

Kinematics of two eruptive prominences observed by EUVI/STEREO

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OBJECTIVE

- **3 D reconstruction of two northern polar crown filaments**
- **Study of kinematics of eruptive phase**
- **3D study allows study of changes in latitude and longitude of reconstructed features**
- **Important to understand the forces acting upon erupting filaments**

Previous Work

Various forms of motion in Erupting filaments

Twist : Srivastava et al. 1991, 1999, Vrsnak et al. 1993

Srivastava and Ambastha (1998), Gilbert et al. 2007

Rotation: (Thompson 2010)

Kinematics: Two phases of eruption

Slow rise and fast-rise eruption (Tandberg-Hanssen et al. 1980; Sterling and Moore 2005, Sterling et al. 2007, Schrijver et al. 2008)

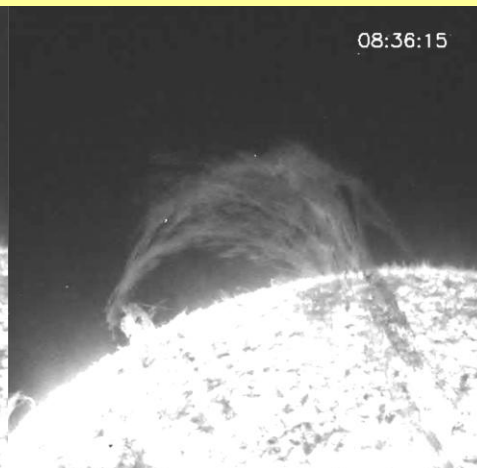
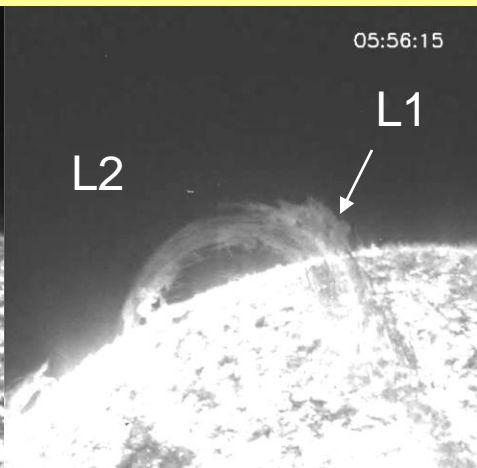
Constant Velocity: Sterling and Moore 2004 a & b

Constant Acceleration : Joshi and Srivastava (2007)

Two cases of eruptive filaments

- EUVI 304 A filaments observed on observed on April 13 and August 1, 2010,
- 3-D Reconstruction of several features in the prominence body at several instants
- Previous works on 3D reconstruction
Gissot et al. 2008, Liewer et al. 2009
Bemporad 2009 and Li et al. 2010

April 13, 2010



August 1, 2010

04:56:15



07:26:15



08:16:15



09:26:15



04:57:04



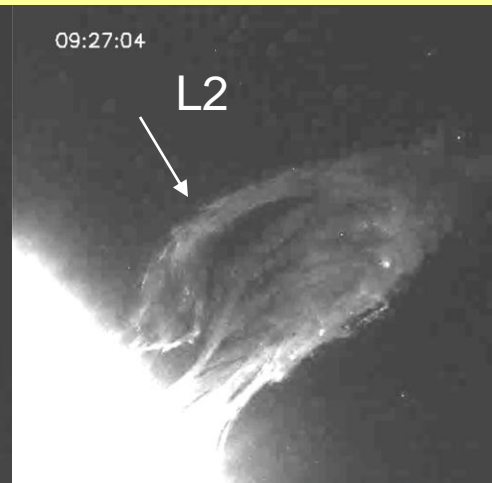
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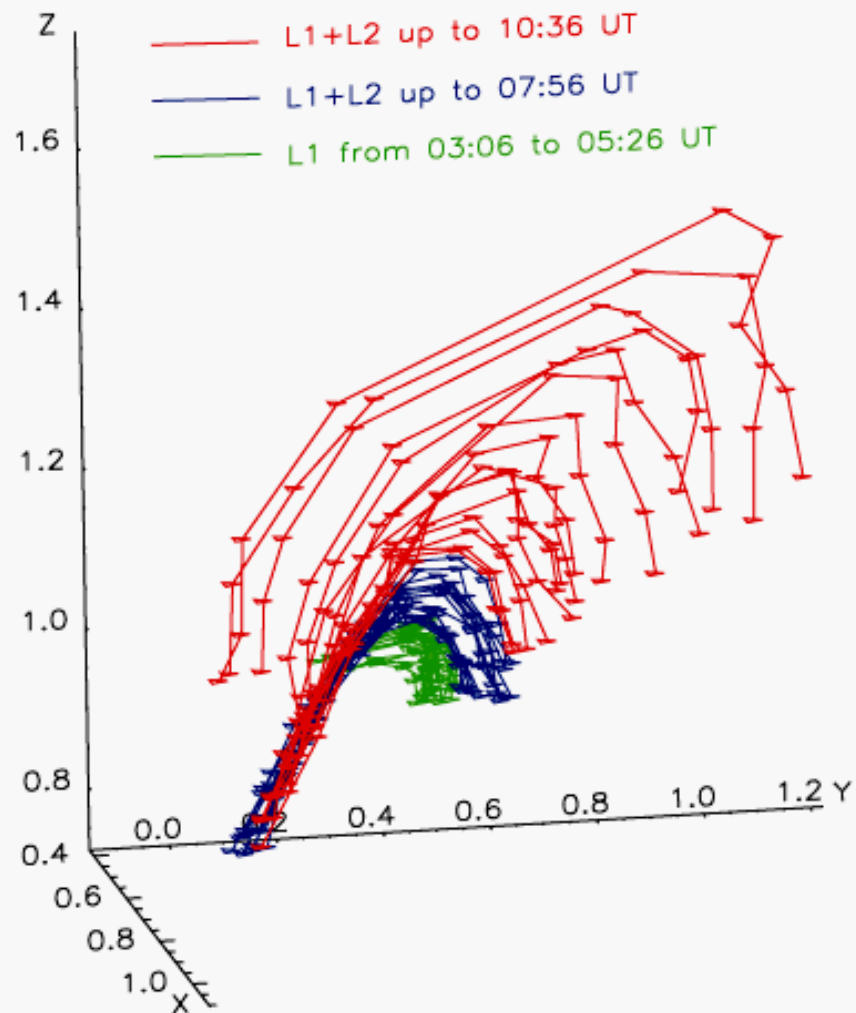
08:17:04



09:27:04



Evolution of the erupting prominence on 2010 April 13 as seen in three dimensions in heliographic coordinate system.



April 13, 2010

Slow rise phase:

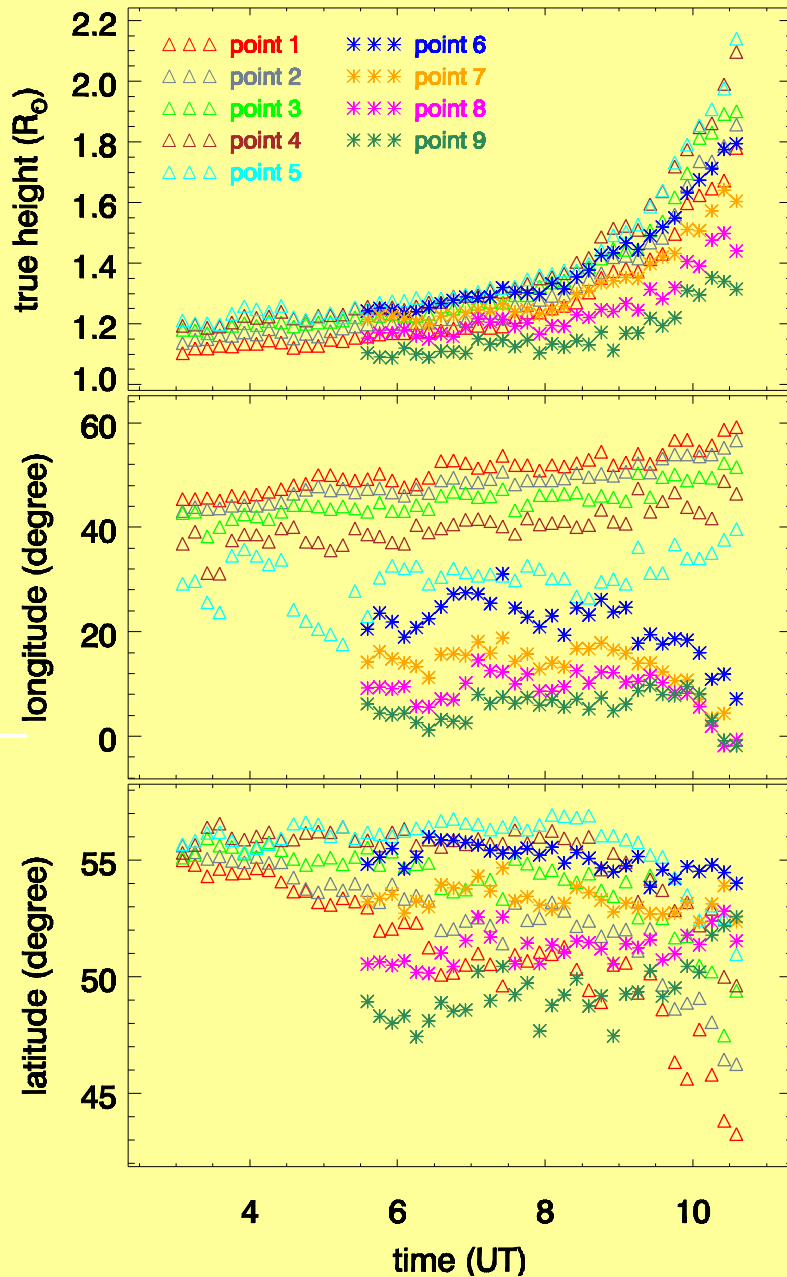
The features in leg L1 ~average acceleration of 67 cm s^{-2} .

Features in L2 showed acceleration upto to 120 cm s^{-2} .

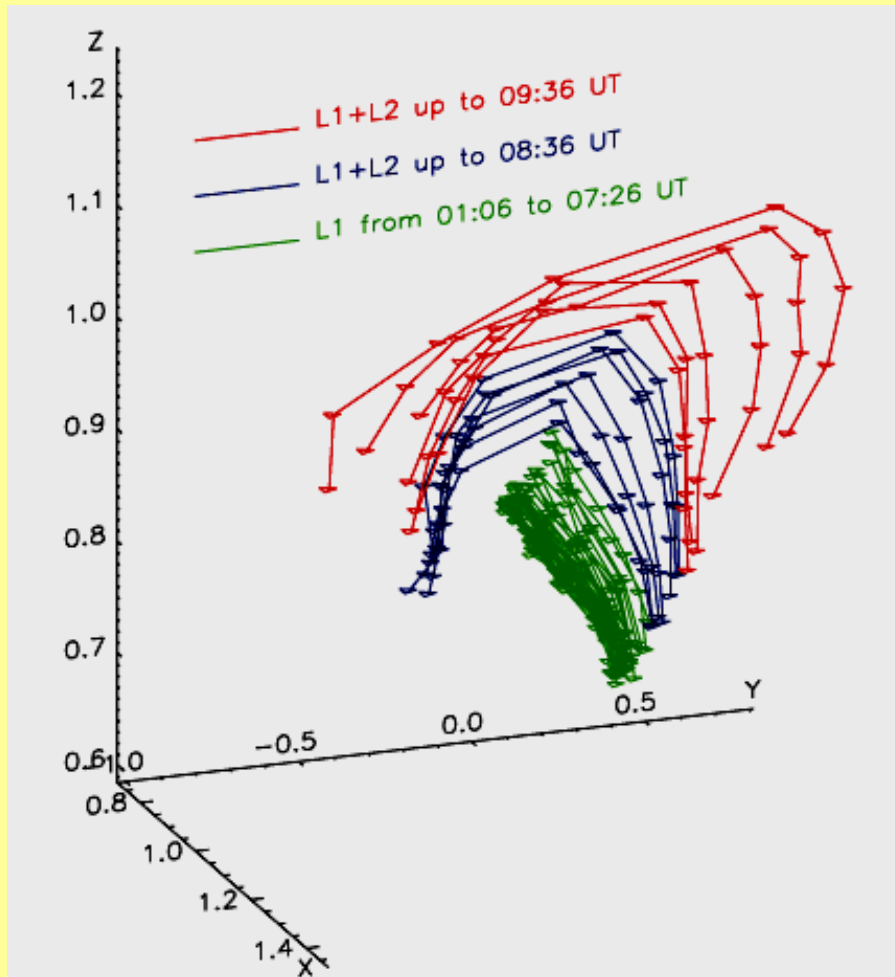
Eruptive phase:

A constant value of acceleration ranging from 9 m s^{-2} to 12.0 m s^{-2} .

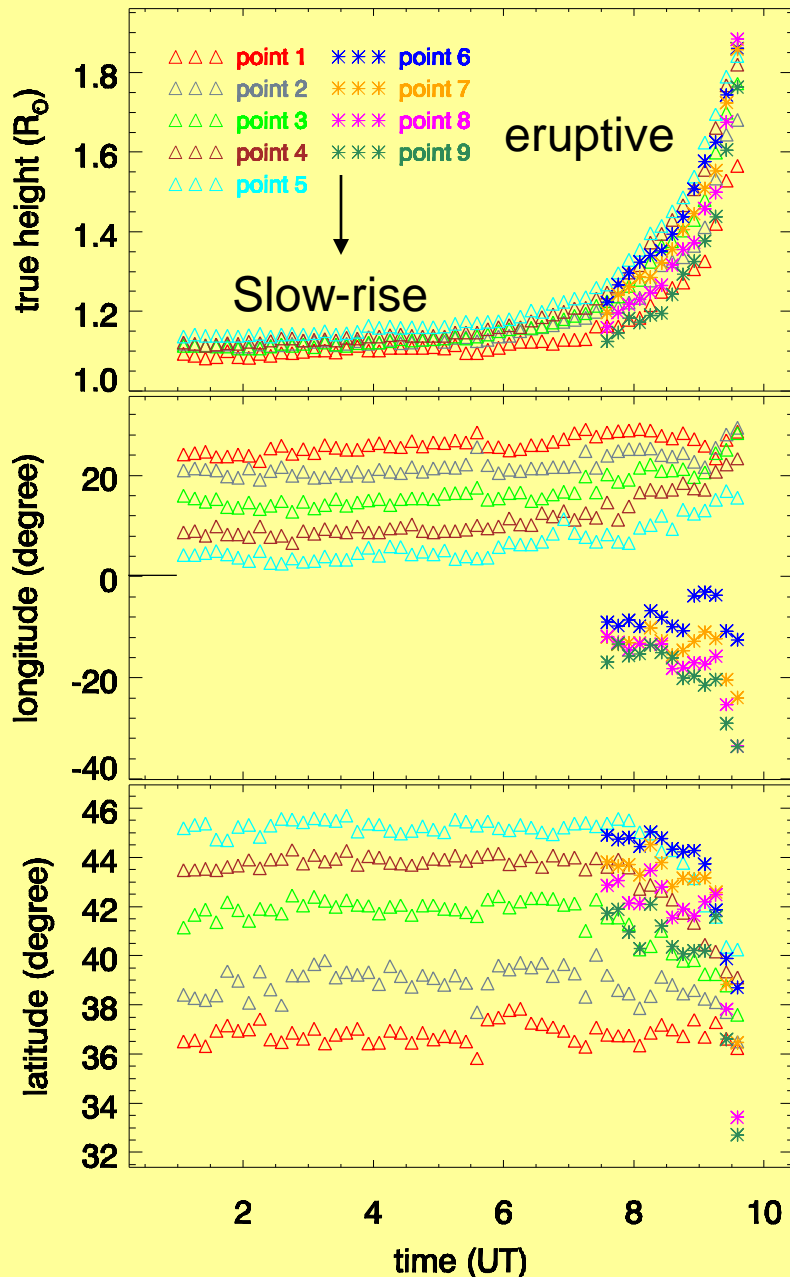
Whereas, the four features in leg L2 showed an average acceleration of 5 m s^{-2} .



Evolution of the erupting prominence on 2010 August 1 as seen in 3D in heliographic coordinate system.



AUGUST 1, 2010



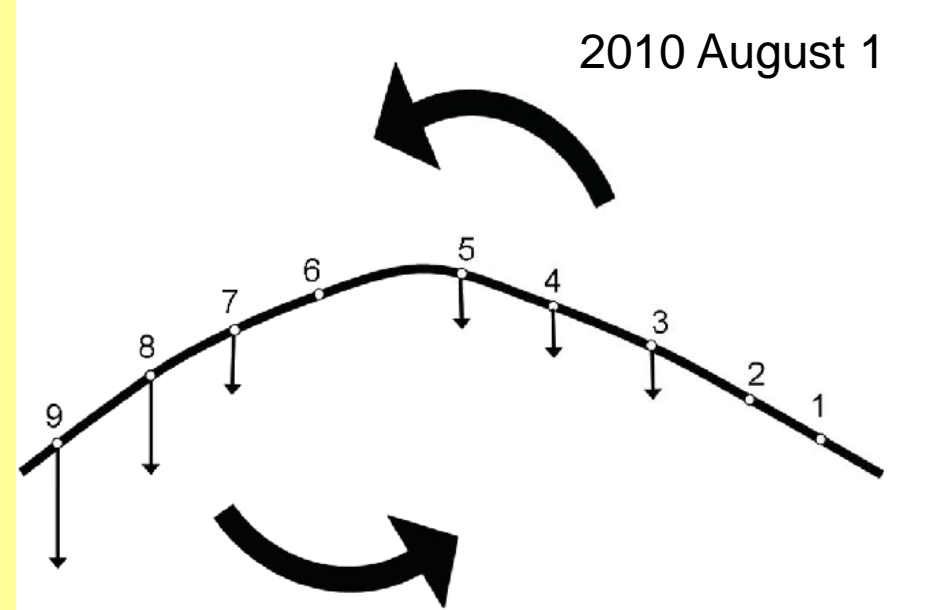
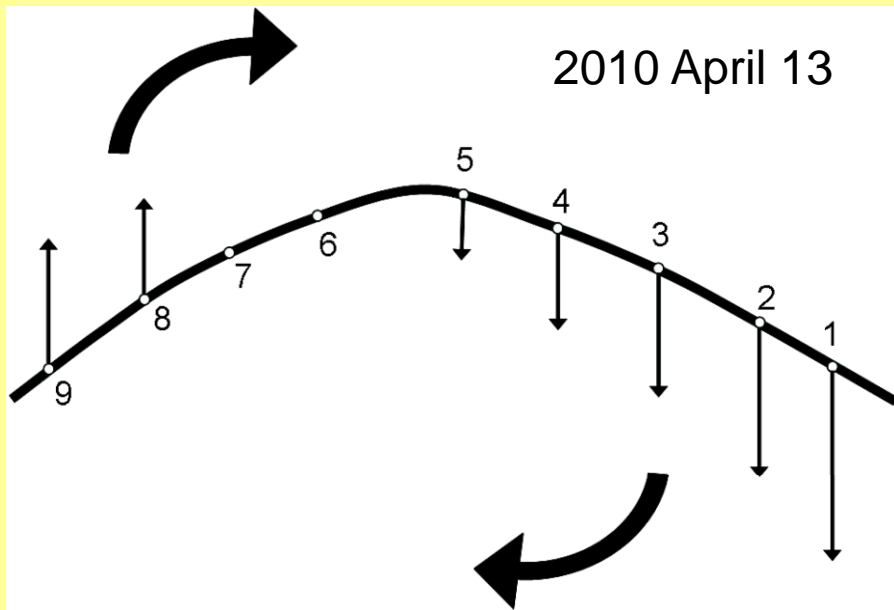
Slow rise phase:

Spread in heights is smaller

Slow rise phase : 30 cm s^{-2}

Fast rise phase: 20 m s^{-2}

The values for constant acceleration obtained are considerably higher than those obtained by Joshi & Srivastava (2007) which were in the range $4 - 12 \text{ cm s}^{-2}$.



