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Kinematical properties of coronal mass ejections

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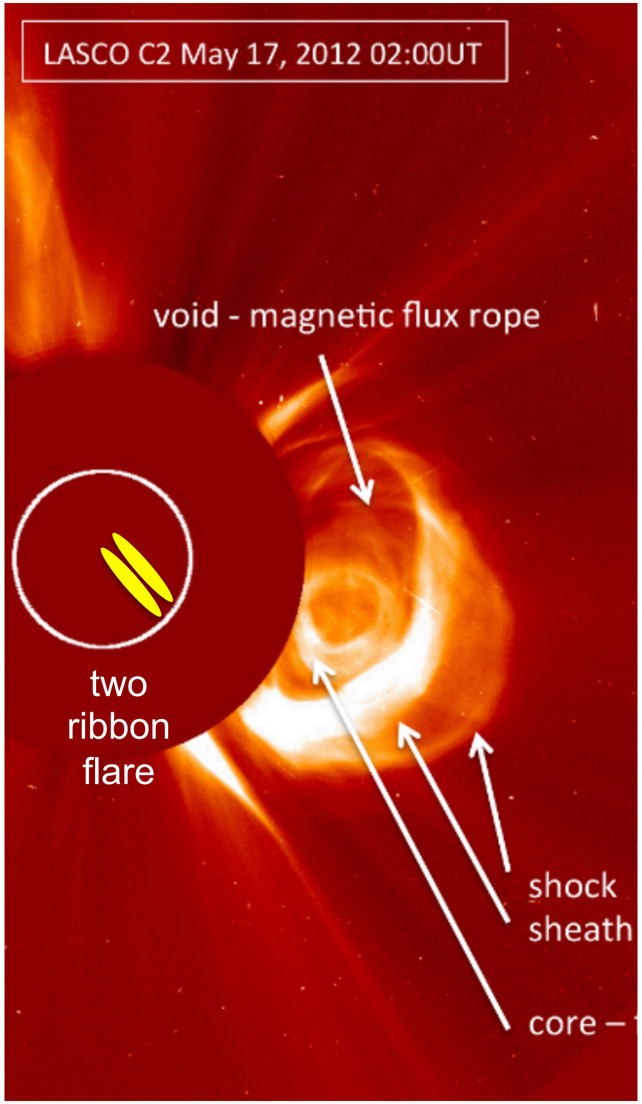
Evolution of CMEs



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

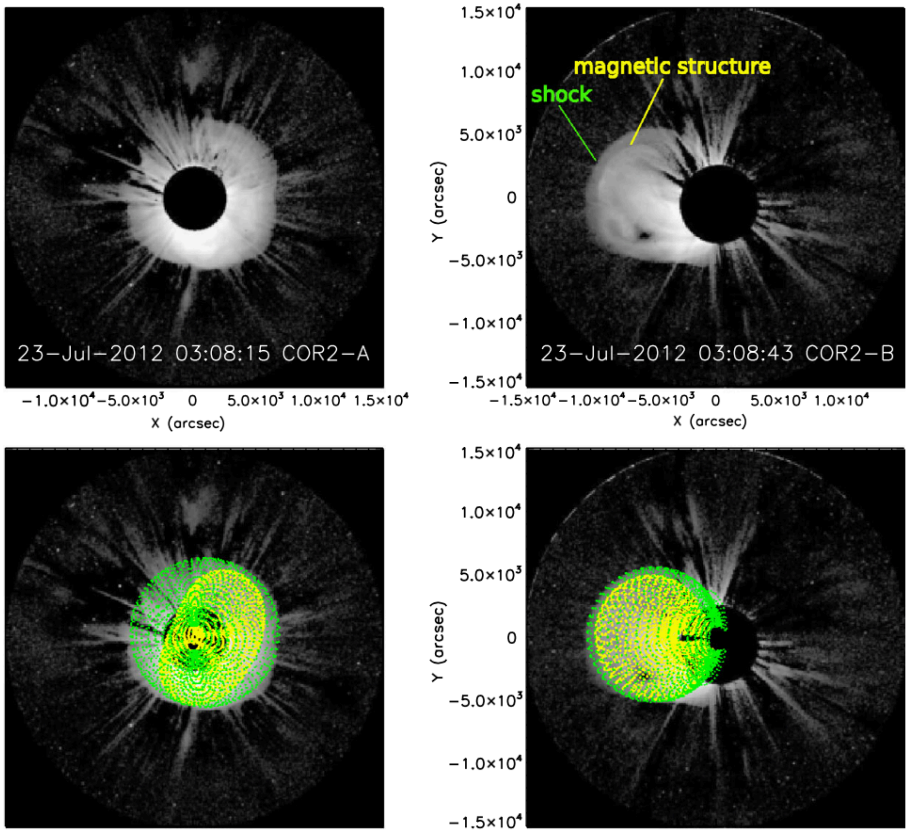
CME front formed due to plasma-pileup /shock compression of plasma / or successive stretching of magnetic field lines (see review e.g., Chen 2011)

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?



