Initiation of Solar Eruptions

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Abstract.
    We consider processes occurring just prior to and at the start of the onset of flare- and CME-producing solar eruptions. Our recent work uses observations of filament motions around the time of eruption onset as a proxy for the evolution of the fields involved in the eruption. Frequently the filaments show a slow rise prior to fast eruption, indicative of a slow expansion of the field that is about to explode. Work by us and others suggests that reconnection involving emerging or canceling flux results in a lengthening of fields restraining the filament-carrying field, and the consequent upward expansion of the field in and around the filament produces the filament's slow rise; that is, the reconnection weakens the magnetic "tethers" ("tether-weakening" reconnection), and results in the slow rise of the filament. It is still inconclusive, however, what mechanism is responsible for the switch from the slow rise to the fast eruption.

1. Introduction

Solar eruptions are due to an explosive release of magnetic energy stored in a relatively confined region of the solar atmosphere. This energy release occurs where the photospheric magnetic field switches polarity, a magnetic "polarity inversion line." Filaments often form in the low corona along these inversion lines and are ejected with the eruption of the field, a factor that we can utilize to explore the evolution of the field toward eruption. Although we cannot observe directly the erupting coronal field itself, we can frequently observe and follow motions of the filament material entrained in that field throughout the pre-eruption and eruption process. That is, we can use the filament observations to trace the evolution of a portion of the field that erupts. Over the past several years we have been applying this technique to several eruptions in an effort to understand the field evolution immediately before and during eruption (Sterling, Moore, & Thompson 2001b; Sterling & Moore 2003, 2004a,b, 2005; Sterling, Harra, & Moore 2007; Sterling et al. 2007). Here we present a summary of some of our findings, along with contextual discussion of other workers, with a focus of the behavior of the field just prior to rapid-eruption onset.

2. Filament Motions: Slow-Rise and Fast-Rise Phases

Work by us, and others (e.g., Tandberg-Hanssen et al. 1980; Kahler et al. 1988; Feynman & Ruzmaikin 2004) shows that filaments frequently undergo a relatively slow rising motion ("slow-rise phase") prior to rapid eruption (which we refer to as a "fast-rise phase" or the "fast eruption"). The switch from slow to fast rise can be abrupt (e.g., Sterling, Moore, & Thompson 2001b; Sterling & Moore 2004a) or relatively smooth (e.g., Sterling & Moore 2004b), while other events show no obvious slow-rise phase (e.g., Kahler et al. 1988). We found that for eruptions occurring in quiet regions, where field strengths tend to be relatively weak, the slow-rise-phase filament velocities are generally ~ 1 km s^{-1}, and in the early stages of the fast rise the velocities are $\gtrsim 10$ km s^{-1}. In active regions, where field strengths are greater, these velocities are both about a factor of five to ten times larger. (Most of our values are based on measurements of movements projected against the solar disk, and so radial velocities away from the Sun will be a few times higher, but the ratio of the velocities during the slow-rise and fast-rise phases should be about the same for both the projected measurements and de-projected estimates.) Similarly, the duration of the slow rise depends on the eruption region, with quiet-region slow rises lasting six hours or longer in some cases (Sterling & Moore 2004a; Sterling, Harra, & Moore 2007), while active region eruptions may have a well-defined slow rise lasting only tens of minutes (Sterling & Moore 2005).

More than the filament alone, however, is undergoing these pre-eruption motions; rather, we also see evidence that a more extensive magnetic structure is involved. Observations of intensity changes in EUV and soft X-rays (SXRs) during in an event studied by Sterling & Moore (2004a) show that the filament-holding channel of sheared field along the polarity inversion line undergoes a relatively subtle "dimming" during the slow-rise phase, prior to a much-more-prominent dimming beginning with onset of the fast-rise phase. Similar features were seen in the event studied by Sterling, Harra, & Moore (2007). This is consistent with the field containing the filament rising with the filament, with the weak dimming resulting from a density decrease as the field expands outward. Then, strong dimming occurs when the field opens as the rapid eruption takes place. Perhaps more direct evidence of the movement of an extensive field containing the filament is from observations of "coronal cavities" (Tandberg-Hanssen 1974; Hudson et al. 1999; Gibson & Fan 2006, and references therein) erupting along with the filaments in two cases presented by Sterling & Moore (2004b) (see also Yurchyshyn 2002). These cavities are magnetic bubbles or flux ropes that contain the filament, and the entire structure rises with the filament during the pre-eruption phase, and accelerates outward essentially together with the filament during the fast-rise phase (Sterling & Moore 2004b). Indeed, there is evidence that larger-scale coronal structures, probably closed field areas overlying the coronal cavities, also undergo a pre-eruption expansion prior to fast eruption. These structures, including both the cavities and the overlying field, become an integral part of coronal mass ejections (CMEs) (Hiei et al. 1993; Zhang et al. 2001).

