Kinetics of the post-eruptive phase of an eruptive prominence on 8 May, 1979

P. Duchlev[1], M. Dechev[1], K. Koleva[1], J. Kokotanekova[1], B. Rompolt,[2] P. Rudawy[2]
[1] Institute of Astronomy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria
[2] Astronomical Institute, Wroclaw University, 51-622 Wroclaw, Poland
duchlev@astro.bas.bg
(Research report. Accepted on 26.12.2009)

Abstract. The kinetic pattern of the post-eruptive phase of the quiescent prominence which erupted on 8 May, 1979, was studied. The eruption of the helically-twisted polar prominence originated in the southern leg of the huge magnetic system (HMS) that later produces a coronal mass ejection (CME). The kinetic evolution of the post-eruptive process was estimated by time profiles of the heights of the two main flux ropes (FRs), composing the body of the eruptive prominence (EP) and the horizontal expansion between the main FRs feet. The inflow velocity of the prominence plasma back to the chromosphere increased with constant acceleration of 76 m/s^2 and it reached a value of up to 200 km/s. The horizontal expansion between the main FRs feet of the EP increased with an average constant velocity of 12 km/s in first order approximation, but in fact it has changed non-linearly. The obtained results were discussed as indicative ones for the kinetics and evolution of the magnetic field at the bottom of the erupting HMS.
Key words: Prominences, Eruptions, Coronal Mass Ejections, Magnetic fields

Кинетика на пост-еруптивната фаза на еруптивен протуберанс от 8 май 1979 г.

П. Духлев, М. Дечев, К. Колева, Й. Кокотанекова, Б. Ромполт, П. Рудави

Изследвана бе кинетичната картина на пост-еруптивната фаза на спокоен протуберанс, еруптирал на 8 май 1979 г. Ерупцията на спирално усукан полярен протуберанс възниква в южния „крак” на огромна магнитна система, която по-късно произвежда изхвърляне на коронална маса. Кинетичната еволюция на пост-еруптивния процес бе оценена чрез времевите профили на височините на двете основни магнитни въжета (МВ), съставящи тялото на еруптивния протуберанс (ЕП) и хоризонталното изместване между „стъпките” на МВ. Скоростта на втичане на протуберансовата плазма обратно към хромосферата нараства с постоянно ускорение от 76 м/c^2 и достига стойности до 200 км/с. Хоризонталното изместване между „стъпките” на основните МВ на ЕП нараства средно с постоянна скорост от 12 км/с, но в действителност то се изменя нелинейно. Получените резултати са дискутирани като показателни за кинетиката и еволюцията на магнитното поле в дъното на еруптиращата огромна магнитна система.

Introduction

Both quiescent and active region solar prominences (filaments, when they are observed against the solar disk) often undergo more or less violent activation during their lifetime. The activation can lead to eruption that results in complete disappearance of the prominence in few hours (a phenomenon is referred as "disparition brusquie" (DB) in the case of a filament). In some cases, the prominence reforms after eruption in the same place and nearly in the same shape a few hours or days later (Foukal, [1990]). That is known as a temporary DB in the case of a filament.

The eruptive prominences (EPs) are frequently associated spatially and temporally with CMEs and solar flares (Gopalswamy et al, [2003]; Filippov and Koutchmy, [2007]; Schrijver et al., [2008]; Yashiro et al, [2008]), forming complex phenomena generally occurring in the destabilized or even violently evolving huge magnetic systems (HMS) (Rompolt, [1984]). In white-light observations, CMEs often exhibit a three-part morphology, consisting of a relatively bright rim (leading edge of the plasma bubble) encircling a relatively dark cavity, which often, but not always, contains a bright core presumed to be a white-light counterpart of the EP (Munro et al., [1979]; House et al., [1981]; Illing and Hundhausen, [1985] and [1986]). The EP could also be recorded on images taken in hydrogen Hα light as a bright structure moving outwards within the expanding dark cavity. An universal model of the CME eruptions, describing all characteristics and processes, does not exists jet (Ugarte-Urra, [2007]), while the most widely accepted are magnetic breakout (Antiochos et al., [1999]; Lynch et al., [2004]), tether-cutting (Moore and LaBonte, [1980]; Sturrock, [1989]) and flux rope (Lin et al., [2001]; Amari et al., [2004]; Török and Kliem [2005]) models. In particular, the flux rope model describes well the CMEs with classic three-part structure (Forbes, [2000]; Chen et al., [2006], and references therein), where the CME and the associated EP could be treated as different parts of a flux rope with specific geometrical relationships among the CME, EP, and flux rope itself (referred together as the CME-EP-MFR system). An eruption of a preexisting magnetic flux rope (MFR) formed in the corona is a natural consequence of the conservation of magnetic helicity (Low, [1994]).

