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Magnetic Reconnection in Space Plasmas

John Gosling*, William Feldman, and David Walthour (Dartmouth College)

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Magnetic reconnection produces fundamental changes in the magnetic field topology of plasmas and leads ultimately to substantial plasma heating and acceleration. The transfer of stored magnetic field energy to the plasma occurs primarily at thin conversion layers that extend outward from the reconnection site. We performed a comparative study of the structure and nature of these conversion layers as observed during reconnection at Earth's magnetopause and in the geomagnetic tail. Our research utilized plasma and magnetic field data from the Earth-orbiting ISEE satellites during crossings of the conversion layers at the magnetopause and in the geomagnetic tail, as well as data obtained during a long-duration balloon flight in Antarctica and simultaneously from satellites in geosynchronous orbit. We have found that the reconnection layer at the magnetopause usually does not contain a slow mode shock, contrary to earlier theoretical expectations. Through a coordinated analysis of data obtained from balloon altitudes and at geosynchronous orbit, we obtained evidence that reconnection can occur simultaneously in both hemispheres at the magnetopause above the polar caps. The final year of our study was oriented primarily towards the question of determining the magnetic topology of disturbances in the solar wind associated with coronal mass ejections (CMEs) and understanding how that topology is affected by magnetic reconnection occurring near the Sun.

1. Background and Research Objectives

Magnetic reconnection is an important process that occurs commonly in space plasmas and is thought to be important in a number of laboratory and astrophysical contexts as well. It

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is the prime means by which the magnetic topology of a plasma is changed, and it produces substantial plasma heating and acceleration. Both theory and observation indicate that this heating and acceleration occur at thin conversion layers that extend outward for long distances from the merging region where reconnection occurs. This project was aimed primarily at two goals: (1) obtaining an understanding of the conversion layers as they occur during reconnection at the Earth's magnetopause and in the geomagnetic tail, and (2) obtaining an understanding of the magnetic topology changes in interplanetary space associated with reconnection in the solar corona.

2. Importance to LANL's Science and Technology Base and National R&D Needs

A major part of the on-going mission of LANL is to understand the physics of the space environment surrounding the Earth in support of Laboratory responsibilities for verification programs and national security. A space physics capability is also essential to the Arms Control program. The research pursued in this project was aimed at obtaining an understanding of a fundamental physical process that is important in many space plasma and astrophysical contexts, including those that directly affect the near-Earth space environment.

3. Scientific Approach and Results

The first two years of this study utilized plasma and magnetic field data from the Earth-orbiting ISEE 1 and 2 satellites during crossings of the conversion layers at the magnetopause and in the geomagnetic tail. It also utilized data obtained during a long-duration balloon flight in Antarctica and simultaneously from satellites in geosynchronous orbit.

We have found that the reconnection layer at the magnetopause usually does not contain a slow mode shock, contrary to earlier theoretical expectations. We believe the reason for this is the very asymmetrical nature of the boundary conditions on either side of the magnetopause – cold and dense plasma with relatively weak magnetic field on the magnetosheath side and hot and tenuous plasma with relatively strong magnetic field on the magnetospheric side. Nevertheless, one crossing was identified where a slow mode shock was clearly present at the magnetopause. Quantitative tests indicated several anomalous properties of the shock, which have been resolved.

A coordinated analysis of data obtained from balloon altitudes and at geosynchronous orbit have yielded a comprehensive picture of the particle precipitation of energetic electrons into the Earth's polar cap regions during a geomagnetic substorm. The event began ~15

minutes after an abrupt northward turning of the interplanetary magnetic field. Measured ionospheric convection velocities in the polar cap were consistent with a pattern driven by reconnection at the Earth's magnetopause. The observations have been interpreted in terms of reconnection between the interplanetary magnetic field and the open field lines of the polar caps just tailward of the geomagnetic cusps, with the reconnection occurring simultaneously at the magnetopause above the polar caps in both the northern and southern hemispheres. Such simultaneous reconnection has been hypothesized in the past, but direct evidence for it has previously been lacking.

