Initiation of Coronal Mass Ejections

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This paper is a synopsis of the initiation of the strong-field magnetic explosions that produce large, fast coronal mass ejections. The presentation outlines our current view of the eruption onset, based on results from our own observational work and from the observational and modeling work of others. From these results and from physical reasoning, we and others have inferred the basic processes that trigger and drive the explosion. We describe and illustrate these processes using cartoons. The magnetic field that explodes is a sheared-core bipole that may or may not be embedded in surrounding strong magnetic field, and may or may not contain a flux rope before it starts to explode. We describe three different mechanisms that singly or in combination can trigger the explosion: (1) runaway internal tether-cutting reconnection, (2) runaway external tether-cutting reconnection, and (3) ideal MHD instability or loss or equilibrium. For most eruptions, high-resolution, high-cadence magnetograms and chromospheric and coronal movies (such as from TRACE and/or Solar-B) of the pre-eruption region and of the onset of the eruption and flare are needed to tell which one or which combination of these mechanisms is the trigger. Whatever the trigger, it leads to the production of an erupting flux rope. Using a simple model flux rope, we demonstrate that the explosion can be driven by the magnetic pressure of the expanding flux rope, provided the shape of the expansion is "fat" enough.

1. INTRODUCTION

An intense, days-long solar energetic particle (SEP) storm in interplanetary space, one that could kill astronauts and spacecraft, is generated by the bow shock of a large, fast coronal mass ejection (CME) (Kahler 1992; Reames 1999, 2001). The driving CME is a magnetic explosion that also produces a flare in the source region on the Sun (MacQueen & Fisher 1983; Moore et al 2001; Falconer et al 2002). The magnetic fields that explode to drive the fastest CMEs and the most dangerous particle storms are in active regions with large sunspots, the regions of the strongest magnetic fields found on the Sun (e.g., Gopalswamy et al 2004).

Plate 1 shows a CME that is representative of those that drive SEP storms. A SOHO/LASCO difference image captures this CME as it blasts through the outer corona. Here, and in the original (non-differenced) LASCO images, this CME shows the three-part bubble structure (bright envelope around a dark void with a bright core) typical of large, fast CMEs. Plate 1 also shows the onset of the magnetic explosion as observed by SOHO/EIT in Fe XII images. Although the magnetic field was too weak to have sunspots, and hence was weaker than in many still stronger CME explosions, the explosion produced a large CME that was fast enough [900 km/s (SOHO/LASCO CME Catalog)] to drive a bow shock and SEP storm. No SEP storm from this CME was observed at SOHO because SOHO was shielded from the particles by the interplanetary magnetic field: the CME occurred in a sector of the interplanetary magnetic spiral far behind of that of SOHO and Earth.

The magnetogram and Fe XII coronal images in Plate 1 show that the exploding field initially was a closed arcade with a dark filament of chromospheric temperature plasma suspended in its core. The filament stands above the neutral line (polarity dividing line) straddled by the arcade and shows that the magnetic field in the core of the arcade is strongly

