Kinematics of CMEs using SECCHI/HI observations

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Motivation

- Understanding CME propagation, tracking CMEs in the heliosphere
- Arrival Time prediction of CMEs
- Association of remote observations with in-situ solar wind observations
- Role of CME structures in geo-effectiveness

Constraints

- CMEs undergo acceleration/deceleration: Changing dynamics due to ambient solar wind medium
- CMEs interact, merge (Gopalswamy et al. 2001, Harrison et al. 2012, Liu et al. 2012, Temmer et al. 2012….)
- Interaction of CMEs may lead to deflection in CME trajectory (Lugaz et al. 2012, Martinez-Oliveros et al.2012…)
- Shocks from the following CME may affect the preceding CME structure (Liu et al. 2012)

These may lead to errors in arrival time prediction

CME-CME Interaction

- How does the dynamics of CMEs change after interaction? (Lugaz et al. 2012)
- What is the regime of interaction, i.e. elastic, inelastic or super-elastic? (Shen et al. 2012)
- What are consequences of the interaction of CME-shock structure?
- How the overtaking shock changes the plasma and magnetic field properties into preceding magnetic cloud? (Liu et al. 2012)
- What are the favorable conditions for the CME cannibalism and role of magnetic reconnection? (Gopalswamy et al. 2001)
- Whether these interacted structures produce different geomagnetic consequences than individual CME, on their arrival to magnetosphere? (Farrugia et al. 2006).

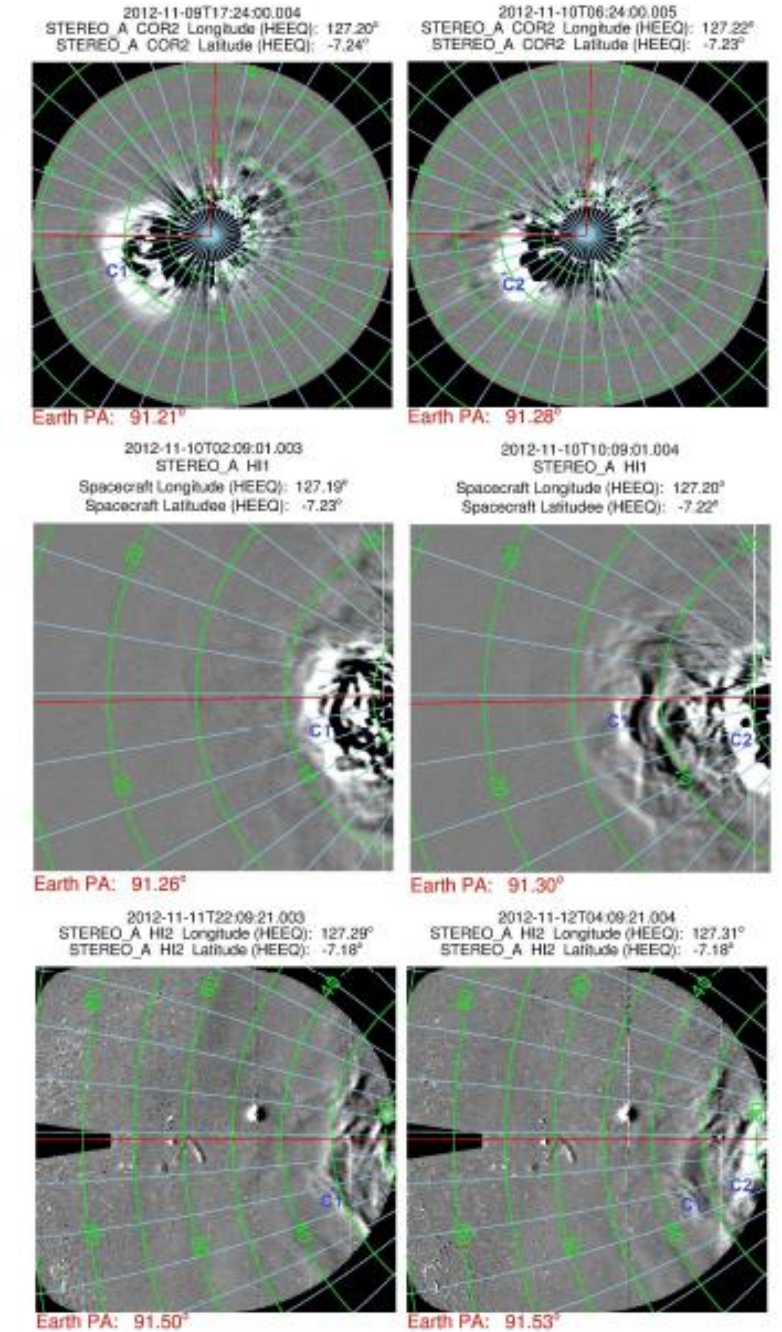
Prediction of arrival time of interacting CMEs and association of remote observations with in -situ is challenging.

