LA-UR- 95-2853

Title:

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Submitted to:

Solar Wind 8 Proceedings

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Magnetic Topologies of Coronal Mass Ejection Events: Effects of 3-Dimensional Reconnection

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Abstract. New magnetic loops formed in the corona following coronal mass ejection, CME, liftoffs provide strong evidence that magnetic reconnection commonly occurs within the magnetic “legs” of the departing CMEs. Such reconnection is inherently 3-dimensional and naturally produces CMEs having magnetic flux rope topologies. Sustained reconnection behind CMEs can produce a mixture of open and disconnected field lines threading the CMEs. In contrast to the results of 2-dimensional reconnection, the disconnected field lines are attached to the outer heliosphere at both ends. A variety of solar and solar wind observations are consistent with the concept of sustained 3-dimensional reconnection within the magnetic legs of CMEs close to the Sun.

Introduction

Coronal mass ejections, CMEs, are transient solar events in which plasma and magnetic fields from the solar atmosphere are propelled outward into interplanetary space; they result from the disruption of magnetically closed coronal structures not previously participating in the solar wind expansion. CMEs play a central role in the long-term evolution of the structure of the solar corona [e.g., *Hundhausen*, 1995] and are the prime link between solar activity and large, transient interplanetary and geomagnetic disturbances [e.g., *Gosling*, 1993]. Our interest here is in the magnetic topology of CMES in the solar wind and how that topology is affected by magnetic reconnection close to the Sun.

Magnetic topologies near and within CMEs in the solar wind can be inferred from measurements of suprathermal electrons at energies above ~ 60 eV. These electrons carry the solar wind electron heat flux and are beamed outward from the Sun along the interplanetary magnetic field, IMF [e.g.,

Feldman et al., 1975]. As illustrated in Figure 1, fluxes of suprathermal electrons in the normal solar wind are unidirectional, reflecting the fact that field lines there are open and effectively connected to the hot corona at only one end. Closed field lines connected to the hot corona at both ends can be identified in interplanetary space by fluxes of suprathermal electrons counterstreaming along the IMF. Experience shows that most CMEs in the solar wind can be identified by the presence of counterstreaming fluxes of these electrons [e.g., *Gosling*, 1990], indicating that field lines within CMEs near 1 AU are usually attached to the solar corona at both ends. Finally, IMF lines disconnected from the Sun and attached to the outer heliosphere at both ends can be identified by dropouts in the suprathermal electron flux since any hot electrons originally on such field lines will escape rapidly to the outer heliosphere (see, for example, *McComas et al.* [1989])

Three-Dimensional Reconnection and The Origin of Magnetic Flux Ropes in the Solar Wind

Approximately 1/3 of all CMEs identified in the solar wind by the counterstreaming suprathermal electron signature exhibit internal field rotations characteristic of nearly force-free magnetic flux ropes [*Gosling*, 1990]. Such ropes are characterized by a series of helical field lines of ever increasing pitch wrapped about a central axis. When the field strength is high and the plasma beta (ratio of plasma to field pressure) is low these CMEs are known as “magnetic clouds” [e.g., *Burlaga*, 1991] Figure 2 shows Ulysses solar wind observations at 4.6 AU and S33° of a CME (distinguished by the counterstreaming suprathermal electron signature) that was also a magnetic cloud (distinguished by the smooth rotation in magnetic field polar angle and by the low plasma beta).

It has been suggested [e.g., *Rust*, 1994] that magnetic clouds are the interplanetary extensions of solar filaments, which often have helical magnetic field topologies and which often are embedded within CMEs observed by coronagraphs. We believe, however, that it is unlikely that magnetic clouds are simply interplanetary extensions of solar filaments since filaments typically comprise only small fractions of the volumes of CMEs when viewed by coronagraphs. Based on coronal observations we would expect to find filaments either deep within the interiors of CMEs in the solar wind or trailing along behind them. On the other hand, the objects identified as magnetic

flux ropes in the solar wind typically, as in Figure 2, are the entire CMEs, not small portions thereof.

