Theory of Coronal Mass Ejections

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Coronal mass ejections (CMEs) are extremely important phenomena, both for understanding the evolution of the global corona and for understanding and predicting space weather. Despite this importance, the physical explanation of CMEs remains largely confused. A variety of theoretical models have been proposed, and we here attempt to organize them according to a classification scheme that identifies and differentiates their essential physical attributes. We propose five distinct classes of models, which we present with the aid of simple analogues involving springs, ropes, and weights. We also indicate how some of the models appear to be inconsistent with certain observations.

1. INTRODUCTION

Coronal mass ejections (CMEs) are the most energetic events in the solar system. They are spectacular displays representing the sudden eruption of up to 10^{16} gm of coronal material at speeds of typically several hundred kilometers per second [e.g., *Hundhausen,* 1999; *St. Cyr et al.,* 2000]. In more colloquial terms, they are a billion tons of super heated matter flying away from the Sun at a million miles per hour!

We now know that CMEs are more than just interesting natural phenomena. They are also the primary cause of the largest and most damaging space weather disturbances [e.g., *Gosling,* 1993; *Webb et al.,* 2000]. Effects include the temporary and sometimes permanent failure of satellites, the degradation or disruption of communication, navigation, and commercial power systems, and the exposure of astronauts and polar-route airline crews to harmful doses of radiation. Some of these effects are delayed approximately 3 days, the time it takes a CME to propagate to Earth and interact with the magnetosphere. Others begin almost immediately after the CME lifts off from the Sun due to the production of solar energetic particles (SEPs) that travel at relativistic speeds. Clearly, there is a need to understand CMEs and ultimately to predict them before they occur. This need will grow even greater as society's dependence on space and space-based technologies steadily increases over time.

A number of interesting theoretical models have been proposed to explain the nature and origin of CMEs. This article attempts to review these models in something of a tutorial fashion. The goal is not to produce an exhaustive compilation of all the work that has been done on the subject, but rather to identify the essential physics involved in the CME problem, and to distinguish the various types of models in terms of their most basic physical differences.

We find that existing CME models can be logically organized into five distinct classes. These are in turn grouped into two major divisions called "storage and release" models and "directly driven" models. We present the five classes with the aid of analogues involving everyday items such as springs, ropes, and weights. Our hope is that these simpler systems will help reveal the fundamental ways in which the more complex CME models differ. Note that this is not the first CME classification scheme to be proposed. *Forbes* [2000], for example, has recently advocated an approach that em-

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phasizes resistive versus ideal instabilities. This is a complementary and equally useful way of looking at the problem. Additional physical insights of a general nature can be found in *Low* [1994, 1996, 1999].

Ultimately, we must rely on observations to determine which of the proposed models is correct. Perhaps none is, or perhaps several are. There are hints that CMEs originating in active regions are different from those originating in quiet areas [e.g., *MacQueen and Fisher,* 1983; *St. Cyr et al.,* 1999; *Delannée, Delaboudinière, and Lamy,* 2000]. Additional studies are necessary to quantify the differences. Whether they are due to fundamental physical differences in the CME mechanism or are simply a reflection of the different environments in which the CMEs occur is a completely open question.

We will show that most of the proposed models have difficulty explaining one or more aspects of the observations. In some cases the discrepancies appear to be fatal, while in other cases their significance needs further evaluation. For a more complete discussion of the observational properties of CMEs, see one of the many excellent reviews [e.g., *Wagner,* 1984; *Hundhausen,* 1988, 1999; *Kahler,* 1992; *St. Cyr et al.,* 2000; *Webb et al.,* 2000].

As a background for our discussion of the different classes of models, we begin with a generic treatment of the structure, dynamics, and energetics of CMEs. These three aspects are of course closely related, but it is instructive to consider each of them separately.

2. STRUCTURE

The structure of CMEs and the pre-eruption configurations which spawn them are not well determined at this time. This is due largely to the optically thin nature of coronal observations. What we see in images are two-dimensional projections of three-dimensional structures, and it is often difficult to disentangle the overlapping features. The situation should improve dramatically with the STEREO mission, since its two spacecraft will provide views from different angles, allowing us to resolve many of the line-of-sight ambiguities.

In most models, the pre-eruption magnetic field has one of the two basic topologies illustrated in Figure 1. Arcade field lines arch directly over the magnetic neutral line to connect the opposite polarity parts of the photosphere. The configuration may be sheared, in which case the positive and negative footpoints are displaced in opposite directions parallel to the neutral line. Sheared fields are stressed and contain magnetic free en-

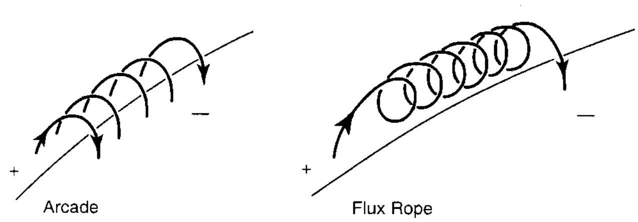

Figure 1. Arcade (left) and flux rope (right) magnetic topologies adopted by most CME models. Representative field lines are shown.

ergy that can be released during an eruption to power the mass motions. The single arcade in Figure 1 corresponds to a dipolar configuration. We can also imagine a quadrupolar configuration consisting of three arcades lined up side-by-side. Multipolar fields of this type are a fundamental property of the "magnetic breakout" model discussed later.

The flux rope topology is very different. Field lines form a helical structure that lies above the neutral line, disconnected from the photosphere except at the ends (in 2D models it is completely disconnected). Our cartoon drawing shows much more twist than we would expect in a real structure. There may be situations of one turn or less, in which case the distinction between flux rope and sheared arcade becomes blurred [*Titov and Démoulin,* 1999]. Many CMEs have what is commonly known as a "classic three-part structure" consisting of a bright frontal loop, a dark cavity underneath, and an embedded bright core [e.g., *Hundhausen,* 1988]. Plate 1 shows a typical example observed by the LASCO C3 coronagraph on the *Solar and Heliospheric Observatory (SOHO).* It has been suggested that cavities correspond to flux ropes seen edge-on [e.g., *Chen et al.,* 1997]. Support for this interpretation comes from the fact that the tops of most cavities are well rounded and the recent result that upwardly curved striations are sometimes detected at the trailing edge of the cavity [*Dere et al.,* 1999]. It is further believed that the embedded core is prominence material that is trapped at the bottoms of the helical field lines and dragged upward during the eruption. We must remember, however, that not all CMEs have a clear three-part structure. In fact, only a minority do [*Burkepile and St. Cyr,* 1993; see also *Dere et al.,* 1999]. Most CMEs are much more complex in appearance, as in the example of Plate 2. It is not obvious that these are flux ropes.

