

Evidence for a Flux Rope Model for CMEs Based on Observations of the Limb Prominence Eruption on January 4, 2002

Vasyl B. Yurchyshyn^{1,2}

¹Big Bear Solar Observatory, Big Bear City, CA 92314, USA

²Crimean Astrophysical Observatory, 98409, Nauchny, Crimea, Ukraine

ABSTRACT

We report on a prominence eruption as seen in Kanzelhöhe Solar Observatory $H\alpha$, SOHO/EIT 195Å and coronal SOHO/LASCO C2 images. Our data favour the flux rope model for CMEs, which suggests that a flux rope is formed long before the eruption. Our conclusion is based on a three part structure of the pre-erupted configuration of the magnetic field and on the fact that the first $H\alpha$, SOHO/EIT 195Å brightenings occurred some 15 minutes after the filament began to ascend.

The data also clearly demonstrate two rarely observed components of the standard flare model: i) magnetic loops which overlay the pre-erupted filament and ii) magnetic field lines stretched vertically by the ascending filament. These field lines are compressed horizontally and move toward each other where they reconnect to form an apparently growing post flare loop system.

1. Introduction

Filament eruptions, and associated photospheric activity and coronal mass ejections (CMEs), are manifestations of the relaxation of large scale highly stressed solar magnetic fields. In order to understand the mechanism which produces CMEs we must first understand how the energy in solar magnetic fields is stored and released? There are several approaches to explain magnetic eruptions, which we intend to discuss briefly.

The tether cutting model (Moore and LaBonte 1980) and the breakout model (Antiochos 1998; Antiochos et al. 1999) both suggest that there is no flux tube prior to an eruption and that the large scale reconnection of magnetic fields forms the flux tube that is typically present after an eruption. One expects to see an associated increase in intensity in EUV and/or $H\alpha$ images before the eruption. There are observations which strongly support this expectation. Sterling and Moore (2001) and Sterling et al. (2001) interpret EIT crinkles as evidence for the breakout model. Yurchyshyn et al. (2001) reported that the

February 17, 2000 two ribbon flare started before activation of the active region’s filament. It was also concluded that an accompanying halo CME was the product of the reconnection of sheared arcades, which favors the tether cutting model. Dere et al. (1999) did not find evidence for preexisting helical structures and suggested that the flux rope may be formed during the ejection of a CME.

Another approach has also been developed by many authors over the years (Van Tend and Kuperus 1978; van Ballegooijen and Martens 1989; Forbes and Isenberg 1991; Kumar and Rust 1996; Wu et al., 1999; Amari et al. 2000). This approach advocates the idea that the energy for eruptions is stored in a flux rope, which is formed long before the eruption occurs. According to these models, the flux rope is part of the pre-erupted magnetic configuration and no reconnection is needed to form the flux rope. Therefore, no EUV and/or $H\alpha$ brightenings should precede the eruption.

In this study we present Kanzelhöhe Solar Observatory $H\alpha$ and SOHO/EIT 195Å observations of a quiet region prominence eruption. This limb eruption was associated with a spectacular CME observed with the SOHO/LASCO coronagraph. The high time resolution of the chromospheric images allowed us to follow the pre-eruption evolution of the prominence and compare it with the evolution of chromospheric brightenings.

2. Data

The following data sets were used in this study.

1. Full Disk $H\alpha$ data from the Global $H\alpha$ network (<http://www.bbso.njit.edu/Research/Halpha/>), which utilizes facilities at the Big Bear Solar Observatory in California, the Kanzelhöhe Solar Observatory (KSO) in Austria, the Catania Astrophysical Observatory in Italy, and the Yunnan Astronomical Observatory and Huairou Solar Observing Station in China (Steiniger et al. 2000). In this study we use $H\alpha$ images acquired with the KSO 10 cm telescope equipped with a 2K x 2K Apogee KX4 detector. The instrument is able to monitor the Sun with a spatial resolution of 1 arcsec per pixel and a time resolution of 1 minute.

2. The SOHO/EIT instrument produces full disk images of the Sun with a resolution of 2.6 arcsec per pixel at four different wavelengths (Delaboudiniere et al. 1995). For this study, we use images acquired of the Fe XII 195Å spectral line with a time resolution of 12 minutes.

