Understanding the Nature of Collision of CMEs in the Heliosphere

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Outline

- Introduction (SOHO and STEREO era)
- Interaction of CMEs
- Two Case Studies

(1) Interacting CMEs of 2011 February 13-15

(2) Interacting CMEs of 2012 November 9-10

- Results & Conclusion

Introduction

- Coronal Mass Ejections (CMEs) are drivers of many space weather events.
- Since the discovery of CME, several attempts have been made to estimate CME arrival time.

- In SOHO era, for our unsuccessful attempts, blame was on "single viewpoint" CME observations and "lack of the observations" continuously between Sun and Earth. (Lindsay et al. 1999, Vrsnak and Gopalswamy 2002, Yashiro et al. 2004, Gopalswamy et al. 2001, 2005, Schwenn et al. 2005).
- These approaches give an average error of ± 15 hr and sometimes can be larger than 35 hr.

- In STEREO era, the crucial and large observational "gap" could be filled in addition to "multiple" viewpoints on the Sun.
- Using STEREO observations, few tens of publication focused on tracking of CMEs, estimating their kinematics and arrival time at Earth have been made (Kahler and Webb, 2007, Harrison et al. 2009, Davies et al. 2009, Lugaz et al. 2010, Liu et al. 2010, Möstl et al. 2011, Davies et al. 2013, Mishra et al. 2013, 2014, Liu et al. 2013, 2014, Hess and Zhang 2014, Harrison and Davies 2014, Möstl et al. 2014, Davis et al. 2015, Shi et al. 2015).
- These approaches resulted in a half-day improvement in predicted CME arrival time, however revealed that estimating an accurate arrival time is challenging.
- This is because of (a) physics of CME appearance (measurement of optically thin medium along the LOS) (b) geometry and physics of CME evolution is not well understood.

- However, the continuous tracking of CMEs from Sun to Earth and even beyond, could provide chance to witness the interaction of CME with small/large scale solar wind structures or solar wind.
- It has been established that CME speed near the Sun cannot be sufficient for its accurate arrival time prediction at 1 AU.
- The use of suitable 3D reconstruction techniques combined with models (drag-based or MHD), can be the best approach for predicting the CME arrival time.

CME-CME Interaction

Travel time of CMEs: 1 to 4 days, Launch rate: ~ 4 around solar maximum

- Therefore, the collision or merging of CMEs is possible (depends on kinematics), especially around the solar maximum.
- However, the polar coronal holes around solar minimum can also push the CMEs around the ecliptic plane. Therefore, even during solar minimum CME-CME interaction is possible.
- CME-CME interaction seems to be a common phenomenon in the heliosphere.

- Even before STEREO era, CME-CME interaction was inferred analysing in situ observations.
  Intriligator (1976) [Pioneer 9] & Burlaga et al. (1987) [Twin Helios spacecraft]
  Complex ejecta at by Burlaga et al. (2001)

- Evidence for CME-CME interaction was given by Gopalswamy et al. (2001) using SOHO/LASCO and radio observations of a CME.

- It was also argued that interacted CMEs can lead to multiple magnetic clouds and major geomagnetic storms. (Wang et al. 2003, Farrugia & Berdichevsky 2004, Farrugia et al. 2006)
  Penetration of shock & its effect on CME parameters.

- Before wide angle imaging facility, a major tool to understand the CME-CME interaction was MHD simulation (Vandas et al. 1997, Odstrcil et al. 2003, Manchester and Gombosi 2005, Wang et al. 2005, Lugaz et al. 2005, Xiong et al. 2006).

Investigation in STEREO era

Events:

Interacting CME cases of 2008 November 2 (Shen et al. 2012), and 2010 May 23-24 (Lugaz et al. 2012), 2011 February 13-15 (Maricic et al. 2013, Temmer et al. 2012),

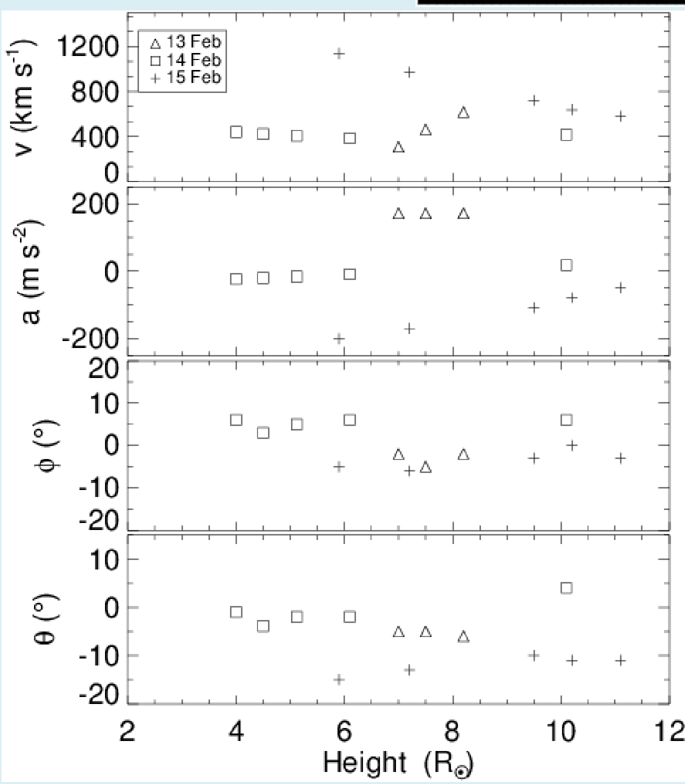
Extensively studied: : 2010 Aug 1
(Harrison et al. 2012, Liu et al. 2012, Mostl et al. 2012, Temmer et al. 2012)

Questions:

- Favourable conditions for CME-CME interaction/collision and CME merging ? Role of magnetic reconnection in the process?
- Regime of collision ? Physical process responsible for changing the dynamics of the CMEs?
- Consequences of overtaking shock on the plasma and magnetic properties of preceding CME?
- Different geomagnetic consequences from interacting structures than individual CMEs?
- Uncertainties in the approach undertaken for answering aforementioned questions?

