Multiple spacecraft flux rope modeling of the Bastille Day magnetic cloud


Abstract.
The Bastille Day magnetic cloud in July 2000 occurred with NEAR in conjunction with the Earth at a radial distance of 1.76 AU and 1.9° from the Earth-Sun line. Propagation time from ACE at 0.99 AU to NEAR indicates the cloud did not decelerate significantly between the Earth and 1.76 AU. Using a non-force-free, kinematic flux rope model we find the rope contained 130 Twb of magnetic flux, was oriented with clock and clock axes of 50° and 83°, and had a radius of 0.25 AU at ACE. At NEAR its radius had expanded to 0.43 AU. Simultaneous modeling of ACE and NEAR data indicate the axial and poloidal magnetic fields vary as R-1.4 and R-1.2 where R is heliocentric distance. Magnetosheath thicknesses of 5.14 AU and 0.23 AU indicate the rope cross section is elongated normal to the cloud axis and the radial direction.

Introduction
Coronal mass ejections (CMEs) are solar eruptions releasing vast quantities of plasma not previously participating in the solar wind expansion. When counterparts of these eruptions are observed at 1 AU, proton temperatures are colder than the ambient solar wind and the magnetic field is often enhanced and twisted. These interplanetary counterparts of CMEs or ‘ICMEs’ can thus be easily distinguished from the ambient solar wind. Unfortunately it is difficult to do more than relate the time and speeds of CMEs and ICMEs because coronagraph images the density and not the magnetic field. Measurements made by single spacecraft near 1 AU provide information about local magnetic structure, plasma composition, and nonevaporation of an ICME to the Sun as the ICME convects across the solar wind. Coronagraph images above the limb of the Sun show CMEs average about 45° in azimuth (St. Cyr, personal communication, 1999). The lack of multi-point (e.g., stereo) imaging results in only a weak understanding of the 3-D structure of CMEs. Thus multi-point measurements of ICMEs at 1 AU are necessary to deduce this structure.

In the specific cases of magnetic clouds, which are considered a subset of ICMEs [Gosling 1990], we can make simplifying assumptions about their 3-D structure in terms of flux rope topology [Goldstein 1983, Burlaga 1991]. However, such assumptions have led to pictures of flux ropes as cylindrically symmetric structures [Burlaga et al. 1994]. These models do not take into account properties such as azimuthal stretching of flux rope cross sections, bending along the rope axis, and expansion. These properties have not been examined in detail because they cannot be uniquely determined from single spacecraft observations that have generally been made to date. Multipoint measurements of clouds are needed to determine the azimuthal extent of their cross sections, their axial curvature, and expansion with heliocentric distance. Recently the NEAR, Wind, and ACE spacecraft have provided a series of such opportunities at relative elongations of up to 180° and radial separations up to 0.8 AU. In this study we examine two observations of a single magnetic cloud that were obtained at locations 0.76 AU apart.

Herein we use a model of a flux rope that is not force-free despite the apparent success of the cylindrically symmetric constant alpha force-free solutions [Lepping et al., 1990]. We are not the first to attempt to improve upon this model, Farris et al. [1995] first compared differences between force-free and non-force-free models showing a non-force-free model enables us to model the structure of a larger number of “magnetic clouds” in which it is obvious the force-free assumption has broken down. Marubashi et al. [1997] improved upon the static force-free model by including kinematic effects such as expansion. By combining a kinematic approach with non-force-free rope topologies, we are able to broaden the range of flux rope signatures that can be modeled and increase the accuracy of current flux rope fits. Using multipoint measurements of clouds requires an extended model to optimize data from multiple spacecraft simultaneously.

In this paper we model magnetic field observations of the Bastille Day cloud on July 12-16, 2000 from the ACE-NEAR pair of spacecraft taken when the two spacecraft were near radial alignment, allowing the study of ICME expansion with heliocentric distance. From February 14, 2000, to February 12, 2001, NEAR was in orbit around 433 Eros making interplanetary magnetic field measurements [Anderson et al., 2001]. During the July event, Eros was in conjunction with the Earth located less than 2° from the Earth-Sun line at 1.76 AU heliocentric distance. ACE was along the Earth-Sun line at the L1 libration point ~0.01 AU sunward of the Earth [Stone et al., 1998]. The observations provide a unique opportunity to examine the expansion of this cloud as it moves away from the Sun. We first review the inversion technique.