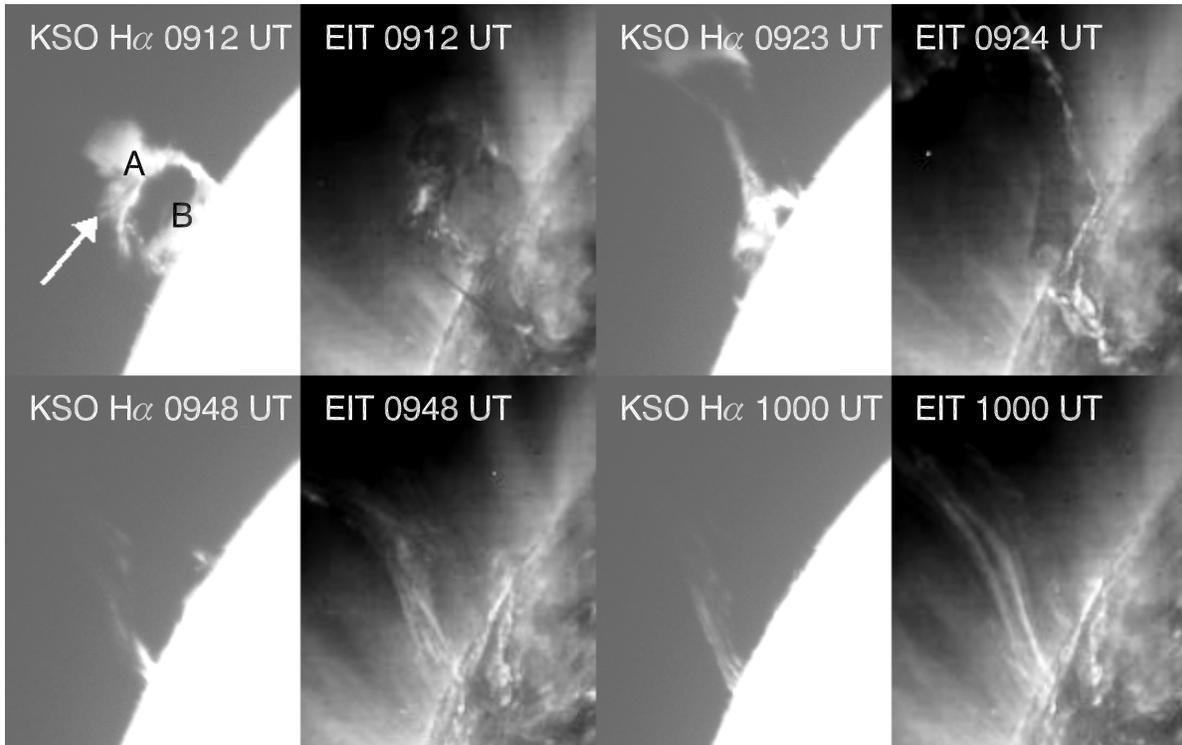


Fig. 1.— $H\alpha$ images from Kanzelhöhe Solar Observatory and SOHO EIT 195\AA images showing the prominence eruption on January 4, 2002. The arrow indicates a strained structure at the bottom part of the lifting $H\alpha$ filament.

3. We also used C2 white-light LASCO data (Brueckner et al. 1995), which covers the range from 2 to 6 solar radii.

3. Chronology of Events

According to the KSO data, the prominence activity started at approximately 08:40 UT on January 4, 2002 (Figure 1). The prominence erupted at 09:05 UT, which resulted in a bright limb CME seen in the LASCO C2 coronagraph (Figure 2). In Figure 1 we label different parts of the prominence with an “A” and “B” to aid our discussion. Below we list the chronology of events during the eruption.

08:40 UT – First signs of filament activation seen in the KSO and EIT data.

