Coronal Mass Ejection [and Discussion]

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Coronal mass ejection

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We summarize the observational aspects of the transient solar coronal features known as coronal mass ejections. Recognizing the importance of understanding this form of solar activity, particularly in the light of relations to flare and prominence activity, and geomagnetic effects, we consider the spectrum of models which have been used to describe these events and assess their viability. We find most models to be unphysical and all represent a gross over simplification of solar conditions. In conclusion we set up a cartoon model which best fits the observations and which we feel should be further developed.

1. Introduction

A coronal mass ejection (CME) is a discrete event which involves the release of up to 10^{13} kg of matter from the Sun as a loop or bubble shaped structure; this matter is ejected from the corona at speeds of anything between 10 km s^{-1} and 2000 km s^{-1}. Such features are related to, and may signal the primary processes leading to, flare activity and prominence eruptions, though these relations are far from clear. The study of CMEs not only provides us with an interesting mathematical problem but suggests a method for the prediction and a better understanding both of solar chromospheric activity, including flares, and geomagnetic activity. Various aspects of CME activity have been reviewed over the last few years (see, for example, Kahler 1987; Hundhausen 1988; Harrison 1991) and it is the purpose of this paper to summarize the observational aspects in such a way as to allow a thorough assessment of CME models. To this end, we provide a comprehensive list of the principal observational features of CME activity. We then discuss recent modelling methods, highlight problem areas, and discuss their application to the CME phenomenon.

2. Observational aspects

Figure 1 shows four images of a CME event observed in 1980. We have been observing such activity for two decades now, and the reviews listed in the introduction can be used to locate detailed observational studies of various aspects of CME activity. In this particular study we are concentrating on the performance of theoretical models of CME activity and thus in this section we simply list, point by point, what we consider to be the salient features of CME activity. The ability of modelling techniques to address these points will be used to assess their value. We note that some aspects of CME activity which are not well established, or are the subject of some debate, are not included in this list, to avoid confusion at this time.

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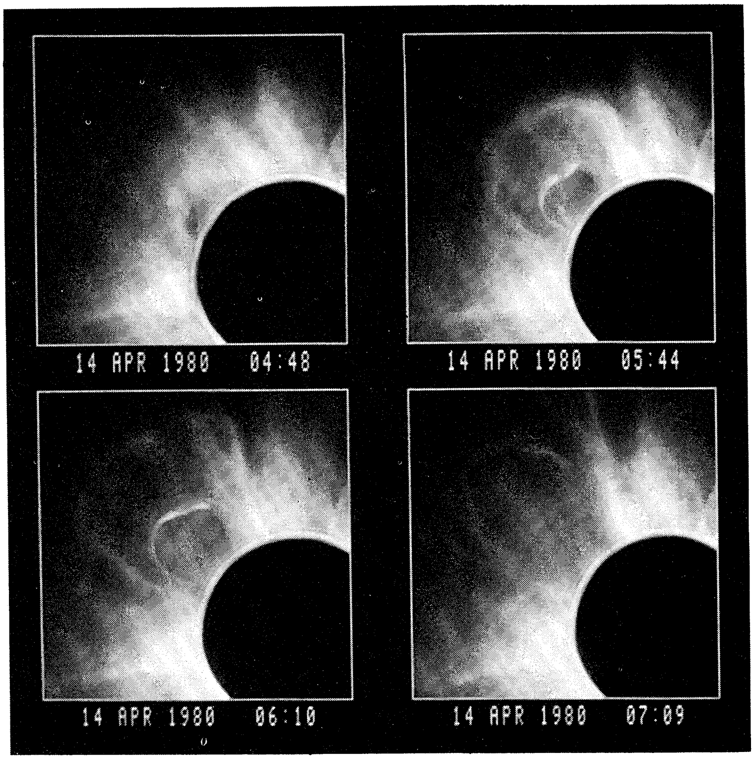

Figure 1. The coronal mass ejection of 14 April 1980 as observed by the High Altitude Observatory's coronagraph on the *Solar Maximum Mission*. The Sun is obscured by an occulting disc of diameter $3R_\odot$.

(*a*) CME *structure*

(i) A CME commonly consists of a three part structure, a smooth, well defined outer loop or bubble of enhanced density, followed by a depleted region or cavity, within which sits an erupted prominence (e.g. figure 1). We know that prominences follow magnetic inversion lines in the photosphere.

