A confined prominence eruption on May 7, 1979

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Abstract. A confined prominence eruption at the solar limb on 7 May 1979 associated with slow coronal mass ejection was observed and reported. The aim was to probe the kinking of the eruptive prominence (EP) loop and its relation to the processes coronal field confinement on erupting flux rope. The EP represents helically writhed (kinked) loop with fixed feet that presents a disturbed segment of a long-lived filament, located within a multipolar magnetic configuration. The rising of the EP apex and its velocity range suggest that the observation span late stage of the eruption. In terms of magnetic flux rope hypothesis, the kinking evolution of the EP flux rope was estimated by the normalized difference between heights of the flux rope apex and projected cross-point of its kinked legs, and the angle α between the kinked legs below the cross-point. The results suggest that the kink instability was in progress at the onset of observations and to the end of the eruption, the EP flux rope presented a large amount of kinking. Oscillations of the angle α with a period of 14 minutes, accompanying its increasing, suggest oscillations of the EP flux rope during the eruption. A possible scenario for confined eruption at the limb on 7 May 1979 was suggested, in which a breakout-type reconnection could occur above the EP but within a flux rope itself.

Key words: Sun: prominences, Sun: eruptions-magnetic fields-instabilities

Ограничена ерупция на протуберанс от 7 май 1979 г.

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Представени са резултати от изследването на ограничена ерупция на протуберанс, наблюдаван на слънчевия лимб на 7 май 1979 г., която се асоциира с бавно изхвърляне на коронална маса. Целта на изследването е да се проучи деформирането (kinking) на примката на еруптивния протуберанс (ЕП) и връзката и с процесите на ограничаващо действие на короналното магнитно поле върху еруптиращ магнитен поток. ЕП представлява спирално деформирана (kinked) примка с фиксирани „стъпки", която представя смутен сегмент на дълговивущо влакно, разположено в мултиполярна магнитна област на Слънцето. Издигането на върха на ЕП и диапазона на скоростите подсказват, че наблюденията покриват късен етап от ерупцията. Използвайки терминологията на изплуващото въже на магнитния поток, кинк-еволюцията на магнитното въже на ЕП бе оценена чрез нормализираната разлика между височините на върха на магнитното въже на ЕП и проектираната на равнината на лимба пресечна точка на деформираните му „крака", както и ъгълът α между „краката" на магнитното въже, под пресечната им точка. Резултатите подсказват, че кинк-неустойчивостта е била в процес на развитие в началото на наблюденията, а към края на ерупцията магнитния поток на ЕП показва висока степен на кинк-деформация. Осцилациите на ъгъла α с период от 14 минути, придружаващи неговото нарастване подсказват осцилации на магнитното въже на ЕП по време на ерупцията. Предложен бе вероятен сценарии за ограничената ерупция на протуберанса от 7 май 1979 г., в който основна роля играе beakout-тип магнитно присъединяване, което би могло да възникне над ЕП, но в самото магнитно въже.

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Introduction

The eruptive prominences (EPs), in contrast to active ones, could be defined as prominences in which all or some of the prominence material appears to escape the solar gravitational field, Gilbert et al. [2000]. In a recent study, Gilbert et al. [2007] distinguished three types of EPs: full, partial and failed (confined) eruptions. Indeed, the observations display that the prominence (filament) activation encompasses a wide range of eruptive-like dynamic activity from the full eruption e.g., Plunkett et al. [2000] through partial eruption e.g., Zhou et al. [2006], Liu et al. [2008] to failed eruption. A remarkable case of a failed eruption of an active region filament on 27 May 2002 was studied by Ji et al. [2003] and later it was revisited by Alexander et al. [2006]. This event appears to be failed eruption as the filament material first accelerated then decelerated as it approached its maximum while the filament threads drains back toward the Sun.

Prominence eruptions are often associated with coronal mass ejections (CMEs) e.g. Munro et al. [1979]; House et al. [1981]; Webb and Hundhausen [2005] and flares e.g. Hirayama [1974]; Kahler et al. [1988]. Despite the differences in morphology, size, and energy release, these eruptive phenomena are manifestation of the same physical processes involving plasma ejection and magnetic reconnection e.g. Shibata [1999]; Priest and Forbes [2002] in the frame of a large-scale coronal magnetic system (Rompolt [1984]). Theoretically, the expanding of such magnetic system has been hypothesized as the eruption of a pre-existing magnetic flux rope (MFR) (Chen et al. [2006]), and references therein. The MFR hypothesis allows the CME and the associated EP to be treated as different parts of a flux rope with specific assumed geometrical relationships among the CME, EP, and flux rope, which could be referred to the CME-EP-MFR system.