On the basis of detailed investigations of the geometry, characteristic features of the expansion and locations on the limb of white-light transients and EPs, observed in Hα, Rompolt ([1984], [1990]) defined two basic types of EPs associated with CMEs. Both types EPs are embedded in the lower part of a HMS that contains the EP and the associated CME. The EPs of type I are located in magnetic arch in the lower part of a HMS. A large magnetic arch of EPs of this type is fully filled by a cool and dense Hα-material and during the HMS eruption these EPs are seen in the shape of large, raising arches. The EPs of type II are located in one leg of a magnetic arch in the lower part of a HMS. The EPs of this type look as if there is not enough of the cool and dense material in the remaining part of the HMS arch to become visible in Hα. So, during the eruption, the EPs of type II changed the inclination of their main body from being roughly parallel to the limb at the beginning of the eruption up to being perpendicular to it in the late phase of the eruption. Similar to the EP of type I, the body of the EP of type II consists of intertwisted and intertwined thin threads or flux-ropes, in context of MFR hypothesis. One of the essential differences between these two types EPs is that the EPs of type II show distinct post-eruptive phase when the prominence plasma flows back to the chromosphere up to the full prominence disappearing in Hα.

EUV and coronagraph Hα images of some quiescent and many EPs contain twisted plasma structures (Vršnak, Ruždjak and Rompolt, [1991]; Vršnak et al., [1993]1993; Martens [1998]; Dere et al. [1999]; Chen et al., [2000]) that are especially well exposed in the prominence legs. In the eruption phase, the morphology of EPs often changes dynamically and can be very intricate (Rompolt, [1975], [1990]; Schrijver et al., [2008]), but in the course of a eruption the internal structure of the prominence gradually transforms from a complicated structure into a simpler one, frequently remaining helical-like twisted (Rušin and Rybanský, [1982]; Rompolt, [1990], Karpen et al., [2003] and references therein). In this paper, we present results from a detail study of the kinetic pattern of the post-eruptive phase of a type II EP of 8 May 1979, associated with CME.

1 Eruptive prominence on 8 May 1979

1.1 General description

The investigated EP was initially a quiescent prominence seen on the disk as a polar filament spread approximately between 48°S and 61° S in latitude and between 243° and 305° in longitude. On 8 May 1979, the prominence crossed the western solar limb at S53° at the angle of 70°, so it was seen almost in edge-on position (see Fig. 3). It was a long-lived filament with lifetime of 10 solar rotations, lay along C-type magnetic neutral line and according to Leroy, [1989] it has inverse configuration of the magnetic field.

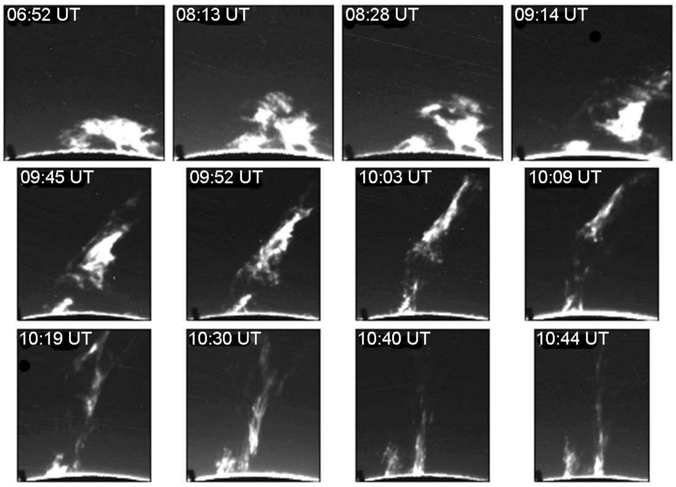

Fig. 1. A sequence of Hα filtergrams presenting the whole evolution of the type II eruptive prominence of 8 May, 1979. The prominence reached maximum projected height of about 320 000 km above the solar limb at 10:23 UT

On 8 May 1979, the prominence was visible as a quiescent one between 06:53 UT and 07:05 UT. Between 07:05 UT and 08:10 UT, the activation of