(ii) The footpoints of the outer loop are separated on average by about 45°, i.e. much larger than an active region or flare (few degrees at most). The distribution of spreads ranges from a few degrees to a full 360°. The footpoints are rarely seen to move apart significantly (perhaps to an accuracy of *ca.* 10°) even down to the lowest observations at $0.2R_\odot$ above the limb. Thus, the source structure of the CME must be larger than an individual flare or active region.

(iii) The prominence structure is not always detected. This may indicate that the magnetic structure which forms a prominence has not erupted as part of the CME or that such a structure is just not visible due to the lack of cool material which characterizes such an event. When the prominence is detected it may rise symmetrically or asymmetrically within the CME outer shell and even be highly chopped up without any influence on the smoothness of the outer shell.

(iv) The cavity may not always be present and the CME may appear as a tongue of enhanced density.

(v) At the lowest altitudes (less than $0.5R_\odot$) the outer bright shell has often not yet formed, we simply seen an ascending void.

(vi) The form or behaviour of a CME is no indicator of whether it will contain a prominence or not.

(vii) CME spans show a weak correlation with the angle of the line of sight with respect to the axis of any associated prominence, suggesting that the CME is slightly elongated in the direction of the prominence axis. This suggests that we are not dealing with a single loop or flux tube erupting, and since a bubble is not a realistic magnetic configuration, we must consider the eruption of an arcade or part of an arcade which may be overlying a prominence.

(viii) After a CME has left the corona, field lines appear to remain open for some considerable time, suggesting that the CME may still be connected to the Sun for many hours or even days.

(b) CME *dynamics*

(ix) The velocity of ascent of the top of the outer shell of the CME is usually constant or displays a modest acceleration, never deceleration, and sits in the range 10–2000 km s^{-1}. The average velocity lies at about 300–350 km s^{-1}. A large fraction cannot involve shocks since the sound speed and Alfvén speed lie in the few hundred kilometres per second region. Many do not achieve an escape speed.

(x) The velocity of ascent of the prominence is also commonly constant or shows a modest acceleration, but it is always less than the ascent velocity of the overlying CME shell.

(xi) There is no such thing as a coronal mass injection (CMI). We see CMEs leaving the corona, they do not fall back and similar events are not seen in reverse.

(xii) Given a snapshot of a CME there are no clear features which can be used to identify whether it is a fast or slow event.

(c) *Other properties*

(xiii) The rate of occurrence of CMEs has been under some dispute but certainly lies in the range 0.1 to 2 per day, depending on the stage of the solar cycle and the particular dataset used for the estimate.

(xiv) The mass ejected through a CME is commonly of order 10^{12}–10^{13} kg. Given about one per day this is of order 3% of the solar wind flux.

(xv) The energy content (kinetic, potential) of a CME is commonly of order 10^{23}–10^{25} J. This ranges from the equivalent energy of a small flare to the largest flares.

(d) *Relation to other activity*

(xvi) Flares are often found in association with a CME onset. They are not distinct from flares apparently unassociated with CMEs. This may suggest that all flares are in fact associated with some kind of CME activity, but that we do not view many CMEs because of sensitivity problems. If, for example, we use the word 'flare' loosely to include all X-ray bursts, we have not been able to show that a CME occurs without a flare.

(xvii) Unless the CME launch is from a high altitude, which ought to be seen in coronagraph fields of view, it seems that the CME onset precedes the flare onset, perhaps by up to several tens of minutes.

(xviii) The flare may lie anywhere under the CME span but commonly lies adjacent to one footpoint.

(xix) In the pre-flare period we frequently, if not always, witness soft X-ray precursor activity, a weak burst from a magnetic structure much larger than the flare but probably not as large as the CME structure. The flare lies within one portion of the precursor structure. The precursor burst can be evident at remote points at almost identical times, suggesting a coronal driver.

(xx) CMEs are often preceded by an expansion of an overlying streamer structure over a period of several days, i.e. the corona is not surprised by the CME but is expecting it!

