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OBSERVATIONAL EVIDENCE OF A MAGNETIC FLUX ROPE ERUPTION ASSOCIATED WITH THE X3 FLARE ON 2002 JULY 15

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ABSTRACT

We present the study of an eruption from the low solar atmosphere (photosphere/chromosphere) as seen in *Transition Region and Coronal Explorer* 1600 Å images and with the *Solar and Heliospheric Observatory* Michelson Doppler Imager. The eruption reached its maximum at 20:08 UT on 2002 July 15 in the NOAA Active Region 10030 (N19°, W01°), accompanied by an X3 flare and followed by a fast-halo coronal mass ejection. The main observational results from the data are as follows: (1) the erupting plasma was in a rapidly rising, twisted ropelike structure; (2) the eruption occurred just preceding the onset of its driven flare; and (3) the morphology and magnetic flux of one slender footpoint (~9000 km in length) of the rope developed rapidly on the photosphere. This structure disappeared in white light and in the magnetograms within 60 minutes. This evidence supports the erupting flux rope model. Our data favor the idea that a catastrophic loss of MHD equilibrium can be the primary driving mechanism for the rapid ejection of a flux rope. This conclusion is based on the judgment that the ambient fields of the flux rope were partly opened as a result of the magnetic reconnection.

Subject headings: Sun: coronal mass ejections (CMEs) — Sun: flares — Sun: magnetic fields

1. INTRODUCTION

Magnetic flux rope eruption is an important topic in solar terrestrial research since it is associated with coronal mass ejections (CMEs) that inject large amounts of magnetic flux as well as mass into interplanetary space. CMEs play a central role in the solar terrestrial environment. In addition, successive CMEs can also play important roles in the evolution of the solar corona in the course of an 11 yr cycle (Low 2001; Zhang & Low 2001). Some evidence supports the existence of a magnetic flux rope and its eruption (Kurokawa et al. 1987; Chen et al. 1997; Foley et al. 2001; Yurchyshyn 2002). But the observation of the triggering mechanism for flux rope eruption is rare.

There are several approaches to explain the magnetic flux rope–driven mechanisms. The twisted flux rope model (Amari et al. 2000) and the flux injection–driven model (Krall, Chen, & Santoro 2000; Krall et al. 2001) both suggest that a twist-enhanced flux rope can play a crucial role in a large-scale eruption event. Another approach is based on the idea that the primary mechanism for driving an eruption is a catastrophic loss of MHD equilibrium (see Lin & Forbes 2000, Low 2001, and references therein; Roussev et al. 2003). The failure to confine the cavity flux rope will result in a flux eruption or a CME. Lin & Forbes (2000) found that the flux rope will be allowed to escape with a fairly small reconnection rate in the vertical current sheet created below. Magnetic flux cancellation can modify the line-tying condition for the flux rope and transport the magnetic complexity upward (Moore & Roumeliotis 1992). Also, the drainage of plasmas from a prominence is one possible cause for the flux rope to be accelerated (Tandberg-Hanssen 1974; Gilbert et al. 2000). Low & Zhang (2002) gave an interesting flux rope eruption model for fast CMEs, in which a flux rope is in a specific slingshot field topology.

For a long time, people have investigated the evolution of photospheric magnetic fields during a major flare and CME. About two decades ago, Poland & MacQueen (1981) presented an intriguing observation demonstrating a large-scale weakening of the photospheric magnetic flux before a CME erupted out of a helmet streamer, but they found no clear evidence of an association with one particular photospheric feature of this streamer. Recently, Wang et al. (2002) presented a rapid disappearance of a sunspot associated with an M2.4 flare. What is interesting in their work is that the disappearance of its magnetic flux was closely connected to the *Reuven Ramaty High Energy Solar Spectroscopic* Imager hard X-ray observations.