EPs very often develop a clearly helical axis shape in the course of the eruption, which is the characteristic signature of the MHD kink instability (KI) of a twisted MFR (e.g. Rust and LaBonte [2005]). A MFR becomes kink-unstable if the twist, a measure of the number of windings of the field lines about the rope axis, exceeds a critical value (e.g.Hood and Priest [1981], Fan [2005], Török and Kliem [2005]). The axis of the MFR then undergoes writhing motions and part of the twist is converted to the large-scale writhe, a measure of the twist of the axis itself, due to the conservation of the magnetic helicity in highly conducting corona (e.g. Berger [1998], Gilbert et al. [2007]). The conservation of the helicity in ideal MHD requires the resulting writhe to be of the same sign as the transformed twist (e.g. Hood and Priest [1979], Green et al. [2007]).

Recent observations of kinking motions in a number of filament eruptions with a range of different natures, including full filament eruption (e.g. Williams et al. [2005], Zhou et al. [2006]), partial cavity eruption (e.g. Liu et al. [2007], [2008]; Liu and Alexander [2009]), and confined filament eruption (e.g. Ji et al. [2003], Alexander et al. [2006]), suggest the kink instability as an important process in the interactions of the filament with its magnetic environment. An observational definition of kinking, as well as definitions of different types of filament eruptions, are given by Gilbert et al. [2007]. In many cases, a MFR can be used to match the magnetic flux and chirality of precursor structure to EPs and CMEs. Sakurai [1976] firstly suggested the KI as the driver of prominence eruptions (confined and ejective) but it has been generally regarded as a possible explanation only for confined events e.g. Gerrard and Hood [2003]. Török and Kliem [2005] and Fan [2005] succeeded in modeling of full ejection of a MFR from the Sun. A successful eruption may result from a partially ejected MFR with significant magnetic helicity kept behind in the lower part of the rope e.g. Gibson and Fan [2006]. Recently, DeVore and Antiochos [2008] succeeded in modeling of confined ejection via breakout magnetic reconnection.

Many observations were made of kinking motions in a number of filament eruptions, including the confined ones. An interesting avenue in future work would be to consider limb observations of partial or confined prominence eruptions e.g. Tripathi et al. [2009].

In this Paper, we present an observational study of a confined (failed) prominence eruption at the solar limb on 7 May 1979, associated with a CME. The morphological evolution of the EP, representing a helically writhed loop, is indicative of magnetic kink evolution and it suggests the kink instability as a possible driver of the eruption. Because of kink-like features, we will interpret the observations against the magnetic kink instability models.

1 Eruptive prominence of 7 May 1979

An EP with confined eruption processes was registered on 7 May 1979 in the H_α hydrogen line with the Small Coronagraph (130/3450 mm) at the Astronomical Institute of University of Wroclaw. The H_α filtergrams of the EP were taken through a 3Å H_α filter. The event was registered between 13:50 UT and 14:27 UT and comparatively short series of 20 H_α filtergrams were obtained with an average cadence of about 1.5 minutes. Exposure time of 1/8 of a second was used. Fig. 1 shows a sample of filtergrams, tracing the evolution of the prominence eruption. All H_α filtergrams were digitized with the automatic Joyce-Loebl microdensitometer at the National Astronomical Observatory Rozhen, Bulgaria. The two-dimensional scans were taken with pixel size of 20×20 $microns^2$ and 20 microns long steps between the pixels in both directions. The pixel corresponds to little more than $1''$on the Sun.

The EP of 7 May 1979 (Fig. 1) was observed on the western limb at mean northern latitude of 38°. The EP initially had a big height of about 120×10^3 km and a complicated structure. The prominence slowly rose during 40-min observational time interval and it reached a maximum height of 180×10^3 km in the end of the eruption. The EP rising was accompanied with mass draining along apparent magnetic field lines back into the chromosphere that is well traceable in Fig. 1. Its structure remained complicated up to 14:02 UT and after that a simplification of the structure was registered. The simplification suggests that the EP represents a clear helically writhed loop, composed of helical twisted threads. After 14:18 UT, the EP loop faded and almost disappeared in H_α to the end of the observations (14:27 UT).