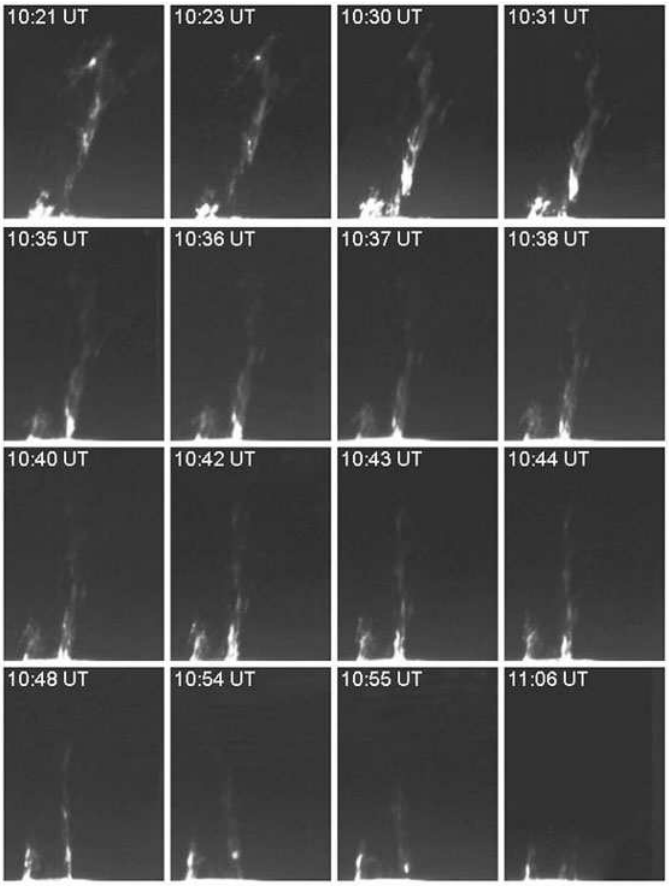

Fig. 2. A sequence of the Hα filtergrams presenting in detail the evolution of the post-eruptive phase of the EP between 10:21 UT and 11:07 UT on 8 May 1979

the prominence was observed. The eruption of the prominence was registered at 08:10 UT for the first time but apparently it started to raise much earlier, before 08:10 UT. At the beginning of the observed eruptive phase, between 08:10 UT and 08:49 UT, the prominence rose slowly and gradually build morphology. After 08:49 UT, its raising become very fast and the prominence reached maximum height of about 320 000 km above the solar limb at 10:23 UT. The post-eruptive phase of the prominence's evolution lasted between 10:21 UT and 11:07 UT (see Fig. 2), when the prominence considerably faded out and most of its material fell back to the chromosphere. The prominence's southern leg (left in the Fig. 1) was visible up to the chromosphere during the whole eruption at S58° W.

The eruption of the filament was associated with slow CME of 8 May 1979 (Michels et al., [1980]). The CME occupied the region from S15° W

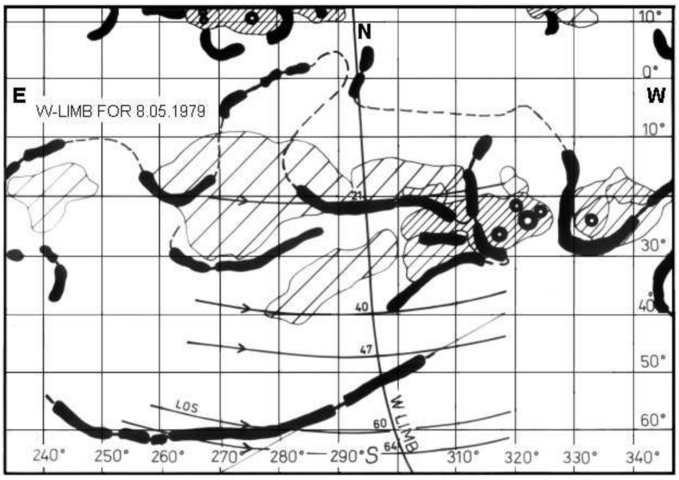

Fig. 3. Meudon synoptic map of the solar chromosphere for the Carrington rotation 1681 with overplotted projection of the solar limb (thin line pointed out by small arrow). The type II eruption of the prominence was seen at S53° on 8 May, 1979

to S60° W and its center of symmetry was located at S30° W. During the eruption, the EP was embedded in the southern leg of the CME big bubble (Fig. 4).

1.2 Eruption of the prominence

The EP of 8 May 1979 was a classical example of the eruptive prominence of type II according to Rompolt ([1984], [1990]). The EP's body was frozen into the associated HMS/MFR system that changed in the course of the eruption. The general kinetic pattern of the EP's evolution is presented on the height-time diagram (see Fig. 5), where two main phases in the evolution: eruptive and post-eruptive are clearly distinguishable.