The long dark line is the prominence, while features 1 to 9 are marked as circles.

The changes in latitude are shown as straight arrows, and the large curved arrows show the rotation direction of the prominence legs.

These variations in latitude and longitude of the reconstructed features suggest that the spine of the prominence on 2010 April 13 twisted in a clockwise direction & that of the prominence on 2010 August 1 twisted in an anticlockwise direction during eruption.

Results

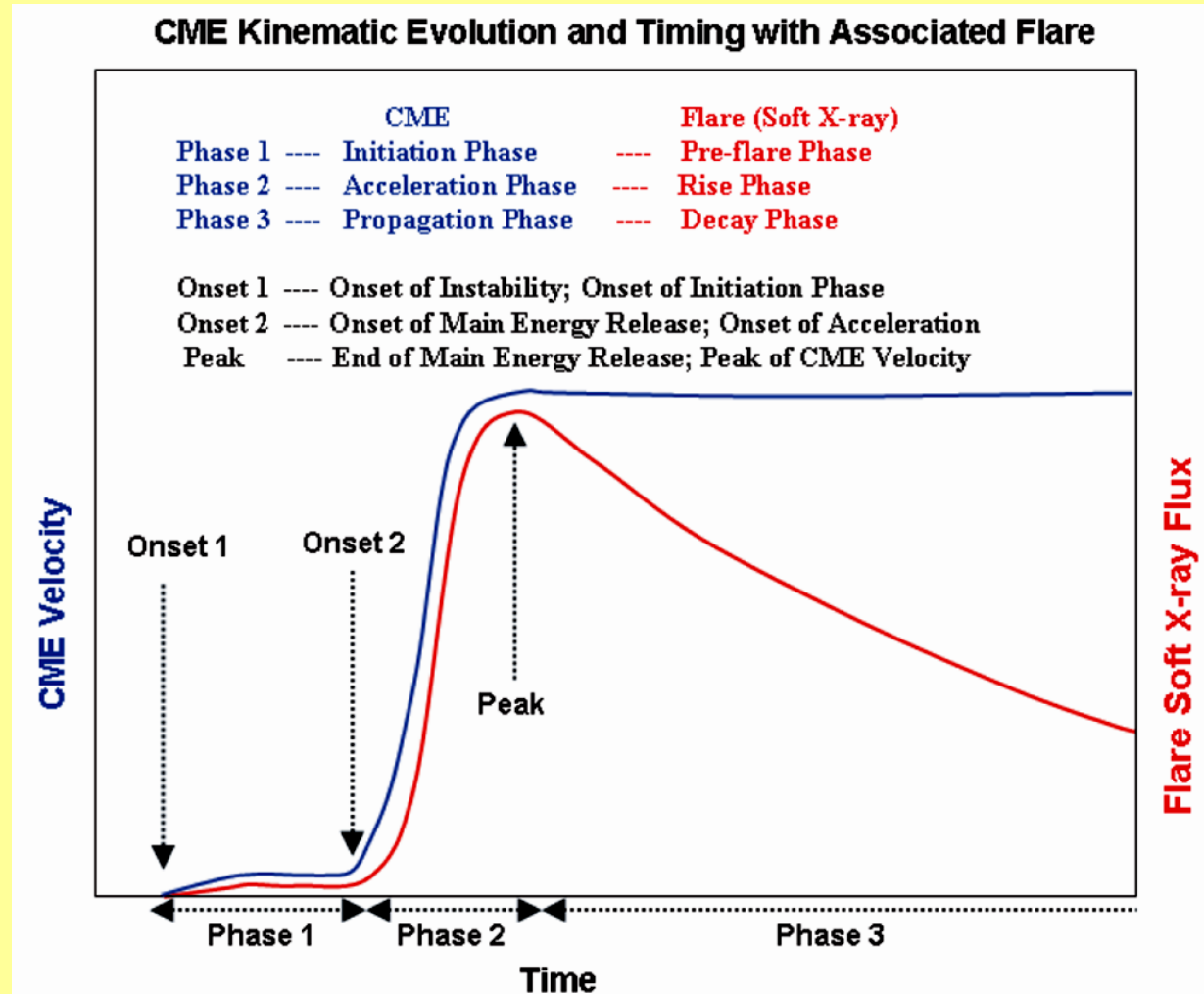
- 3D reconstruction led to estimation of true shape of the EPs
- Variations in longitude and latitude of the reconstructed features in both the legs of the prominences was observed as they erupted.

Variation due to interplay of 2 motions (a) Overall non-radial motion of the prominence towards the equator (b) the twist in the spine.
- Net effect of non-radial motion and twisting motion produced a higher acceleration 11 m s^{-2} (5) in W leg (April 13) while in case of Aug 1, produced a higher acceleration 20 m s^{-2} (10) in E leg.
- Two distinct phases of eruption (Sterling and Moore (2005) & Joshi and Srivastava (2007)).
- Slow rise phase in agreement with Joshi and Srivastava (2007) showing constant acceleration phase and not constant velocity (Sterling and Moore 2005)

Acceleration of CMEs and Prominences Observed from STEREO

Phases of CME Propagation

- **Statistical study of 50 CMEs** (Zhang et al, 2001; Zhang & Dere 2006)
- **3 phases:**
 - a) initiation
 - b) acceleration
 - c) propagation
- **Increase in velocity correlates with increase in GOES soft X-ray flux** (Maričić et al. 2007)

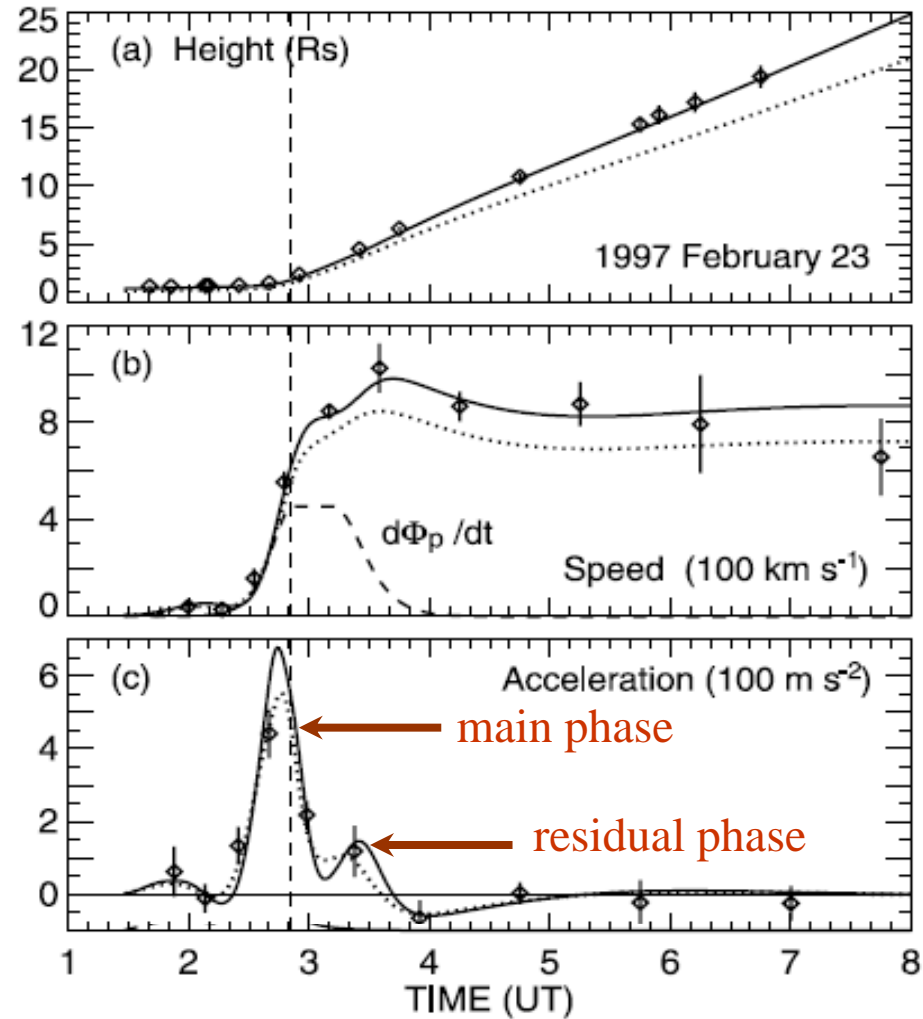


Classification based on CME acceleration

- **Flare-associated CMEs show high speed, little acceleration; Prominence-associated CMEs show large acceleration** (Gosling et al. 1976; MacQueen & Fisher 1983)
- **CMEs are classified into 2 types based on their speeds: fast and slow** (Sheeley et al. 1999; Moon et al. 2002; Low & Zhang 2002):
 - a) **Fast or Impulsive CMEs coming from compact ARs, associated with flares**
 - b) **Slow or Gradual CMEs associated with eruptive prominence (EPs)** (using LASCO-C1 data, Srivastava et al. 1999, 2000)

Main & Residual Acceleration Phases

- CME acceleration occurs in 2 phases, main phase and residual phase (Chen & Krall 2003)
- Main phase:
 - a) typically occurs below 2-3 R_{\odot}
 - b) Lorentz force is the strongest
- Residual phase:
 - a) typically occurs above 10 R_{\odot}
 - b) Lorentz force comparable with drag and gravity



Dynamics of CME on 1997 Feb 23 observed from SoHO/LASCO C1, C2 & C3. Solid curve is for LE, dashed for centroid of CME (Chen & Krall 2003)

Motivation

- All the earlier studies were done using observations from a single spacecraft
- 3D observations using STEREO images would reveal the true dynamics of CMEs

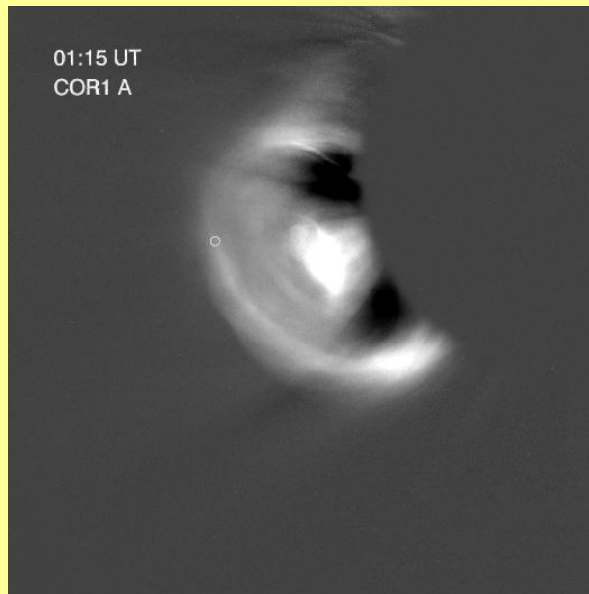
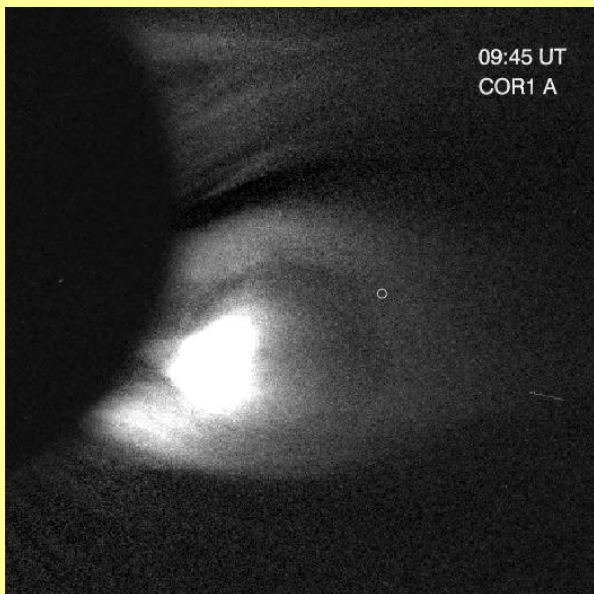
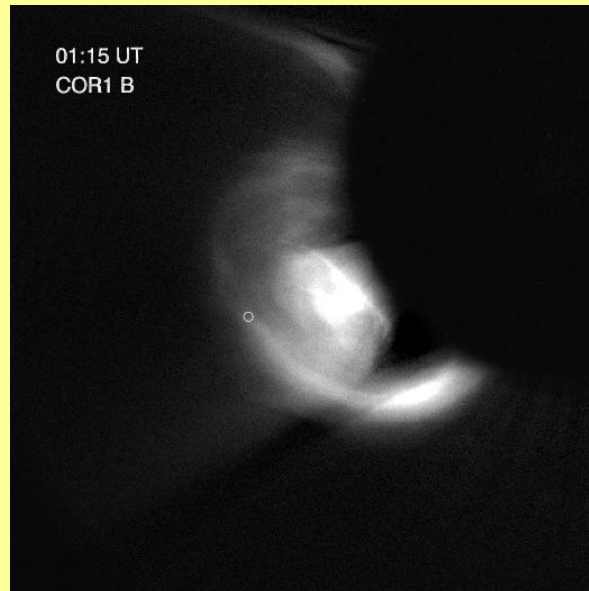
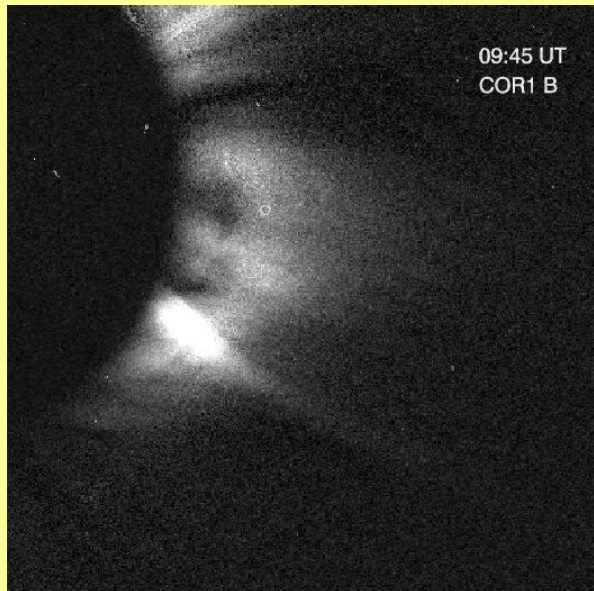
Objective

- To study acceleration profiles of flare-associated CMEs vis-à-vis EP-associated CMEs
- To examine whether acceleration profiles of CME (leading edge) and EP are similar
- To determine the true height of maximum acceleration of CMEs
- To examine if CMEs show bimodal acceleration profile

Observations & Analysis

- **6 CMEs are chosen, 3 of them associated with EPs**
 - flare-CMEs:** (i) 2007 Nov 16 (ii) 2007 Dec 31 (iii) 2009 Dec 16
 - EP-CMEs:** (i) 2008 Apr 09 (ii) 2010 Apr 13 (iii) 2010 Aug 01
- **CMEs analysed using images from coronagraphs COR1 and COR2. EPs analysed using EUVI 304 Å images**
- **Stereoscopic reconstruction of images was carried out to determine true height (Joshi & Srivastava, ApJ, 730, 2011a). Velocity and acceleration of CMEs was determined.**