In this study, we present an eruption observed by *Transition Region and Coronal Explorer* (*TRACE*) 1600 Å image sequences in a high cadence of 1–2 s that provide us with important clues for answering what can trigger the onset of an erupting flux rope originated from the lower solar atmosphere (photosphere and chromosphere). This event was associated with an X3 flare and a subsequent fast, violent halo CME shown in the *Solar and Heliospheric Observatory* (*SOHO*) Large Angle and Spectrometric Coronagraph (LASCO). We will analyze this case, with an emphasis on the cause of the catastrophic behavior of the flux rope, and present the corresponding photospheric evolution.

2. OBSERVATIONS AND DATA

The eruption and its accompanied X3 flare on 2002 July 15 occurred in the NOAA Active Region 10030, which was located close to the center of the solar disk (N19°, W01°). The *GOES* soft X-ray (SXR) light curve peaked at about 20:08 UT. This region was in a complicated magnetic morphology (Fig. 1). Full-disk Hα observations show that a large loop system connecting the outer main sunspots P1 and F1 dominated this active region. Another main sunspot (P), together with sunspot f and other small pores nearby, were in the middle of the active region. It was suggested that in such a magnetic morphology, the external magnetic field can be disturbed by internal eruption or reconnection (Moore et al. 1999).

We used (1) high-cadence UV data from *TRACE* 1600 Å

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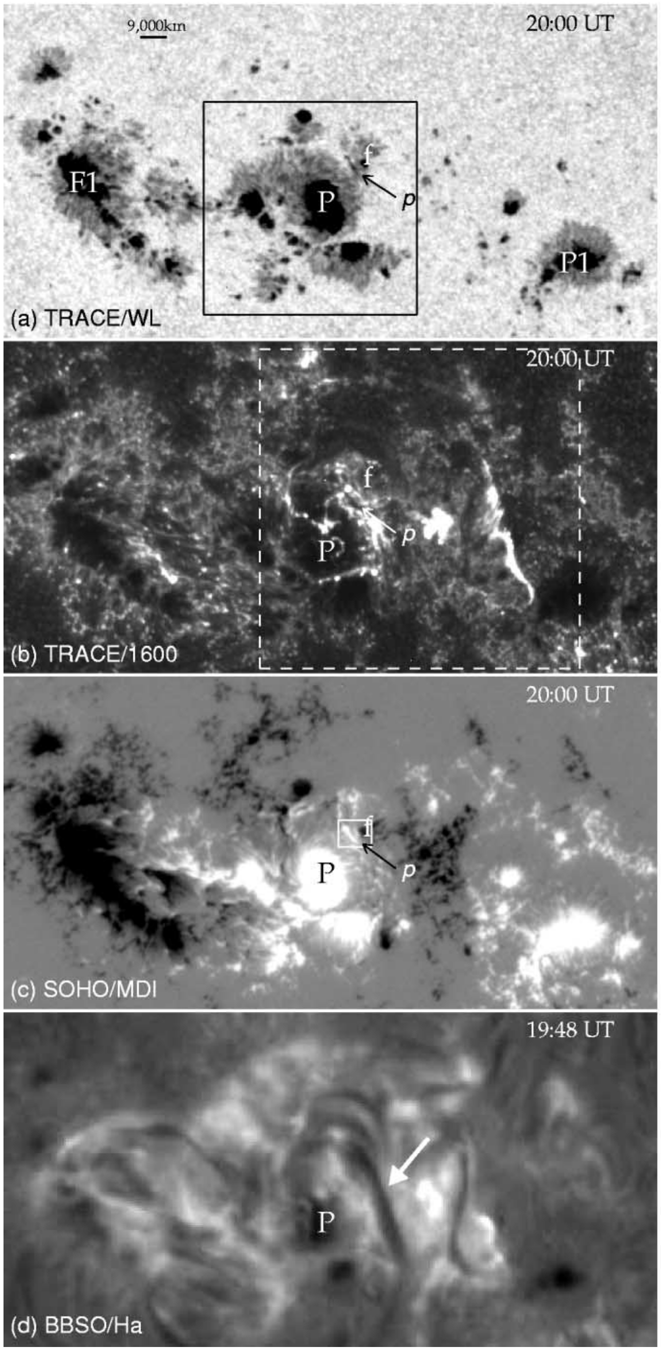

