Solar Coronal Mass Ejection: Theory
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Solar coronal mass ejections (CMEs) are episodic expulsions of mass out of the solar corona involving large-scale reconfigurations of the corona. In a typical event, several $10^{15}$–$10^{16}$ g of plasma pre-existing in the low corona is expelled into interplanetary space, with a rate of occurrence varying from one event every few days at activity minimum to as high as three events per day at activity maximum in the course of a solar cycle. The CME and the flare are the two most energetic phenomena, liberating some $10^{31}$–$10^{32}$ erg of energy in each case, among the myriad of time-dependent phenomena in the corona. Since it involves length scales of the order of the solar radius and time scales characteristic of sound and Alfvén speeds in the corona, the CME is appropriately described by magnetohydrodynamics (MHD) and is thus one of few known MHD processes in astrophysics which are accessible to direct imaging as a spatially resolved time-dependent event (see Solar Coronal Mass Ejection: Observations).

Discovered in the 1970s, CMEs have been a subject of intensive research, with several outstanding questions to which contending theoretical answers have been proposed. The rest of this article treats some of these questions: those dealing with the causes and consequences of CMEs, the origin of the CME energy, the nonlinear, time-dependent MHD flows of CMEs in the corona, and the characteristic structural form of the CMEs and their manifestations in the solar wind.

Causes and consequences of CMEs

The observed close association between CMEs and the other two major forms of coronal eruptions, namely flares and eruptive prominences, was the basis for the theory, once seriously considered, that CMEs are the responses of the corona to these other eruptions occurring lower down in the corona. This suggestion was attractive because of its physical simplicity. It was also in keeping with the reasonable idea prevalent before CMEs were discovered that the impulsive flare might produce a blast wave traveling out of the corona. This blast wave was identified with type II traveling radio noise and with shock wave structures observed in the solar wind by satellites at 1 AU. In this theory the CME would be identified with the blast wave generated by the flare. This scenario was pursued with many simulations with time-dependent MHD numerical codes treating CMEs as the results of impulsive inputs of flare-like energies at the base of static atmospheres embedding a potential magnetic field.

The flare initiation of CMEs as a theoretical idea was shown to be not tenable by the observational results of R Harrison and by the follow-up work of A Hundhausen. Although the question is still being debated by some theorists, it is widely accepted that where observation is of sufficient good quality, when a CME is associated with an observed flare, the flare does not as a rule precede the CME onset. Actually, events were found which showed that the CME preceded the associated flare. This rules out the flare as a cause of CMEs. From the theoretical point of view, there are several other aspects of the CME phenomenon which suggest that flares are not likely to be the cause of CMEs, notable of which are the following two points. Firstly, an impulsive ejection of the corona would involve the highest speeds of the MHD medium whereas the observed CME speeds vary in a huge range, from 10 to 2000 km s$^{-1}$, with a median of about 400 km s$^{-1}$. Secondly, CMEs tend to show a characteristic three-part structure in white-light coronagraph observation—a bright loop leading a dark cavity containing a bright core. This structure is reasonably interpreted to be corresponding to that of the pre-existing helmet streamer—a bright dome overlying a dark cavity containing a quiescent prominence (see Coronal Streamers). The breaking up of a coronal helmet has been commonly observed to be the origin of a CME. Thus the CME is a nonlinear but not necessarily impulsive ‘breaking loose’ of a large-scale coronal structure which preserves the coherence of the three-part structure.

The rejection of a flare as the cause of the CME is an important theoretical development, for it brings about a new or different way of viewing the large-scale corona. This view has a strong theoretical appeal because it integrates various theoretical and observational results in terms of simple MHD principles.

The solar corona is ordered by an interplay between two competing effects as the result of heating and the presence of magnetic fields. The hitherto still poorly understood heating maintains the corona at temperatures of the order of 1 to 2 million degrees with such a degree of relentlessness that at no time is the corona in any large bulk part able to cool down significantly below these temperatures. One of the consequences of its high temperature is the high thermal conductivity of the corona. Combined with the inverse square fall-off in solar gravity, the hot corona can extend so far out from the solar surface that the natural state of the corona is one of outward expansion into the solar wind, as first pointed out by E N Parker. This expansion is not ballistic or forced from below. The expansion results from a failure of gravity to confine the upper atmosphere. The upper atmosphere continuously expands to supersonic speeds, during times of more or less steady conditions, while the lower atmosphere heaves continuously outward, departing only weakly from hydrostatic equilibrium, to make up for the expansion.