FLARE-ASSOCIATED

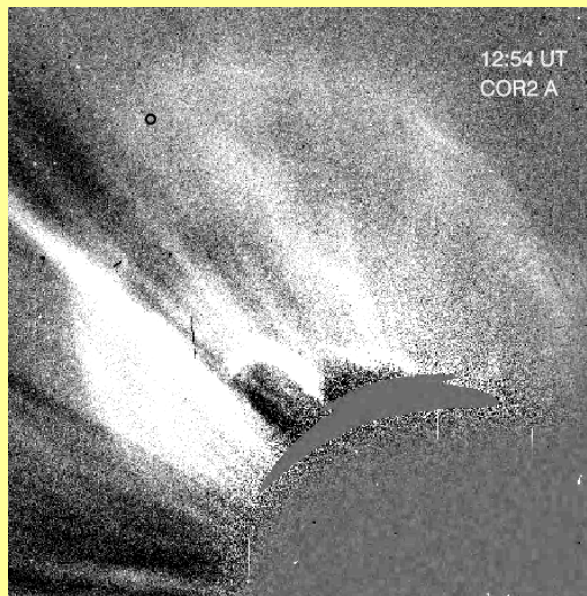
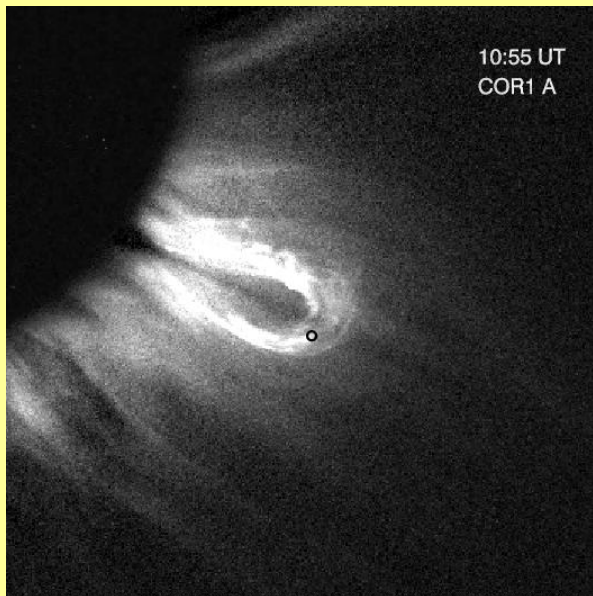
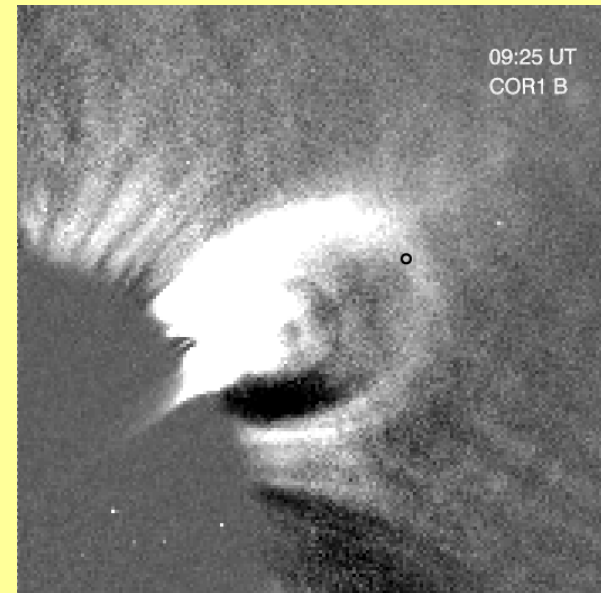
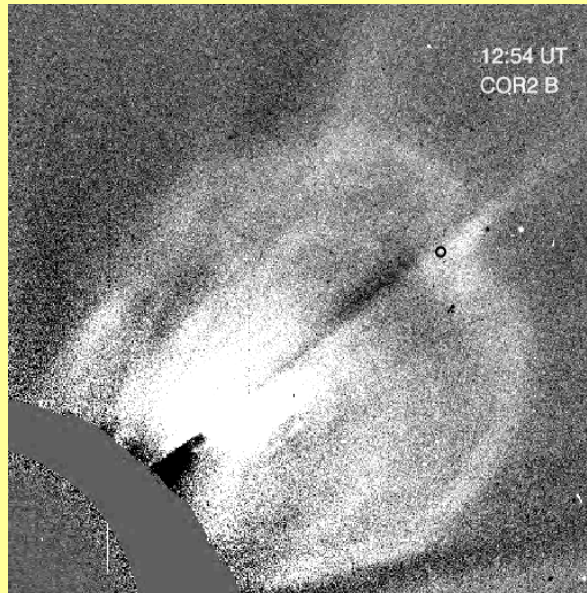
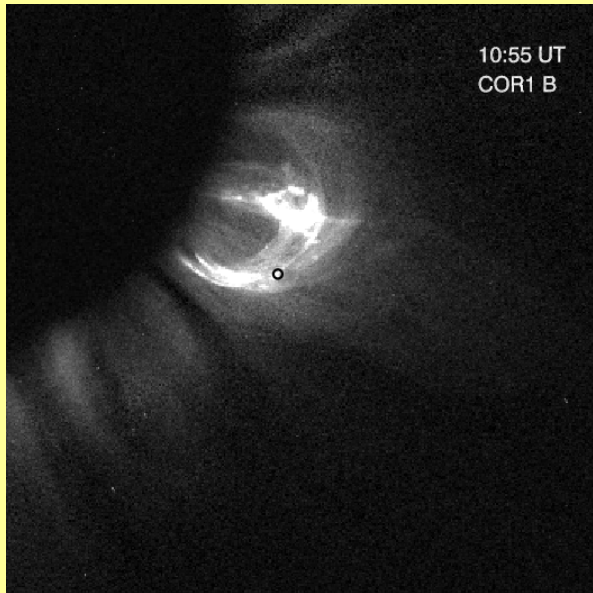


2007 Nov 16 COR1

2007 Dec 31 COR1

2009 Dec 16 COR1

EP-ASSOCIATED



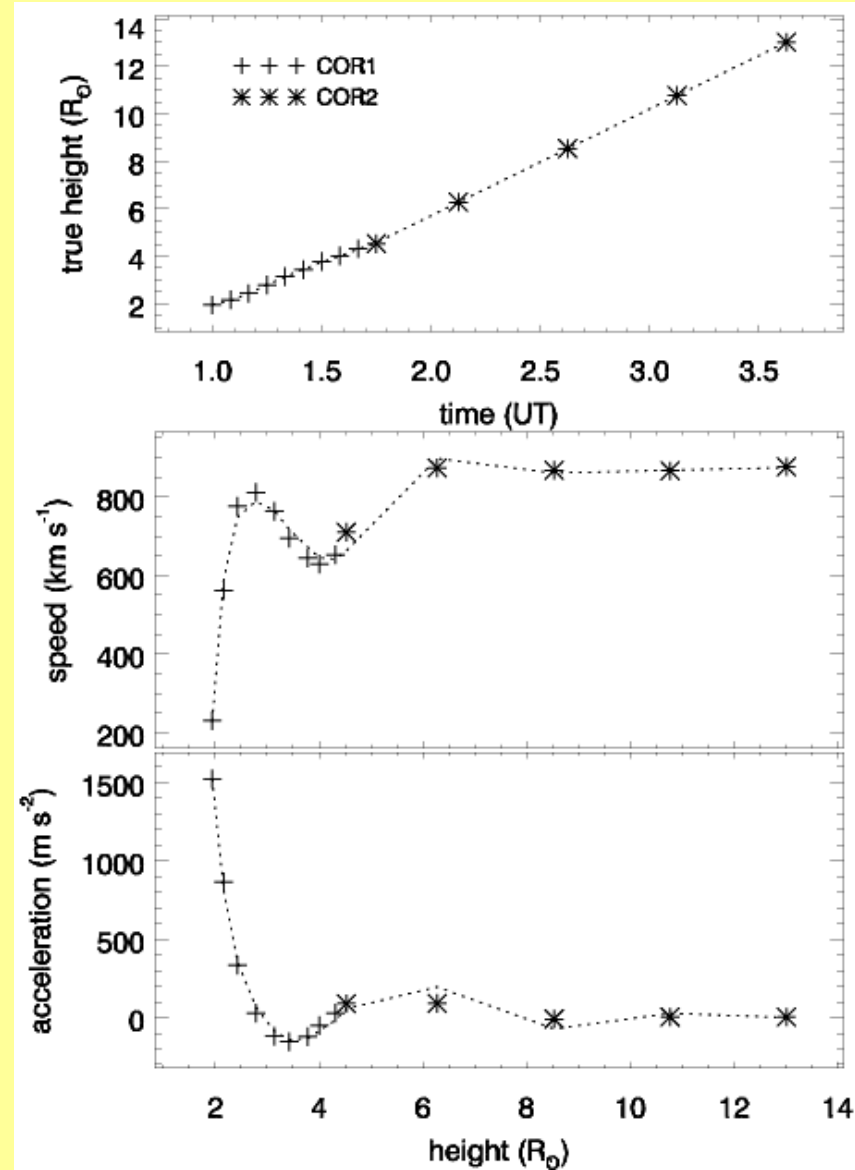
2008 Apr 09 COR1

2010 Apr 13 COR2

2010 Aug 01 COR1

Results

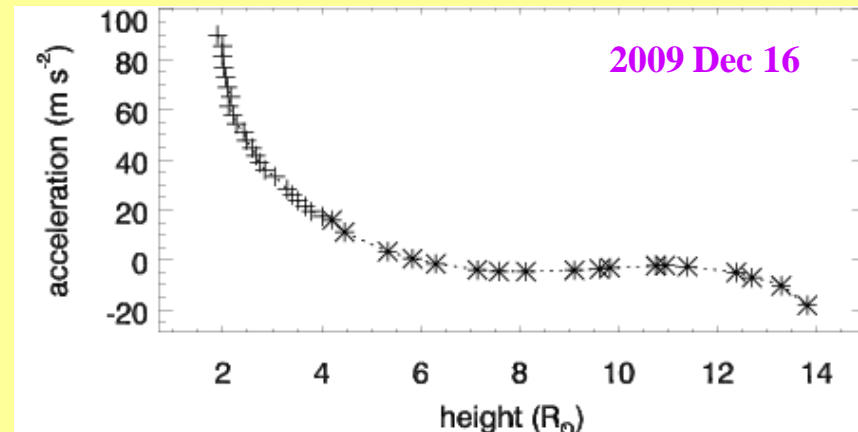
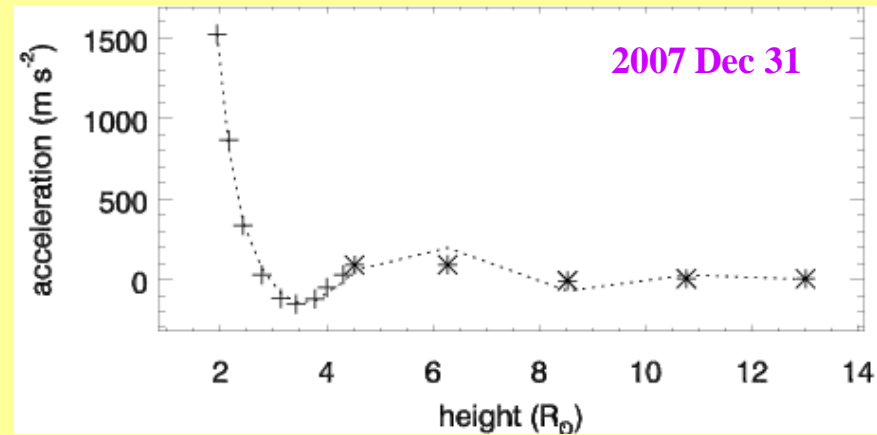
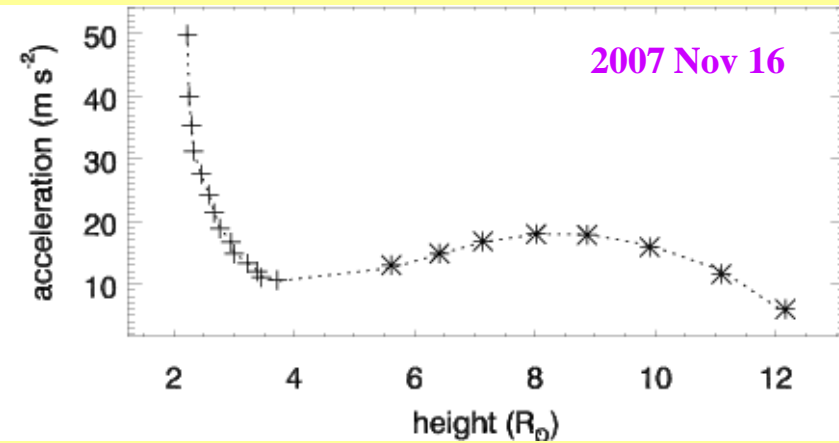
- **CME on 2007 Dec 31** associated with a flare having soft X-ray class C8, at SE limb of Sun in A & B.
- **Showed acceleration peak of 1524 m s^{-2} , highest for the events analysed**



Results

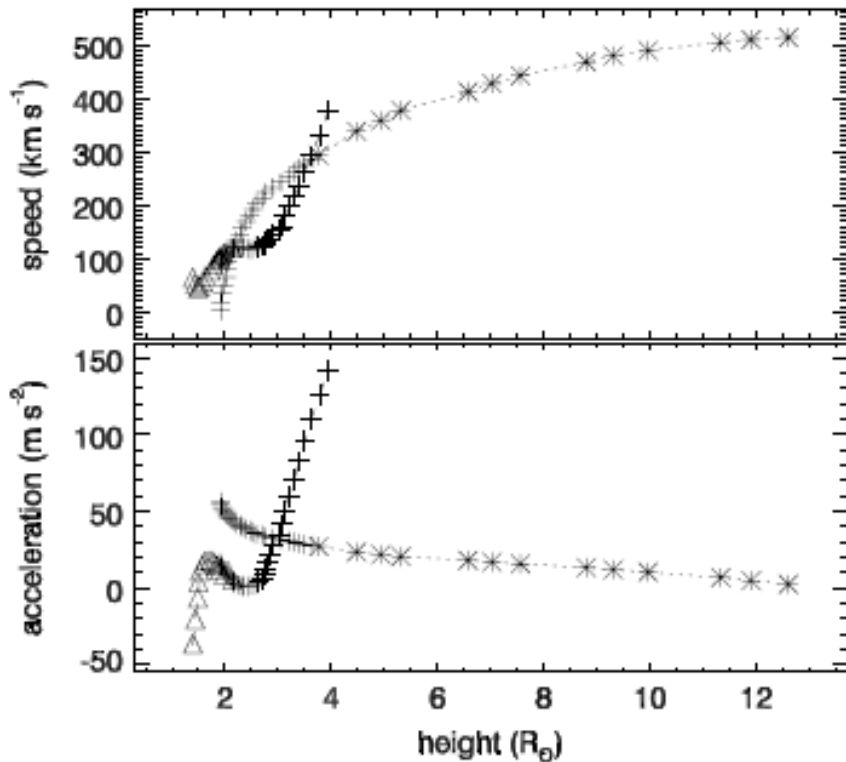
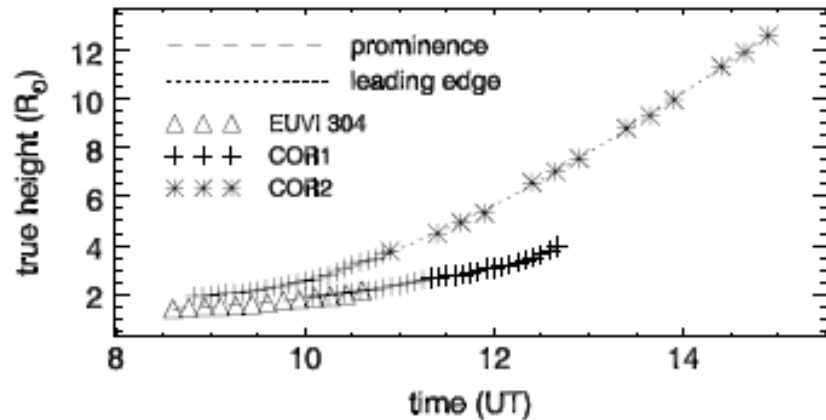
- All the 3 CMEs associated with flare showed that the initial acceleration (**main phase**) occurs below $2 R_{\odot}$
- showed a 2nd peak (**smaller**) in their acceleration, corresponding to the **residual acceleration phase**

	res. acc.	height
2007 Nov 16	18 m s ⁻²	8.5 R _⊙
2007 Dec 31	90 m s ⁻²	6.2 R _⊙
2009 Dec 16	-2 m s ⁻²	11 R _⊙

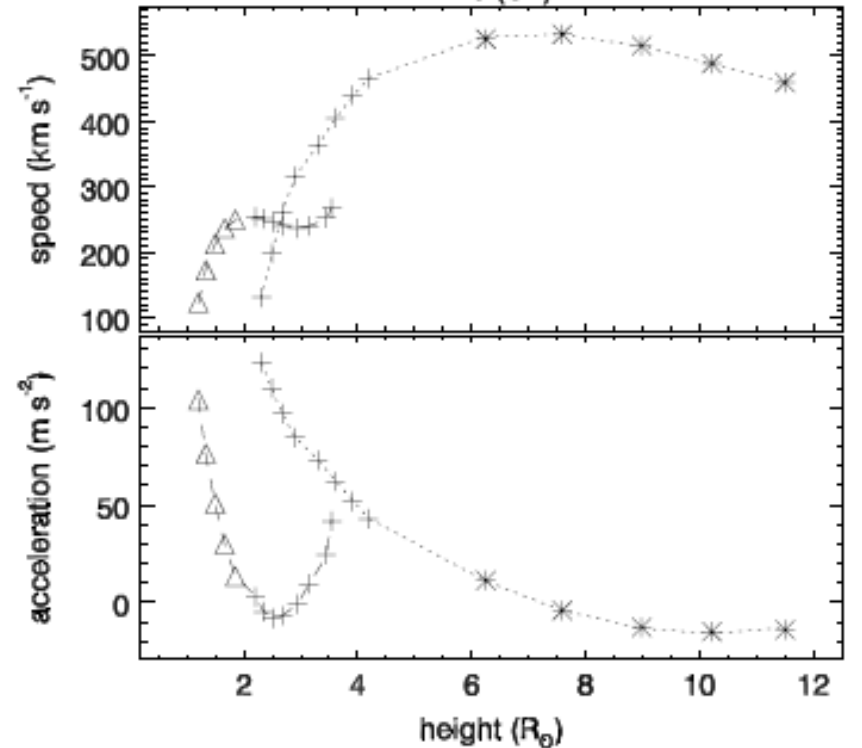
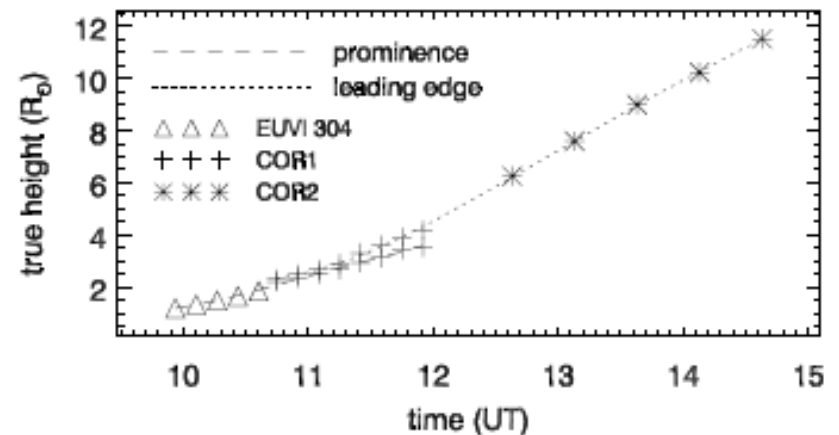


- EP-associated CMEs do not show the residual phase

13 April 2010



9 April 2008



• 2 out of 3 of the EPs (2009 April 8 & 2010 Apr 13) showed a positive and increasing acceleration even up to 4 R_{\odot} while acceleration of LE decreased.