The final year of our study was oriented primarily towards the question of determining the magnetic topology of disturbances in the solar wind associated with coronal mass ejections, CMEs, and understanding how that topology is affected by magnetic reconnection occurring near the Sun. Topology is not only of intrinsic interest but is also important in determining how CMEs can be distinguished in the solar wind near Earth and in determining the geomagnetic response when they encounter Earth's magnetosphere. The study has utilized plasma and magnetic field data from the ISEE 3 spacecraft stationed in the solar wind well upstream from Earth, as well as results from numerical simulations of the reconnection process.

Using suprathermal solar wind electrons (which originate in the hot solar corona) as tracers of magnetic field topology, we have determined that magnetic field lines threading CMEs in interplanetary space are normally "closed", i.e. they are normally attached to the Sun at both ends. This observation is consistent with the fact that CMEs originate in closed field regions on the Sun not previously participating in the solar wind expansion. Nevertheless, the suprathermal electron observations also reveal that magnetic field lines threading the interiors of CMEs are occasionally either "open", i.e., connected to the Sun at only one end, or are disconnected from the Sun entirely and attached to the outer heliosphere at both ends. We have found that mixtures of closed, open, and disconnected magnetic field lines within CMEs in interplanetary space find a natural explanation in terms of sustained magnetic reconnection within the magnetic "legs" of CMEs close to the Sun.

Magnetic reconnection is commonly visualized in two dimensions. Figure 1 illustrates successive stages of reconnection occurring within rising coronal magnetic loops of a CME as visualized in two dimensions. The innermost loop reconnects first to form a closed detached loop and a new coronal loop attached to the Sun at both ends (panel b). Later, rising loops, whose footpoints are ever farther from the center of the loop system, reconnect to form additional pairs of attached and detached closed loops (panel c). Finally, open field lines on opposite sides of the loop system reconnect to form U-shaped field lines connected to the outer heliosphere at both ends, as well as additional coronal loops (panel d).

In two dimensions it is difficult to understand how reconnection can produce magnetic field lines within CMEs in interplanetary space that are either open or that are attached to the outer heliosphere at both ends. The explanation of how such topologies arise requires three-dimensional (3-D) considerations. Because of the required high symmetry of the magnetic field it is unlikely that rising magnetic loops ever actually reconnect with themselves in the manner illustrated in Figure 1. Any skewing or shearing of the field results in reconnection between neighboring loops to form the helical field lines characteristic of magnetic flux ropes. We have previously suggested that the flux rope magnetic topology of some CMEs in interplanetary space is a consequence of 3-D reconnection. Such reconnection should also produce the newly formed coronal loops observed during long-duration soft x-ray events that often occur in association with CME releases from the Sun.

Figure 2 illustrates the field topologies resulting from sustained 3-D reconnection in the corona behind a CME. The sketches are based upon results of numerical simulations of 3-D reconnection in the qualitatively similar field geometry that prevails in the geomagnetic tail. Each panel in the figure represents a successive stage in the 3-D reconnection process. In panel a, two sheared loops threading a CME reconnect to form a helical field line connected to the Sun at both ends and a closed loop in the corona below. This is the basic process by which we believe interplanetary flux ropes and new coronal loops are formed. 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 threading the CME and a new coronal loop. In panel c, reconnection occurs between an open helical field line threading the CME 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. Finally, in panel d, reconnection behind the CME of two open field lines of the normal solar wind 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.

We believe that 3-D reconnection as described above provides a natural explanation for a variety of coronal and interplanetary observations of CMEs. We hope to test these ideas in the future with further observational work and by performing physically realistic numerical simulations of 3-D reconnection for the coronal case.

