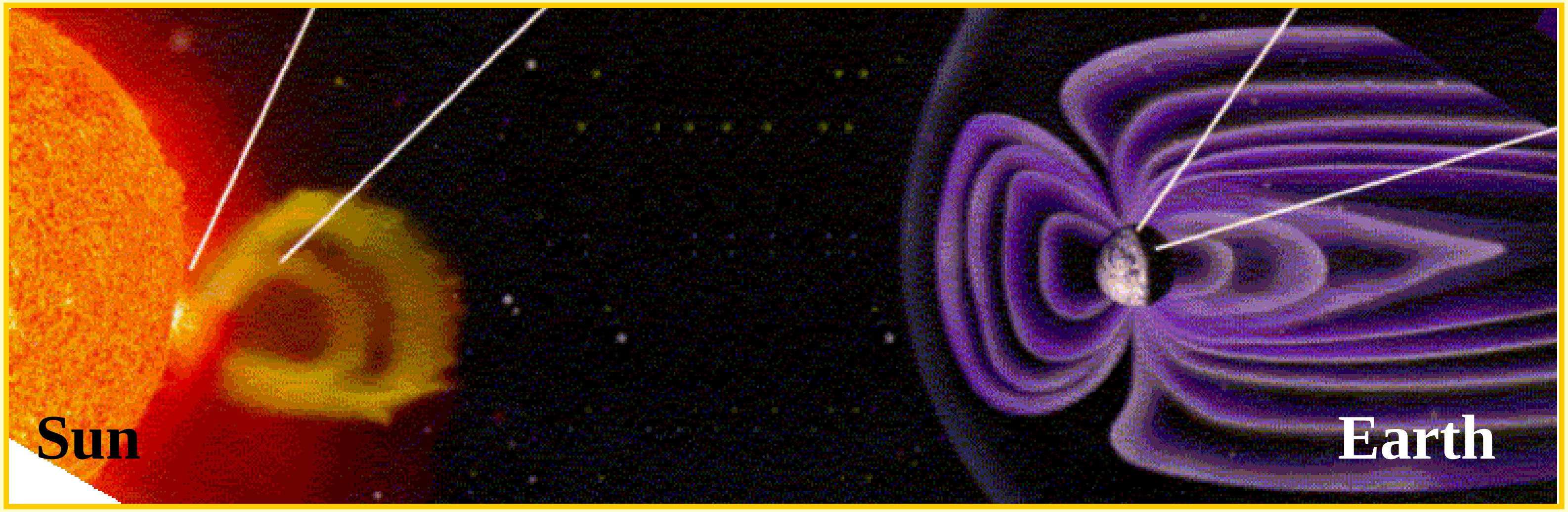
CMEs and Space Weather

What is Space Weather?

Conditions on the Sun and in the *solar wind*, *magnetosphere*, *ionosphere* and *thermosphere* that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.



Solar sources → CMEs   IP medium → Magnetosphere

Response to our geo-space to the constantly changing sun

Why important to predict?

Interplanetary Coronal Mass Ejections

There are two classes of large-scale interplanetary (IP) structures related to the two types magnetic field topology on the Sun:

•(i) interplanetary coronal mass ejections (ICMEs) originating from closed field regions (streamers)
(ii) and corotating interaction regions (CIRs) due to high speed streams originating from open field regions

