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CMEs in the inner heliosphere – propagation and interaction with the solar wind

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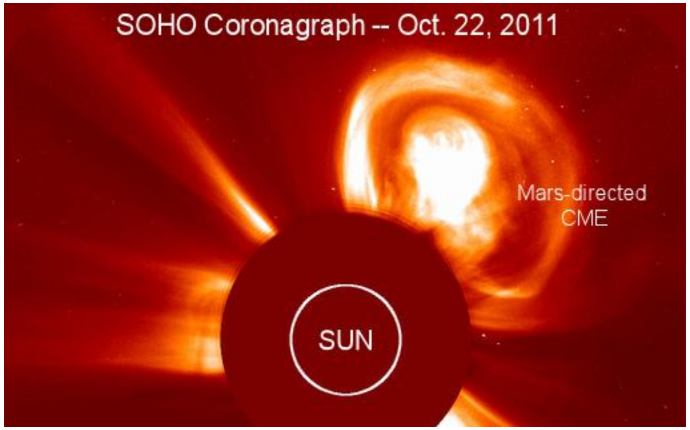
SEVENTH FRAMEWORK PROGRAMME

eHeroes

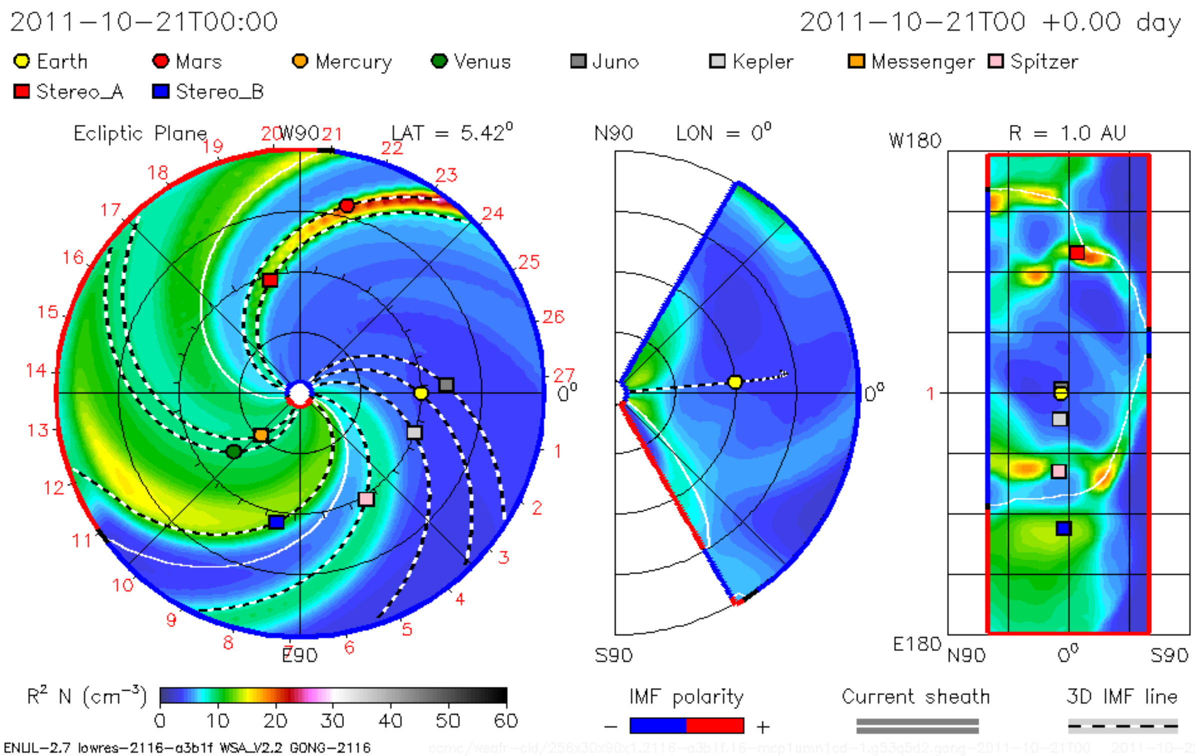
MESEP

ESWW10 Antwerp – November 19, 2013

CMEs‘ influence on the solar system



- CMEs - severe impact on space exploration, erode planetary atmospheres (e.g., Moon, Mars)
- Study CME propagation characteristics, SW and CME-CME interactions → forecasting arrival times and impact



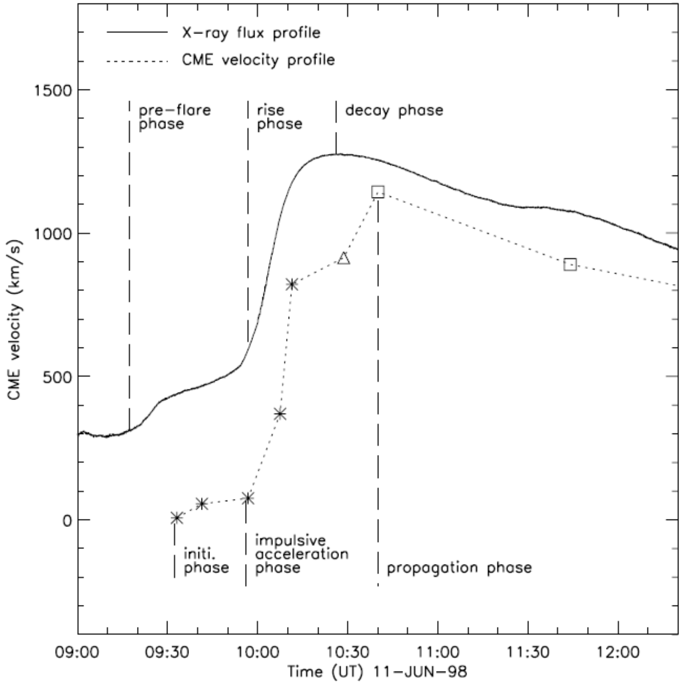

Credit: ESA

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)
- 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., 2012)
- Transition from slow to fast expansion @ start of flare impulsive phase (Sterling & Moore, 2005)

