Examining the drag force on coronal mass ejections

Chia-Hsien Lin[1] & James Chen[2]

[1]Graduate Institute of Space Science, National Central University, Taiwan
[2]Naval Research Laboratory, Plasma Physics Division, Washington D.C., U.S.A.

January 19, 2017

What is coronal mass ejection (CME)?

- a large-scale erupting magnetic fluxrope that carries large amount of magnetic flux, energy, and plasma from the Sun to the interplanetary space.
- main driver of space weather disturbance and can cause hazard to Earth.
- typical eruption process:
  (1) initial quasi-static slow rising
  (2) fast and sudden upward acceleration and expansion
  (3) final propagation at speed ≈ ambient solar wind speed.

Prediction of CME arrival time

Equation of motion of CME:

$$M_{\rm CME} \frac{d\vec{V_{\rm CME}}}{dt} = \vec{F_{\rm tot}} = \vec{F_L} + \vec{F_{\rm drag}} + \vec{F_g} + \vec{F_p}. \qquad (1)$$

(F_L: Lorentz force; $F_{\rm drag}$: drag force; F_g: gravitational force; F_p: pressure force)

How to predict the CME arrival time?

Given $F_{\rm tot}$ and initial $V_{\rm CME}$
$\Rightarrow$ integrating Eq. 1 to get propagation time.

Drag-based prediction method

$$F_{\mathrm{drag}} = C_D A \rho_a (V_{\mathrm{SW}} - V_{\mathrm{CME}})|V_{\mathrm{SW}} - V_{\mathrm{CME}}|,$$

C_D: drag coefficient; A: diameter of CME cross section; ρ_a: ambient density

- Assumption:
  $F_L \ll F_{\mathrm{drag}}$ in the interplanetary space.
  $\Rightarrow F_{\mathrm{tot}} \approx F_{\mathrm{drag}}$
- Procedure:
  1. Using many observed CME trajectories to determine the profile of F_{drag}
  2. Using the determined F_{drag} and $M_{\mathrm{CME}} dV_{\mathrm{CME}}/dt = F_{\mathrm{drag}}$ to predict the arrival time of future CMEs.

Drag-based prediction method

$$F_{\mathrm{drag}} = C_D A \rho_a (V_{\mathrm{SW}} - V_{\mathrm{CME}})|V_{\mathrm{SW}} - V_{\mathrm{CME}}|,$$

C_D: drag coefficient; A: diameter of CME cross section; ρ_a: ambient density

- Assumption:
  $F_L \ll F_{\mathrm{drag}}$ in the interplanetary space.
  $\Rightarrow F_{\mathrm{tot}} \approx F_{\mathrm{drag}}$
- Procedure:
  1. Using many observed CME trajectories to determine the profile of F_{drag}
  2. Using the determined F_{drag} and $M_{\mathrm{CME}} dV_{\mathrm{CME}}/dt = F_{\mathrm{drag}}$ to predict the arrival time of future CMEs.
- **Problem:**
  $F_{\mathrm{tot}} = F_{\mathrm{drag}}$ **may be invalid**

Drag-based prediction method

$$F_{\mathrm{drag}} = C_D A \rho_a (V_{\mathrm{SW}} - V_{\mathrm{CME}})|V_{\mathrm{SW}} - V_{\mathrm{CME}}|,$$

C_D: drag coefficient; A: diameter of CME cross section; ρ_a: ambient density

- Assumption:
  $F_L \ll F_{\mathrm{drag}}$ in the interplanetary space.
  $\Rightarrow F_{\mathrm{tot}} \approx F_{\mathrm{drag}}$
- Procedure:
  1. Using many observed CME trajectories to determine the profile of F_{drag}
  2. Using the determined F_{drag} and $M_{\mathrm{CME}} dV_{\mathrm{CME}}/dt = F_{\mathrm{drag}}$ to predict the arrival time of future CMEs.
- **Problem:**
  $F_{\mathrm{tot}} = F_{\mathrm{drag}}$ **may be invalid**
  CME fluxrope not force-free at 1 AU (Subramanian et. al. 2014)

Drag-based prediction method

$$F_{\mathrm{drag}} = C_D A \rho_a (V_{\mathrm{SW}} - V_{\mathrm{CME}})|V_{\mathrm{SW}} - V_{\mathrm{CME}}|,$$