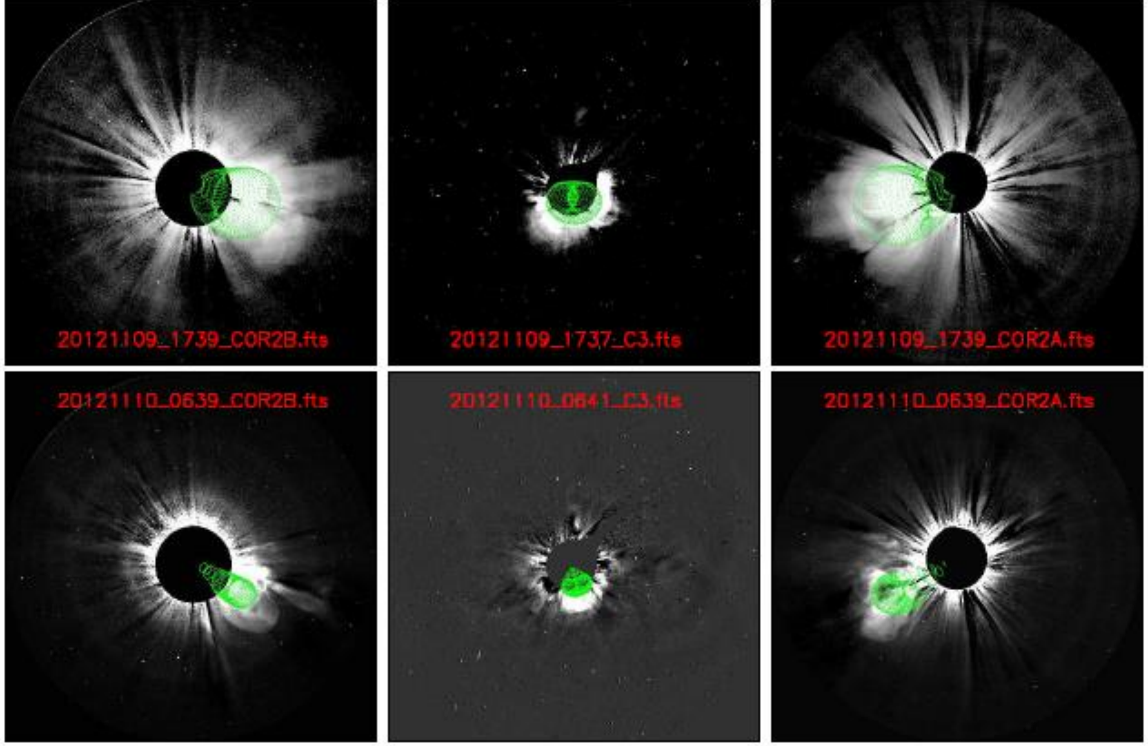
Interacting CMEs of 2012 November 9-10

LASCO C2 observations:

CME of 2012 November 9 (CME1) : 15:12 UT, partial halo, 560 km/s
CME of 2012 November 10 (CME2): 05:12 UT, partial halo, 900 km/s

Both STEREO are behind the Sun (separation angle from Earth view = 250^0). CMEs were seen in SE and SW quadrant from COR1-A and B





3D reconstruction in COR2 FOV:

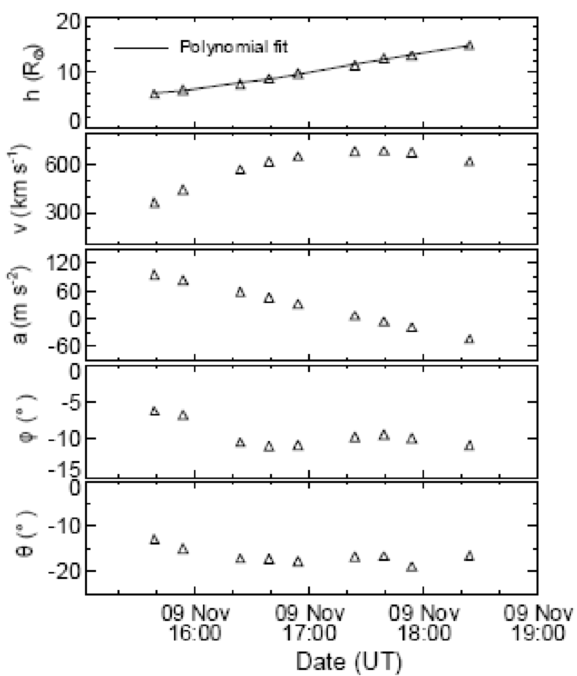
(Tie-pointing: Thompson 2009) and (Forward modeling: Thernisien et al. 2009)