There are other long-observed pre-eruption "filament activation" phenomena (e.g., Tandberg-Hanssen 1974; Zirin 1988; Wiik et al. 1997), but it is not yet clear how these relate to the upward motions of the filament in the slow-rise

phase. Finally, many filaments also show rising motions over a much longer period than the slow-rise phase we described here; for sake of differentiation from our slow rises, here we will call these longer-period rises "evolutionary rises." Zirin (1988) says that filaments rise over several days, erupting within 48 hrs after reaching 50,000 km. Martin (2006) also found that the evolutionary rises can last for several days, with the filaments showing a steady gradual rise over that period. Several of our events also seemed to be undergoing an evolutionary rise, and then show an increase in the rise velocity when the "slow rise" begins.

3. Evidence for the Cause of the Slow Rise: Case Studies

We now consider three specific studies which give insight into the possible cause of the slow-rise phase of filaments.

3.1. Quiet Region Eruption of 2001 Feb 28

Sterling, Harra, & Moore (2007) discuss a large-scale ($\sim$ 300,000 km) filament that erupted from a solar quiet region. Figure 1a shows the filament in EUV from the EUV Imaging Telescope (EIT) on the *SOHO* spacecraft, and Figure 1b shows the same region in SXRs from the Soft X-ray Telescope (SXT) on *Yohkoh*. Figure 2 shows the filament's rise trajectory as a function of time, including a slow-rise phase that lasts some 6 hours, apparently not atypical for quiet region events such as this (e.g., Sterling & Moore 2004a). In both Figures 1a and 1b, box 1 shows a location where brightenings occurred, and Figure 2 shows the lightcurves from both EUV and SXRs. In EUV, these brightenings are not prominent, but in SXRs they appear as microflares that are outstanding compared to the time in between brightening episodes. At least three microflares are apparent in SXRs (although it is possible that the relatively poor time cadence of SXT conceals others), and these coincide respectively with the onset of the filament's slow rise, an inflection in the filament's trajectory, and the onset of the filament's fast rise, suggesting a connection between the microflaring and the filament's slow rise.

Strong supporting evidence for a connection between the microflaring region and the filament's motions comes from a movie of the eruption in SXRs (available in the electronic edition of Sterling, Harra, & Moore 2007), which shows the growth of an arcade of SXR loops occurring during the time of the slow-rise phase. This fan of loops stemmed from the microflaring location and arched over the filament. Moreover, the box 1 location of Figure 1, where the microflares occur, is the site of newly-emerging flux. There is no indication of this flux in MDI magnetograms as late as 20:48 UT on 2001 Feb 27, i.e., about 10 hrs prior to the start of the slow rise, and after that time the new flux grows at the box 1 location. Figure 2 plots the box 1 flux, showing that it increases substantially during the filament's slow-rise phase.