Additional evidence of a flux rope topology, at least in some evolved events, is the *in situ* observation of a rotating magnetic field pattern within interplanetary magnetic clouds. About one-third of interplanetary structures identified with CMEs have this signature [*Gosling,* 1990]. We note that magnetic reconnection may cause flux ropes to form naturally from erupting sheared arcades [*Gosling,* 1993], so the observation of a flux rope CME high in the corona or in the heliosphere does not necessarily imply that a flux rope was part of the initial configuration. Recent observations support the view of flux rope formation *after* the eruption begins [*Dere et al.,* 1999].

3. DYNAMICS

Presumably a CME occurs when the balance of forces that maintains an equilibrium is upset. Something causes the upward forces to become dominant over the downward ones. What are these forces? Gravity and gas pressure play important roles in some models. However, the magnetic field dominates the plasma throughout much of the corona ($\beta \equiv 8\pi P/B^2 \ll 1$), especially within active regions and at lower altitudes, and many models ignore the plasma altogether. In this case the only forces are magnetic.

The two competing magnetic forces are magnetic pressure and tension. Regions of strong magnetic field have enhanced pressure and naturally tend to expand into regions of weak field. An isolated flux rope like that shown in Figure 1 would grow in diameter and its axis would rise upward away from the surface were it not held in place by an overlying field. On the real Sun, magnetic field permeates the entire corona, and arcade-like field lines arch over any flux ropes that may exist. These arcade field lines are rooted in the surface and their tension acts to hold the flux rope in place.

This same interplay between magnetic pressure and tension exists even in simple arcades where no flux rope is present. The field strength is greatest in the center of an equilibrium arcade, and the outward force produced by the gradient in the magnetic pressure is exactly balanced by the inward tension force. An eruption begins when something tips the balance in favor of the outward pressure gradient. If this occurs unstably, as is usually the case, the force imbalance grows with time, and the eruption may become violent.

4. ENERGETICS

Perhaps as much as 10^{32} ergs of energy is required to lift the mass of a CME against solar gravity and accelerate it to the observed high velocities [e.g., *Vourlidas et al.,* 2000]. What is the source of this energy? There is little indication that energy passes through the solar surface from below the corona during the time of an eruption. Consequently, the energy is likely to be stored in the corona before the eruption begins. Since the plasma β is small throughout much of the corona, we can safely conclude that the energy is probably magnetic. Recall that only that part of the magnetic energy that is associated with electric currents, the so-called "free magnetic energy," is available to be converted to other forms. Energy cannot be extracted from a current-free potential field. The field must be stressed. It has been amply demonstrated that the free energy stored in pre-eruption coronal fields is at least as great as the gravitational and kinetic energies of a typical CME [e.g., *Klimchuk and Sturrock,* 1992; *Wolfson,* 1993].

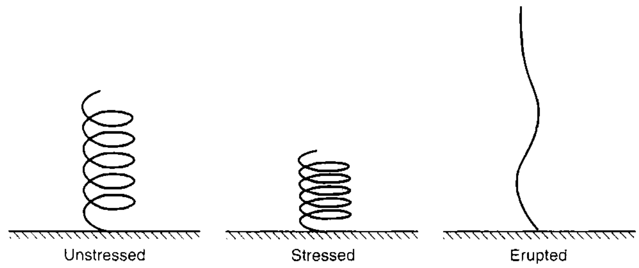

Figure 2. Simple spring analogue to the solar corona. The three states represent the magnetic field when it is unstressed (potential), stressed (current-carrying), and erupted (also current-carrying).

The energy problem is not so easily solved, however. A CME opens up a large portion of the corona, meaning that the field lines are stretched outward into the distant heliosphere. Such open magnetic configurations are themselves highly stressed, containing a current sheet that extends vertically above the neutral line. In the limiting case of a fully open field in which all of the field lines extend to infinity (idealized to be sure), the magnetic energy would actually increase during the eruption [*Aly,* 1984, 1991; *Sturrock,* 1991]. So, the question becomes one of how to open the field to the extent required by observations and at the same time decrease its energy by a sufficient amount to power the mass motions. Models which answer this question are classified as "storage and release" models. Storage refers to the slow buildup of magnetic free energy from the gradual stressing of the field by footpoint motions or mass accumulation. It is a phase of quasistatic evolution. Release refers to the highly dynamic phase when rapid energy conversion and eruption take place.

As a simple analogue, we can represent the corona by a spring attached to a rigid base, as sketched in Figure 2. On the left, the spring is in its natural, or unstressed,