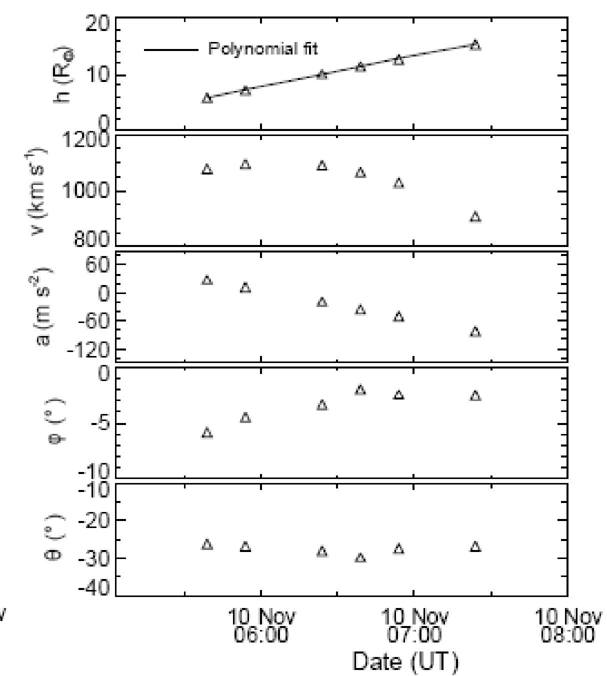
Speed (from 3D reconstruction) of CME1: 620 km/s

CME2: 910 km/s at approx. 15 Rs. Both are Earth-directed.

Chance of collision at 130 Rs on 2:30 UT on Nov 11.

We need to verify the collision of CMEs in HI images (using J-maps)





Kinematics from Heliospheric Imager

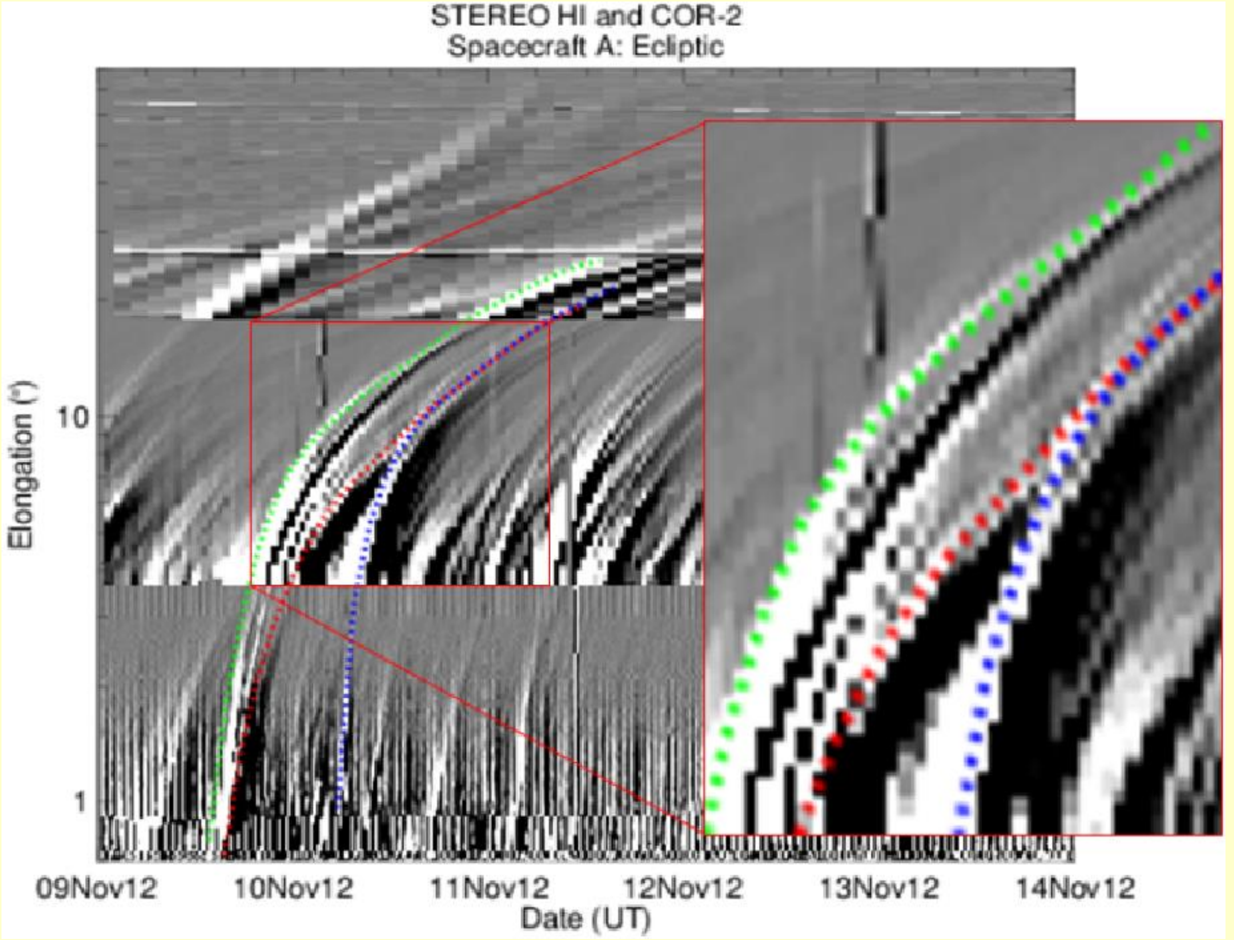
Elongation profiles derived from STEREO-A J-map is converted into height from the Sun using Harmonic Mean (HM) Method. (Lugaz et al. 2009)