3. The approach to CME modelling

The principal question we are asking ourselves is: how does the Sun expel magnetized plasma into space? It has become clear that, to understand the expulsion of mass from the Sun in the CME events, we must focus our attention on the activity, equilibrium and stability of large-scale coronal magnetic loops. Given such structures, to mimic a CME we have four possibilities: (*a*) the magnetic configuration may be stable and is subject to a large amplitude perturbation; (*b*) the configuration evolves from a stable to an unstable equilibrium and is disturbed by a small-scale perturbation; (*c*) the configuration evolves from a stable equilibrium to a position of no equilibrium; and (*d*) the configuration evolves through a sequence of equilibria such that small gradual changes in the photosphere give large, rapid changes in the corona (see the discussion by Klimchuk in Harrison *et al.* (1989)). In solar terms, the first category can only relate to flare driven CMEs and we may reject this mechanism on the basis of overwhelming observational evidence, as given in points (xvi)–(xviii) and (ii) above. The last category (category (*d*)) also has worrying features. Evolution through a sequence of equilibria suggests that the process is reversible and we do not see CMIs (point (xi)) as mentioned above! Furthermore, an event which is basically dynamic in nature would rarely be expected to be described by equilibrium conditions!

The observational evidence points to CME sources being large-scale structures, most likely loop arcades (at least not a single loop or flux tube), though the use of the word arcade does not suggest anything more than a system of field lines along some portion of a magnetic inversion line at the photosphere. It appears to be the case that there is necessarily a hierarchy within the magnetic configuration to cater for the smaller scale structure seen before related flare activity, and the smallest scale loop structures that are involved in the flare. We note that flares occur in active regions and thus stress that enhanced magnetic complexity may be a necessity for a CME, though this may only be evident in what is in effect a very small portion of the structure which involves the CME.

Given this framework, we must now explore the available models. However, we will ignore flare-driven models (category (*a*) above) on the grounds that they are not meaningful in the context of the CME onset, and refer to reader to studies such as Wu *et al.* (1978, 1983), Maxwell *et al.* (1985) and Dryer *et al.* (1979) and the comments of Harrison & Sime (1989).

Various analytical and numerical models have been suggested for CME activity. It is clear that to consider the magnetic behaviour of the solar atmosphere fully we must examine the simple one-fluid ideal magnetohydrodynamic (MHD) equations (see, for example, Low 1990). We use the symbols $\boldsymbol{B}$, $\boldsymbol{v}$, Φ, p, ρ and γ to denote the magnetic field, velocity, gravitational potential, pressure, density and the adiabatic index. First, the momentum equation, given as

$$\rho\,\partial\boldsymbol{v}/\partial t+\rho(\boldsymbol{v}\cdot\nabla)\,\boldsymbol{v}=\boldsymbol{J}\times\boldsymbol{B}-\nabla p-\rho\nabla\Phi \qquad (1)$$

describes the forces on the plasma. The right-hand terms are due to the magnetic, pressure and gravitational forces. Any electrical force is neglected through the assumption that the plasma is neutrally charged.

By considering Ohm's law, along with Maxwell's equations, assuming a small displacement current and a large electrical conductivity, we find equation (2), which is effectively Faraday's law of induction.

$$\partial \boldsymbol{B}/\partial t = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}). \tag{2}$$

Mass conservation is considered by the form

$$\partial \rho/\partial t + \nabla \cdot (\rho \boldsymbol{v}) = 0, \tag{3}$$

and, finally, energy conservation is ensured by inclusion of the equation,

$$\frac{\mathrm{D}}{\mathrm{D}t}\frac{p}{(\gamma-1)\,\rho} + p\frac{\mathrm{D}}{\mathrm{D}t}\frac{1}{\rho} = \sigma, \tag{4}$$

where $\mathrm{D}/\mathrm{D}t$ is the lagrangian derivative and σ represents departures from adiabaticity (see, for example, Low 1990).

To achieve static equilibrium we set $\boldsymbol{v}$ and $\partial \boldsymbol{v}/\partial t$ to zero and require a balance between the Lorentz force and the pressure and gravitational terms of equation (1). Since the majority of the time the complex system of magnetic structures which are clearly seen in wavelengths characteristic of coronal temperatures (X-ray, extreme ultraviolet) are apparently static, this condition must commonly prevail.

To proceed with a CME model we would have to choose between a numerical or analytic approach. For the analytical and some numerical cases the trend is to eliminate one dimension to simplify the system sufficiently to provide solutions: in other words, we are limited by our mathematical techniques. This has been done either by ignoring the third dimension or by making one dimension invariant so that we are effectively dealing with a two-dimensional problem.