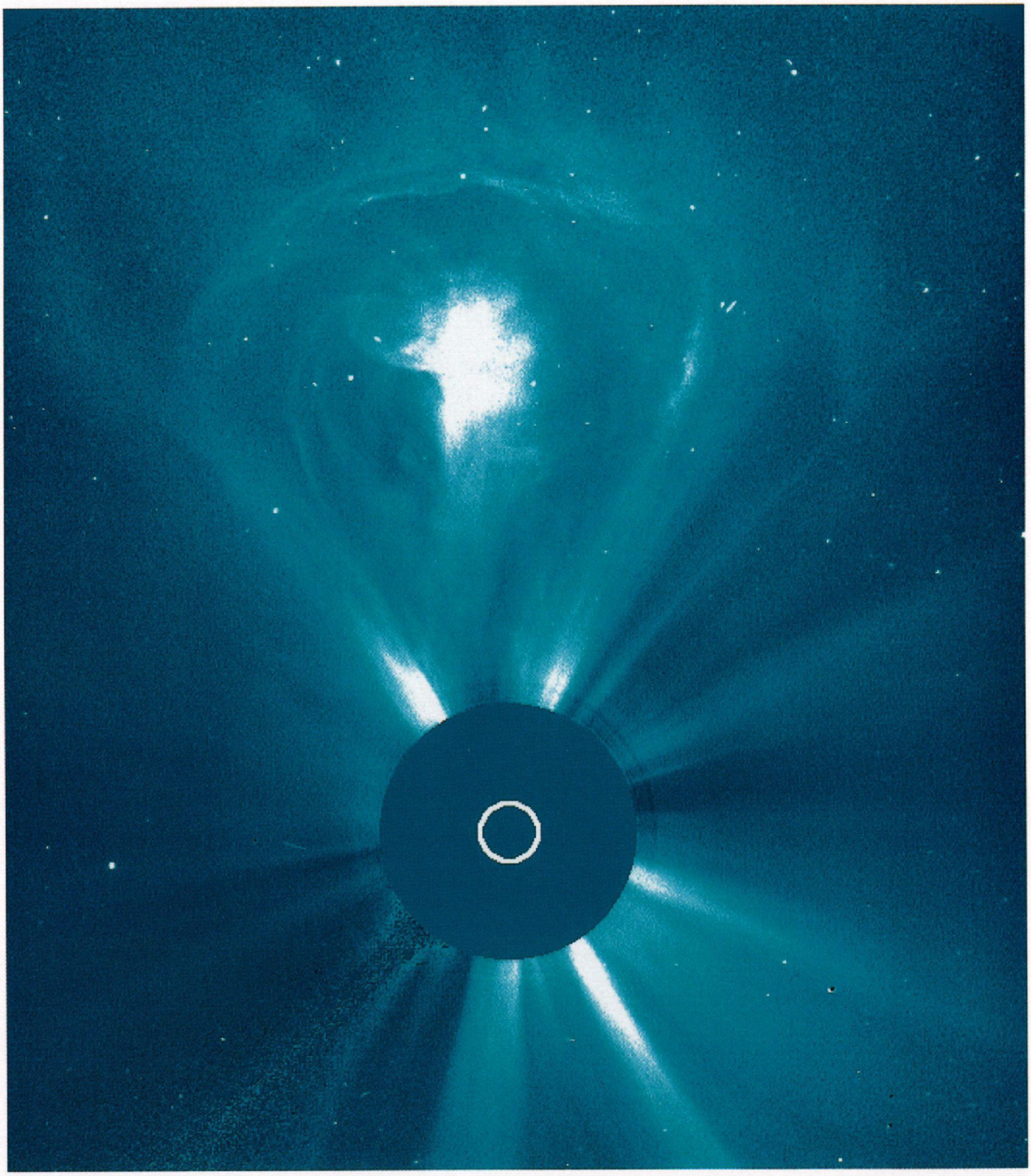

Plate 1. Three-part CME observed near the solar north pole by the LASCO C3 coronagraph on 27 February 2000. The white circle indicates the limb of the solar disk.

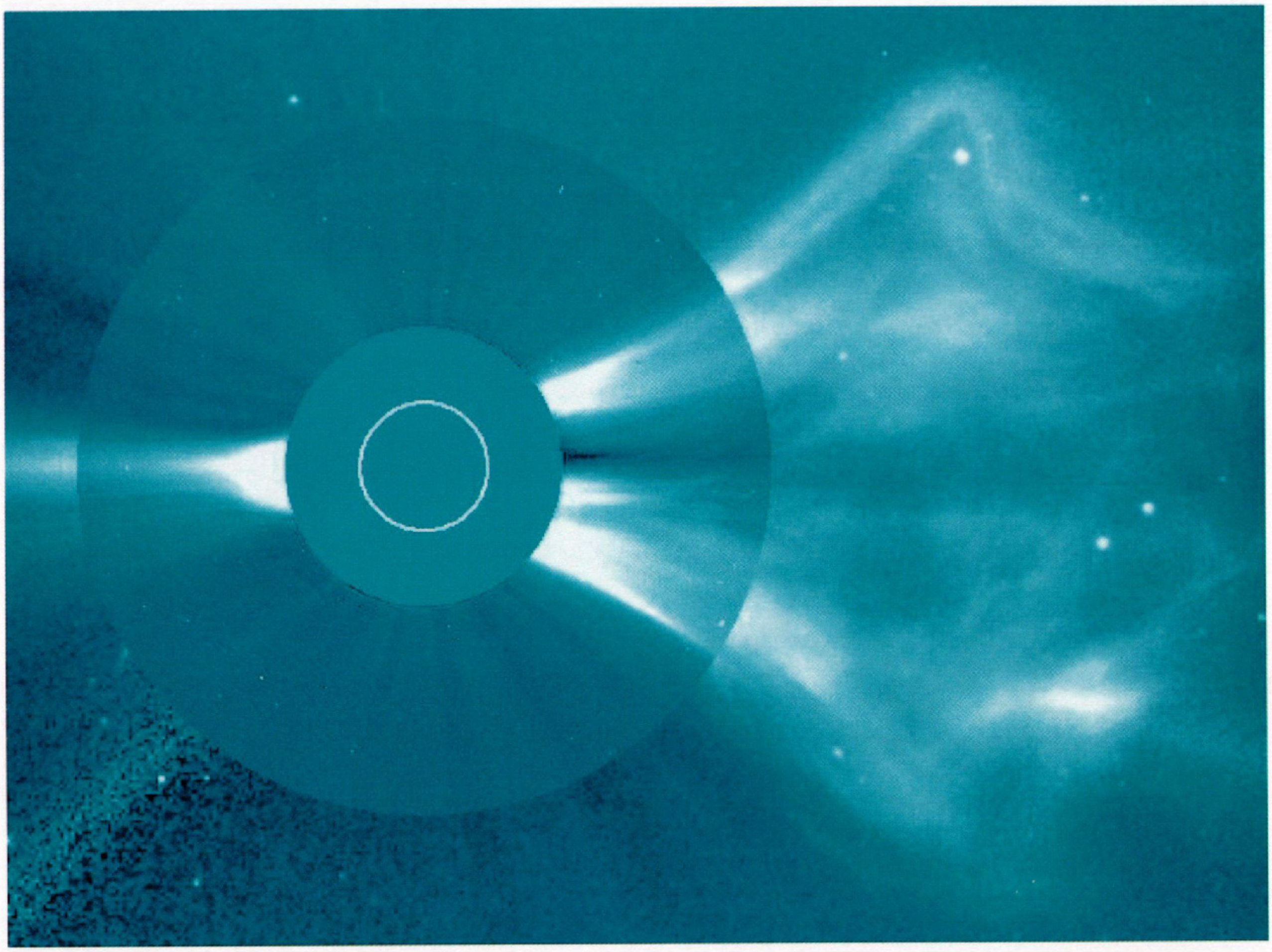

Plate 2. CME observed by LASCO on 28 November 1996. The image is a composite of C2 and C3 coronagraph images. The white circle indicates the limb of the solar disk.