Direction of propagation of CMEs estimated in COR2 FOV is used as input in HM method. For CME1 and CME2 estimated is 10^0 E and 2^0 E from the Sun-Earth line.

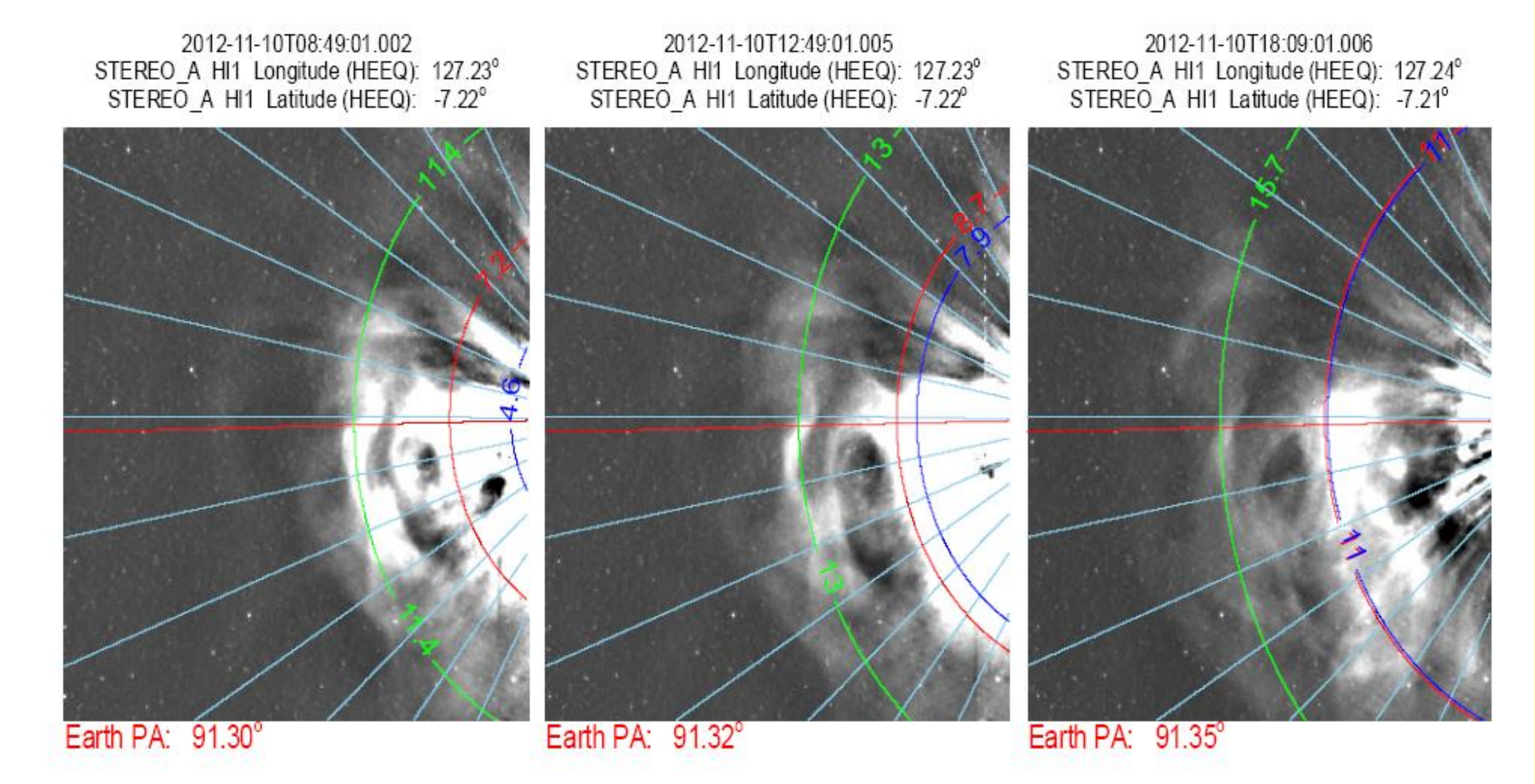
Green: CME1 LE
Red: CME1 TE
Blue: CME2 LE