Interacting CMEs of 2011 February 13-15 (3 CMEs)

3D reconstruction
in COR2 FOV:
GCS model
(Thernisien et al. 2009)



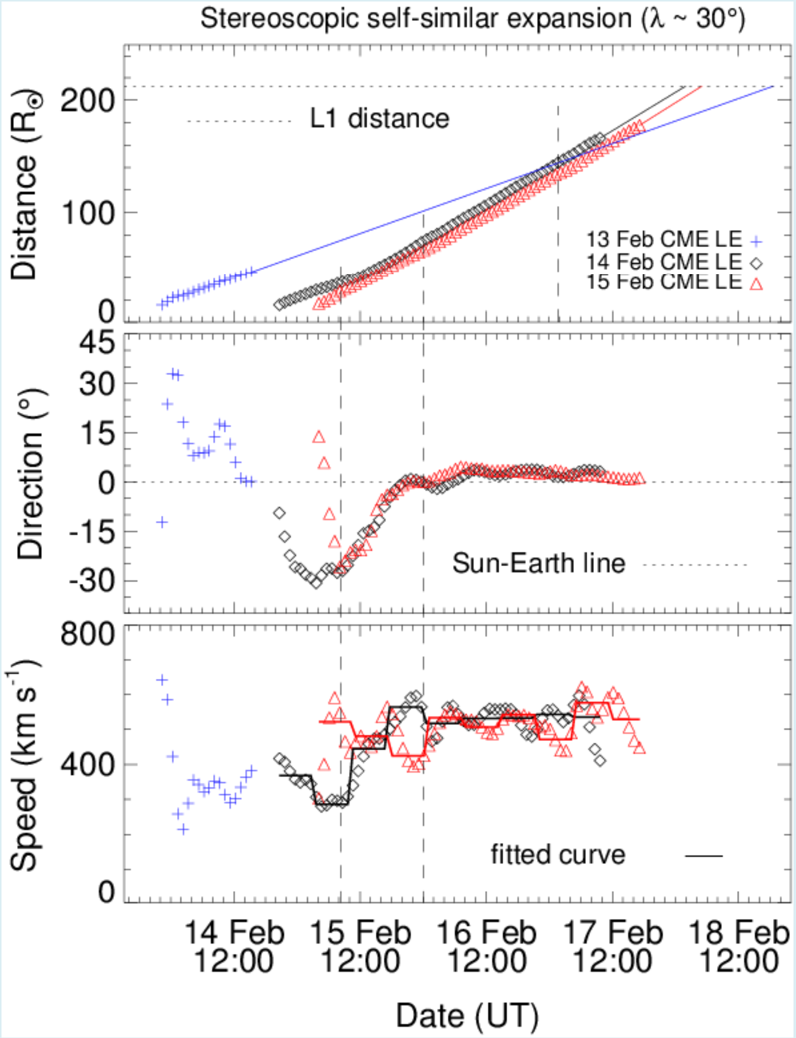
CME2 is launched 9 hr before CME3.
All are in same direction.

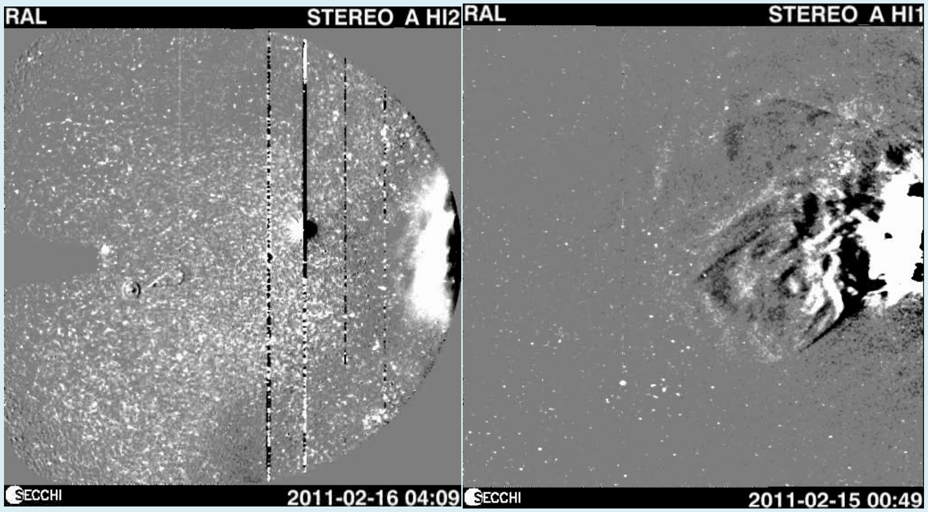
CME1 (Feb13): 618 km/s
CME2 (Feb14): 418 km/s
CME3 (Feb15): 580 km/s

