Towards resolving the velocity distribution inside CMEs

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Outline

- the motivation
- the idea
- the application
- tbd
Conventional CME analysis tools: tracing the leading edge

The leading edge velocity is still one of the key parameters in the investigation of CME kinematics.
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Drawbacks: The leading edge is sometimes difficult to identify. No characterisation of the interior of the CME.
Conventional CME analysis tools: mass evolution diagrams

Coronal white light is optically thin and due to Thomson scatter → coronagraph brightness equivalent to electron column density → CME mass estimate

Empirically: $m(h) = m_0(1 - \left(\frac{h_{occ}}{h}\right)^3 + \Delta m(h - h_{occ})$

Problems: “Total” CME mass not well defined
Continuous increase $\propto \Delta m$ due to pile-up?
Our new approach

Basic assumption: Whatever the CME mass is, it is very probably conserved (deviations will be discussed later)

→ Starting point is the conservation equation

$$\frac{\partial}{\partial t} \rho = - \nabla \cdot v \rho$$
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\[ \frac{\partial}{\partial t} \rho = -\nabla \cdot v \rho \]

After surface integration:

\[ \frac{\partial}{\partial t} m = -\frac{\partial}{\partial r} vm \]

\( m = \) surface mass density, \( v = \) density weighted normal velocity
Our new approach

Provided we can measure $m$ for different times $t$ and at distances $r$ we can determine the effective mass advection velocity $v$

$$v(r, t) = \frac{1}{m(r, t)} \int_r^\infty \frac{\partial m}{\partial t} \, dr'$$
Caveats: integration in $\theta$

Integration in azimuth $\theta$ must be wide enough so that the entire CME is covered.
Caveats: Integration along LOS

This integration is implicit but weighted by the dependence of Thomson scatter on the scattering angle $\chi$ and on the incident intensity at distance $d$ from Sun.

Since we do not know the variation of $\rho$ along the LOS direction $s$ we reduce the weighting to the constant weighting factor at the mean meridional CME propagation direction.
Caveats: Presence of a mass source

It has been speculated that the continuous increase of $m$ is due to pile-up of slow solar wind plasma ahead of the CME.

We need to modify

$$\frac{\partial}{\partial t} m = -\frac{\partial}{\partial r}(v m) + s(r, t)$$

Set $f(r, t) = \int_{r'}^{r} s(r', t)dr'$ then

$$\frac{\partial}{\partial t} m = -\frac{\partial}{\partial r}(v m) + \frac{\partial}{\partial r} f$$

$$= -\frac{\partial}{\partial r}(v m - f)$$

$$= -\frac{\partial}{\partial r}((v - f/m) m)$$

new velocity
Caveats: Presence of a mass source

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We need to modify

$$\frac{\partial}{\partial t} m = -\frac{\partial}{\partial r} (vm) + s(r, t)$$

Set $f(r, t) = \int^r s(r', t) dr'$, then

$$\frac{\partial}{\partial t} m = -\frac{\partial}{\partial r} (vm) + \frac{\partial}{\partial r} f$$

$$= -\frac{\partial}{\partial r} (vm - f)$$

$$= -\frac{\partial}{\partial r} ((v - f/m)m)$$

new velocity
Application: CME on 2010-11-30 18:35

After subtraction of a pre-event background image:
Observed mass profiles

![Graph showing observed mass profiles over distance (Rs)]
Observed mass profiles

After spline interpolation and error estimation
Deduced CME velocities

Profiles $v(r, t)$

large error due to division by small $m$
Deduced CME velocities

Profiles $v(r, t)$

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Test:

Starting from $m(r, t)$ we can predict $m(r, t + dt)$ using $v(r, t \ldots t + dt)$
Deduced CME velocities

Profiles \( v(r, t) \)

Large error due to division by small \( m \)

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Starting from \( m(r, t) \) we can predict \( m(r, t + dt) \) using \( v(r, t \ldots t + dt) \)
Lagrangian velocity profiles

Lagrangian material paths $R(t; t_{occ})$ integrated from Eulerian velocities

$$\frac{\partial}{\partial t} R(t; t_{occ}) = v(R(t; t_{occ}), t)$$

starting at $R(t_{occ}; t_{occ}) = r_{occ}$

no indication of pile-up

∗=“leading edge”
not on material path

mass conservation if paths are interpreted as stream lines
Lagrangian velocity profiles

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- \( *= \) “leading edge” not on material path
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![Graph showing Lagrangian material paths and relevant data points.](image-url)
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**Eruption time:** 17:30

Bernd Inhester CME flow 13/14
We have developed a method to determine the mass flow within a CME

- it's free of manual intervention (e.g., tie-pointing of edges)
- it yields estimates of velocity, mass and energy distribution
- allows to identify pile-up (if there is any)

We have tested the method with one CME, more are to follow, especially fast CMEs which are more probable to produce a pile-up ahead. In addition:

- extend the field of view to $150 \, R_\odot$ by adding HI data
- correlate the mass and velocity distribution near Sun with travel times to 1 AU