The EP of 7 May 1979 was associated with a long-lived filament indicated with coordinates 36°N 302° on Meudon synoptic map for Carrington rotation 1681 (Fig. 2). The EP appeared during second rotation of the filament lifetime that lasts six solar rotations, which suggests that the associated EP was manifestation of a temporary instability of a fragment of the filament. The filament underwent such temporary instability in fifth rotation of its existing when a partial disparition brusque was observed on the solar disk. The filament crossed the limb plane under very small angle so that its long axis almost coincides with the line-of-sight and the EP represents a segment of the middle part of the filament observed in nearly edge-on position at the limb. The filament was formed along the polarity inversion line (PIL) located between two comparatively near active regions (ARs) that are part of a large complex of ARs. Therefore, it was located along PIL of type B according to Tandberg-Hanssen [1974].

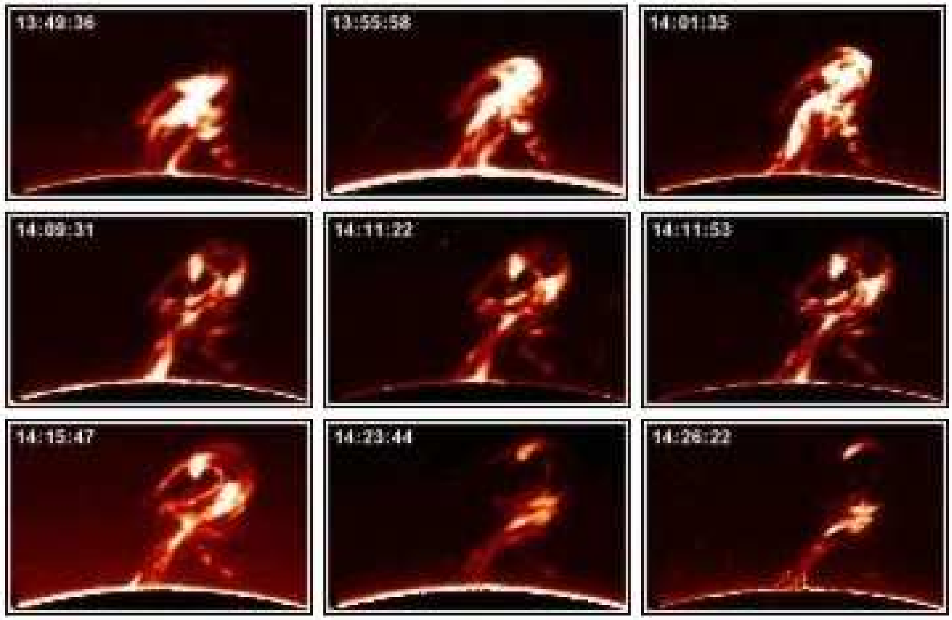

Fig. 1. Sample of the H_α filtergrams of the EP on 7 May 1979

Most probably, this filament had inverse magnetic configuration (Leroy [1989]). In fact, the filament was located in northwestern part of multipolar magnetic region. There were four neighboring ARs in southeastern direction from the filament with high flare activity in the day of the EP registration. Five solar flares in the ARs occurred during an hour before the EP observations and two of them occurred right before the observation onset.

The CME with three-pronged structure was registered at northwestern solar limb on coronagraph images of SOLWIND at 15:22 UT on 7 May 1979 (Sheeley et al. [1980]), an hour later than the end of the EP observations. The CME was very extensive by latitude, spanning almost completely the northwestern limb. The position of the EP coincides with the central prong of the three-pronged CME structure. The central prong faded from 20:43 UT, May 7 up to 08:52 UT, May 8 when the central part of transient structure was cleared of coronal material. There were two clearly separated remnants of CME structure at the northwestern limb during the rest of 8 May 1979. The big remnant had average latitude of 70° that coincided with the position of the northern polar filament and the small, narrow one located bellow 30° northern latitude that coincided with area containing several neighboring active regions (see Fig. 2).

