CME Dynamics: Relative importance of Lorentz force and solar wind drag

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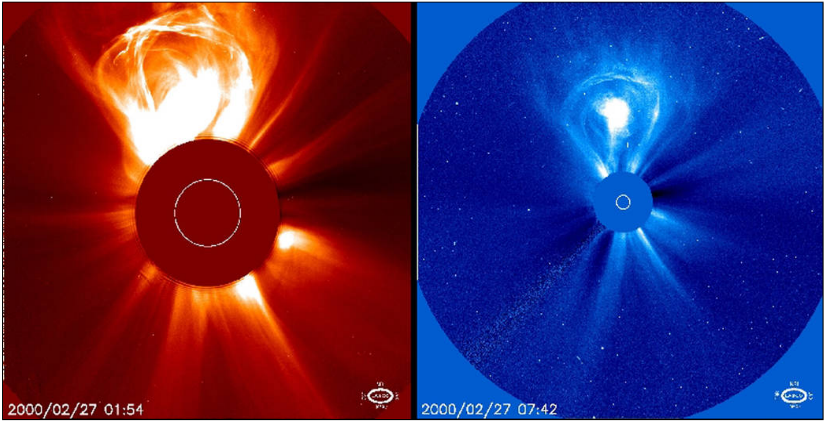
International Study of Earth-Affecting Solar Transients (ISEST-2017)

September 19, 2017

- Coronal Mass Ejections (CMEs) are hot, massive blobs of plasma and magnetic fields that erupt from the solar corona.
- Seen as bright, white-light events in the coronagraph field of view.



A coronal mass ejection on Feb. 27, 2000 taken by SOHO LASCO C2 and C3. Credit: NASA

- When Earth-directed CMEs are the main cause of disturbances in the near-Earth space environment.
- Understanding how these CMEs propagate and evolve is therefore imperative.
- Forces acting on CMEs include:
  Lorentz force, solar wind aerodynamic drag and gravity

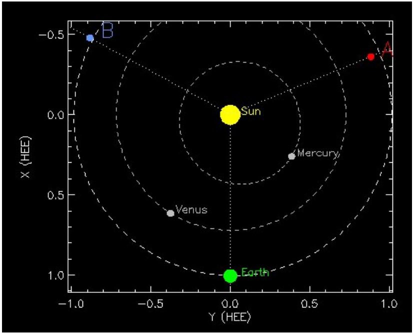
We address the following questions:

- **At what heliocentric distances do each of these forces dominate the CME dynamics?**
- **Where does the Lorentz force peak?**
- **At what heights does it become negligible compared to aerodynamic drag ?**

- We quantify the relative contributions of Lorentz forces and solar wind aerodynamic drag on the propagation of solar Coronal Mass Ejections (CMEs).
- We derive data from using Graduated Cylindrical Shell(GCS) fitting to LASCO/STEREO observations.
- We find that the Lorentz forces peak between 1.65-2.45 $R_\odot$. They become negligible in comparision to solar wind drag above 3-4 $R_\odot$ for fast CMEs and above 12-50 $R_\odot$ for slow CMEs.
- In general, it is accepted that Lorentz forces affect the CME very close to the sun and drag is dominant above just a few $R_\odot$. However, this is the first study to show the Lorentz forces to be substantial upto heights of 12-50 $R_\odot$for slow CMEs.
- Our results are expected to be important in building a physical model for understanding the Sun-Earth dynamics of CMEs.

The three coronagraphs and Heliospheric Imagers:

1. LASCO C2
2. STEREO A
3. STEREO B, provide a 3D view of the CMEs from $\sim$ 3–80 $R_\odot$.



PC: https://stereo-ssc.nascom.nasa.gov/cgi-bin/make_where_gif

Carefully tracking the expanding CME structure in all instruments, we sample a set of 38 CMEs during the rising phase of Solar Cycle 24.

- Each CME is 3D reconstructed using the Graduated Cylindrical Shell model that fits a flux-rope stucture to the observed CMEs.
- GCS fitting provides parameter information:- **CME h-t profile, width, area, radius** etc.