Conclusions

- **First 3D study of acceleration of CMEs using stereoscopic reconstruction on STEREO images**
- **Height of maximum initial acceleration found to be $< 2 R_{\odot}$, while earlier studies found this height to be 2-4 R_{\odot} (Chen & Krall 2003; Vrsnak 2001)**
- **CME on 2007 Dec 31 showed high acceleration (1500 ms^{-2}) which is unusual for a CME associated with C8 flare**
- **CMEs associated with flares showed bimodal acceleration, EP-associated CMEs do not.**
- **EP associated CMEs show that forces acting on LE & EP may not be the same.**

3D Reconstruction of CMEs using Aditya

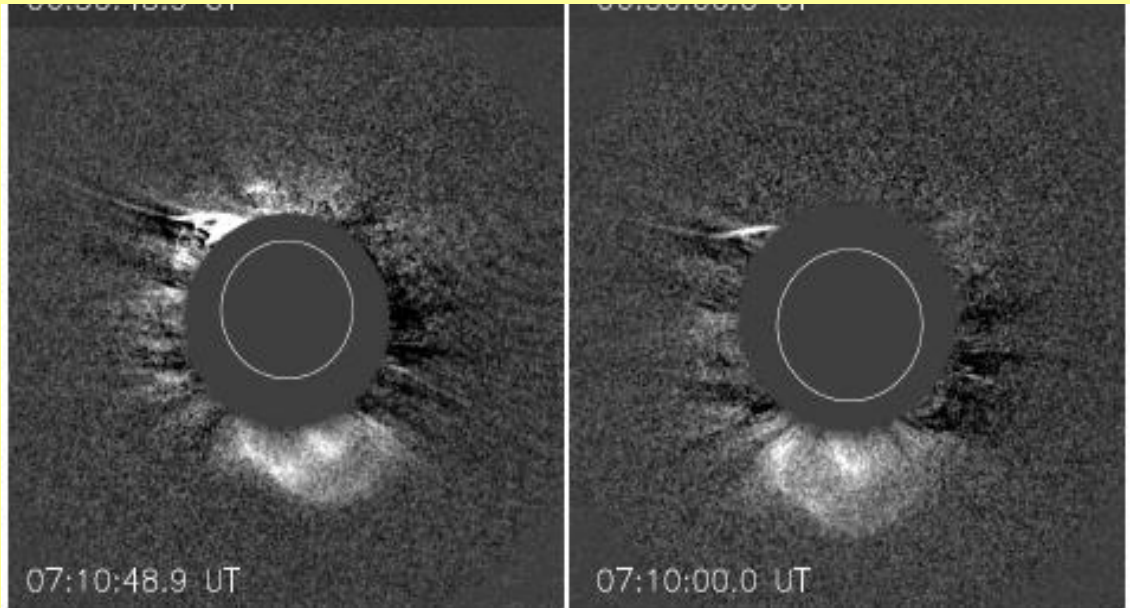
Importance of 3D study of a CME :

(1) to understand the initiation mechanism, initial dynamics

(2) Input for models

(3) Provide true speeds and direction as inputs for estimation of arrival time of CMEs directed towards the Earth.

20 May 2007 CME-COR1/SECCHI



Normal coronagraphic images provide plane-of-sky information of a CME.

Essential is to extract information on the CME structure out of the plane of the sky.

Based on the fact that the degree of polarization of Thomson-scattered light by coronal electrons is a function of the scattering angle between the direction of the incident light and the direction towards the observer. This effect allows estimation of an effective scattering angle from the ratio of polarized to unpolarized brightness.

How to achieve this?

- By recording coronal images through 3 or more polarizers with axes oriented at multiple angles at cadence as fast as possible (*for COR1, the 3 image pol. sequence is taken within 10s to minimize the changes due to evolution of corona*).
- Measurement of brightness ratio determines the line-of-sight average distance from the plane of sky. From these one can construct a view of the CME from above the ecliptic and a view from within the ecliptic perpendicular to the Earth-Sun line.

Past Attempts of 3 D study Using Polarization ratio technique:

Skylab Observations: Poland and Munro, 1976; Crifo et al.(1983)

LASCO/SOHO: Moran and Davila (2004); Dere, Wang and Howard (2005)

Recent 3D studies using triangulation/stereoscopic technique

SECCHI/STEREO observations: Mierla et al. (2008); Srivastava et al. (2009), Srivastava (2009); Mierla et al. (2009), (2010).

Polarization Ratio Technique vs Triangulation/Stereoscopic technique: Comparison

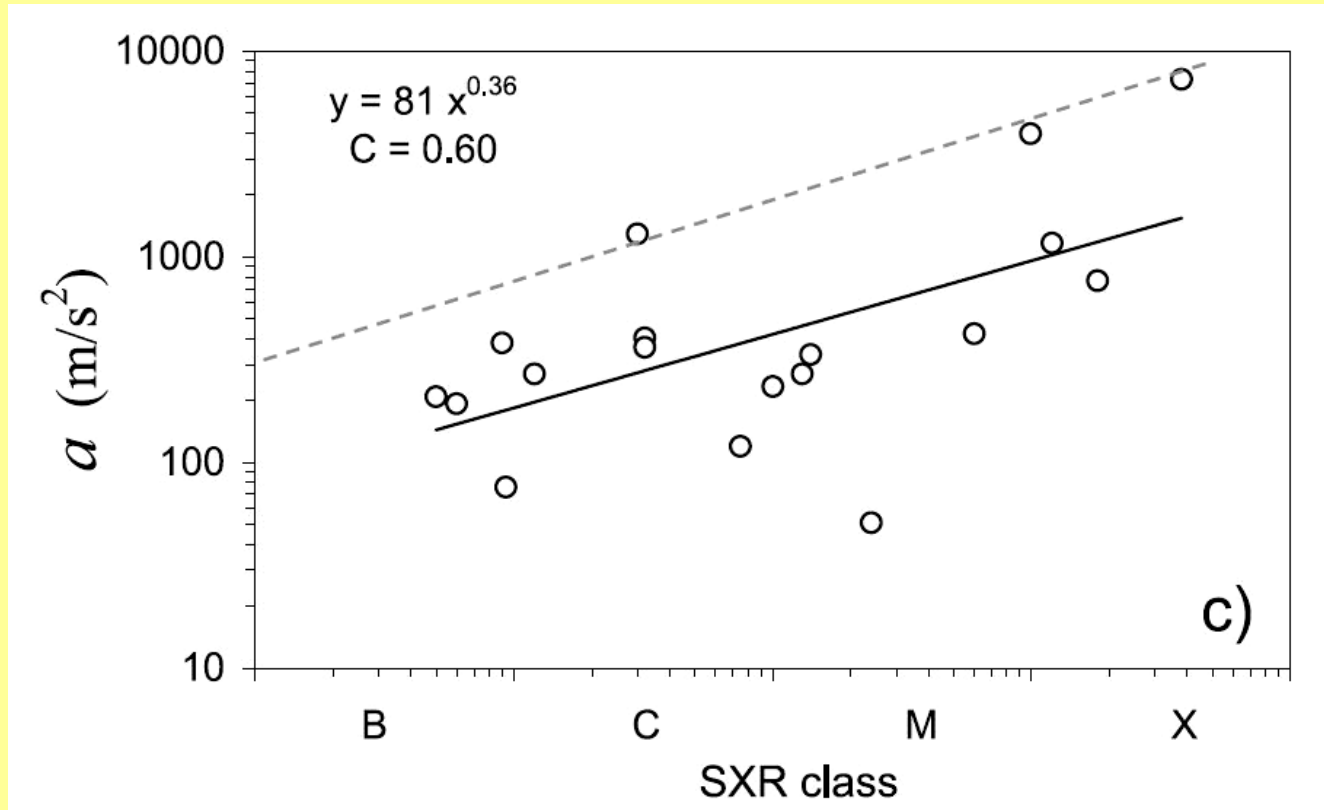
Mierla et al. (2009): General good agreement within 10^0 except a few outliers.

Moran, Davila and Thompson (2010): Good agreement within 5^0 (CME orientation angles)

Polarization ratio method: Effective tool for 3D studies using Aditya polarization images because

1. With increasing separation angle between the two STEREO spacecraft, triangulation technique will be difficult to apply.
2. Both STEREO and SOHO have outlived their planned lives. May become inoperational.
3. Moreover, LASCO does not have the capability of polarimetric measurements close to the Sun, a gap filled by Aditya

Thanks!



Statistical study shows, for C8 class flare, maximum acceleration should be $\sim 300 \text{ m s}^{-2}$ (Maričić et al. 2007)

SXR flux may be underestimated one (Raftery et al. 2010).

Assumptions:

STP plane and ecliptic plane is the same as the angles between the two never exceed 0.5 degrees.

Affine geometry is assumed: spacecraft is at an infinite distance from the sun.

Error estimates:

Manual error of 3 pixels in identification of a feature yields a corresponding error of

0.02 R_{sun} in true height

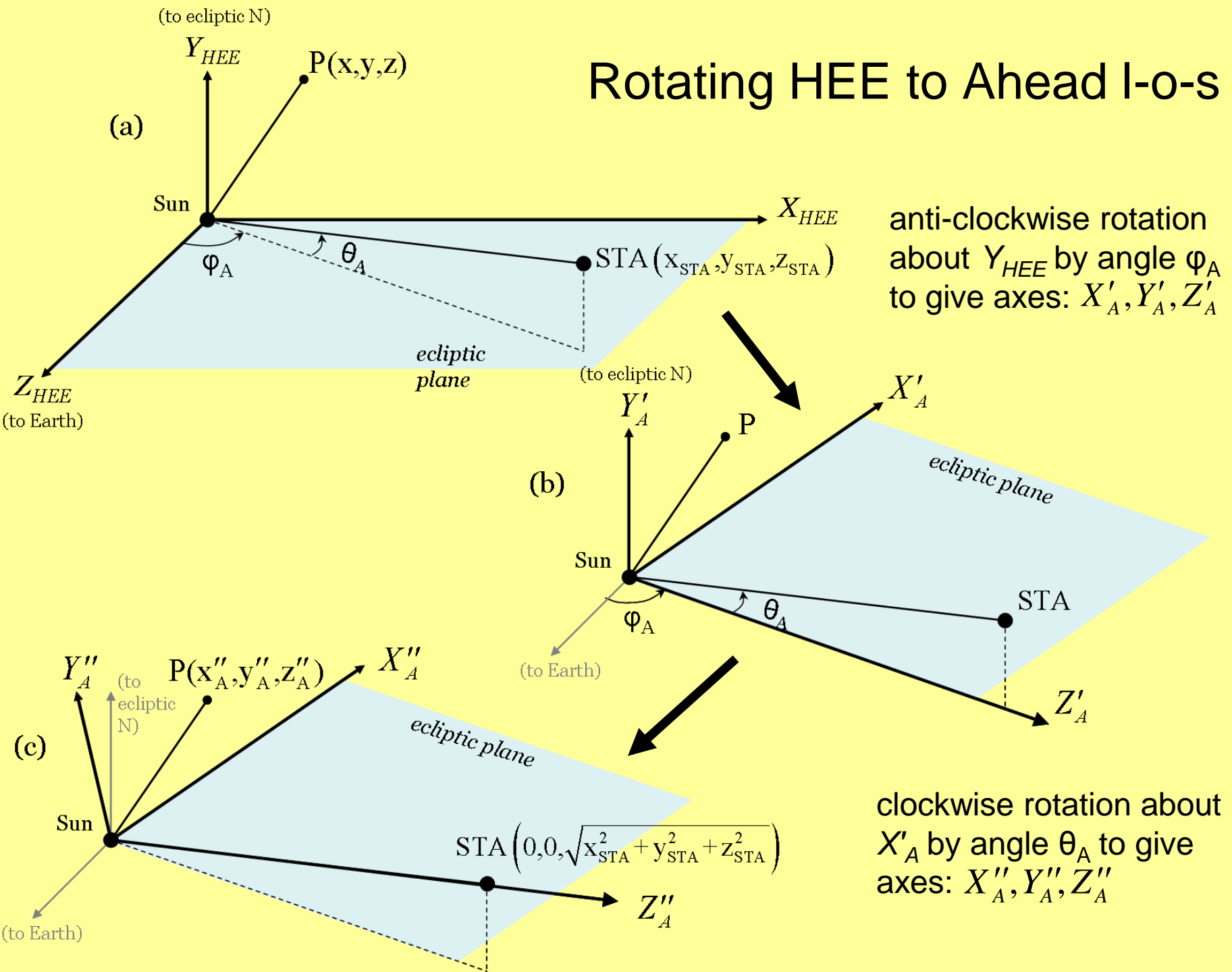
2 degrees in longitude

0.5 degrees in latitude

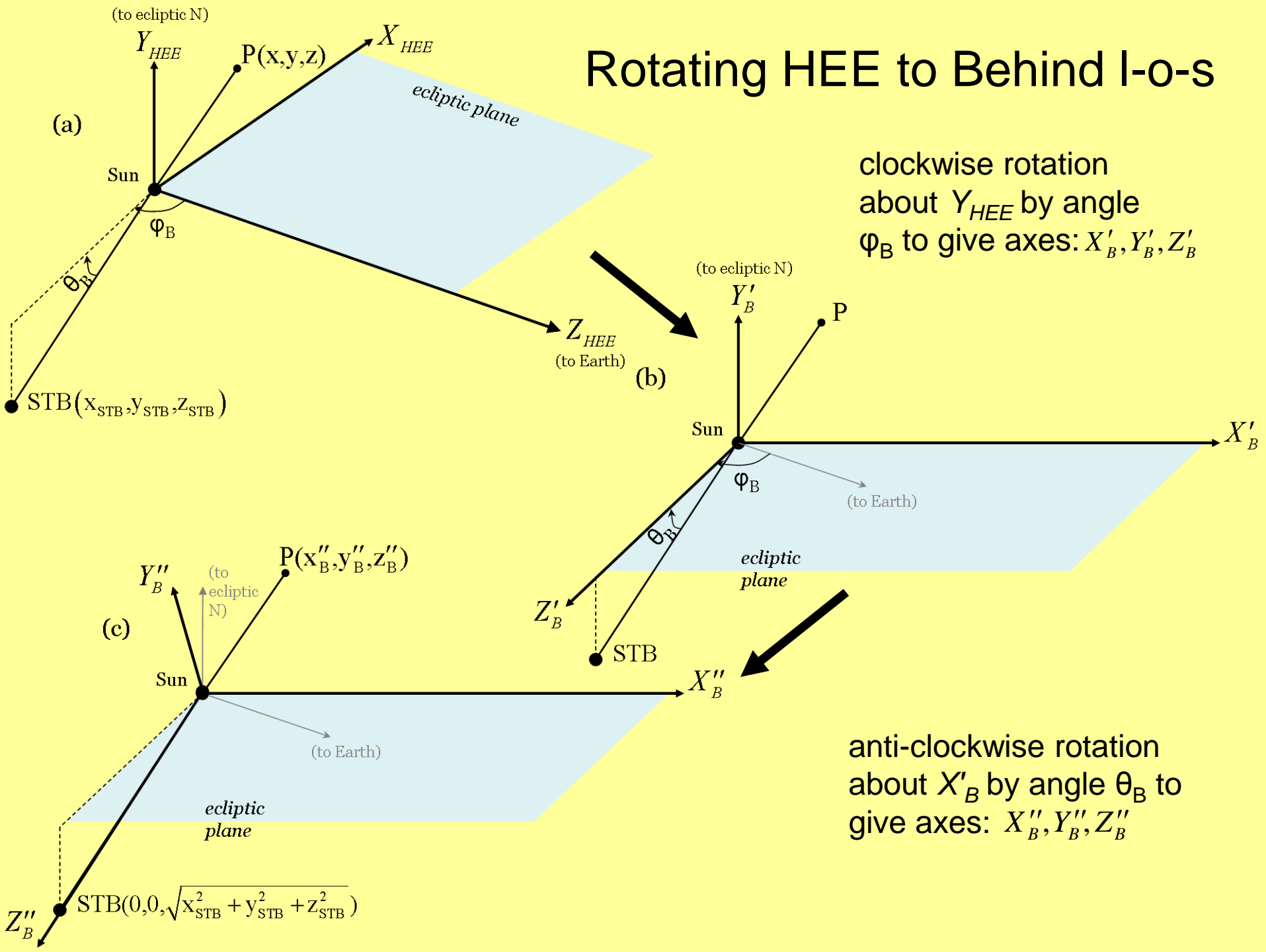
The technique is based on triangulation.

The technique can be applied to both disk and coronagraph images.