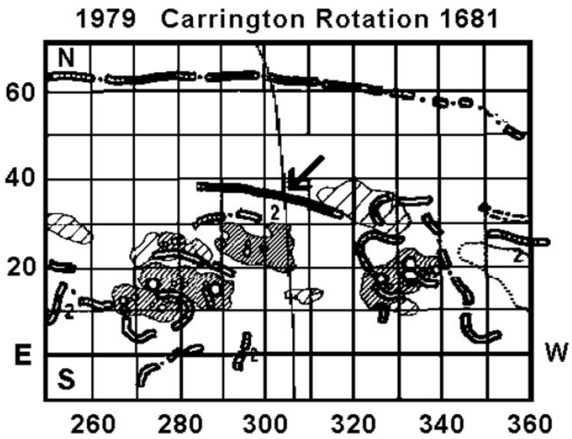

Fig. 2. Synoptic map for Carrington rotation 1681 with overplotted projection of the solar limb (thin line marked W-limb). The filament associated with the EP of 7 May 1979 was located at 36°N

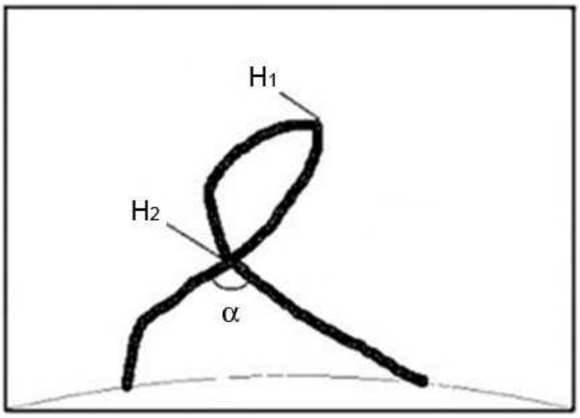

Fig. 3. Simplified sketch of the helically writhed loop of the EP of 7 May 1979. The basic points of measurements H1 and H2, as well as the angle α are indicated on the sketch

The long axis of the filament is almost parallel to the line-of-sight therefore, there is almost a 90-degree angle between the plane of EP loop (erupted filament fragment) and the observer. Hence, the first basic condition for optimum orientation for observing of the prominence kink according to Gilbert et al. [2007] is presented. On the other hand, as one can see in Fig. 1, the loop structure of the EP on 7 May 1979 was filled with well visible in H_α line material almost up to the end of the eruption and that is the second condition for a prominence kinking structure to be observable (Gilbert et al. [2007]).

Figure 3 shows a sketch of the simplified helically writhed prominence loop. The points of measurements that were used to trace kinematics of the prominence eruption and the kinking evolution of the prominence loop are marked on the sketch. H1 marks the height of the apex of prominence loop, projected on the sky plane. H2 marks the sky plane projection of the height of the crossing point of the kinked loop legs. The heights H1 and H2, the distance between the loop feet, and the angle α between the loop legs below the crossing point H2 were determined on every filtergram.

2 Kinematics

Figure 4 presents the height-time variation of the heights H1 and H2. The dependence of the height H1 on time represents the raising of the EP's apex. The observed prominence eruption started at a height of 120×10^3 km and stopped at a height of about 180×10^3 km. The average rising velocity, estimated by linear least-square fit was equal to 28 km s^{-1}. The behaviour of the height H2 had more uncertain character. The height H2 rose during 10 min time interval from the beginning of the EP registration and reached a maximum height of 100×10^3 km at 13:59 UT. After that time, the projection of the crossing point began to move downwards up to the end of the eruption process. In first approximation, the dependence of the height H2 on time could be estimated with linear least-square fit that gives velocity of H2 decreasing of about 10 km s^{-1}. That is a raw estimation because of relatively low confidential probability (65%) of the fit. In fact, the height-time profile of H2 shows two different phases. First phase was between 13:52 UT and 14:11 UT, when the H2 remained relatively high at heights of about 95×10^3 km and second phase that was between 14:12 UT and 14:26 UT, when the H2 remained at heights of about 70×10^3km.