FIG. 1.—Comparison between (*a*) intensity map, (*b*) UV (1600 Å) image, (*c*) magnetogram, and (*d*) Hα image around the beginning of the X3 flare. Their fields of view are the same. The small white box in (*c*) indicates the magnetic field region with rapid changes.

observations (1 frame per second). The 1600 Å channel has a temperature sensitive range of (4.0–10) $\times$ 10^3 K (Handy et al. 1999) and is more sensitive to a higher temperature. We used (2) high-resolution data from the Michelson Doppler Imager (MDI; 0″.626 pixel^{-1}, 1 frame per minute), including the longitudinal magnetic field and Doppler velocity. We used (3) *TRACE* 5000 Å white-light images (0″.5 pixel^{-1}), which can be used to co-align the data of *TRACE* and MDI. We used (4) full-disk Hα images from the Global High-Resolution Hα Network (Steinegger et al. 2000). A filament as a sign for a

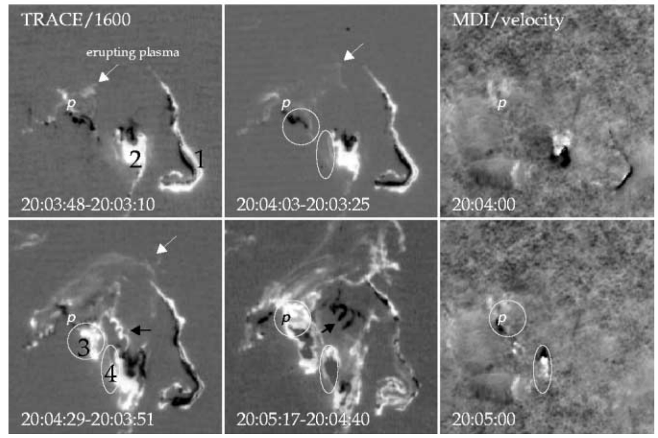

FIG. 2.—Development of the magnetic flux rope in 2 minutes. *Left and middle panels*: Running difference images. *Right panels*: MDI velocity maps. The flares ribbon are marked with numbers 1–4. The regions in circles and ellipses demonstrate the evolution of the driven flare. The white arrows point to the expanding frontier of the plasma, and the black arrows to the twisted structures. The field of view is correspondent to the area of the dashed white box in Fig. 1*b*.

flux rope, existing in the middle west of the active region, was obvious from the Hα images before and after the flare.[6]

3. RESULTS

Figure 1 shows the morphology of the entire active region at the beginning of the X3 flare in different wavelengths. P1 and F1 formed a bipolar system, which can be judged from the fibrils connecting them in the full-disk Hα images. P was a main sunspot in a positive magnetic field; it formed a δ-configuration with a small negative spot f. Inside of the highly sheared magnetic neutral line of this δ-configuration, there was a slender penumbra-like structure arrowed with *p*. A filament along the neutral line is obvious in the Hα (Fig. 1*d*, *arrow*), with *p* located around its north terminal; *p* was also a low-emission region in Figure 1*b* (a 1600 Å image from *TRACE*). Two flare ribbons were developing on the western side of the active region.

According to the movie[7] made from *TRACE* 1600 Å difference images, although the eruption was complicated, it is certain that there were double compact flares (19:59–20:08 UT) that successively broke out before the peak of the SXR flux (20:08 UT). The ribbons of the two flares occurred at different locations and moved in different directions. The eastern (left) ribbon of the first flare, as shown in Figure 1*b*, was a very compact one compared with the western (right) long ribbon. On the contrary, the second flare spread its two compact ribbons just along the direction of the neutral line. One ribbon was around *p*, and the other was in the southwest end of the neutral line.