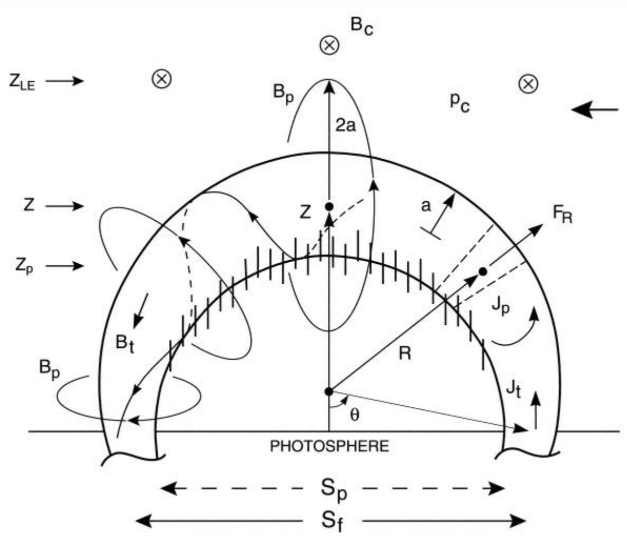
Zhang et al., 2001

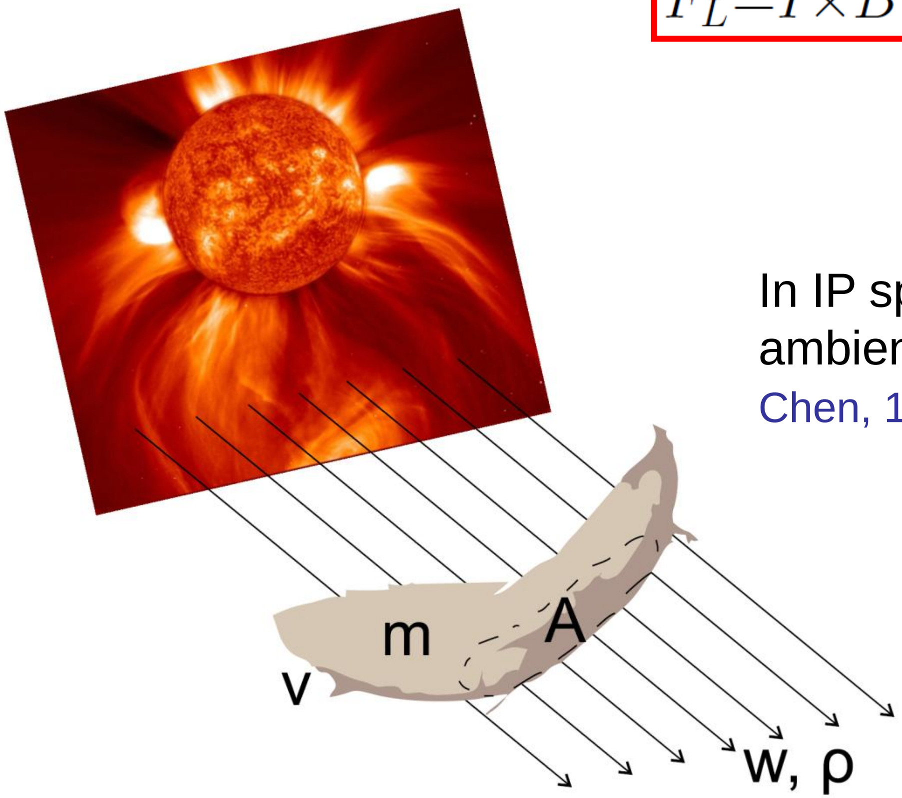


Forces acting on CMEs during propagation
Lorentz vs. drag force

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

$$F_L = I \times B$$





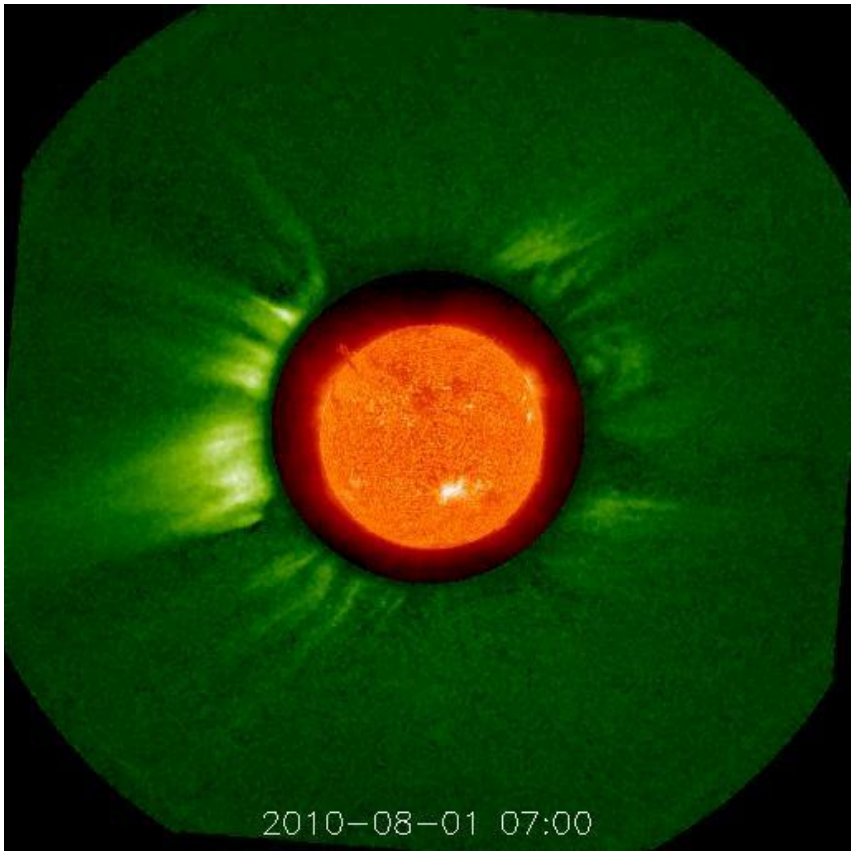
In IP space *drag* acceleration owing to the ambient solar wind flow (e.g. Cargill et al. 1996; Chen, 1996; Cargill 2004; Vršnak et al. 2004):

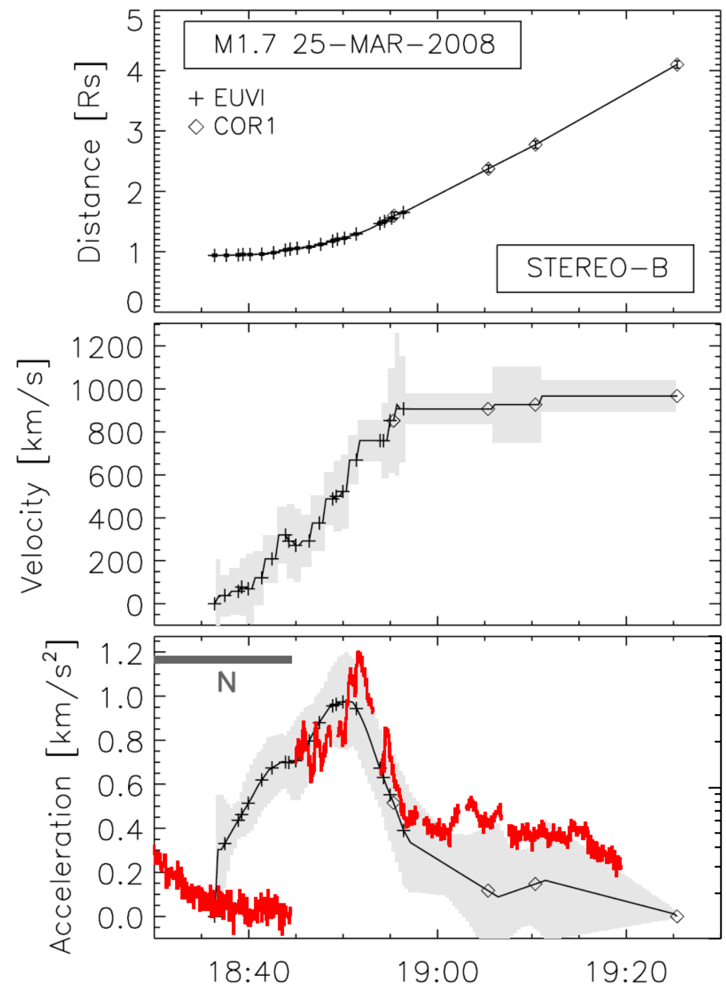
$$a_d = -\gamma (v - w) |v - w|$$
$$\gamma = c_d \frac{A \rho_w}{m}$$
$$A = \pi \varphi^2 r^2$$

Lorentz force – CME-flare relation

Relation between large and small scale activity phenomena (e.g., Chen 1996)
Flare energetics: determination of maximum speed/acceleration of CME?