The behaviour of the heights H1 and H2 between 13:59 UT and 14:26 UT, as one can see in Fig. 4, suggests that the prominence loop underwent helical writhing about vertical to the solar surface axis during that time interval. For a quantitative estimation of the EP loop kinking, the normalized differences between H1 and H2 as a function of time was determined (Fig. 5). In the observational case at the solar limb, such difference was used as a measure of the kinking degree of the EP loop. The normalized difference increased as a whole, from about 1/3 up to about 2/3 of the height H1 during the observed eruption. The distance between H1 and H2, in metrical units rose from 40×10^3 km to 110×10^3 km. In metrical case, that process can be estimated by least-square linear fit that gives an average increasing velocity of 32 km s^{-1}. Taking into account that the average rising velocity of the EP apex is 28 km s^{-1}, then the average downward velocity of the projected crossing point of the EP legs is about 4 km s^{-1}. This estimation is more precise as far as the confidential probability in that case is higher (92%). The time variation of the normalized difference reveals two distinct phases of the loop writhing that is a consequence of the specific height-time profile of the crossing point H2 (see Fig. 5).

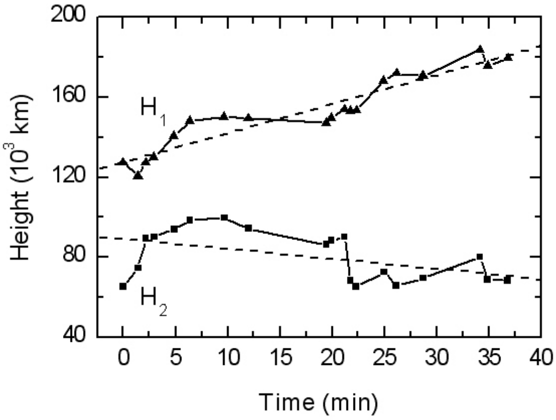

Fig. 4. The heights of the apex of the EP loop (H1) and the projected cross-point of the kinked loop legs (H2) as a function of time. The time is given in minutes after 13:49 UT

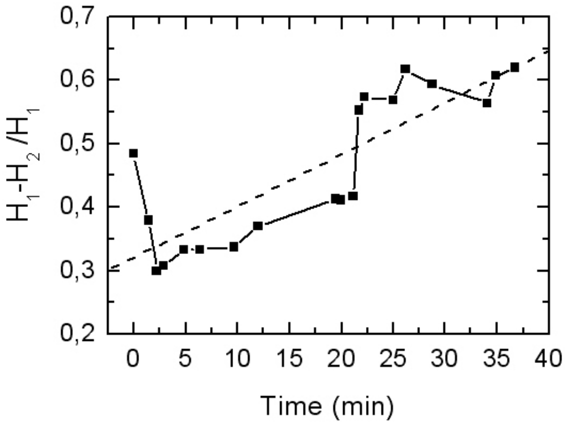

Fig. 5. Normalized difference between heights of the apex of the EP loop and the projected cross-point of the kinked loop legs (H1-H2/H1) as a function of time. The time is given in minutes after 13:49 UT

Figure 6 shows the variation of the angle α as a function of time. The angle between the crossed loop legs was used as an additional measure for the degree of kinking, increased on average from 63° to 77° during the observed eruption. The increasing of the angle α was accompanied by cyclic variation. A T-R periodogram analysis of its variation gives a statistically significant period of about 14 min. The correlation analysis of the time series of the angle α and the normalized difference between H1 and H2 showed that there is a strong correlation between them with a correlation coefficient of 0.68.

3 Discussion

The morphological evolution and kinematic pattern of the EP on 7 May 1979 suggest that it presents a confined (failed) eruption. The EP rose in relatively narrow interval of heights, from 120×10^3 km to 180×10^3 km, during 40-min time interval. The height-time profile of the apex of the EP loop shows only linear increasing with velocity of several ten kilometers per second that is typical for the late phase of the eruptions. The time profile of the EP height is similar to the last part of the one of the confined filament eruption on 27 May 2002 whose ascent was terminated at projected height of ≈ 80 x 10^3 km (Ji et al. [2003]). The height at the observation onset is significantly bigger than the average initial height (42×10^3 km) of eruptive prominences (Liu [2008]), which suggests that most probably the observations started later, when the eruption was in progress, omitting its pre-eruptive and acceleration phases.