Figure 2 displays the rapid development of the eruption during a period of 2 minutes. Hot plasma emissions were seen rising up over the magnetic neutral line at a high speed. The white arrows in the difference images (*left and middle panels*) show the sites of the frontier of the erupting plasma. The area around *p* was the initial site for the eruption. The right panels give velocity measurements from MDI. It should be noted that at the initiation of the eruption, there was no obvious brightening enhancement at *p* (some places nearby even got dimmer);

[6] See these images at the Global High-Resolution Hα Network, http://www.bbso.njit.edu/Research/Halpha.

[7] See the movie rope.avi at http://sun10.bao.ac.cn/staff/lyu.

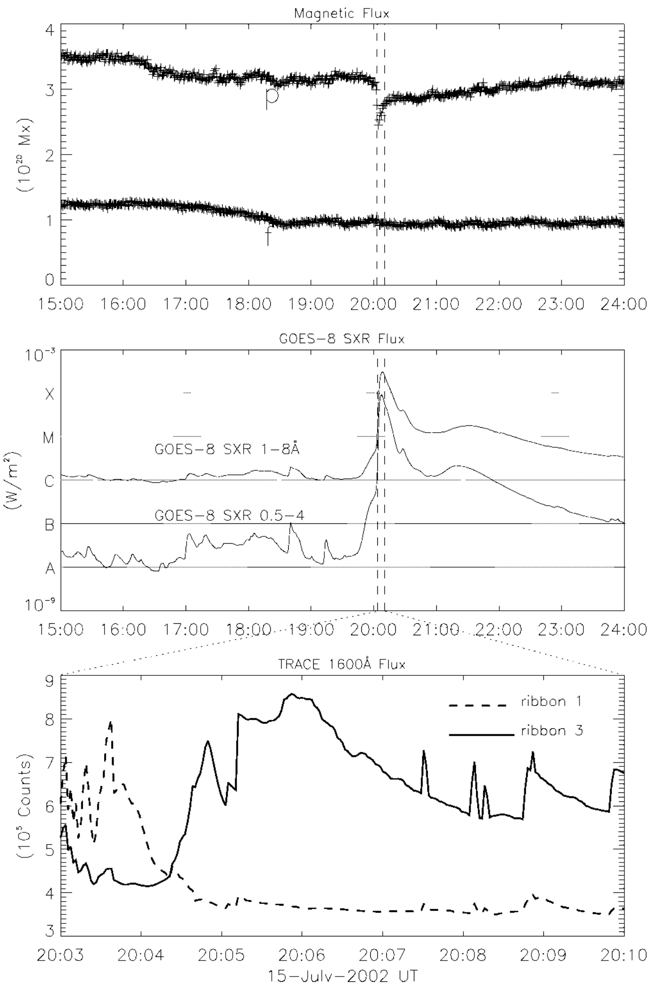

FIG. 3.—*Top panel*: Evolution of the magnetic flux of the slender "filament" (i.e., *p* arrowed in Fig. 1) and the neighboring area (i.e., *f* in Fig. 1). Note that we plot the absolute values for the negative flux of *f* for convenience. *Middle panel*: *GOES* SXR flux profile as a function of time. The two vertical dashed lines indicate the period (20:03–20:10 UT). *Bottom panel*: Average *TRACE* 1600 Å flux profiles for flare ribbons during the period indicated in the top and middle panels.

therefore, there is no direct evidence of driving the eruption from below. The white circles and ellipses outline two new flare ribbons that followed the plasma eruption at 20:04:29 UT. In the hump of the curvy erupting frontier, several strands of flaring plasma were moving upward in an upper right direction. An obvious twisted fine structure in the plasma is exhibited by the black arrows in this figure. It is interesting that the velocity map at 20:04 UT clearly illustrates the first flare with its ribbons (marked 1 and 2), while the one at 20:05 UT reflects an instance of the second flare with its compact ribbons (marked 3 and 4).