Credit: STEREO





Temmer et al., 2010

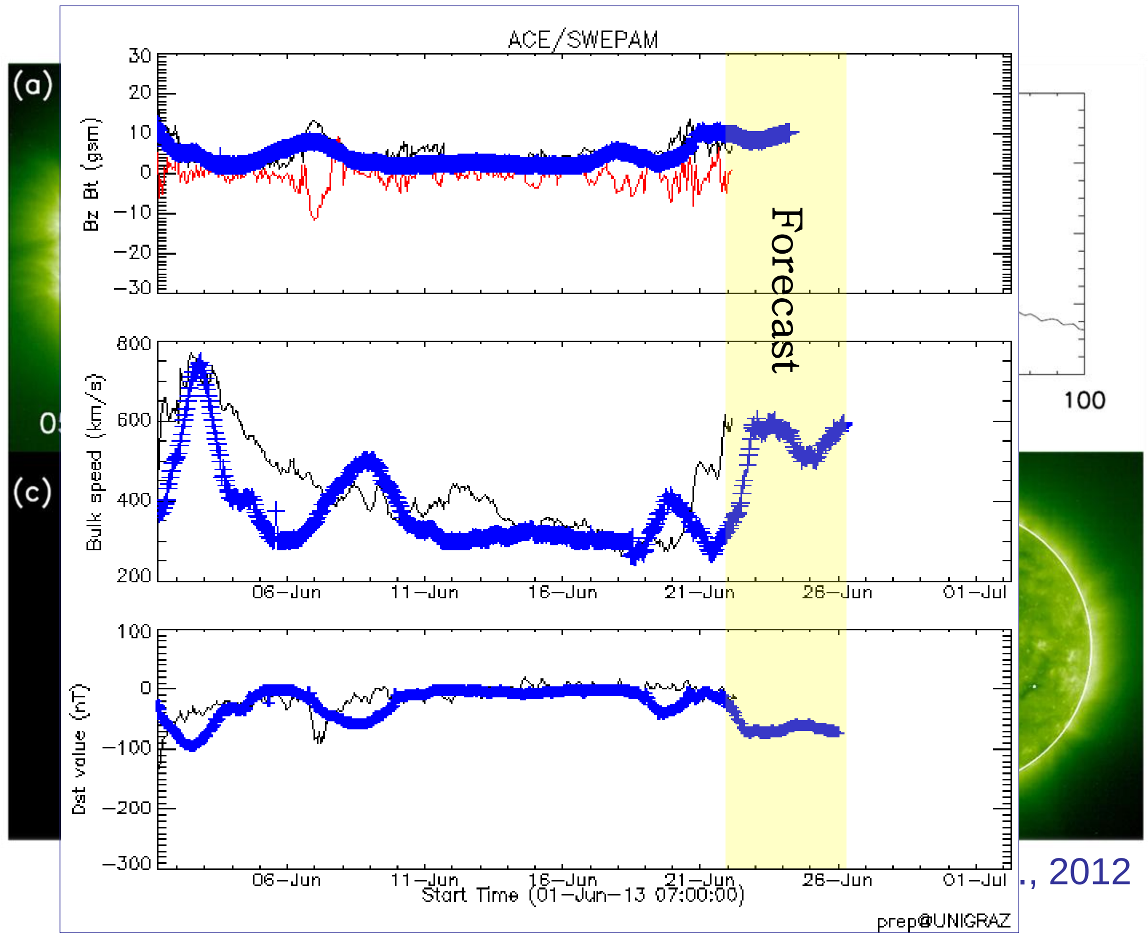
See studies by:
Zhang et al., 2001; 2004; Zhang & Dere, 2006; Maričić et al., 2007;
Vršnak et al., 2007; Temmer et al., 2008, 2010; Chen & Kunkel, 2010; Bein et al., 2012

Drag force – solar wind

CMEs are embedded/get adjusted to the solar wind flow (e.g., Chen 1996; Vršnak et al., 2001; Gopalswamy et al., 2002). Distribution of solar wind flow in IP space not well known – reliability of MHD models is moderate, due to uncertainties in the synoptic magnetic field data (see e.g., Lee et al., 2009; Gressl et al., 2013).

- Empirical relation: area of CHs – solar wind at 1AU (e.g., Robbins et al., 2006; Vrsnak et al., 2007)
- Automatic extraction of coronal hole areas (e.g., Delouille et al., 2007; Kirk et al., 2009; Krista & Gallagher, 2009; Rotter et al.,2012)
- Forecast of solar wind speed at 1AU ~4-days in advance

http://www.uni-graz.at/igam-sophy/comesep/solarwind/



., 2012

Empirical drag-based-model [http://oh.geof.unizg.hr/DBM/dbm.php]

Drag Based Model (DBM; Vrsnak et al., 2013)

$$\frac{d^2 r}{dt^2} = -\gamma(r)\left(\frac{dr}{dt} - w(r)\right)\left|\frac{dr}{dt} - w(r)\right| \quad \text{with} \quad \gamma =$$