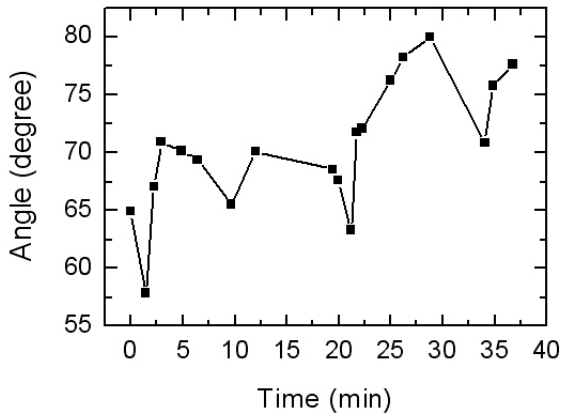

Fig. 6. Angle α as a function of time. The time is given in minutes after 13:49 UT

The EP underwent morphological changes leading to the helical writhing of the prominence loop inferring the kinking motion during the eruption. Its morphological changes are very similar to the ones of the filament eruption on 27 May 2002 in AR NOAA 9957 without a CME association (Ji et al. [2003]) and the filament eruption in AR NOAA 10696, accompanied with fast CME (Williams et al. [2005]). In terms of MFR hypothesis, in cylindrical geometry the prominence represents a twisted MFR with strong line-tied feet in the photosphere as far as the EP feet did not show significant displacements, projected on the sky plane. The careful analysis of the H_α filtergrams showed that the EP flux rope had left-handed twisting (negative magnetic helicity) and flux rope's axis had left-handed helical writhing that is typical for northern high latitude filament with positive (dextral) chirality (Rust and Kumar [1994]). The flux rope's twisting and helical writhing of its axis had the same sign that is basic condition for the kink instability to work (Hood and Priest [1979]). The kinking of the EP rope's axis was in progress during the observational interval of time, therefore the twist of the EP flux rope exceeded the threshold value and the kink instability most probably occurred earlier than the onset of the observations.

The kinking degree of the EP flux rope was quantitatively estimated by two measures: the normalized difference between the heights of the flux rope's apex and the projected crossing point of its kinked legs, and the angle α below the crossing point. The behaviour of the normalized difference between H1 and H2 (see Fig. 5) shows that while MFR apex raised with velocity of 28 km s^{-1} the projected cross-point of the ropes' legs moved downward with velocity of several kilometers per second. Such kinematic pattern have the same global characteristics as the MHD model of Török and Kliem [2005] simulating the confined eruption of a filament on 27 May 2002 (Ji et al. [2003]) by using of a kink-unstable magnetic configuration. One can see in Fig. 1, during the downward motion of the cross-point, the kink degree of the EP flux rope increased and at 14:16 UT the EP loop presented a large amount of kink, corresponding to a counterclockwise turn of the flux rope apex of about 90°.

The variation of the angle α, below the projected cross point H2, is the second quantitative estimation of the kinking degree of the EP MFR. The increasing of the angle α and its strong correlation with the increasing of the normalized difference between H1 and H2 suggest that the rising of the EP apex, downward motion of the projected cross-point and the angle bellow the cross-point are different morphological aspects of the same physical process, the kinking of the EP flux rope with anchored feet. The increasing of the angle α was accompanied by an oscillation with intermediate-period of about 14 minutes, according to common classification of the prominence oscillations (Oliver and Ballester [2002]). That is not unexpected result because the failed eruption does not preclude localized dynamic activity, heating, and flare production (e.g.Alexander et al. [2006]).

The oscillations of a prominence can occur before its eruption (e.g. Chen et al. [2008]) and sometime they can continue even in the eruptive phase (e.g. Isobe and Tripathi [2006]). The EP on 7 May 1979 belongs to the second case but it is not clear the time of the oscillation onset because of the omitted early phase of the eruption process. The oscillation period of the EP loop legs comes into the range of oscillation periods found for individual fibrils or groups of fibrils of the prominences (Yi et al. [1991]; Yi and Engvold [1991]). There are two type of exciters that could cause the oscillation of the EP of 7 May 1979 - an internal or an external. A possible internal agent might be kink instability of the prominence (e.g. Malville and Schindler [1981]). Alternatively, a possible external agent might be Moreton waves, propagating from the complex of active regions southeastward from the EP (see Fig. 2) that had high flare activity an hour before the EP observations.

The termination of the EP growth at a height of 180×10^3 km infers that the overlaying magnetic field remained closed. No prominence material escapes with the associated slow CME, which determines the EP on 7 May

1979 as confined eruption. Moreover, the large degree of its kinking is typical for the failed events according to Gilbert et al. [2007], which suggested that the kinking phenomenon might play an integral role in success or failure of prominence eruption. As pointed out by Gilbert et al. [2007], the relationship and fundamental differences between the types of eruption depend crucially on the role, played by reconnection in both the eruption and kinking processes. The topology of a MFR, leading to a full, partial, and failed eruption, can be understood by considering where reconnection occurs with respect to the prominence (Gilbert et al. [2007]).