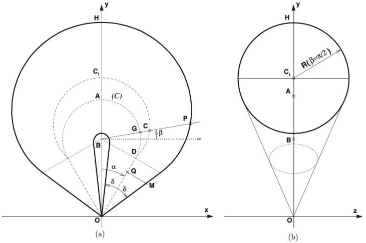
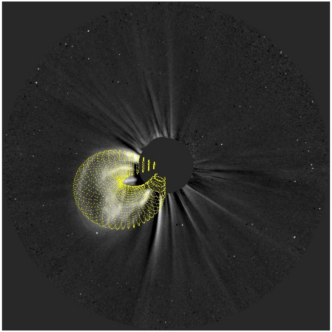


Figure 1. Schematic of the GCS model. The left panel shows a (O, x, y) planar cut of the croissant viewed face-on. The z-axis points toward the reader. The right panel shows a cut in the (O, y, z) plane where the croissant is viewed edge-on. In this view, only the circle (solid line) is in the (O, y, z) plane.



GCS geometry (Thernisien et al. 2006)

GCS fitting

A wire-mesh structure representing a flux rope is fit to the CME in each image.

- Main phases of CME propagation:
  Initiation Phase :- Initial CME eruption &
  Propagation Phase :- Forces affecting subsequent dynamics
- Interplay between the driving Lorentz forces; Solar wind drag & gravity determines the CME propagation dynamics.

$$
\begin{aligned}
F &= m_{cme}\frac{d^2R}{dt^2} \\
&= F_{Lorentz} + F_{drag} \\
&= \left\{ \left[\frac{\pi I^2}{c^2}\left(ln\left(\frac{8R}{b}\right) - \frac{3}{2} + \frac{l_i}{2} \right) \right] - \frac{(\pi R) I B_{ext}(R)}{c} \right\} \\
&\quad - \frac{1}{2}\, C_D\, A_{cme}\, n_{sw}\, m_p \left(V_{cme} - V_{sw}\right) \left|V_{cme} - V_{sw}\right|
\end{aligned}
$$

where, F –total force,
$m_{\rm cme}$– CME mass,
R – heliocentric distance of the leading edge of the CME

- Solar wind can "pick up" a slow CME or "drag down" a fast CME depending on the CME velocity relative to the solar wind velocity.
- **Momentum coupling** between the CME and the Solar wind is represented by:

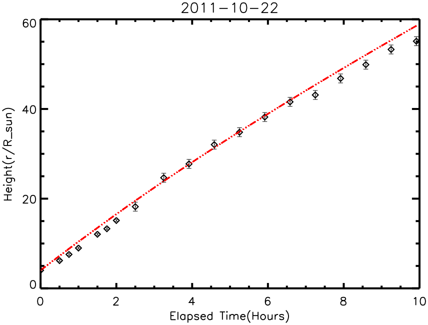
$$F_{drag} = -\frac{1}{2}\, C_{\mathrm{D}}\, A_{cme}\, n_{sw}\, m_p \left(V_{cme} - V_{sw}\right) \left|V_{cme} - V_{sw}\right|$$

Drag Coefficient, C_{D} describes the strength of the momentum coupling between the CME and the solar wind.

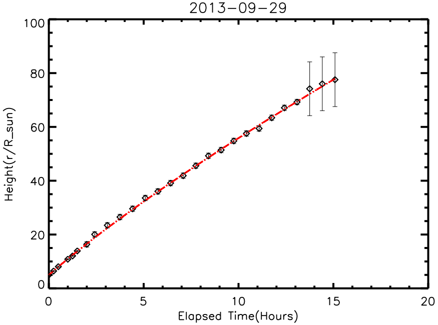
$$C_{\mathrm{D}} = 0.148 - 4.3 \times 10^{4}\, Re^{-1} + 9.8 \times 10^{-9}\, Re$$

- The 1D drag equation is solved from first observed height (h_0), using corresponding observational parameters (i.e., A_{cme}, n_{sw}, V_{sw}, C_{D}).

For Fast CMEs, (Initial velocity $v_0 > 900$ km s^{-1}), the model predictions (Red dash dotted line) match well with observations (black diamonds) when the model is initiated from first observed height.



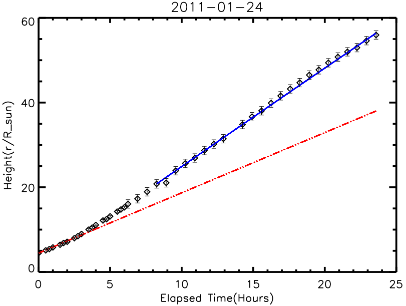
CME 18($\sim 1276\, km\, s^{-1}$& $h_0 = 4R_\odot$)