Rotating HEE to Ahead I-o-s



Rotating HEE to Behind I-o-s



The solution

- Epipolar constraint: the epipolar plane passing through a feature in image has to pass through the same feature as seen from the other image.
- Hence the 4 variables are not really independent, and the problem can be solved

$$x = \frac{x_B'' \sin \varphi_A + x_A'' \sin \varphi_B}{\sin(\varphi_A + \varphi_B)}$$

$$y = (x_B'' - x_A'' \cos(\varphi_A + \varphi_B)) \tan \theta_A + y_A'' \frac{\sin(\varphi_A + \varphi_B)}{\cos \theta_B}$$

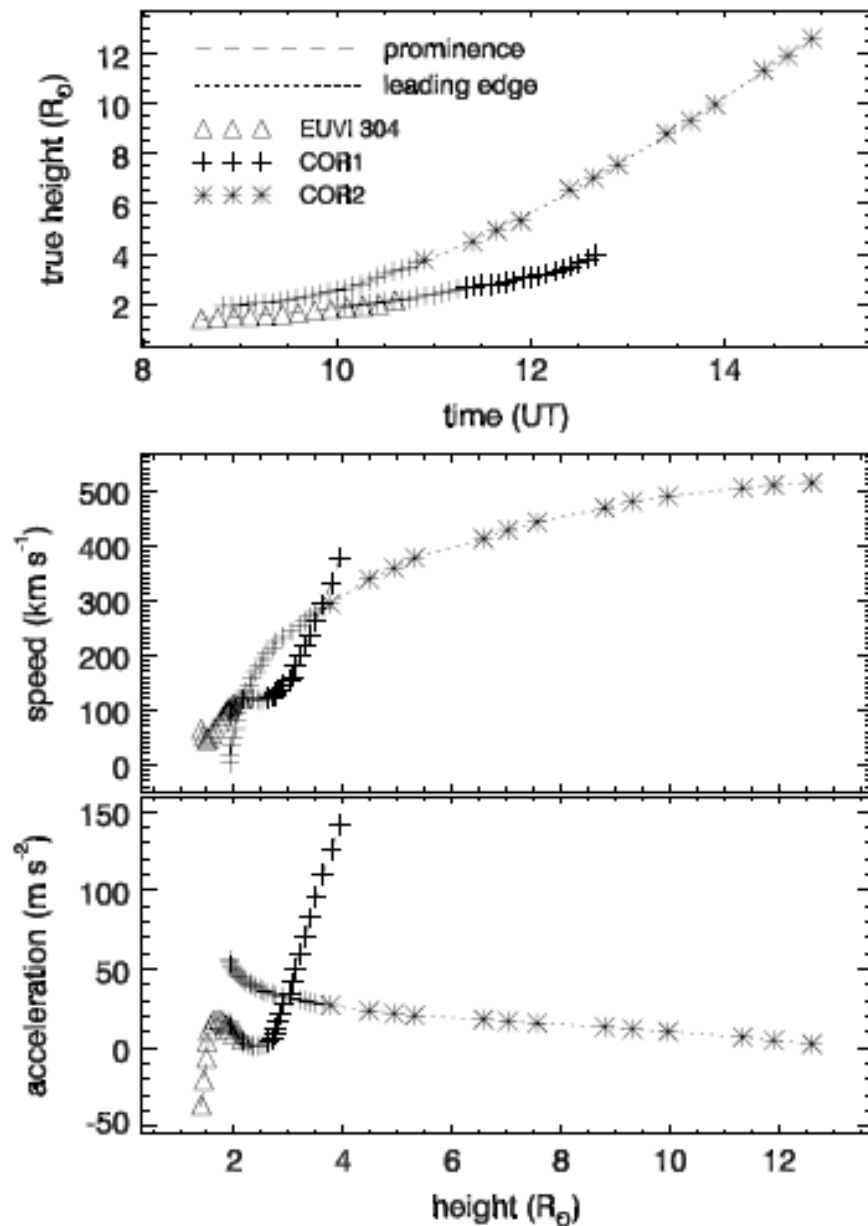
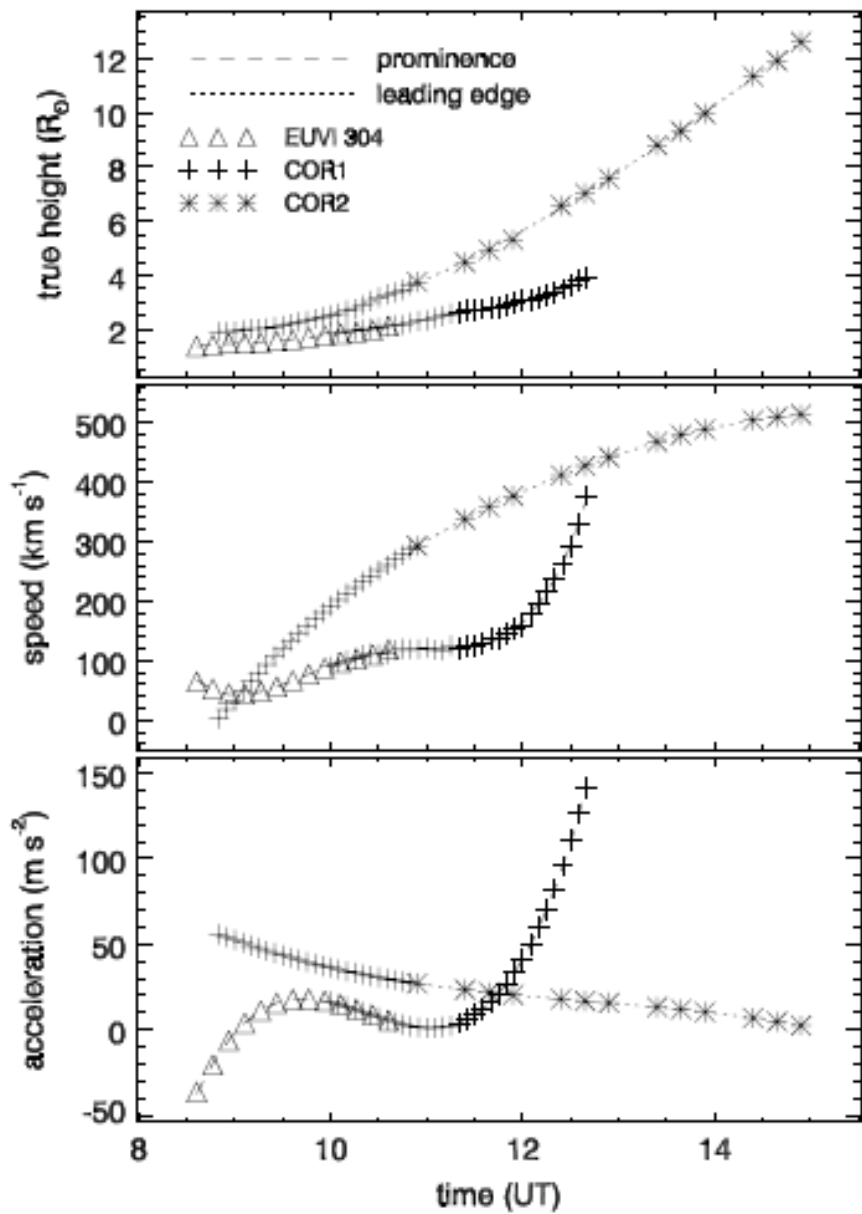
$$z = \frac{x_B'' \cos \varphi_A - x_A'' \cos \varphi_B}{\sin(\varphi_A + \varphi_B)}$$

Summary of the Six LEs and Three EPs Analyzed Using
Three-dimensional Reconstruction

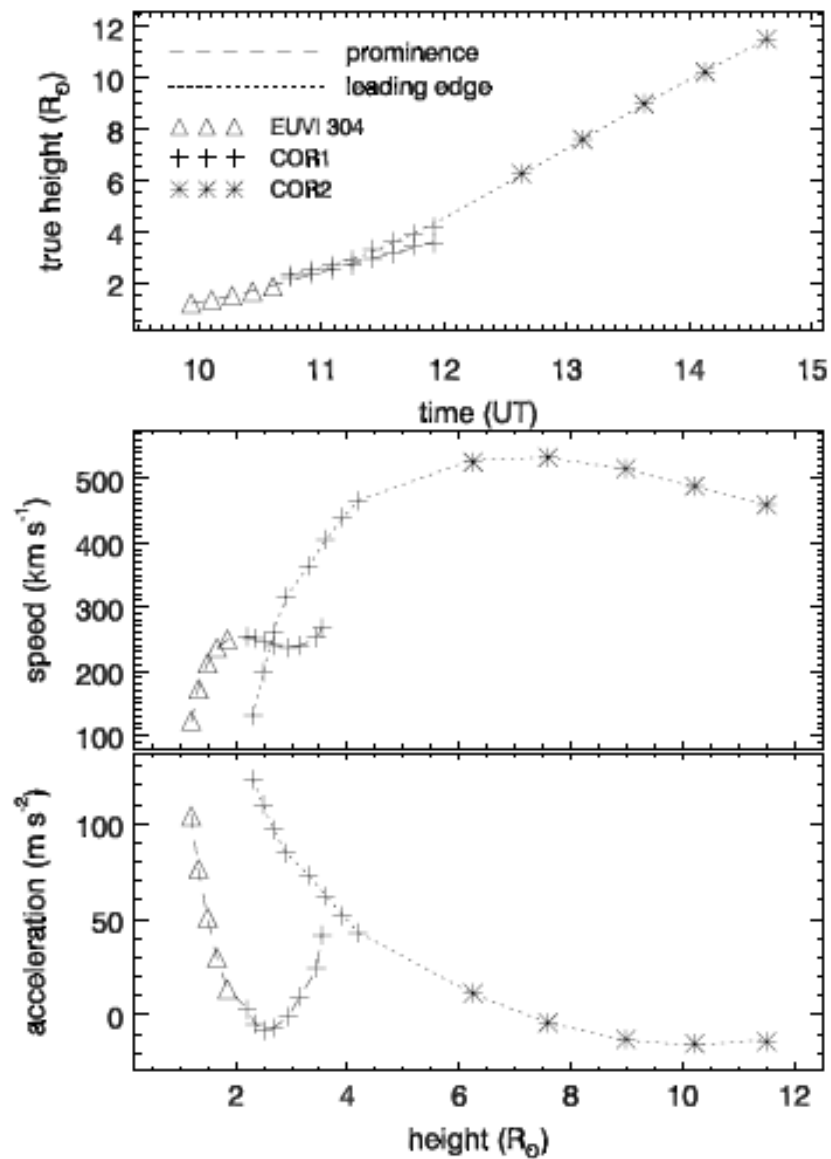
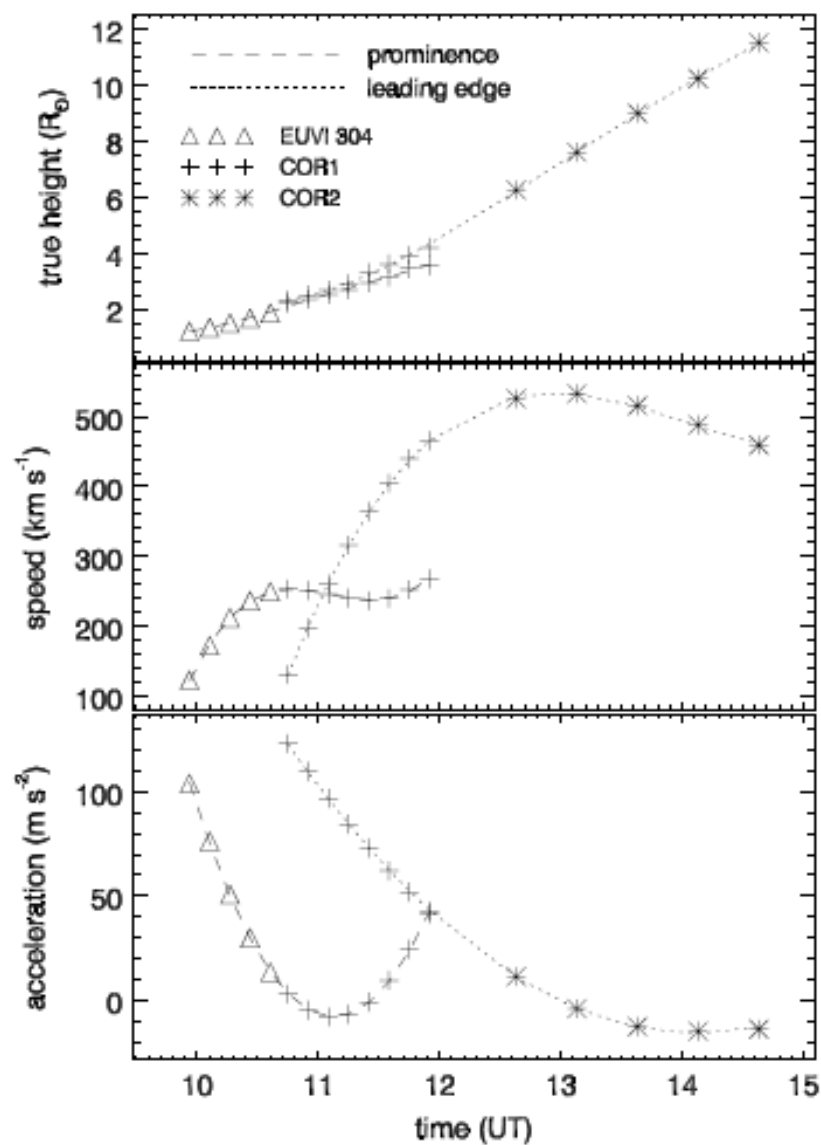
Event	v_{\max} (km s^{-1})	Height of v_{\max} (R_{\odot})	a_{\max} (m s^{-2})	Height of a_{\max} (R_{\odot})	v at $10 R_{\odot}$	a at $10 R_{\odot}$
2007 Nov 16 LE	451	12.2	50	2.2	408	16
2007 Dec 31 LE	876	13.0	1524	1.9	860	2
2008 Apr 9 LE	533	7.6	123	2.3	488	-15
2009 Dec 16 LE	356	5.8	90	1.9	488	-15
2010 Apr 13 LE	522	12.6	61	1.9	193	36
2010 Aug 1 LE	567	4.4	213	4.4
2008 Apr 9 EP	268	3.5	104	1.2
2010 Apr 13 EP	377	3.9	141	3.9
2010 Aug 1 EP	224	2.9	34	1.6

Notes. v_{\max} and a_{\max} denote the maximum speed and acceleration of the CME calculated. The heights at which CMEs attained these values are also provided. The last two columns show the speed and acceleration of the CMEs at a distance of $10 R_{\odot}$.

13 Apr 2010

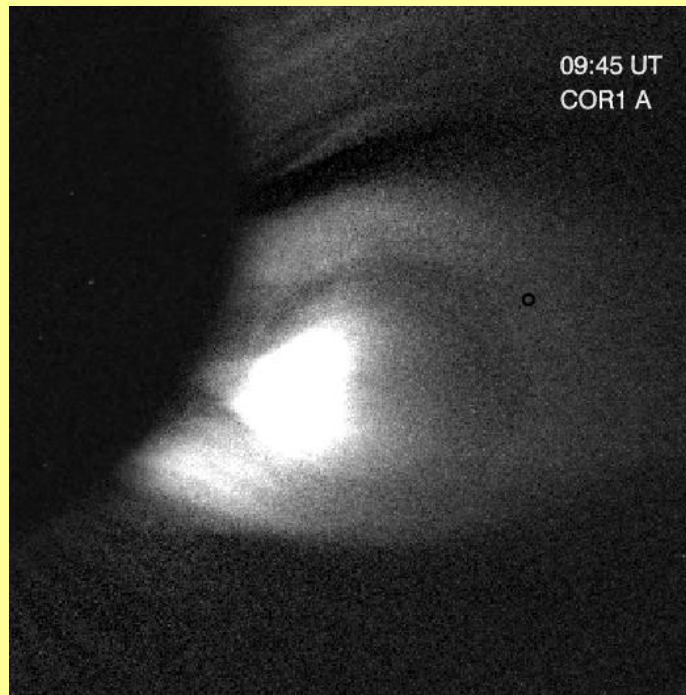
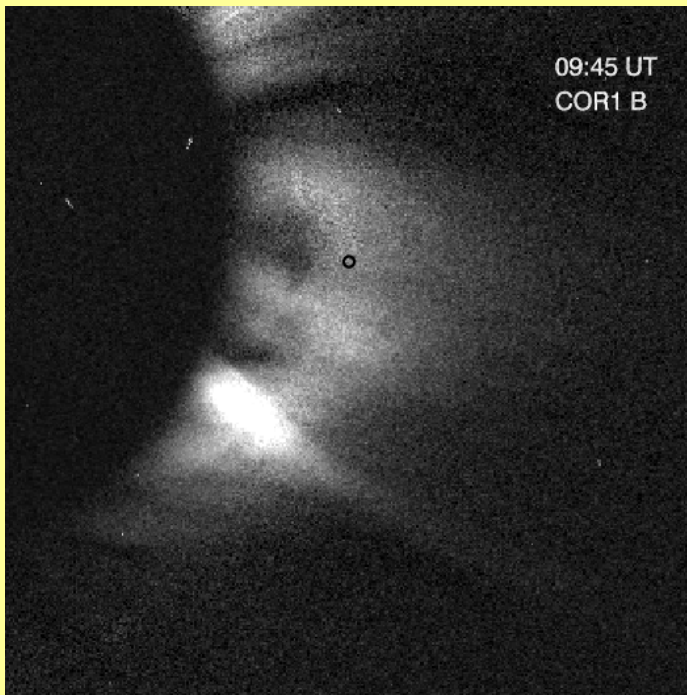