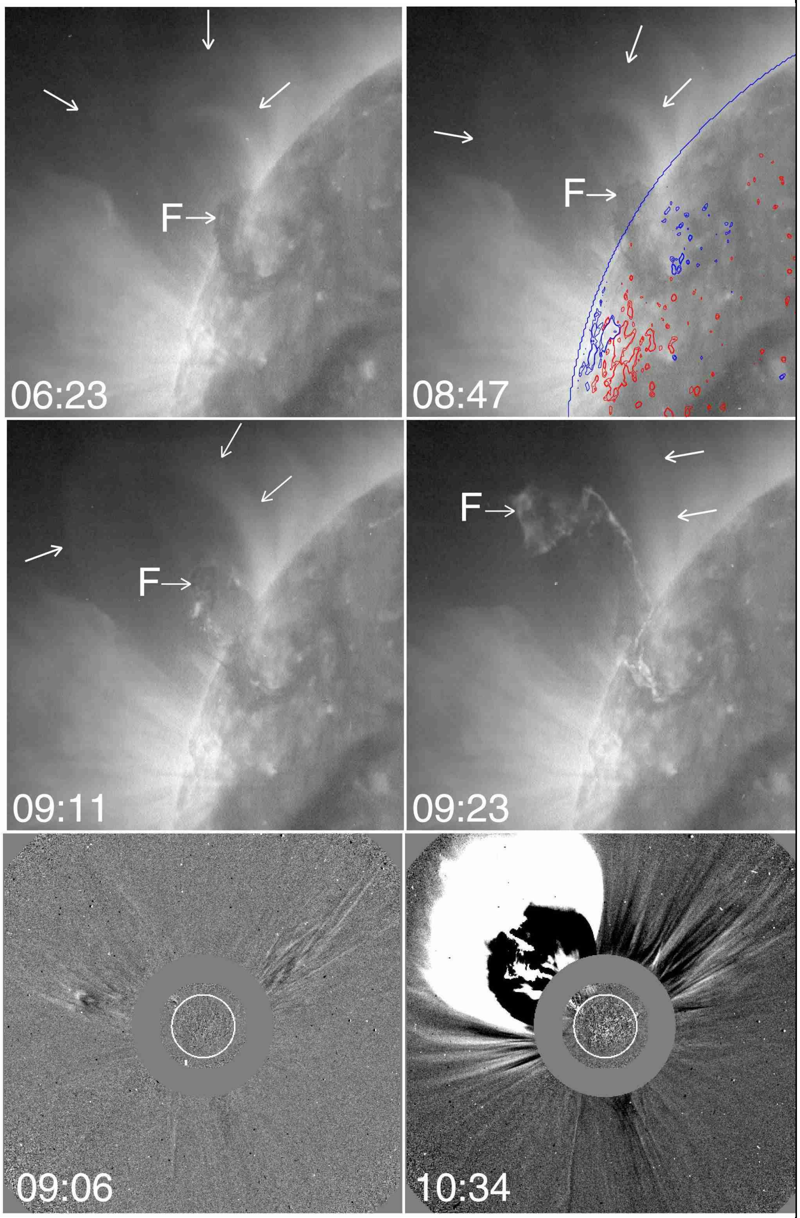

Plate 1. Onset of a typical filament-eruption magnetic explosion and the resulting large, fast CME. This eruption was observed by SOHO on 2002 January 4, and has been studied by Sterling and Moore (2004b). The universal time of each image is in the lower left corner. The upper four panels are EIT 195Å Fe XII coronal images. The arrow labeled F points to the filament before it started to erupt (first panel), during the slow-rise onset of its eruption (second panel), and during the explosive fast-rise phase (third and fourth panels). The other arrows point to the bright arcade that envelops the filament cavity and filament, and that is blown open by their eruption. The superposed MDI magnetogram in the second panel shows the quadrupolar arrangement of positive polarity (red) and negative polarity (blue) magnetic flux in which the filament and cavity are seated. The bottom two panels are LASCO/C2 coronagraph running-difference images of the outer corona at the start of the fast-rise phase of the filament eruption (left) and well after the CME had emerged from behind the occulting disk (right). The white circle outlines the solar disk centered behind the occulting disk.

sheared: the direction of the field threading the filament is nearly parallel to the neutral line rather than nearly orthogonal as it would be if the field were in its minimum-energy potential configuration. That is, the magnetic location and form of the filament show that the core field is greatly deformed from its potential configuration and hence has a large store of non-potential (free) magnetic energy that in principle is available for release in an explosion.

Over the past three decades, there has been a synthesis of various complementary observations of many ejective solar eruptions similar to that in Plate 1. These observations include chromospheric images, line-of-sight magnetograms, vector magnetograms, and coronal X-ray and EUV images of the eruption region, and chromospheric, coronal, and hard X-ray movies of the erupting filament-carrying sheared core field and the ensuing heated foot points and loops of the flare. From these observations a strong case has been made that (1) the pre-eruption configuration of the field that explodes to become a fast CME is typically a sheared-core arcade like that in Figure 1, (2) there is enough free magnetic energy in the sheared core field to produce the explosion, and (3) the energy going into the CME and flare comes from the expanding sheared core field as it erupts in the explosion (Hirayama 1974; Kopp & Pneuman 1976; Heyvaerts et al 1977; Moore & LaBonte 1980; Moore et al 1980, 1987, 1995, 1997, 2001; Moore 1988, 2001; Shibata et al 1995; Shibata 1998; Canfield et al 1999; Sterling et al 2000, 2001a,b; Sterling & Moore 2001a,b, 2003, 2004a,b).

The three-dimensional configuration of a sheared-core arcade prior to eruption is sketched in the first panel of Figure 1. In

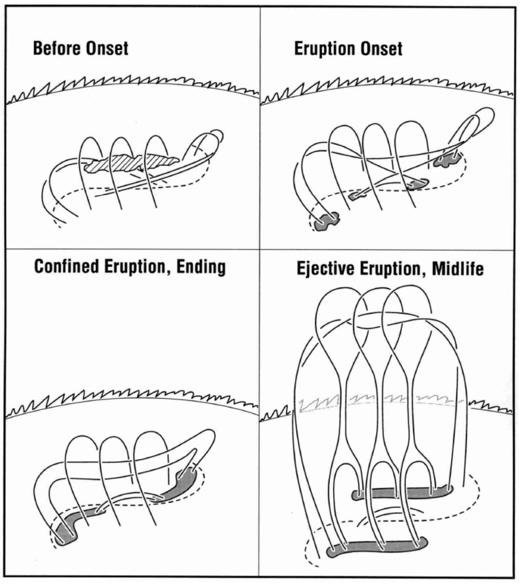

Figure 1. Progression of the three-dimensional configuration of a sheared-core bipolar magnetic field and its internal reconnection in a CME explosion (from Moore et al 2001). The ragged arc in the background is the chromospheric limb of the Sun. The solid curves are magnetic field lines. The dashed curve is the magnetic polarity dividing line (neutral line.) The elongated crosshatched feature in the first panel is a filament of cool material suspended in the sheared core field. This material is carried in the erupting flux rope (as in Plate 1), but is not shown in the other panels for clarity of the field configuration. The shaded areas are flare ribbons at the feet of reconnected field lines. The third panel shows the conclusion of a confined eruption, a "failed-CME" explosion.

some cases, the sigmoidal shape of the sheared core field is as symmetric and as obvious in coronal X-ray images as it is in this drawing, but in many cases it is distorted, asymmetric, and much less obvious [e.g., see examples in Sterling et al (2000)]. This drawing shows only the closed bipolar field that has the sheared field and filament in its core. Any sheared-core bipole on the Sun is embedded in other magnetic fields rooted around it more or less as in Plate 1. If the surrounding fields are of strength and span comparable to those of the sheared-core bipole, they can strongly influence whether and how the sheared-core bipole explodes (Antiochos 1998; Antiochos et al 1999). If the surrounding fields are weak enough compared to the bipole, their effect on the initiation and growth of the explosion can reasonably be ignored. This is the case depicted in Figure 1.

At chromospheric and low coronal heights in sunspot active regions, the magnetic field strongly dominates the weight and pressure of the plasma (Gary, 2001). As a result, the equilibrium configuration of the field is very nearly the force-free configuration that the field would have if the plasma had no weight and no pressure, the configuration determined by the balance between the outward push of magnetic pressure and the inward pull of magnetic tension (e.g., Cowling 1957). So, in an active-region sheared-core bipole the cool filament material and the hot coronal plasma are constrained to trace the field lines, and do not appreciably deform the field from its force-free configuration. The elongation and striation of the filament show that the core field is strongly sheared, and the coronal plasma often illuminates the overall form of the sheared-core bipole, showing that it typically has the sigmoidal character of the initial sketch in Figure 1 (Canfield et al 1999; Sterling et al 2000).

