mercier for her continuous support.

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