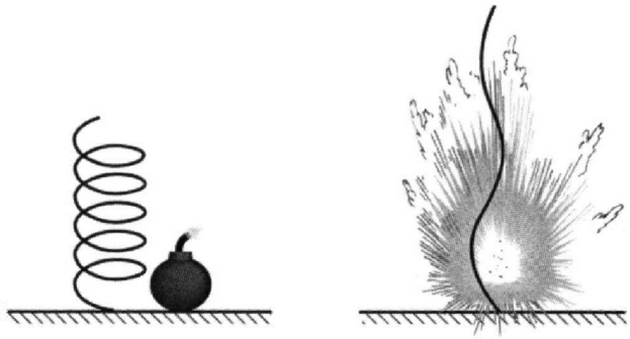

Figure 3. Thermal blast model analogue. The spring is blown open from its initial unstressed state by a sudden pressure pulse corresponding to, e.g., a solar flare.

state; in the middle, it is compressed and contains free energy associated with the stresses; on the right, it is stretched out beyond its natural length and is therefore also stressed. We refer to this last state as the erupted state for obvious reasons. For the sake of discussion, we assume that the spring has more free energy in the compressed (stressed) state than in the erupted state, so that the ordering of the energies is:

$$E_U < E_E < E_S, \tag{1}$$

where the subscripts refer to unstressed, erupted, and stressed.

In storage and release models, the system evolves slowly from the unstressed to stressed states, and then rapidly from the stressed to erupted states. Because $E_E < E_S$, it is energetically favorable for the latter transition to occur, so it can do so in an unstable fashion without any driving by external forces.

The second major category of CME models, called "directly driven" models, behave entirely differently. They bypass the intermediate stressed state and go directly from the unstressed state to the erupted state. There is no slow energy buildup phase. Because $E_E > E_U$, external drivers must rapidly pump energy into the system in real time as the eruption occurs. As alluded to above, and as we now discuss, there is little observational evidence to support this idea.

5. DIRECTLY DRIVEN MODELS

5.1. Thermal Blast

Let us now consider the five different classes of CME models. We begin with "thermal blast" models, largely for historical reasons. As represented in Figure 3, these models are characterized by a sudden release of thermal energy in the low corona. The greatly enhanced gas pressures associated with this release cannot be contained by the magnetic field, and the corona is literally blown open. This was the first explanation given for CMEs and was inspired by the fact that many CMEs occur in conjunction with solar flares. It seemed quite logical at the time to suppose that CMEs are simply a response to the impulsive energy release of the flare [e.g., *Dryer,* 1982; *Wu,* 1982]. We now know that this interpretation is not correct, at least not in a majority of cases. Improved observations have demonstrated that many CMEs are not associated with flares, and that when a flare does occur, it often begins well after the CME is underway [e.g., *Harrison,* 1986]. In many events the timing is very close, however [e.g., *Dryer,* 1996; *Delannée, Delaboudinière, and Lamy,* 2000; *Zhang et al.,* 2000].

At the risk of confusing the reader, we note that the thermal blast model is in some ways better suited to the storage and release category. It is widely accepted that flares derive their energy from the stressed coronal magnetic field, yet early simulations, and even some recent ones, did not take this into account. A thermal pulse (temperature increase) was simply input to the corona from an unspecified source. Very recently, *Krall, Chen, and Santoro* [2000] have considered a more self-consistent scenario in which hot plasma is injected into the corona from below, and they find that the resulting evolved structures do not resemble interplanetary magnetic clouds.

5.2. Dynamo

The second class of directly driven models are called "dynamo" models, because the real-time stressing of the field involves the rapid generation of coronal magnetic flux. We can represent this in our analogue system by the sudden stretching of the spring from its initial unstressed state, as indicated in Figure 4. The external driving is in this case provided by a crank and pulley system. On the Sun, the driving can take the form of rapid displacements of magnetic footpoints in the photosphere, due, for example, to the upward propagation of magnetic stresses generated deeper in the Sun. The footpoint displacements cause an increase in magnetic flux in the direction of motion (i.e., they amplify the shear component of the field). There is an associated increase in the magnetic pressure, and the system responds by inflating [e.g., *Klimchuk,* 1990]. If the driving is rapid enough, the inflation may resemble a CME.

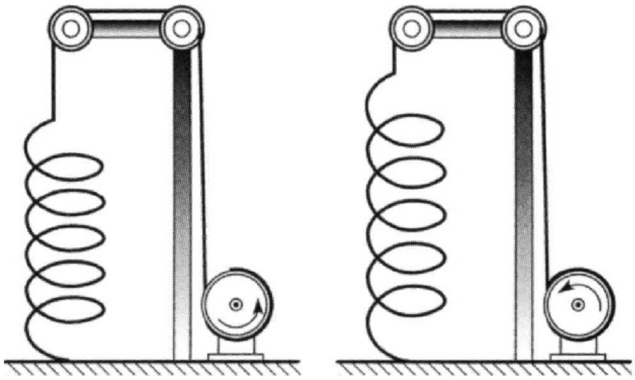

Figure 4. Dynamo model analogue. The spring is rapidly stretched open from its initially unstressed state by a crank and pulley system. On the Sun, this corresponds to a driver external to the corona (i.e., below the solar surface).

Chen [1989, 1997, 2000] and colleagues have proposed a model involving a large coronal flux rope. They prescribe a time-dependent increase in the poloidal (azimuthal) magnetic flux of the rope through a generic process they call "flux injection." Physically, this must correspond to one of three possible scenarios: 1. pre-existing coronal field lines become twisted, as described above; 2. new ring-shaped field lines rise upward into the corona from below, becoming completely detached from the photosphere once they have fully risen; or 3. new arch-shaped field lines emerge into the corona, but retain their footpoint connections to the photosphere. In a highly-conducting plasma like the corona, it is *not* physically possible for new field lines to suddenly appear; the frozen field condition requires that they come from somewhere (i.e., below the photosphere).

It is important to consider which, if any, of these three scenarios is plausible. It has been pointed out by many people [e.g., *Krall, Chen, and Santoro,* 2000] that the twisting of pre-exising field lines can produce CME-like eruptions only if the footpoint motions are at least two orders of magnitude faster than those observed. The first possibility can be safely ruled out. Ring-shaped field lines that rise into the corona from below the photosphere would be entrained by an enormous amount of mass. Such material is never seen in the corona, and furthermore, there are no obvious forces of sufficient magnitude to lift it. Possibility two is therefore also unreasonable. This leaves the third possibility of emerging loops. The subphotospheric material contained in such loops is free to slide down the legs as the loops emerge, so there is no problem with entrained mass. Perhaps the biggest issue is the requirement of increasing flux through the photosphere. Because the loops retain their photospheric connections, the total unsigned vertical flux through the photosphere must increase in order for the poloidal flux in the corona to increase. Simplistic considerations suggest that the increase in vertical flux is at least twice that of the poloidal flux. Whether this is compatible with photospheric magnetogram observations has yet to be investigated.