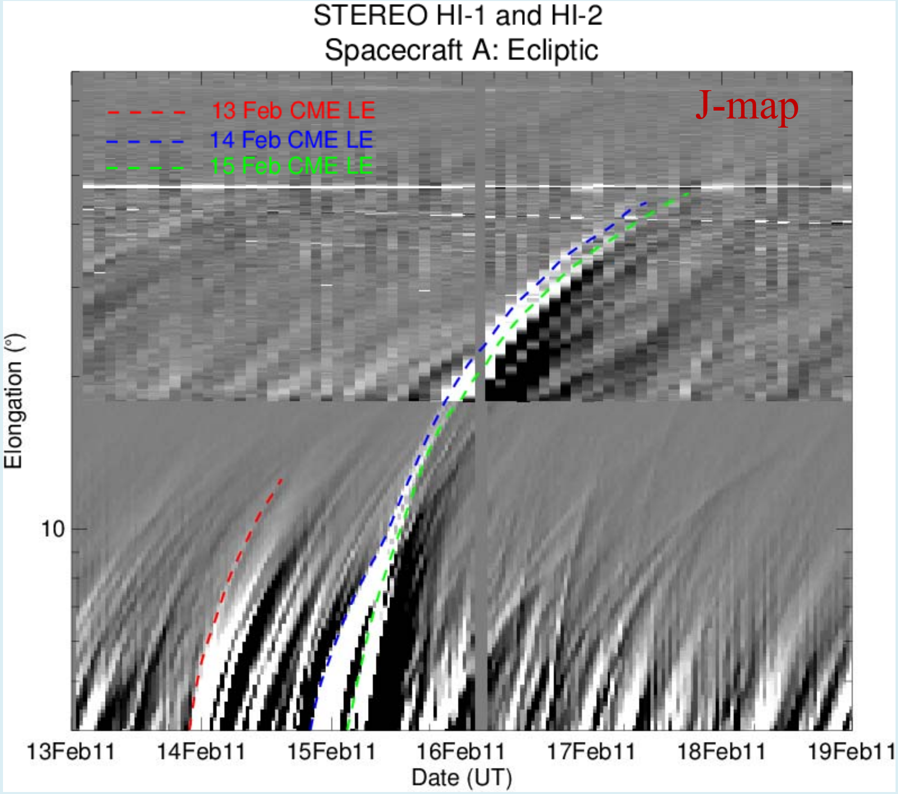
Deceleration of CME3 because of CME2 as a magnetic barrier, i.e. interaction before collision?
(Temmer et al. 2008, 2012)

Further tracking to locate the site of collision and quantify the momentum exchange.

Reconstruction in HI FOV:







Collision phase duration: 18 hr
CME2: 300 km/s to 600 km/s.
CME3: 525 km/s to 400 km/s.

Estimation of Coefficient of Restitution (e)

$$e = \frac{v_2 - v_1}{u_1 - u_2}$$

True mass: Colaninno & Vourlidas (2009)

$$M_A / M_B = B_e(\theta_A) / B_e(\theta_A + \Delta)$$

For CME2 at 10 Rs:
True mass M_1 = 5.40×10^{12} kg

For CME3 at 12 Rs:
True mass M_2 = 4.78×10^{12} kg

Mass of CME is assumed to be constant
Even in HI FOV.

For e = 0.85 and **σ** = 142 km/s
when (v_1, v_2) = (600,400) km/s
and (u_1, u_2) = (300,525) km/s

Total KE decreased by 2%

We admit the errors in the estimated speed and mass. Therefore, to constrain the conservation of momentum we follow a approach:

We define variance

$$\sigma = \sqrt{(v_{1th} - v_1)^2 + (v_{2th} - v_2)^2}$$

and solve the following equations for the suitable value of **e** corresponding to which **σ** is minimum.

$$v_{1th} = \frac{m_1 u_1 + m_2 u_2 + m_2 e(u_2 - u_1)}{(m_1 + m_2)}$$

$$v_{2th} = \frac{m_1 u_1 + m_2 u_2 + m_1 e(u_1 - u_2)}{(m_1 + m_2)}$$

Mishra, W., and Srivastava, N., ApJ, 2014, 794, 64

Uncertainties in the calculation

Uncertainties in speeds

Taking error of ±100 km/s in the observed final speed:

(v_1, v_2)=(700,500) then e = 0.80, σ = 288 km/s

(v_1, v_2) = (500,300) then e = 0.90, σ = 2 km/s [Most suitable]

Total kinetic energy decrease = 1.3%

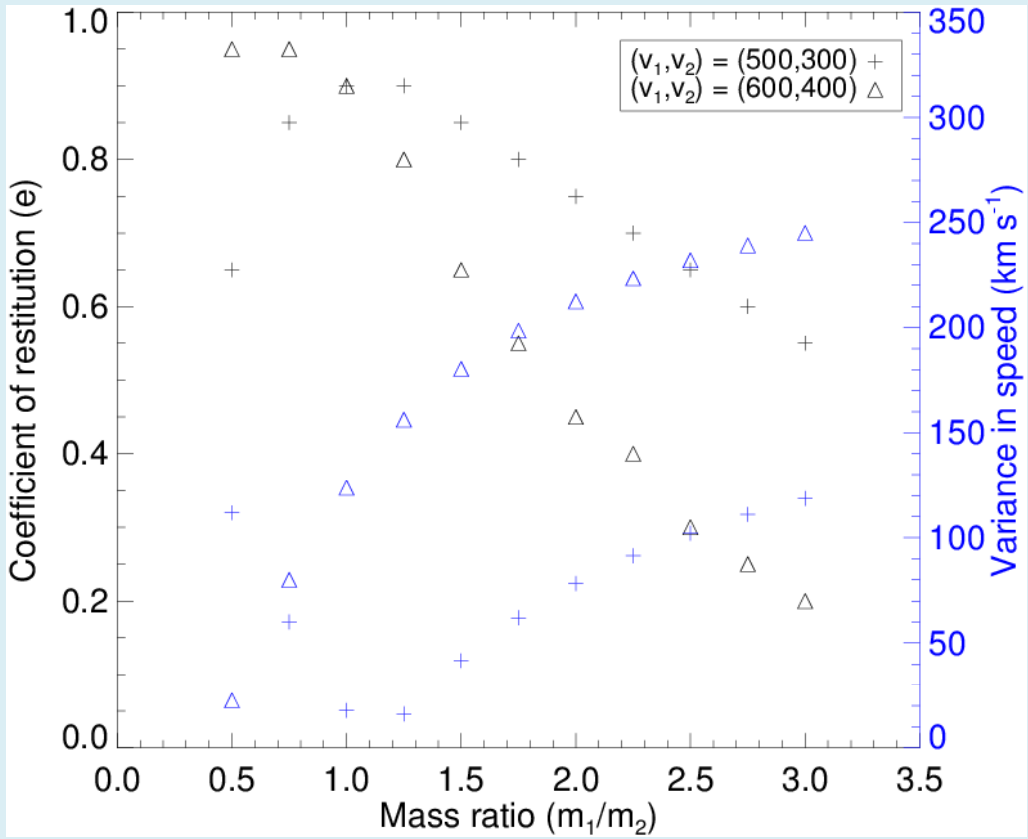
Kinetic energy of CME2 increased by 177% and decreased by 67% for CME3 of its value before the collision. This means collision nature is close to elastic.