The vertical rise of the prominence consisted of three distinct dynamical stages: acceleration, constant velocity and deceleration, thus, in accordance with kinetic classification of Vršnak ([1998]) the prominence was of type C. The acceleration stage lasted for 66 minutes, from 08:10 UT up to 09:16 UT. During this stage, the prominence underwent a constant acceleration of 15 m/s^2 (estimated using second-degree polynomial fit of the observed heights) and it reached a projected height of 170 000 km above the solar limb.

After the acceleration phase, from 09:16 UT up to 10:03 UT, the prominence raised with constant projected vertical velocity of 42 km/s and reached the projected height of 300 000 km above the limb. Next, the EP decelerated gradually with negative acceleration of 33 m/s^2 (acceleration, estimated using second-degree polynomial fit of the observed heights). At 10:23 UT, the EP reached the maximum projected height of 320 000 km and after that the most of prominence's plasma flowed back to the chromosphere.

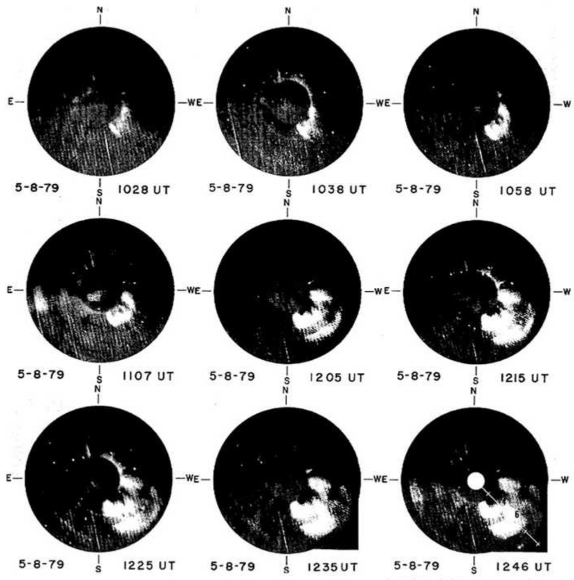

Fig. 4. A sequence of SOLWIND coronagraph images showing the detailed evolution of the 8 May 1979 transient (CME) relative to the pre-transient corona at 08:52 UT (Sheeley et al. [1980])

Before the eruption, the prominence's body consisted of two twisted flux ropes (FRs) each of them consisted of numerous twisted small thin magnetic FRs, containing the prominence plasma. During the eruption, the visible inclination of the EPs changed from being roughly parallel to the limb at the beginning of the eruption up to being nearly perpendicular to the limb in the late stage of the eruption (see Fig. 1). The filtergrams taken after 09:51 UT showed that in the course of the eruption the main FRs untwisted and at 10:19 UT, just before the EP reached the maximum projected height and its body was nearly perpendicular to the limb, the main FRs were completely untwisted. Later on, after 10:30 UT, the feet of the FRs showed apparent horizontal expansion, moving away from each other up to the end of eruption, as well as during the post-eruptive phase.

2 Kinetics of the prominence during the post-eruptive phase

2.1 Data and analysis

The prominence was observed on the solar western limb at the mean latitude S53° from 06:53 UT up to 11:09 UT on 8 May, 1979 in the hydrogen Hα line with the Small Coronagraph (130/3450 mm) of the Astronomical Institute of University of Wroclaw equipped with a 3 Å band-pass Lyot filter (see Fig.

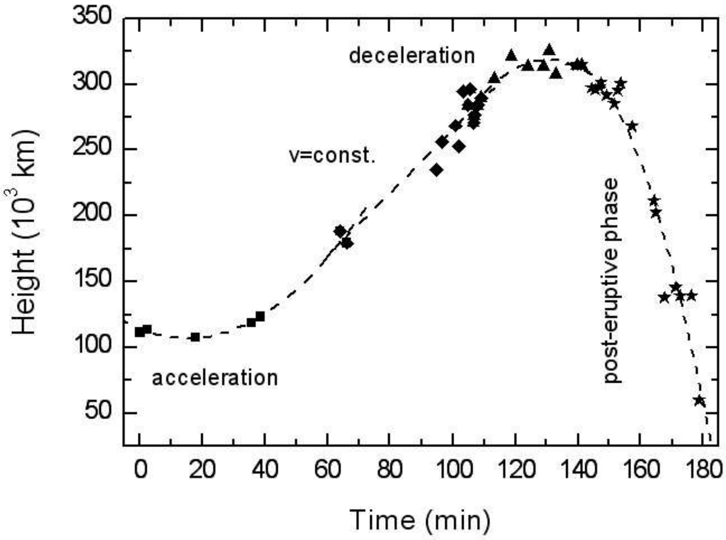

Fig. 5. Height-time diagram of the type II EP of 8 May 1979. The time is given in minutes after 06:52 UT

1). Most of the images were taken with exposure time of 1/8 of a second. All 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 steps in both directions. The pixel size of the images corresponds to a little more than $1''$on the Sun.