Figure 3 shows schematically our interpretation of these features. As usual, the filament and the field containing it reside above the magnetic inversion line. This filament-containing field is essentially a coronal cavity (not pictured in the schematic), and is either a flux rope or a magnetic region inflated by high shear. Overlying this filament field is a field that contains and restrains the filament field; blue lines over the filament represent this field in Figure 3. Near the
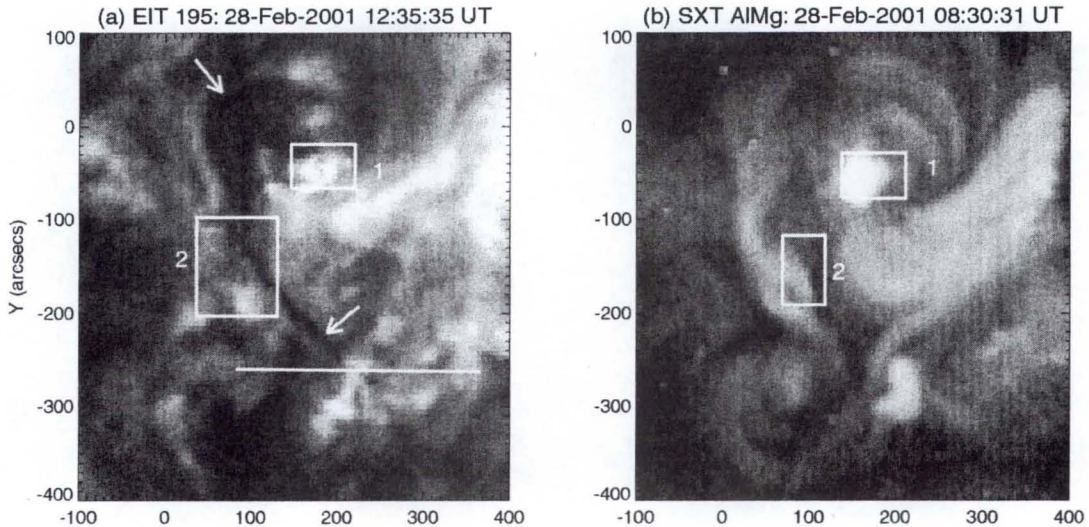
Figure 1.   *Left:* *SOHO*/EIT 195Å filter image. Arrows point to the filament, which is starting to erupt, and the horizontal line is a fiducial along which we measured the height (actually, displacement projected against the solar disk) of the filament in Fig. 2. *Right:* The same region in SXRs from *Yohkoh*/SXT. In both images, box 1 shows a region that undergoes microflaring, and box 2 is where the main flare loops develop. North is up and west is to the right.

north end of the filament at the box 1 location, new flux emerges and interacts with the filament-containing field. As shown in the schematic, the polarities for these fluxes (determined from MDI magnetograms, see Sterling, Harra, & Moore 2007), are such that the emerging and filament-containing field can interact and reconnect with each other, with the result being a lengthening of field lines that arched over the filament-containing sheared core field, allowing the filament-containing field to puff up, producing the slow rise of the filament. Moore & Roumeliotis (1992) termed the type of reconnection occurring here as "tether weakening" reconnection, and it seems to be responsible for the slow rise of the filament in this event.

3.2.   Enhanced-Network Region Eruption of 2007 Mar 2

This was the first filament eruption that we observed using data from the *Hinode* spacecraft, and we describe the results in detail in Sterling et al. (2007). The eruption occurred in a region of enhanced network field, and some of the coronal loops involved had connections extending to a nearby sunspot. We analyzed the motions of the filament in EUV images from *TRACE*. Pre-eruption motions for this event were not as well-defined as that of several of the other events that we have examined, and it had complex motions, including a twist during the fast rise that might be indicative of a kink instability (similar to an event observed by Williams et al. 2005).
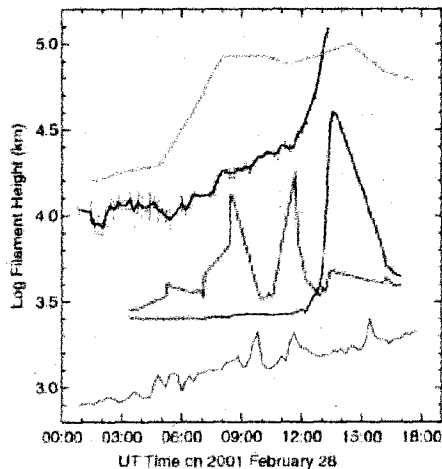
Figure 2. The black curve shows the trajectory of the filament of Fig. 1a. The red and green lines are lightcurves from respectively SXT and EIT of the microflaring region in box 1 of Fig. 1. The blue line is the SXR lightcurve from the flaring region in box 2 of Fig. 1, and the brown curve shows the time variation of the total unsigned *SOHO*/MDI magnetic flux from the region in box 1.