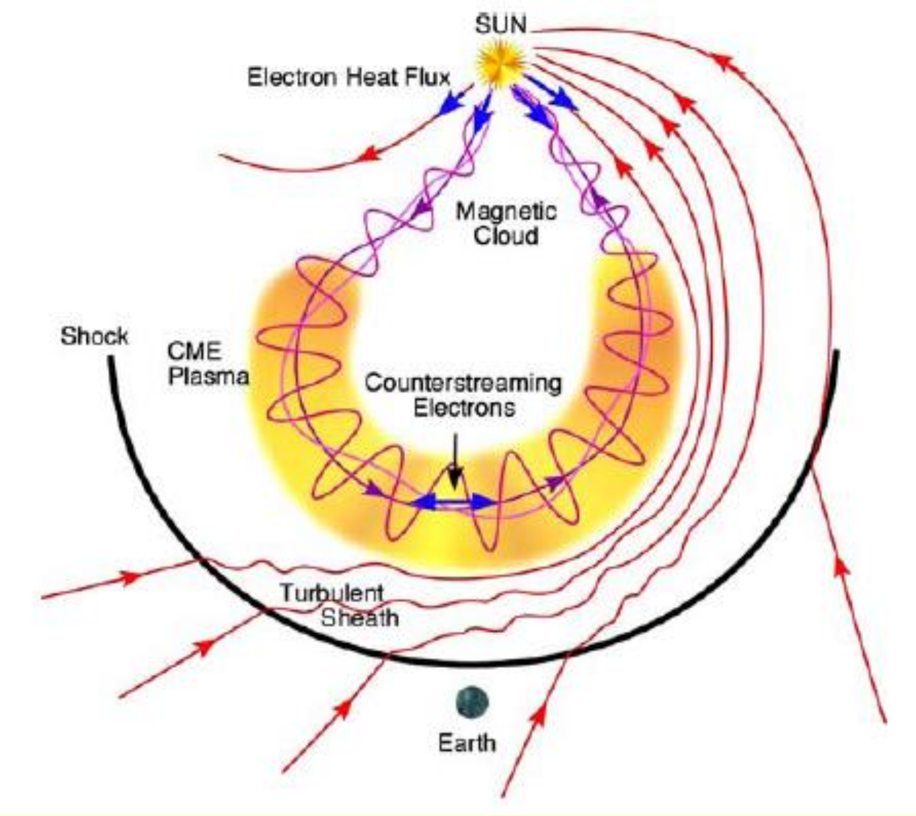
•Both CIRs and ICMEs are capable of driving shocks, which accelerate charge particles.

Difference? : The CIR shocks generally form far beyond 1 AU, although they are occasionally observed near 1 AU.

•ICME are the IP manifestations of CMEs. CMEs drive shocks from close to the Sun to far into the IP medium

•CME-driven shocks accelerate charged particles from close to the Sun and in the IP medium. ICMEs are responsible for the severest of geomagnetic storms.

CMEs and ICMEs:



5 classes of signatures of ICMEs:

- Magnetic field
- Plasma dynamics
- Plasma composition
- Plasma waves
- Energetic particles

)