The last 16 filtergrams from the full series of the EP of 8 May 1979 were used for determination of the basic kinetic parameters of the post eruption phase (Fig. 2). Since during the post-eruptive phase two main FRs of the EP were completely untwisted, the kinetic evolution of each of them was traced. The two untwisted prominence FRs, northern (N) one and southern (S) one are presented in Fig. 6. The Height-time profiles of the N and S FRs were determined from each filtergram their by measurements of the projected heights. The distance between them as a function of time was also determined by measurements of the positions of the FRs feet.

2.2 Vertical expansion

During the post-eruptive phase, the main FRs of the EP were completely untwisted (see Fig. 2) thus their evolution could be traced separately. The height-time relation of the northern FR compared with those one in Fig. 5 suggests a massive inflow of the prominence's plasma back to the chromosphere along the northern FR, being a part of a rising magnetic skeleton of

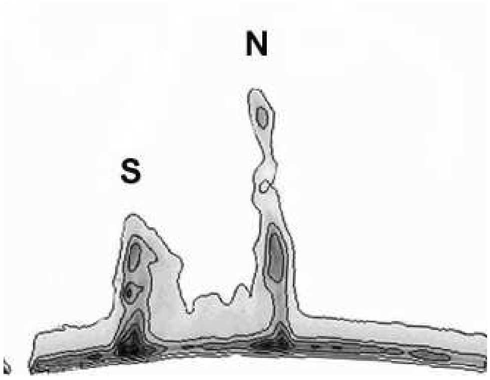

Fig. 6. A simplified sketch of the completely untwisted northern (N) and southern (S) main flux ropes of the EP's body

the prominence embedded into erupting HMS. The estimated constant acceleration of the plasma along the southern FR toward the solar surface was 76 m/s^2 and the plasma reached a velocity of 200 km/s at the end of the post-eruptive phase.

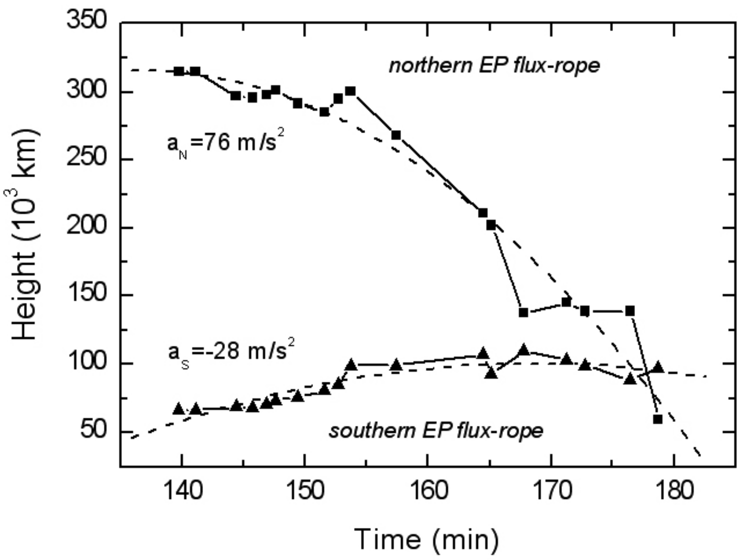

Fig. 7. Temporal changes of the heights of the two main flux ropes during the post-eruptive phase of the EP of 8 May 1979. The time is given in minutes after 06:52 UT