6. STORAGE AND RELEASE MODELS

6.1. *Mass Loading*

We now move on to storage and release models, which represent the bulk of the more recent theoretical work on CMEs. Recall that these models are characterized by a slow buildup of magnetic stress before the eruption begins. As we have indicated, shearing the magnetic footpoints is one way to do this. Another is to load the field with mass. This is represented in Figure 5, where our spring is being compressed by a heavy weight. If the weight is shifted to the side, the spring will suddenly uncoil, releasing much of the stored energy. Models which do this on the Sun are called "mass loading" models.

The existing work on mass loading has mostly involved comparisons of pre- and post-eruption equilibrium configurations in an effort to show that the mechanism can produce an energetically favorable situation for eruption to occur [e.g., *Low and Smith,* 1993; *Chou and Charbonneau,* 1996; *Wolfson and Dlamini,* 1997, 1999; *Wolfson and Saran,* 1998; *Guo and Wu,* 1998; *Low,* 1999]. It is presumed that the pre-eruption field is metastable, so that mass loading can build up sufficient free energy before the system destresses. A CME is then possible with a large perturbation. If the system were to destabilize prematurely, something less energetic than a CME would occur.

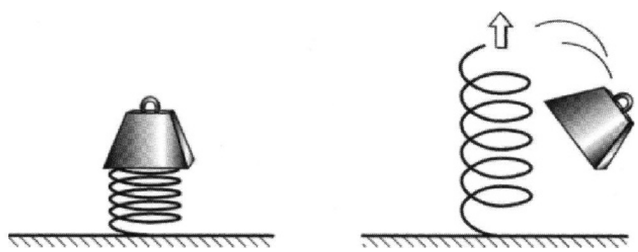

Figure 5. Mass loading model analogue. The spring is compressed by a heavy weight and explosively uncoils when the weight is shifted to the side.

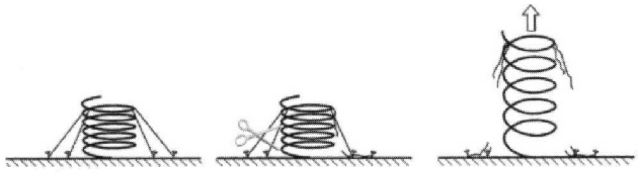

Figure 6. Tether release model analogue. The spring is held in a compressed state by rope tethers. The tethers are slowly released, one by one, until the remaining tethers break from the additional strain. The spring explosively uncoils.

The substantial mass necessary for adequate compression can come in two possible forms: higher-than-normal density coronal material distributed over a large volume, or extremely dense prominence material confined to a small volume. Prominences are structures of chromospheric temperature and density that are suspended in the low corona and that frequently erupt at the same time as CMEs. Their mass can sometimes rival that of the CME itself. It has been suggested by *Low* [1996, 1999] and others that prominences play a fundamental role in the CME process. For observational reasons, we must question whether this can be universally true: first, many CMEs occur without a prominence being present; and second, in at least some of the cases where a prominence is involved, most of the prominence mass appears to rise rather than fall, further increasing the energy requirements on the pre-eruption magnetic field [*Gilbert et al.,* 2000]. We conclude that mass loading by prominences can explain at most a subset of CMEs.

"Ordinary" coronal material may also provide the mass necessary to explain CMEs. Unfortunately, there are observational difficulties here, too. The plasma β must be larger than what we normally attribute to the corona (β approaches unity in portions of the low corona in the models of *Wolfson and Dlamini* [1997]). Furthermore, the material must be distributed in a rather specific way, with higher density material overlying lower density cavities [*Wolfson and Saran,* 1998]. Many CMEs, especially those having the classic three-part structure, originate from coronal helmet streamers that contain such cavities [e.g., *Hundhausen,* 1988, 1999], but many other CMEs come from configurations that show no obvious signs of a low-density internal region. The existence of such regions cannot be ruled out at this time because of the possibility of bright foreground or background structures obscuring the signal. It is hoped that STEREO will resolve this ambiguity.

We end our discussion of mass loading by noting that some models of this variety have been referred to as "buoyancy driven" models. Buoyancy is the tendency for low-density material to rise upward by trading places with higher density material, thus decreasing the total gravitational energy. Under these circumstances, an eruption could be completely gravitationally powered, with no need for the magnetic energy to decrease. As we have indicated, there is little observational evidence that buoyancy plays a significant role in real CMEs. Prominences, when they are present, often rise instead of fall, and cavities, when they exist, are not usually replaced by higher density coronal material until long after the eruption has occurred.

6.2. Tether Release

Mass plays no significant role in the next class of models, which we refer to as "tether release" models. As discussed in Section 3, magnetically dominated configurations generally involve a balance between the upward force of magnetic pressure and the downward force of magnetic tension. The field lines that provide the tension are sometimes called tethers. In our analogue system, they are represented by ropes that hold the compressed spring in place (Figure 6). Imagine that the tethers are slowly and systematically released, as indicated in the middle sketch. Each time a new tether is released, the strain on the remaining tethers increases. Eventually the strain becomes so great that the tethers start to break. This proceeds catastrophically, and the spring uncoils in an explosive fashion.

We note that the slightly different term "tether cutting" has been used in the past, usually in reference to the final explosive phase. We distinguish this from tether release, which is the gradual phase leading up to the explosion.

We also caution that our rope analogy for magnetic field lines must not be taken too far. When a rope is cut, two free ends are created. This can never happen to a magnetic field line, since it would imply the existence of magnetic monopoles. Instead, a pair of magnetic field lines (or two sections of a single field line that doubles back on itself) reconnect at a point of contact to produce two new field lines with different connectivity (i.e., different topology) from the original pair.

The translationally-symmetric model of *Forbes and Isenberg* [1991] is a good example of how tether release might work on the Sun [see also *Isenberg, Forbes, and Démoulin,* 1993; *Lin et al.,* 1998; *Van Tend and Kuperus,* 1978; *VanBallegooijen and Martens,* 1989]. It consists of an infinitely long flux rope and overlying arcade. Figure 7 shows a projection of the field onto a vertical plane orthogonal to the main axis. As described previously, the arcade field lines act as the tethers that prevent the flux rope from rising. Their footpoints are slowly brought together by a converging flow imposed at the photosphere. When the footpoints meet at the neutral line, they reconnect to form a new circular field line at the perimeter of the flux rope, disconnected from the photosphere (panels *a* through *c*). After enough of the arcade field lines have been converted to flux rope field lines, force balance is no longer possible, equilibrium is lost, and the flux rope abruptly rises (panel *d*).