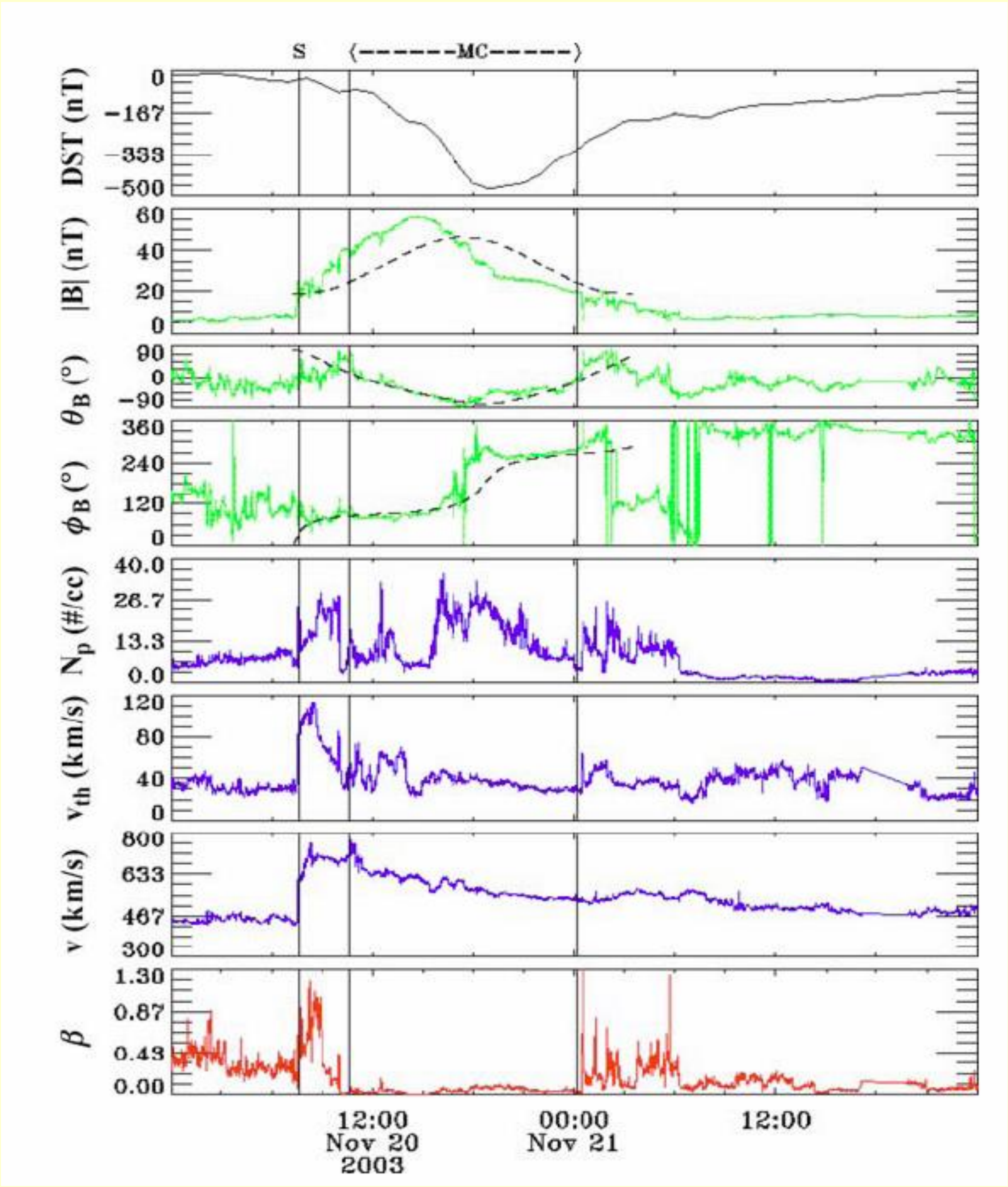
TABLE I

In-situ signatures of ICMEs (description applies to ~1 AU heliospheric distance) in the magnetic field (B), plasma dynamics (P), plasma composition (C), plasma waves (W), and suprathermal particles (S)

Signature	Description	Selected references
B1: *B* Rotation	$\gg 30^\circ$, smooth	Klein and Burlaga (1982)
B2: *B* Enhancement	>10 nT	Hirshberg and Colburn (1969); Klein and Burlaga (1982)
B3: *B* Variance decrease		Pudovkin *et al.* (1979); Klein and Burlaga (1982)
B4: Discontinuity at ICME boundaries		Janoo *et al.* (1998)
B5: Field line draping around ICME		Gosling and McComas (1987); McComas *et al.* (1989)
B6: Magnetic clouds	(B1, B2 and $\beta = \frac{\sum nkT}{B^2/(2\mu_0)} < 1$)	Klein and Burlaga (1982); Lepping *et al.* (1990)
P1: Declining velocity profile/expansion	Monotonic decrease	Klein and Burlaga (1982); Russell and Shinde (2003)
P2: Extreme density decrease	≤ 1 cm^{-3}	Richardson *et al.* (2000a)
P3: Proton temperature decrease	$T_p < 0.5 T_{\text{exp}}$	Gosling *et al.* (1973); Richardson and Cane (1995)
P4: Electron temperature decrease	$T_e < 6 \times 10^4$ K	Montgomery *et al.* (1974)
P5: Electron Temperature increase	$T_e \gg T_p$	Sittler and Burlaga (1998); Richardson *et al.* (1997)
P6: Upstream forward shock/"Bow Wave"	Rankine-Hugoniot relations	Parker (1961)
C1: Enhanced α/proton ratio	$He^{2+}/H^+ > 8\%$	Hirshberg *et al.* (1972); Borrini *et al.* (1982a) See page 37 for more recent ref
C2: Elevated oxygen charge states	$O^{7+}/O^{6+} > 1$	Henke *et al.* (2001); Zurbuchen *et al.* (2003), Richardson & Cane 2005
C3: Unusually high Fe charge states	$\langle Q \rangle_{\text{Fe}} > 12$; $Q_{\text{Fe}}^{\geq 15+} > 0.01$	Bame *et al.* (1979); Lepri *et al.* (2001); Lepri and Zurbuchen (2004)
C4: Occurrence of He^+	$He^+/He^{2+} > 0.01$	Schwenn *et al.* (1980); Gosling *et al.* (1980); Gloeckler *et al.* (1999)
C5: Enhancements of Fe/O	$\frac{(\text{Fe/O})_{\text{CME}}}{(\text{Fe/O})_{\text{photosphere}}} > 5$	Ipavich *et al.* (1986), Mitchell, 1983
C6: Unusually high $^3He/^4He$	$\frac{(^3\text{He}/^4\text{He})_{\text{CME}}}{(^3\text{He}/^4\text{He})_{\text{photosphere}}} > 2$	Ho *et al.* (2000)
W1: Ion acoustic waves		Fainberg *et al.* (1996); Lin *et al.* (1999)
S1: Bidirectional strahl electrons		Gosling *et al.* (1987)
S2: Bidirectional ~MeV ions	2nd harmonic > 1st harmonic	Palmer *et al.* (1978); Marsden *et al.* (1987)
S3: Cosmic ray depletions	Few % at ~ 1 GeV	Forbush (1937); Cane (2000)
S4: Bidirectional cosmic rays	2nd harmonic > 1st harmonic	Richardson *et al.* (2000b)