- CME time/speed @ 20Rs
- CME angular width/direction

Meas

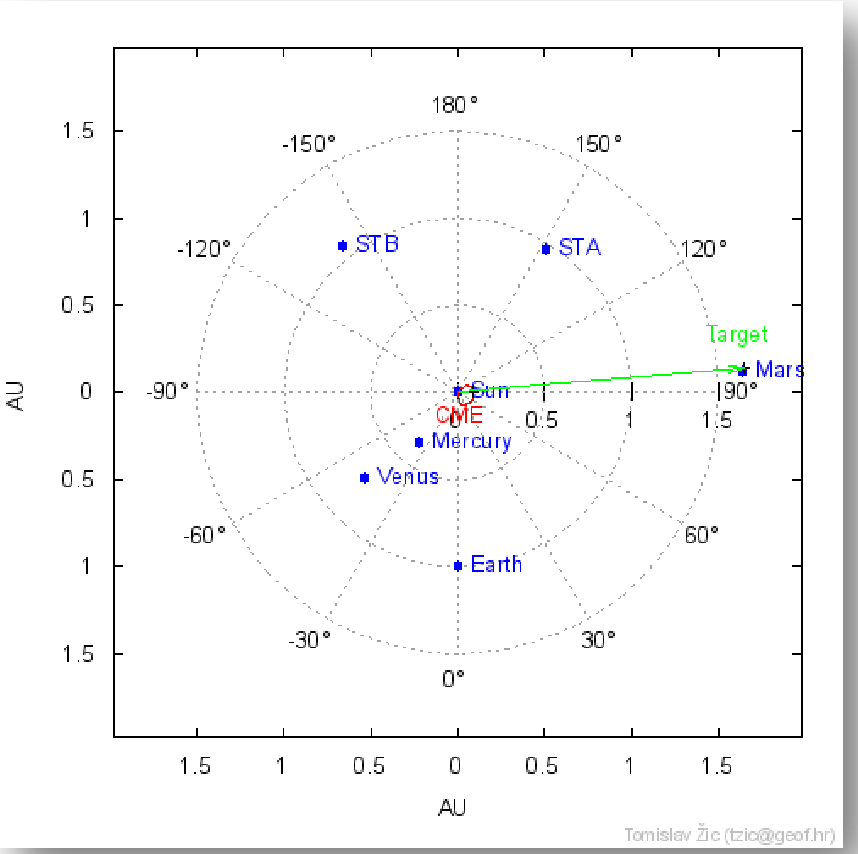
- *gamma factor*
- solar wind speed at target

$\gamma - h$

Distr
(prox

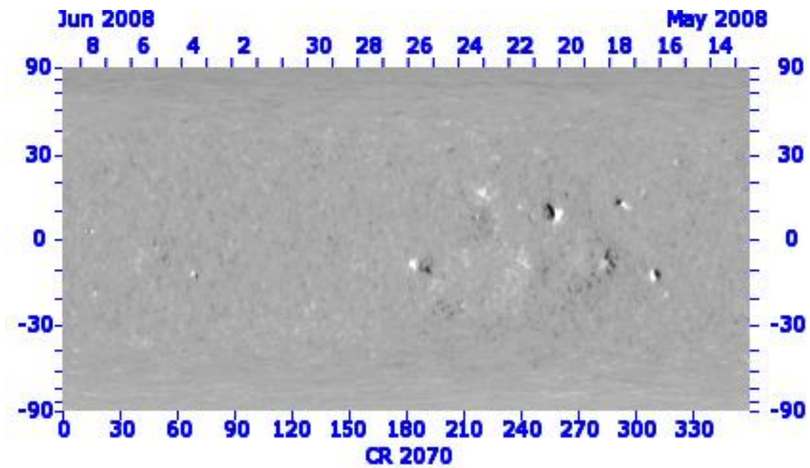
- (I)CME Arrival time
- Impact speed at target

Com

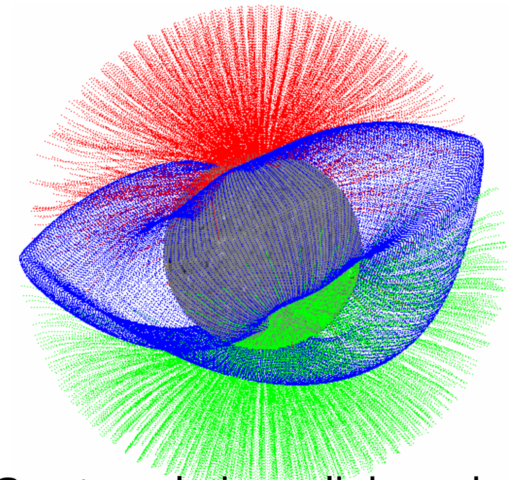


Empirical acceleration-velocity relationships proposed by:
Gopalswamy et al. (2000) and Gopalswamy et al. (2001)
GopEtAl00: a = 1.41 – 0.0035*v
GopEtAl01: a = 2.193 – 0.0054*v *(based on data with minimal projection effects)*

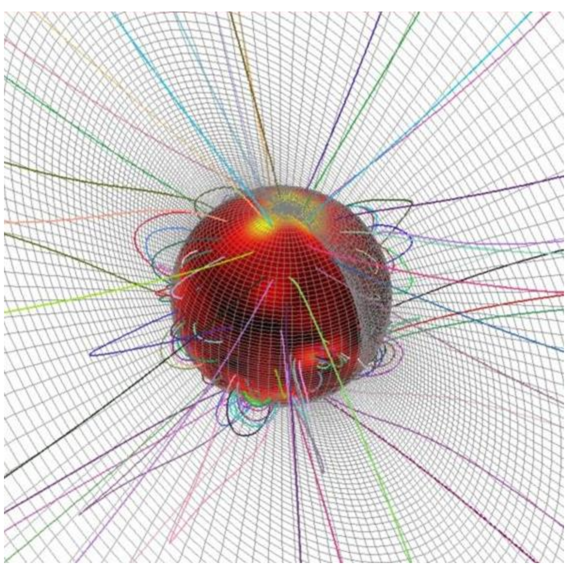
Solar wind: numerical model ENLIL



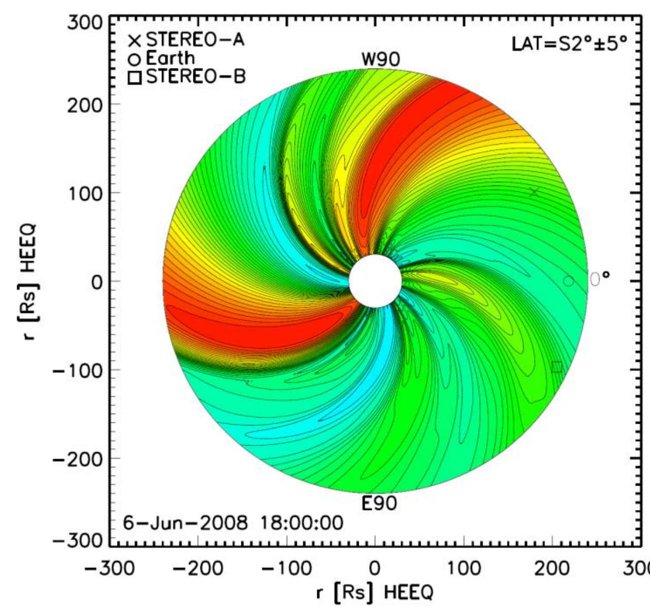
Initial point: synoptic B-field for selected CR