The presence of magnetic fields in the electrically highly conducting corona introduces the Lorentz force, whose action may be decomposed into that of a magnetic pressure force combined with that of a magnetic tension force. The magnetic pressure can only enhance the tendency of the corona to expand. The magnetic tension force provides a means of restraining the expansion provided it acts towards the Sun and provided the magnetic field is sufficiently intense. This occurs low in the corona where magnetic fields are bipolar with the magnetic feet anchored to the solar surface on the two sides.
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of a polarity inversion line. The low corona is dominated by the typically 10 G magnetic field, with a plasma $\beta$ of the order of less than 0.1, that is, with the plasma pressure typically of the order of a tenth of the magnetic pressure. In such a region, the closed magnetic fields may trap a parcel of plasma in more or less static equilibrium against the global tendency to expand. This is the origin of the ubiquitous coronal helmet streamer straddling a photospheric magnetic inversion line. Outside of the helmet, the field is strong but, because it extends too far out where the solar wind dominates, it is kept open into interplanetary space by the solar wind.

Another way of seeing the effect of the magnetic tension force is to note that, under the condition of high electrical conductivity, a bipolar magnetic field anchored to the surface of the Sun has a tendency to remain closed because this is a state of minimum magnetic energy. The competition alluded to above is then between this magnetic tendency and the opposing expansion of the global corona. The balance between these competing effects determines how much mass and magnetic flux is trapped in a coronal helmet surrounded by open magnetic fields where the wind flows. The CMEs are then the consequence of the failure of this balance when the helmet would break loose to move out along with the global solar wind.

In this view, the term ‘loss of equilibrium or non-equilibrium’ is invoked to make the point that it is not just an instability. The remarkable aspect of a CME is that, when initiated, it expands out in a global nonlinear flow with a total mass of ejection characterized of the order of a few times $10^{15}-16$ g. The idea of an instability merely implies that the system would evolve away from an initial equilibrium when perturbed, but such a behavior does not a priori require the ejection of a huge amount of material out of the corona, a basic feature of the CME phenomenon. It is the teetering between confinement and expansion of plasmas trapped in the coronal helmets to result in a global loss of equilibrium that underlies the CME phenomenon, in this theoretical interpretation. Depending on physical circumstances under which this loss of equilibrium develops, it is theoretically conceivable that the structure breaking up may maintain its internal form with coherence and may move out with a broad range of speeds as opposed to the case of an impulsive blast-off.

The coronal magnetic field that produces the CME is also the agent for producing the PROMINENCE and its eruption, and the solar flare. Thus it is not a simple causal relationship one needs to find among these major eruptions making up the activity in the corona. This is an important point for theory, and it is reflected in the fact that flares, as defined as a sudden localized heating of the corona, have several different varieties and that the rate of flare occurrence increases by orders of magnitude over a solar cycle as opposed to an increase of a factor not larger than 10 in the CME rate over the same period of time.

There is, however, a particular relationship between CMEs and flares of a special kind, often referred to as the two-ribbon flares, which is of theoretical significance. The adjective ‘two-ribbon’ came originally from observations of the H\alpha part of this type of flare, referring to the characteristic heating occurring at the chromosphere along two bands which separate in time. This type of flare, known long before the discovery of CMEs, has been well explained in terms of magnetic reconnection taking place above the flaring chromosphere which recloses a magnetic field that has been caused to open up. The two flare ribbons in the chromosphere are then reasonably interpreted to be marking the footpoints of newly reconnected fields containing heated plasma. As more magnetic fields reconnect, newly heated footpoints light up while footpoints heated earlier cool out of visibility to produce the effect of the separating ribbons. With soft x-ray observations available from space these days, the two-ribbon flares are observed as long duration outputs of soft x-rays (hours to a fraction of a day) rising above the full-disk output, or as arcades of flaring loops in soft x-ray images.

Before CMEs were known, this flare mechanism lacked a physical reason why the magnetic field should open up on its own to produce a two-ribbon flare. The idea that a CME is the opening up of the magnetic field in a coronal helmet provides the missing ingredient. If the two-ribbon flare is indeed the result of the reclosing of opened magnetic fields by reconnection, and the CME is indeed responsible for the opening up of an initially closed magnetic field, the CME necessarily has to precede the two-ribbon flare associated with it. Theoretically, the reconnection could begin as soon as the CME takes off with the field opening up, or the reconnection could be delayed until after the field has completely opened up and the CME is well on its way out of the upper corona. The latter is supported by some observations and the former leaves the temporal sequence ambiguous because the flare would have an onset very close to, or, in practical terms, almost simultaneously occurring with the CMEs. What this theory would not accommodate would be the observation of a two-ribbon flare preceding the associated CME. If it can be shown that such an event occurs and that the association between the flare and CME is not by chance, then the event cannot be explained by the theory, pointing to a much more complex physical behavior than the one envisioned in the theory.