Let us consider an arcade with the photosphere in the xy plane at $z = 0$, and let the altitude above the photosphere be denoted by positive z values. The photospheric magnetic inversion line is considered to be straight and directed along the x axis. It is common to let the direction of invariance be along the x axis. We may write $\partial B_x/\partial x = 0$, and since $\nabla \cdot \boldsymbol{B} = 0$, we may write the solution

$$\boldsymbol{B} = (B_x, \partial A/\partial z, -\partial A/\partial y),$$

which is independent of the coordinate x. Because there is no gravitational or pressure force acting along the axis of the magnetic structure, x, the Lorentz force in that direction must vanish. This demands that B_x is a function of A.

This technique has allowed us to consider the equilibrium and stability of a coronal magnetic system in one plane, though we must recognize that we have selected a special solution in order to do it. The force balance in that plane can be described by the forms,

$$\partial p(A,z)/\partial z + \rho g = 0,$$

and

$$\nabla^2 A + \mathrm{d}[\mu p(A,z) + \tfrac{1}{2}B_x^2(A)]/\mathrm{d}A = 0. \tag{5}$$

Gravity is taken to have a uniform acceleration g in the $-z$ direction. The function A is a scalar. It is consistent along each magnetic line of force and is in fact the x component of the magnetic vector potential. Contours of constant A in the zy plane represent the projections of the field lines on that plane, so this method is useful for examining the evolution of any particular coronal structure.

We often come across one more simplification to make the problem more tractable, and that is to assume that gravitational and pressure forces may be neglected and that the plasma is in a force-free state, i.e. $\boldsymbol{J} \times \boldsymbol{B} = 0$.

The approach described above has been taken by several authors, for example, Low (1977, 1981, 1982), Wolfson (1982), Jockers (1978), Priest & Milne (1980), Priest (1988), though some are not explicitly directed to CME activity and they are not all force free. All involve the examination of quasi-static equilibrium solutions, that is there is no built in time dependence and an equilibrium is sought for each iteration of the model. For example, in Low's model he constructs snapshots of an arcade with selected footpoint positions. As the footpoints separate or shear due to photospheric motion, under certain conditions, the top of the arcade ascends rapidly. This is akin to point (*d*) of the list at the start of this section. Certain conditions will also lead to a point beyond which no solutions can be found. It is assumed that this represents a loss of equilibrium, and it is shown that the top of the arcade achieves an infinite altitude. It is claimed that this is the CME. The analytical models due to Priest & Milne (1980) and Wolfson (1982), and the two-dimensional numerical model due to Jockers (1978) are similar, though Jockers expresses some doubt over claims from the analytical work that a non-equilibrium condition is met.

In similar analytical models some workers include scenarios which involve more complex magnetic configurations with a magnetic arcade which may or may not contain plasma surrounded by a non-magnetic region containing plasma. One such model is due to Priest (1988), whose arcade is void of plasma and is surrounded by a non-magnetic, isothermal atmosphere in hydrostatic equilibrium. He describes a potential field ($B_z = 0$) which is invariant along the arcade axis and considers the balance of pressure at the interface between the arcade and the atmosphere, i.e. the magnetic pressure of the arcade versus the plasma pressure of the atmosphere. By altering the width of the arcade, or the base flux, or external plasma pressure, whilst keeping the other two fixed, the equations describing the system allow a solution where the top of the arcade approaches infinity. He argues that this is a CME driven by increased magnetic flux, changes in pressure or photospheric motion. Forces due to gravity are not considered. In the same report, Priest (1988) discusses an arcade with a straight axis and a cylindrical magnetic field which contains plasma. The plasma and magnetic forces at the boundary balance the external pressure. There is no solution when the internal pressure exceeds a certain value: this is described as an eruption due to non-equilibrium.

A further analytical model produced by Wolfson & Gould (1985) produces a similar point beyond which they claim there is no equilibrium and in this case the driver is simply the increased density in the magnetic structure. They also use a quasi-static approach with a sequence of equilibrium solutions based on an axisymmetric relation derived from the momentum equation and Ampère's law.

Few models take into account the three part CME structure, they are usually only concerned with the stability of a loop or arcade. However, this has been attempted by Steele & Priest (1989). They defined an overlying arcade within which is a cavity and prominence structure. They derive a sequence of static equilibria which involve an increase in the altitude of the structure as flux is increased at the base. When a threshold flux is reached the equilibrium is either lost or becomes unstable.