Temmer and Nitta, 2015

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

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

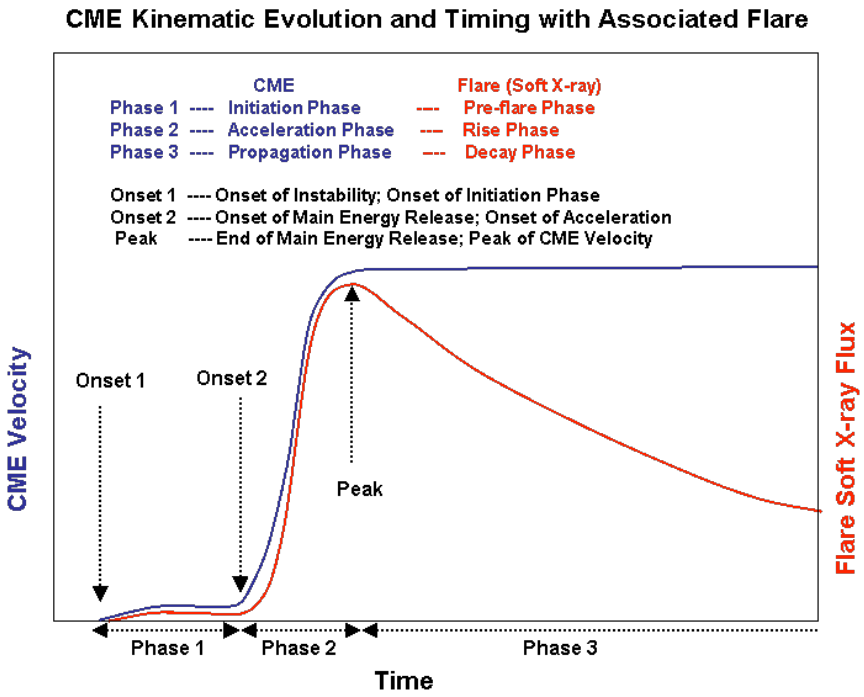
CME WL observations mostly mean to observe the shock-sheath structure due to shock compression (see e.g., Ontiveros and Vourlidas, 2009)

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)

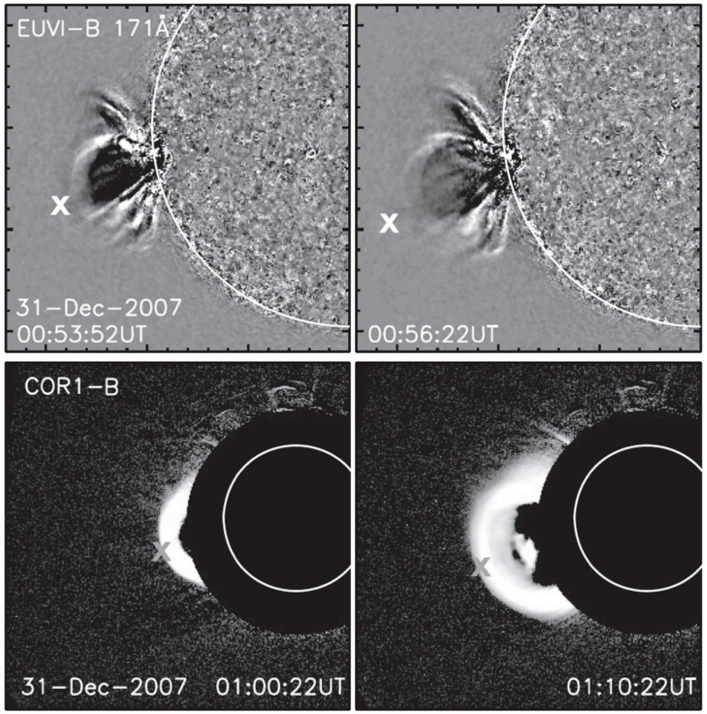


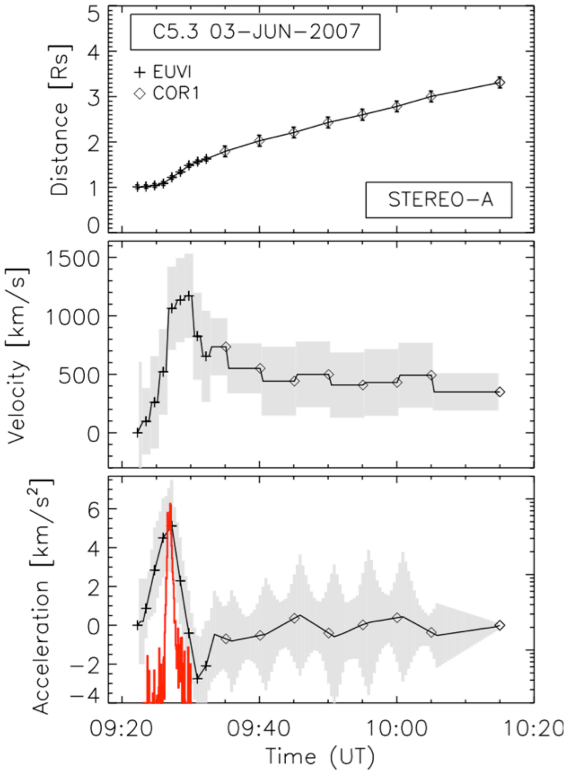
Zhang et al., 2001

Impulsive acceleration phase

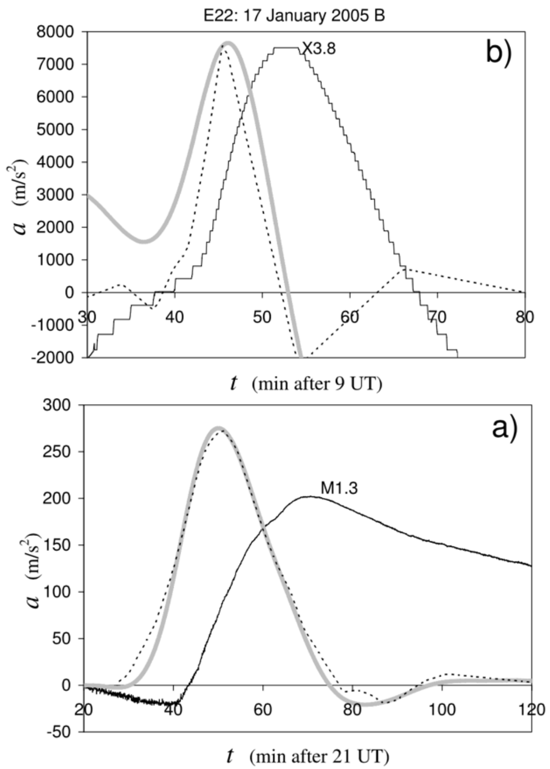
- Detailed *h-t* profiles enable to study the impulsive acceleration phase with max. very low in the corona <0.5Rs (Gallagher et al., 2003; Zhang and Dere, 2006; Vršnak et al., 2007; Bein et al., 2011)

