

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

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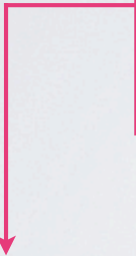
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CME masses - why do we care?

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

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

Total Force



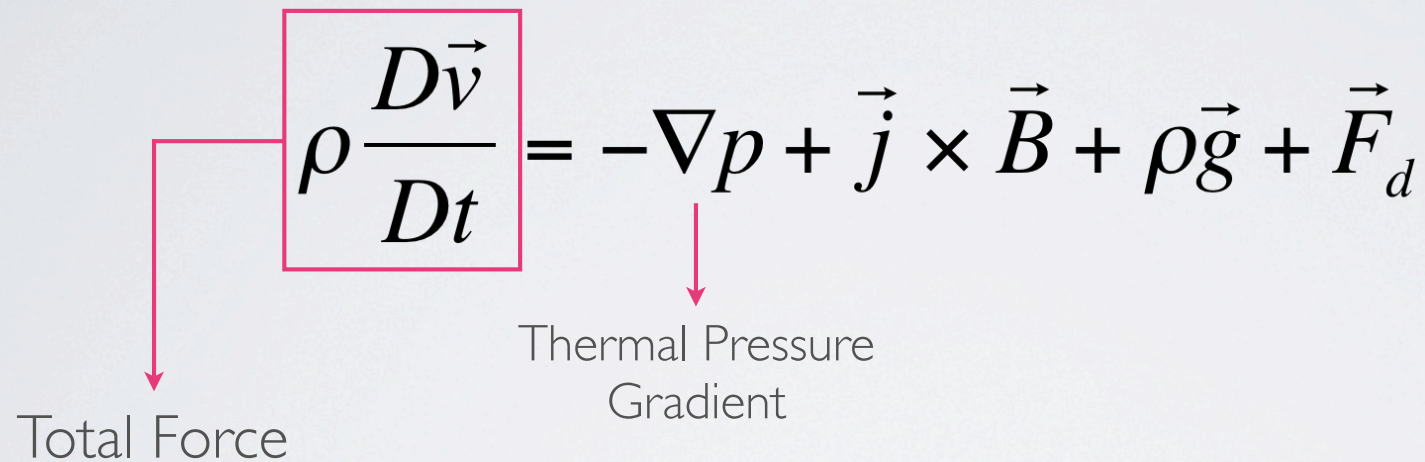
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Total Force

Thermal Pressure Gradient

The diagram shows the equation of motion for CME masses. The left side of the equation, $\rho \frac{D\vec{v}}{Dt}$, is enclosed in a red rectangular box. A red arrow points from the bottom of this box down to the text "Total Force". The right side of the equation consists of four terms: $-\nabla p$, $\vec{j} \times \vec{B}$, $\rho \vec{g}$, and \vec{F}_d . A red arrow points from the $-\nabla p$ term down to the text "Thermal Pressure Gradient".

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Magnetic Forces

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Total Force

Thermal Pressure Gradient

Magnetic Forces

Gravitational

The diagram shows the equation of motion for CME masses. The left side of the equation, $\rho \frac{D\vec{v}}{Dt}$, is enclosed in a red box and labeled 'Total Force' with a red arrow pointing down. The right side of the equation consists of four terms: $-\nabla p$ is labeled 'Thermal Pressure Gradient' with a red arrow pointing down; $\vec{j} \times \vec{B}$ is labeled 'Magnetic Forces' with a red arrow pointing down; $\rho \vec{g}$ is labeled 'Gravitational' with a red arrow pointing down; and \vec{F}_d is not explicitly labeled but is part of the total force.

CME masses - why do we care?

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- Equation of motion

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

The diagram illustrates the equation of motion for CME masses. The left side of the equation, $\rho \frac{D\vec{v}}{Dt}$, is enclosed in a red box and labeled "Total Force" with a red arrow pointing down. The right side of the equation consists of four terms, each with a red arrow pointing down to a label: $-\nabla p$ is labeled "Thermal Pressure Gradient", $\vec{j} \times \vec{B}$ is labeled "Magnetic Forces", $\rho \vec{g}$ is labeled "Gravitational", and \vec{F}_d is labeled "Drag".

