Reconnection of magnetic field lines at the solar surface during CME propagation

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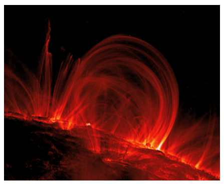
ABSTRACT

Coronal mass ejections (CMEs) are a well known phenomenon resulting in the transport of magnetic flux into the heliosphere. The cumulative effect of this addition of magnetic flux must be balanced by a corresponding reduction of heliospheric flux. This paper describes a model of the reconnection of CME field lines with open field lines, based on observational and theoretical explanations of open magnetic field motions and reconnections in the corona. The model is solved both analytically and numerically. We compare these solutions with observations of CME ejecta (represented in this study by enhanced oxygen charge states) and a subset of those CME ejecta with a closed magnetic connection to the Sun (represented by bidirectional electrons, or BDEs). Good agreement is found between the model solutions and the observations.

Model Summary

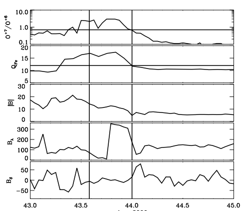


(TRACE image)

- Solved analytically and numerically
- Describes the erosion of CME magnetic flux over time
- Based on interchange reconnection and diffusion of magnetic flux
- Allows reconnection of CME field lines long after the CME leaves solar surface
- Predicts whether a given CME will retain a solar connection at 1 AU
- Compared to connection of in situ CME ejecta

1 Introduction

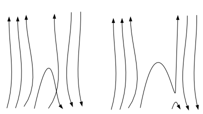
1.1 Example of in situ CME ejecta



- Slight rotation in B_λ
- Enhancements ($O^{+7}/O^{+6} > 0.7$, $Q_{Fe} > 12$) above horizontal lines
- BDEs (between vertical lines) appear in last 2/3 of event
- Events defined as 4+ hours of enhanced O^{+7}/O^{+6}
- 60% of our events contain BDEs

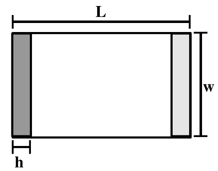
1.2 Open Flux Transport

- Open field lines travel on the solar surface by reconnection with small coronal loops [1, 2]
- At the edge of a CME, interchange reconnection [3] occurs opening the CME field lines into the heliosphere



2 Analytic Method

2.1 Footprint geometry



- left shaded region = newly open field lines
- right shaded region = conjugate footpoints of left region

Applying simple diffusion ($\kappa = \frac{(\delta h)^2}{2\delta t}$), we determine the erosion area ($h^2 \approx 2t\kappa$) of CME field lines that have reconnected. By this reasoning, we form an equation which relies only on the ejecta transit time (t=1AU/v) and duration:

$$t_{duration} + 0.81L^2/2\kappa < 2t_{transit} \quad (1)$$

If this inequality is met, the event should contain BDEs.

2.2 Comparison with Data

- We find 256 events in 5 years of data (1998-2002)
- We separate them into slow/fast events and short/long events

	velocity $\leq$ 400 km/s	velocity > 400 km/s
duration $\leq$ 12 hrs	31.6% (57)	68.2% (66)
duration > 12 hrs	56.7% (60)	89.0% (73)

- Faster and/or wider events are more likely to retain solar connection
- The trend is consistent with Equation 1
- Individually, Equation 1 correctly predicts presence of BDEs 77% of the time

2.3 Assumptions

- simplistic initial geometry
- defining CME width as duration
- poorly defined CME boundaries
- spatial/temporal effects
- assuming CME velocity is constant to determine transit time

Given these potential errors, the 77% success rate is remarkable

3 Numeric Method

3.1 Equations

Now we try a more rigorous numeric treatment

$$\frac{\partial B}{\partial t} = \nabla^2 \kappa B$$

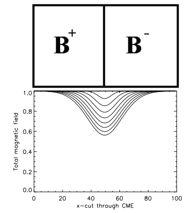
Assuming κ is constant over the CME and include equations for B^+ and B^-:

$$\frac{\partial B^+}{\partial t} = \kappa \nabla^2 B^+ - \frac{B^+ B^-}{(B^+ + B^-)\tau} \quad (2)$$

$$\frac{\partial B^-}{\partial t} = \kappa \nabla^2 B^- - \frac{B^- B^+}{(B^- + B^+)\tau} \quad (3)$$

