Kinematical properties of coronal mass ejections

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Evolution of CMEs

Disrupted equilibrium (see e.g., Forbes 2000), magnetic reconnection process (fast versus slow reconfiguration, e.g., ‘stealth’ CMEs by Robbrecht et al., 2009)

CME front formed due to plasma-pileup /shock compression of plasma / or successive stretching of magnetic field lines (see review e.g., Chen 2011)

2-front morphology (see Vourlidas et al., 2013)

Space Weather effects:
(see e.g., Bothmer et al., 2006):

• Compression (=speed) and magnetic field: energy input $E = v \times B_z$

• $B_z$ (min) related to thermospheric neutral density increase (see Krauss et al., 2015)
What do we actually observe?

CME speeds, widths, locations measured from single v/p are projections on the plane-of-sky (e.g., Hundhausen, 1993)

All derived parameters are severely affected by projection effects (see e.g., Burkepile et al., 2004; Cremades and Bothmer, 2004)

CME WL observations mostly mean to observe the shock-sheath structure due to shock compression (see e.g., Ontiveros and Vourlidas, 2009)

Q: Are halo CMEs different from limb CMEs (Chen, 2011)?
A: Halo CMEs do not show the actual size of a CME but the fast shock wave (Kwon et al., 2015)
Kinematic properties of CMEs

Evolution of CMEs can be divided into three-phase scenario (Zhang et al., 2001; 2004):

- Initiation of slow rising motion (some tens of minutes)
- Impulsive or major acceleration phase where the maximum of acceleration and velocity is reached
- Propagation phase during which the CME is adjusted to the speed of the ambient solar medium (e.g., Chen & Krall, 2003; Vršnak et al., 2004)
- First two phases in the inner corona (<2Rs) (St.Cyr et al., 1999; Vršnak et al., 2001)
- Maximum acceleration and velocity might be reached very low in the corona (<0.5Rs) (Zhang & Dere, 2006; Temmer et al., 2008; 2010; Bein et al., 2011)
Impulsive acceleration phase

• Detailed $h$-$t$ profiles enable to study the impulsive acceleration phase with max. very low in the corona $<0.5Rs$ (Gallagher et al., 2003; Zhang and Dere, 2006; Vršnak et al., 2007; Bein et al., 2011)

• Flare-CME feedback relation (Maričić et al., 2007; Temmer et al., 2008; 2010; Chen and Kunkel, 2010; Bein et al., 2012; Berkebile-Stoiser et al., 2012)

Temmer et al. (2010)

Maričić et al., 2007
CME dynamics: Lorentz vs. drag force

Close to the Sun propelling *Lorentz force* as consequence of magnetic reconnection (e.g. Chen 1989, 1996; Kliem & Török 2006)

In IP space *drag* acceleration owing to the ambient solar wind flow (e.g. Vršnak 1990; Cargill et al. 1996; Chen, 1996; Cargill 2004; Vršnak et al. 2004; 2013; Maloney and Gallagher 2010, Carley et al., 2012).
CME properties are set in low corona

CMEs that start at lower heights also reach their peak acceleration at lower heights.

\[ h_0 \quad [R_{\text{Sun}}] \]

\[ h_{\text{max}} \quad [R_{\text{Sun}}] \]

\[ c = 0.82 \]

\[ k = 0.85 \]
\[ d = -0.40 \]

CMEs that are accelerated at lower heights reach higher peak accelerations.

\[ h_{\text{max}} \quad [R_{\text{Sun}}] \]

\[ q_{\text{max}} \quad [\text{m s}^{-2}] \]

\[ c = -0.54 \]

\[ k = -0.62 \]
\[ d = 2.32 \]

The acceleration phase duration is proportional to the source region dimensions (compact CMEs are accelerated more impulsively; Vršnak et al., 2007).

→ a consequence of stronger Lorentz force and shorter Alfvén time scales involved in compact CMEs (with stronger magnetic field and larger Alfvén speed being involved at lower coronal heights; Vršnak et al., 2007).
CME mass and energy – low corona

Projection effects - errors of factor 2 at 50-60° from POS (Vourlidas et al., 2000)

3D/total mass: use two (or three) different vantage points (Colaninno and Vourlidas, 2009)

3D parameters for mass evolution:
\[ m_0 = 10^{14} g - 10^{16} g \ (r < 3Rs; \text{ initial mass}) \]
\[ \Delta m(r) \text{ mit } r=10-20Rs: 2\%-6\% \]
Kinetic energy: \( 10^{23} J - 10^{25} J \)
(see Bein et al., 2013)

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

Important for studies on global energetics of flares and CMEs (see e.g., Emslie et al., 2004, 2012)
CMEs in IP space: elongation and geometry

Fixed-Φ (Sheeley et al., 1999; Kahler & Webb, 2007; Rouillard et al., 2008)
Harmonic Mean (Lugaz et al., 2009; Howard and Tappin, 2009)
Self Similar Expansion (Davies et al., 2012; Möstl and Davies, 2012)