The evolution of an inverse polarity MFR model with horizontal reconnection occurring above the prominence and within the flux rope forecasts an X-type neutral line above the original flux rope, creating two flux ropes: the original and one above. No prominence material escapes with the CME in this scenario (Gilbert et al. [2000]). Such reconnection, namely, "breakout-type" could be responsible for the removal of overlaying arcade as predict magnetic "breakout" models (e.g. Antiochos et al. [1999]). Moreover, the breakout reconnection could lead to confinement of prominence eruption as shows the three-dimensional simulation of DeVore and Antiochos [2008], that is the first demonstration of confined solar eruption via magnetic breakout. In this context, we discuss here the possibility a reconnection to occur above the EP on 7 May 1979, but within the EP MFR that could realize the confining process of the eruption. For that purpose, we consider the magnetic environment of the filament, associated with the EP and the characteristics of the associated CME.

There are three observational arguments in favor of the occurrence of a magnetic reconnection above the EP (within MFR). The first one is the inverse magnetic configuration of the filament, associated with the EP that was located along a PIL in a multipolar magnetic field. Such configuration is potentially vulnerable to breakout initiation of eruptions (DeVore and Antiochos [2008]). The second argument is both temporal and spatial an association between the EP and the CME that was registered on SOLWIND images (see Section 2). The central prong of the CME structure that coincided by position with the EP faded and darker-than-grey structure moved radially outward at approximately 80 km s^{-1} (Sheeley et al. [1980]). The front of this outward-moving depletion apparently marks the trailing end of material that has been ejected out of the field of view. The third argument is the asymmetrical location of the EP in the multipolar magnetic configuration. According to Liu et al. [2009], the coronal fields overlying filaments (prominence) in an asymmetric way provide in general a stronger confinement for filament/prominence eruption than symmetric fields do. The re-construction of the eruptive events at the northwestern limb on 7 May 1979 and their relationships infer that the inverse MFR, containing the EP at its base, is most probably involved the horizontal reconnection occurring above the prominence within the MFR. Such reconnection could create a second MFR above the original one that moves outward and subsequently it could produce the associated CME.

Conclusion

In our research, we have studied a confined eruption of a prominence on 7 May 1979 most probably induced by kink instability. The EP represents helically writhed flux rope with fixed feet that presents a disturbed segment of a long-lived filament, located along the PIL within multipolar magnetic field configuration. Several key issues related to the kinematic pattern, kinking process and confining mechanism of the eruption could be addressed.

1. The height-time profile of the EP apex and its rising velocity that is typical for the late stage of the EPs suggest that the observation span late stage of the eruption, omitting its pre-eruptive and acceleration phases.

2. The helical writhing of the EP loop axis and helical twisting of the EP MFR, in the observational case at the solar limb, clearly shows that the basic conditions for development of kink instability are available.

3. The kinking degree of the EP flux rope was quantitatively estimated by two measures: the normalized difference between the flux rope apex and projected cross-point of its legs and the angle α between the flux rope's legs below the cross-point. We found that the kink instability was in progress at the onset of observations and to the end of the eruption, the EP flux rope presented a large amount of kinking. The results are consistent with another observational (e.g. Ji et al. [2003]) and theoretical (e.g. Török and Kliem [2005]) ones, which suggests that the used measures are good signatures of the EP kinking in the case of its observations at the solar limb.

4. Oscillations of the angle α with a period of 14 minutes, accompanied its increasing, suggest the oscillations of the EP flux rope during the eruption. Such oscillations could be excited either by an internal agent, e.g. kink-instability itself or external agent, e.g. Moreton waves from high flare activity in the active regions southeastward of the EP a hour before the EP observation.

5. A possible scenario for failed eruption on 7 May 1979 was proposed, in which a breakout-type reconnection could occur above the EP but within a flux rope itself. The slow CME associated the EP might be considered as signature of the creation of a second flux rope, above the original and its eruption. Subsequently, the overlaying magnetic field of the EP remained closed terminating its growth at a height of 180×10^3 km.

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