We show in Figure 3 the magnetic flux evolution in the small rectangular area in Figure 1*c*, *GOES* SXR flux profiles, and *TRACE* 1600 Å flux profiles. Two parallel vertical dashed lines indicate the important period (20:03–20:10 UT). It is shown that coinciding with the impulsive rise of the SXR flux, the positive magnetic flux impulsively fell down. This change of magnetic field should be credible since it was irreversible in the following 2–3 hr. The total loss of magnetic flux of *p* during the eruption was about 0.3×10^{20} Mx, nearly 10% of the total flux in the box. On the other hand, the negative flux in this rectangular region was almost kept at the same level in the impulsive phase.

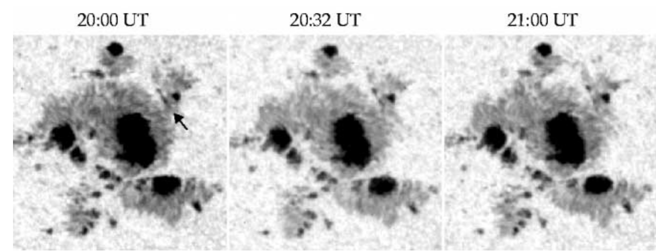

FIG. 4.—Time sequence of *TRACE* intensity images showing the rapid evolution of the slender filament *p* (*arrow*). The field of view is corresponds to the area of the black box in Fig. 1*a*.

We also note that the fluxes in *p* and f showed a slightly smooth decrease long before the eruption, implying a slow flux cancellation between them. Since there were two flares that successively broke out in the active region, then it is necessary to make it clear which was the dominant one during the eruption. The average flux evolutions of ribbon 1 and ribbon 3 are compared in the bottom panel of Figure 3. It is obvious that the second flare (along the neutral line) was the main factor that had caused the impulsive rise of the SXR flux. When this flux in ribbon 3 reached its peak at 20:06 UT, the flux in ribbon 1 had already fallen down to its lowest level after peaking at 20:03 UT.

Corresponding to Figure 3, Figure 4 demonstrates the evident evolution of *p* in 60 minutes in a sequence of *TRACE* intensity images. It can be seen that this structure was cut to be two parts from the middle after the eruption and that its southwestern half gradually disappeared before 21:00 UT. The magnetic flux profiles indicated in Figure 3 have been described above. Obviously, *p* was an important object for us to understand the ejecting event.

In summary, the complicated eruption (19:59–20:08 UT) can be divided into two short stages: Before 20:04 UT, a flare occurred with two ribbons (1 and 2 in Fig. 2) at the west side of the magnetic neutral line, and soon after 20:04 UT, a dominant flare broke out with two ribbons (3 and 4) running along the neutral line, preceded by the violent ejection of plasma. The main observational results are as follows: (1) The erupting plasma was in a rapidly rising ropelike structure. Some evidence of the twisted structures is shown by the black arrows in Figure 2. (2) The eruption occurred preceding the onset of its driven flare (the second flare), which consequently caused the impulsive rise of the *GOES* SXR flux. (3) The morphology and magnetic flux of one slender structure (*p*) developed rapidly on the photosphere, fading in white light associated with the magnetic flux dropping steeply and irreversibly within 60 minutes. The observational evidence strongly supports the erupting flux rope model. In this case, *p* is thought to be one of the footpoints that drag the flux rope at the coronal base because *p* was located around the northern terminal of the filament, and the flux rope should be confined by the overlying field lines of the bipolar structure (P1 and F1).

The process of the eruption on 2002 July 15 can be well explained in Figure 5, which briefly represents three important developing phases. Before its erupting, the flux rope of the twisted field was in a relatively stable equilibrium (Fig. 5*a*). Along with the expansion of the field lines of the δ-configuration, P and f, a strong current sheet was generated (labeled X in Fig. 5*b*). Rapid reconnection in the current sheet decreased the confining force on the flux rope, resulting in a loss of MHD equilibrium (Fig. 5*c*). Thus, the first flare in the west of the active region partly opened the arcade fields, and this was thought to