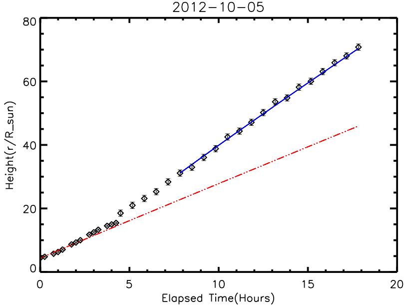
CME 36($\sim 1217\, km\, s^{-1}$& $h_0 = 4.9R_\odot$)

- **Observed for all the fast CMEs ($v_0 > 900\, km\, s^{-1}$).**
- **Fast CMEs are drag dominated from as low as 3-4 $R_\odot$.**
- **Fast CMEs are governed by solar wind drag from very early on.**

For slow(er) CMEs ($v_0 < 900\,km\,s^{-1}$), when initiated from h_0, model solutions disagree considerably. Model is initiated from progressively later heights till the model trajectory matches the observations (Blue).



CME8($\sim 276\,km\,s^{-1}$& $\widetilde{h}_0 = 21R_\odot$)



CME29($\sim 461\,km\,s^{-1}$& $\widetilde{h}_0 = 31R_\odot$)

- **$\widetilde{h}_0$ lies between 12–50 $R_\odot$ for slow CMEs.**
- **Dynamics of slow CMEs is dominated by solar wind drag only beyond $\widetilde{h}_0$.**
- ***Sachdeva et al. (2015), The Astrophysical Journal, 809, 158.***

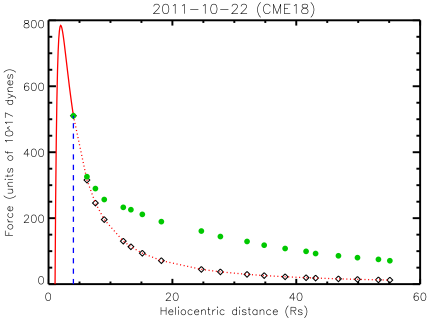
Lorentz force:

$$F_{Lorentz} = \left\{ \left[\frac{\pi I^2}{c^2} \left(ln\left(\frac{8R}{b}\right) - \frac{3}{2} + \frac{l_i}{2} \right) \right] - \frac{(\pi R) I B_{ext}(R)}{c} \right\}$$

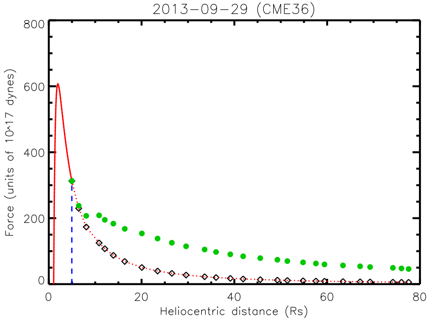
where, I – CME current, c – speed of light, b – CME minor radius & l_i – internal inductance.

- Lorentz force prescription follows *Kliem and Török, 2006* who model Torus Instability.
- It requires that the external field (i.e B_{ext}) should fall rapidly enough so that the CME can launch.
- First Term represents the Lorentz self forces i.e. $((1/c)J \times B)$ acting on the expanding CME current loop that accelerate the CME.
- Second term is the force due to the external poloidal field $(B_{ext} \propto R^{-n})$ that tends to hold down the expanding CME.
- CME current, I is estimated using the conservation of total magnetic flux(i.e. Internal + External).

Fast CMEs ($v_0 > 900\,km\,s^{-1}$),



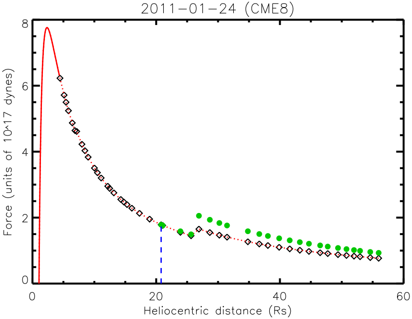
$v_0 \sim 1276\,km\,s^{-1}$,$h_{peak} = 1.95R_\odot$,n=2.1



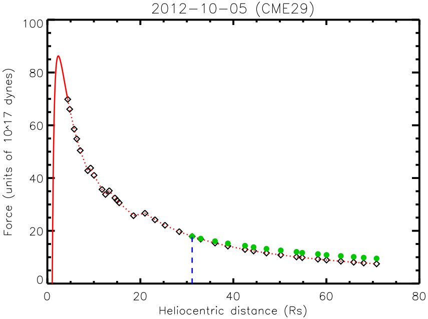
$v_0 \sim 1217\,km\,s^{-1}$,$h_{peak} = 1.95R_\odot$,n=2.1

- **Lorentz force profile increases from the equilibrium position,** h_{eq}, **peaks** at h_{peak} and then **decreases** gradually.
- For all fast CMEs, we find that the **solar wind drag is much larger than the Lorentz force in magnitude**.
- *Fall%*-Decrease in Lorentz Force from peak value at (h_{peak}) upto $\widetilde{h}_0$.
- For CME 18, Fall % =35 % and for CME 36 it is 48 %.