Most but not all of the models discussed so far make use of the generating function method. In this class of modelling it is common to neglect the pressure term in equation (5) and note the family of solutions $B_x = \lambda F(A)$, where $F(A)$ is a selected functional relation. Solutions can be computed for various values of the constant λ. This method commonly leads to the concept of a loss of equilibrium when λ exceeds a critical value beyond which the above equation no longer has solutions (see, for example, Low 1977; Priest 1988).

There has been recent doubt concerning the generating function method regarding global equilibrium. Klimchuk & Sturrock (1989) argue that it does not fully consider the boundary conditions for the footpoint displacement. For a particular example, they show that the use of Clebsh variables, which they claim does properly consider the footpoint location, they are able to show that the field evolves continuously, with no sudden change or loss of equilibrium, beyond the critical shear value given by a generating function method.

We have briefly mentioned the two-dimensional numerical model due to Jockers (1978). Although many of the other numerical approaches come into the 'flare drives CME' category there are some valuable contributions to the CME question such as Klimchuk & Sturrock (1989), Zwingmann (1987) and Steinolfson (1990). Klimchuk & Sturrock use a force-free magneto-frictional method. That is, with given footpoint positions, a guess at the field configuration is relaxed to a force free state. Again, quasi-static evolution is considered by varying footpoint locations. They find that an arcade (which is again invariant along the axis) displays an ascending or expanding behaviour as the footpoints are sheared with respect to one another. They see effects similar to those of Low (1977) but do not find a loss of equilibrium, merely a continuation of well-behaved equilibria. They feel this is due to a thorough treatment of the boundary conditions.

Steinolfson (1990) has produced an impressive model for shear induced coronal evolution. It is a numerical simulation in the meridional plane of a spherical coordinate system. He starts with a dipole in a static, exponential atmosphere and introduces shear by azimuthal motions in opposite senses on each side of the equatorial plane. He includes a continuous iterative feedback between the instantaneous coronal magnetic field and the field line footprints which forces the field to move with the surface motion; that is, there is no 'resistive slippage'. Failure to do this in earlier models resulted in a system with no eruptive behaviour. He finds two stages of activity in the corona. First the structure expands outwards at about the shear speed and then it expands more rapidly until it exceeds the characteristic Alfvén velocity. As an example, with a 2.6 km s^{-1} shear velocity and a beta of 0.2, the eruptive phase was produced after 21 h when the footpoint shear separation was $0.6R_{\odot}$.

Most models that have been discussed so far simply consider the stability and equilibrium of an arcade. To include the prominence association one would have to assume that the prominence eruption is driven by the loss of equilibrium and alteration of the overlying structure. On the other hand, some models consider the prominence stability and evolution and if these are to drive a CME then they must be responsible for destabilizing overlying magnetic structures. This point is often ignored and the stability and evolution of an isolated prominence structure considered. Examples of such prominence models are given by Martens & Kuin (1989) and Vrsnak (1991). References to further models can be found in these reports. As an example, we consider the Martens & Kuin numerical model, which is designed to describe the onset of a prominence and a two-ribbon flare. As mentioned, the lack of consideration of the properties of the CME suggest that some extension of this work is necessary. They use a dynamic evaluation of a circuit model which includes a current signifying the prominence and a current sheet between the prominence and the ambient field. The balance on the prominence plasma between the Lorentz forces and the gravitational component is considered and an eruption is found when the current strength is increased beyond certain values.

We do not have the space to discuss every model pertinent to CME and prominence activity, but by describing the details of the selected models and including remarks on related studies, we feel that the principal features of most if not all available models are covered. Therefore, we now move on to a discussion of the relevance of these models to a real understanding of CME activity.

4. Comments on the models

Clearly we have no problem is describing how the solar corona may expel magnetic loop systems, but are the described scenarios rather exotic for solar situations, and have the simplifications, assumptions and exclusion of some features made the models useless in the context of CME/flare activity?

There are many points of considerable concern, and it is not always possible to assess their significance when discussing the viability of certain models. Certainly the lengths which we go to describe a two-dimensional, symmetrical picture are perhaps throwing away much of the physics. The generating function method and similar approaches are derived from a special solution of the MHD equations. Can we justify the inclusion of a direction of invariance, i.e. $\partial B_x/\partial x = 0$, when we know that flares and CMEs are intimately related and flares occur in regions of great magnetic shear which is clearly highly variable along the inversion line? This may actually be a requirement for a flare and thus a CME. Furthermore, there is no such thing as a straight axis to a prominence, and correlations with activity and the curvature of the inversion line have been noted on several occasions. The use of potential fields or cylindrical fields would seem to be irrelevant to solar conditions in general, and especially for fields associated with activity.