09:05 UT – Part A of the filament begins to ascend. The height of the top of the filament, at this time, is about 40,000 km. A strained structure is seen at the bottom part of

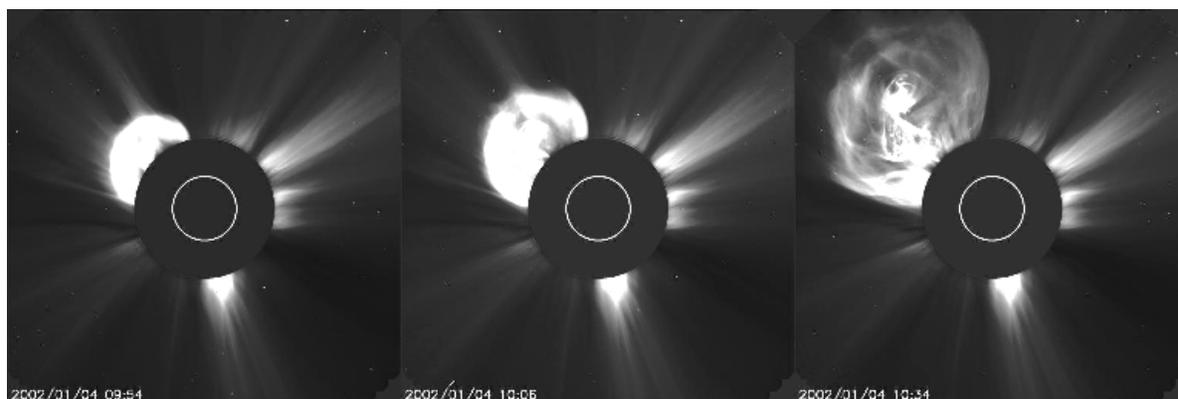


Fig. 2.— LASCO C2 images of the CME on January 4, 2002 associated with the prominence eruption.

the lifting $H\alpha$ filament (Figure 1, indicated by the arrow). Asterisks in Figure 3 show the filament’s height, speed and acceleration as measured from the EIT images. A magnetic loop, which overlays the filament, is clearly seen in the EIT difference image (Figure 4, 09 : 12 – 09 : 00UT). During the ascending phase the overlaying loop was pushed up and expanded.

09:15 UT – The first two compact $H\alpha$ and EIT brightenings occurred in the region.

09:20 UT – Part *B* begins to ascend.

09:22 UT – Additional $H\alpha$ brightenings and ribbons rapidly occur in the region.

09:48 UT – Two sets of curved magnetic field lines, seen in the $H\alpha$ and the EIT images against the sky, appear on either side of the erupted filament channel (Figure 1, image at 09:48 UT and Figure 4).

09:54 UT – The first appearance of the CME in the LASCO/C2 field of view (Figure 2). Diamonds in Figure 3 show the CME’s height, speed and acceleration as measured from the LASCO images. The CME may be classified as a fast CME. It propagates across the LASCO C2 field of view with a high ($> 1000 \text{ km s}^{-1}$) speed and a constant acceleration.

10:00 UT – The first signs of a newly formed post-flare loop system, seen in the EIT 195\AA images. The curved field lines are still visible above the post flare loop system.

11:01 UT – The curved field lines are, by this time, fading away in the EIT 195\AA difference images (Figure 4, 11 : 01 – 10 : 51 UT). The post flare loop system reaches the height