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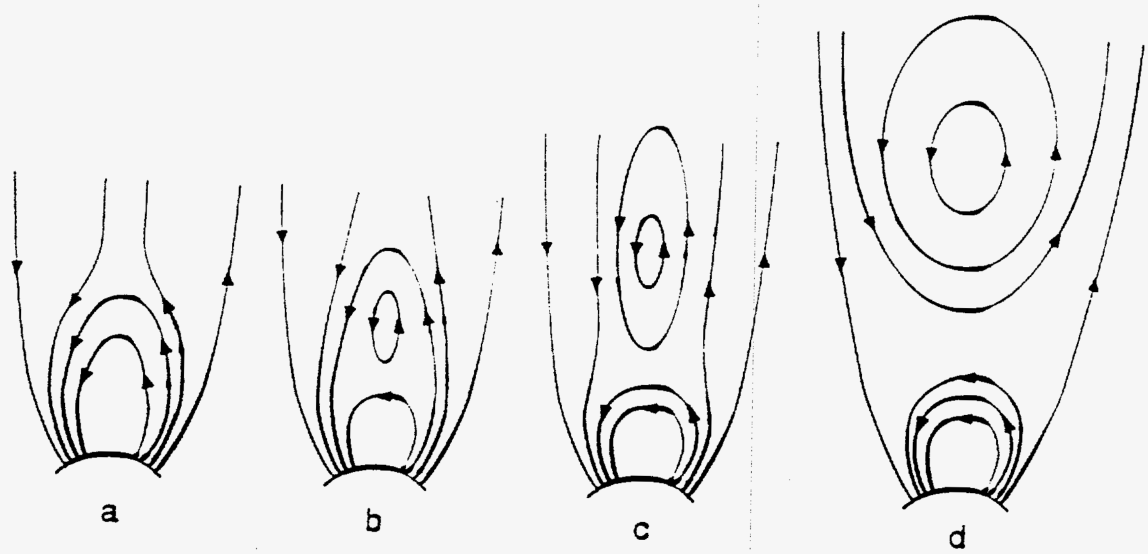

Figure 1. Magnetic reconnection within rising coronal loops threading a coronal mass ejection as is commonly envisioned in two dimensions.

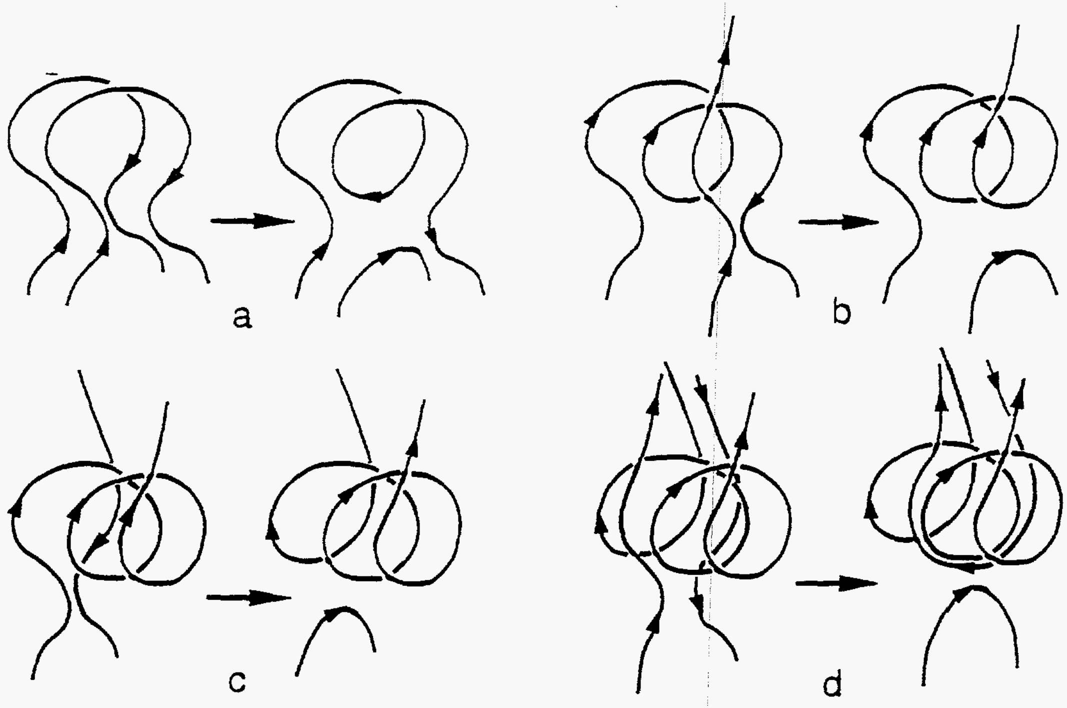

Figure 2. Sketches of successive steps in three-dimensional reconnection of magnetic field lines threading coronal mass ejections. The sketches are not to scale and are intended only to illustrate successive changes in magnetic topologies resulting from reconnection. These changes are consistent with numerical simulations of reconnection in a qualitatively similar geometry in the geomagnetic tail, and appear to be consistent with a variety of solar and interplanetary observations of coronal mass ejections.