Still considering the structural aspects, the three part CME structure is rarely included (the work of Steele & Priest is to be applauded on that score!). Also, overlying and adjacent magnetic structures are usually ignored, yet CMEs must interact with streamers and possibly nearby arches. This may be central to the CME onset. Certainly a lack of consideration of any magnetic field outside the arcade is totally unrealistic.

Some models assume that the plasma plays a passive role to the extent that it can be ignored, either inside or outside of the magnetic arcade. This may be a dangerous assumption.

Most models determine static or quasi-static solutions to the MHD equations, simply searching for sequences of equilibria in order to mimic temporal dependence. A CME certainly represents a dynamic state so an equilibrium analysis may be pointless. However, the models that suggest a point beyond which there is no equilibrium, merely construct the conditions for a CME but cannot describe its subsequent behaviour or structure. Is this a realistic approach?

Some issues specific to certain models should be noted. For example, Low's model suggests that an arcade driven upwards by footpoint separation should be such that the footpoint separation will be observable. This is not supported by observation (point (ii)). Wolfson & Gould's model involving mass flux destabilizing the system cannot be the case in general because CMEs observed low in the corona have not developed enhanced outer loops but are depleted (point (v)): they appear to be ascending magnetic structures which have not yet swept up or collected material out of the ambient corona. Steinolfson's picture appears to require shear of order a significant fraction of a solar diameter for eruption, is this realistic? Models similar to those of Martens & Kuin, where the CME is driven by the prominence are subject to criticism simply because there is a large class of CMEs which have no observed prominence and the velocity, asymmetry and topological behaviour of the prominence relative to the CME shell in the other events is not suggestive of such a scenario (points (iii), (vi), (x) above).

Beyond those points already made, more assumptions abound. Force-free conditions and neglecting gravity are two which are commonly used.

In our opinion the most severe fault is that all of the models appear to miss one very basic feature. By definition the active regions and active phenomena of the Sun are magnetically complex yet the models we use are all simple loops or arcades. Complexity appears to be a necessary condition for most if not all active solar features, so to describe a feature of solar activity in relatively inactive conditions with a simple geometry appears to be meaningless. For example, we associate flares with CMEs and flares are associated with active regions containing strong fields and areas of great magnetic shear. The inclusion of a flare appears to add asymmetry and complexity in a way that no models predict. If we believe that a 'flare' (in the most general interpretation of the word) is a necessary or common component of a CME, the models are all non-starters.

A CME is of course, a time dependent, three-dimensional feature. Much of this assessment is suggestive of the fact that we may not expect to realistically describe a CME using equilibrium solutions in (approximately) two dimensions. Since for the analytical case we are forced to use special solutions, this may mean that we are forced to accept a numerical approach for the present.

5. Conclusions

Let us build a realistic cartoon model which reflects the observational aspects of a CME. Figure 2*a*, *b* shows an initial configuration that caters for the hierarchical magnetic structure displayed by the flare, prominence, precursor activity and CME activity. The largest structure, which will be the source of the CME, must have a scale length of (on average) several tens of degrees (hundreds of thousands of kilometres). It may link two active regions or simply have roots in an active region and remote quiet sites. It should not be regarded as a flux tube but as part of an arcade since magnetic field must pervade the whole atmosphere. We can, of course, only draw representations of some of the field lines. We also show some overlying structure, in this case a streamer. The intermediate magnetic structure will be the source of the precursor and it may be rooted at a remote site within or beyond the active region. The active region itself is drawn as an arcade of loops of scale-length 10^4 km.