Inversion Technique
For multipoint observations in which the spacecraft are radially aligned from the Sun such as the Bastille Day cloud, it is possible to determine the azimuthal extent of the rope. Thus we use a kinematic, non-force-free flux rope model

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having cylindrical symmetry [Mulligan and Russell, 2001]. The magnetic field has an axial component that falls off as an exponential power to a power of the distance from the axis of a cylinder. The azimuthal or poloidal field increases as a minus an exponential power to a power so that it maximizes at the edge of the rope. This model is fit to the data using the downhill simplex method of Nelder and Mead [1965] and solves for the orientation of the rope in three dimensions, the size of the structure, the axial and poloidal fields, an impact parameter (the distance of the closest point of observation to the flux rope axis), and an expansion factor that aids in determining the degree of asymmetry between the leading edge and trailing edge of the rope. The expansion factor, expressed as \( \delta = (1+\gamma \Delta \lambda) \), where \( \gamma \) is the average speed of the rope divided by its diameter, \( \Delta \lambda \) is the time measured from the start of the cloud, and \( \gamma \) is a free parameter ranging from 0 to 1, is a linear factor added to account for a decreasing field strength through the rope that we interpret as the expansion of the structure as it moves past the spacecraft [Mulligan and Russell, 2001].

**Single Spacecraft Flux Rope Analysis**

On July 15 at 1500 UT ACE observes a shock followed by a magnetic cloud. About 1 day later NEAR observes a shock and a similar cloud structure. Because NEAR does not have a plasma instrument, the average speed of the cloud at NEAR is determined by dividing the radial separation of the two spacecraft by the travel time of the cloud from ACE to NEAR. Timing the arrival of the cloud gives an average radial speed of 1060 km/sec at NEAR, consistent with the plasma speed of \(~\approx1100\) km/s observed at ACE located closer to the Sun. Using these speeds to determine the size of the magnetosheath gives 0.14 AU at ACE and 0.23 AU at NEAR. These distances are much larger than the expected shock stand off distance for a cylindrically symmetric flux rope having a diameter equal to the observed thickness of the cloud at each spacecraft location.

Modeling each spacecraft observation independently gives two flux rope solutions. At ACE the rope has a radius of 0.24 AU and its axis is oriented with a clock angle of 13° and a cone angle of 92°. (The clock angle \( \Theta \) is defined in the plane of the sky in a counterclockwise sense with 0° corresponding to the axial field pointing northward. The cone angle \( \Theta \) is defined such that \( \Theta = 0 \) when the axis of the rope is aligned along the Earth-Sun line.) The maximum strengths of the axial and poloidal fields in the ACE flux rope are 77 nT and 58 nT. The flux content is \(-0.65\) Twb. At NEAR the rope has expanded to 0.43 AU in radius and has a clock angle of 5° and a cone angle of 76°. The maximum in both axial and poloidal fields is 27 nT and the flux content is \(-137\) Twb. Both spacecraft pass to the east of the rope axis with ACE being \(-0.01\) AU to the East and NEAR being 0.06 AU further east. The velocity vector of the magnetic cloud is not aligned exactly with the Earth-Sun line but is aberrated by \(-1.5\)° as the cloud moves from ACE to NEAR and when taking into account this aberrated solar wind direction, the relative positions are within 0.01 AU of the expected locations of the spacecraft. We note that the impact parameters are poorly determined because a cylindrically symmetric model is used to fit a structure that is not probably not cylindrically symmetric as inferred from the standoff distance of the shock in front of the ICME and as found in previous multi-satellite studies [Mulligan and Russell, 2001].

**Multiflap Flux Rope Analysis**

Since the observations were obtained at different radial distances from the Sun, we can determine the flux rope expansion as the rope convects from ACE at 0.99 AU to NEAR at 1.76 AU. Fitting the data from both spacecraft simultaneously requires establishing how the magnetic field decreases as the rope expands with increasing heliocentric distance. If we consider the field component along the rope axis the magnetic flux through its cross section is conserved (i.e., \( B_{\theta} = const. \), where \( B_\theta \) is the axial field and \( B_a \) is the cross sectional area of the rope). Similarly, the poloidal field component satisfies \( B_{\phi} \) conservation through the rope extending from its axis to its edge, which is simply the flux rope radius \( R \), and over a height \( h \) along \( \phi \) axis, where \( R \) and \( h \) are assumed to be linear functions of \( R \) and \( h \) is the distance to the Sun. Using these assumptions we find that both axial and poloidal fields fall off as \( R^{-2} \). However, depending on the dynamical interaction of the rope with the solar wind, the fall off may be different than expectations and other radial variations have been postulated by Cargill et al. [2000] and Mulligan and Russell [2001].