C_D: drag coefficient; A: diameter of CME cross section; ρ_a: ambient density

- Assumption:
  $F_L \ll F_{\mathrm{drag}}$ in the interplanetary space.
  $\Rightarrow F_{\mathrm{tot}} \approx F_{\mathrm{drag}}$
- Procedure:
  1. Using many observed CME trajectories to determine the profile of F_{drag}
  2. Using the determined F_{drag} and $M_{\mathrm{CME}} dV_{\mathrm{CME}}/dt = F_{\mathrm{drag}}$ to predict the arrival time of future CMEs.
- **Problem:**
  $F_{\mathrm{tot}} = F_{\mathrm{drag}}$ **may be invalid**
  CME fluxrope not force-free at 1 AU (Subramanian et. al. 2014)
  $\rightarrow$ **the predicted arrival times would be incorrect.**

Objective:

To examine the validity of the assumption $F_{\mathrm{tot}} = F_{\mathrm{drag}}$ in the interplanetary space.

Objective:

To examine the validity of the assumption $F_{\rm tot} = F_{\rm drag}$ in the interplanetary space.

Method:

- The trajectory of the entire CME process is computed from a 3D eruptive fluxrope model (Chen 1989, 1996).
- Parameters in the model are tuned until the computed and observed trajectories match
- The parameters of the trajectory most consistent with the observation are used to derive the forces acting on the CME

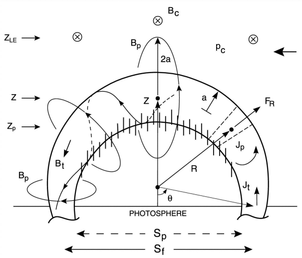
Eruptive Fluxrope Model (Chen 1989, 1996, Chen & Kunkel 2010)

- **Radial motion of the centroid at the fluxrope apex:**

$$M\frac{d^2Z}{dt^2} = \frac{\Phi_p^2}{c^4L^2R}\left[\ln\left(\frac{8R}{a}\right) - 1 + \frac{\xi_i}{2} - \frac{1}{2}\frac{\bar{B}_t^2}{B_{\rm pa}^2} + \frac{1}{2}\beta_p + 2\left(\frac{R}{a}\right)\frac{B_c(Z_{\rm ce})}{B_{\rm pa}}\right] + F_g + F_{\rm dra}$$

- **Expansion of the minor radius:**

$$M\frac{d^2a}{dt^2} = \frac{I_t^2}{c^2a}\left(\frac{\bar{B}_t^2}{B_{\rm pa}^2} - 1 + \beta_p\right).$$



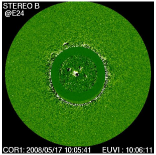
M: the mass per unit length;
Z: the height of the flux-rope centroid;
Φ_p: the poloidal magnetic flux;
L: the self-inductance;
B_p and B_t: poloidal and toroidal components of the fields;
$\bar{B}_t$: average toroidal magnetic field;
$B_{\rm pa}$: the poloidal field at $r = a$;
$\beta_p \equiv 8\pi(\bar{p} - p_c)/B_{\rm pa}^2$, where $\bar{p}$ is average internal pressure and p_c is ambient coronal pressure;
B_c: the ambient coronal field;
ξ_i: the internal inductance;
I_t: net toroidal current.

The selected events:

- **2008 May 17: (Wood et al. 2009)**

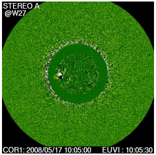
2008/05/17 10:05

STEREO-B



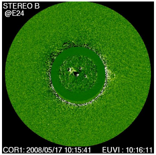
2008/05/17 10:05

STEREO-A



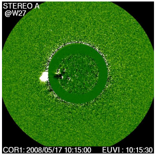
2008/05/17 10:15

STEREO-B

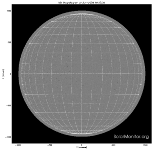


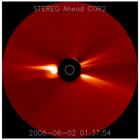
2008/05/17 10:15

STEREO-A



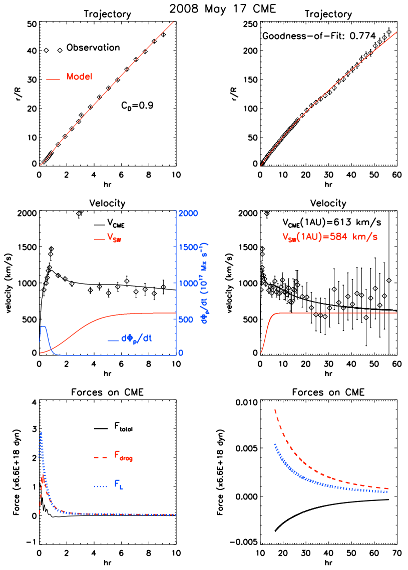
- **2008 June 01: (Wood et al. 2010)**





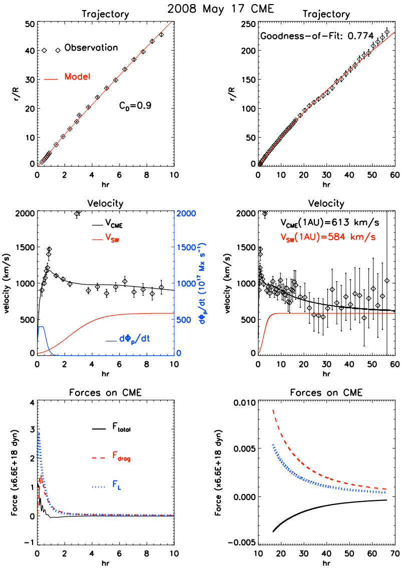
- No visible magnetic source region on the surface
- No visible eruptive feature in EUVI and COR1
- Earliest detection of the eruption is in COR2

Results: 2008 May 17 CME



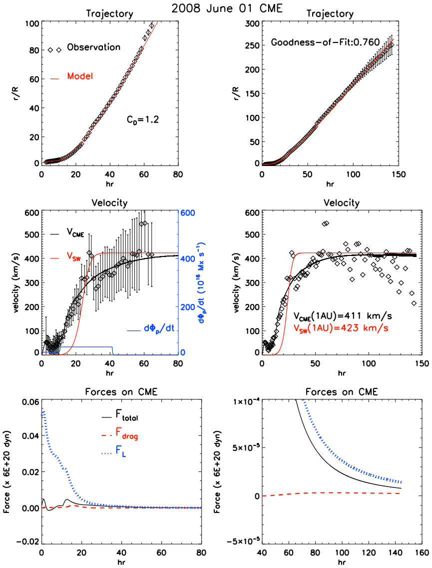
- The model is consistent with the entire observed CME trajectory
- $V_{\rm CME}^{\rm model}$(1 AU)$\approx$ 613km s^{-1}
  $V_{\rm CME}^{in-situ}$ $\approx$ 600km s^{-1}
- $V_{\rm SW}^{\rm model}$(1 AU)$\approx$ 584km s^{-1}
  $V_{\rm CME}^{in-situ}$: 450 $\rightarrow$ 550km s^{-1}

Results: 2008 May 17 CME



- The model is consistent with the entire observed CME trajectory
- $V_{\rm CME}^{\rm model}$(1 AU)$\approx$ 613km s^{-1}
$V_{\rm CME}^{in-situ} \approx$ 600km s^{-1}
- $V_{\rm SW}^{\rm model}$(1 AU)$\approx$ 584km s^{-1}
$V_{\rm CME}^{in-situ}$: 450 $\rightarrow$ 550km s^{-1}
- $|F_L| > |F_{\rm drag}|$ initially but
$|F_L| < |F_{\rm drag}|$ later
- $|F_L|$ and $|F_{\rm drag}|$ are comparable
- $|F_{\rm tot}| = |F_L - F_{\rm drag}| < |F_{\rm drag}|$

Results: 2008 June 01 CME



- The model is consistent the entire observed CME trajectory
- $V_{\mathrm{CME}}^{\mathrm{model}}$(1 AU)$\approx$ 411km s^{-1}
  $V_{\mathrm{CME}}^{in-situ} \geq$ 400km s^{-1}
- $V_{\mathrm{SW}}^{\mathrm{model}}$(1 AU)$\approx$ 423km s^{-1}
  $V_{\mathrm{CME}}^{in-situ}$: 500 $\rightarrow$ 300km s^{-1}
- $|F_L| > |F_{\mathrm{drag}}|$ during the whole process
- $|F_{\mathrm{drag}}| \rightarrow 0$ and
  $|F_{\mathrm{tot}}| = |F_L - F_{\mathrm{drag}}| \approx |F_L|$
  after $r > 30R$

Conclusion:

Our results show that

- F_L is not negligible in the interplanetary space.
- The ratio $|F_L|/|F_{\rm drag}|$ depends on the dynamics of the CME
- $F_L > F_{\rm drag}$ for some slow CMEs.
- The Lorentz force must be included in order to correctly predict the CME propagation time.

References:

- Chen, J. 1989, ApJ, 338, 453
- Chen, J. 1996, JGR., 101, 27499
- Chen, J. & Kunkel, V. 2010, ApJ, 717, 1105
- Subramanian et al., 2014, ApJ, 790, 125
- Wood et al. 2009, ApJ, 259, 163
- Wood, B. E. et al., 2010, ApJ, 715, 1524