CME energy

The mechanical energy of a CME is impressively large. The often quoted CME energy of $10^{31-32}$ erg is the sum of its kinetic energy and the work done against solar gravity to lift its mass of $10^{15-16}$ g out of the corona. The gravitational potential energy typically is about a half of the sum, as can be seen from the fact that the gravitational escape speed in the low corona is about 500 km s$^{-1}$ whereas the observed median speed of CMEs is about 400 km s$^{-1}$ with the large range mentioned above. The sound speed of the 2 million degree corona is about 120 km s$^{-1}$. The Alfvén speed in the low corona can be estimated to be in excess of...
700 km s$^{-1}$. Therefore, a striking feature of the CME is that a great many CME speeds are supersonic, sub-Alfvénic, and below the low-coronal gravitational escape speed.

It is widely held that the CME energy originates from energy contained within the corona previously stored in the magnetic field. This view is based on noting that the CME moves at speeds near the limit or in excess of the characteristic MHD speeds of wave propagation in the corona. In this case, it is not possible for the CME to be driven by photospheric processes which involve typical speeds of 0.5 km s$^{-1}$. It is possible that the photosphere may stress the coronal magnetic field over a long period of time to result in a build up of energy in the corona, but it is not likely in this view that the photospheric motion, given its small magnitude, is relevant during the course of the CME moving out of the corona at the characteristic high speed of the latter. This point of view is supported by the fact that to date no surface photospheric motions of a particular type have been shown to be indicative of a CME leaving the solar corona directly above the photospheric region of observation.

A minority view has persisted, hinting at some possible large-scale non-MHD effects in which the CME is driven by currents generated at the photosphere or in the solar convection region. This view has remained speculative and non-quantitative.

Accounting for the CME energy in terms of magnetic energy stored in the corona has turned out to be a deeper problem than previously appreciated. Taking the simplifying limit of the corona as a perfect plasma conductor with negligible inertia, it was an attractive idea to try to account for the energy in the field-aligned currents of a force-free magnetic field anchored to the surface of the Sun. These currents were taken to be induced by the stressing of the field by slow but persistent photospheric motion taking the embedded magnetic footpoints along with it. It was proposed in the 1970s that the spontaneous opening up of a closed force-free magnetic field may result from a build-up of magnetic energy by surface stressing to a level above that of an open state. This idea was shown to be incorrect by J J Aly in the 1980s, who proposed a now widely accepted conjecture that the build-up of energy in a closed and anchored force-free magnetic field cannot exceed the energy of any open magnetic field having the same anchored footpoints on the solar surface.

The energy demand of a CME is especially impressive if one has to account not only for its energy but also for the energy of the open field it leaves behind, in the light of Aly’s conjecture. The large amount of energy in the open field left behind by the CME would neatly account for the post-CME flare that results from the reclosing of the opened magnetic field. Therefore, the theoretical question on the energy storage for the CME is one of determining that there could be coronal structures with closed magnetic fields in possession of two huge amounts of free energy, that carried away in the gravitational and kinetic energy of the CME and that left behind in the open magnetic field to fuel the CME-associated flare. This, by Aly’s conjecture, cannot be accounted for by the stressing of force-free magnetic fields.

A first step in the resolution of this problem is to realize that the force-free assumption is not valid over the large scale of the corona. In the thermally highly conducting corona, pressure is almost isothermal and it falls with height less rapidly than the magnetic pressure, especially with gravity dropping inversely with distance squared. Both the pressure and the solar wind dominate over the magnetic field at increasing distance from the Sun and the force-free assumption is invalid over such scales, for example, as characterized by the radial extent of the helmet streamer. Over these scales, the Lorentz force is not zero everywhere but interacts with pressure gradient and gravitational forces, and all these forces also produce the solar wind in the open-field regions.

Once this is recognized, models of the corona in static equilibrium can be constructed to show that the necessary amount of magnetic energy can be stored to fuel ejection of a CME and its associated flare. Of particular note is that the magnetic energy is most efficiently stored if a part of the magnetic field is not in the form of simple bipolar anchored field but is in the form of a flux rope detached in its main part from the coronal base, that can be identified with the cavity under the helmet-streamer. The confinement of this flux rope in equilibrium requires the weight of the large mass in the helmet dome. In this model, the large mass of the CME plays the very role of trapping the magnetic energy in the pre-eruption stage that eventually drives the CME.