Incorporating these scalings laws for the axial and poloidal fields into the model and inverting ACE and NEAR data simultaneously results in the fits in Figures 1 and 2. The magnetic field components are shown as solid lines in Figure 2 and the model fit is shown by dashed lines. The fitted rope has clock and cone angles of 50° and 83°. Figure 3 shows 3-D di-
grams of the rope in context with the spacecraft locations in solar equatorial coordinates. The view is in the ecliptic plane with the Sun at the origin and Earth at 1 AU. The z axis points radially along the Earth-Sun line. Circular cylin-
ders represent the outer boundaries of the rope at ACE and NEAR. The radii of these cylinders are 0.25 AU and 0.43 AU, respectively. Solid lines show the extrapolation of the axial field back to the Sun using a dipole approximation. Be-
cause the spacecraft are radially aligned for this event we cannot gain information about the azimuthal dimensions of the rope. However, as clearly shown in Figure 3 the multi-
point analysis reveals details about the expansion of the rope as it moves from ACE to NEAR.

The maximum axial and poloidal fields of the rope at ACE are 80 nT and 41 nT. If an assumed above the $R^{-2}$ scaling applies, the model gives a maximum axial field strength of 29 nT and a maximum poloidal field strength of 23 nT at NEAR. These results are similar to the field strengths ob-
tained independently at each spacecraft in the previous sec-
tion. However, if we allow parameterization of the scaling laws and hold the orientation of the cloud constant (clock and cone angle of 50° and 83°), the multipoint fit is im-
proved, suggesting a $R^{-1.4}$ and $R^{-0.5}$ scaling of the ax-
ial and poloidal fields is a better approximation to the rope expansion from 0.99 AU to 1.76 AU. In other words, the Bastille Day flux rope expanded much less than anticipated. Since the axial and poloidal scaling laws are related to the radius of the rope, we can test their accuracy by comparison with the rope radius at NEAR shown in Figure 3.

Figure 3. Inversion of Bastille Day contemporaneous events at ACE and NEAR. The model showing the expansion of the rope from ACE to NEAR.

Figure 4. ACE current densities associated with the model fit and plotted from the center of the flux rope. Inbound/outbound currents including temporal expansion of the rope shown by solid lines. Time stationary currents shown by dotted lines. The vertical line shows ACE closest approach to the rope axis.

Figure 5. NEAR current densities shown in the same man-
er as Figure 4.

As described previously, the expansion parameter is a lin-
ear factor that measures the rate of change in the magnetic field strength due to the expansion of the rope as it conver-
tes past a single spacecraft. When fitting multiple spacecraft, data simultaneously, the expansion parameter represents the average rate of change of the field magnitude at both space-
craft locations. Using this information in conjunction with the size of the rope at ACE and conservation of magnetic flux, it is possible to predict the flux rope radius at NEAR. This calculation gives a radius of 0.38 AU, which is consist-
tent with within about 0.05 AU of both the single spacecraft model fit and the multipoint model fit. The corresponding scaling in diameter of the rope from ACE to NEAR obtained by the fall off in the axial magnetic field is $R^{-1.1}$ in agree-
ment with the multipoint studies of Boerner and Schwenn [1994], which find flux rope diameters scale as $R^{-0.1}$. The model returns radii that nearly double in size from ACE to NEAR. It is expected that the Bastille Day magnetic cloud is also stretched azimuthally [Cargill et al., 2000; Mul-
ligan and Russell, 2001] and as such the radial dimensions and flux content should be considered to be lower bounds. The impact parameters show ACE to be 0.11 AU east of the center of the rope and NEAR to be 0.06 AU further east, also consistent with the fits in the previous section. Again we note that cylindrically symmetric fits to noncylindrically symmetric structures would not be expected to return accu-
rate impact parameters. Estimates of the flux content are between 108-130 TWb.