Collision of CME1 TE (red) and CME2 LE (blue) in HI1 FOV.

Collision phase can be marked from the kinematic profiles of these tracked features.



Contour of derived elongation overplotted on HI images



Kinematics of Interacting CMEs

Deceleration of CME2 LE (950 km/s at 10 Rs to 430 km/s at 46 Rs) is noticed.

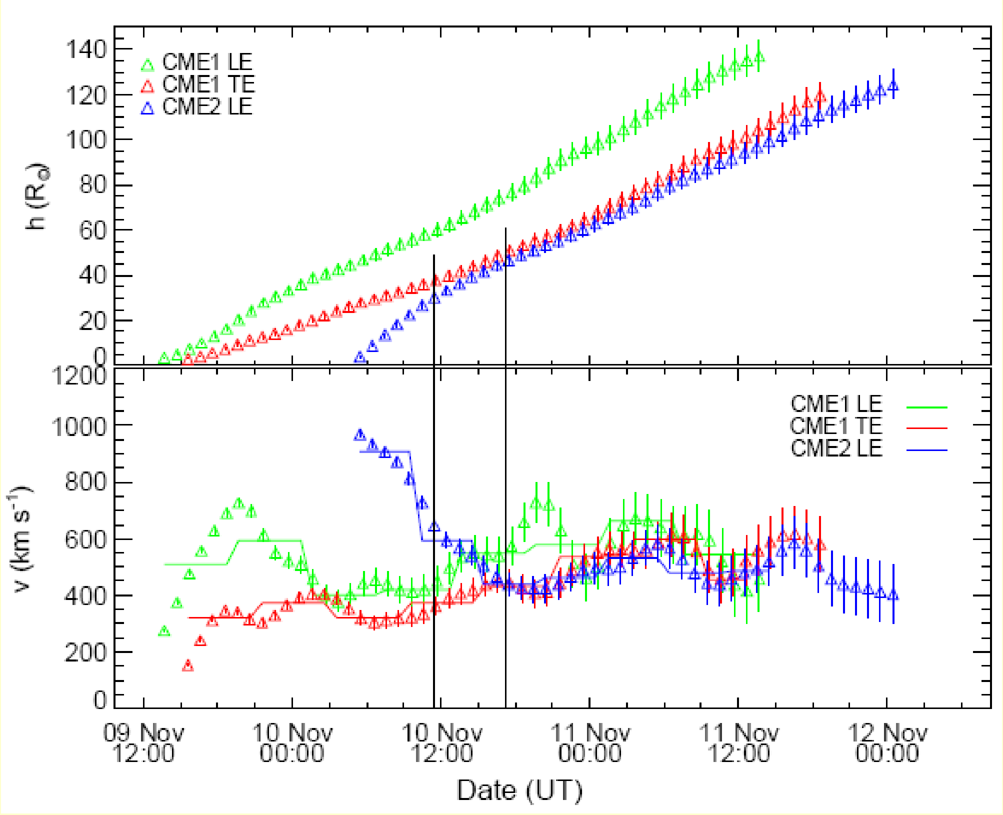
Even before the actual collision of tracked features, fast deceleration of CME2 in COR2 FOV is possibly due to preceding CME1.

Speed (averaged over few data points at the entrance in HI1 FOV) for CME1 LE is 500 km/s and for CME1 TE is 350 km/s.

Collision phase:
Nov 10 11:30 UT – Nov 10 17:15 UT

At the beginning of collision phase CME1 **TE is at 37 Rs and CME2 LE is at 30 Rs.**

At the end of collision phase CME1 TE is 50 Rs and CME2 LE is at 46 Rs.