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

Diagram illustrating the equation of motion for a CME mass. The left side of the equation, $\rho \frac{D\vec{v}}{Dt}$, is enclosed in a red box and labeled "Total Force". The right side consists of four terms, each with a red arrow pointing to a label below it:

- $-\nabla p$ is labeled "Thermal Pressure Gradient".
- $\vec{j} \times \vec{B}$ is labeled "Magnetic Forces".
- $\rho \vec{g}$ is labeled "Gravitational".
- \vec{F}_d is labeled "Drag".

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

↓
Observationally
problematic

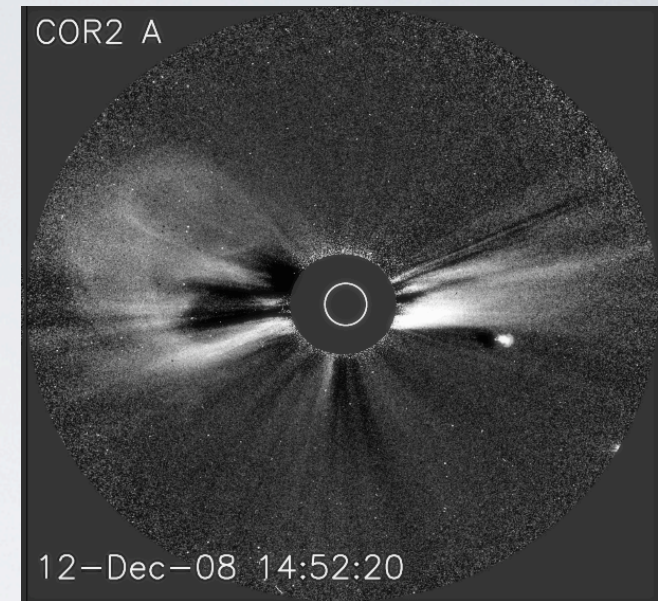
How do we measure CME masses?

- Use white-light coronagraph observations

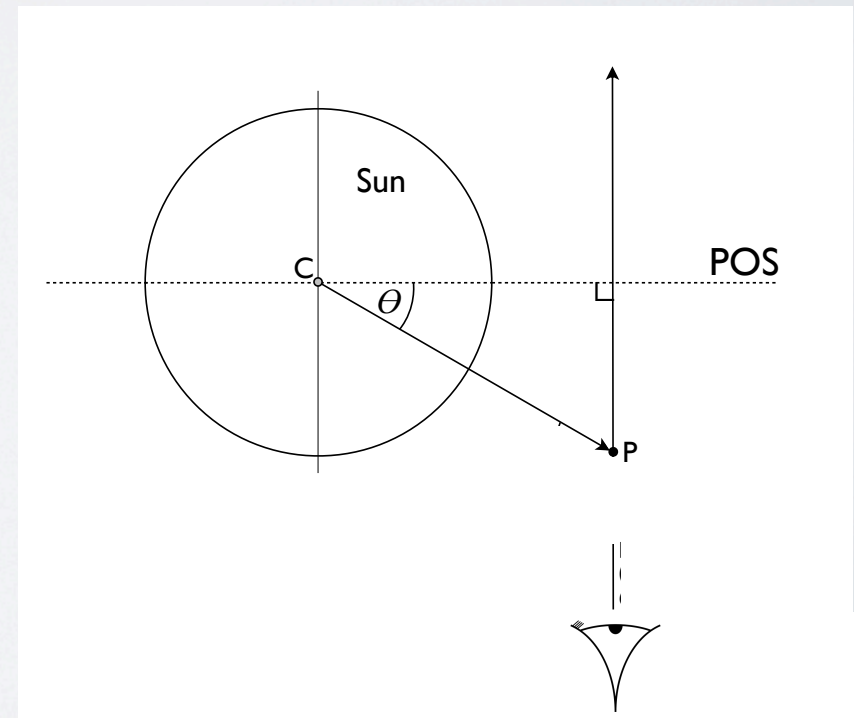
$$m_{pixel} = \frac{B_{pixel}}{B_e(\theta)} \times 1.97 \times 10^{-24} \text{ g}$$

