Coronal Mass Ejection Mass, Energy, and Force Estimates using *STEREO*

Eoin P. Carley[1], R. T. J McAteer[2], Peter T. Gallagher[1]
[1]Trinity College Dublin, Ireland
[2]New Mexico State University, USA

Trinity College Dublin

CME masses - why do we care?

- The forces that drive CMEs are still not yet quantified
- Equation of motion

$$\boxed{\rho\frac{D\vec{v}}{Dt}} = -\nabla p + \vec{j} \times \vec{B} + \rho\vec{g} + \vec{F}_d$$

Total Force

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Thermal Pressure
Gradient

Total Force

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Total Force

Thermal Pressure Gradient

Magnetic Forces

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Total Force

Thermal Pressure Gradient

Magnetic Forces

Gravitational

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- How big is $F = \underbrace{M_{cme}}_{\text{Observationally problematic}} * a_{cme}$?

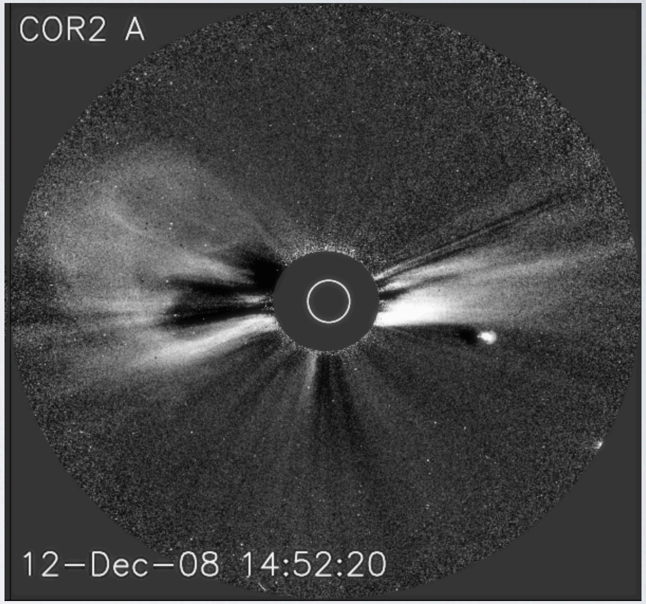
How do we measure CME masses?

- Use white-light coronagraph observations

Pixel Brightness

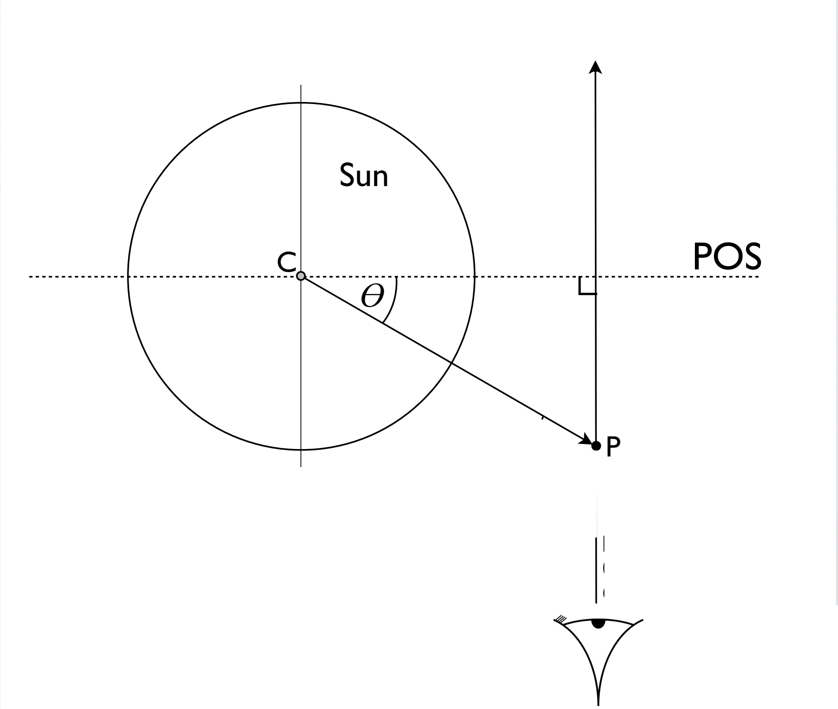
$$m_{pixel} = \frac{B_{pixel}}{B_e(\theta)} \times 1.97 \times 10^{-24} g$$