PFSS extrapolation – linkage between magnetogram and coronal model

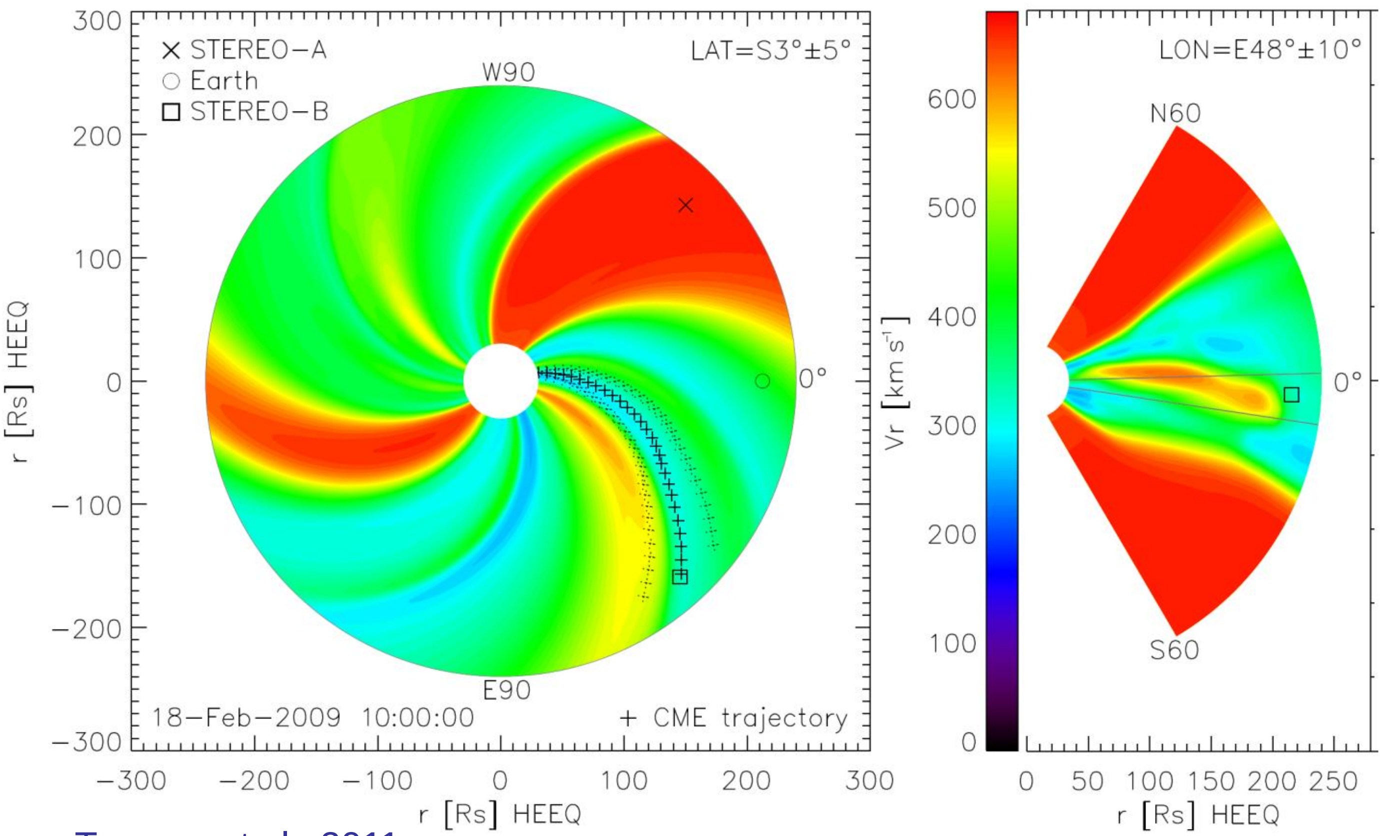


Coronal models: MAS (e.g., Linker et al., 2003) or WSA (Arge and Pizzo, 2000)



Heliospheric model ENLIL

Comparing results to observations 1) using ENLIL/MAS…



Temmer et al., 2011

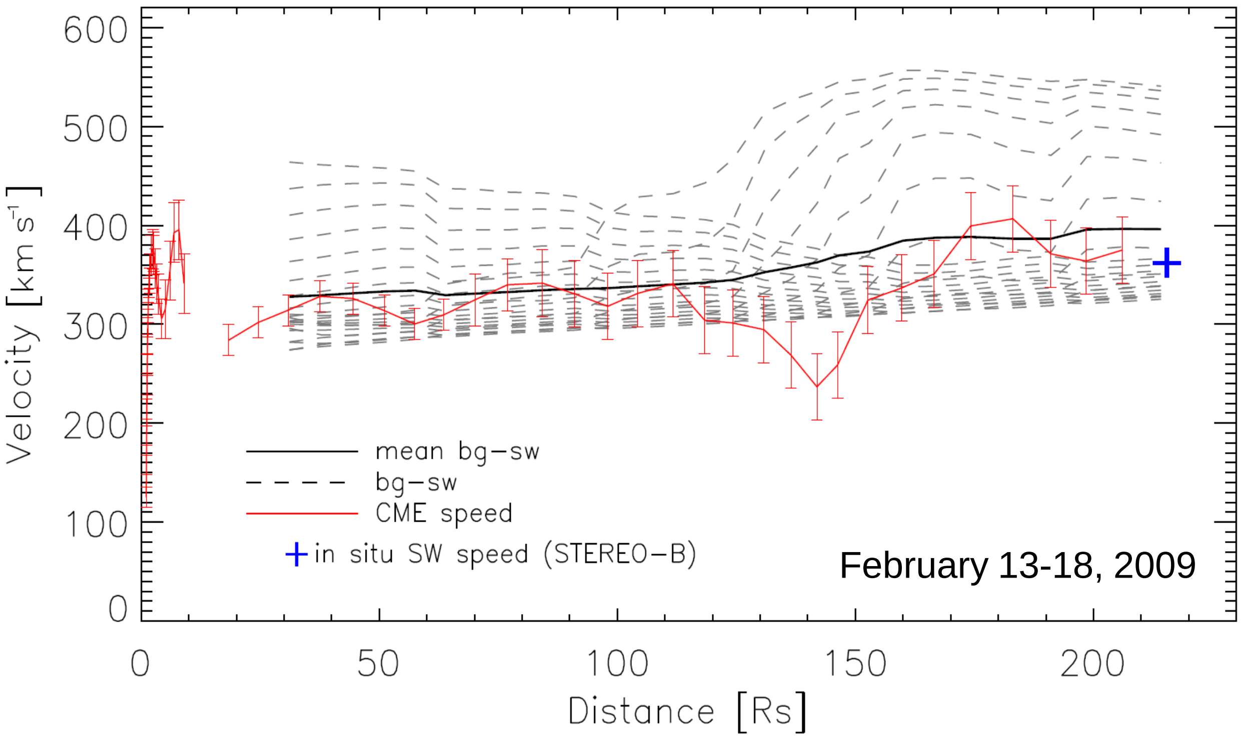
MAS+ENLIL model runs (NASA/CCMC):

solar wind distribution in the ecliptic plane and for meridional cut along the CME trajectory along E48.

CME trajectory crosses solar wind region of enhanced speed

Note: CME is observed from the Sun (non-inertial observer) which causes a deviation from the expected radial motion of the CME.