Figure 4 shows the associated model rope currents at ACE derived from $V \times B$ rotated into the field-aligned coordi-
nate system of the rope. Figure 5 shows the rope currents derived at NEAR. The currents are separated into two pan-
els, the upper being the field-aligned or force-free compo-
nent and the lower being the component perpendicular to the field, also called the non-force-free component. Both are plotted against radial distance from the center of the rope with the impact parameter indicated by vertical dashed lines. The solid lines represent the currents for both the inbound and outbound traversal through the rope. Temporal expa-
nsion during the finite spacecraft traversal time has been taken into consideration. Dotted lines show the inbound and out-
bound currents without expansion effects (i.e., time station-
ary). Both the static and temporal current profiles at each spacecraft indicate a nearly force-free flux rope configura-
tion with $L_1/L_2 < 0.3$. We infer from the similarities be-
tween the current distributions in both the static and kine-
matic current profiles that the expansion effects do not have a significant effect on the force-free nature of the flux rope.
Conclusions

Multipoint observations and modeling of ICMEs have revealed much about the structure of ICMEs. Prior studies have shown that ICMEs may have oblate cross sections extending more than 1.5 R⊙. This suggests that the solar wind flow can be in any direction (Mulligan and Russell, 2001). Although the azimuthal spacecraft separations are too small to fit an oval rope to the Bastille Day observations, the radial separation of ACE and NEAR provides insight as to how clouds expand as they move through the solar wind.

We have modeled the rope in three ways: independent analyses at ACE and NEAR, a joint analysis assuming R−3 scalings of the magnetic field, and a joint analysis allowing arbitrary scaling of both the axial and poloidal field components with heliocentric distance. The single spacecraft model fits ACE indicates the radius of the rope is 0.23 AU at the Earth. At NEAR’s location of 1.76 AU, the rope radius has expanded to 0.43 AU. Modeling the observations simultaneously and constraining the expansion to allow R−2 fall off in the field components provides a fit to the data that is consistent with the field properties of the independent single spacecraft rope fits. Parameterization of the scaling laws while holding the orientation of the cloud constant improves the fit and suggests that a R−1.4 and R−1.5 scaling of the axial and poloidal fields is a better approximation to the expansion of the rope from 0.99 AU to 1.76 AU. Using the expansion parameter of the multipoint fit in conjunction with the size of the rope at ACE and conservation of magnetic flux predicts a radius at NEAR of 0.38 AU. Thus there are two independent methods in the model useful in determining flux rope expansion. The 0.05 AU discrepancy between the predicted radius (0.38 AU) and the single and multipoint models at NEAR (0.33 and 0.38) is likely most likely the result of our inability to accurately determine a speed profile for the rope at 1.76 AU due to the absence of a plasma instrument aboard NEAR. The clock and cone angles of the simultaneous fit (50° and 35°) are intermediate between the independent fit at ACE and NEAR as should be expected. The axial and poloidal field magnitudes of the simultaneous fit are nearly identical to the field magnitudes obtained in the single spacecraft inversion as are the flux constant and field directions. As such, every ICMF for which we have had the capability of detecting noncylindrical geometries in the spacecraft is outlined and indicates that flux ropes are preferential to cylindrically symmetric flux ropes, the flux content and radial dimensions of the rope was considered to be lower bounds. The preferred oblate shape of flux ropes is consistent with the large shock standoff distances of 0.14 AU and 0.23 AU at ACE and NEAR. The large magnetic field sizes suggest the ICME thickness is that of a shell of material whose radius of curvature is much larger than its thickness. Indeed the shock standoff distance in Figure 1 and 2 is indicative of an obstacle whose radius of curvature is nearly twice that implied by its observed thickness. Finally, both the time- stationary and instantaneous current distributions indicate the rope is nearly force-free. We interpret the similarities in these current distributions to mean that the expansion of the rope does not significantly affect its force-free nature. At 0.99 AU to 1.76 AU. That the rope is force-free despite the R−1.4 and R−1.5 scaling for the fields is strong evidence that its cross section is not cylindrical because a cylindrical symmetric force-free flux rope requires the ratio of axial to poloidal fields to scale as R−3. The model returns an axial to poloidal field ratio of R−0.6 suggesting the axial field will be only moderately depressed relative to the poloidal field at large R. Thus it is expected that many of the magnetic field characteristics of the flux rope will be maintained as it moves further out in the heliosphere.

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