- 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)





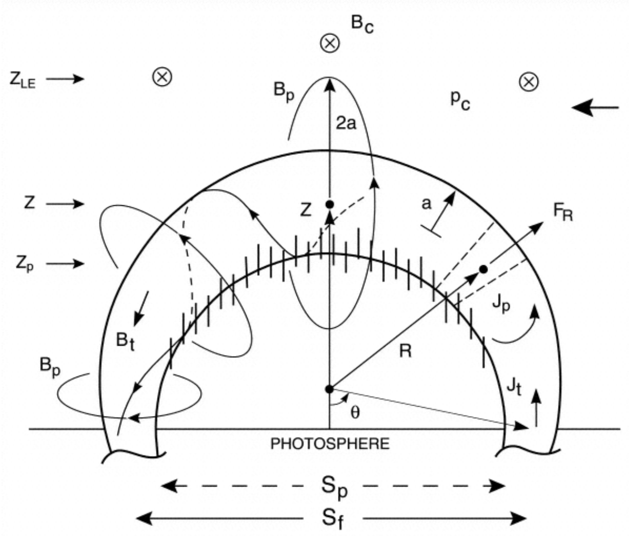
Temmer et al. (2010)



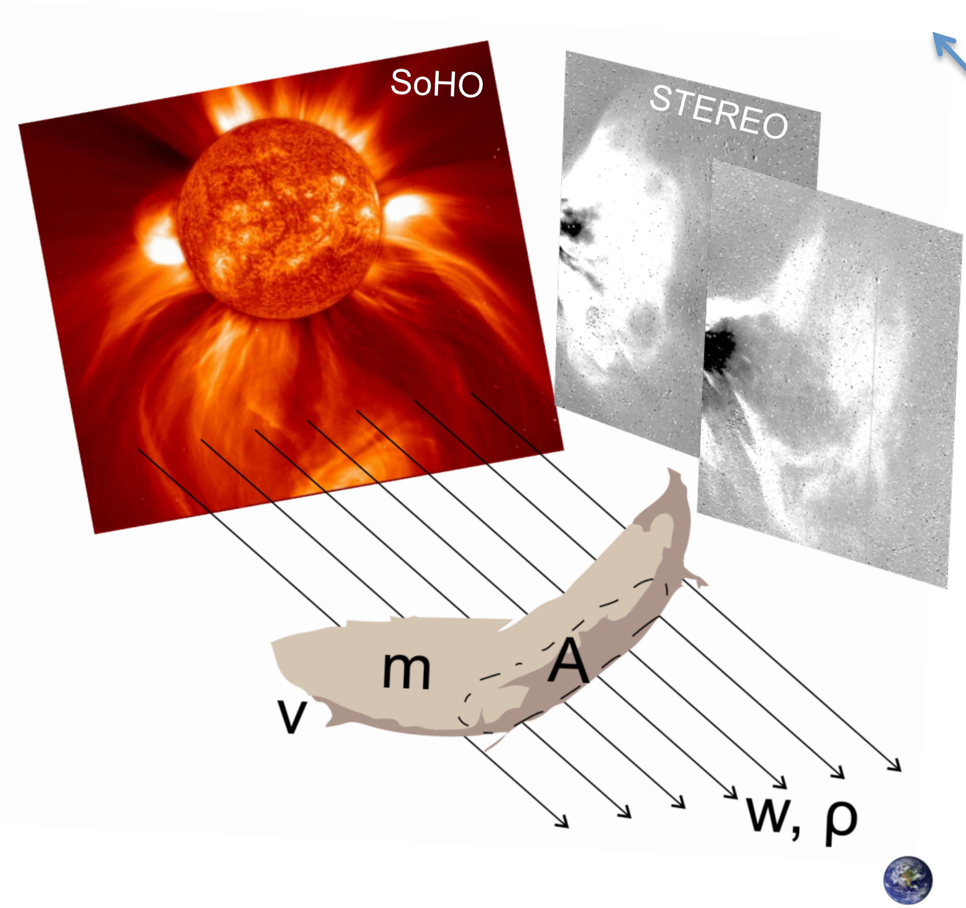
Maričić et al., 2007

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)