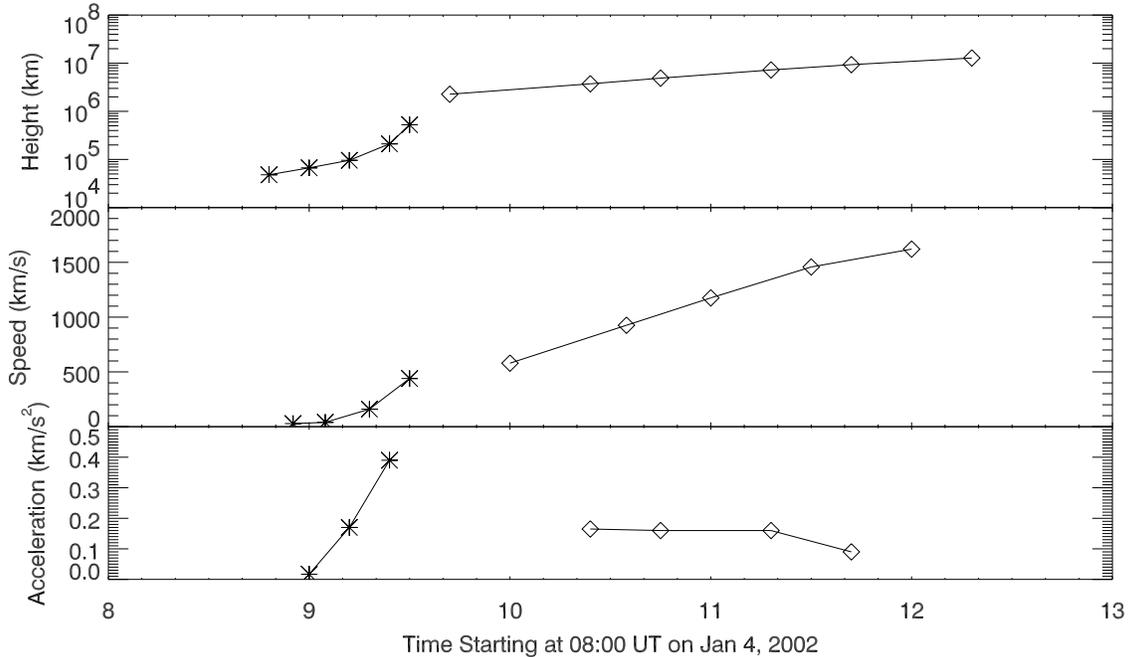


Fig. 3.— Plots showing height, speed and acceleration measured for the prominence (asterisks, EIT data) and for the CME (diamonds, LASCO C2 data).

of about 80,000 km above the photosphere. However, it is never detected in the $H\alpha$ images.

4. Discussion and Conclusions

In general, our observations favour the flux rope model (Van Tend and Kuperus 1978; van Ballegoijen and Martens 1989; Forbes and Isenberg 1991; Kumar and Rust 1996; Wu et al., 1999; Amari et al. 2000). The $H\alpha$ and EIT data studied here convincingly show that the flux rope existed before the eruption. Below we list and discuss several key points in the data, which strongly support the above conclusion.

1. *Preflare configuration:* It is generally accepted that the three part structure of a CME consists of a magnetic flux rope (cavity) with a prominence sitting at the bottom (bright core), which is surrounded by a bright shell which represents a stretched closed magnetic loop. On the other hand, there are observations which demonstrate the three-part structure in pre-erupting streamers (Sime, Fisher and Mickey 1988; Sime and Streete 1993; Tandberg-Hanssen 1995; Low and Hundhausen 1995). The flux-rope model provides