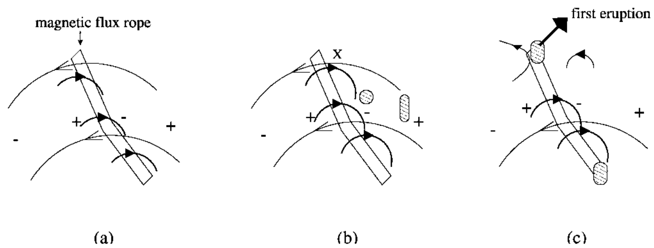

FIG. 5.—Cartoon demonstrating a possible model to explain the observations. (*a*) Before eruption, a flux rope was confined near the photosphere; (*b*) the current sheet was generated; and (*c*) the magnetic flux rope began to erupt as the overlying fields were partly opened. The flare ribbons are denoted by the hatched areas.

be the trigger for the subsequent rapid eruption. The long ribbon 1 and the compact ribbon 2 came into being at the west of the neutral line. The highly sheared core fields (P, f, and the flux rope) broke out and reconnected with the overlying unsheared fields. Therefore, the compact ribbons 3 and 4 of the second flare were almost on the neutral line.

4. CONCLUSION AND DISCUSSION

In this Letter, we present rarely observed evidence of a magnetic flux rope erupting, seen in *TRACE* 1600 Å images in a cadence of 1–2 s. Since we observed no breakout in the high atmosphere from other space instruments (the EUV Imaging Telescope and LASCO) before this eruption seen from *TRACE*, we believe that the source region of the eruption is low. The flux rope eruption, associated with a consequent X3 flare on 2002 July 15 in NOAA AR 10030 when it was on the central meridian of the solar disk, was clearly demonstrated with the *TRACE* 1600 Å movie. This flux rope, harboring along the highly sheared magnetic neutral line in a δ-type magnetic configuration, rooted its northern terminal at a slender penumbra-like structure (~9000 km in length) that divided two oppositive sunspots on the photosphere. Around the location of this penumbra-like structure, the eruption was associated with substantive changes in photospheric magnetic flux and white-light morphology.

Double compact flares broke out in 2 minutes during the flux rope eruption. Based on the observations, we deduce that the early flare was driven by the explosion of sheared fields in the initially closed δ-dipole, and later by the breakout of the core fields including the flux rope and the dipole. Because the first flare had partly opened the overlying fields confining the flux rope, an MHD instability must be introduced into the entire rope system. We think that this event provides us with good observational evidence of the flux rope eruption because of the partial opening of overlying field.

Similar to the rapid disappearance of a sunspot presented by Wang et al. (2002), the footpoint (*p*, arrowed in Figs. 1 and 4) also obviously changed in association with the onset of the eruption: it faded in a white-light continuum in 60 minutes, and its total magnetic flux dropped steeply and irreversibly. As suggested by previous studies (Martin & Livi 1992; Jiang & Wang 2001; Kim et al. 2001), the slow flux cancellation between spots f and *p* may play a role in the trigger of the eruption by modifying the line-tying condition for the flux rope and transporting the magnetic complexity upward. But in this event, although flux cancellation was involved, we cannot find any satisfactory negative flux change corresponding to the positive footpoint *p*, which is seemingly contradictory to the condition in Maxwell's law that the total magnetic flux in one closed system should be kept zero ($\nabla \cdot B = 0$). This puzzling result maybe due to the limited resolution of the magnetic field observation. For example, the opposite magnetic flux for *p* could exist in a wider area with a weaker intensity. In fact, high-quality white-light observations with an excellent resolution of less than 100 km had revealed that the tiny compact structure–like filament *p* could have abundant fine structures as well as complicated dynamic characters (Scharmer et al. 2002). These high-quality data may help us to search for the answer to the unbalance of flux evolutions during solar eruptions.

Observations have shown the well-known three-part structure for CMEs: a bright leading edge, a dark cavity, and a bright core (Illing & Hundhausen 1986). But the precise relationship between these substructures and the twisted flux rope is not clear. The initiating stage of the flux rope eruption may be an important period for the formation of the substructures. Undoubtedly, high-resolution observations around the fine structure of the flux rope as well as the magnetic morphology under it will be the key to this problem.

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