Single e$^-$ brightness



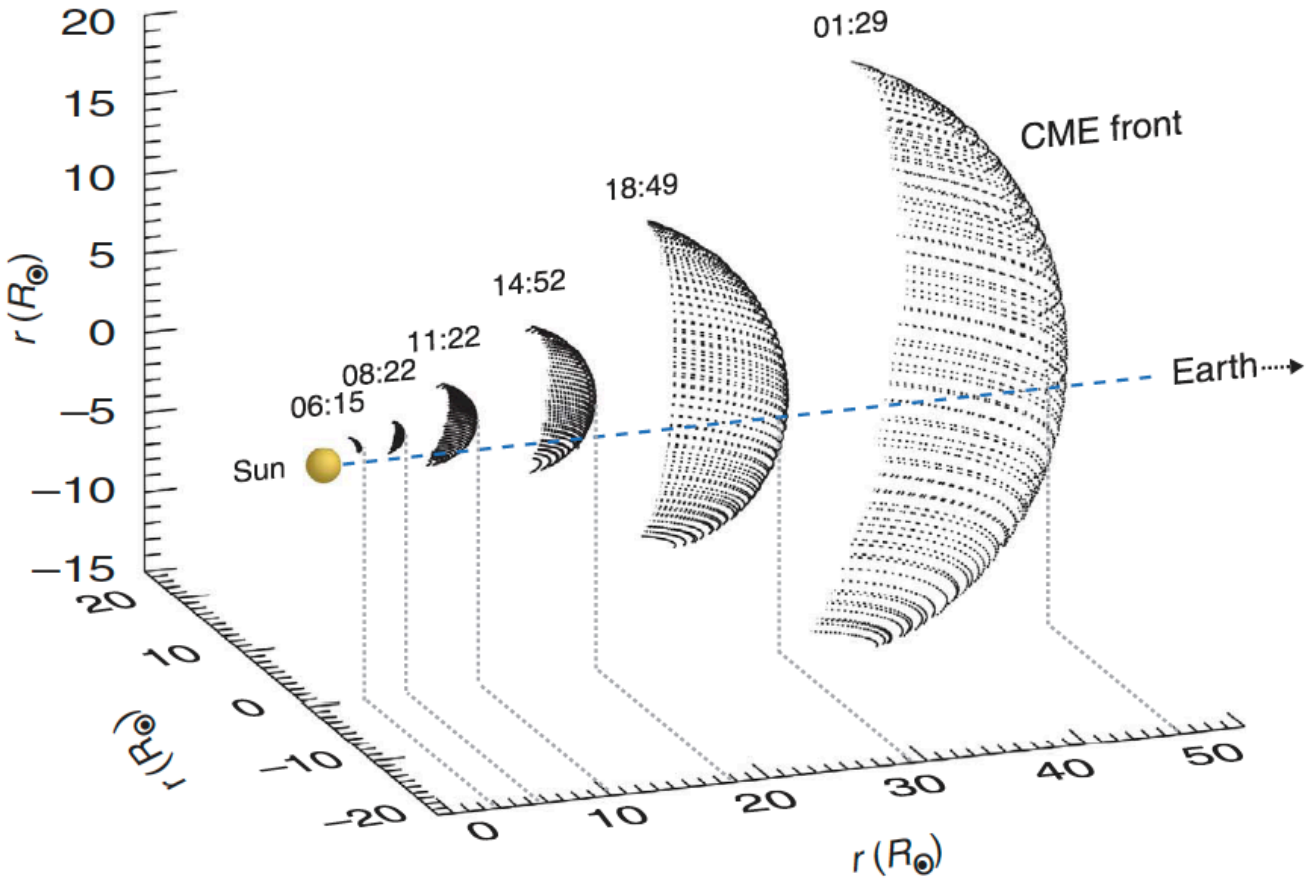
- B_e depends on plane-of-sky (POS) angle $\boldsymbol{\theta}$