Portions of the filament showed slow rise motions from the earliest available *TRACE* images, about 30 min prior to fast-rise onset, while other portions showed no motion until about the time of the start of the fast rise. Tracking the moving portion shows that there was an inflection in the trajectory about 20 min prior to onset of the fast rise, and this coincided with a brightening in the *TRACE* images and flows along a newly-visible loop in those EUV images, near the site where the subsequent flare occurred. Data from the *Hinode* X-Ray Telescope (XRT) show that coincident with the pre-eruption brightening in EUV, there is a microflare brightening in SXRs from near the location where the EUV loop emanates. An SXR S-shaped "sigmoid" forms at this time, and erupts outward concurrent with the onset of the filament's fast rise and with the onset of flaring in the region. Magnetograms from the Solar Optical Telescope (SOT) on *Hinode* show that flux cancelation occurs at the base of the EUV loop, the location of the SXR microflare brightening in the birth of the sigmoid. We used MDI data to supplement the SOT magnetograms (as the latter were not yet flux calibrated as of the time of the analysis), and found that there was a drop by a factor of three in the amount of unsigned magnetic flux in the neighborhood of the converging field during the five-hour period (the cadence of the available magnetograms) prior to fast eruption.

Figure 4 shows a schematic of our interpretation of these features. Reconnection among pre-existing loops beneath the filament results in formation of the sigmoid loop, together with new loops below the reconnection point; we see
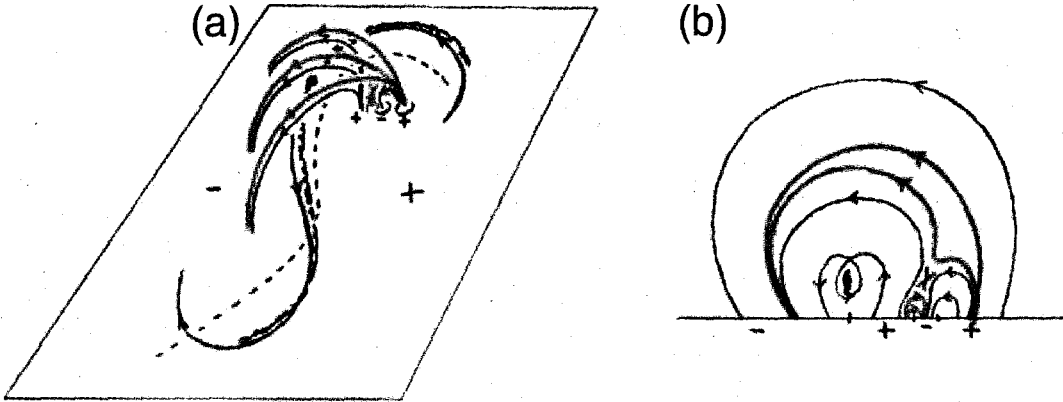
Figure 3.   Schematic drawings of the erupting region in the vicinity of the filament during the slow-rise phase of the filament of Fig. 1. (a) 3D view, with black dashed line representing the magnetic neutral line, black wavy line the filament, arched blue lines the magnetic field prior to a tether-weakening-reconnection episode, and adjacent red lines the same field slightly displaced by the reconnection episode; the red cross shows the location of the reconnection. These red field lines form a fan-like structure that arches over the filament, and is illuminated in SXRs (Sterling, Harra, & Moore 2007). (b) A cross-sectional cut of (a) at the position of the emerging flux. Blue and red lines are the same as in (a), and the filament is in the dip of a twisted field line; the tether-weakening reconnection lengthens field lines of the confining arcade, allowing the sheared core field to expand upward, resulting in the filament's slow rise.

bright features in the XRT images that coincide with where we expect these new low-altitude loops to be (Sterling et al. 2007). We expect that the filament "rides" in the field of the sigmoid as it erupts outward. Formation of the sigmoid occurs during the time of the filament's slow rise, and the SXR microflare brightening coincides with an inflection in the filament's trajectory, and so we expect that again the slow rise is a result of flux changes (flux cancelation in this case) prior to onset of the fast eruption. Examination of a XRT movie constructed from the XRT images (Sterling et al. 2007) suggests that prior to the formation of the most prominent sigmoid, there were similar but weaker SXR loops formed at earlier times, and presumably they would also be due to reconnection episodes similar to that we see evidence for here. We suspect that such earlier reconnection episodes would result in disturbances to and perhaps upward movement of the filament, but we have not verified this since *TRACE* data are not available for these earlier times.