For e=0.9, momentum of CME2 increased by 68% and decreased by 35% for CME3

Uncertainties in mass:

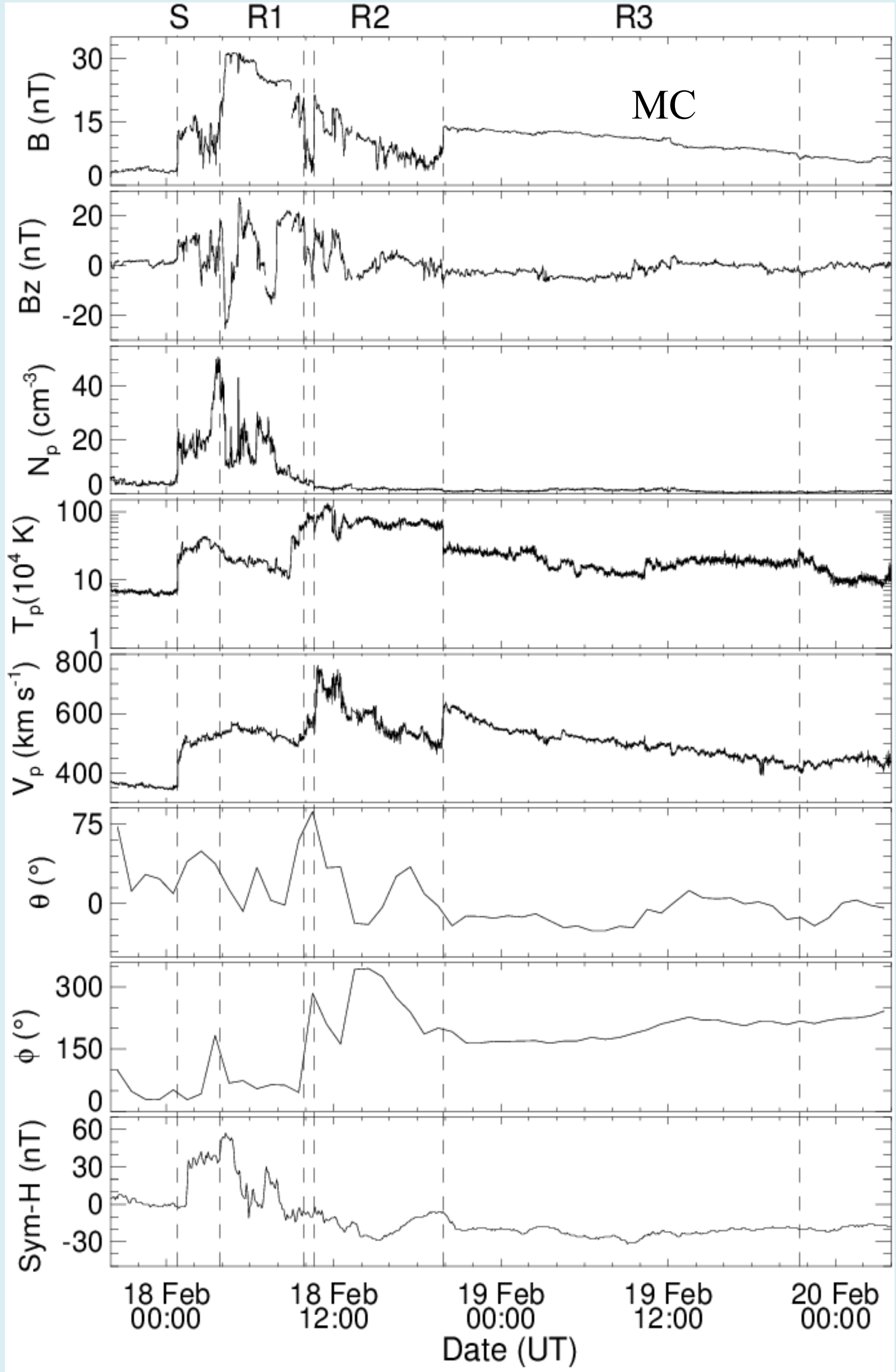
Error of 15% considered, then estimated mass ratio (m_1/m_2 = 1.12) can range between 0.97 to 1.28. However, we have varied the mass ratio for 0.5 to 3.0. (large values)

For smaller value of variance, collision remains close to elastic.