- We can use *STEREO* to measure $\boldsymbol{\theta}$



Obtaining the correct θ

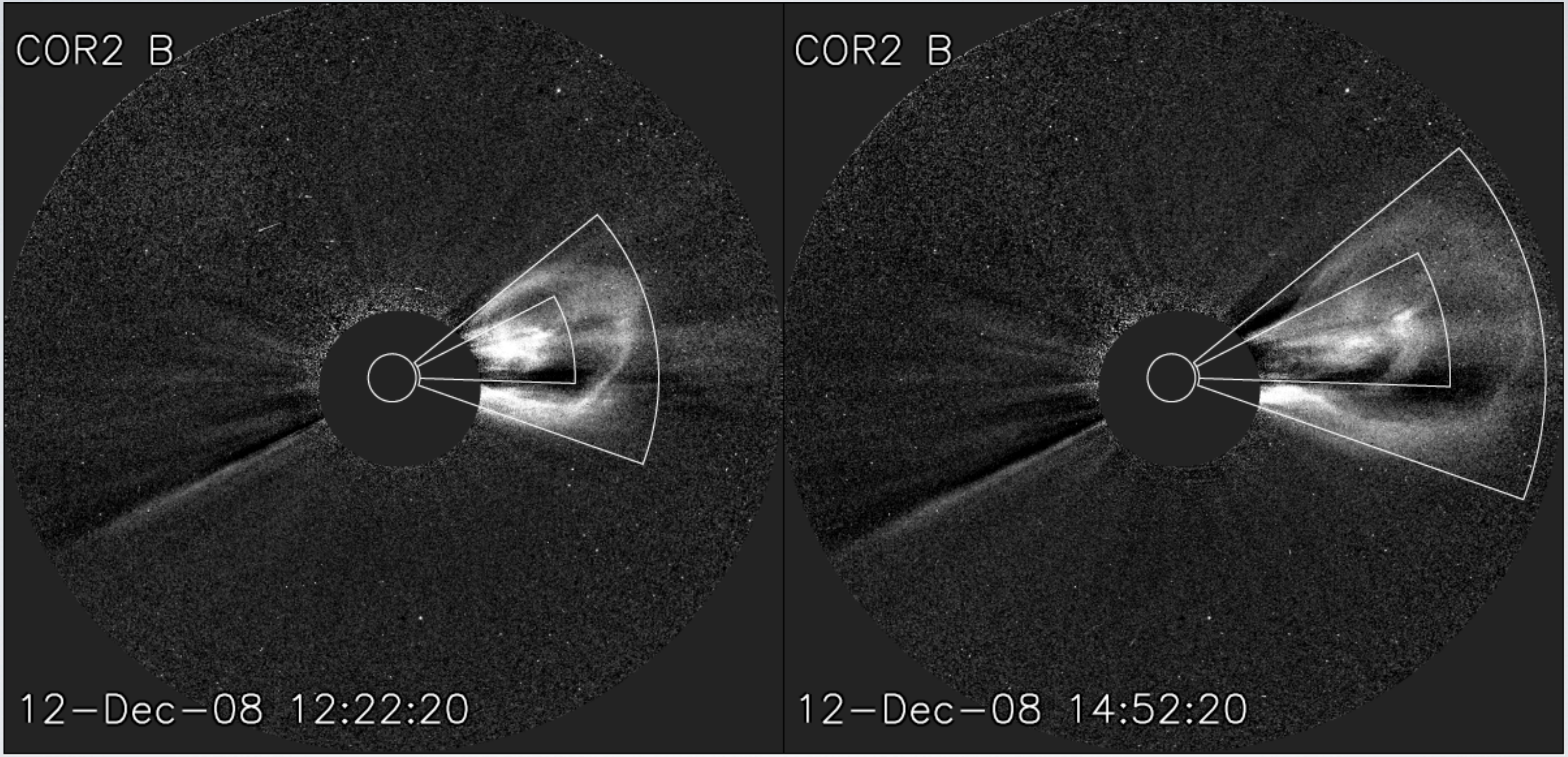
- *STEREO*'s provides 3-D positional information of a CME



(Byrne et al., Nature Communications, 2010)