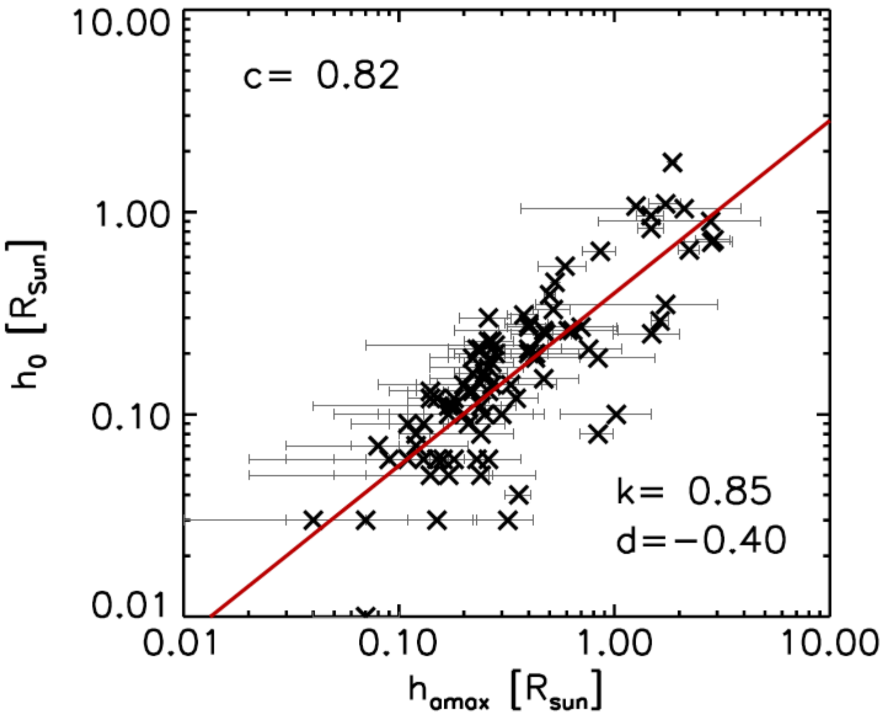
$$F = F_L + F_G + F_D$$



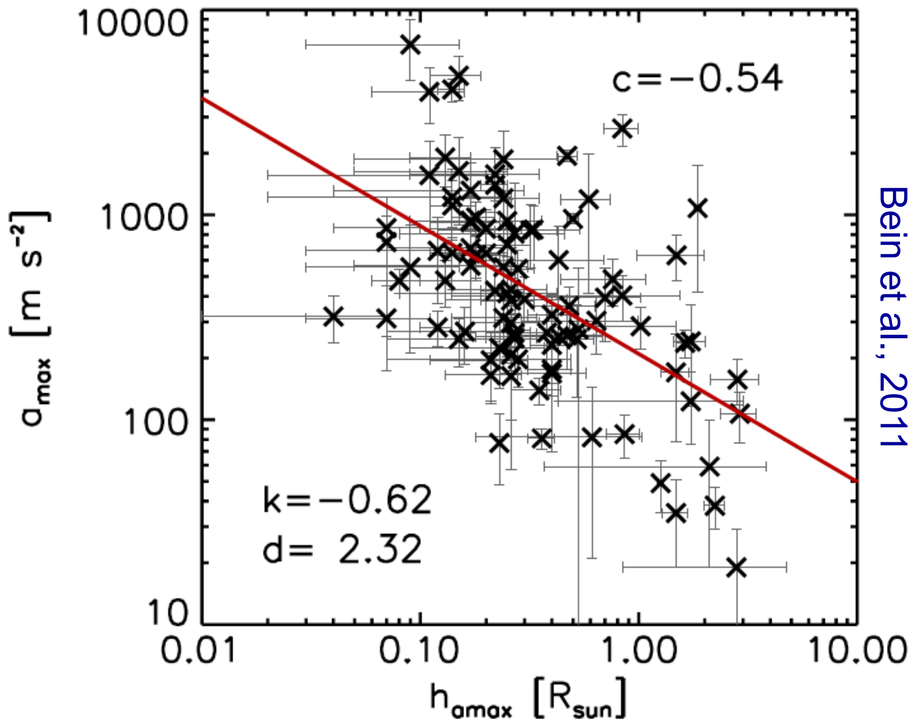
In IP space *drag* acceleration owing to the ambient solar wind flow (e.g. Vršnak 1990; Cargill et al. 1996; Chen, 1996; Cargill 2004; Vršnak et al. 2004; 2013; Maloney and Gallagher 2010, Carley et al., 2012).

CME properties are set in low corona

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



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



Bein et al., 2011

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

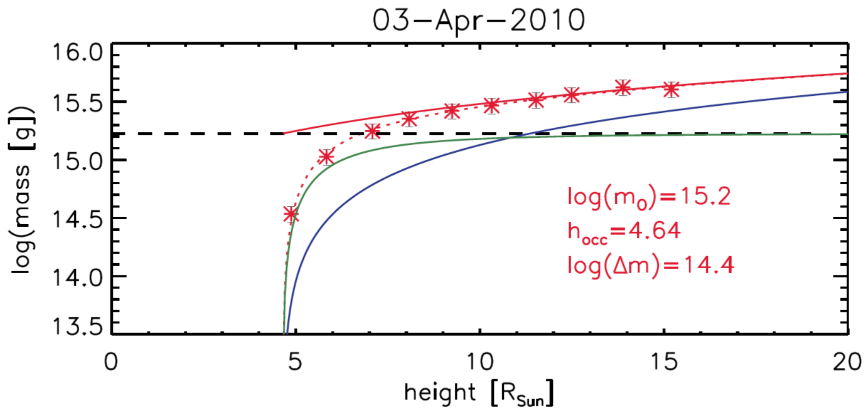
→ a consequence of stronger Lorentz force and shorter Alfvén time scales involved in compact CMEs (with stronger magnetic field and larger Alfvén speed being involved at lower coronal heights; Vršnak et al., 2007).

CME mass and energy – low corona

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

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

Bein et al., 2013



3D parameters for mass evolution:

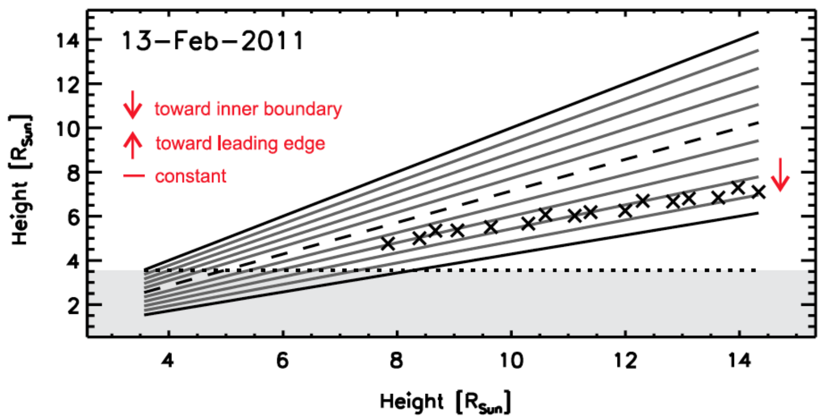
$m_0 = 10^{14}$g – 10^{16}g (r < 3Rs; initial mass)

Δm(r) mit r=10-20Rs: 2%-6%

Kinetic energy: 10^{23}J – 10^{25}J

(see Bein et al., 2013)