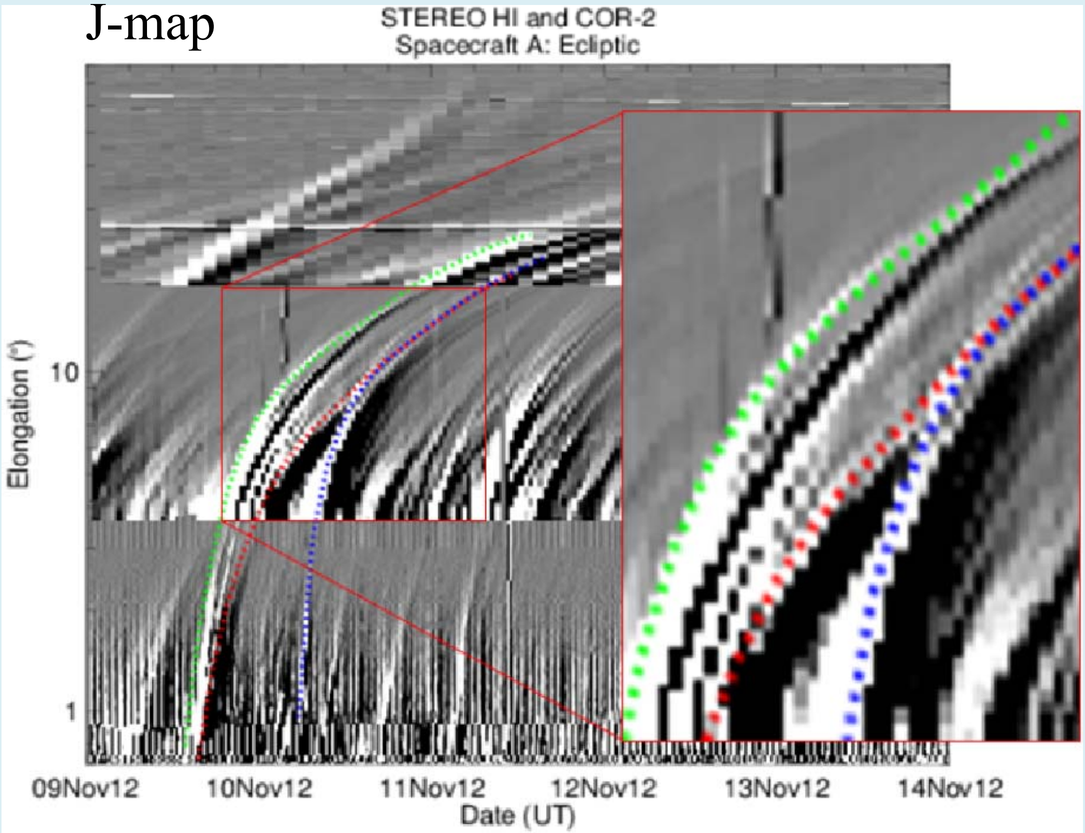
In situ observations and arrival time of interacting CMEs of February 13-15

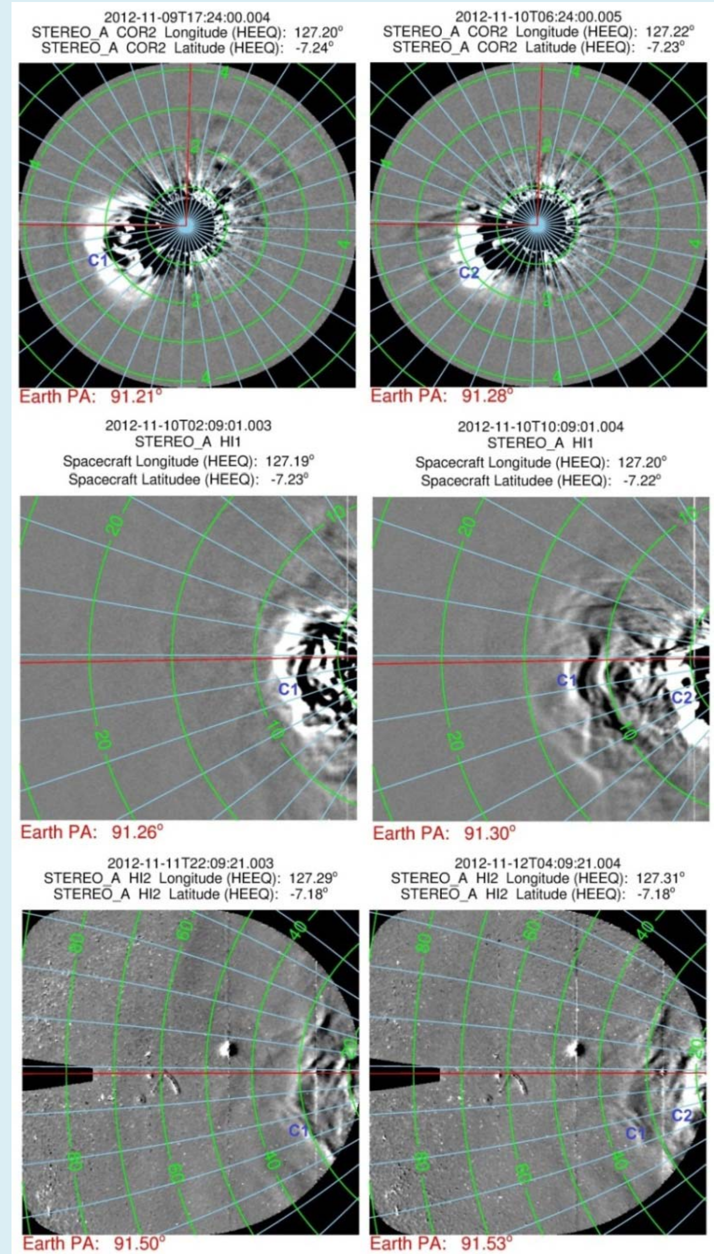
- Distinct structures R1, R2 and R3 correspond to CME1, CME2 and CME3.
- Predicted arrival times improved using speeds obtained in HI (especially, post-collision speed).
- Magnetic hole = 09:52 – 10:37 UT,
  R2 is overheated.
  Fast expansion of R2
  (reconnection at its front possibly).
- SSC =57 nT
  but minor geomagnetic storm (Dst~ -30 nT)
- Possibility of flank encounter or incorrect association cannot be ignored.