Remote sensing+in-situ:
Constrained Harmonic Mean (Rollett et al., 2012; Rollett et al., 2013)
Constrained Self Similar Expansion (Rollett et al., 2014)
3D CME propagation direction (2 s/c)

- **Tie-point reconstruction, triangulation**
  (e.g., Liu et al., 2009; Maloney et al., 2009; Mierla et al., 2009; Temmer et al. 2009; Byrne et al., 2010; Liu et al., 2010)

- **Forward fitting of a model to white light images**
  (Thernisien et al., 2006; 2009; Wood et al., 2009)

- **CME mass calculation** (Colannino and Vourlidas, 2009; Bein et al., 2013)

- **Polarization ratio techniques**
  (Moran et al., 2009; deKoning et al., 2009)
Environmental conditions

Rotation of CMEs and adjustment to ambient magnetic field structure (see e.g., Yurchyshyn et al., 2001; 2009; Vourlidas et al., 2011; Panasenko et al., 2013)

Longitudinal/Latitudinal deflection – non-radial motion (e.g., MacQueen et al., 1986; Burkepile et al., 1999; Byrne et al., 2010; Foullon et al., 2011; Bosman et al., 2012; Wang et al., 2014; Möstl et al., 2015)

CME propagation and interaction with the ambient SW (e.g., Manchester et al., 2004; Savani et al., 2010, Temmer et al., 2011; Rollett et al., 2014; Mays et al., 2015).
Solar wind drag effect

Empirical relation by Gopalswamy et al., 2001

\[ a = -0.0054 \ (v - 406) \]

Observations using LASCO, SMEI, SECCHI data show drag effects (e.g., Tappin 2006; Howard et al., 2007; Morrill et al., 2009, Webb et al., 2009; Davis et al., 2010).

Drag Based Model (DBM; Vršnak & Žic, 2007; Vršnak et al., 2013)

\[ \frac{d^2 r}{dt^2} = -\gamma(r) \left( \frac{dr}{dt} - w(r) \right) \frac{dr}{dt} - w(r) \]

with

\[ \gamma = \frac{c_d A \rho_w}{V(\rho + \frac{\rho_w}{2})} = \frac{c_d}{L(\rho + \frac{1}{2})} \]

Disturbed solar wind conditions (Žic, Vršnak, Temmer, 2015):

\[ w(R) = \begin{cases} w_0(R) + w_p(R), & R_1 < R < R_2 \\ w_0(R), & \text{otherwise} \end{cases} \]

To fully understand the CME propagation behavior in IP space we need to know the spatial distribution of SW parameters.

http://oh.geof.unizg.hr/DBM/dbm.php & swe.uni-graz.at
Preconditioning of interplanetary space

CME occurrence rate: 0.3 per day (solar min) to 4-5 per day (solar max) e.g., St. Cyr et al. (2000), Gopalswamy et al., (2006) w/ $TT \approx 1-4$ days (w/ 500-3000km/s).

CMEs may „clear the way“, making follow-up events super-fast (e.g., Liu et al., 2014; Temmer and Nitta, 2015).

During times of high solar activity, preconditioning due to successive CME eruptions is highly likely.

Odstrčil et al., 2012 (EGU 2012); see also Lee et al., 2015
CME – CME interaction

Successive CMEs (similar directions) may merge and form complex ejecta of single fronts (e.g., Gopalswamy et al. 2001; Burlaga et al. 2002, 2003; Wang et al. 2002; Wu et al., 2007).

Radio enhancements, SEPs – acceleration at shock front or from regions with access to solar wind magnetic field lines? (e.g., Gopalswamy et al. 2001; 2002; Hillaris et al., 2011; Kahler & Vourlidas 2014)

Effects at Earth:

• extended periods of negative Bz (e.g. Wang et al. 2003; Farrugia et al. 2006)

• intense geomagnetic storms (Burlaga et al. 1987; Farrugia et al. 2006a,b; Xie et al. 2006; Dumbović et al., 2015)
Observing the interaction process?

Strong deceleration hours before interaction of CME leading edges – transfer of momentum (see e.g., Farrugia & Berdichevsky, 2004; Lugaz et al., 2009; Maričić et al., 2014). Interaction process related to MFR location (Temmer et al., 2014).
Summary and conclusions

• CME properties are set in the low corona (source region characteristics, magnetic reconnection process which links flares and CMEs)

• Ambient magnetic field configuration controls CME kinematics close to Sun (strong overlying fields, see e.g., Thalmann et al., 2015).

• Propagation behavior of CMEs in IP space strongly affected by the characteristics of the ambient solar wind flow

• CME-CME / CME-HSS interaction: extreme changes in CME dynamics; may happen quite often

• Preconditioning (density, $B$) may play an important role

• CME/Space Weather forecast: tools might need *permanent* update (implement EACH event!); event-based forecasts might not improve accuracy