Observed (u_1, u_2) = (365,625) km/s
& (v_1, v_2) = (450,430) km/s

Momentum, Energy Exchange and Nature of Collision

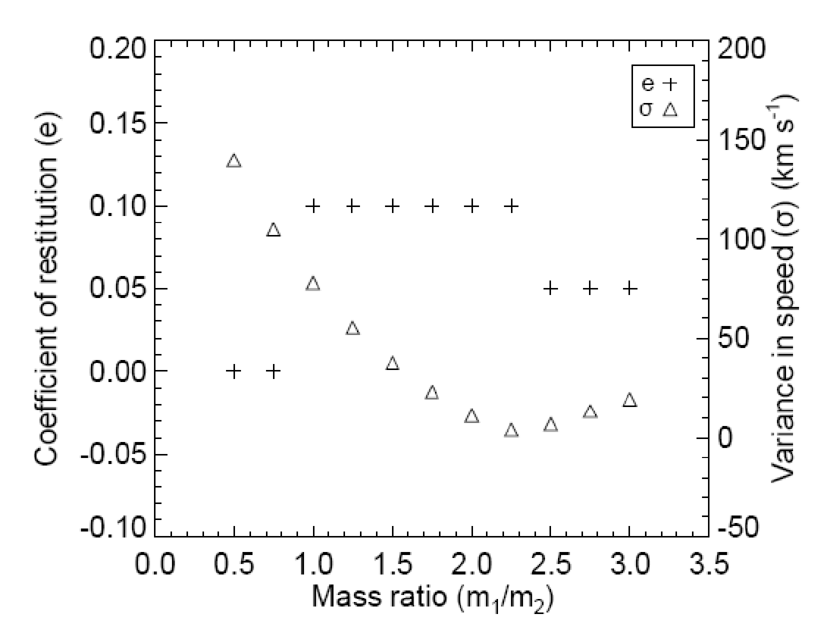
Using Thomson scattering theory propagation direction and true mass of CMEs can be determined. (Colaninno and Vourlidas 2009)

For CME1 at 15 Rs:
$M_A = 4.60 \times 10^{12}$ kg, $M_B = 2.81 \times 10^{12}$ kg, propagation direction = 19^0 West from Sun-Earth line, True mass $M_1 = 4.66 \times 10^{12}$ kg

For CME2 at 15 Rs:
$M_A = 2.25 \times 10^{12}$ kg, $M_B = 1.31 \times 10^{12}$ kg, propagation direction = 21^0 West from Sun-Earth line, True mass $M_2 = 2.27 \times 10^{12}$ kg

Total KE of the CMEs is found to decrease by 6.7% of its value before the collision.

KE of the CME1 increased by 51% that of the CME2 decreased by 54.5%. Momentum of CME1 increased by 23% and that of CME2 decreased by 31%.



Taking different mass ratios do not affect the nature of collision

Combining the momentum conservation and coefficient of restitution equation:
e = 0.1 for variance = 9, From the observed speeds e = 0.08
i.e. close to perfectly inelastic collision.