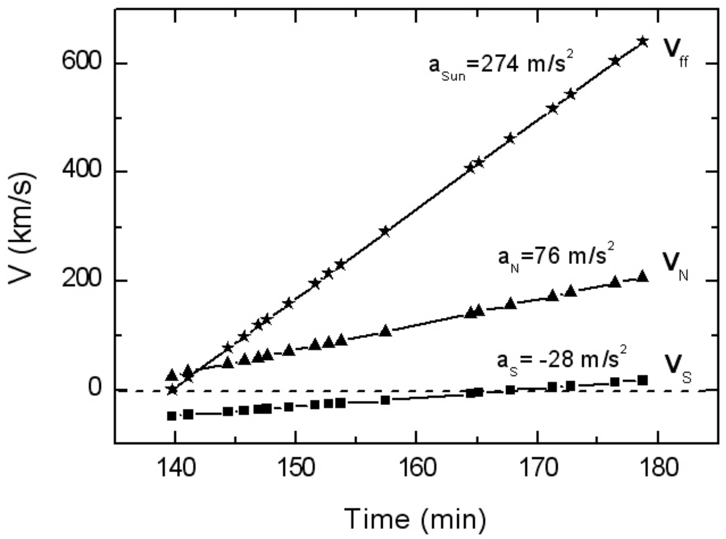

Fig. 8. Temporal variations of the velocities of the untwisted main flux ropes presenting the EP during the post-eruptive phase, estimated using two-degree polynomial fits (Fig. 7). Theoretical free-fall velocities of the objects at acceleration of 274 m/s^2 are given too. The time is given in minutes after 06:52 UT

The temporal variation of the observed height of the southern FR is more different. After the end of the eruptive phase, the southern FR increased slowly from 70 -000 km up to 100 000 km at 10:58 UT, and next it decreased to about 80 000 km. The observed deceleration of the material was equal to about -28 m/s^2. A significant simplification of the internal structure of the flux rope occurred during the deceleration phase. Fig. 7 presents the temporal variations of the heights of the northern (N) and southern (S) FRs of the prominence during the post-eruptive phase of the evolution, and Fig. 8 shows the temporal variations of their velocities.

2.3 Horizontal expansion

The feet of the EP's main flux ropes underwent horizontal relative expansion (the distance between the feet varied in time) during the eruption of the prominence. The expansion process started at around 09:51 UT, one hundred minutes after the onset of the prominence eruption (08:10 UT). The expansion consisted of two stages. The first one lasts up to the end of the eruption phase and it is characterized with untwisting of the main flux ropes of the EP's body. During the first stage, the horizontal expansion had more or less a chaotic character. The second stage of the horizontal expansion coincided in time with the post-eruptive phase of the evolution of the EP. It started after 10:21 UT, when the prominence reached the maximum height of 320 000 km and when its vertical main flux ropes were completely untwisted. During this second stage the feet of the untwisted flux ropes of the prominence body exhibited an apparent horizontal expansion.

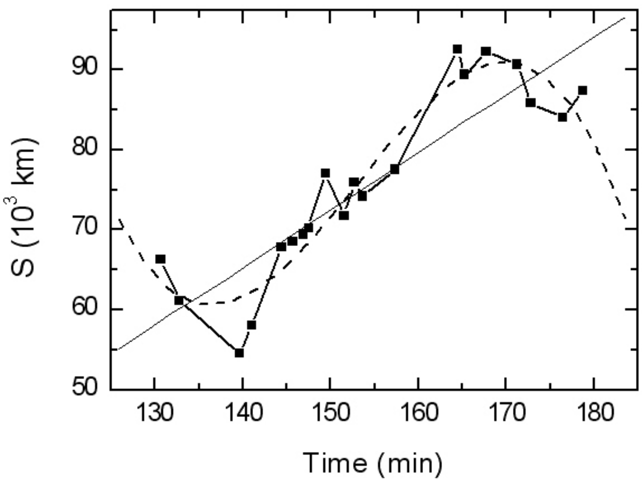

Fig. 9. Temporal variations of the relative horizontal expansion of the flux ropes of the EP. The time is given in minutes after 06:52 UT

Fig. 9 presents temporal variations of the horizontal distance between the feet of the main flux ropes of the EP. The mean velocity of the expansion, estimated by linear least square fit, was equal to 12 km/s. The estimation of the horizontal expansion by third-degree polynomial fit infers that during the post-eruptive phase the distance between the feet has changed non-linearly. It decreased initially from 67 000 km to 55 000 km, next it increased up to 90 000 km for 25 minutes between 10:30 UT and 10:55 UT, and finally it decreased back to 85 000 km at the end of the post-eruptive phase (see Fig. 9). The accelerations and velocities of the relative horizontal expansion, fitted with a third-degree polynomial, are shown in Fig. 10.