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



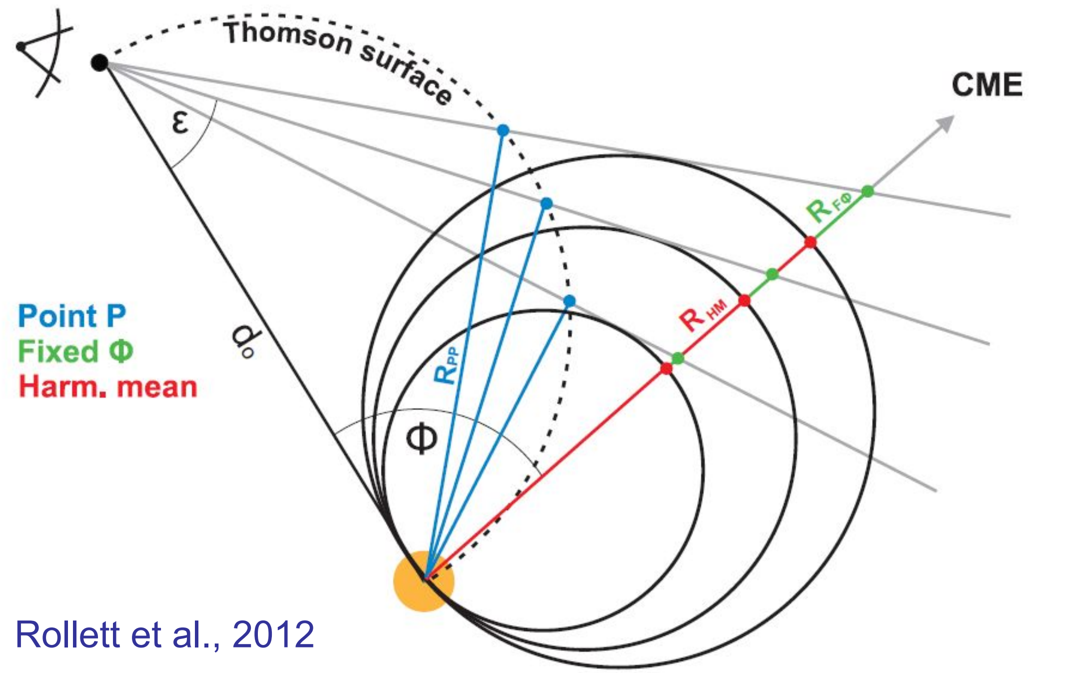
Important for studies on global energetics of flares and CMEs (see e.g., Emslie et al., 2004, 2012)

CMEs in IP space: elongation and geometry

Fixed-Φ (Sheeley et al., 1999; Kahler & Webb, 2007; Rouillard et al., 2008)

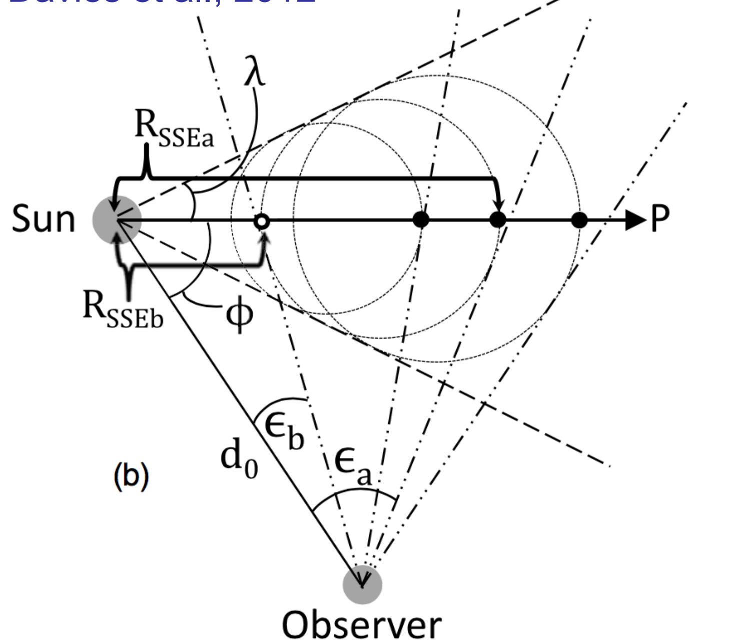
Harmonic Mean (Lugaz et al., 2009; Howard and Tappin, 2009)

Self Similar Expansion (Davies et al., 2012; Möstl and Davies, 2012)



Rollett et al., 2012

Davies et al., 2012



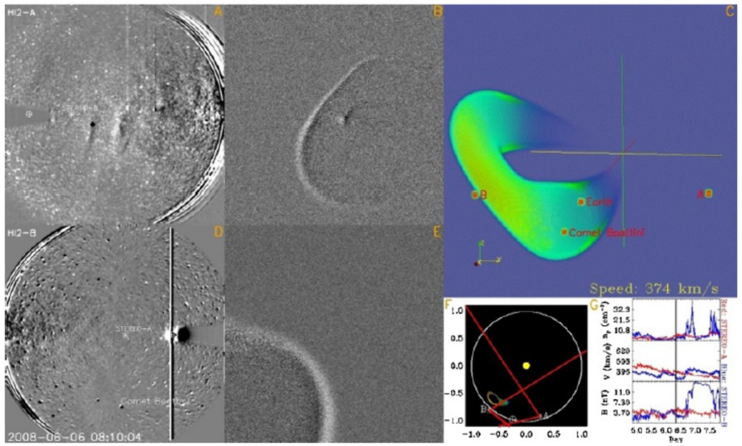
Remote sensing+in-situ:

Constrained Harmonic Mean (Rollett et al., 2012; Rollett et al., 2013)

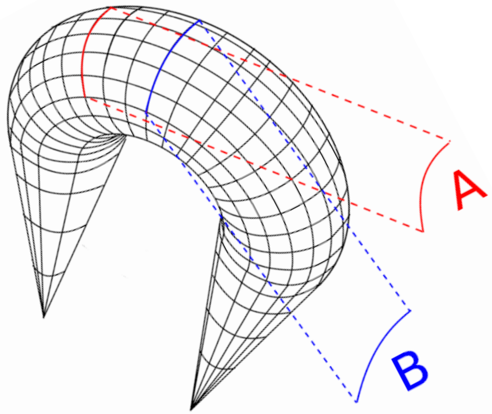
Constrained Self Similar Expansion (Rollett et al., 2014)