In Situ Observations and Arrival Time of Interacting CMEs of November 9-10

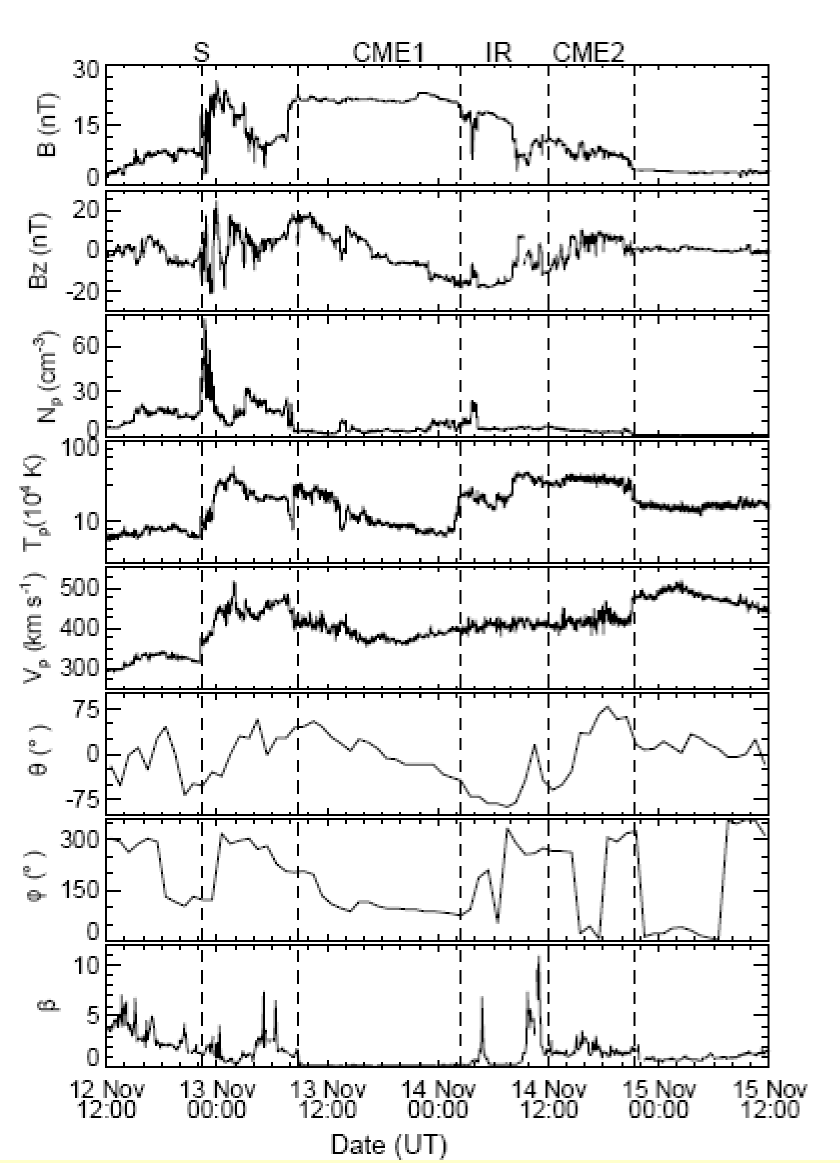
Arrival of shock: November 12 22:20 UT
CME1 (MC):
Nov 13 08:52 UT – Nov 14 02:25 UT

CME1: Signatures of MC (beta <1, T low, rotation of field)

Interaction region (IR):
Nov 14 02:25 UT – Nov 14 12:00 UT

CME2: Nov 14 12:00 UT – Nov 14 21:21 UT (no MC)

Two possible magnetic holes (MH)
during 08:05 UT– 10:15 UT and
02:25 UT- 03:45 UT on Nov 14 => signature of reconnection/heated plasma



Arrival Time of Tracked Features

Actual arrival time of CME1 LE = Nov 12 23:00 UT
Actual arrival time of CME1 TE = Nov 13 23:30 UT
Actual arrival time of CME2 LE = Nov 14 12:00 UT

Tracked Features	Kinematics as inputs in DBM [t_0, R_0 ($R_\odot$), v_0 (km s^{-1})]	Predicted arrival time (UT) using kinematics + DBM [γ = 0.2 - 2.0 (10^{-7} km^{-1})]	Predicted transit speed (km s^{-1}) at L1 [$\gamma = 0.2$ - 2.0 (10^{-7} km^{-1})]	Error in predicted arrival time (hr) [$\gamma = 0.2$ - 2.0 (10^{-7} km^{-1})]	Error in predicted speed (km s^{-1}) [γ = 0.2 - 2.0 (10^{-7} km^{-1})]
CME1 LE	Nov 11 13:42, 545, 137	Nov 12 18:10 - Nov 13 00:30	490 to 380	-5 - 1.5	115 - 5
CME1 TE	Nov 11 18:35, 120, 470	Nov 13 15:25	375	-8	-15
CME2 LE	Nov 12 00:30, 124, 455	Nov 13 19:40	375	-16	-35

Using 3D speed (derived in COR2 FOV) the predicted arrival time of CME1 and CME2 will be 10-16 hr and 44 hr earlier, respectively, than the predicted arrival times using post collision speeds (in HI) combined with DBM.