The activity must ultimately be driven by the complexities and they are most enhanced in the active region. Let us shear the active region arcade. We know that such activity is commonly associated with flare activity. From studies by various authors, notably Klimchuk (1991), this means that the active region arcade will become inflated (figure 2*c*). This activity may lead to reconnection within the active region arcade resulting in prominence formation as described by van Ballegooijen & Martins (1989). Whether prominence formation takes place or not, the interaction

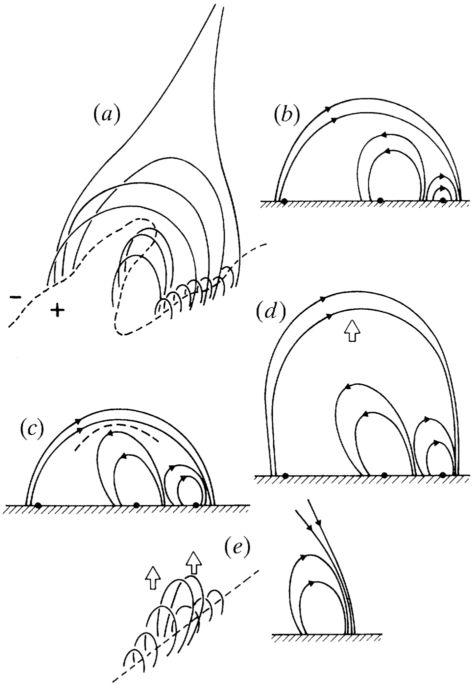

Figure 2. A cartoon model for the coronal mass ejection. (*a*), (*b*) The initial structure includes a hierarchy of magnetic arcades which are subsequently indicated by the CME, the precursor activity, the flare and the prominence. An overlying streamer is shown. (*c*) Shear in the active region causes the active region arcade to expand. This deforms the adjacent structure and leads to the precursor. (*d*) Continued shear leads to the eruption. (*e*) A flare may result from the eruption of the active region arcade or the interaction of the CME and active region structures (see text for details).

between the inflating arcade and the adjacent structures may result in some restructuring on a larger scale. This may include some expansion of the overlying streamer as the arcade becomes bloated. The intermediate loop in our cartoon model will become distorted at this time. As the system approaches a critical point the intermediate structure and the overlying fields experience some reconnection high in the corona. A current sheet is indicated by the dashed line. This results in the precursor as modest acceleration and heating are witnessed, perhaps simultaneously from both footpoints of the intermediate structure (point (xix) above).

At any point the shear could relax and no further activity take place. However, if the magnetic restructuring contained within the largest magnetic structure persists, we may expect the onset of an unstable situation or a point with no equilibrium. This is easy to imagine if one considers continued shear activity with the middle-coronal response being ‘capped’ by the overlying field. In response the overlying system will suddenly balloon out (figure 2*d*). It will sweep up material and manifest itself as a CME. This sudden change will cause a restructuring of the smaller scale structures. The active region arcade/prominence may erupt in sympathy as the stabilizing effects of the overlying system have gone or it may be stable enough to simply readjust. In the former case, we would witness a prominence eruption and at the site of the greatest complexity, perhaps though not necessarily, we may expect to find a flare as field lines reconnect in a Kopp & Pneuman (1976) type scenario. An alternative view is that the magnetic field lines at the CME footpoints rooted in the photosphere at the active region interfere with the active region arcade and produce a flare through a configuration remarkably similar to the model due to Heyvearts *et al.* (1978). Both of these scenarios are drawn in figure 2*e*.

The onset of a flare will bring other features commonly observed, such as a coronal response to a shock in the form of a type II burst, and type III radiation as electrons stream up the open magnetic structures of the active region (figure 2*a*).

The cartoon can be adjusted, with the same basic magnetic configuration, to allow for a variety of scales, symmetries or asymmetries between the flare, CME and prominence. One should regard the three components of the hierarchy as being representative of the common structure of the corona.

For the modellers, this scenario is presently unacceptable. For example, it has no symmetry, non-potential fields, is not force free, contains multiple magnetic structures and has no direction of invariance. For the observer it contains all of the relevant features described in the observational aspects list above and includes a magnetic hierarchy which is characteristic of the corona.