3D information → POS θ → Better Mass estimate

CME masses in sequence



$$m_{pixel} = \frac{B_{pixel}}{B_e(\theta)} \times 1.97 \times 10^{-24} g$$

$$M_{cme} = \sum m_{pixel}$$

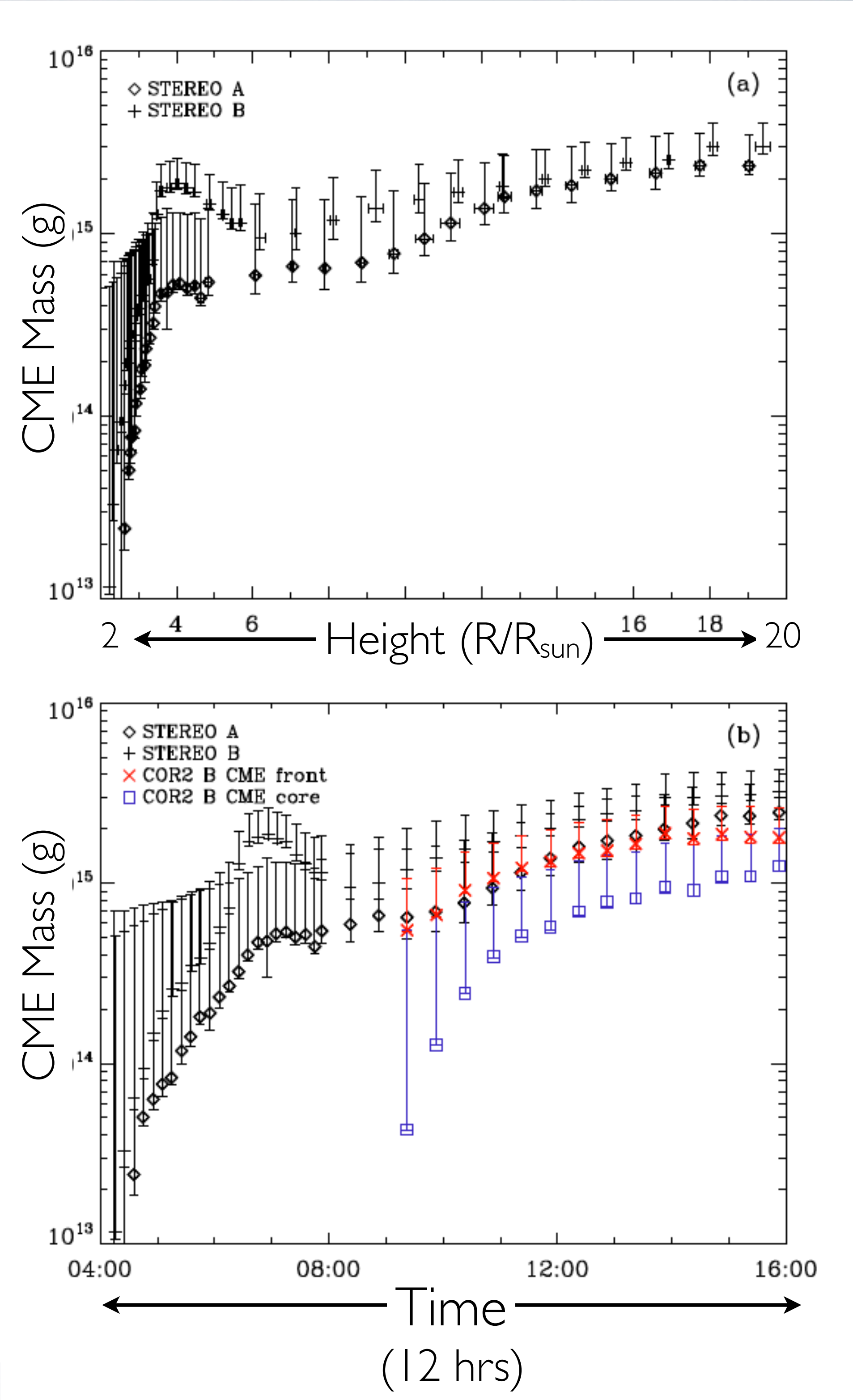
CME masses - Results

- STEREO A and B give same mass

- CME mass approaches:

$$M_{cme} = (3.4 \pm 1.1)\times10^{15}\ \text{g}$$

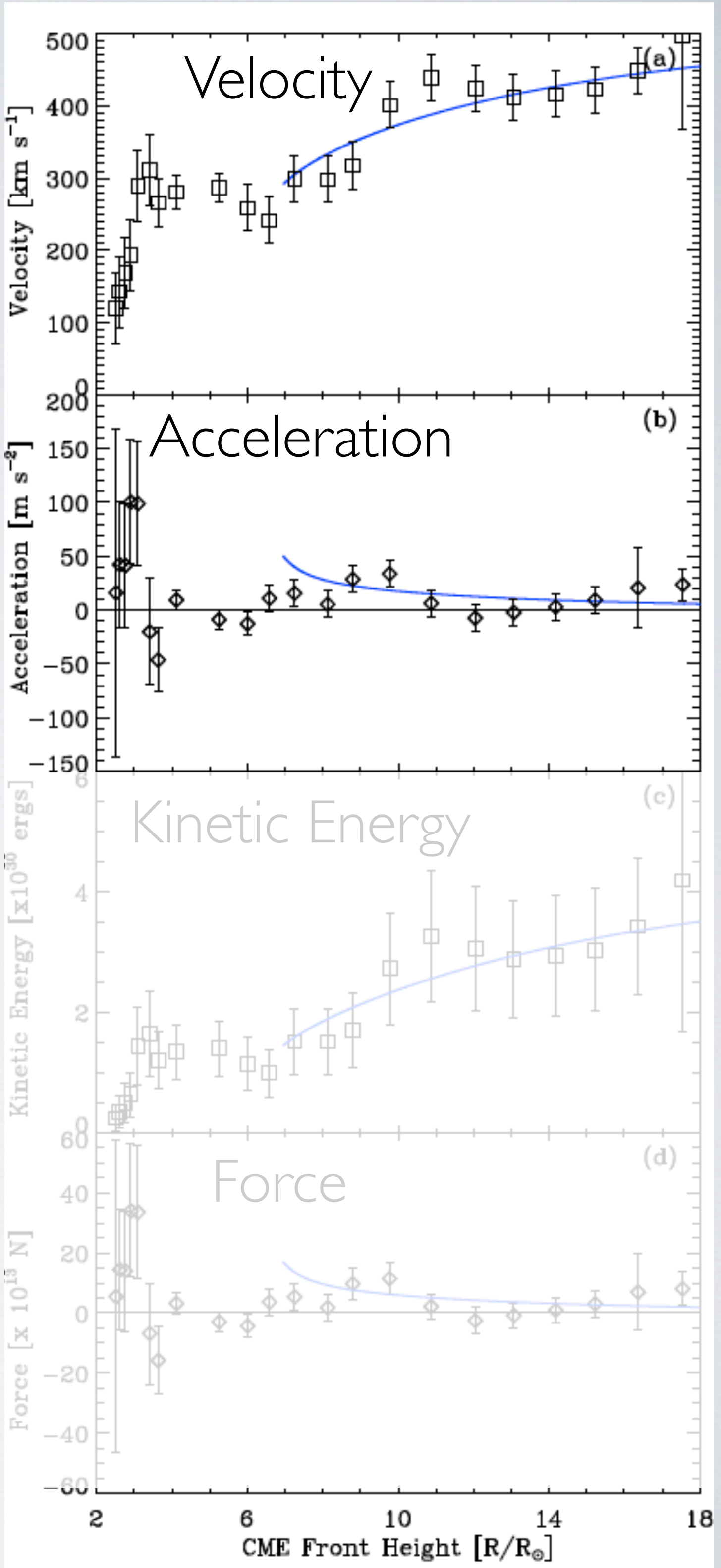
Carley et al. *(ApJ, in review)*



CME Dynamics - Results

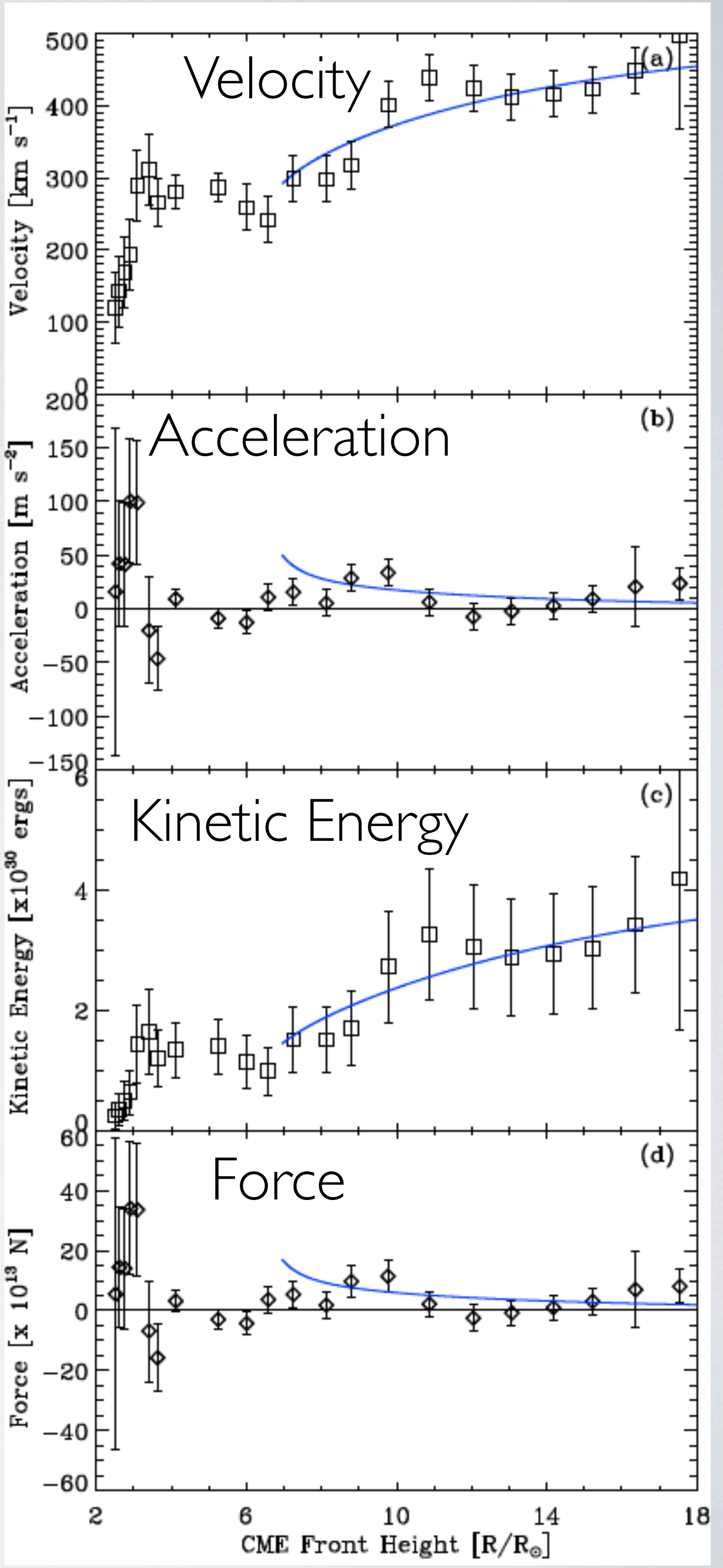
- Byrne et al. (2010) computed velocity and acceleration from 3D data

- Blue curve is fit to velocity using solar wind drag model



CME Dynamics - Results

- Byrne et al. (2010) computed velocity and acceleration from 3D data
- Blue curve is fit to velocity using solar wind drag model
- Combined with our mass estimates
  - Kinetic Energy: $E_k = \frac{1}{2} M_{cme} v_{cme}^2$
  - Force on CME: $\boldsymbol{F} = \boldsymbol{M}_{cme} \boldsymbol{a}_{cme}$