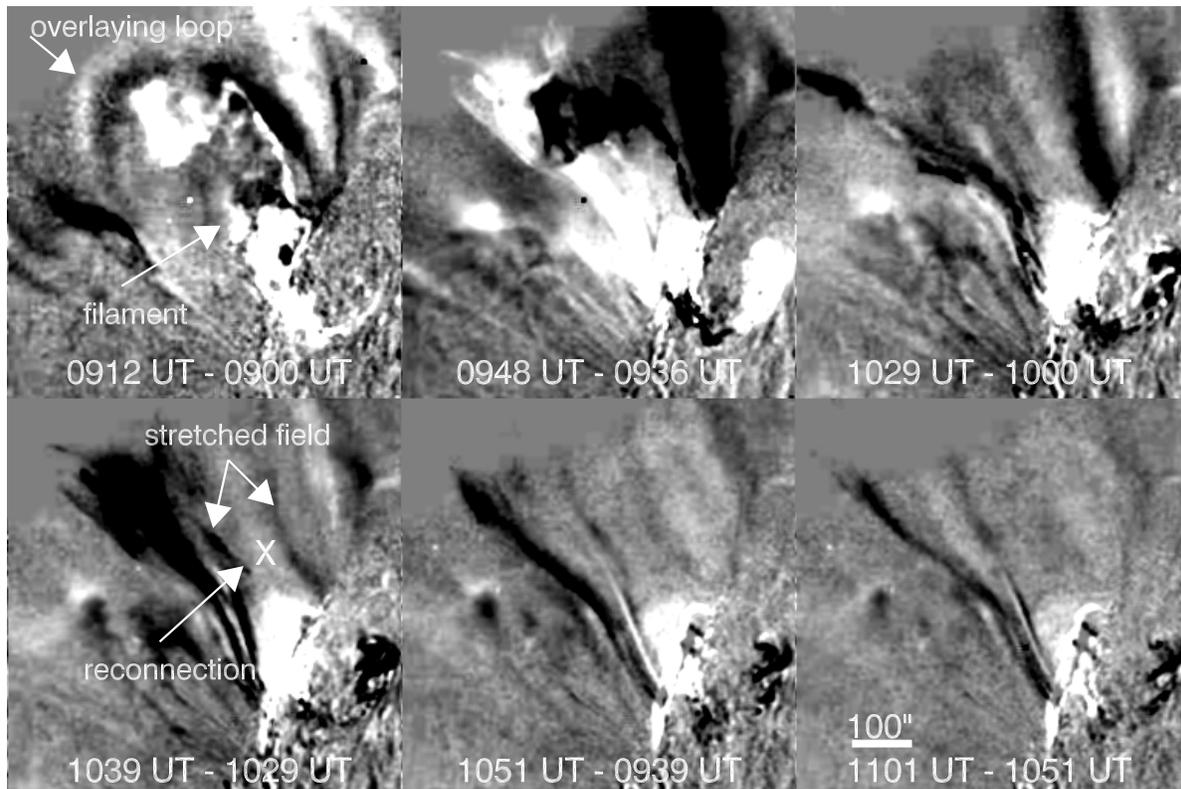


Fig. 4.— EIT difference images showing the overlying loop (the 09 : 12 – 09 : 00 UT image) and the stretched field lines (the 10 : 39 – 10 : 29 UT image).

the simplest explanation for the existence of a three-part structure in the pre-erupting configuration (Low 2001). The 09 : 12 – 09 : 00 UT difference image (Figure 4) also shows a three-part structure prior to the eruption, which we interpret as the presence of a twisted flux rope in the pre-erupted magnetic configuration.

2. *Eruption first, reconnection second:* The $H\alpha$ and EIT images of the erupting filament show that two compact brightenings occurred at 09:15 UT, well after the filament began to ascend (09:00 UT). The filament activation and ascension started about 15 minutes before the first visible release of energy, which implies that a flux rope was formed prior to the eruption. Generally, flare emissions associated with a reconnection process may occur at the onset of an event. However, if any such emissions do exist in our case, they must be associated with a release of energy which is quite small and less than that associated with a microflare. Note, that, according to the break out model for CMEs, one would expect the opposite sequence of events: the $H\alpha$ and/or EIT brightenings are expected to occur first, followed by the eruption (Sterling and Moore 2001; Sterling et al. 2001). The flux rope is seen in the 09:12 UT $H\alpha$ image, before the $H\alpha$ and EIT brightenings, which is

demonstrated by striations that are concaved outward at the bottom part of the ascending prominence (feature *A*). These striations are also evidence that the prominence is situated at the bottom part of a twisted flux rope.

We further interpret our data in the framework of the standard flare model. Due to a MHD instability, the central part of a twisted flux tube, that is overlaid by a magnetic arcade, may begin to rise by the displacement of the field lines of the arcade (see Figure 2 in Sturrock 1989). The rising filament pushes the overlaid arcade up into the corona and stretches its field lines. As the eruption proceeds, the inner stretched field lines reclose via reconnection beneath the lifting filament. During this process, the stretched field lines are compressed and move toward the vertical current sheet (Shibata et al. 1995), where they reconnect to form apparently growing post flare loops. We would like to point out that only two components of that model – the filament eruption and the post-flare loop system – are normally seen in solar data. Sometimes cusp-like structures are observed in long duration events (Tsuneta et al. 1992). However, images of the overlaying loops and/or stretched field lines are very rare and incomplete due to the low density of the corona.

Due to this lack of data from the corona, various ideas have been discussed as to what is the pre-eruption magnetic configuration and how a flux rope is formed. We have already discussed the images showing the overlaying magnetic loops. Next, we would like to point out the $H\alpha$ and the EIT 195Å data which shows the stretched field lines just above the post flare loop system. In the 10:39 - 10:29 UT difference image in Figure 4, two sets of slightly curved magnetic field lines can be seen, which we interpret as the vertically stretched field lines being compressed horizontally near the reconnection site, which is marked with an "X" in Figure 4 (see also the sketch in Figure 1 in Shibata et al. 1995; Yokoyama et al. 2001). The height of the reconnection site is about 80,000 km.