Slow CMEs ($v_0 < 900 \, km \, s^{-1}$),

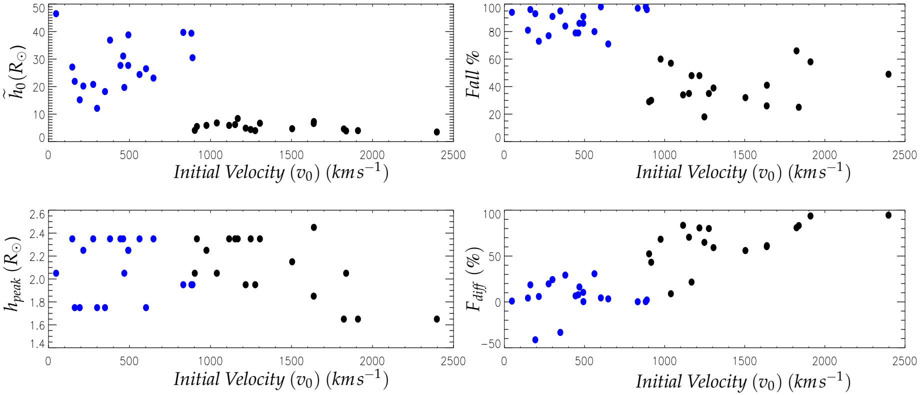


$v_0 \sim 276 \, km \, s^{-1}$, $\widetilde{h}_0$=20.8 $R_\odot$, n=1.6, $h_{peak} = 2.35 R_\odot$, Fall%=77%



$v_0 \sim 461 \, km \, s^{-1}$, $\widetilde{h}_0$=31.1 $R_\odot$, n=1.6, $h_{peak} = 2.35 R_\odot$, Fall%=79%

- **Lorentz forces peak fairly early on ($h_{peak} \approx$ 1.65–2.45 $R_\odot$).**
- **They become negligible only as far out as 12-50 $R_\odot$.**
- **For slow CMEs, *Fall%* lies between 70-98 %.**
- **Thus, Lorentz force governs the CME dynamics upto 12-50 $R_\odot$ in case of slow CMEs.**



- Slow CMEs-Blue circles, Fast CMEs-Black circles
- $\widetilde{h}_0$-Height beyond which Solar Wind drag dominates
- h_{peak}- Lorentz Force peak position
- $Fall\%$- Fall in Lorentz Force between h_{peak} and $\widetilde{h}_0$;
- $F_{diff} = \frac{F_{drag} - F_{Lorentz}}{F_{drag}} \times 100\%$

- While fast CMEs are drag dominated from very early on $\sim 3-4R_{\odot}$, we find that dynamics of slow CMEs is dominated by aerodynamic drag above heights 12-50 $R_{\odot}$.
- The Lorentz Forces are dominant below these heliocentric distances and negligible above it.
- The Lorentz Force decerease from h_{peak} upto $\widetilde{h}_0$ lies between 20-60 % for fast CMEs and 70-98% for slow CMEs.
- Drag force is 50-90 % larger than Lorentz Force (at 40 $R_{\odot}$) for most of the fast CMEs. Drag model succeeds for fast CMEs.
- In case of slow CMEs, this number ranges from 0.2-30%. That is, Lorentz force is only slightly smaller than the drag.
- Thus, for slow CMEs, the dominance of drag force is not as pronounced when compared to the Lorentz Force, or the difference between the two forces is more pronounced for fast CMEs than for slow ones.

- Since, the drag-only model describes the data well for all CMEs, the computed lorentz forces may be an overestimate for slow CMEs.
- Magnetic flux which is assumed to be frozen in, might infact be partly dissipating in either expanding the CME or heating the plasma.
- This magnetic energy which is expended is not taken into account.
- Therefore, this work suggests that such dissipation effects might be important especially in the case of slow CMEs.
- To the best of our knowledge, this is the first systematic study in this regard using a diverse CME sample.
- **Sachdeva et al. (2017) Solar Physics, 292, 118.**

Thesis writing near completion.

THANK YOU
for your attention

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