A Scenario for the Large-Scale Magnetic Field Evolution in CMEs

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This report gives a summary of the principal properties of coronal mass ejections (CMEs) from the view-point of magnetic field transport through the solar corona. The origin of a coronal streamer system is discussed in the context of a large-scale magnetic field configuration pre-existing to CMEs. Reconnection driven by the solar wind is highlighted for its non-steady character as well as for its key role in the global dynamics of plasma flows in the corona.

1. Introduction

CMEs are significant to solar-terrestrial physics because they involve a large discrete injection of mass and magnetic fields into the interplanetary space which can strongly perturb the solar wind and the Earth's environment. They also play a significant role in the acceleration of solar cosmic rays (KUNDU *et al.*, 1989). It is probably the CME which forms the link between the solar disturbance and its effects at the Earth. The acceptance of this view-point carries important implications for the observation of predictive signatures at the Sun and within the vicinity of the Earth (WEBB, 1991).

There are many reviews on CMEs and solar flares, their relation (e.g., WAGNER, 1984; HILDNER, 1986; HARRISON *et al.*, 1990). Many properties of these non-steady phenomena seem to be studied well. Here we do not attempt to repeat either of these studies or "to clear some of the dead-wood" (HARRISON, 1990). Instead we try to summarize briefly some conclusions reached by the authors mentioned above and to present a slightly different insight on the problem by concentrating on CMEs. The problem does exist since observations suggest a picture which is inconsistent with most models of the CME phenomenon. Anticipating the conclusion of this report, we agree with a rather negative answer to the question—Do we understand CMEs yet?—in the title of the review by HILDNER (1986). However, another question seems to be also interesting—How should we try to understand them?

2. Some Observational Features of CMEs

CMEs are a type of coronal transients, the general name given to the disruption of coronal structures. Not surprisingly, large-scale magnetic fields are related to CMEs. The slowly evolving coronal density structure is now recognized as marking the location of fields and, ultimately, the instantaneous state of the solar dynamo (WAGNER, 1984). The occurrence rate of CMEs tends to track the activity cycle in both amplitude and phase,

but no one class of solar activity tracer is better correlated with CME rate than any other (WEBB, 1990). The CME-rate (day^{-1}) is well related with the evolution of the K-corona. The dependence of this rate on “correlation lifetime”, characterizing the evolution of the corona with time, also suggests that the key to the physics of CMEs is in the large-scale coronal fields, and not necessarily in the response of the corona to impulsive events of the low atmosphere (SIME, 1989).

The important feature of CMEs is the high altitude activity of coronal streamers prior to CME events. In many cases, the streamer which overlies the CME site shows a steady broadening. It lasts for several days; and at the time of the CME launch the streamer either disappears or becomes narrow again. This shows that the coronal structure “is aware of the impending launch of a CME” several days before the event (SIME, 1989), and therefore demonstrates that the CME cannot be the result of a chromospheric event ejected into the corona.

CMEs are associated with active regions but structures from which CMEs originate extend well beyond the confines of an active region (e.g., KAHLER *et al.*, 1989). An associated active region may appear to lie anywhere under a CME, but preferentially in one leg (HARRISON *et al.*, 1990). There appears to be a “principal X-ray event” (flare or X-ray gradual rise and fall event) associated with all CMEs. CMEs launches typically precede the onset of the “principal X-ray event”. The “principal X-ray event” commonly lies on one side of the axis of the CME span. However, CME-associated flares may be not the dynamic or eruptive flares presumed to be associated with CMEs, but may be well confined (KAHLER *et al.*, 1989). A possible explanation may be found in the scheme by HARRISON (1986) in which the flare follows the CME onset. In this view, the flare as the “principal event” is only a secondary result of the disruption of a coronal magnetic structure.