Solar wind influences CME speed



CME speed increases at 150-180Rs due to high speed solar wind stream (conversion method CHM Rollett et al., 2011)

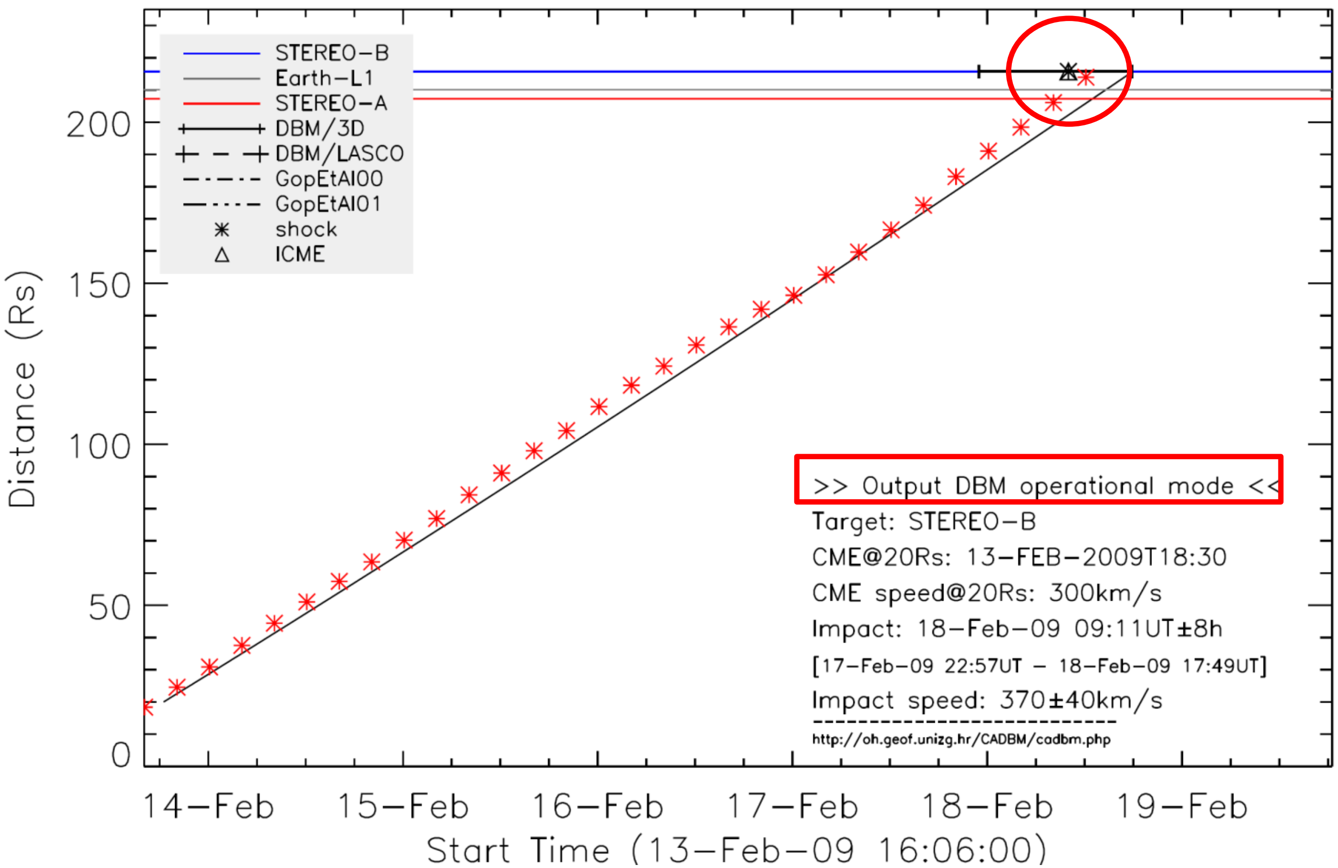
No signatures of growing post-flare loops, i.e. propelling force which would still drive CME (more details see Temmer et al., 2011)

Heliographic observational data and measurements beyond the coronagraphic field of view are essential for a more accurate prediction of CME arrival (see e.g., Colaninno et al., 2013).

Equally important: solar wind distribution in interplanetary space!

Comparing results to observations 2) using empirical relations…

Weak shock at ST-B February 18, 10:00 UT (Möstl et al., 2011)

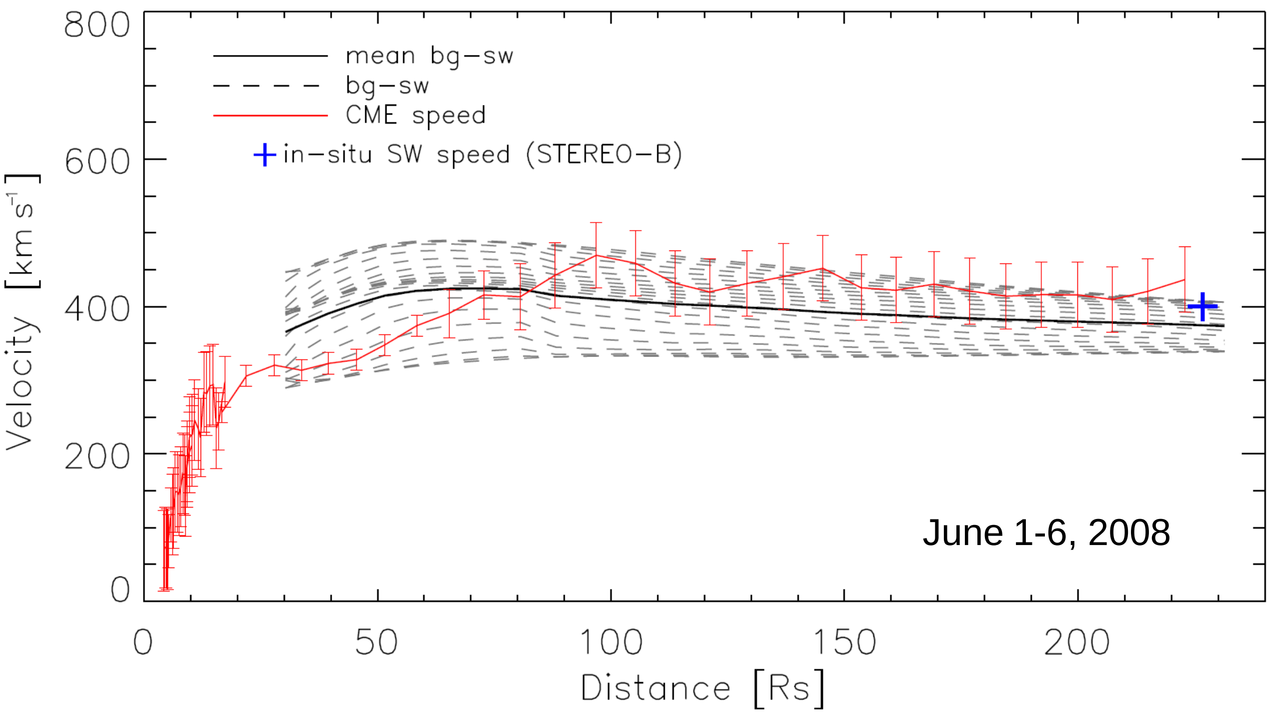


ICME in-situ impact speed of 360km/s (average speed of sheath region)

DBM operational mode: average of four different input values.
Combinations of w = [400, 500 km/s] and γ = [0.1, 0.2]*10^{-7} km^{-10}

„Special“ CME events

Stealth CMEs are „pulled“ out by the solar wind and propagate with the ambient solar wind speed. No on-disk signatures (flares, filament eruptions, dimmings, waves, etc., see also Webb et al., 2000; Robbrecht et al. 2009.). CMEs w/o obvious surface association usually attributed to “backside” events (e.g., Webb & Hundhausen 1987).