2008 April 9

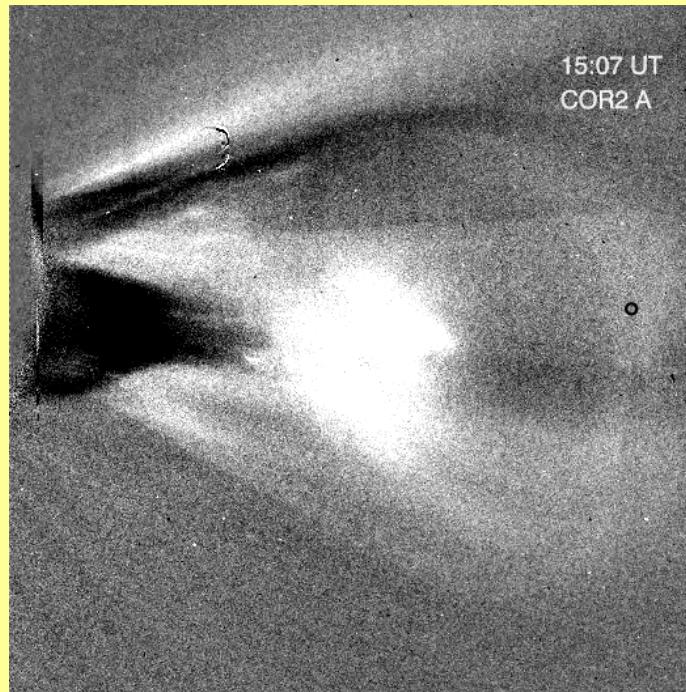
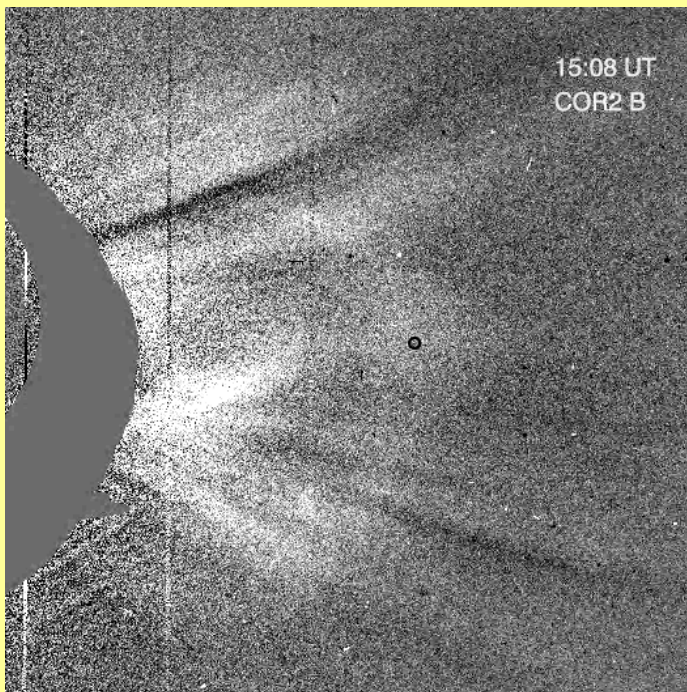


2007 Nov 16

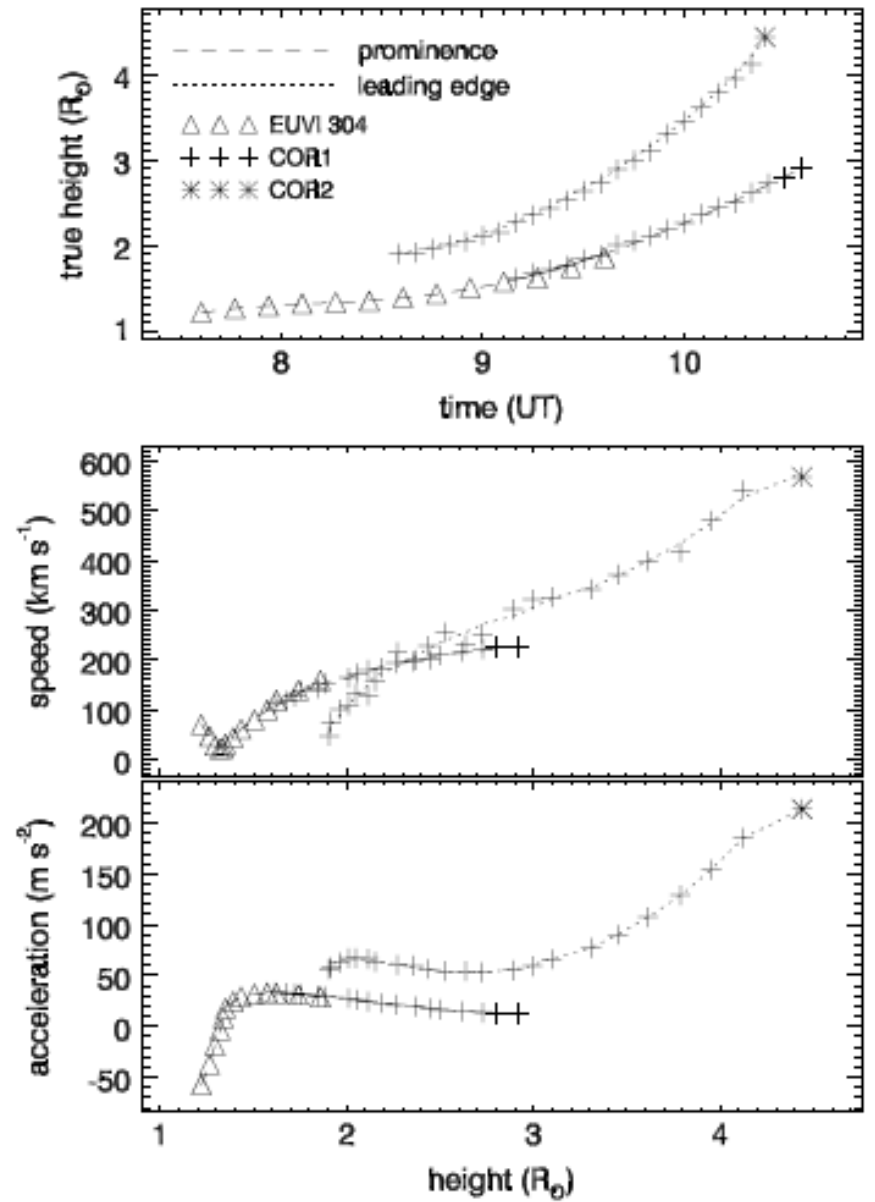
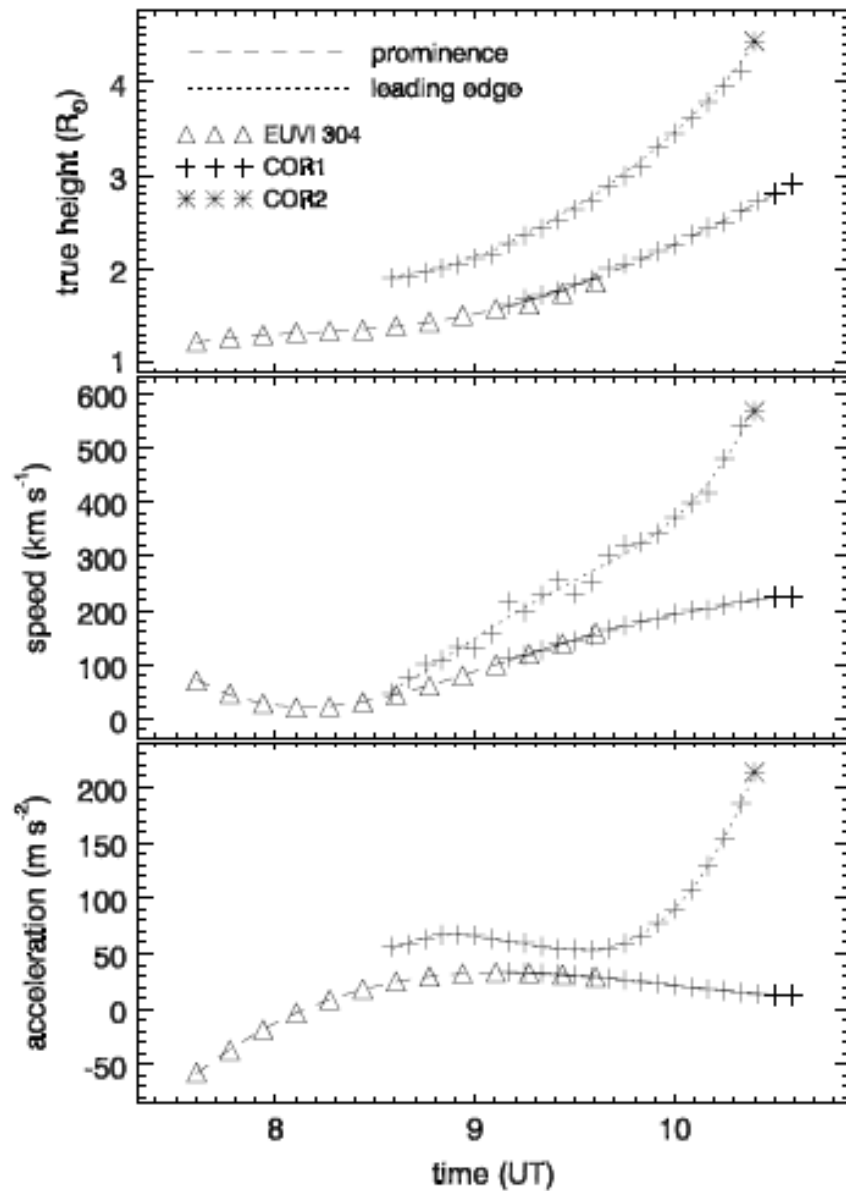
COR1



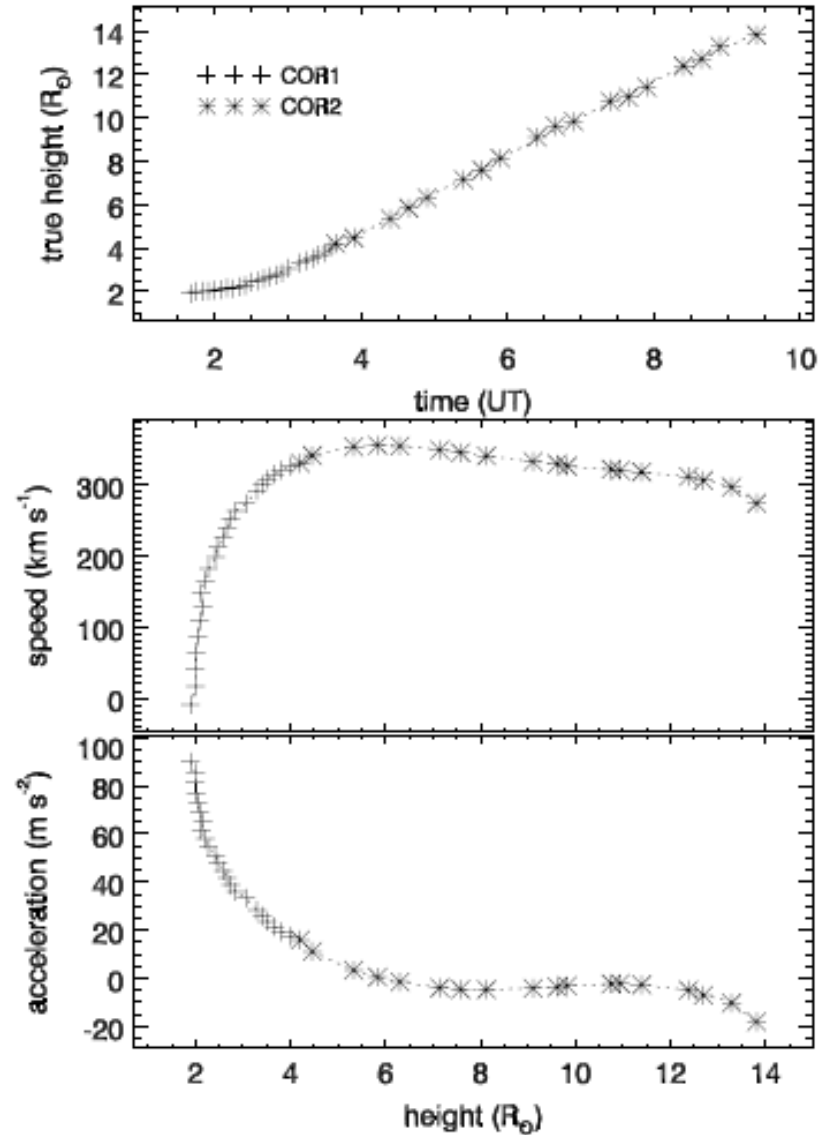
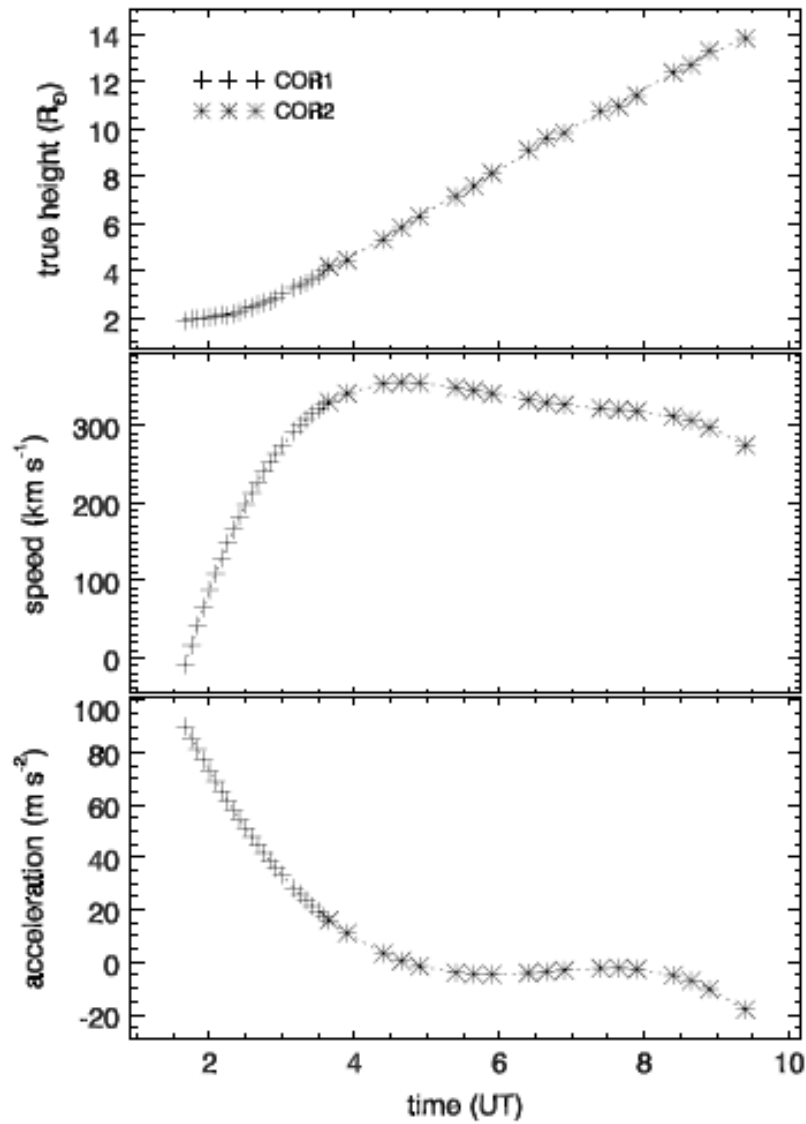
COR2



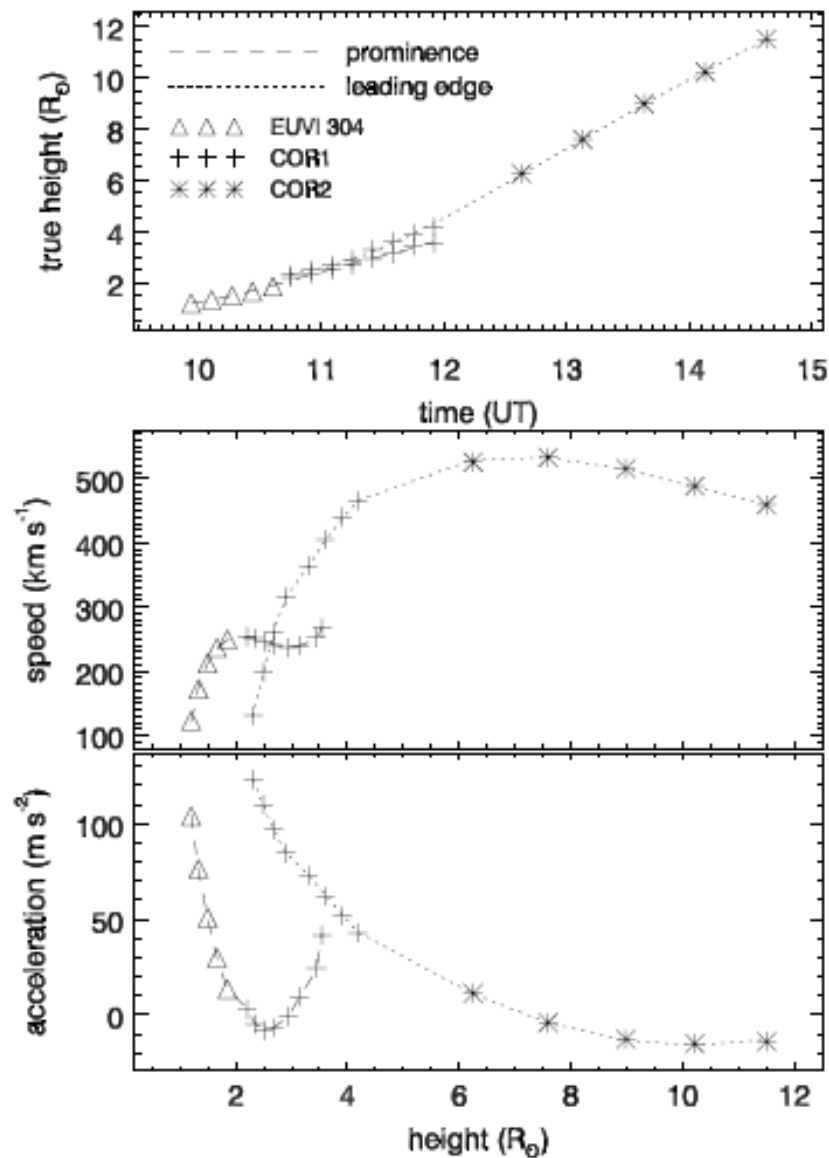
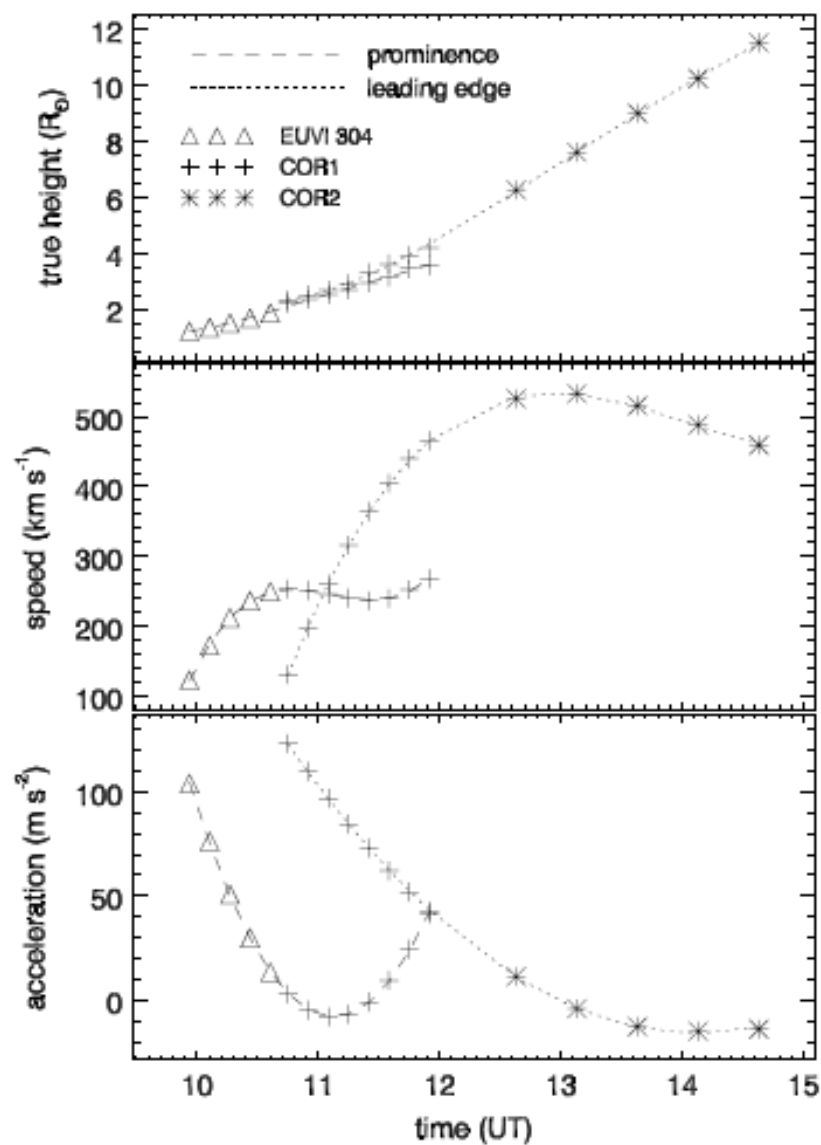
August 1, 2010