Interacting CMEs of 2012 November 9-10

3D speed: CME1 (Nov9): 620 km/s,
CME2 (Nov10): 910 km/s at approx. 15 Rs.
Both are Earth-directed.





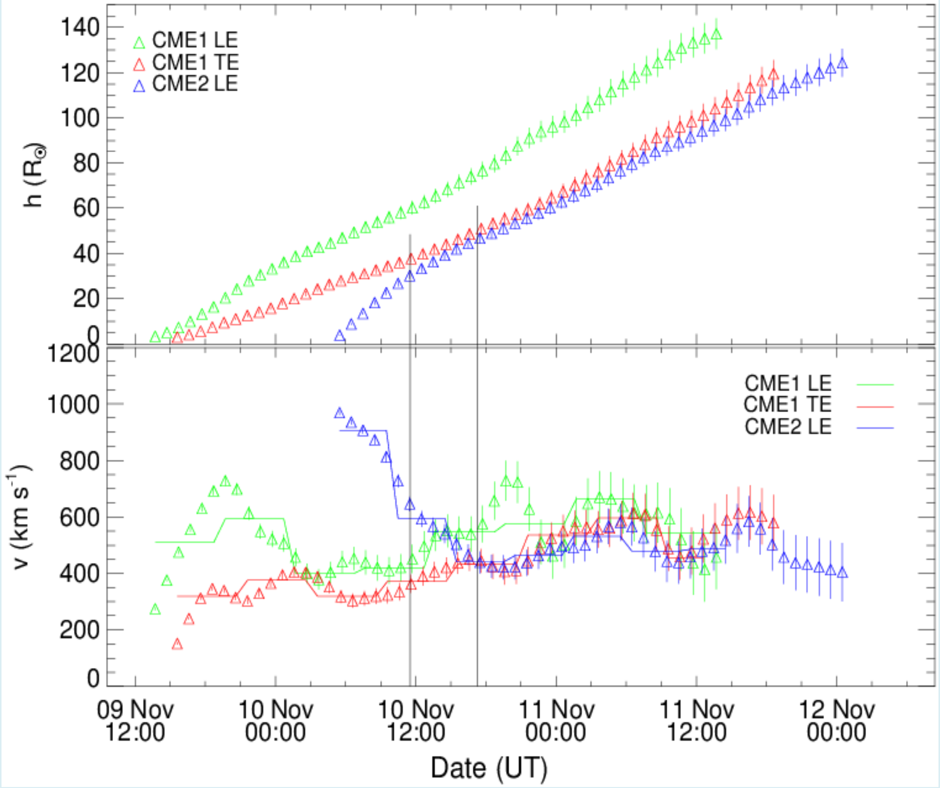
Green: CME1 Leading edge (LE),
Red: CME1 Trailing edge (TE), Blue: CME2 LE

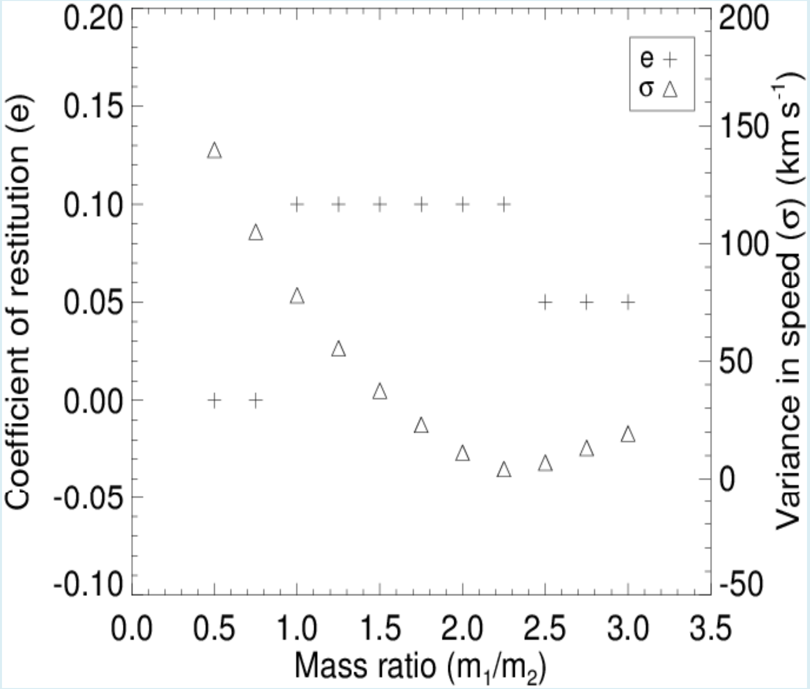
Kinematics and nature of Collision

Observed (u_1, u_2) = (365,625) km/s
& (v_1,v_2) = (450,430) km/s
True Mass Calculation:
$M_1 = 4.66 \times 10^{12}$ kg , $M_2 = 2.27 \times 10^{12}$ kg

Collision phase: ~ 6 hr
Nov 10 at 11:30 UT (37-30 Rs) –
Nov 10 at 17:15 UT (50-46 Rs)
We found e = 0.1 for σ = 9 km/s
Collision close to perfectly inelastic
Total kinetic energy of the system decreased by 6.7%