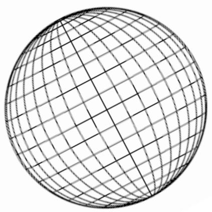
3D CME propagation direction (2 s/c)

- 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)

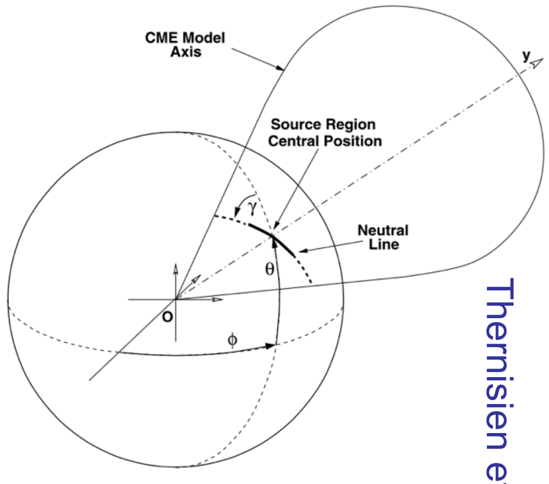


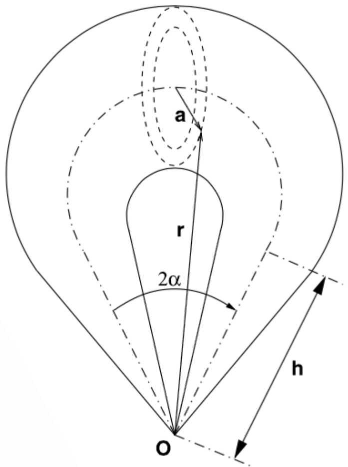
Wood et al., 2009





Mierla et al., 2009





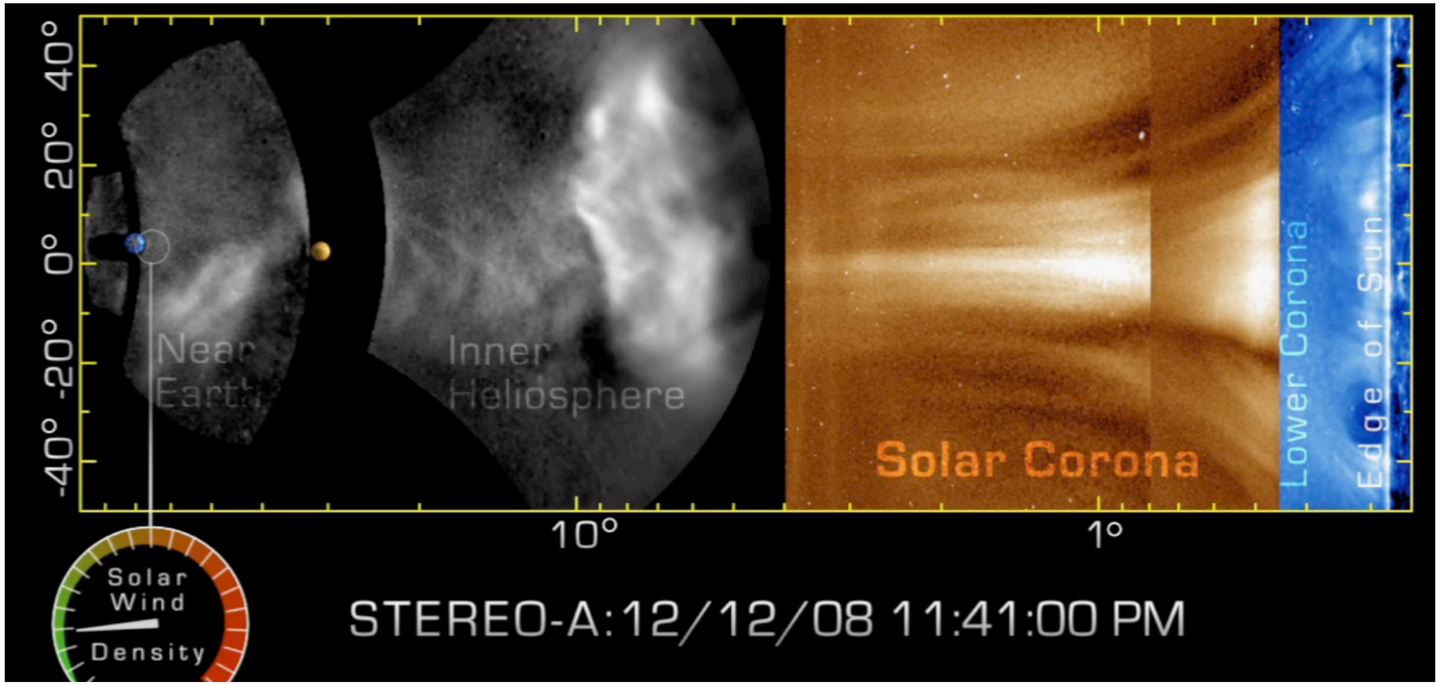
Thernisien et al., 2006

Environmental conditions

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



STEREO/SECCHI, C.deForest

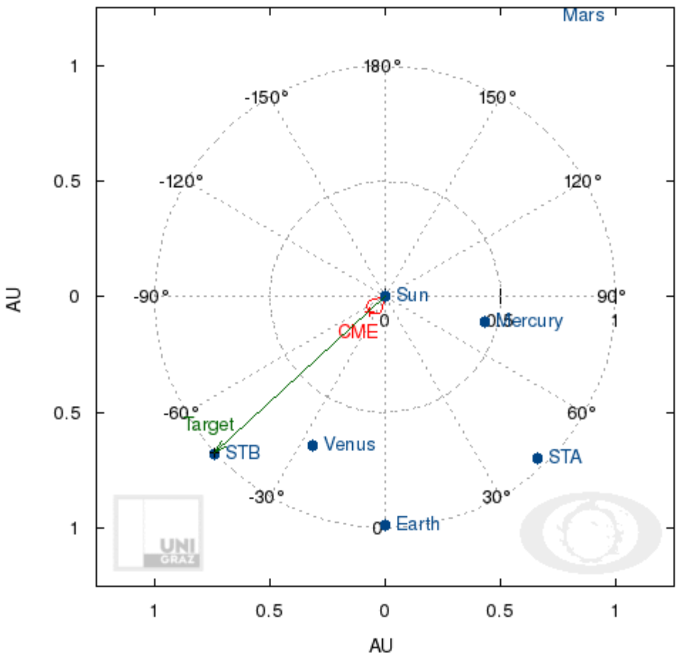
Solar wind drag effect

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)