The model of Forbes and colleagues is actually an equilibrium sequence. There is a continuous change in the field in going from *a* to *b* to *c* and then a discontinuous jump from *c* to *d*. The field in panel *d* is nonetheless a valid equilibrium, suggesting that the eruption may be aborted shortly after it begins. This is not likely to be the case in a resistive system, however. The partial eruption produces a vertical current sheet extending downward from the flux rope. Reconnection at this current sheet should allow the eruption to proceed to completion [*Forbes,* 1991; *Lin and Forbes,* 2000]. This has recently been verified in fully time-dependent 3D versions of the model that include a more realistic flux rope of finite length [*Mikić and Linker,* 1999; *Amari et al.,* 2000]. Thus, an ideal loss of equilibrium leads to fully dynamic resistive evolution.

The reconnection necessary for full eruption has an important observational consequence. It produces closed loops *underneath* the erupting flux rope. They form a new arcade that steadily grows with time as more and more reconnected flux accumulates (Figure 8). Many such arcades are observed in association with CMEs, but whether their timing, size, and location are consistent with the model predictions is not so clear [e.g., *Hundhausen,* 1988, 1999]. In many instances, the first indication of the arcade does not appear until well after the eruption has begun. Hence their common description as "post-eruption arcades" [e.g., *Klimchuk,* 1996]. Furthermore, coronagraph observations suggest that the horizontal scale of the opened field can be many times greater than that of the reconnection arcade, and this may be difficult to reconcile with the geometry of the model (although see *Delannée and Aulanier* [1999]).

6.3. *Tether Straining*

Our last class of model is called "tether straining." It is similar to tether release in that a slow evolution leads to a situation where the tethers can no longer withstand the upward forces and catastrophically break. In tether release, the total stress is approximately constant in time but is distributed over fewer and fewer tethers. In tether straining, the number of tethers is constant but the total stress increases. In both cases, the stress per tether steadily builds to the breaking point. Our analogue representation of tether straining is shown in Figure 9. The spring now sits on a platform that is slowly lifted. Ropes attached to the ground hold the top of the spring at a fixed height. As the spring becomes compressed, the strain on the ropes increases until they finally break, releasing the spring.

One example of tether straining is the "breakout" model shown in Plate 3 [*Antiochos,* 1998; *Antiochos, DeVore, and Klimchuk,* 1999]. It is fundamentally quadrupolar in nature, with four distinct flux systems that are color coded blue (central arcade), green (two side arcades), and red (overlying field). Shearing motions imposed near the equator stretch the inner field lines of the central arcade in an east-west direction. They are shown as thicker blue lines. This type of situation is well suited to prominence support [*Antiochos, Dahlburg, and Klimchuk,* 1994], so one might associate these thick lines with a prominence, although this has no direct bearing on the model.

The enhanced magnetic pressure associated with the shear causes the core of the central arcade to inflate. Red field lines and unsheared (thin) blue field lines are the tethers which counter this tendency. As the system becomes more and more stressed, the magnetic X-point above the central arcade distorts, closing like a pair of scissors to form a horizontal region of enhanced electric current (the red and blue field lines are oppositely directed). Once the stress is sufficiently great and the current layer sufficiently thin, the adjacent red and blue field lines reconnect to become green field lines that pull away from the X-point. With fewer tethers to resist, the central arcade bulges more, and a runaway eruption ensues.

The system shown in Plate 3 is global and perfectly symmetric. This need not be the case for the breakout mechanism to work. In fact, *Aulanier et al.* [2000] discuss a well observed active region eruption that appears to be due to breakout.

Another example of tether straining is the model of *Forbes and Priest* [1995]. The basic configuration resembles Figure 7, except that all of the photospheric flux is concentrated in two point sources (line sources in 3D), as shown in Figure 8. A converging flow is imposed, as in the earlier model, but because the footpoints never meet, no reconnection occurs and none of