Pixel Brightness

Single e⁻ brightness

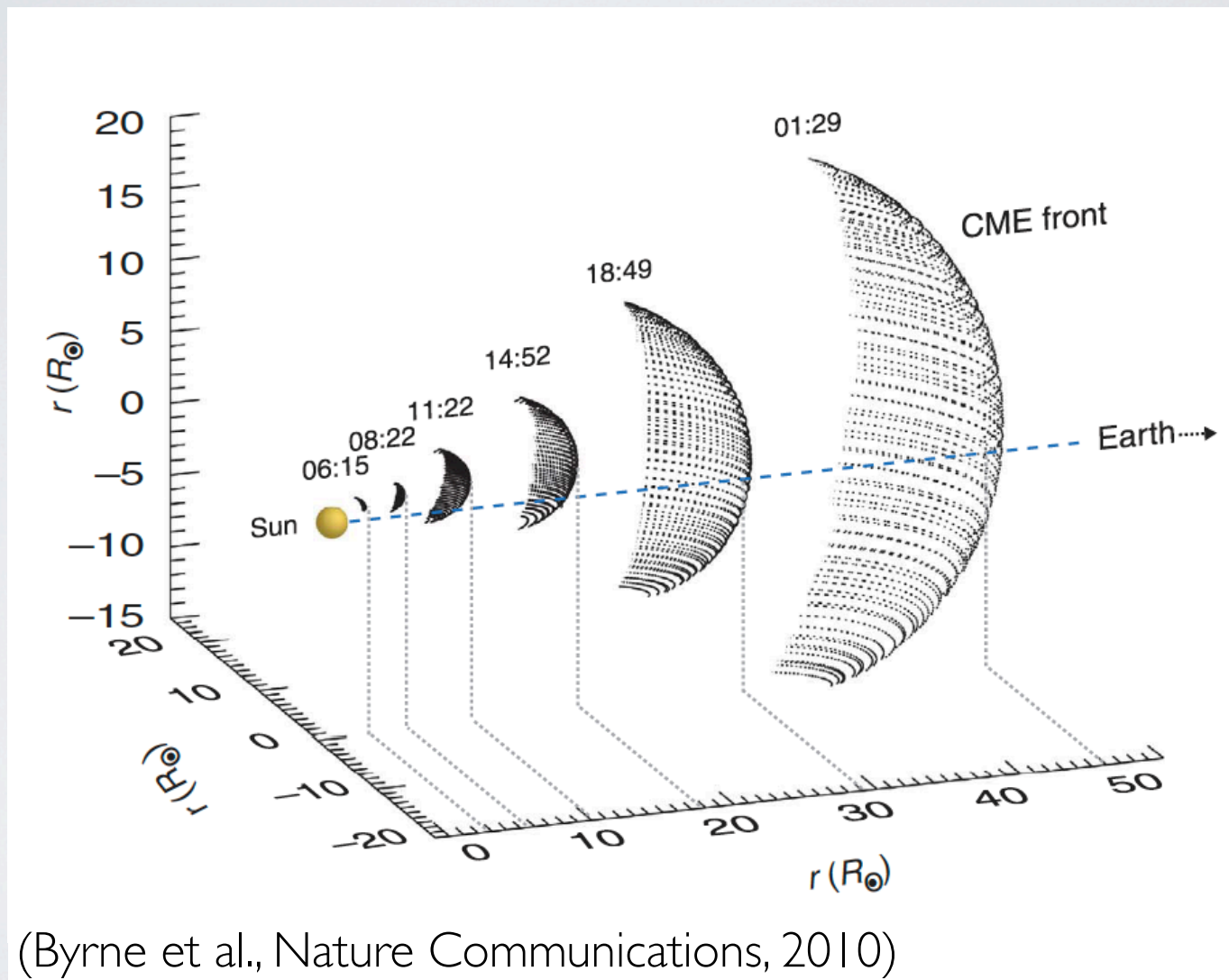


- B_e depends on plane-of-sky (POS) angle θ
- We can use *STEREO* to measure θ



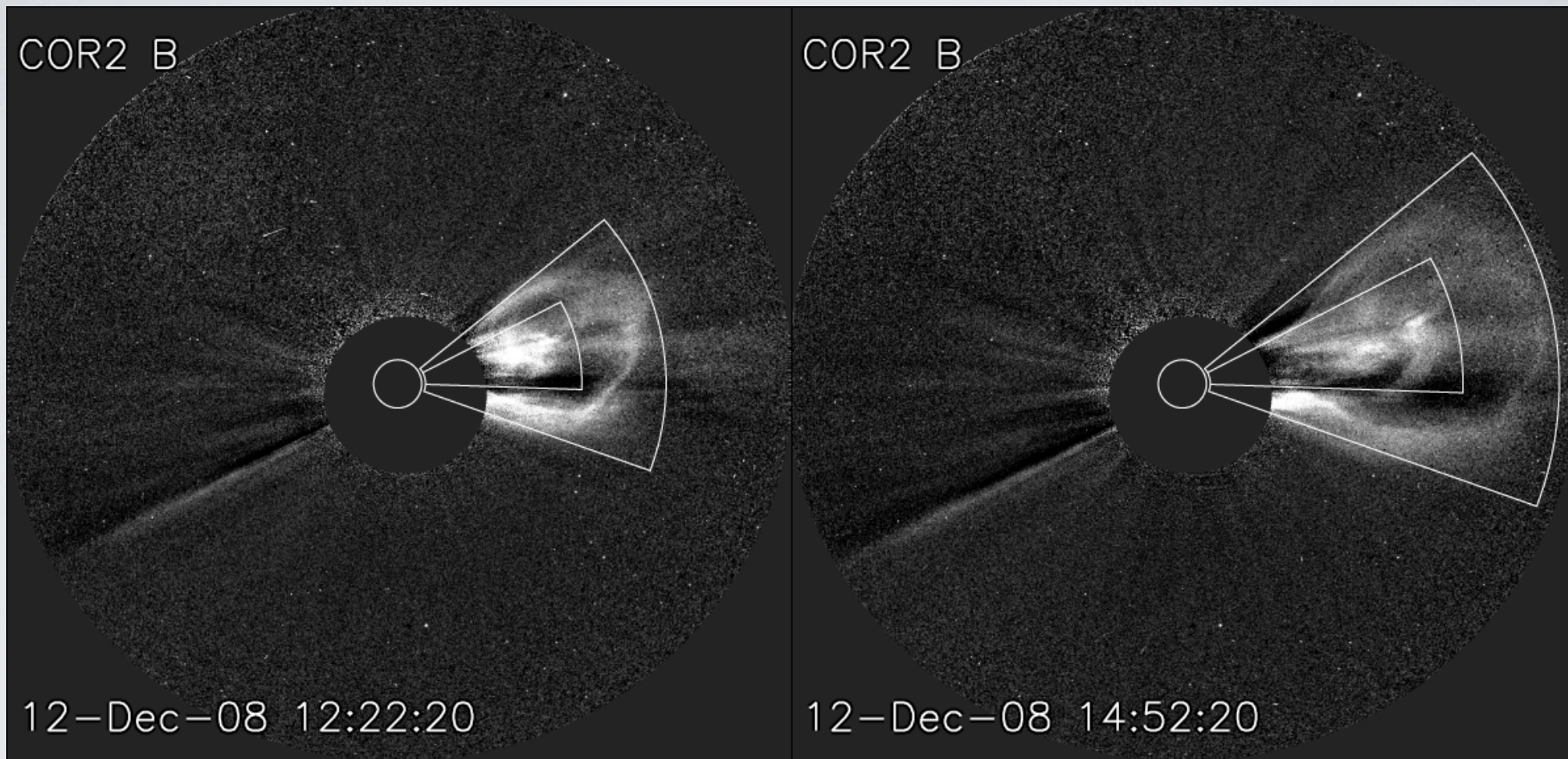