An alternate suggestion is that the flux rope topology characteristic of some CMEs in the solar wind is a consequence of 3-dimensional magnetic reconnection [Gosling, 1990; Gosling *et al.*, 1995b]. Evidence for reconnection within the rising magnetic loops that comprise CMEs can be found in the fact that new magnetic loops often form in the corona beneath CMEs shortly after they lift off from the Sun. Emission from these loops produces the long-duration, soft X-ray events (sometimes also called gradual flares) often associated with CME departures [e.g., Sheeley *et al.*, 1983]. It is commonly believed that these newly formed magnetic loops are a consequence of reconnection occurring near the foot points of the outward-moving magnetic loops threading the CMEs [e.g., Kopp and Pneuman, 1976]. As visualized in two dimensions the magnetic loops interconnect with themselves to produce closed magnetic loops threading the CME that are completely detached from the Sun, as well as new magnetic loops statically confined to the corona. It is unlikely, however, that magnetic loops threading CMEs ever actually reconnect with themselves in this manner because of the required high symmetry of the magnetic field. Any skewing or shearing of the field results in reconnection between neighboring loops. As illustrated in Figure 3, reconnection in the presence of skew or shear produces helical field lines threading the CME as well as new magnetic loops in the corona below. When the plasma beta is low the helical field lines within the CME eventually relax to the nearly force-free structure characteristic of a magnetic cloud. In contrast to the 2-dimensional case, reconnection in 3 dimensions does not initially result in magnetic disconnection of the CME from the Sun.

Because the center of the CME/magnetic cloud shown in Figure 2 was neither overtaking slower plasma ahead nor being pushed outward by faster plasma from behind, it should have traveled out to Ulysses at a nearly constant speed of 740 km s^{-1} . It thus should have left the Sun ~11 days earlier, near the middle of the day on May 31, 1993. At the time of these observations Ulysses was located slightly behind the southeast limb of the Sun as viewed from Earth. Figure 4 shows two images of the Sun obtained by the soft X-ray telescope on Yohkoh on May 31. These images reveal that large coronal loops, which persisted for many hours, formed on and probably slightly

behind the southeast solar limb (lower left) almost directly beneath Ulysses between 08:26 and 17:51 UT, near the time when we calculate that the CME should have departed from the Sun. The combined Ulysses and Yohkoh observations thus provide substantial support for the idea that the flux rope topology of magnetic clouds is a result of 3-dimensional reconnection occurring close to the Sun as sketched in Figure 3.

Sustained Three-Dimensional Reconnection and the Creation of Open and Disconnected Field Lines Within CMEs

Despite the usefulness of the counterstreaming suprathermal electron signature for identifying CMEs in the solar wind, it has long been apparent that not all portions of CMEs and perhaps not even all CMEs can necessarily be identified in solar wind data by that signature [e.g., *Zwickl et al.*, 1983; *Crooker et al.*, 1990; *Gosling*, 1990; *Richardson and Cane*, 1993; *Kahler*, 1994]. This suggests that some field lines within CMEs are occasionally open. For example, counterstreaming was not observed continuously throughout the CME/magnetic cloud event shown in Figure 2. Rather, as indicated in the figure, the interval from ~0400 to ~1400 UT on June 12 was characterized by the unidirectional fluxes of suprathermal electrons indicative of open field lines. We have suggested that open field lines within the interior of a flux rope CME are a natural consequence of sustained 3-dimensional reconnection at the footpoints of the CME close to the Sun [*Gosling et al.*, 1995b].

Figure 5 illustrates the field topologies resulting from sustained 3-dimensional reconnection in the corona behind a CME. The sketches are based upon results of numerical simulations of 3-dimensional reconnection in the qualitatively similar field geometry that prevails in the geomagnetic tail in the presence of a cross-tail field component [*Birn and Hesse*, 1991; *Hesse and Birn*, 1991]. Each panel in the figure represents a successive stage in the 3-dimensional reconnection process. In panel a, two sheared loops threading the CME reconnect to form a helical field line connected to the Sun at both ends and a closed loop in the corona below. As already noted, this is the basic process by which we believe interplanetary flux ropes are formed. The reconnection can be confined to pairs of adjacent loops as drawn or can include three or more loops joined together.

In panel b, reconnection occurs between a closed helical field line and an open field line of the normal solar wind. The result is an open helical field line and a new coronal loop. In panel c, reconnection occurs between an open helical field line and an open field line of the normal solar wind to produce a helical field line that is connected to the outer heliosphere at both ends and a new coronal loop. Such disconnected field lines might be detected both within the flux rope and in the region well ahead of it. Finally, in panel d, reconnection between two open field lines of the normal solar wind behind the CME produces a U-shaped field line that is disconnected from the Sun and that wraps around the CME, as well as a new coronal loop.

It is generally thought that CMEs open new magnetic flux into interplanetary space (see, for example, *McComas* [1995]). The amount of flux opened up by a CME is reduced by the process of reconnection. Here we note that when reconnection proceeds to the point illustrated in panel b of Figure 5 that portion of the CME adds no net open magnetic flux to interplanetary space. When it proceeds to the point illustrated in panel c, that portion of the CME produces a net decrease in the open magnetic flux in interplanetary space and an increase in the amount of flux closed off at the Sun.