23 signatures (Zurbuchen and Richardson (2006)

Insitu plot of an ICME on November 20, 2003



Observational Signature of ICMEs:

ICME are large scale structures with magnetic field enhanced w.r.t to SW

Distinctly different plasma and composition signatures.

B high

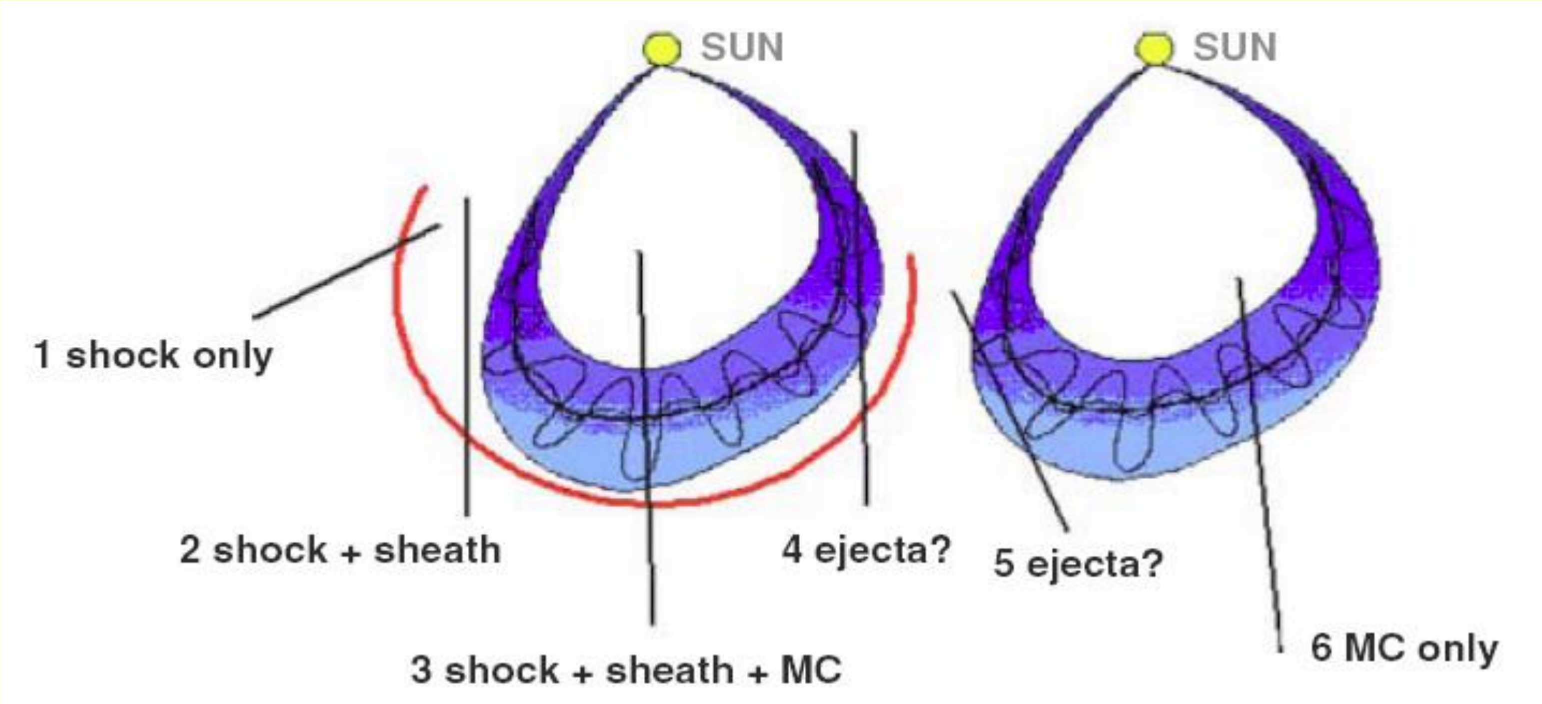
Theta and phi show smooth variation

Density high

Beta low

Expands, Size is 0.21 AU

Six possible scenarios:



Magnetic Cloud: Helios detected a MAGNETIC CLOUD (Burlaga et al. 1981) with high B, smooth field rotation and low proton temperatures

.

ICMEs can have cloud structure but the vantage point decides its appearance as a cloud/ejecta.

Multi space-craft from different vantage points helpful

Gopalswamy 2006