Finally, we would like to point out that, in spite of the fact that our data supports the idea that the flux rope is formed prior an eruption, we do not exclude the possibility that other mechanisms are also operating in the solar atmosphere and are responsible for producing CMEs.

5. Acknowledgement

We thank T. J. Spirock for carefully proofreading this manuscript and offering critical comments. We are also thankful to anonymous referee valuable comments and remarks. This work was supported by ATM-0076602, ATM-9903515 and NASA (NAG5-9682) grants. SOHO is a project of international cooperation between ESA and NASA.

REFERENCES

- Amari, T., Luciani, J.F., Mikic, Z., and Linker, J., 2000, *ApJ*, 529, L49.
- Antiochos, S.K., 1998, *ApJ*, 502, L181.
- Antiochos, S.K., DeVore, C.K., and Klimchuk, J.A., 1999, *ApJ*, 510, 485.
- Brueckner, G.E., et al. 1995, *Sol. Phys.*, 162, 357.
- Delaboudiniere, J.-P., et al. 1995, *Sol. Phys.*, 162, 291.
- Dere, K.P., Brueckner, G.E., Howard, R.A., and Michelis, D.J., 1999, *ApJ*, 516, 465.
- Forbes, T. G., and Isenberg, P. A., *ApJ*, 373, 294.
- Kumar, A., and Rust, D.M., 1996, *JGR*, 101, 15667.
- Low, B.C., and Hundhausen, J.R., 1995, *ApJ*, 443, 818.
- Low, B.C., 2001, *JGR*, 106, A11, 25141.
- Moore, R.L., and LaBonte, B., 1980, in *IAU Symp. 91, Solar and Interplanetary Dynamics*, ed. M. Dryer and E. Tandberg-Hanssen (Boston: Reidel), 207.
- Sime, D.G., Fisher, R.R., Mickey, D.L., 1988, *ApJ.*, 333, L103.
- Sime, D.G., and Streete, J., 1993, *ApJ*, 408, 368.
- Shibata, K., Masuda, S., Shimojo, M., Hara, H., Yokoyama, T., Tsuneta, S., Kosugi, T., and Ogawara, Y., 1995, *ApJ*, 451, L83.
- Steiniger, M., Denker, C., Goode, P.R., Marquette, W.H., Varsik, J., Wang, H., Otruba, W., Freislich, H., Hanslmeier, A., Luo, G., Chen, D., Zhang, Q., 2000, in *Proc. 1st SOLSPA Euroconference “The Solar Cycle and Terrestrial Climate”*, ESA SP-463, 617.
- Sterling, A.C. and Moore, R.L., 2001, *ApJ*, 560, 1045.
- Sterling, A.C. and Moore, R.L., Qiu, J., and Wang, H., 2001, *ApJ*, 561, 1116.
- Sturrock, P.A., 1989, *Solar Phys.*, 121, 387.
- Tandberg-Hanssen, E., 1995, *The Nature of Solar Prominences*, Kluwer Acad., Norwell, Mass.
- Tsuneta, S., Hara, H., Shimizu, T., Acton, L.W., Strong, K.T., Hudson, H.S., and Ogawara, Y., 1992, *Publ. Astron. Soc. Japan*, 44, no. 5, L63.
- van Ballegoijen, A. A., and Martens, P. C. H., 1989, *ApJ*, 343, 971.
- Van Tend, W., and Kuperus, M., 1978, *Solar Phys.*, 59, 115.
- Wu, S. T., Guo, W. P., Michels, D. J., and Burlaga, L.F., 1978, *Solar Phys.*, 59, 115.
- Yokoyama, T., Akita, K., Morimoto, T., Inoue, K., and Newmark, J., 2001, *ApJ*, 546, L69.
- Yurchyshyn, V.B., Wang, H., Goode, P. R., and Deng, Y., 2001, *ApJ*, 563, 381.