In this paper, we consider the onset of CME explosions in which, until it begins to explode, the driving magnetic field is a nearly force-free sheared-core bipole of the sigmoidal form sketched in Figure 1. The feet of all the field lines are locked to the massive body of the Sun. The magnetic pressure pushes against the photosphere and outward in all directions, trying to explode the field, but is held in check by the magnetic tension pulling back toward the feet. So, for the case of force-free equilibrium in the part of the pre-eruption field that is the source of the energy released in the explosion, the problem of the initiation of the CME explosion is that of how this equilibrium is destabilized or broken, so that the magnetic pressure is unleashed to drive the explosion.

We present three basic alternatives for triggering the explosion: internal tether cutting, external tether cutting (breakout), and ideal MHD instability or loss of equilibrium. The presentation outlines our current view of the eruption onset, based on our own observations and on the observations and theoretical work of others. In our view, for the strong-field (initially force-free) case we are considering, the three presented alternatives cover the range of possibilities for triggering the explosion. Each alternative is illustrated by cartoons representing the driving field, a surrounding field, and their interaction. No observations other than in Plate 1 and no numerical simulations of CME onsets are shown, but published observations and modeling studies are cited and briefly discussed in relation to each alternative. Our exposition of CME initiation is similar in approach to both that of Moore and Roumeliotis (1992) and that of Klimchuk (2001). It is an extension of Moore and Roumeliotis in that they did not consider the role of surrounding magnetic fields. Also in contrast to Moore and Roumeliotis, we do not explicitly portray the role of emerging magnetic fields in destabilizing the sheared-core bipole; in our scheme, reconnection between crossed strands of the sheared core field has basically the same role. Our considerations of CME initiation are narrower in scope than those of Klimchuk (2001), which included the possibilities of either plasma weight or plasma pressure being important in causing the explosion, and the possibility that the energy for the explosion comes from below the photosphere during the explosion. We limit our considerations to the force-free situation appropriate for the initiation of fast CMEs that come from strong-field regions and that are driven by the release of magnetic energy stored above the photosphere. Within this scope, our approach is a refinement of that of Klimchuk (2001). In Klimchuk (2001), the basic alternatives for CME initiation are illustrated by cartoons of analogous simple mechanical systems (springs, weights, strings, and pulleys) and thermal explosions (bombs). We illustrate our alternatives by cartoons that more directly represent the magnetic field in observed CME explosions in strong-field regions.

For each of the three trigger mechanisms, we describe the initiation of the CME explosion with the aid of a sequence of three cartoons of the magnetic field (before eruption onset, just after eruption onset, and after the eruption is well underway) for the case in which the erupting sheared core field is in the central lobe of a quadrupolar field. It is observed that when a sheared core field (traced by a filament) erupts, the eruption often begins with a relatively long-lasting slow-rise phase (having little acceleration and during which the filament noticeably ascends) and then rather abruptly transitions to an explosive fast-rise phase of strong acceleration (e.g., Kahler et al 1988; Sterling and Moore 2004a,b, 2005). In the quadrupolar cases that we depict in our cartoons, there are two places that reconnection can occur: (1) at the magnetic null (X-point) above the erupting central lobe, and (2) between the sheared legs of the erupting core field (below the erupting filament). Reconnection at the null is expected to produce coronal and chromospheric brightening in the two side lobes of the quadrupole, and reconnection below the filament is expected to produce coronal and chromospheric brightening in the sheared core field. The expected brightenings have been observed in many eruptions, and are taken as evidence of the reconnection (e.g., Aulanier et al 2000; Gary and Moore 2005; Sterling and Moore 2001a,b, 2004a,b, 2005). In the cartoons, we use the label "slow runaway reconnection" for reconnection that occurs during the slow-rise phase of the eruption, and we use the label "explosive reconnection" for reconnection that occurs during the explosive phase of the eruption. These terms are not intended to mean that there is necessarily different physics in the reconnection in the two phases, but only that, as observed brightenings strikingly indicate, the reconnection is much faster and stronger in the explosive phase than in the slow-rise phase of the eruption.

In each of our initiation alternatives, sooner or later, reconnection within the sheared core field creates a flux rope that erupts upward, carrying the filament (if present) within it. Observations indicate that the explosion is driven by the release of magnetic energy from the erupting flux rope via its expansion (Moore 1988). We point out that in order for this to work, that is, in order for there to be a net decrease in the magnetic energy in the exploding flux rope, the shape of the expansion must be sufficiently "fat."

2. CANNONICAL PRE-ERUPTION FIELD CONFIGURATION

In Plate 1, the pre-eruption filament and sheared core field run along the middle neutral line of a triplet of roughly parallel neutral lines. These three neutral lines divide the polarity domains of a quadrupolar arrangement of magnetic flux that spans about a solar radius laterally from southeast to northwest. This magnetic setting of a sheared-core bipole is shown schematically in Plate 2. The style of the depiction is that used by Antiochos et al (1999) in displaying their simulation of CME initiation by breakout reconnection. Whereas their simulation was for a 2-D global quadrupolar field that straddled the equator and circled the Sun, our sketch is for an analogous 3-D quadrupolar field of the scale of that in Plate 1 or smaller. The 3-D form of the central sheared-core bipole is the same as that in Figure 1 (except that the sense of the magnetic shear and twist in the sigmoid is right-hand rather than left-hand).