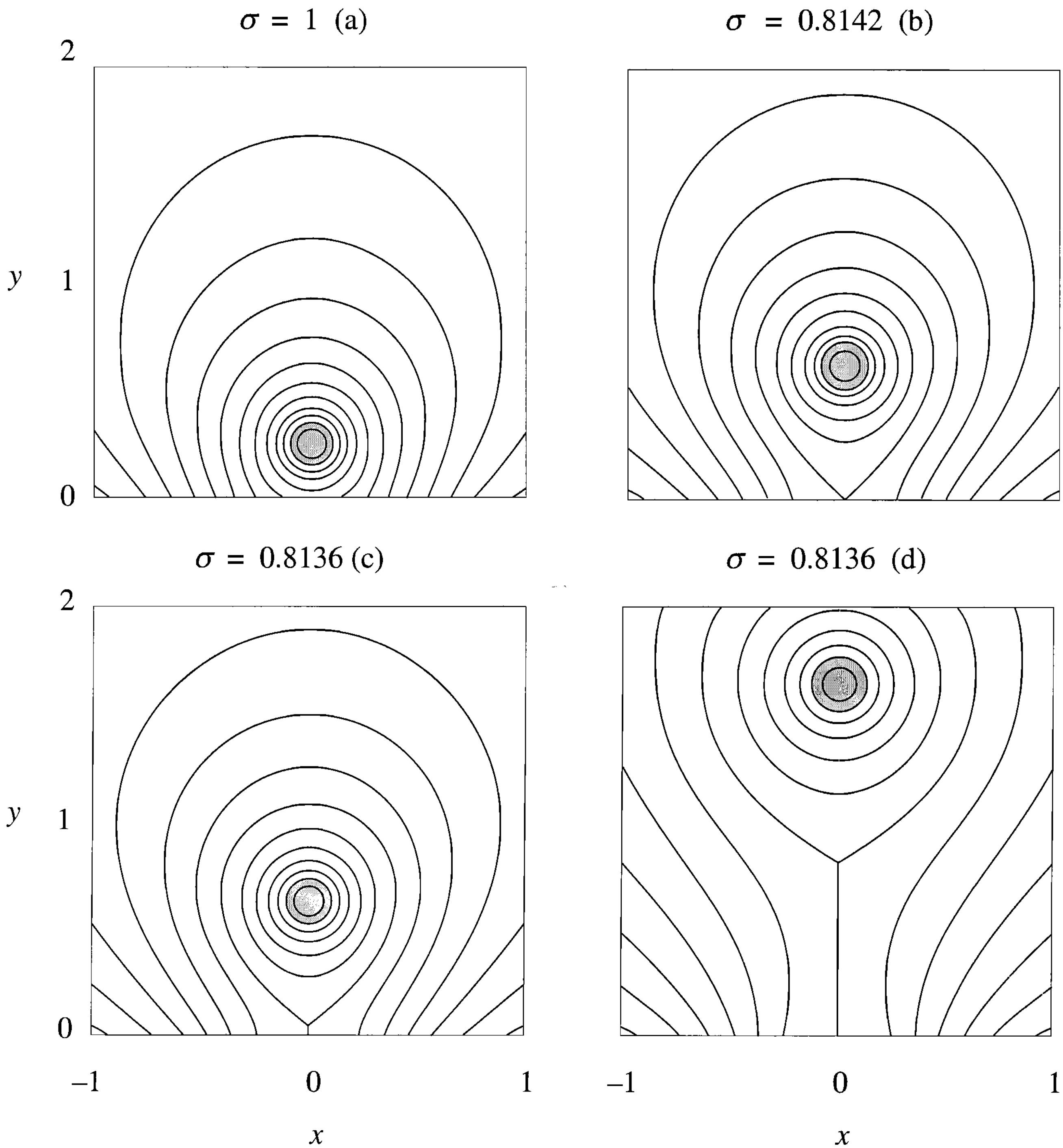

Figure 7. Equilibrium sequence showing the evolution of a flux rope and overlying arcade when the footpoints are subjected to a converging flow. The flux rope rises slowly from a to b to c and then jumps abruptly from c to d because of an ideal loss of equilibrium. It is presumed that magnetic reconnection at the vertical current sheet in d would allow the eruption to proceed to completion. From *Isenberg, Forbes, and Démoulin* [1993].

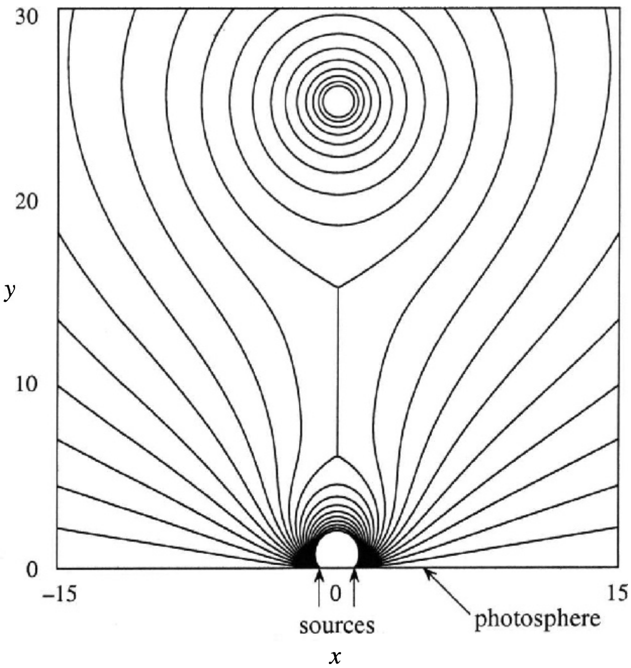

Figure 8. Magnetic reconnection at a vertical current sheet in configurations like Figure 7*d* produces a growing arcade of closed loops underneath the erupting flux rope. After *Lin and Forbes* [2000].

the tethers are released. Instead, there is a buildup of magnetic pressure underneath the flux rope as the point sources are brought closer together. This increases the strain on the tethers, and equilibrium is eventually lost. Once again, the flux tube abruptly rises, a vertical current sheet is formed, and reconnection allows the eruption to proceed.

One of the important differences between this and the breakout model is that this model requires reconnection underneath the erupting structure, whereas breakout requires reconnection above it. Breakout thus avoids the observational difficulties discussed earlier. It may face other observational challenges, but detailed comparison with data has only just begun. We note that breakout should be accompanied by post-eruption arcades, since it too produces a vertical current sheet, but this is only a secondary process not integral to the eruption process, and the arcades might not appear until long after the eruption is underway.

Other examples of tether straining include, but are not limited to, the sheared arcade models of *Mikić and Linker* [1994], *Linker and Mikić* [1995], *Choe and Lee* [1996], and *Amari et al.* [1996], and the flux rope models of *Wu, Guo, and Wang* [1995] and *Wu et al.* [2000]. Like *Forbes and Priest* [1995], these models ultimately require reconnection at the base of the arcade, but unlike *Forbes and Priest*, the eruption tends not to happen until the arcade has become highly distended during the quasistatic buildup phase. It is well known observationally that streamers often swell for 2-3 days leading up to a CME, but generally not to the degree of the simulations. How serious this discrepancy is must be looked at more carefully.

7. SUMMARY AND CONCLUSION

We have proposed a classification scheme for CME models that we believe identifies and differentiates the essential physical attributes of the models. Storage and release models are powered by magnetic free energy that is slowly built up in stressed configurations by footpoint shearing motions and/or the accumulation of mass. The fields could also be pre-stressed before they emerge (slowly) from below the solar surface. In marked contrast are the directly driven models, which acquire the energy for eruption in real time.

We have cited many specific models that are published in the literature, although we have not attempted a complete compilation. We have excluded some models from discussion because they are not so easy to classify within our adopted scheme. For example, *Sturrock et al.* [2000] describe a magnetic configuration that is metastable and thus susceptible to eruption with a large perturbation, but they do not address whether the configuration is achieved through a tether straining or tether release type of process. Similarly, *Moore*

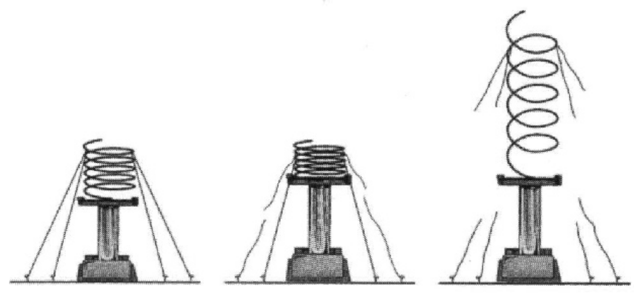

Figure 9. Tether straining model analogue. The bottom of the spring is slowly raised on a moveable platform while its top is held fixed by rope tethers attached to the ground. The strain on the tethers builds to the breaking point, and the spring explosively uncoils.