$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\gamma(r)\left(\frac{\mathrm{d}r}{\mathrm{d}t} - w(r)\right)\left|\frac{\mathrm{d}r}{\mathrm{d}t} - w(r)\right| \quad \text{with} \quad \gamma = \frac{c_\mathrm{d} A \rho_\mathrm{w}}{V(\rho + \frac{\rho_\mathrm{w}}{2})} = \frac{c_\mathrm{d}}{L(\frac{\rho}{\rho_\mathrm{w}} + \frac{1}{2})}$$



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

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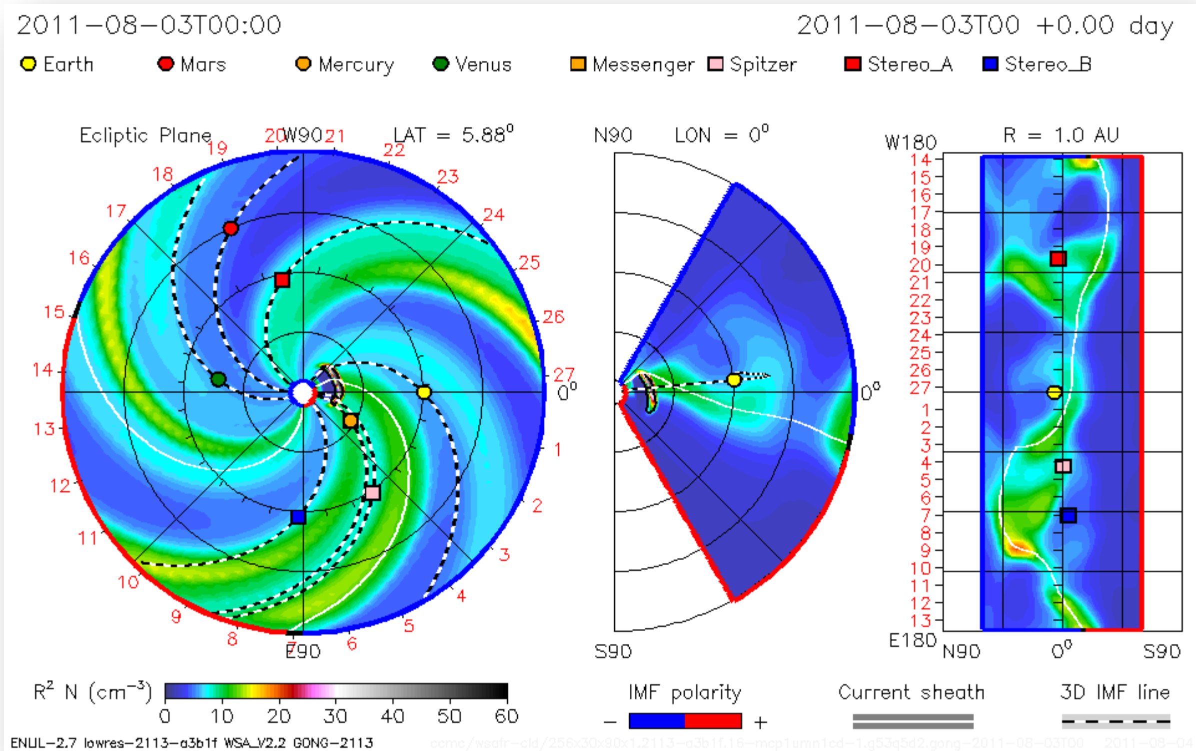
Preconditioning of interplanetary space

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*≈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).

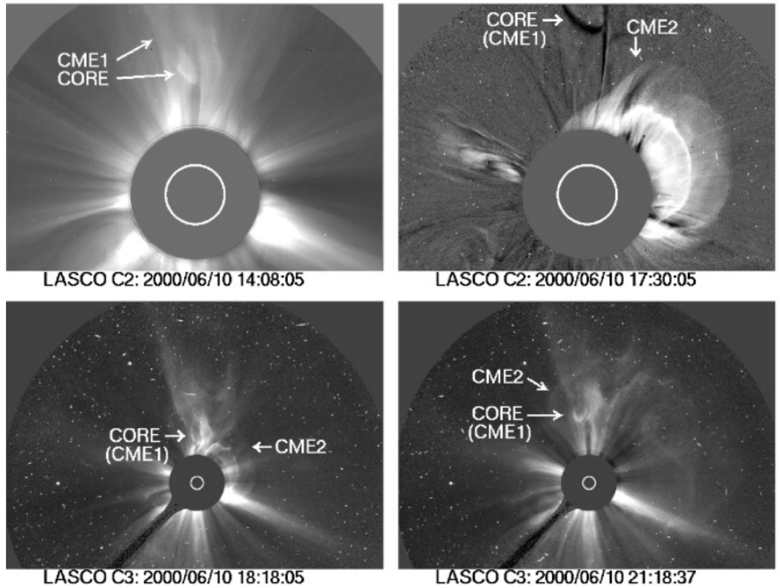
During times of high solar activity, preconditioning due to successive CME eruptions is highly likely.