The situation depicted in Plate 2 is the ideal symmetric one, much more symmetric than in the example observed case in Plate 1, but having the same topology. Nearly symmetric pre-eruption quadrupolar configurations of this topology do occur (e.g., Sterling & Moore 2004a). In other observed quadrupolar situations, the sheared-core bipole is one of the side lobes rather than the central lobe (e.g., Sterling & Moore 2004b). However, the situation in Plate 2 encompasses our three basic alternatives for CME initiation in basically the same way as for any multi-polar configuration in which there is an

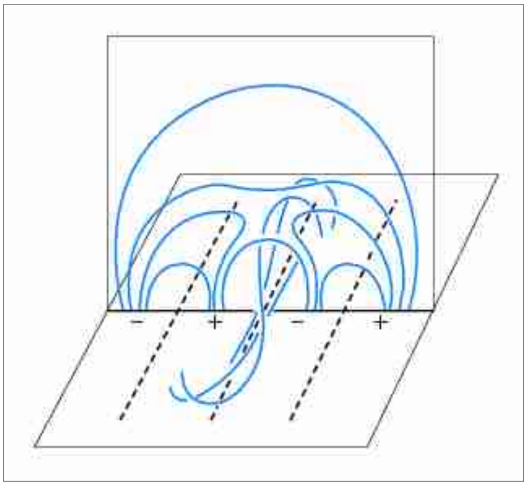

Plate 2. The three-dimensional topology of the quadrupolar magnetic field configuration for CME explosions such as in Plate 1. This is the canonical configuration, which has the exploding sheared core field in the central lobe of the quadrupole. As in Figure 1, the solid curves are field lines and the dashed lines are polarity dividing lines. The polarity of the field on each side of each of the three neutral lines is specified by a plus sign or a minus sign, and matches the polarity arrangement in Plate 1.

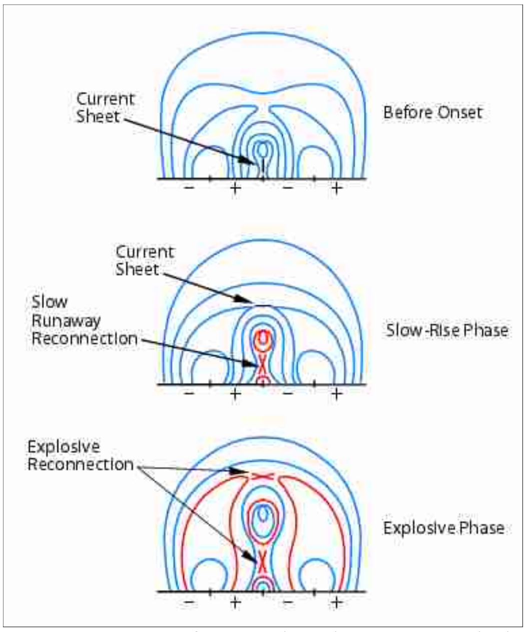

Plate 3. Onset of a quadrupolar CME explosion triggered by runaway internal tether-cutting reconnection. Here and in Plates 4 and 5, the drawings are 2-D renditions of the 3-D configuration in Plate 2 viewed from the front end.

embedded sheared-core bipole with an external magnetic null somewhere above it. In this canonical configuration, there are two places where reconnection can begin: within the sheared core field as depicted in Figure 1, or at the magnetic null between the envelope of the sheared-core central lobe and the oppositely-directed overarching envelope of the quadrupole. In the following section, for each of our CME-initiation alternatives, we depict the 3-D field configuration of Plate 2 with 2-D cartoons representing this configuration viewed horizontally along the direction of the neutral lines.

3. ERUPTION ONSET

In this section we describe how the three alternatives for CME initiation would occur in our canonical single-bipole and quadrupolar field configurations, and consider their observable signatures.

3.1. Eruption Triggered by Internal Tether-Cutting Reconnection

Our first alternative for CME initiation is depicted by the 2-D cartoons in Plate 3. Here, before eruption onset, the 3-D sigmoidal sheared core field sketched in 3-D in Figure 1 and Plate 2 is represented by the innermost loop of the central lobe of the quadrupole. We have drawn this loop with a symbolic spiral dip in it to indicate that the core field is twisted and sheared along the neutral line and that it is thereby able to suspend cool filament material within it. Before eruption onset, the quadrupole is in overall force-free equilibrium. In particular, the magnetic pressure of the sheared core field is balanced by the combination of its own magnetic tension and the magnetic pressure and tension in the rest of the quadrupole. Also before eruption onset, the field around the magnetic null above the central lobe is sufficiently relaxed that there is no current sheet at the null. But we do have a current sheet low in the sheared core field, between the inner legs of the two elbows of the sigmoid where they shear past each other under the filament (as sketched in Figure 1). We suppose that this current sheet has been formed by the legs being slowly pushed together by photospheric flows, perhaps involving flux cancellation at the neutral line as in the preeruption slow tether cutting of Moore and Roumeliotis (1992). The current sheet is the contact interface between the two legs. Across this interface the vertical component of the sheared core field reverses direction. As it forms, the current sheet itself may or may not become non-force-free before it is thin enough for reconnection to begin across it.

When the current sheet becomes sufficiently thin, reconnection begins as depicted in the second cartoons in Figure 1 and Plate 3. This is a runaway tether-cutting process as follows. The reconnected field lines above the reconnection site have had their number of footpoints cut from four to two (Figure 1), so that they are no longer tied to the photosphere under the filament and now run the length of the sigmoid. This releases them to erupt upward, which allows the inner legs of the sigmoid to further collapse together and drive more reconnection. The reconnection and eruption begin slowly, but due to this positive feedback the flux rope that is built and released by the reconnection becomes progressively farther out of force balance, and the eruption speed and reconnection rate progressively increase. In this manner, the CME explosion is initiated by the onset and runaway growth of tether-cutting reconnection internal to the sheared core field (Moore and LaBonte 1980; Sturrock et al 1984; Sturrock 1989; Moore and Roumeliotis 1992).