CME Dynamics - Results

- CME kinetic energy at 18 R_{sun} is

$$E_{kin} = (4.2 \pm 2.5) \times 10^{30} \text{ ergs}$$

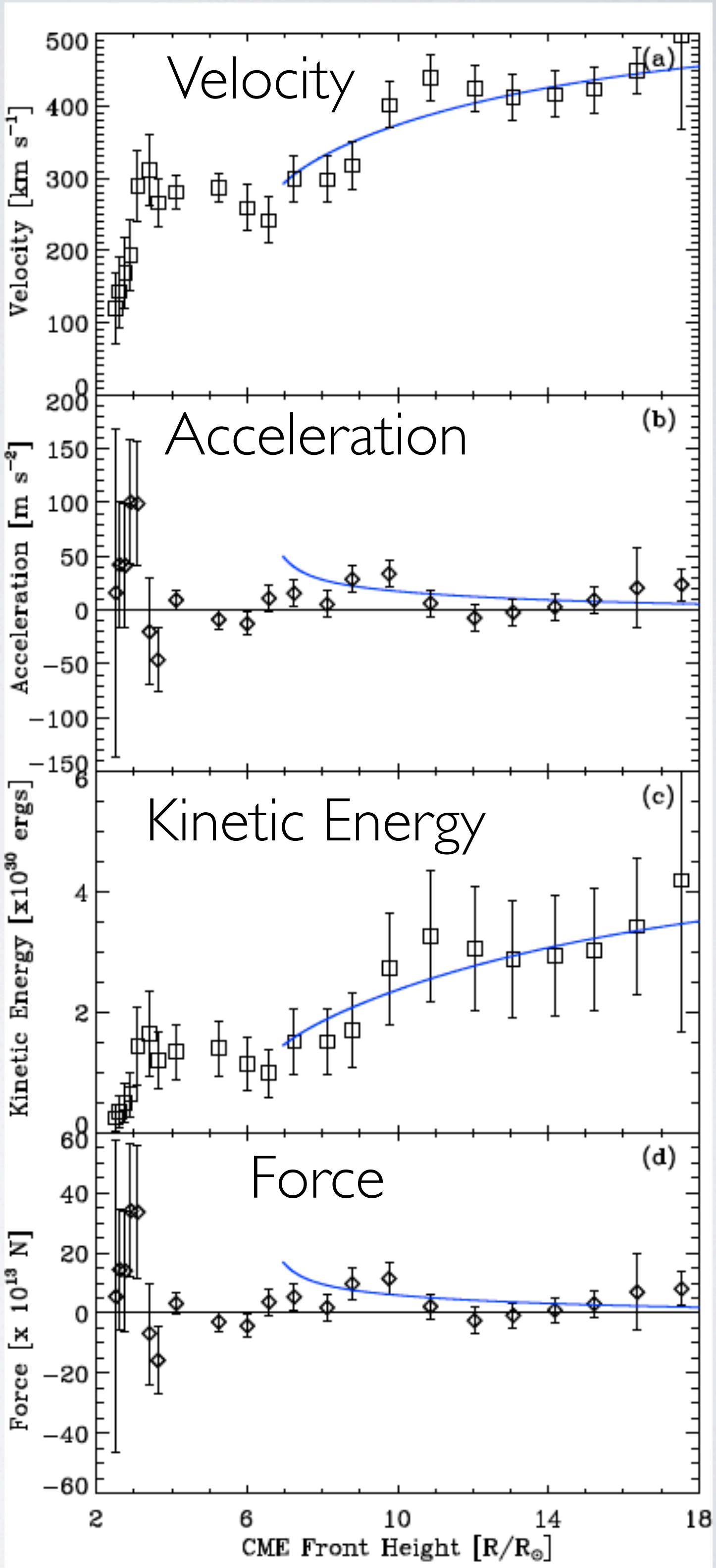
- Force initially peaks at 3 R_{sun}

$$F = (3.4 \pm 2.2) \times 10^{14} \text{ N}$$

- From 7-18 R_{sun} force has average of

$$F = (3.8 \pm 5.4) \times 10^{13} \text{ N}$$

Carley et al. *(ApJ, in review)*



CME Dynamics - Results

- Total force given by

$$\boxed{F_{total} = F_{mag} + F_{gravity} + F_{drag}}$$

- $F_{total} = 3.4\times10^{14}$ N
- $F_{gravity} = -1.0\times10^{14}$ N
- $F_{drag} = -8.0\times10^{12}$ N (aerodynamic drag)
- Lorentz force at 3 R_{sun}: $F_{mag} \sim 4.5\times10^{14}$ N

CME Masses & Dynamics - Results

- Previous observations (*SOHO*-LASCO) suffered from large uncertainties
- *STEREO*'s two-vantage points allows for 3-D positioning of CME
- Leads to more accurate kinematics
- ...and more accurate mass estimates
- Combination of gives good energy and force estimates
- In future, more CME forces will be studied with the better accuracy offered by *STEREO*
- Work submitted to *ApJ* (Carley et al., *in review*)

eoincarley@gmail.com

Extra info...

- Aerodynamic drag: $F_{drag} = -\frac{1}{2} C_d \rho_{sw} A_{cme} (\vec{v} - \vec{v}_{sw}) |\vec{v} - \vec{v}_{sw}|$
- Byrne et al. (2010) velocity data