The loss term describes reconnection on timescale of $\tau \approx 38$ hours

3.2 Results

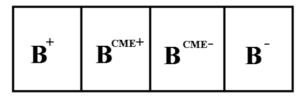


We start with the positive magnetic field on the left and negative field on the right and then allow diffusion to take place

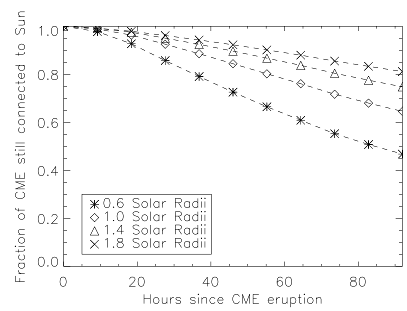
Equations 2 and 3 are solved using the Crank-Nicholson technique. $|B|$ is plotted every 10 hours. After 92 hours (1 AU @ 450 km/s) the magnetic field at the center has dropped to 55%

3.3 Including CME+ and CME-

In order to determine the degree of CME erosion we treat the CME field lines separately, resulting in 4 equations with 2 loss terms each (not shown)



Then we plot the percentage of B^{CME+} and B^{CME-} that are still connected to the Sun as a function of time for several initial sizes

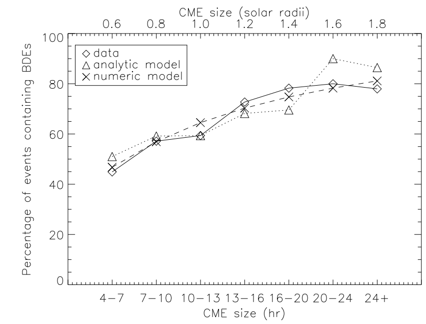


- Erosion is approximately linear after 10 hours
- 40-85% of the field lines are still connected after 92 hours
- Again, the erosion is time and size dependent

3.4 Assumptions

- simplistic CME geometry and constant reconnection rate
  - symmetry causes all reconnections to be disconnections
  - in accounting for this we underestimate the available open flux
  - however, doubling the initial open flux changes the final percentages by less than 3%, so the resulting error is not significant

4 Both methods compared with data



ICME size	data	analytic (%correct)	CME size	numeric
4-7 hrs	45%	51% (69%)	0.6 $R_\odot$	47%
7-10 hrs	57%	59% (69%)	0.8 $R_\odot$	57%
10-13 hrs	59%	59% (81%)	1.0 $R_\odot$	65%
13-16 hrs	73%	68% (86%)	1.2 $R_\odot$	70%
16-20 hrs	78%	70% (65%)	1.4 $R_\odot$	75%
20-24 hrs	80%	90% (90%)	1.6 $R_\odot$	78%
24+ hrs	78%	86% (75%)	1.8 $R_\odot$	81%

- Both methods are a good fit to the data
- Analytic results are a better match to specific features
- Numeric results are better overall (2.6% difference per bin versus 5.7%)

5 Conclusions

- Analytic method predicts if a given CME will retain its solar connection
  - indicates CME reconnection is a continuing process which depends strongly on the velocity and size of ejecta
- Numerical method predicts solar connection for a given initial CME size
  - reconnection appears to be linear as CME expands
- Both methods fit the data
  - supports the argument that CME field line erosion is occurring through reconnection
- Future work
  - merging of methods to utilize strengths of each
  - comparison with Ulysses data to look at temporal aspects
  - inclusion of a more complex CME structure, random reconnection rate, and an method to calculate disconnection of open flux

References

[1] Fisk, L. A. J. Geophys. Res., 108(A4), 1157, doi:10.1029/2002JA009284, 2003.

[2] Schrijver, C. J. et al., ApJ, 577, 1006, 2002

[3] Crooker, N. U. et al., J. Geophys. Res., 107, 10.1029/2001JA000236, 2002.