3D Reconstruction in HI FOV using
HM method (Lugaz et al. 2009)

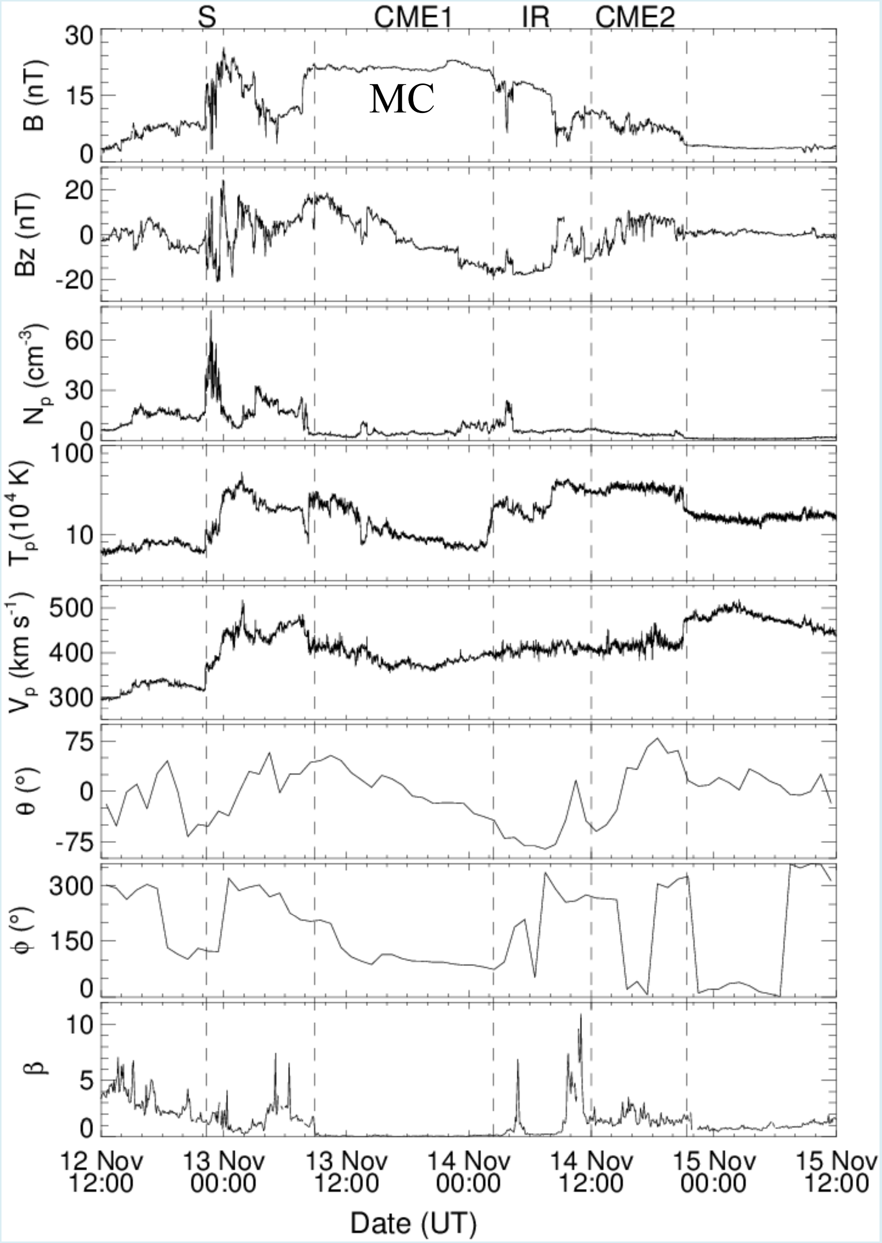




From observation M_1/M_2=2.05; however we have varied the ratio between 0.5 to 3.0, and examined the effect on our calculation. In each case collision remains perfectly inelastic.