Owing to the shear of the original CME loops, helical field lines threading the center of the CME are exposed to ordinary open field lines of opposite polarity at the base of the CME near the ends of the overall loop system. In simulations in the qualitatively similar geometry in the geomagnetic tail [*Birn and Hesse*, 1991; *Hesse and Birn*, 1991], these tend to be the helical field lines that are opened up first. As a result, a variety of field topologies can simultaneously be present within a flux rope. Figure 6 illustrates an example where a rising magnetic loop not yet reconnected coexists with a helical field line connected to the Sun at both ends and an open helical field line threading the interior of the flux rope. The crucial point here is that reconnection along the flanks of the sheared loop system can produce open or disconnected field lines within the heart of the flux rope. We believe that such reconnection is the cause of open field lines embedded in the interiors of some CMEs in the solar wind. It also provides an explanation for the relatively rare CMEs that do not exhibit the counterstreaming suprathermal electron signature at all near and beyond 1 AU.

In the geomagnetic tail case the flux rope typically consists entirely of open and disconnected field lines before the leading edge of the flux rope reaches 200 Earth radii down tail [e.g., *Hesse and Birn*, 1991]. On the other hand interplanetary observations suggest that it is unlikely that reconnection in the corona ever proceeds to the point where all field lines threading a CME are entirely disconnected from the Sun since suprathermal electron flux dropouts are relatively rare. Indeed, as already noted, there is good evidence that most field lines threading CMEs are attached to the Sun at both ends. However, suprathermal electron dropouts are occasionally observed within volumes nominally identified as CMEs or in the surrounding plasma, indicating that complete magnetic disconnection from the Sun occurs at least occasionally. Notable examples of brief (1/2 hr) suprathermal electron dropouts [*McComas, et al.*, 1989; *Lin and Kahler*, 1992] and more prolonged unidirectional streaming occurred in conjunction with the October 29-31 1978 magnetic cloud studied by *Crooker et al.* [1990]. Our examination of ISEE 3 data reveals that open and (less frequently) disconnected magnetic field lines can be distinguished in ~ 20% of all CMEs events previously identified in the solar wind near 1 AU in the 1978-1982 interval. A more detailed study of those events is in progress.

Conclusions

The concept of 3-dimensional reconnection provides a framework for explaining a variety of solar and solar wind observations related to CMEs. Our arguments have been mostly qualitative, but have been based on the results of numerical simulations of 3-dimensional reconnection in the geomagnetic tail. We recognize that there are substantial differences between the corona and the geomagnetic tail in terms of spatial scale size, magnetic field strength, plasma beta, etc. Nevertheless, the field geometries are qualitatively similar in the two cases and the topologies resulting from reconnection should be the same. We hope to witness realistic simulations of 3-dimensional reconnection behind CMEs in the near future.

Acknowledgements. I thank my colleagues A. Balogh, S. Bame, J. Birn, B. Goldstein, M. Hesse, D. McComas, J. Phillips, V. Pizzo, E. Scime, K. Strong, and L. Weiss, all of whom

participated on portions of the original work summarized in this paper. This work was supported by a Los Alamos National Laboratory Directed Research and Development grant.

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Figure Captions

Figure 1. Sketch illustrating open and closed magnetic field topologies in the solar wind and the corresponding types of suprathermal electron streaming observed. Such streaming is observed whether or not the field lines are planar as drawn or are three-dimensional helices.

Figure 2. Selected Ulysses observations of an expanding CME in the solar wind that was also a magnetic cloud. The parameters plotted from top to bottom are proton density, bulk flow speed, magnetic field strength, field polar angle, and plasma beta. The short horizontal bar in the second panel from the top indicates an interval of open field lines within the CME. Adapted from *Gosling et al.* [1994].

Figure 3. Sketches illustrating the pinching off (reconnection) of magnetic loops in a rising CME whose legs are sheared relative to one another. Reconnection produces a magnetic flux rope topology within the CME and a new coronal loop beneath it. Prolonged reconnection like this is thought to be the origin of long-duration, soft X-ray events associated with CMEs. Adapted originally from *Gosling* [1993].

Figure 4. Images of the Sun taken by the soft X-ray telescope on Yohkoh on May 31, 1993. Note the large coronal loops that formed on the southeast limb (lower left) directly beneath Ulysses in the interval between 08:26 and 17:51 UT. From *Gosling et al.* [1995a].

Figure 5. Sketches of successive steps in 3-dimensional reconnection in the corona. The sketches are not to scale and are intended only to illustrate successive changes in magnetic topologies

Figure 6. An example of several different magnetic topologies possible in a CME that has undergone 3-dimensional reconnection. The sketch is not to scale and not all possible topologies are represented. Adapted from *Gosling et al.* [1995b].

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6