Geomagnetic Consequences of 2012 November 9-10 CMEs

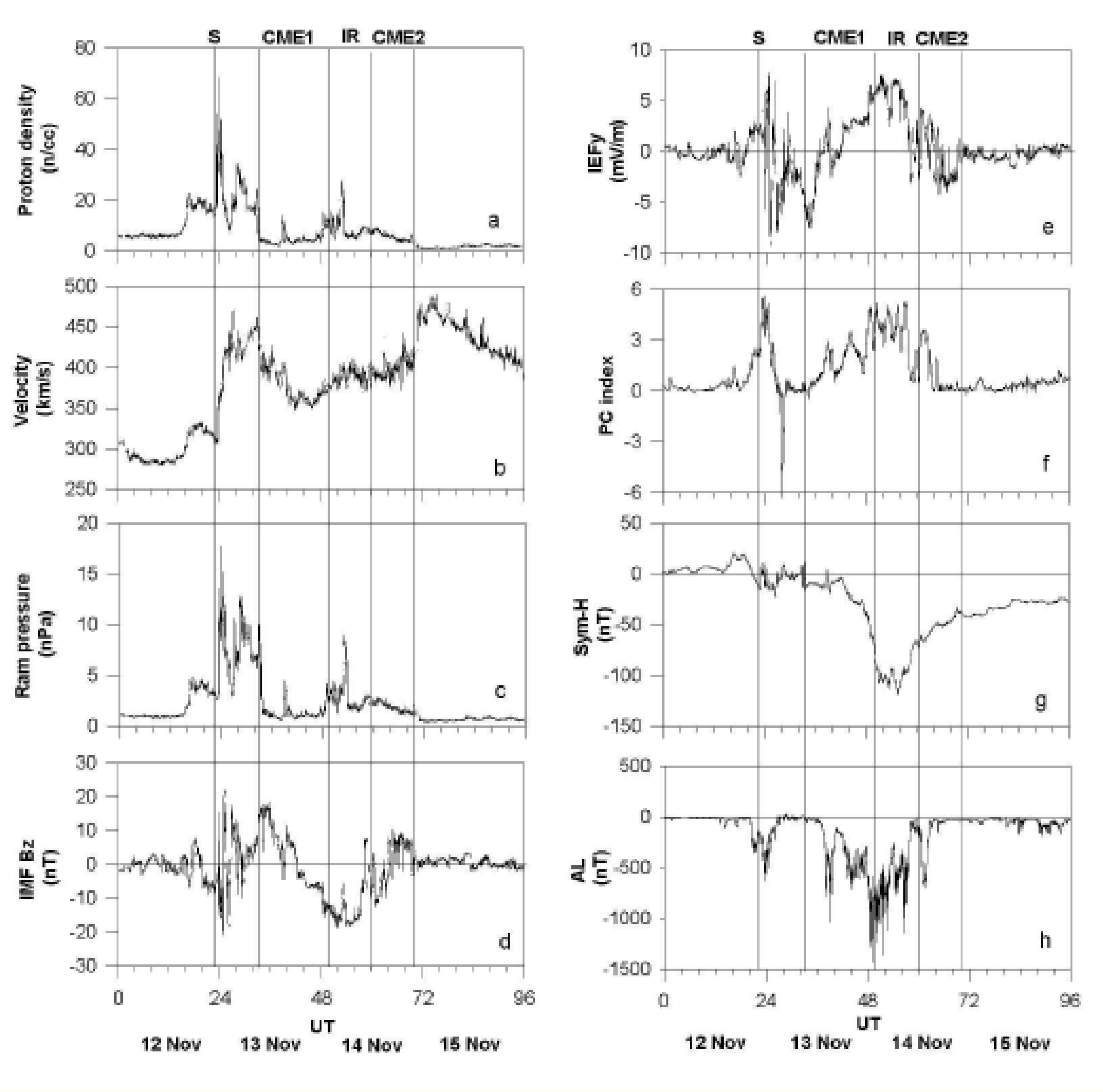
Strong geomagnetic storm Sym-H = -115 nT (Dst -108 nT on 14 Nov)

Two density enhancements: Shock-sheath region & IR.

AL intensification along with peak PC index values are closely correlated with IEF_y amplitudes in CME TE and IR region.

CME1 & (IR) produced storms & substorms CME2 did not directly trigger the substorms.

High dense plasma associated with CME1 TE & IR significantly contributed in the intensification of P_{dyn}, B_z, and IEF_y, imp for substorm activity.



IR is important for major geomagnetic disturbances.

Summary

- The analysis of propagation kinematics obtained from Jmaps provide evidence that the two CMEs collided at 35 Rs much earlier than expected (at 130 Rs) using kinematics obtained in COR2 FOV. This emphasizes the significance of heliospheric imaging particularly for interacting CMEs and ascertaining their impact and arrival at the earth.
- Speed and momentum of CMEs changed from 23% to 30% compared to their values before the collision. Our results highlight that kinematics after the collision are important to combine with DBM for improved arrival time prediction.
- The kinetic energy of the system decreased by 6.7% to its value before the collision. Nature of observed collision is found to be close to perfectly inelastic.
- Our study provides signatures of CME-CME collision i.e. in the formation of magnetic holes and heating.
- Tracking of different features of CME seems to be important. Interaction region of colliding CMEs is found to have intense long duration southward magnetic field responsible for major geomagnetic storm.
- We found that persistence of southward magnetic field is more important in driving the substorm (AL index) activity.

Thank you