The sigmoid we observe here is of a type discussed by Rust & Kumar (1996) and Pevtsov, Canfield, & Zirin (1996), that forms about concurrent with
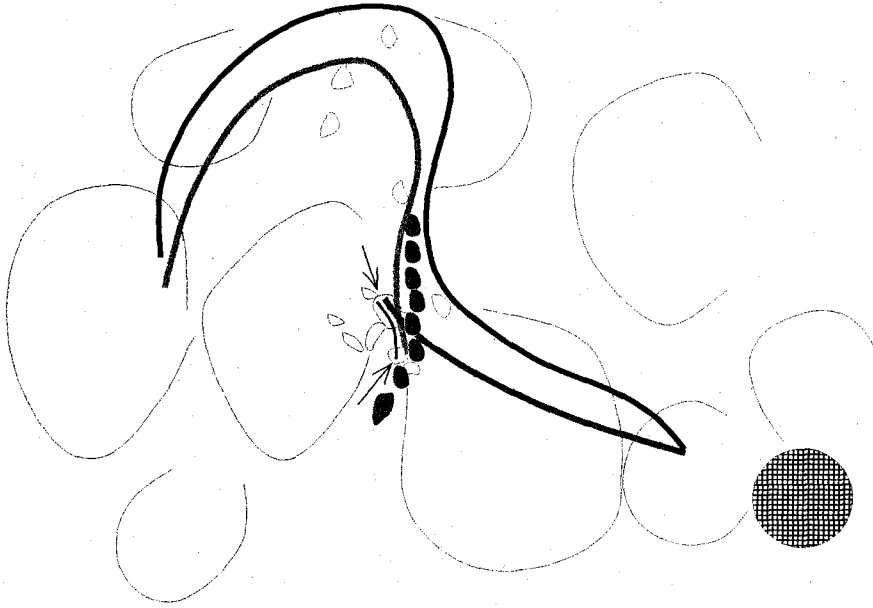
Figure 4. Schematic interpretation of the eruption of § 3.2. Red and blue contours roughly correspond to the magnetic pattern in observed in MDI and SOT FG/V magnetograms, the broken shaded feature represents the filament along the neutral line. The green field curve represents the loop seen in EUV, and the magenta curve represents a field line extending from the region around the sunspot. Magnetic reconnection between the field of the green and magenta structures results in two reconnection products: the sigmoid loop (situated above the green and magenta loops), and smaller loops that straddle the neutral line and which have footpoints indicated by the two arrows; both of these reconnection products are drawn as black lines.

eruption onset. The term "sigmoid" is also used to describe solar regions with an overall S-shape, and there has been much discussion of the propensity of such regions to erupt (e.g. Sterling et al. 2000; Canfield, Hudson, & McKenzie 1999; McKenzie et al. 2008). These types of sigmoids are likely related in that the overall shear of the region gives it an S-shape, and reconnection of adjacent separated sheared elements results in a more continuous S-shape such as that of the above papers and that which we see here (and also seen in Fig. 5 of Moore et al. 2001). This would explain why many AR sigmoids in detail appear as two overlapping reversed J's, i.e., with a break in the middle of the S rather than a continuous S (e.g., McKenzie et al. 2008). It is only after reconnection of the central field (in a symmetric case) that a continuous S-shape field forms that is visible in coronal images (e.g., Pevtsov, Canfield, & Zirin 1996).

3.3. Active Region Eruption of 1998 July 11

This eruption involved a filament in an active region, and was studied by Sterling & Moore (2005) using EUV and SXR images from *TRACE* and SXT, respectively, magnetic data from MDI, and other data. It occurred close to the solar

limb, and so it was not possible to be certain of the magnetic configuration at the time of eruption (since MDI only provides longitudinal magnetic field information). But using magnetograms from some days earlier, and insights gained from the two events discussed in the previous subsection, we can make inferences as to the nature of the mechanism for the filament's pre-eruption motions.