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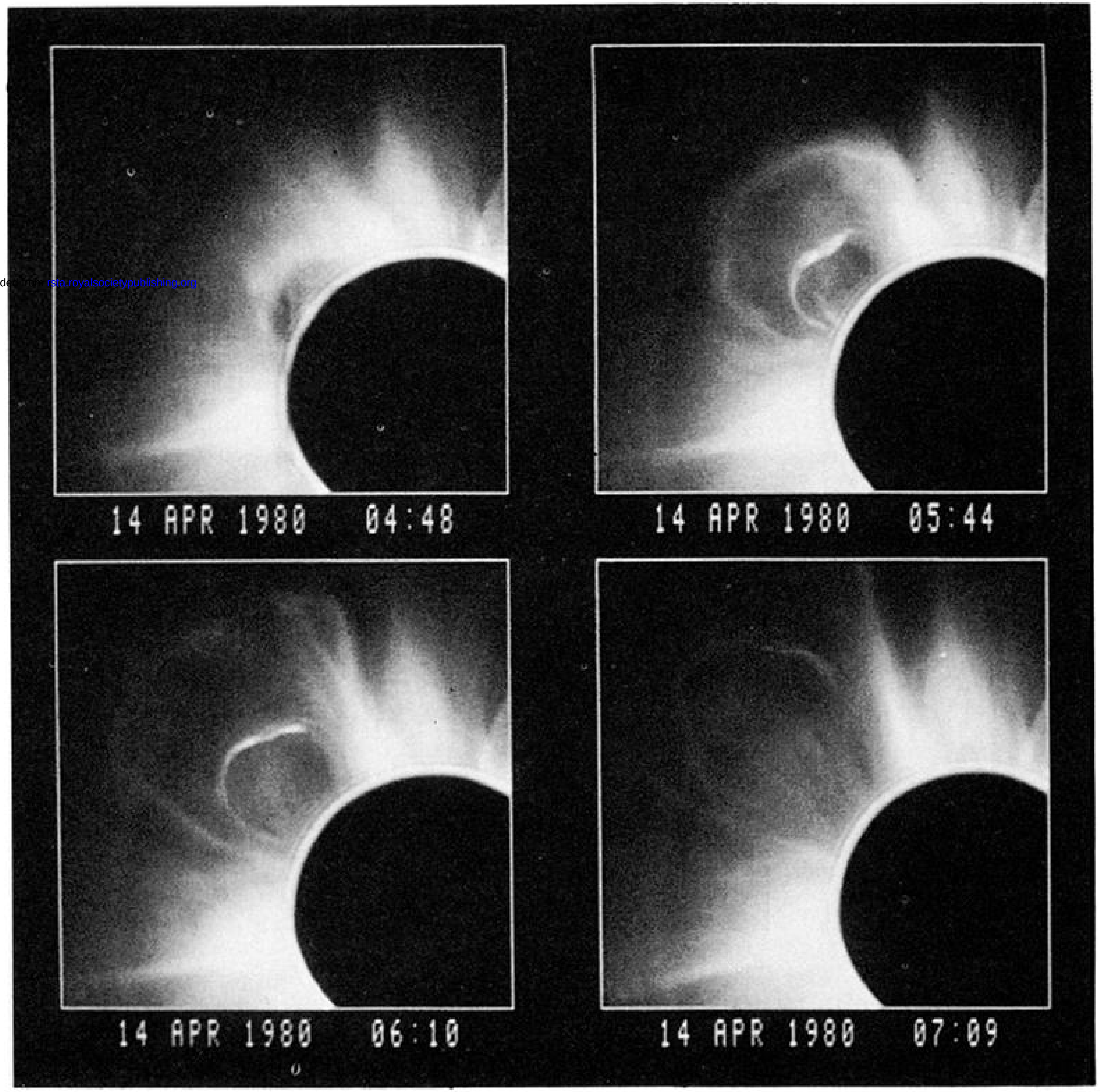
Discussion

E. R. PRIEST (*The University, St Andrews, U.K.*). (i) You mentioned the controversy about how magnetostatic fields evolve. This has now been largely resolved and the current understanding is that, if a simple force free arcade evolves due to slow footpoint motions, it always appears to be in equilibrium. However, if the plasma pressure increases, it may reach a point of non-equilibrium (for example, Priest, *Astrophys. J.* **328**, 848 (1988)) and this is consistent with Hundhausen's observations that in many cases a helmet streamer swells and becomes brighter just before it erupts to give a CME. (ii) I agree with you that there is much complex behaviour on the Sun before and during a CME, but this does not necessarily mean that the underlying cause is a complex one. The basic physical mechanism may be a simple or elegant one, and once it has been found (for example the pressure increase I mentioned above) the next task is to add in more effect and so explain more of the detailed observations.



igure 1. The coronal mass ejection of 14 April 1980 as observed by the High Altitude bservatory's coronagraph on the *Solar Maximum Mission*. The Sun is obscured by an occulting isc of diameter $3R_\odot$.