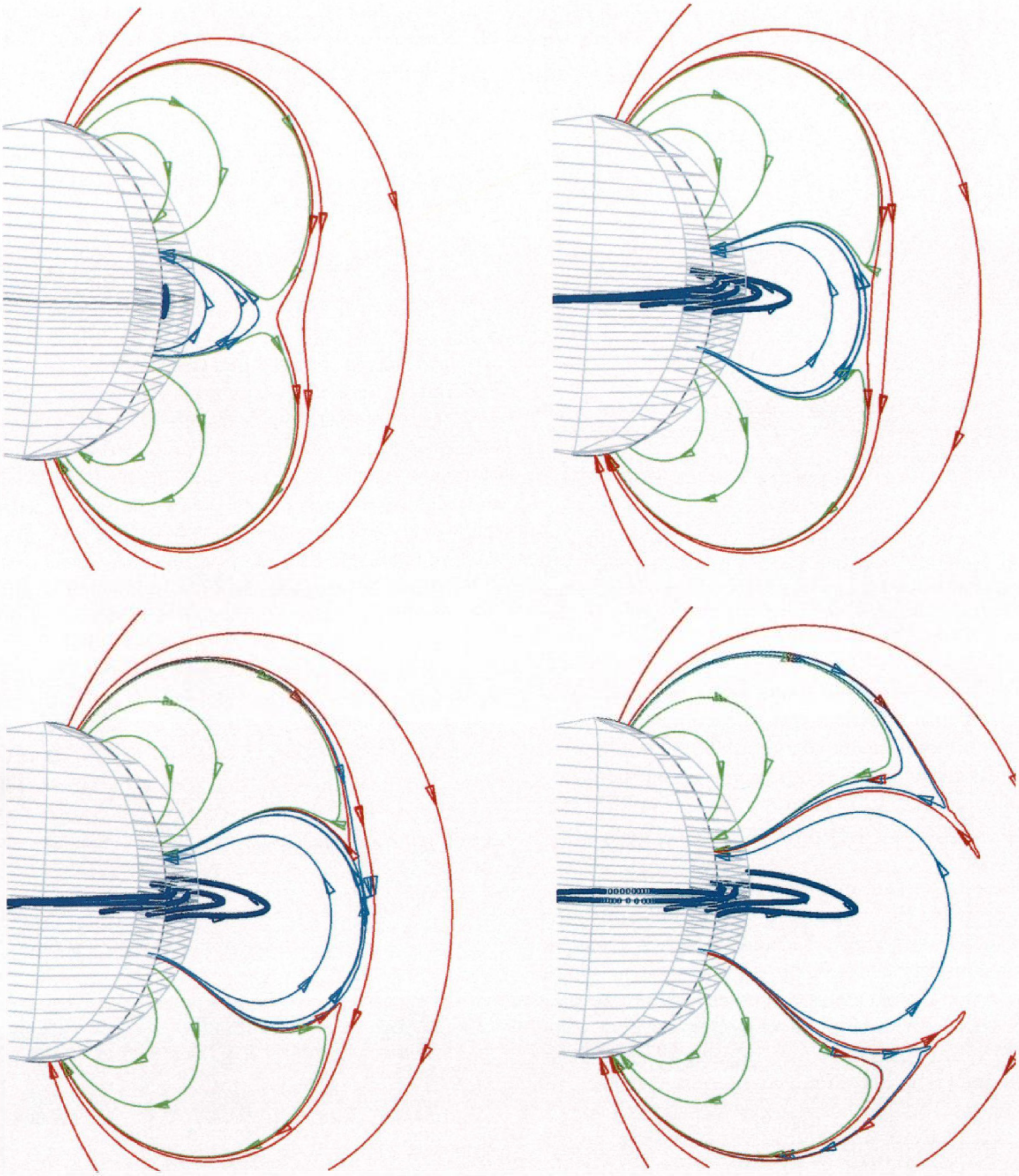

Plate 3. Breakout CME model showing the evolution of a quadrupolar system in which the inner part of the central arcade are sheared by antiparallel footpoint motions near the neutral line (equator). The field bulges slowly until the red and blue field lines begin to reconnect, and a runaway eruption ensues. From *Antiochos, DeVore, and Klimchuk* [1999].

[2000] describes a possible eruption scenario, but does not consider the slow evolution leading up to the eruption.

We have demonstrated that many models have difficulty explaining one or more aspects of the observations. In some cases the inconsistency is quite severe, whereas in others it is relatively modest. The real Sun is very complex, and all of the models are highly idealized by comparison. Whether the addition of more complexity to the models will improve their agreement with the observations remains to be seen.

It would be nice if there were a universal explanation of CMEs, but we must leave open the possibility that more than one model might be correct. The fact that prominence mass loading cannot be important in all events does not rule it out as the primary mechanism in some cases. As we have already indicated, observational evidence is accumulating for at least two different types of CMEs on the Sun.

It is clear that much more work needs to be done, both theoretically and observationally. On the theoretical front, models must be made more realistic and constructed on the basis of actual observations, such as photospheric magnetograms and velocity maps. Although challenging, this should now be possible with the recent advances in computer hardware and software. Adaptive mesh refinement (AMR) schemes, which provide high numerical resolution only where it is needed, are especially promising in this regard. Not only can AMR simulations handle more complex boundary conditions, but they can also treat magnetic reconnection in a much more realistic fashion.

On the observational front, specific and meaningful tests of the models must be devised. These should include existing data, which is far from fully exploited, as well as new data to come from missions like STEREO, *Solar-B, Solar Probe*, and the *Solar Dynamics Observatory*. Among the key questions that must be addressed are the following. Does the pre-eruption structure necessarily have a flux rope topology? Does it necessarily have a low-density cavity? Does eruption begin as an ideal process, in which case there is no reconnection heating in the early stages? Does reconnection occur above the main erupting structure, as in the breakout model, or below it, as in the models represented in Figures 7 and 8? Are all erupting systems multipolar, as required for breakout, or can bipolar systems also erupt? Is there a particular photospheric flow pattern (e.g., converging flow) leading up to eruption?

The realization of the practical importance of space weather has ushered in a marvelous new era for space physics. With carefully planned missions and a strong theory, modeling, and data analysis program, we can hope to make great progress in the exciting years ahead!

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