As Figure 1 and Plate 3 indicate, this alternative for CME initiation is a possibility for either an isolated sheared-core bipole or a quadrupolar field having a sheared-core bipole within it. For a single-bipole CME explosion, the eruption of the unleashed flux rope is strong enough to overcome the restraint of the envelope of the bipole, the envelope field is blown out with the flux rope inside it as in Figure 1, and the legs of the "opened" envelope field re-close by reconnection in the wake of the CME expulsion. Early in the eruption, when the bipole is still closed, the reconnection produces a "four-ribbon" flare. As the reconnection seamlessly progresses from being between the closed sheared magnetic loops of the sigmoid early in the eruption to being between the stretched legs of the extruded envelope field late in the eruption, the flare loops that are formed and heated by the reconnection and issue downward from the rising reconnection site progress from being low and strongly sheared across the neutral line to becoming an increasingly less-sheared, growing arcade rooted in two separating flare ribbons (Figure 1). Such progression from four to two flare ribbons has been observed in ejective filament-eruption flares (e.g., Moore et al 1995).

No matter how the eruption of the sheared core field is triggered, and whether or not the exploding bipole is embedded in strong surrounding field, flare brightening indicative of internal tether-cutting reconnection is usually observed to begin early in the eruption (e.g., Moore and LaBonte 1980; Kahler et al 1988; Moore et al 1984, 1995, 2001; Sterling and Moore 2004a,b, 2005). Because this reconnection produces closed flare loops and begins while the exploding bipole is still closed, only part of the bipole's field is "opened" in producing the CME (as in Figure 1). This is compatible with the Aly-Sturrock theorem: no stressed closed magnetostatic field has enough free energy to explode itself entirely open (Aly 1991; Sturrock 1991).

Is internal tether-cutting reconnection observed to be the trigger of single-bipole CME explosions? It appears to be in cases in which flare brightening (presumably from reconnection) is observed to begin low in the sheared core field in near synchrony with the onset of the slow rise of the filament/flux rope (e.g., Moore and LaBonte 1980; Moore et al 2001; Sterling and Moore 2005). However, because of finite time resolution and brightness noise thresholds, it remains uncertain whether (1) the internal reconnection begins at the start of the rising motion (which would be evidence for internal tether-cutting as the trigger) or (2) the rising motion begins first. That is, observations of any single-bipole eruption have not yet ruled out the possibility that the sheared core field first begins to erupt via an ideal MHD instability or loss of equilibrium, and that this soon drives the production of a current sheet and reconnection low in the erupting field (e.g. Rust and Kumar 1996; Rust and LaBonte 2005). This possibility is our third alternative for CME initiation. Many magnetostatic and magnetohydrodynamic modeling studies of single-bipole CME onsets based on prescribed evolution of the magnetic flux and/or magnetic shear have found results favoring an ideal MHD trigger (e.g., Isenberg et al 1993; Titov & Demoulin 1999; Amari et al 2000; Linker and Mikic 1995; Chen and Shibata 2000; Roussev et al 2003; Gibson et al 2004). Triggering of eruption in a single-bipole configuration by spontaneous onset of tether-cutting reconnection in the sheared core field has not yet been demonstrated by MHD modeling (Antiochos 2005). Observations of filament-eruption flares with early brightening at sites of emerging magnetic flux near the neutral line suggest that such flux emergence may be required for internal tether-cutting reconnection to be the trigger in practice (e.g., Heyvaerts et al 1976; Moore et al 1984; Sterling and Moore 2005). That is, if the configuration is initially MHD stable, local flux emergence may be required to produce the internal current sheet and start the runaway reconnection.

When the sheared-core bipole is embedded in a quadrupolar field as in Plate 3, once an explosion is triggered in this bipole, it erupts upward, compresses the null, and soon drives reconnection there. Before the explosion is triggered, the null may or may not be so relaxed as to have no current sheet as we have drawn it in Plate 3. Either way, for our present alternative for CME initiation (triggering by internal tether cutting), there is no reconnection at the null until it is further compressed by the eruption from below. The eruption from below is triggered and starts to grow in the same way as in the single-bipole case. Once reconnection at the null begins, it amounts to external tether cutting and is a runaway (explosive) process in the same way as the internal tether-cutting reconnection. Before reconnecting, the field lines of the envelope of the sheared-core bipole and the field lines of the overall envelope of the quadrupole act to tie down the sheared-core bipole. The null-point reconnection cuts these tethers and produces reconnected field lines that sling themselves out the way. Hence, the external reconnection further unleashes the exploding bipole, which makes the explosion stronger and drives the reconnection faster.

In the present scenario (triggering by internal tether-cutting), the external reconnection at the null, once it gets started, is the same as the breakout reconnection in the model of Antiochos et al (1999) and in our second alternative for CME initiation, and could equal or exceed the internal reconnection in further unleashing and growing the explosion. The essential difference between the present scenario and the breakout scenario is in the cause and effect relation between the onset of breakout reconnection and the onset of internal tether-cutting reconnection. In the present scenario, internal tether cutting begins first and leads to breakout reconnection, whereas the opposite occurs in the breakout scenario.

In each of our three alternatives for the canonical quadrupolar situation, before and during its eruption, the central lobe has the form of the erupting bipole in Figure 1. The external reconnection strips away some of the outer envelope of the erupting bipole. While the erupting bipole is thereby breaking through the envelope of the quadrupole, internal reconnection is growing the flux rope above it and the flare arcade below it. Once the erupting bipole has broken out of the quadrupole, it explodes on out to become a CME and its legs continue to re-close, further growing the arcade as in Figure 1.