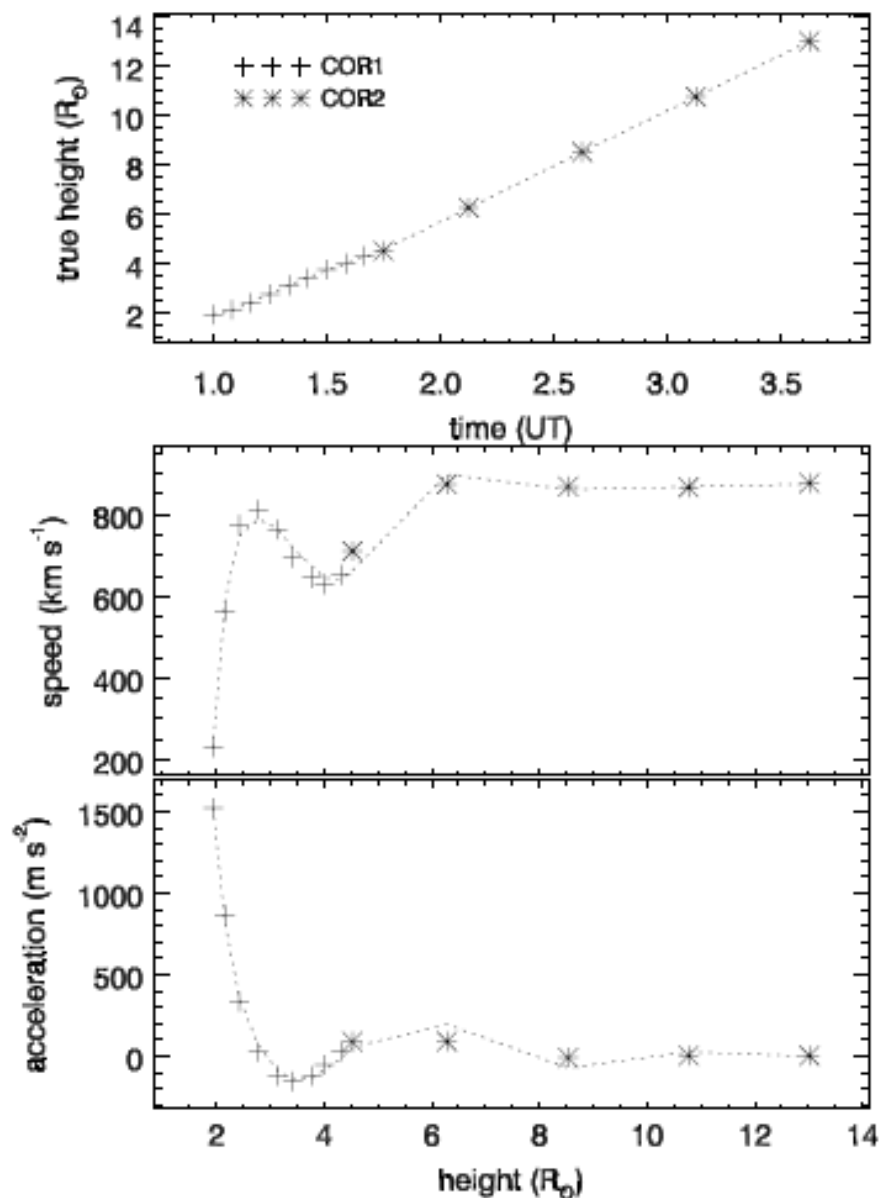
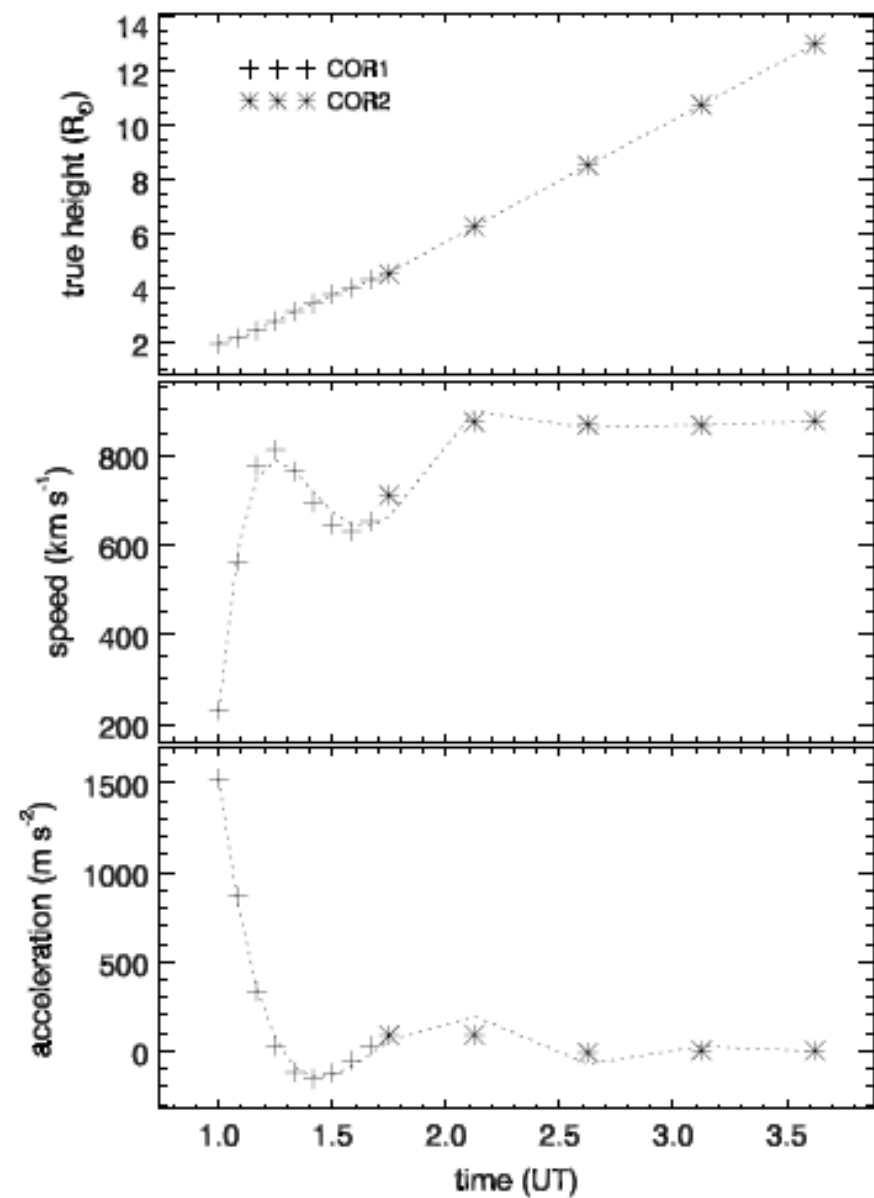
2009 dec 16



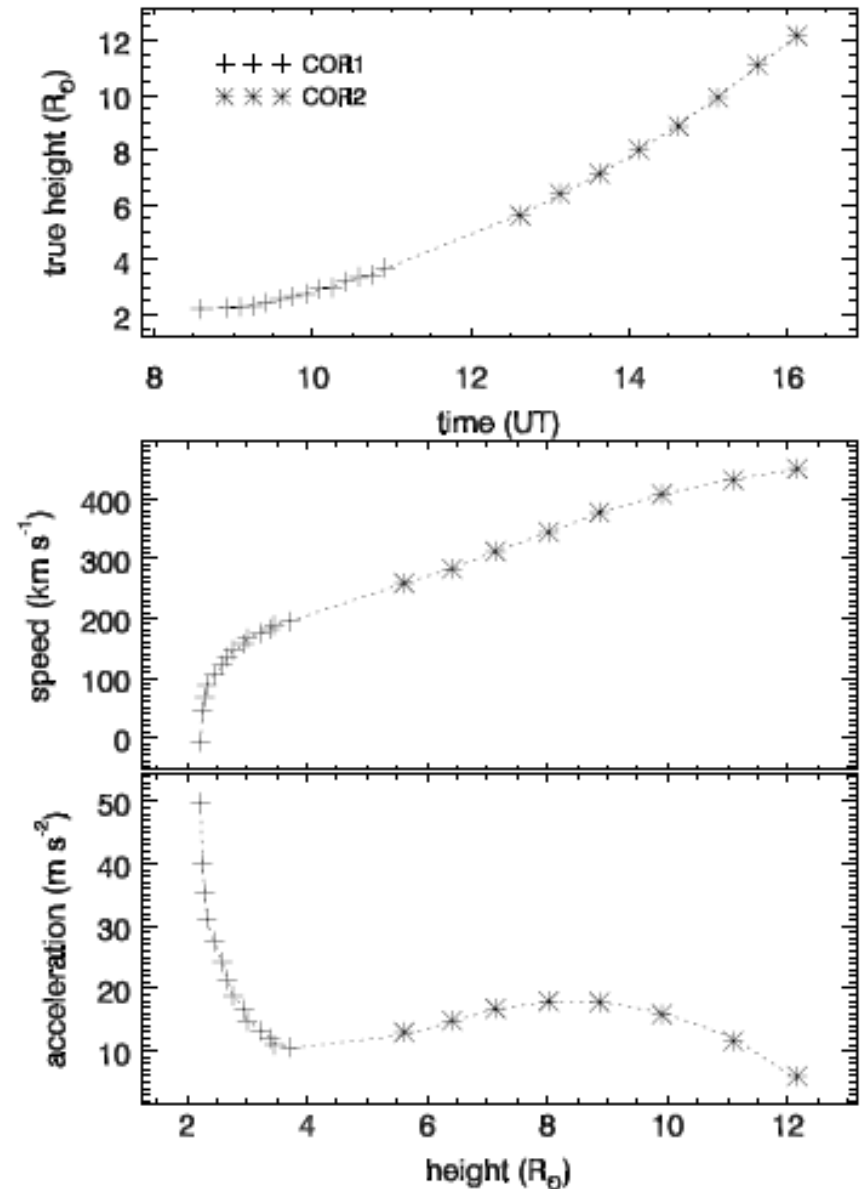
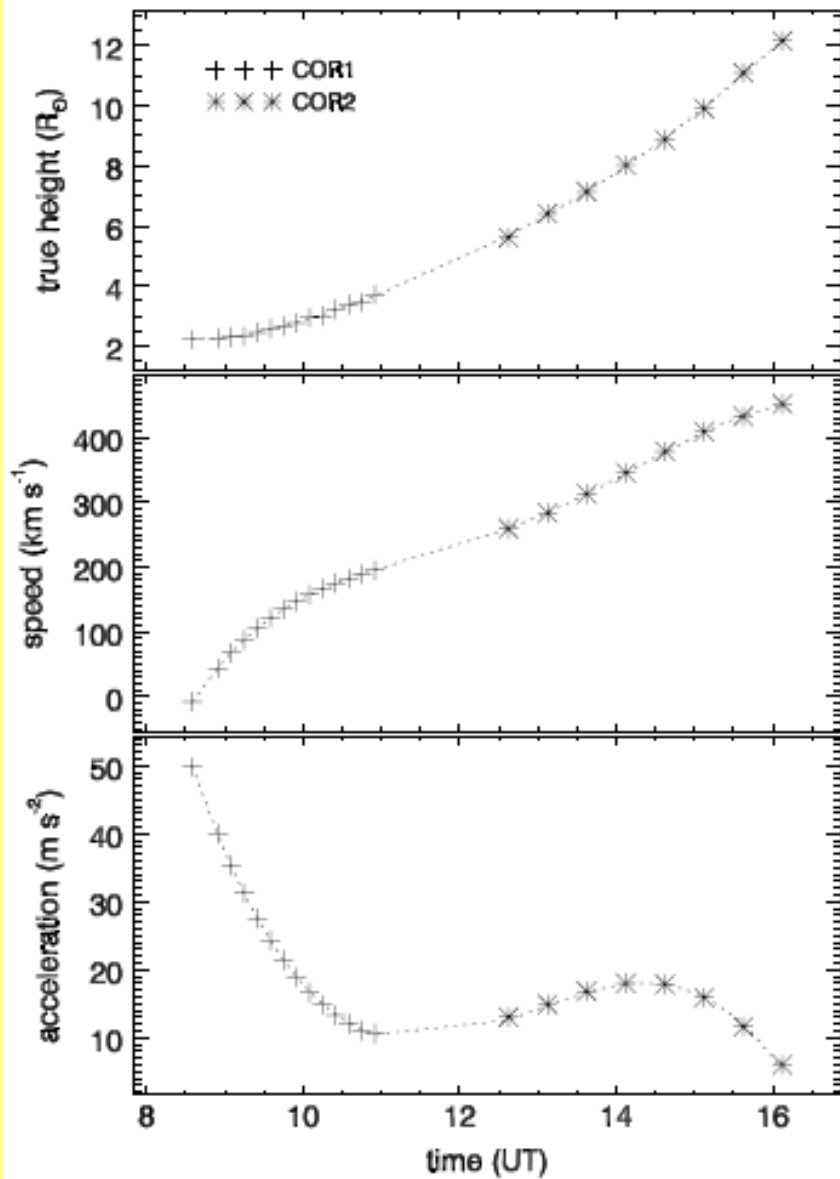
2008 April 9



2007 Dec 31



2007 Nov 16



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2010 Aug 1 EP	224	2.9	34	1.6

Notes. v_{\max} and a_{\max} denote the maximum speed and acceleration of the CME calculated. The heights at which CMEs attained these values are also provided. The last two columns show the speed and acceleration of the CMEs at a distance of $10 R_{\odot}$.