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

CME – CME interaction

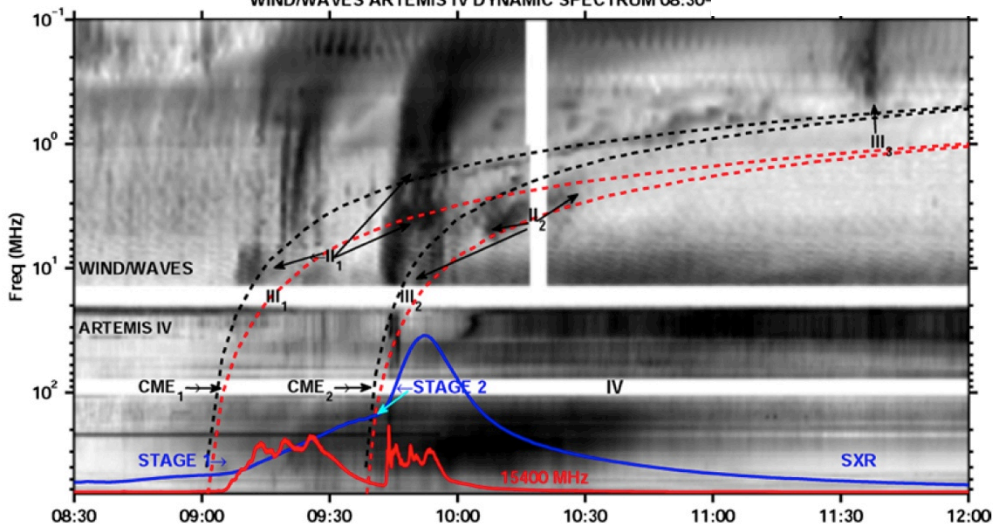
Gopalswamy et al. 2001



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)

Hillaris et al. 2011



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)

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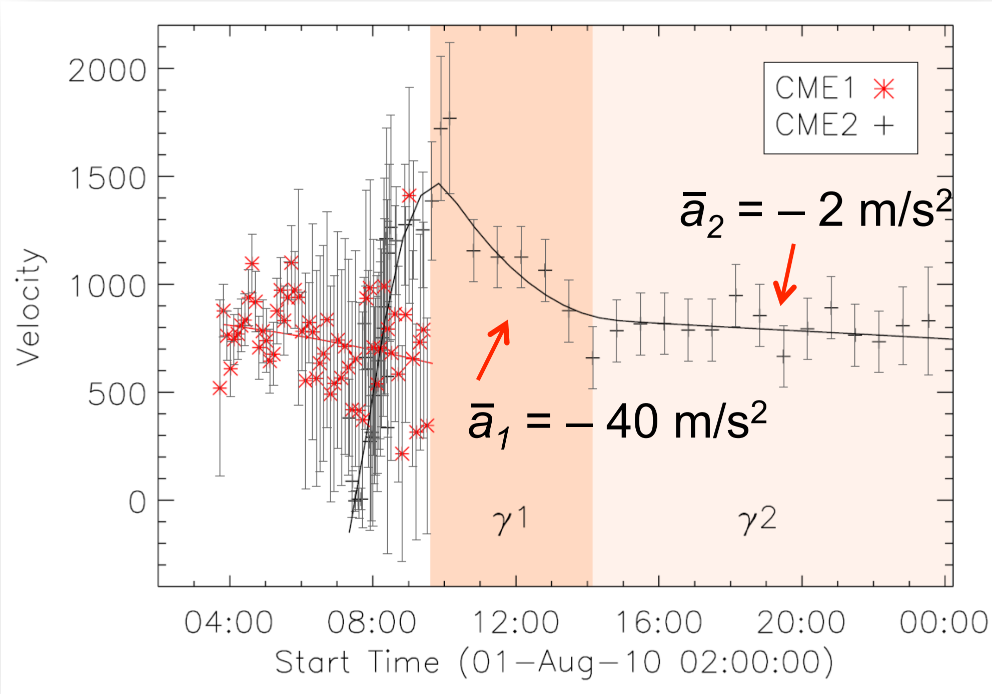
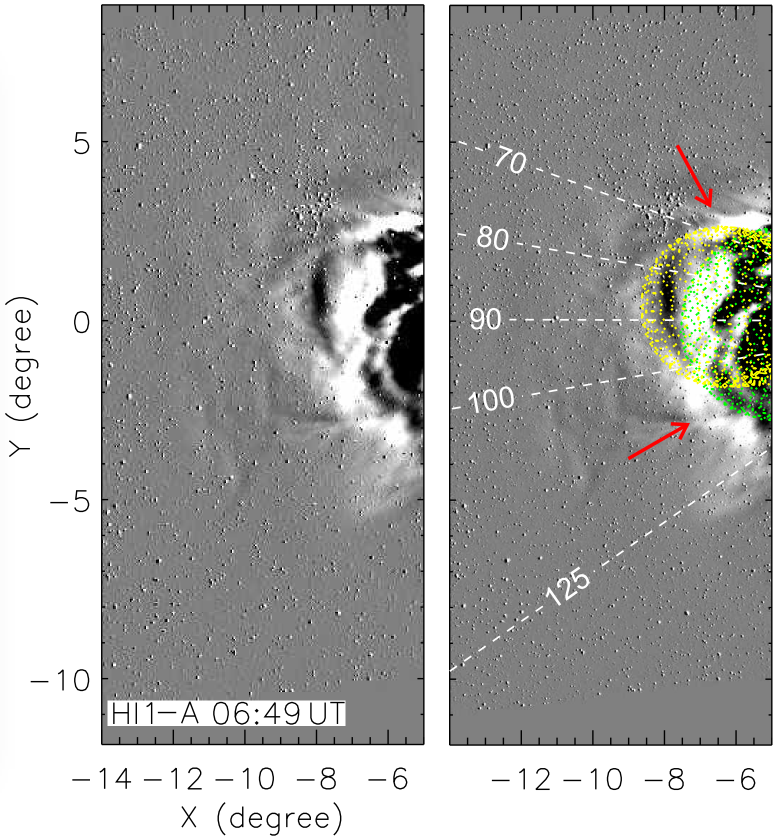
Observing the interaction process?

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).

Temmer et al., 2012



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

ILWS Jan 24-29, 2016!

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