A “minor X-ray event” (precursor), a small discrete soft X-ray enhancement, leads to the CME onset in most cases (HARRISON *et al.*, 1985). The relationship between CMEs and prominences is not yet clear. The observational analyses (HARRISON and SIME, 1989) have highlighted the complexity of the initial stages of a CME and this has demanded a re-examination of past studies where the clear relationship was claimed.

3. Some Principal Questions

In spite of many years of observational and theoretical studies, our knowledge about the physical properties of CMEs and the mechanisms responsible for their initiation is still incomplete. Now, it seems to be generally accepted that CMEs occur as a consequence of a disruption of large-scale magnetic configurations. It seems also to be supported by observations that, at least for some class of CMEs, such a disruption is a primary effect, with flares and prominence eruptions being of a secondary nature (e.g., HARRISON *et al.*, 1990). By assuming this, we have several basic questions: (1) What is a pre-existing magnetic configuration? (2) What does the disruption cause? (3) How does the system evolve once the disruption begins?

Many attempts to answer these questions are summarized in the review by HARRISON *et al.*, (1989). In what follows, we would like to point out only one aspect which, in fact, we know well in the context of coronal heating and solar flare problem. Let us assume that the solar dynamo mechanism works as a steady generator of magnetic fields. Even for this unreal case, the corona could not be considered as a passive load for

such a generator because the transport of magnetic fields through the corona is certainly a non-steady process. This is shown from the following consideration.

4. Non-Steady Reconnection in Coronal Streamers

A “new” magnetic field emerging into the corona always interacts with an “old” coronal field. Such interactions create stresses in non-force-free configurations of a large scale. The relaxation of them to low-energy states (force-free or potential fields) is mostly realized via magnetic reconnection. The solar wind also interacts with magnetic fields, and creates reconnecting current sheets in the corona.

The important point is that even if the solar dynamo builds up the stresses in the corona at a rate comparable to that at which reconnection relaxes them, the last process is a non-monotonous one. It goes through several different stages (see, SYROVATSKII, 1981):

(a) Formation of a current sheet in the place of a “singular zeroth line” or, in general, a separator. Therefore, the current sheet accumulates an excess magnetic energy as compared with the energy of the potential magnetic field. We call this excess the “free magnetic energy”.

(b) Quasi-steady evolution of the current sheet. Even if the current sheet is steady, usually there is no stationary solution for density. The last decreases monotonically on the field lines flowing to the sheet. But on the field lines which have undergone reconnection in the sheet, the plasma is raked-up and compressed. Therefore, the density of plasma near the current sheet changes monotonically (SYROVATSKII and SOMOV, 1980).

(c) Non-steady evolution (or rupture) of the current sheet, and its disappearance. As it is clear from (b), the current sheet represents a meta-stable formation. The sheet is either stable and slowly changes or, depending on external parameters (the plasma density, the magnetic field intensity and the rate of the magnetic field variation in its vicinity), reaches some instability and is destroyed. The rupture of the sheet is especially essential for the impulsive phase of flare according to SYROVATSKII (1981).

(d) Creation of a new current sheet in the same place seems to be responsible for homologous flares in active regions (e.g., MACHADO *et al.*, 1983).

This sequence of stages is well studied theoretically and in laboratory experiments (e.g., BOGDANOV *et al.*, 1986). The purpose of this report is to illustrate how the non-steady character of magnetic reconnection can lead to non-steady large-scale phenomena in the corona, like CMEs. By going this way, let us start from the answer to the first question formulated above—What is the large-scale configuration pre-existing to a CME?

We consider the simplest model in which a current sheet appears as a result of capture and extension of a bipolar magnetic field of an active region by the solar wind. The model assumes that the field of a two-dimensional dipole has partially penetrated through some semi-cylindrical boundary at an initial time (see Fig. 1 in SOMOV and SYROVATSKII, 1972). Later on, the boundary is expanding with magnetic field lines frozen into it. This seems to be the simple model for the transition region from the “inner” corona, where the magnetic field is strong, to the “upper” corona in which the kinetic energy of the plasma flow, i.e. the solar wind, dominates. In the absence of plasma, with an expansion of the boundary, there appears a line of neutral X-points of a

magnetic field (Fig. 2 in SOMOV and SYROVATSKII, 1972). One can see that the electric field E at this line is nonzero. This fact means that in a plasma of high conductivity a current sheet has to develop.