In Situ Observations and Arrival Time

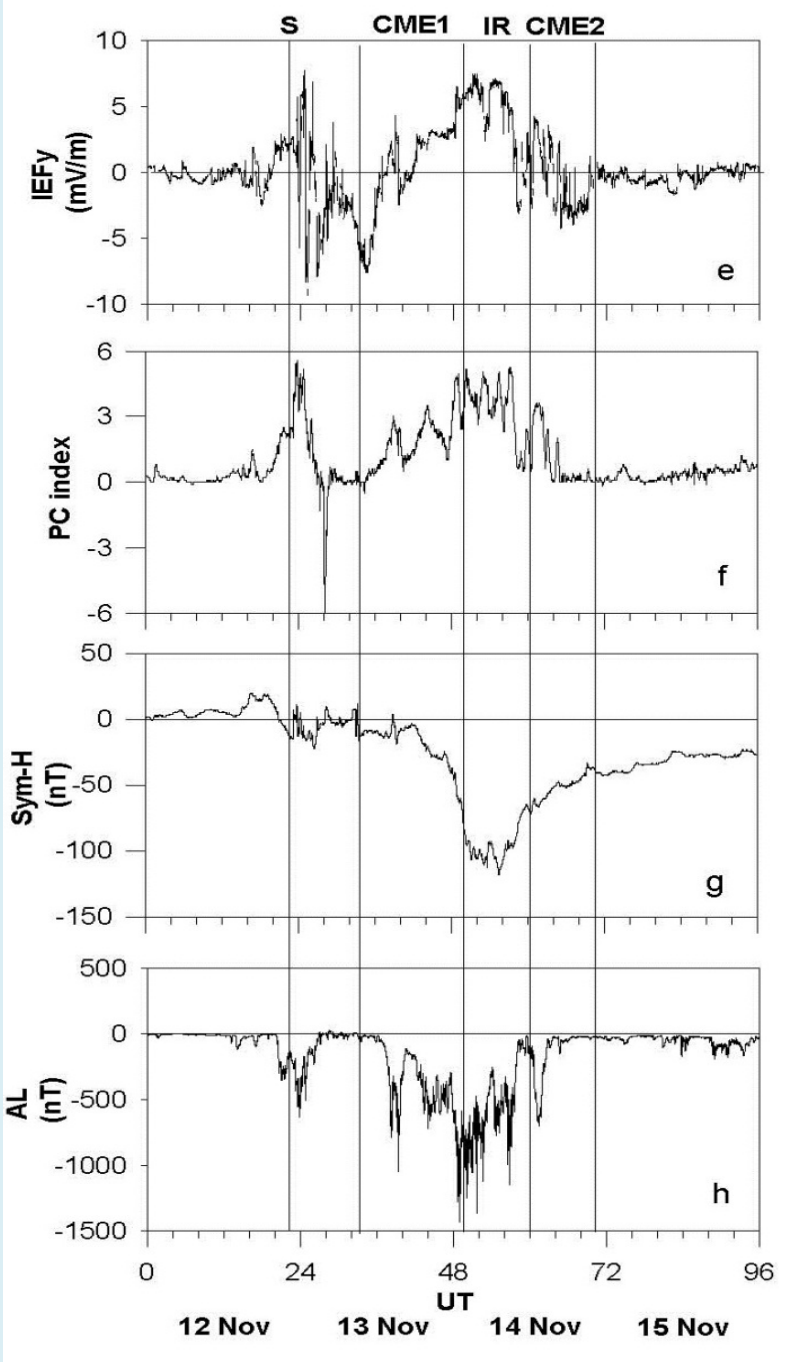
- Interaction region (IR) has elevated temperature, plasma beta, fast rotating B vectors and presence of magnetic hole (MH).
- Two MH in IR region are the signature of magnetic reconnection.
 (Burlaga and Lemaire, 1978)
- CME2 flank encounters the in situ spacecraft.
- Passage of shock through CME1 => Smooth B, heated and pile up density at its front.
- Intense heating of CME2 (rarely observed).
- Post-collision speeds of the CME1 and CME2 combined with Drag Based model (DBM), give at least half day and one day improvement, respectively over their arrival time using 3D speed in COR FOV or pre-collision speed.
- We considered higher value of drag parameter in DBM for CME1 TE and CME2 LE.



Mishra, Srivastava and Chakrabarty 2015, Solar Physics, 290, 527

PC index: Variation in ionospheric electric field over polar region. AL index: Westward (midnight sector) auroral electrojet

- Sym-H = -115 nT and AL=-1400 nT during the arrival of CME1 TE-IR .
- Fluctuation in IEF_y (in shock-sheath) had negligible impact on AL. Its duration is more important than the amplitude in driving the substorm activity.
- AL intensification along with peak PC index values are closely correlated with IEF_y amplitudes in CME TE-IR region.
- Peak amplitude of PC is same in CME1 LE and CME1 TE-IR region, but AL index is different in these regions.
- Storm-time AL intensification takes place when magnetosphere encounters the CME1 TE and IR.
- Flank of CME2 encounters the in situ spacecraft the and therefore it did not produce geomagnetic activity.



Results

Characteristics	2011 February 13-15 CMEs	2012 November 9-10 CMEs
Interaction distance	CME2-CME3 at 25 Rs (expected at 37 Rs from speeds in COR2).	CME1-CME2 at 35 Rs (expected at 130 Rs from speeds in COR2).
Momentum exchange	35% to 68%	23% to 30%
Total kinetic energy	Reduced by 1.3%	Reduced by 6.7%
Nature of collision	Close to elastic	Close to perfectly inelastic
Geomagnetic	Minor storm (Dst=-30nT), Strong SSC	Major Storm (Dst=-108nT)

Conclusions

- CMEs (launched in quick succession) cannot be treated as completely isolated magnetized plasma blobs. Pre-conditioning of the background wind (CME, CIRs) is important which influence the geometry and kinematics of the CMEs in the heliosphere.

- Evidence of CME-CME collision is revealed. Nature of CME interaction may be elastic/inelastic.

- Use of 3D speed in COR2 FOV is not sufficient for arrival time estimation, at least for fast and interacting CMEs. Improved prediction of arrival time of CMEs using their post-collision kinematics.

- Collision occurs much closer to the Sun than expected based on COR2 observations. Tracking of different features of CMEs in HI FOV (longer elongation) and their association with in situ observations is necessary for understanding their evolution in the heliosphere.

- Heliospheric and geomagnetic consequences of colliding/interacting CMEs are significant and depend on the interaction region (IR).

Discussion/Future work

- How much change do we expect on considering the 2D or 3D picture of collision instead of 1D, i.e. possible change in propagation direction of centroid of the interacting CMEs?
- How much change do we expect on including CME expansion speed in our calculation?
- Can we think other observational signatures (instead of kinematics) for precisely marking the start and end of the collision phase?
- How to decouple the effect of following CME and its shock on the acceleration of preceding CME?
- How much important is the role of orientation of CME flux ropes in deciding the nature of collision? What is the relative role of orientation of flux ropes, mass and speed of interacting CMEs in deciding their merging or preserving their distinctness.
- Does the participation of total mass of a CME in collision sounds well? Can we think transfer of mass between the colliding CMEs responsible for another source of uncertainties?
- We need to examine if the characteristic of CMEs, location and the duration of collision phase decide the nature of collision.

Thank you!