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Dynamics of Coronal Mass Ejections (CMEs)

J. Chen,¹ P.W. Schuck,¹ and V. Kunkel²

¹Plasma Physics Division

²George Mason University

Introduction: Strong geomagnetic storms cause disturbances in the ionosphere that can modify conditions in the operational environment of the Navy around the globe. If severe enough, they can degrade or cause outages in SATCOM and GPS operations, impairing the Navy's ability to maintain environmental awareness and continuous connectivity of the widely dispersed fleet. The ultimate cause of strong storms is the eruption of Earth-directed coronal mass ejections (CMEs) at the Sun. CMEs, which are strongly magnetized plasma structures, represent ejection of 10^{16} g of material at up to 2000 km/s from the Sun.

The magnetic geometry and the driving mechanism of CMEs have been two major questions of modern solar physics. These questions are closely related: the driving forces acting on a magnetized plasma structure critically depend on its magnetic geometry in three dimensions. Unfortunately, neither the magnetic field of the eruptive structure nor the forces acting on it can be directly measured. Under an NRL basic research program supplemented by NASA grants, we have developed a first-principles theory to understand the 3D magnetic geometry and the nature of the force from directly observable quantities.

What is the 3D Magnetic Geometry of CMEs?

With the launch of NRL's Large Angle and Spectrometric Coronagraph (LASCO) instruments on the Solar and Heliospheric Observatory (SOHO) satellite in 1995, CME acceleration—the net accelerating force per unit mass—has been extensively documented in the region 2–30 solar radii ($R_\odot$). Our work with LASCO data has shown that the underlying magnetic field of a CME is that of a “flux rope”: pictorially speaking, a bent coil of magnetic field lines, whose two ends are connected to the Sun. Figure 3 shows a composite image of a CME (arrow) observed by the LASCO C2 and C3 telescopes on 20 August 2000. In this figure, the small white circle at the bottom indicates the limb of the Sun. The circular disk of radius $2R_\odot$ corresponds to the occulter of the C2 telescope. The two legs of the CME connected to the Sun are separated by distance S_f , as illustrated in the figure.

Using a theoretical model previously developed at NRL, we demonstrated that the height $Z_{\max}$ above the photosphere at which the acceleration of the leading edge attains its maximum value scales with the distance S_f between the photospheric footpoints of the CME's legs in such a way that the following inequality is satisfied:¹

$$\frac{S_f}{2} \leq Z_{\max} \leq \frac{3}{2} S_f. \quad (1)$$

This relationship was directly tested against 17 well-observed CMEs and eruptive prominences (EPs), where (i) the source regions were visible so that we could determine the approximate distance (S_f) between the footpoints and (ii) the data contained sufficient numbers of height measurement to allow us to determine the maximum-acceleration height ($Z_{\max}$). Radio data and data from the Extreme Ultraviolet Imaging Telescope (EIT) on SOHO were used to estimate S_f .

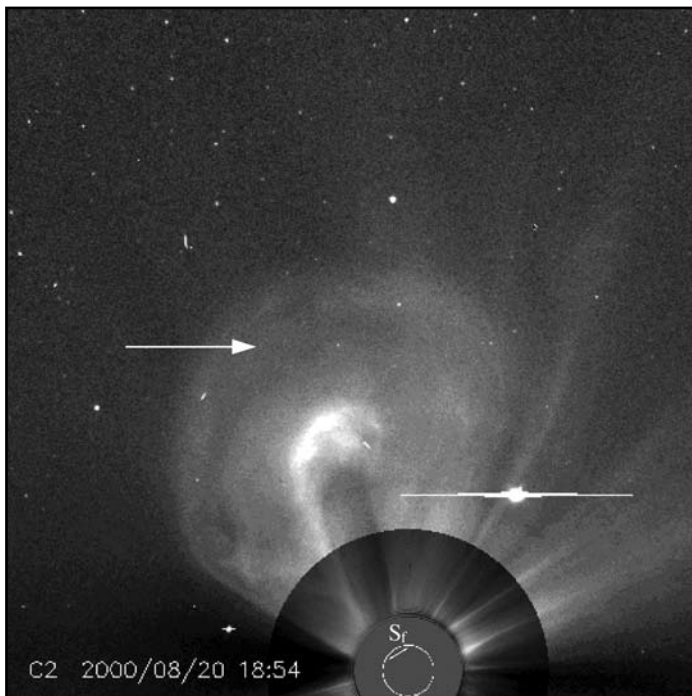
Each event was analyzed to determine a pair of numbers, $Z_{\max}$ and S_f . Figure 4, adapted from Ref. 1, shows the data points for the 17 events. The lines A and B are defined by $Z_{\max} = S_f/2$ and $Z_{\max} = 1.5 S_f$, respectively, corresponding to the lower and upper limits of the inequality above. The plot shows that inequality (1) is satisfied by all the events in this sample consistent with the uncertainties in the data.