This filament had a slow rise that began (or entered a new phase) about 10 min prior to fast-rise onset. As with the 2001 Feb 28 event described above, coincident with the slow-rise onset there was a microflare-like brightening, in both in EUV and SXRs at this time and at the same location. Although we do not know the magnetic situation at the time of the eruption, MDI magnetograms show that new flux emerged at the location near where the eruption occurred about two days prior to the eruption itself. If we spectate that flux continued emerging, or new flux again emerged, at that location just prior to the eruption, then the resulting flux changes could have led to the slow rise of the filament in a manner similar to that proposed for the two events described above.

4. Cause of the Switch from Slow-Rise to Fast-Rise: Still Being Debated

An ultimate goal of eruption studies, of course, is to determine the cause of the onset of the fast eruption, i.e., the fast-rise phase. We have considered this question in several studies, with a focus on three specific mechanisms: "tether cutting" (Moore & LaBonte 1980; Sturrock 1989; Moore & Roumeliotis 1992; Moore et al. 2001), "breakout" (Antiochos 1998; Antiochos et al. 1999), and ideal MHD instability (Sturrock et al. 2001; Linker et al. 2001; Fan & Gibson 2004; Rust & LaBonte 2005; Gibson & Fan 2006). We discuss these in detail in Moore & Sterling (2006). So far however, our results have not been decisive in answering this question. The basic point is that observational signatures we use for all three mechanisms occur too close together in time to allow for us to differentiate between the mechanisms; signatures for all three mechanisms are not always present in all events, but this is to be expected due to normal non-ideal observing conditions. Thus, our observations allow that any of the mechanisms could be responsible for fast-eruption onset, or some combination of the mechanisms may be required.

There are other views regarding this question, however. Bong et al. (2006) report signatures of breakout occurring *after* the start of fast filament eruption. This is in contrast to other work (e.g., Aulanier et al. 2000; Sterling et al. 2001a; Gary & Moore 2004; Harra et al. 2005) that reported breakout-like signatures *before* the start of fast eruption. Our view now of this question in regard to the Sterling et al. (2001a) work is that the breakout signatures could still be evidence for breakout being the trigger for the fast eruption, but it is also possible that the breakout "signatures" are a by product of a more fundamental mechanism that is triggering the eruption. Thus at this time we hold that our work to date gives no conclusive answer to the question of the trigger for the fast-eruption onset. Williams et al. (2005) similarly concluded that a combination of mechanisms could have been responsible for the eruption of a filament that they observed. On the other hand, Chifor et al. (2007) studied several eruptions, and concluded that tether cutting was the likely cause for the fast-eruption onset.

5. Discussion

Filaments often undergo a slow rise prior to onset of rapid eruption. We conclude that, based on two well-observed events, and inferences from a third, flux changes in the form of flux cancelation or flux emergence is responsible for the slow rise of filaments prior to eruption for the events we consider. We suspect that frequently tether-weakening reconnection results from these flux changes, and the tether weakening results in the slow rise of the filament, as depicted in Figure 3. Feynman & Ruzmaikin (2004) also found an association between emerging flux and the onset of the slow rise in a filament. Our observations to date do not allow us to determine with confidence which, if any, of the mechanisms of tether cutting, breakout, or ideal MHD instability is responsible for the transition from the slow rise to the fast eruption. Results from other workers on this question are mixed, and so there is still no clear answer.

It has long been known that localized newly-emerging flux frequently plays an important role in the onset of solar eruptions (e.g., Rust 1976; Moore et al. 1984; Parker 1987), and this has resulted in emerging-flux-based theoretical models since at least Heyvaerts, Priest, & Rust (1977), and there have been many such models since (e.g, Forbes 2000; Klimchuk 2001; Chen & Shibata 2000). van Ballegooijen & Martens (1989) suggest that long-term flux cancelation can result in filament-supporting flux-tube geometries, and to the eventual destabilization and eruption of the filament; this could be what occurred in the eruptions discussed in §§ 3.2 and 3.3, and could possibly explain the evolutionary rise, the "slow-rise phase," and also perhaps the eventual fast rise.

A suggestion from our work is that SXR data are important for inferring evolution of the field during the slow-rise phase, as many of the important features are not prominent in EUV images (e.g., the microflares of Fig. 2). Previous filament slow-rise studies may have missed signatures for tether weakening because they generally either did not include SXRs, or used SXR images of insufficient cadence.

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