The white light CMEs observed near the Sun are typically 10 times more abundant than the ICMEs observed *in situ* (Gopalswamy, 2004).

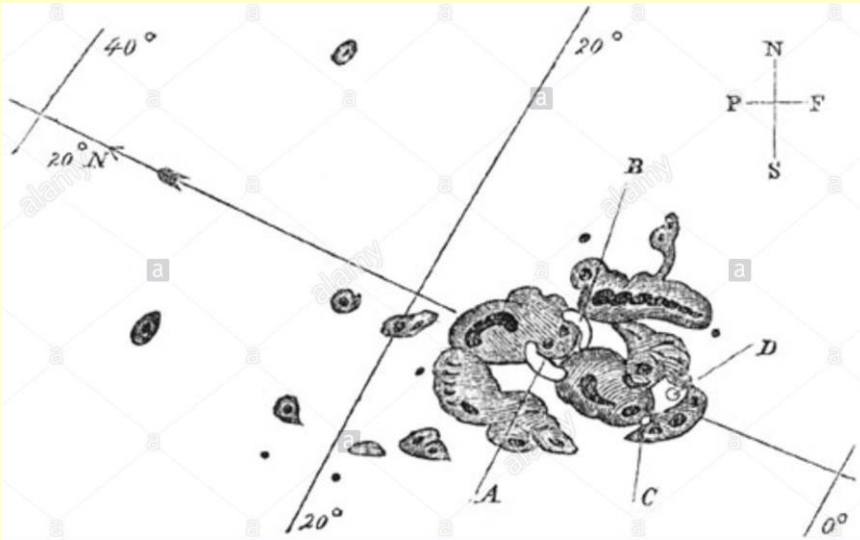
ICMEs are therefore a special population that makes significant impact on the heliosphere.

Earth is merged in the flows related to ICMEs from 10% of the time (solar minimum) to 35% of the time (solar maximum) (Cliver *et al.*, 2003).

Space Weather Prediction Requirements

It is important to know their source region, their mechanism of eruption, **their 3D configuration**, **their propagation direction and unprojected speed** in order to predict their arrival time and impact.

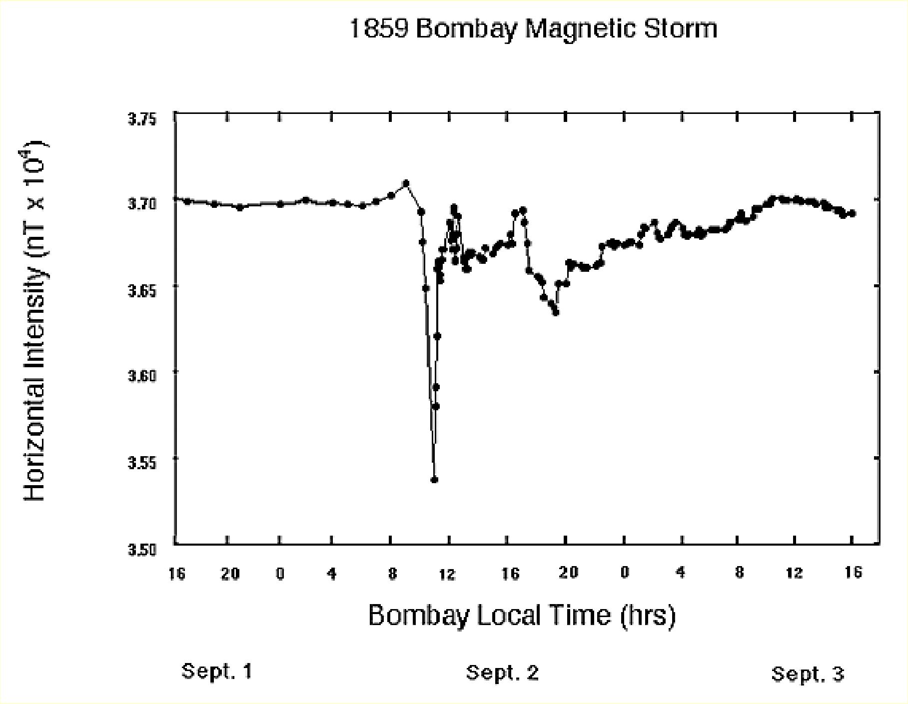
Historical Geomagnetic Storm of September 1-2, 1859