As indicated in Plate 3, reconnection driven at the null produces hot plasma on the reconnected field lines, resulting in bright coronal loops in the side lobes and remote flare brightening at the feet of these loops. If runaway internal tether-cutting reconnection is the trigger of the explosion, and not breakout reconnection, then flare heating in the sheared core field should begin together with the onset of the filament eruption and before the onset of the heating effects of the breakout reconnection. We know of no published example of an observed embedded-bipole CME explosion onset in which this is clearly the case. However the number of published well-observed events that have been studied in this respect is still small (<~10). While most of these show evidence for breakout reconnection starting early in the eruption, some also show brightening in the core field early in the eruption, and so leave open the possibility that either internal tether cutting or MHD instability is the trigger (e.g., Sterling and Moore 20004a,b). It is also possible that any two or all three of our CME-initiation alternatives play together so closely from the beginning in some events that the trigger should not be assigned to only one alternative. Since internal tether-cutting reconnection begins early in the onsets of what appear to be single-bipole CME explosions (Moore et al 2001), it will be surprising if no embedded-bipole CME explosions are triggered in the same way, with no initial help from breakout reconnection.

3.2. Eruption Triggered by External Tether-Cutting Reconnection (Breakout)

Our second alternative for CME initiation is depicted in Plate 4. This is similar to the first alternative in that the explosion of the sheared core field is again triggered by runaway tether-cutting reconnection, but this time the reconnection is at the external null rather than between the crossed legs of the core field. Unlike the other two alternatives, this alternative is not an option for the initiation of single-bipole CME explosions because these, by definition, have no appreciably strong surrounding fields and hence can have no significant external tether cutting. When the exploding bipole is embedded in an arrangement of strong field giving an external null, as in our canonical quadrupolar configuration, the explosion can be triggered by reconnection at the null as follows.

It is supposed that photospherically-driven evolution of the sheared core field, via shearing flows or further emergence of sheared core field, gradually inflates the middle lobe of the quadrupole without producing a current sheet within the sheared core field. This gradually compresses the field at the null and produces a current sheet there that becomes progressively thinner. Eventually reconnection begins at the current sheet. This reconnection may begin slowly, but because it renders the sheared-core bipole progressively farther out of force balance, it is a runaway process. As the filament/flux rope rises

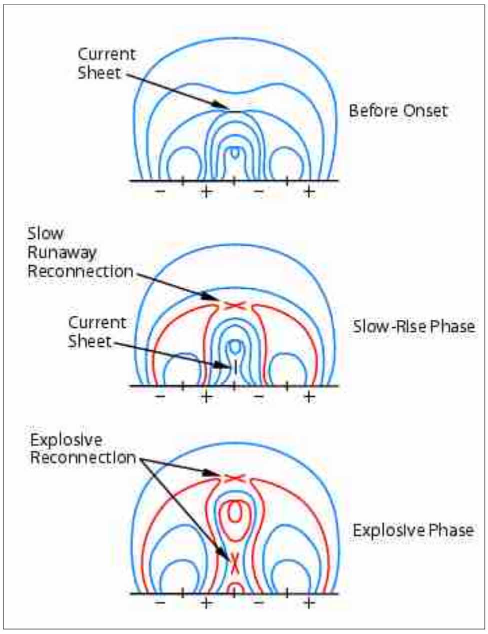

Plate 4. Onset of a quadrupolar CME explosion triggered by breakout reconnection (runaway external tether-cutting reconnection).

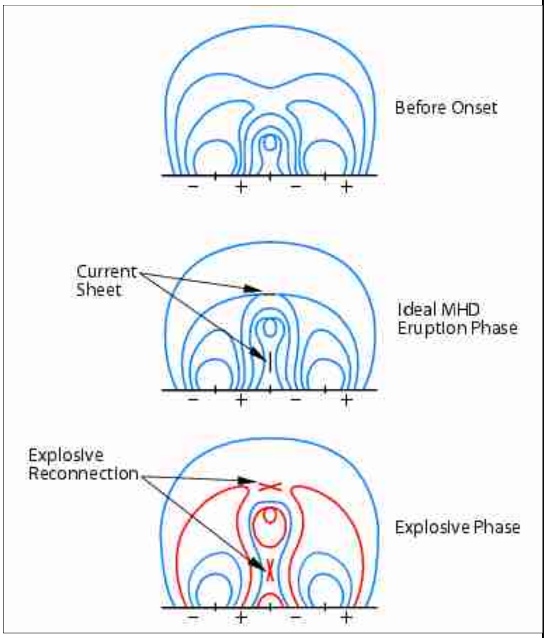

Plate 5. Onset of a quadrupolar CME explosion triggered by ideal MHD instability or loss of equilibrium.

up, the stretched legs of the central-lobe core and envelope field begin to collapse together under it and form a current sheet at their interface (Plate 4, second cartoon). As the external reconnection and the core-field eruption continue to grow, the internal current sheet grows and thins and runaway tether-cutting reconnection is soon driven there as well, which further unleashes the explosion.

The sequence of events described above is that demonstrated by Antiochos et al (1999) in their numerical MHD 2-D simulation of the breakout scenario for CME initiation conceived by Antiochos (1998). In a CME explosion from a sheared-core bipole embedded in strong surrounding field with an opposing polarity arrangement, there will be a null more or less above the exploding bipole, and, regardless of how the explosion is triggered, the explosion will drive breakout reconnection at the null. Clear evidence for this reconnection has been observed in several such explosions (Aulanier et al 2000; Sterling et al 2001a,b; Sterling and Moore 2001a,b, 2004a,b; Gary and Moore 2004; Li et al 2005). Among these, the strongest cases for the explosion being triggered by breakout reconnection, that is, the cases having the most compelling evidence that remote flare brightening occurred before the onset of the filament/flux-rope eruption, are the event studied by Aulanier et al (2000) and the event studied by Gary and Moore (2004) and by (Li et al (2005). Even in these two cases, the observations do not rule out that the breakout reconnection started in response to an unnoticed ideal MHD convulsion in the sheared-core bipole. In the other cases, either no clear tracer of the onset of the core-field eruption (such as a slowly rising filament) is present or to within the time resolution of the observations the remote brightening begins together with the slow-rise phase of the filament eruption. So, in these cases the observations are consistent with either that the breakout reconnection triggered the slow-rise phase of the core-field explosion or that the slow-rise onset was triggered by one or both of the other alternatives and initially drove the breakout reconnection.