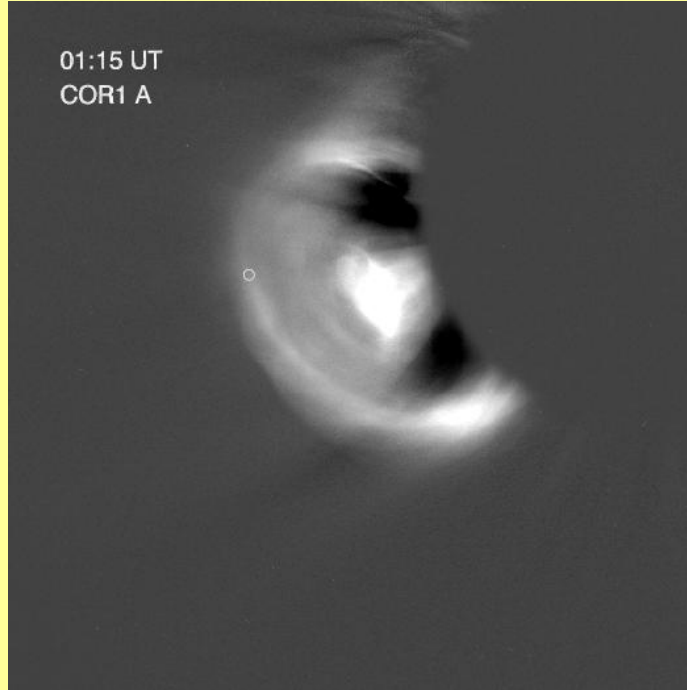
2007 Dec 31

COR1

01:15 UT
COR1 B

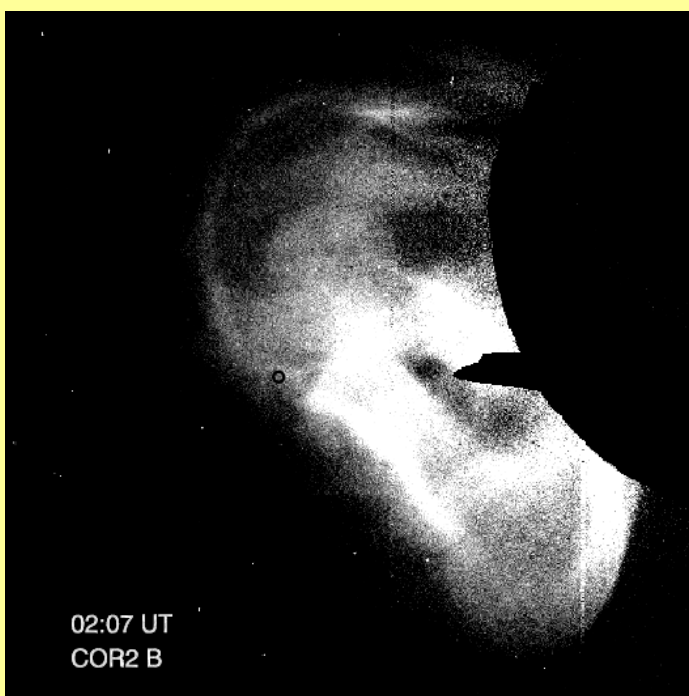


01:15 UT
COR1 A



COR2

02:07 UT
COR2 B



02:07 UT
COR2 A

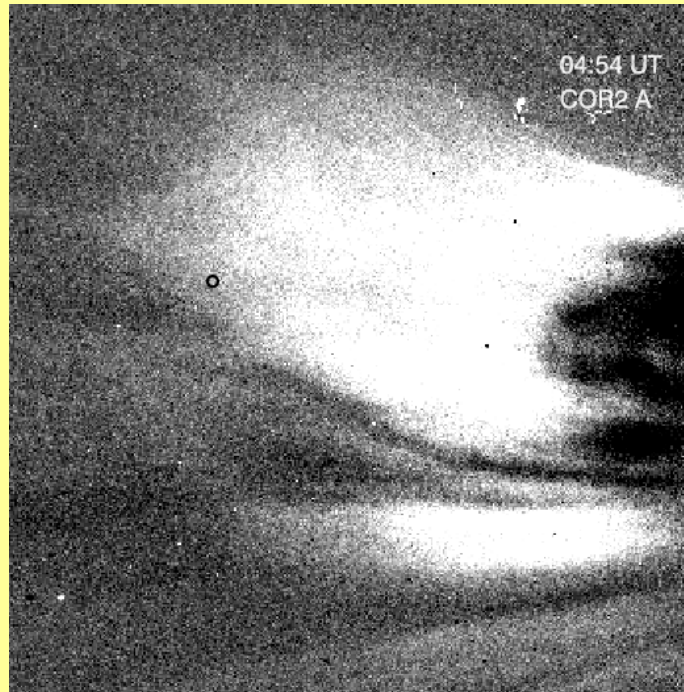
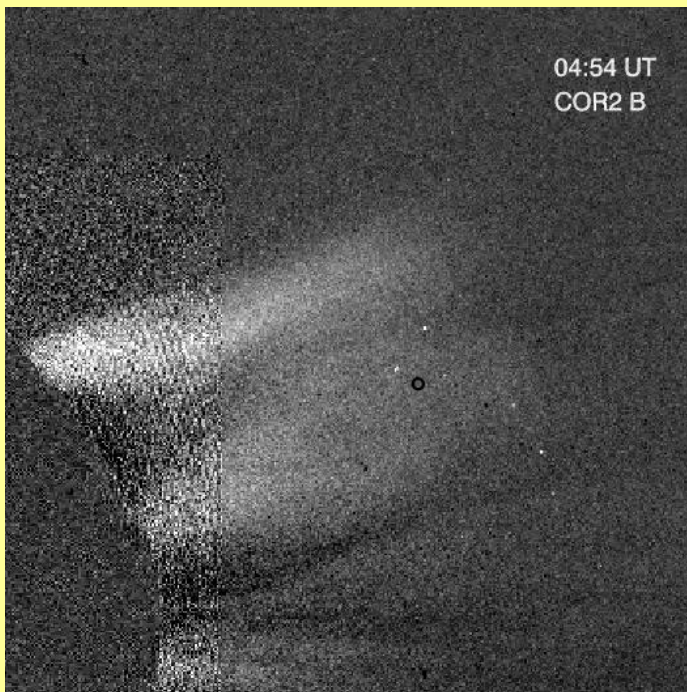


2009 Dec 16

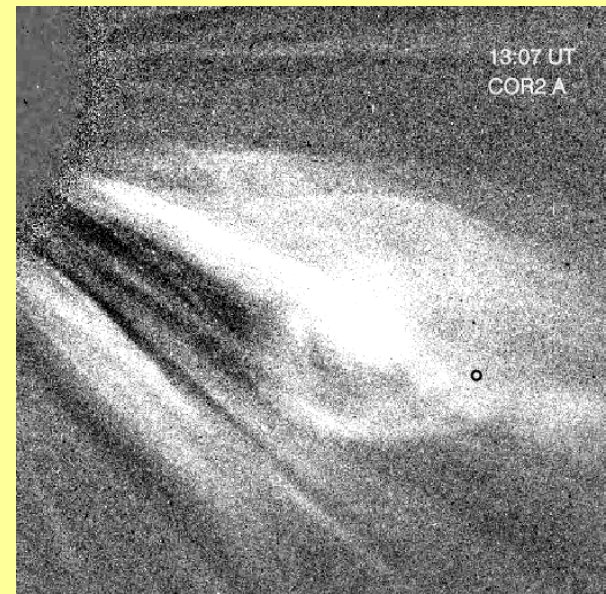
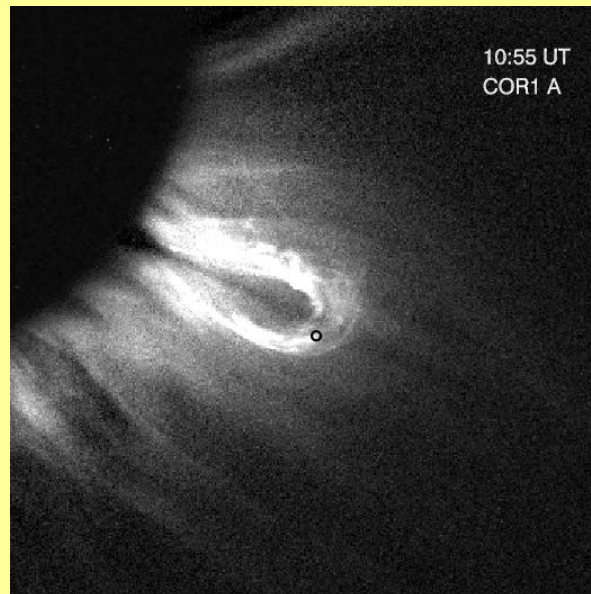
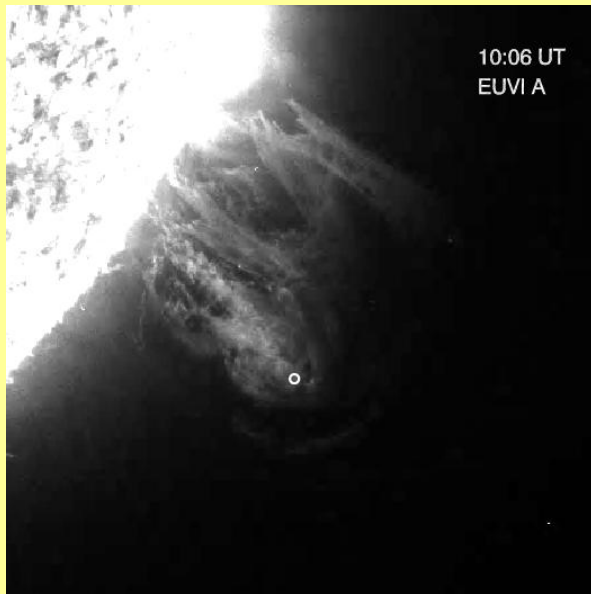
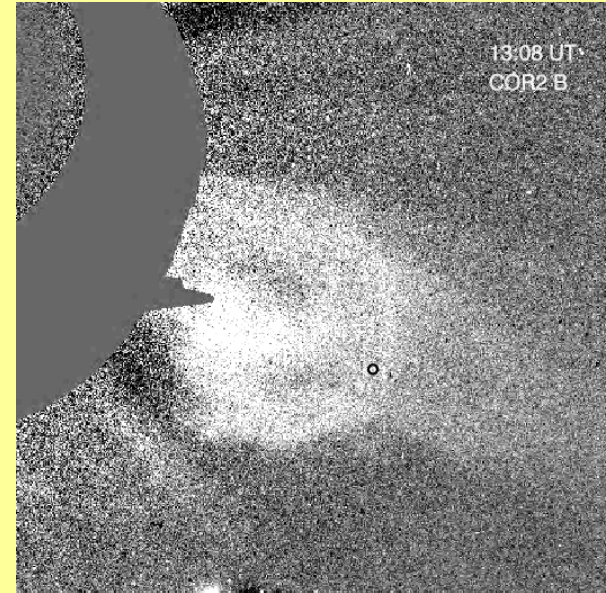
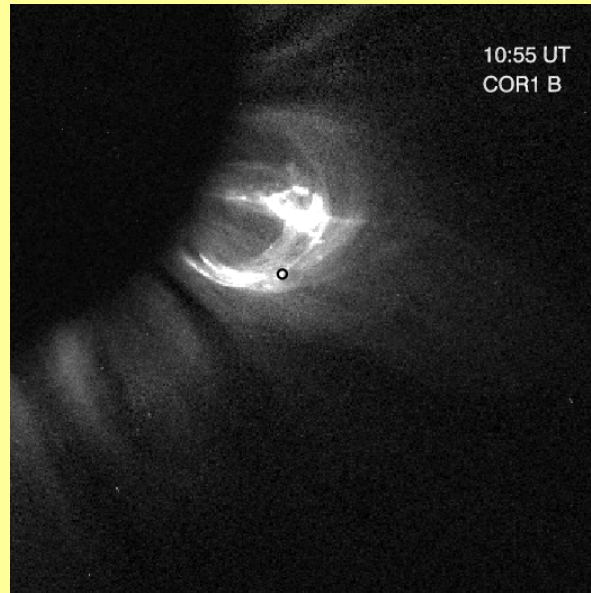
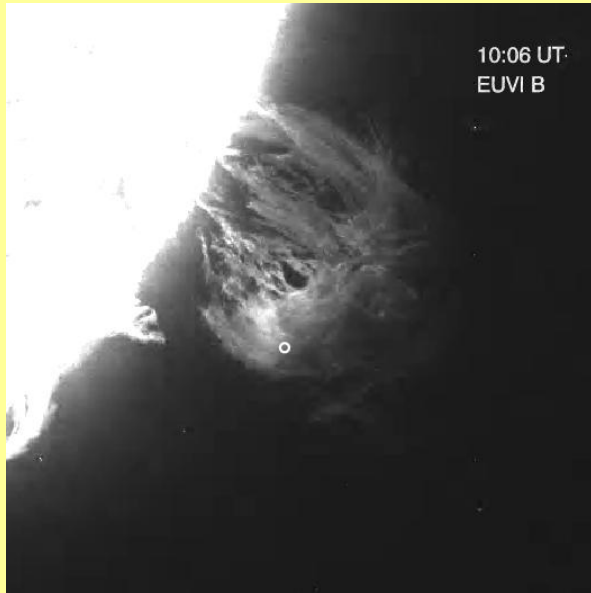
COR1



COR2



2008 Apr 09

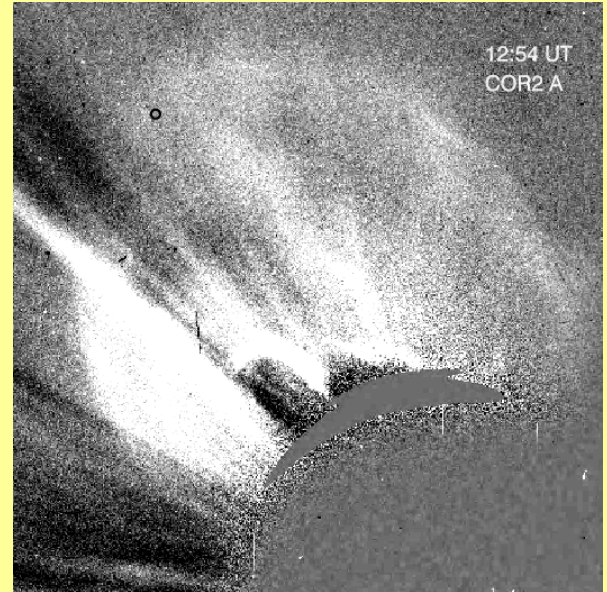
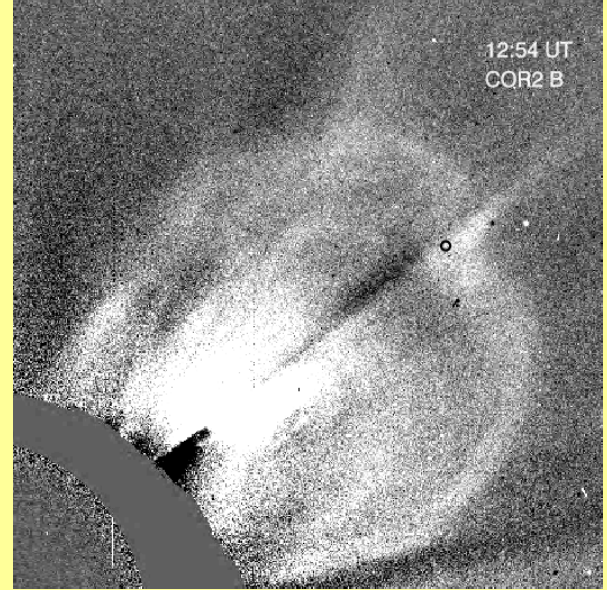


EUVI 304 Å

COR1

COR2

2010 Apr 13

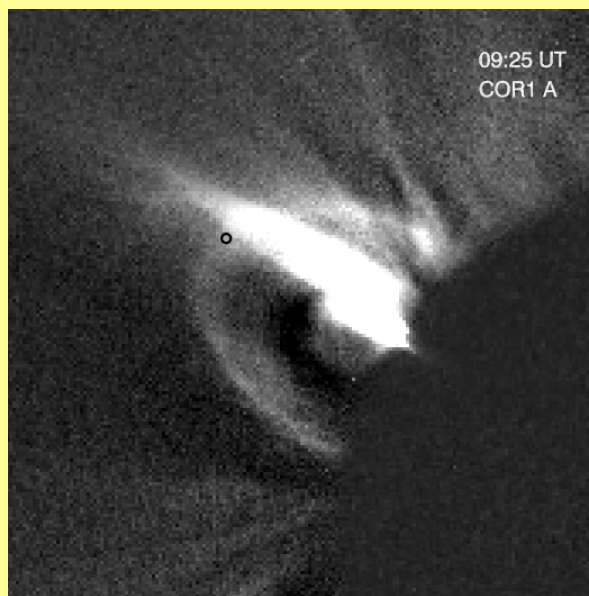
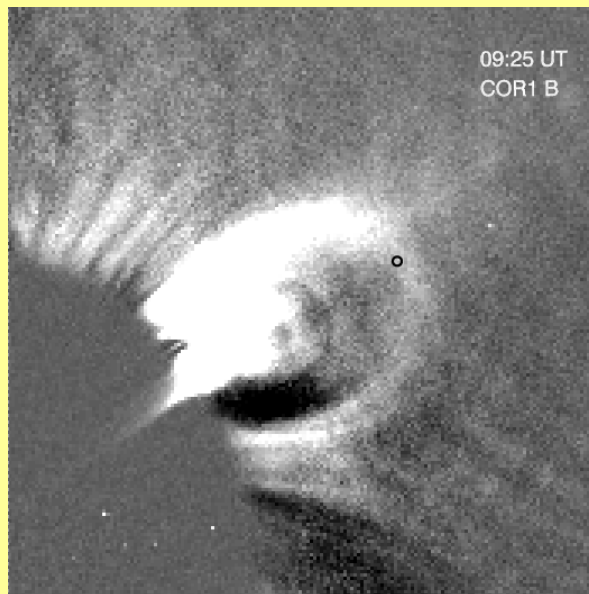


EUVI 304 Å

COR1

COR2

2010 Aug 01

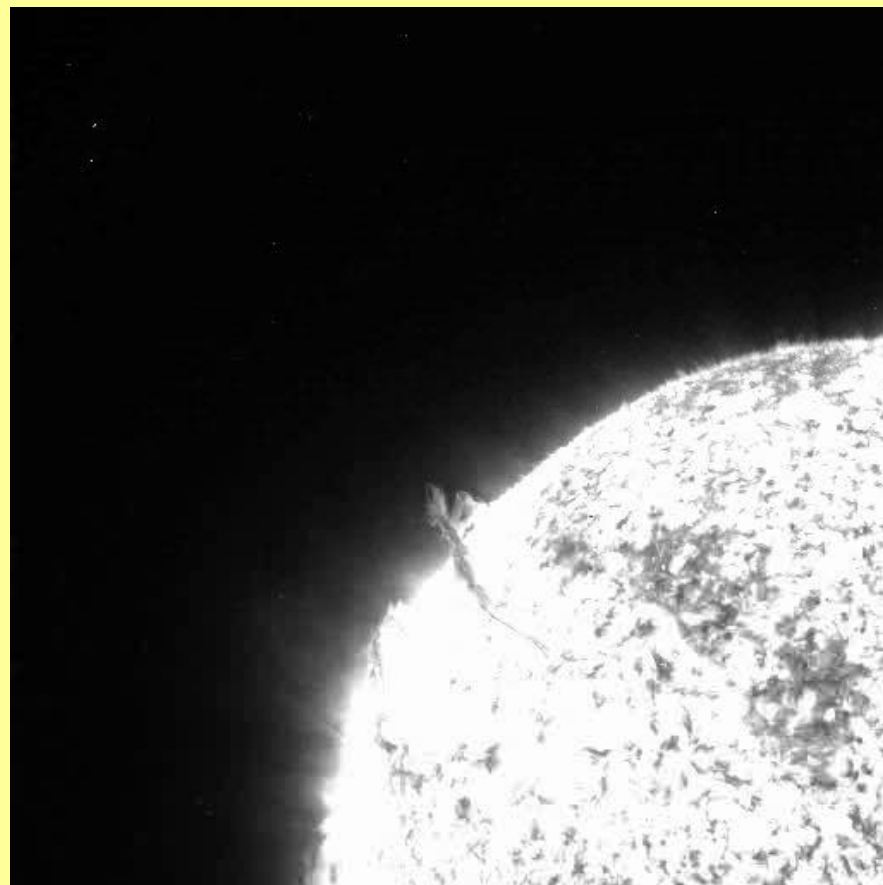


EUVI 304 Å

COR1

COR2

August 1, 2010 (STB & STA movie)



April 13, 2010 (STA& STB movie)