This promising resolution of the energy problem has also raised a new question. If the magnetic energy needed to drive the CME requires interaction between the plasma and the field for its storage, it must follow that plasma pressure forces must also play a significant role in the CME outflow. This implication is not surprising when it is realized that the Lorentz force cannot work against gravity in the direction of the magnetic field, only the component of the pressure force in that direction can. And, working against gravity is an essential aspect in the energetics of the CME. Ultimately, to understand the effect of pressure would require an understanding of the nature of coronal heating under the time-dependent circumstance of the moving CME.

The time-dependent MHD flow of a CME

The simplest description of the CME in fully developed motion uses the one-fluid MHD equations including the presence of solar gravity. To avoid the complication of the energy and heating of the plasma, a polytropic assumption with an index taken smaller than 5/3 is usually made to simulate the heating of the coronal, largely proton, gas in expansive motion.

The only general approach to treat the MHD equations is by the use of numerical codes with the capability of dealing with at least two dimensions in space. Previous work had treated the flare-initiated CME theory and the shearing of magnetic footpoints to force
a spontaneous opening up of the coronal magnetic field. These works had been instructive in their respective ways but have not dealt with the CME nonlinear flows such as observed in the low corona. Recent numerical modeling efforts have begun to address the idea that the CME cavity is a magnetic flux rope and morphological agreement between two-dimensional models and the observed three-part structures of CMEs have been obtained, lending credence to the suggestion of magnetic flux ropes playing a role in the CME phenomenon.

The MHD equations for a polytrope of index 4/3 admit a family of self-similar solutions both in two- and in three-dimensional space. These solutions have been useful in capturing the essence of the MHD time-dependent expulsion of mass out of a gravitational potential well. Among the properties directly demonstrated with these solutions is that the transport of magnetic field, mass and the 4/3 polytropic pressure may proceed in a mode such that gravity can be countered throughout the expulsion process. The result is that the modeled CME could in this mode of behavior travel out of the corona with mildly accelerated or constant speeds in an enormous range of speeds, such as seen in the observed CMEs. The possibility of generating solutions in this class with fully three-dimensional variations was also exploited to produce a CME geometrically sophisticated enough for direct (favorable) comparison with white-light observations.

The large range of observed CME speeds implies that a rich variety of MHD shocks may be associated with this highly nonlinear flow. The fast MHD shock has behaviors which are intuitively simple modifications of the hydrodynamic shock by the presence of magnetic fields. The slow and intermediate MHD shocks have properties which can be counter-intuitive, such as the possibility of having a shock surface shaped with a concavity away from the shock driver. The leading fronts of observed CMEs have shown a variety of shapes suggestive of such unconventional shock-surface geometry. Recent time-dependent MHD models have demonstrated that these observations may be explained in terms of the MHD shocks formed by the CMEs plowing into the ambient corona at speeds in the supersonic but sub-Alfvénic range. Much work remains to be done in this classical area of MHD shock theory, especially in the discovery of the role of the intermediate shock in the CME outflow.

In interplanetary space, the signatures for recognizing a CME in the solar wind are being developed. Among these signatures are the bidirectional streaming electrons indicative of magnetic lines of forces with both ends anchored to the low corona such as might be expected from the stretching out of bipolar lines of force by the CMEs. The three-part structure of the CMEs seen in the corona has not been unambiguously identified with their counterparts in interplanetary space but some promising results have been obtained, including the identification of the CME cavity with the so-called interplanetary magnetic clouds. Both the cavity and the magnetic cloud may be the manifestation of a magnetic flux rope. It is conceivable that the CME will undergo significant evolution as it travels along with the solar wind. Much theoretical work and modeling remain to be done in parallel with observational studies of coronal and interplanetary observations to address these issues.

Conclusion

The discovery of CMEs in the 1970s has ushered in a new chapter for coronal physics, taking us from the concern with the solar wind structures in the synoptic regime to the time dependence of episodic mass expulsions, and taking us from the preoccupation with flares to a new form of eruption involving just as much energy. Worthy of note is the fact that the flare is dissipative in nature, heating of the coronal plasma; whereas, the CME involves liberation of energy in the ordered forms, gravitational potential and kinetic motion. The two forms of eruption are related in ways that are not simple and the physics of the corona is richer than many would have realized when CMEs were first discovered. Much remains to be done, and there is a confusion of ideas. These have been partially resolved and the view will probably continue to evolve.

Bibliography

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