3.3. Eruption Triggered by Ideal MHD Instability or Loss of Equilibrium

Our third alternative for CME initiation is shown in Plate 5. This alternative differs from the other two in that the first step in the eruption, the trigger, does not involve reconnection. Like the internal reconnection alternative, it is a possibility for the trigger whether or not the sheared-core bipole is embedded in strong surrounding field. In the quadrupolar case in Plate 5, before eruption onset there is no current sheet either at the null or in the sheared legs of the core field, or if there is, neither current sheet is yet thin enough for reconnection to start. It is supposed that photospherically-driven evolution of the flux distribution, perhaps including flux emergence and/or cancellation, gradually evolves the field configuration in the central lobe until the field in the filament/flux rope is so twisted and/or untethered that its force-free magnetostatic equilibrium becomes unstable (e.g., to kinking) or untenable (the core field looses its equilibrium and seeks a new equilibrium by erupting upward). Magnetostatic and magnentohydrodyamic 2-D and 3-D modeling studies of this scenario have shown (at least in single-bipole situations) that such dynamic behavior can be initiated without resistive dissipation (reconnection) at current sheets (e.g., Isenberg et al 1993; Linker and Mikic 1995; Titov and Demoulin 1999; Amari et al 2000; Chen and Shibata 2000; Roussev et al 2003; Gibson et al 2004). In these bipolar models, the instability or loss of equilibrium leads to the formation of a current sheet below or low in the erupting flux rope, between the legs of the envelope field or in the fold of a kink in the flux rope. In the quadrupolar situation in Plate 5, the upward eruption in the central lobe also produces a current sheet at the null. As soon as either current sheet is thin enough, runaway reconnection occurs there. As in the other two alternatives, this tether cutting further unleashes the explosion of the central lobe and helps the eruption open the quadrupole and become a CME (Plate 5, third cartoon). (Again, we emphasize the difference between an ideal MHD trigger and either of the two tether-cutting options for the trigger: only in the ideal MHD option does the eruption begin without any pre-existing current sheets, or if any current sheets are present, without any reconnection at these current sheets. Ideal MHD instability or loss of equilibrium starts the eruptive motion, even though, as the above modeling studies indicate, this soon produces one or more reconnection current sheets and the subsequent reconnection is essential for the production of a full-blown CME.)

The amount of twist displayed by sigmoidal core fields before or during eruption onset suggests that the eruption may be triggered by kink instability, and many erupting filament/flux ropes doe appear to kink as they erupt (Rust and Kumar 1996; Rust and LaBonte 2005). While these observations are consistent with triggering by ideal MHD instability, in observed eruption onsets this alternative is difficult to distinguish from the other two, unless the formation of the tether-cutting current sheets is sufficiently delayed from the start of the ideal MHD eruption. As noted in the Introduction, observed filament/flux rope eruptions often begin with a slow-rise phase that persists with little acceleration until the filament has ascended markedly and then rapidly transitions to an explosive fast-rise phase of strong acceleration (Sterling and Moore 2004a,b, 2005). During the slow-rise phase, if there is internal tether-cutting reconnection or external breakout reconnection in progress, it is apparently slow and its heating effects (flare brightening) should be relatively weak [as is seen in Moore et al (2001) and in Sterling and Moore (2004a)] or perhaps below detection threshold (Sterling and Moore 2003). In the few cases we have studied so far, the brightening becomes obvious before or soon after the start of the fast phase of the eruption. As a rule, the stronger the erupting magnetic field, the faster the eruption develops, and the stronger the flare heating. If reconnection heating is occurring in the slow-rise phase, it should be easier to detect in active-region eruptions than in quiet-region eruptions, given adequate time resolution. So, if an active-region filament eruption were observed to enter its fast phase with no sign of flare heating anywhere in the active region, that would be strong evidence for initiation by an ideal MHD process. To our knowledge, no such strong-field filament eruption has yet been observed in either a bipolar or multi-polar setting. If MHD-triggered eruptions do occur, they will be easier to detect in bipolar situations than in multi-polar situations if, as seems likely, the MHD eruption takes longer to produce a reconnecting current sheet in the legs of the erupting bipole than at an external null.

4. SHAPE OF EXPANSION OF THE ERUPTING FLUX ROPE

In CME explosions of sigmoidal sheared core fields, whether the pre-eruption sigmoid is in an isolated bipole as in Figure 1 or in an embedded bipole as in Plate 2, and regardless of which of our three alternatives or any combination of these triggers the eruption, observations show that by the time the filament-carrying field has erupted to a height of order the original length of the sigmoid, internal tether-cutting reconnection is in progress between the legs of the erupting bipole (e.g., Sterling and Moore 2004b, 2005). For example, the last Fe XII image in Plate 1 captures the erupting filament at about this height and shows flare ribbons brightening along the neutral line. Before the eruption, it is reasonable to consider the field lines holding the filament to comprise a flux rope, but these field lines may or may not run the length of the sigmoid without rooting in the photosphere. By the time internal reconnection is well underway and producing flare ribbons as in Plate 1, any ties of the filament field to the photosphere under it have apparently been cut, and the filament can be considered to be carried in an erupting flux rope then and after, if not before. It appears to be the expansion of the field in this flux rope that drives the explosion, depleting the magnetic energy in the flux rope (Moore 1988).