No signatures of reconnection = no driving force; go with the flow…

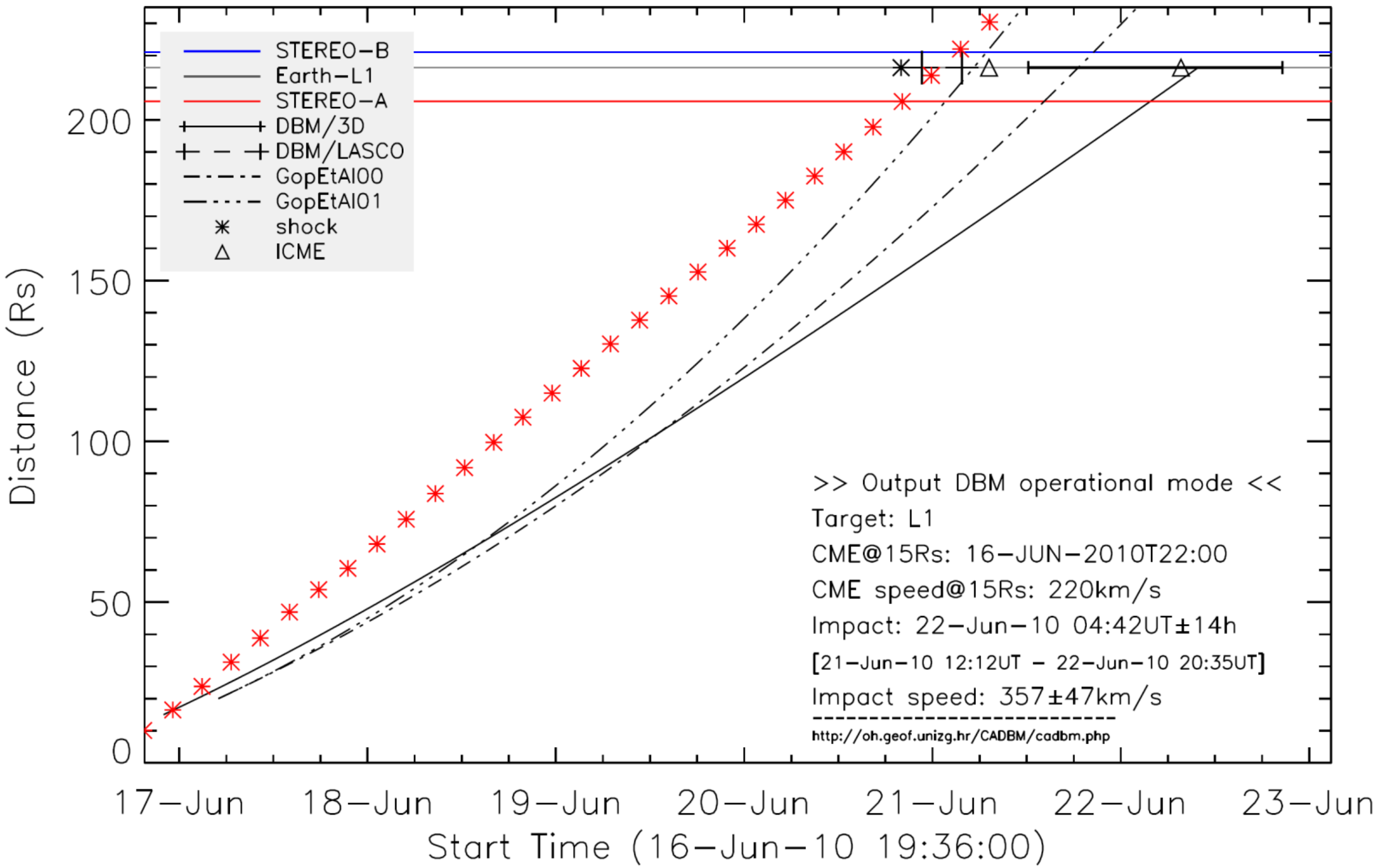
A third of the CMEs were “stealth” (Ma et al., 2010)

Start higher up in the corona (see review by Howard & Harrison 2012).

“Problem” geomagnetic storms are caused by stealth CMEs (see e.g., Dodson & Hedeman, 1964; McAllister et al., 1996).

Type-stealth CMEs …

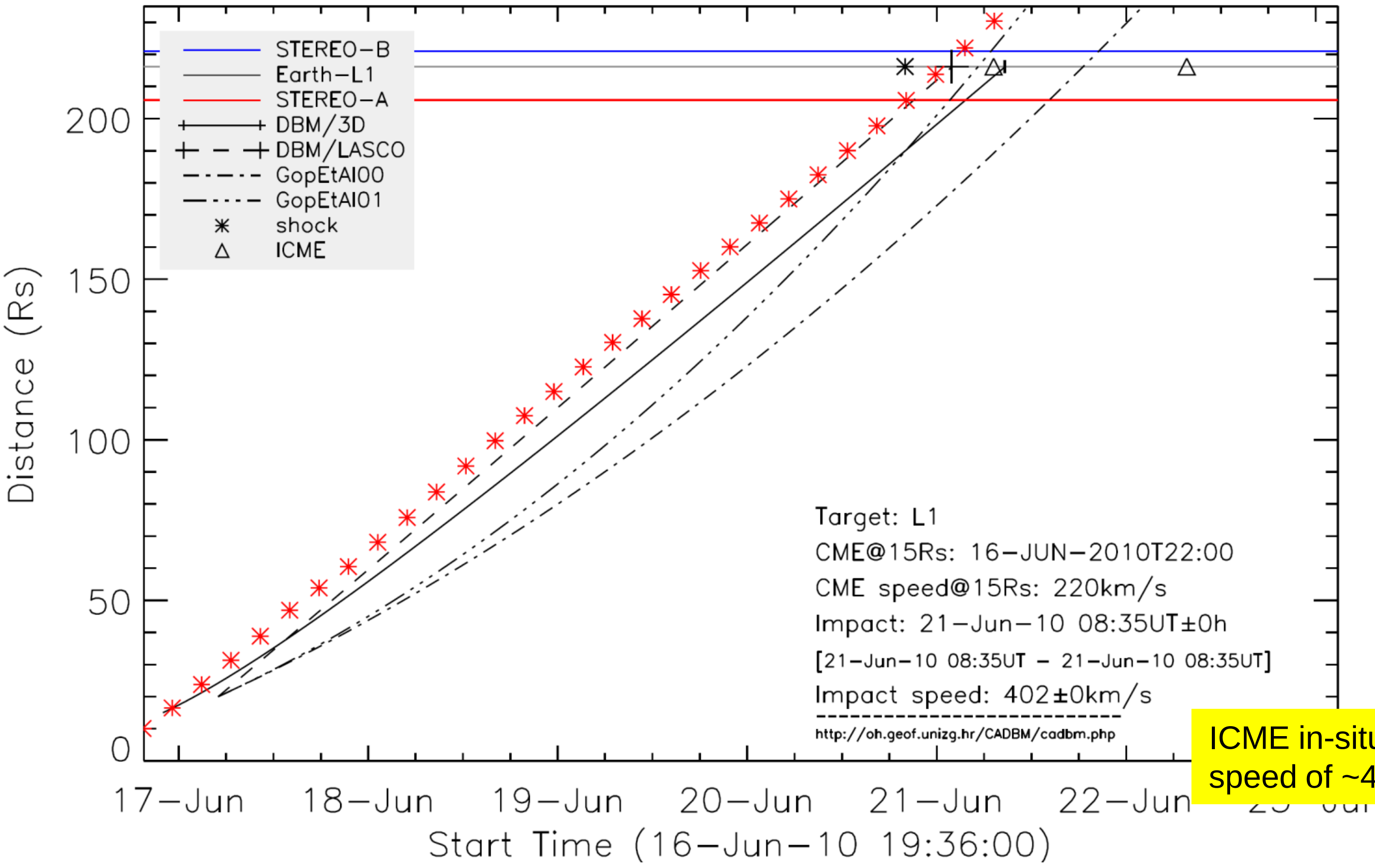
CME measurements using SATPLOT
(see ESWW10 Poster by Peinhart et al.)