Obtaining the correct θ

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



3D information \rightarrow POS θ \rightarrow Better Mass estimate

CME masses in sequence



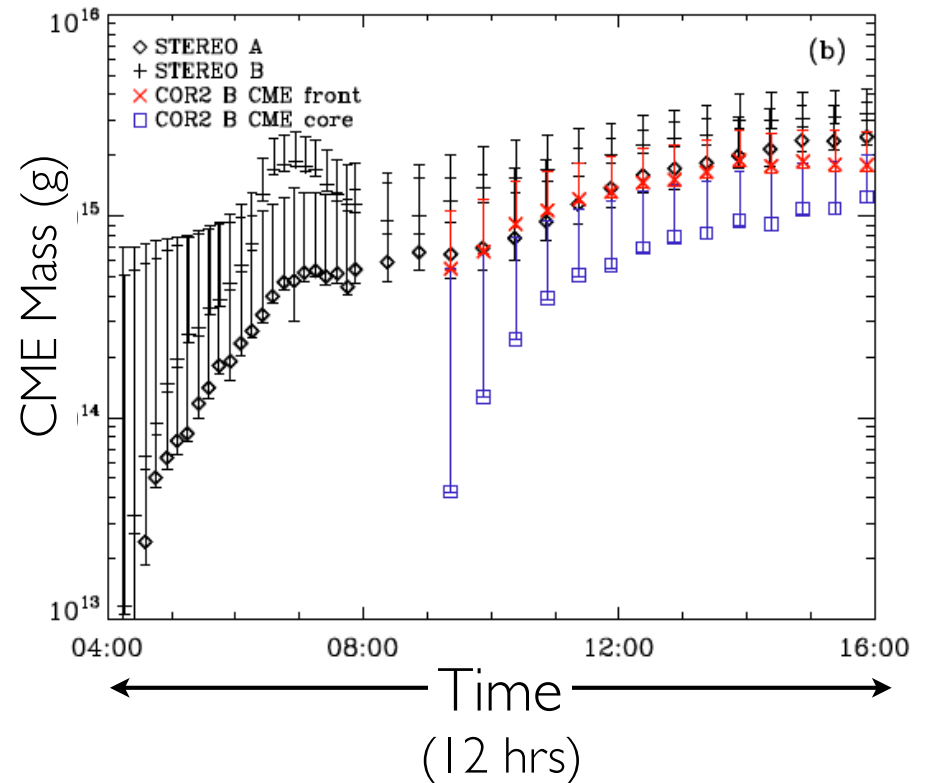
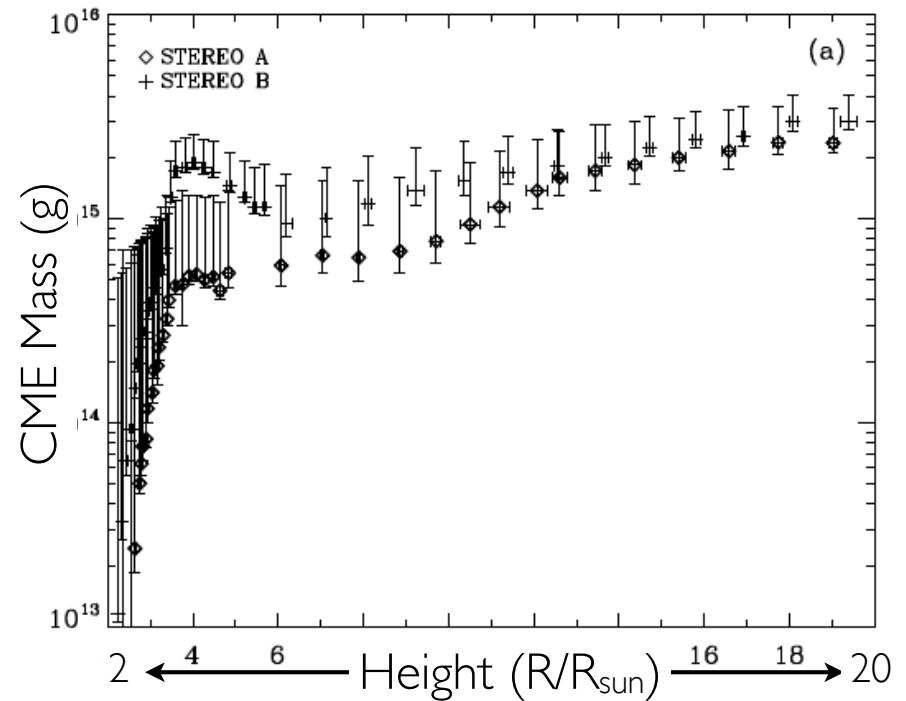
$$m_{\text{pixel}} = \frac{B_{\text{pixel}}}{B_e(\theta)} \times 1.97 \times 10^{-24} \text{ g}$$