For the magnetic energy content of the flux rope to decrease as it erupts, it must expand in cross-sectional area enough faster than it expands in length. That is, the shape of the expansion must be sufficiently "fat." We will demonstrate this requirement by using the simple cylindrical model flux rope shown in Figure 2. For simplicity, and because sigmoids and filaments in active regions are only mildly twisted, having no more than a full turn from end to end, we ignore the twist. We also ignore the curvature of the erupting rope and the plasma pressure in the rope, and take the magnetic field to be uniform inside the model rope and the cross section to be constant along the length. At any instant in the eruption, the magnetic energy content E_{mag} of the model flux rope is the magnetic energy density times the volume:

$$E_{mag} = (B^2/8\pi)Al = (\Phi^2/8\pi)l/A, \qquad (1)$$

where B is the field strength, A and l are the cross-sectional area and length of the rope, and Φ is the magnetic flux in the rope (Φ = BA). Due to the high electrical conductivity, the magnetic field in the rope obeys the frozen-in condition and defines the flux rope, and Φ remains constant as the rope expands. So, differentiation of Equation (1) gives

$$(\Delta E_{mag})/ E_{mag} = (\Delta l)/l - (\Delta A)/A \qquad (2)$$

for the incremental change in the magnetic energy content from incremental changes in the length and area of the rope as it expands. For the expansion of the flux rope to be driving the explosion, the magnetic energy content of the rope must be decreasing ($\Delta E_{mag} < 0$), which requires

$$(\Delta A)/A > (\Delta l)/l. \qquad (3)$$

Thus, the shape of the expansion, $[(\Delta A)/A]/[(\Delta l)/l]$, must be "fatter" than unity for the explosion to proceed. If the area expands at the same fractional rate as the length or slower, the magnetic energy content of the rope remains constant or increases, and

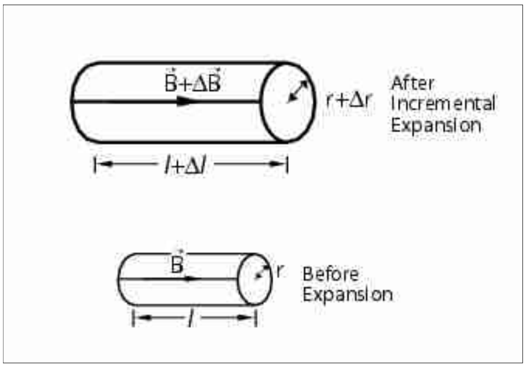

Figure 2. Simple (untwisted) model for the erupting flux rope in a CME explosion.

the explosion has to be driven by something other than the expansion of the flux rope. Twist in the flux-rope field would lower the above limit on the expansion fatness, because the energy in the component of the field perpendicular to the length of the rope would be decreased by expansion of the rope along its length.

In Plate 1, the expansion of the erupting flux rope (the erupting filament and filament cavity) appears to be roughly isotropic; that is, the diameter of the filament cavity and the length of the filament appear to increase at roughly the same rate. For isotropic expansion, $r \propto l$, where r is the radius of the flux rope, $A \propto l^2$, and $E_{mag} \propto 1/l$. So, in the CME explosion in Plate 1, the magnetic energy of the flux rope rapidly decreases as it erupts, consistent with the explosion being driven by the magnetic pressure of the flux rope.

5. SUMMARY AND DISCUSSION

From observations of CME explosions from strong sigmoidal sheared core fields traced by filaments, it is nearly certain that the explosion is driven by the magnetic pressure in the erupting filament-carrying flux rope that is unleashed as the explosion is triggered and grows. Before it explodes, the sheared core field is in force-free equilibrium; its magnetic pressure is balanced by its own magnetic tension together with the tension and pressure of surrounding fields. Gradual evolution of the arrangement and amount of magnetic flux in and around the sheared core field can eventually upset this equilibrium and trigger the explosion. When the sheared field is the core of an isolated bipole, there are two different possibilities for the triggering process: (1) runaway tether-cutting reconnection could begin inside the core field, or (2) the equilibrium could become MHD unstable or impossible without an abrupt change in the field configuration (loss of equilibrium). When the sheared-core bipole is embedded in surrounding strong fields arranged in polarity so that there is a magnetic null above the embedded bipole, the explosion could be triggered by either of the above two alternatives for single bipoles or by a third alternative: breakout reconnection, which is runaway tether-cutting reconnection at the external null.

So far as we know, good evidence for breakout reconnection being the trigger has been found in only a couple of observed quadrupolar eruptions. In many observed eruptions in multi-polar configurations, while it is clear that external tether-cutting reconnection occurs, the observations permit the explosion to be triggered by one or both of the other two alternatives. Likewise, in observed single-bipole eruptions, there is often clear evidence for internal tether cutting reconnection starting early in the eruption, but in no case yet have the observations ruled out that the eruption was initiated by ideal MHD instability or loss of equilibrium. There is no a priori reason that pairs or all three of our alternative mechanisms could not act in concert as the trigger in some situations. For most eruptions, sorting out from observations which of these various possibilities is the trigger apparently requires (at least) high-cadence, high-resolution movies in chromospheric, transition-region, and coronal emission, such as are provided by TRACE and are expected from Solar-B, along with high-cadence, high-resolution magnetograms.

However the eruption is triggered, the erupting sheared core field is or soon becomes a flux rope that carries the erupting filament within it and continues to be built and further unleashed by tether-cutting reconnection below it. The expanding flux rope drives the explosion provided that its expansion results in a decrease in its magnetic energy content. This occurs if the shape of the expansion is sufficiently "fat." Specifically, the rate of logarithmic increase in the cross-sectional area of the flux rope [(1/A)dA/dt] must be enough faster than the rate of logarithmic increase in the length of the flux rope [(1/*l*)d*l*/dt]. In observed active-region filament eruptions, the expansion often appears to be roughly isotropic [e.g., see the filament eruptions shown in Moore (1987), Kahler et al (1988), or Sterling and Moore (2004b, 2005)], which indicates that the magnetic energy of the erupting flux rope rapidly goes into the explosion. If an erupting flux rope were observed to have an expansion shape of only about unity or less ([(1/A)dA/dt]/[(1/*l*)d*l*/dt] <~ 1), this would indicate that the eruption of the flux rope was not driven by the flux rope acting on its surroundings but by the surroundings acting on the flux rope.

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