June 16-21 2010 event see also Nieves-Chinchilla et al., 2012

… need specific input!

Behavior of CMEs w/o flares do not follow „standard parameters“.

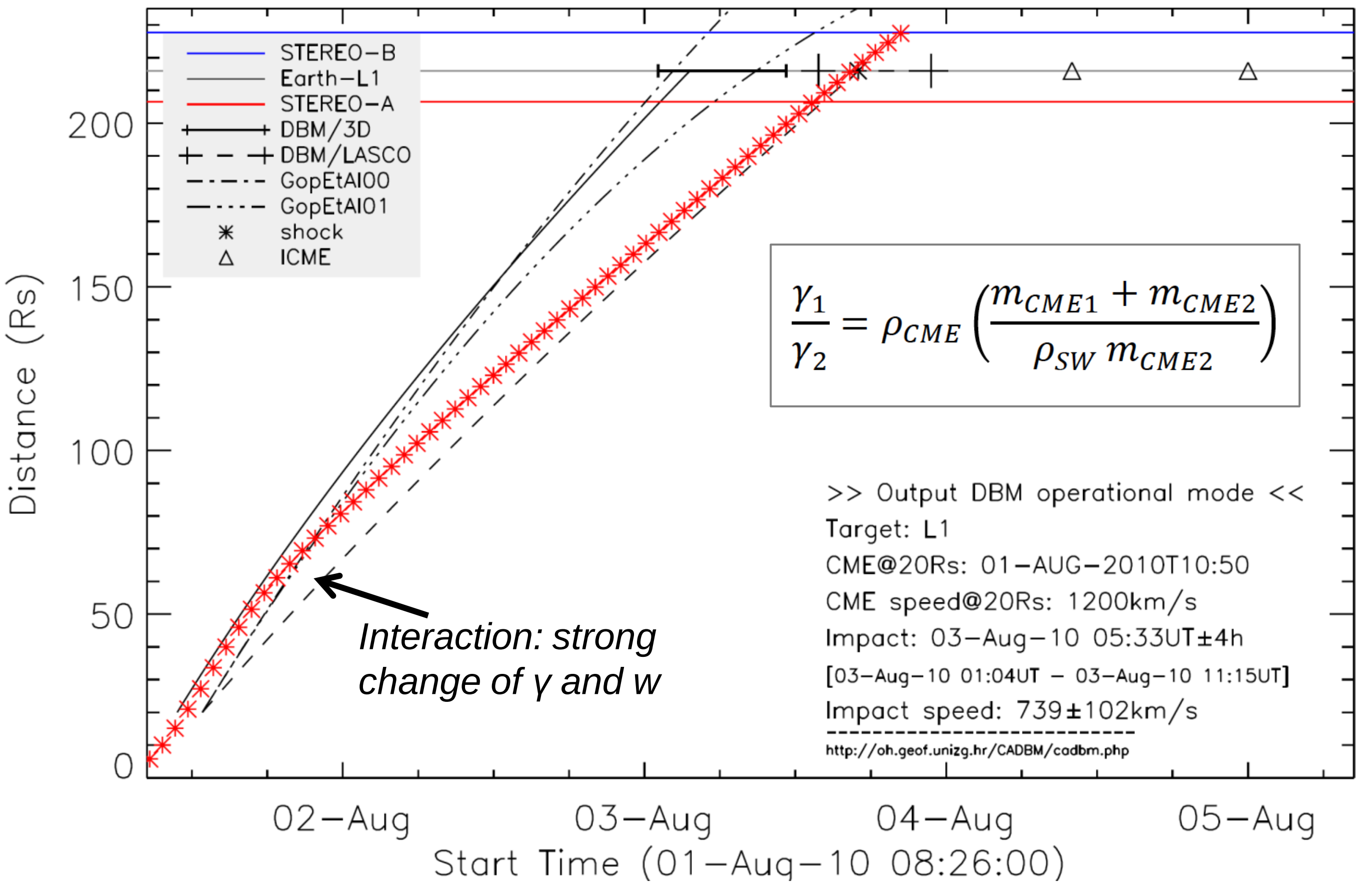


ICME in-situ impact speed of ~400km/s

DBM model input: w=430 km/s and $\gamma=0.7*10^{-7}$ km^{-1}

CME-CME interaction events

CME-CME events cause prolonged geomagnetic storms and are of special interest when investigating Space Weather. Strongly changing conditions in IP space let empirical models fail. But…information content is extremely high!



August 1 2010 events see: Harrison et al., 2012; Liu et al., 2012; Martinez-Oliveros et al., 2012; Möstl et al., 2012; Temmer et al., 2012; Webb et al., 2013

Summary

- Propagation behavior of CMEs in IP space clearly influenced by the environmental conditions which can be reproduced by MHD models reliably (only) for low solar activity.
- MHD models of solar wind speed are less reliable for high solar activity; how can we derive an appropriate solar wind speed for IP space?
- Good results for empirical models like DBM for isolated CME events, and simple SW behavior
- DBM: parameterization of γ to better understand drag in IP space
- „Stealth“ CMEs may cause „problem“ geomagnetic storms and are hard to forecast w/o solar surface signatures – propagation behavior is simple
- CME-CME interaction events are very important and need more detailed studies. Complex events, but very rich in information!
- Need to test and validate models for solar wind parameters in IP space against observations for more events and changing solar activity levels