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

CME masses - Results

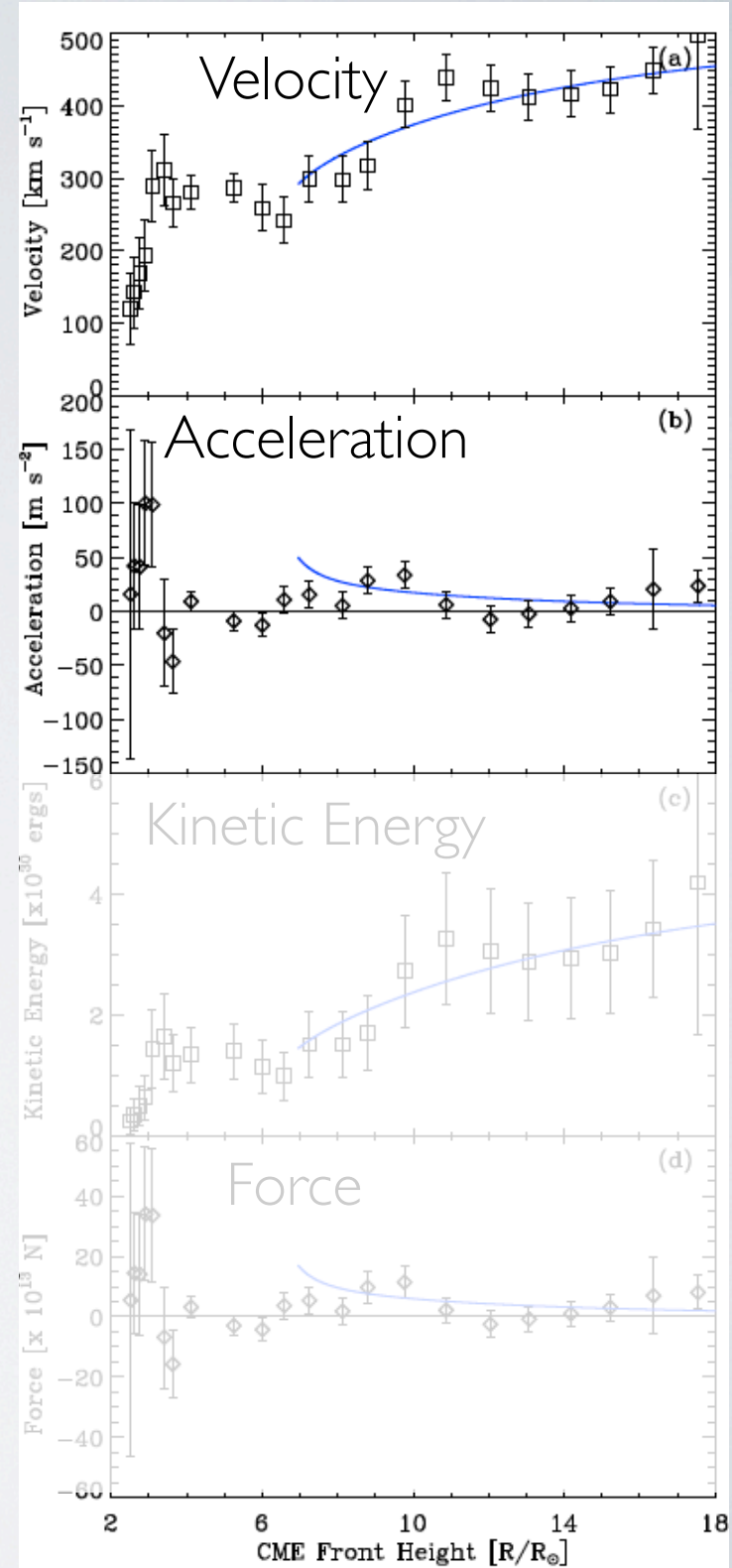
- STEREO A and B give same mass
- CME mass approaches:

$$M_{\text{cme}} = (3.4 \pm 1.1) \times 10^{15} \text{ g}$$



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

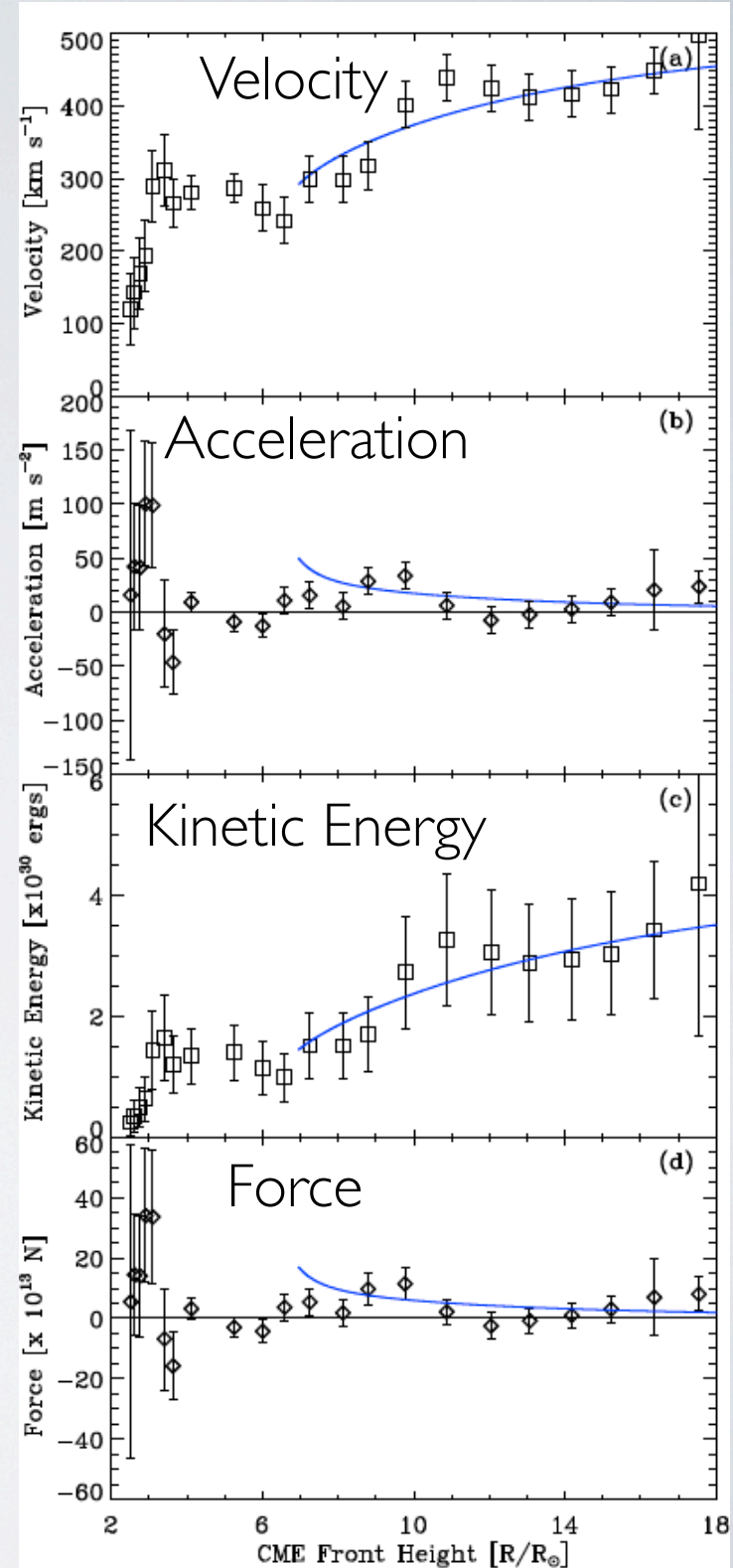


CME Dynamics - Results

- 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: $F = M_{cme} a_{cme}$



CME Dynamics - Results

- CME kinetic energy at 18 R_{sun} is

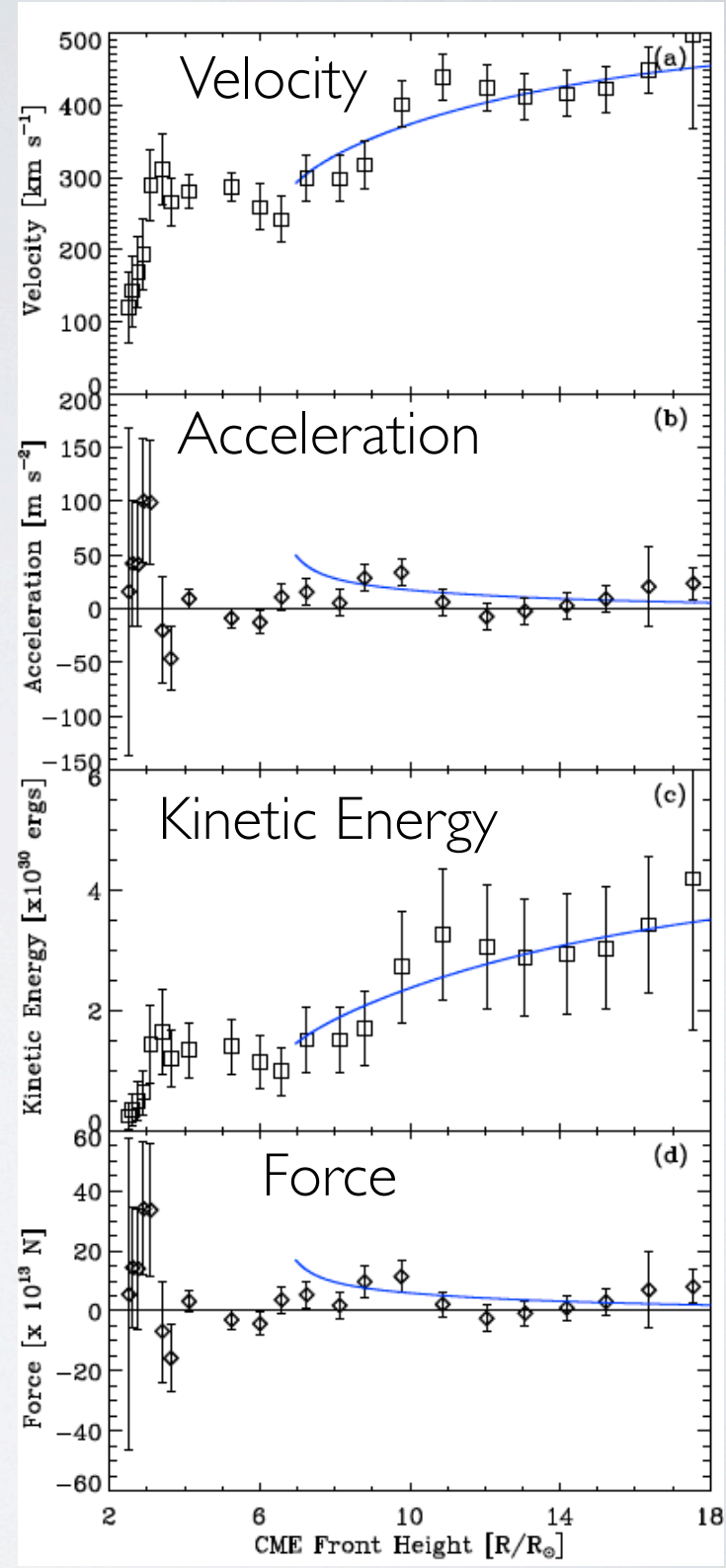
$$E_{\text{kin}} = (4.2 \pm 2.5) \times 10^{30} \text{ ergs}$$

- 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

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



CME Dynamics - Results

- Total force given by

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

- $F_{\text{total}} = 3.4 \times 10^{14} \text{ N}$
- $F_{\text{gravity}} = -1.0 \times 10^{14} \text{ N}$
- $F_{\text{drag}} = -8.0 \times 10^{12} \text{ N}$ (aerodynamic drag)
- Lorentz force at $3 R_{\text{sun}}$: $F_{\text{mag}} \sim 4.5 \times 10^{14} \text{ N}$

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*)

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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