The width of the current sheet grows with the increase of the boundary radius. The magnetic field rapidly reaches its asymptotical form (Fig. 5 in SOMOV and SYROVATSKII, 1972). Near the dipole, the field has its usual structure. At large distances, the field lines tend to become radial straight lines. This configuration of the field depends on only two parameters: the value of magnetic dipole and the fraction α of the magnetic flux penetrated into the solar wind.

In what follows, we assume that the large-scale magnetic configuration pre-existing to CMEs is created by the same mechanism. This means that the coronal structure consists of several (at least two) streamers. Of course they may have quite different sources and boundary conditions in the photosphere (see SOMOV, 1990). We can easily imagine the quasi-steady slow flows driven by the wind originated in the inner corona between two streamers. One of them is a low (young) streamer, the second is a high (old) one. Both of them are supported by the energy of plasma flows in the space between them. In a two-dimensional steady model, these flows, as well as the reconnection process in streamers, can be characterized by a constant electric field E . The supposed picture of flows is shown in Fig. 1 (top).

Plasma moves up in the space between the streamers and brings new magnetic field lines to them. These field lines reconnect inside current sheets. By so doing, they create plasma down-flows under streamers and up-flows in the upper parts of streamers, parallel to the solar wind. This is a quasi-steady configuration pre-existing to a CME. To understand a possible non-steady evolution of the system, we have to consider the question of the current velocity in streamers.

Fig. 1. The initial stage of a CME. The pre-existing large-scale magnetic field configuration (top). Fast reconnection in the old streamer as the cause of the CME onset (bottom).

For this purpose, we estimate the thickness a of a current sheet inside a coronal streamer as follows:

$$a = v_m/v = c^2/(4\pi\sigma v). \quad (1)$$

Here σ is conductivity of the plasma inside the current sheet, v is velocity of the plasma flow into the sheet. Then, we find the current velocity u of electrons inside the current sheet by using the inductance equation and formula (1):

$$u = (m_i\sigma/e)(B/\rho)(v/e) = (m_i\sigma/e)(E/\rho). \quad (2)$$

This formula shows that the current velocity is larger in the high (old) streamer than in the low (young) one. Even a small event (precursor) can initiate some current instability in the higher streamer if this velocity exceeds the threshold velocity. This means that anomalous conductivity may create faster reconnection of field lines inside the current sheet of the higher streamer and initiate the onset of streamer disruption (Fig. 1, bottom). By this assumption our model differs from the model by WOLFSON *et al.* (1987), which describes the quasi-static evolution of a coronal streamer in response to loading with excess mass before the eruptive phase of a CME.

In turn, fast reconnection in the high streamer may induce some activity (flare or another “principal X-ray event”) in the low one. Magnetic field near the current sheet is stronger in the lower streamer. Therefore, we may expect some impulsive event also as the “principal event” (see, KÄHLER *et al.*, 1989).

This scenario seems to be useful to discuss the questions mentioned above. Now we can reformulate them as follows. (1) Is it possible to relate the large-scale magnetic field configuration, pre-existing to a coronal transient or CME, with the system of streamers and magnetic reconnection in them driven by solar wind? (2) Do properties of coronal streamers allow us to explain the onset of a CME as the result of a current instability and the rupture of the current sheet inside one of the streamers? (3) May the disruption of one streamer initiate some activity (flare, prominence eruption, etc.) near another streamer, and how much plasma can be ejected in the region between magnetically interacting streamers by the global magnetic field rearrangement? We hope these questions will help us in the way to a better understanding of CMEs as well as of their relations with solar flares and prominence eruptions.

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