3 Discussion and conclusion

The basic results of the presented detailed study of kinetics of the post-eruptive phase of the EP of 8 May 1979 are summarized as follow:

1. The kinetics of the southern main FR of the EP body is representative for the kinetic pattern of the post-eruptive phase of the prominence. Moreover, the morphological evolution of the southern FR is indicative for the evolution of the magnetic topology at the bottom of the expanding HMS that later produce a CME. This southern FR of the EP can be well traced

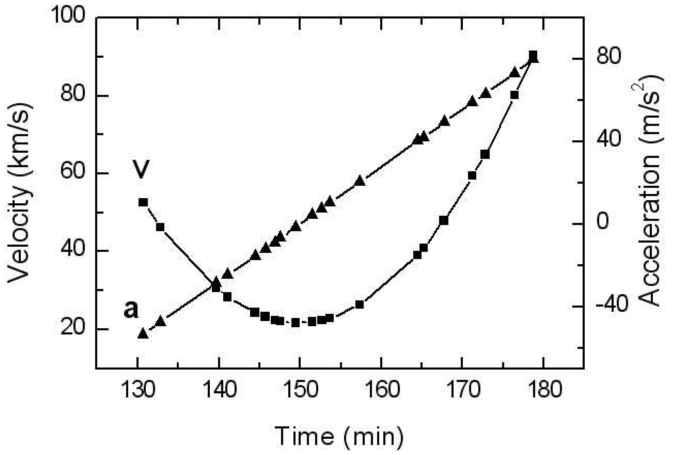

Fig. 10. Temporal variations of the acceleration and velocity of the horizontal relative expansion of the feet of the EP's FRs, estimated using third-degree polynomial fit (Fig. 9). The time is given in minutes after 06:52 UT

in the SOLWIND coronagraph images that were obtained between 10:28 UT and 10:58 UT as brighter southern edge of the developing magnetic system of the CME (Michels et al., [1980]).

2. The inflow velocity of the prominence plasma in the southern FR of the EP increased with constant acceleration of 76 m/s^2 and reached a value of up to 200 km/s in the end of the post-eruptive phase, which is about 3 times less than free-fall velocity.

3. The horizontal expansion between the feet of the main FRs of the EP body increased during the post-eruptive phase from 55 000 km up to 85 000 km with an average constant velocity of 12 km/s in first order approximation. However, the detail analysis of the horizontal expansion suggests that, in fact it has changed non-linearly inferring that the horizontal motion of the separate magnetic FRs has more complex character. The post-eruptive phase temporarily coincides with the early stage of the HMS eruption when the onset and development of a CME were registered on SOLWIND images. During the stretching up of the HMS, its lower part containing the EP expands mainly laterally (Hundhausen, [1994]) that could explain the apparent character of the horizontal expansion during the post-eruptive phase. As for the complex character of the horizontal motions of the FR's feet, leading to its non-linear changes (Fig. 8), most probably it is closely connected with physical mechanisms responsible for the dynamics of MRs rising in the solar atmosphere, similar to those proposed by Emonet et al., [2001].

4. The process of horizontal expansion was accompanied by an untwisting of the threads/ropes inside the main FRs of the EP. When the post-eruptive phase finished and the EP fully disappeared in Hα line, the separate threads/ magnetic tubes were completely untwisted. Consequently, the full untwisting

of the EP threads/ropes and their perpendicular position to the solar limb could be considered as a signature for a crucial stage in the eruptive evolution of the HMS/MFR. So, the horizontal expansion of the EP threads/ropes during the post-eruptive stage traces kinetic and topological changes in the lower part of the HMS/MFR system preceding and accompanying the CME appearance and development. Therefore, the kinetics studies of the post-eruptive phases of EPs of type II provide important information about the kinetics and evolution of the magnetic field at the bottom of the erupting HMSs.

Acknowledgments

The authors greatly benefit from the open data policy of the teams of Meudon Observatory. The National Scientific Foundation of Bulgaria under Grant F1510/2005 and Grant number N203 022 31/2991 of Polish Ministry of Science and Higher Education supported this study.