What is the Force that Drives CMEs? What can we deduce from the excellent agreement between the theoretical prediction and observational data? The flux-rope scaling law, inequality (1), is based on two assumptions: (i) the magnetic structure is that of a flux rope with footpoints separated by S_f and (ii) the structure is driven by the “hoop force,” a particular form of Lorentz force acting on curved, current-carrying plasmas, including tokamaks in laboratories for magnetic fusion. This force has the unique property that

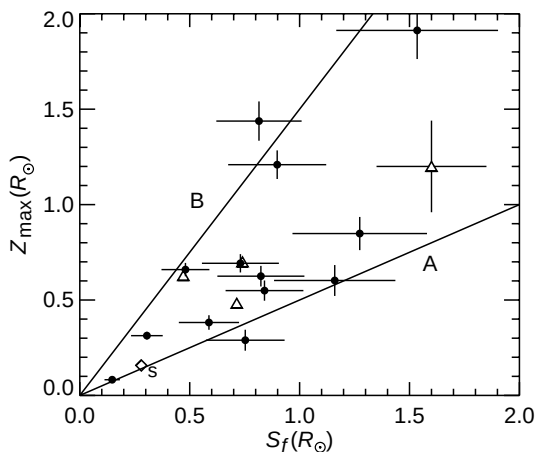
$$\frac{d^2 Z}{dt^2} \propto \left(\frac{1}{R} \right)^2 \left(\frac{1}{\ln R} \right)^2 \quad (2)$$

where R is the major radius of the flux rope. The right-hand side is maximum where curvature ($1/R$) is maximum.

The physics of this process is schematically illustrated in Fig. 5. Imagine that the lowest arc corresponds to the initial flux rope characterized by radius R_1 or curvature $1/R_1$ and footpoint separation S_f . As the flux rope rises with the footpoints held stationary, the curvature increases. Curvature reaches its maximum value when the arc is a semi-circle with $Z = R = S_f/2$, where Z is the height of the apex. Thereafter, the curvature monotonically decreases. Thus, if the flux rope is driven by the hoop force, the acceleration, i.e., the force per unit mass, necessarily peaks when the flux rope reaches the semi-circular position. The good agreement shown in Fig. 4 implies that CMEs are consistent with magnetic flux ropes and expand under the Lorentz force. Physically, the result shows that CME acceleration is governed by the footpoint separation distance S_f .

**FIGURE 3**

A LASCO C2-C3 composite image of a CME, indicated by an arrow, observed on 20 August 2000. The white circle at the bottom indicates the Sun. The bright object on the right is a planet, with the horizontal rays caused by the saturated instrument.

**FIGURE 4**

Comparison of theory and data. $Z_{\max}$ and S_f are determined from data. The point marked "S" denotes a numerical simulation result. Data points lying between lines A and B satisfy the flux-rope scaling law, inequality (1).

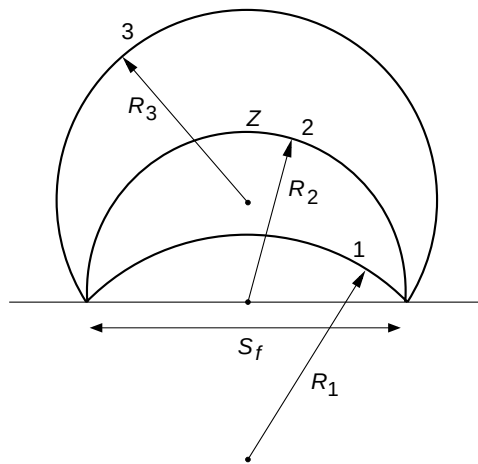
How Does a CME Propagate? After the initial acceleration, a CME continually expands away from the Sun. The propagation through the interplanetary medium, however, could not be observed until recently. With the launch of a pair of Solar Terrestrial Relations Observatory (STEREO) satellites with the NRL suite of instruments called Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI)² on board, it has now become possible to quantitatively study the dynamics of CMEs in interplanetary space.

Figure 6 shows the trajectory of a CME observed by SECCHI (COR2, HI 1, and HI 2) and LASCO (C2 and C3) in May 2007. The height of the leading edge of the CME measured from the solar surface is shown by various symbols corresponding to different instru-

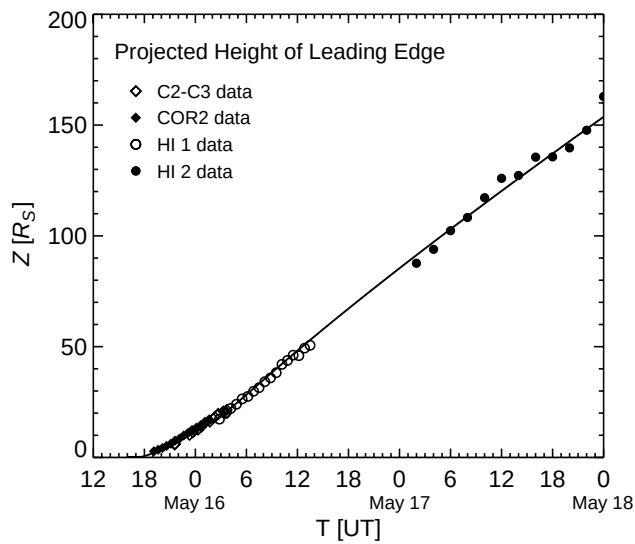
ments. The curve is the initial-value solution of the theoretical model. The figure shows that the model is capable of producing a solution that accurately reproduces the observed dynamics throughout the field of view, from $R_{\odot}$ to about $3/4$ AU.

We have established with strong quantitative evidence that CMEs are magnetic flux ropes accelerated by the Lorentz hoop force. Figure 6 represents the first successful theoretical modeling of CME acceleration in the inner corona and the subsequent propagation in interplanetary space.

[Sponsored by ONR and NASA]

**FIGURE 5**

Flux-rope scaling law. The arcs schematically represent a rising flux rope.

**FIGURE 6**

Theoretical solution directly compared with SECCHI data. Measured height-time data are represented by various symbols corresponding to different telescopes. The curve is the "best-fit" theoretical solution.

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