References

Amari, T., Luciani, J. F., and Aly, J. J., 2004, *ApJ*, ***615***, *L165*
Antiochos, S. K., DeVore, C. R., and Klimchuk, J. A., 1999, *ApJ*, ***510***, *p. 485*
Chen, J., Santoro, R. A., Krall, J., Howard, R. A., Duffin, R.,Moses, J. D., Brueckner, G. E., Darnell, J. A. and Burkepile, J. T., 2000, *Astrophys. J.*, ***533***, *p. 481*
Chen, J., Marqué, C., Vourlidas, A., Krall, J., and Schuck, P. W., 2006, *Astrophys. J.*, ***649***, *p. 452*
Dere, K. P., Brueckner, G. E., Howard, R. A., Michels, D. J. and Delaboudiniere, J. P., 1999, *Astrophys. J.*, ***516***, *p. 465*
Emonet, T., Moreno-Insertis, F., and Rast, M. P., 2001, *Astrophys. J.*, ***549***, *p. 1212*
Filippov, B., and Koutchmy, S., 2007, *arXiv:0711.4752*
Forbes, T. G., 2000, *J. Geophys. Res.*, ***105***, *p. 23153*
Foukal, P., 1990, *Solar astrophysics, New York, Wiley-Interscience*
Gopalswamy, N., Shimojo, M., Lu, W., Yashiro, S., Shibasaki, K., Howard, R. A., 2003, *ApJ*, ***586***, *p. 562*
House, L. L., Wagner, W. J., Hildner, E., Sawyer, C., 1981, *Astrophys. J.*, ***244***, *L117*
Hundhausen, A. J., 1994, in K. T. Strong, J. L. R. Saba, and B. M. Haisch (eds.) *The Many Faces of the Sun: Scientific Highlights of the Solar Maximum Mission, Springer-Verlag*
Illing, R. M. E. and Hundhausen, A. J., 1985, *J. Geophys. Res.*, ***90***, *p.275*
Illing, R. M. E. and Hundhausen, A. J., 1986, *J. Geophys. Res.*, ***91***, *p. 10951*
Karpen, J. T., Antiochos, S. K., Klimchuk, J. A. and MacNeice, P. J., 2003, *Astrophys. J.*, ***593***, *p. 1187*
Leroy, J.-L., 1989, *in Dynamics and Structure of Quescent Solar Prominences, E. R. Priest (ed.), Kluwer Acad. Publ., p.77*
Lin, J., Forbes, T. G., and Isenberg, P. A., 2001, *J. Geophys. Res.*, ***106***, *p. 25053*
Low, B. C., 1994, *Phys. Plasmas*, ***1***, *p. 1684*
Lynch, B. J., Antiochos, S. K., MacNeice, P. J., Zurbuchen, T. H., and Fisk, L. A., 2004, *ApJ*, ***617***, *p. 589*
Martens, P. C. H., 1998, in New Perspectives on Solar Prominences, *IAU Colloq.* ***167***, *D. Webb, D. Rust and B. Schmieder (eds), ASP CS-150, p. 294*
Michels, D. J., Howard, R. A., Koomen, M. J., Sheeley, N. R. Jr. and Rompolt, B., 1980, in Solar and Interplanetary Dynamics, *IAU Symposium* ***91***, *M. Dryer and E. Tandberg-Hanssen (eds.), p. 387*
Moore, R. L., and LaBonte, B. J., 1980, in Solar and Interplanetary Dynamics, *IAU Symp.* ***91***, *M. Dryer and E. Tandberg-Hanssen (eds.), p.207*
Munro, R. H., Gosling, J. T., Hildner, E., MacQueen, R. M., Poland, A. I., and Ross, C. L., 1979, *Sol. Phys.*, ***61***, *p. 201*

Rompolt, B., 1975, *Rotational Motions in Fine Solar Structures, Acta Universitatis Wratislaviensis, Wroclaw, Poland*
Rompolt, B., 1984, *Adv. Space Res., **4**, No. 4, p. 357*
Rompolt, B., 1990, *Hvar Obs. Bull., **14**, p. 37*
Rušin, V. and Rybanský, M., 1982, *Bull. Astron. Inst. Czech., **33**, p. 219*
Schrijver, C. J., Elmore, C., Kliem, B., Török, T. And Title, A. M., 2008, *ApJ, **674**, p. 586*
Sheeley, N. R. Jr., Michels, D. J., Howard R. A., and Koomen, M. J., 1980, *ApJ, **237**, L99*
Sturrock, P. A., 1989, *Sol. Phys., **121**, p. 387*
Török, T., and Kliem, B., 2005, *ApJ, **630**, L97*
Ugarte-Urra, I., Warren, H. P. and Winebarger, A. R., 2007, *ApJ, **662**, p. 1293*
Vršnak, B., 1998, in New Perspectives on Solar Prominences, *IAU Colloq. **167**, D. Webb, D. Rust and B. Schmieder (eds), ASP CS-150, p. 302*
Vršnak, B., Ruždjak, V. and Rompolt, B., 1991, *Solar Phys., **136**, p. 151*
Vršnak, B., Ruždjak, V., Rompolt, B., Roša, D. and Zlobec, P., 1993, *Solar Phys., **146**, p. 147*
Yashiro, S., Michalek, G., Akiyama, S., Gopalswamy, N., and Howard, R. A., 2008, *ApJ, **673**, p. 1174*