- Carrington Flare Sketch

Space Weather, Sun-Earth Connection Not Known

No knowledge of CME, no coronagraphs

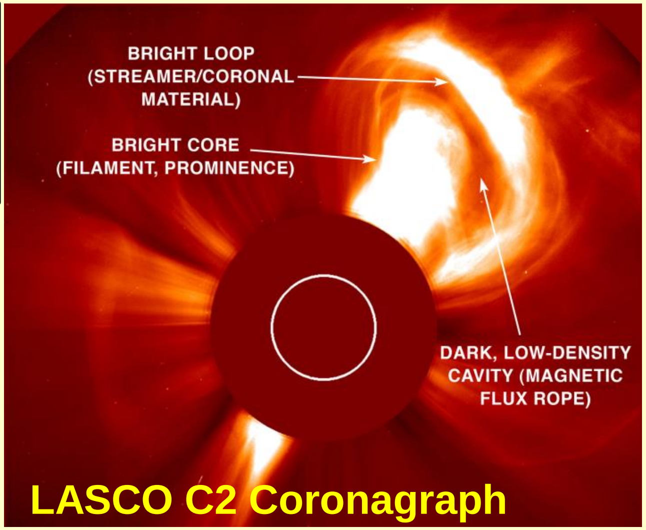


Sun-Earth Connection: The Bz problem for space weather prediction

3 part structure of CME observed near the Sun

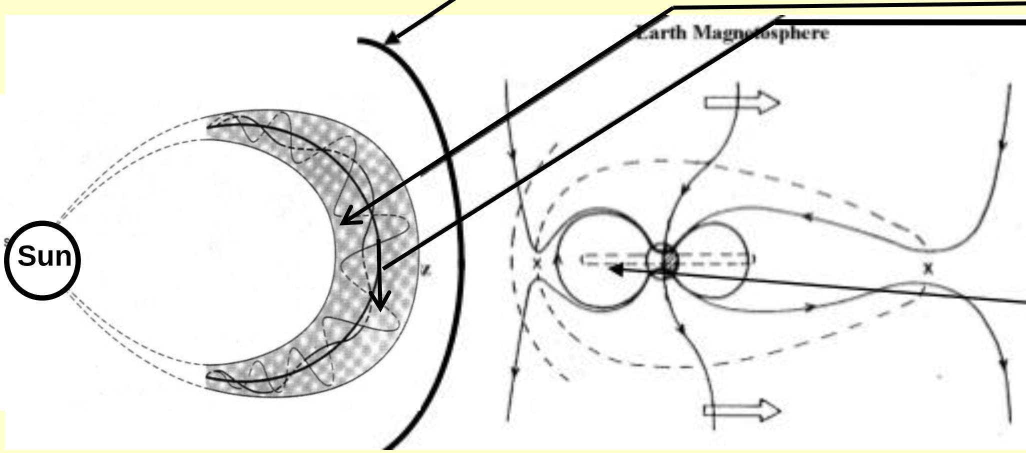
CME near the Sun	CME in the solar wind (ICME)
Coronal Shock	IP Shock
Frontal Structure	Sheath
Cavity	Magnetic Cloud Ejecta
Prominence Core	Pressure Plug

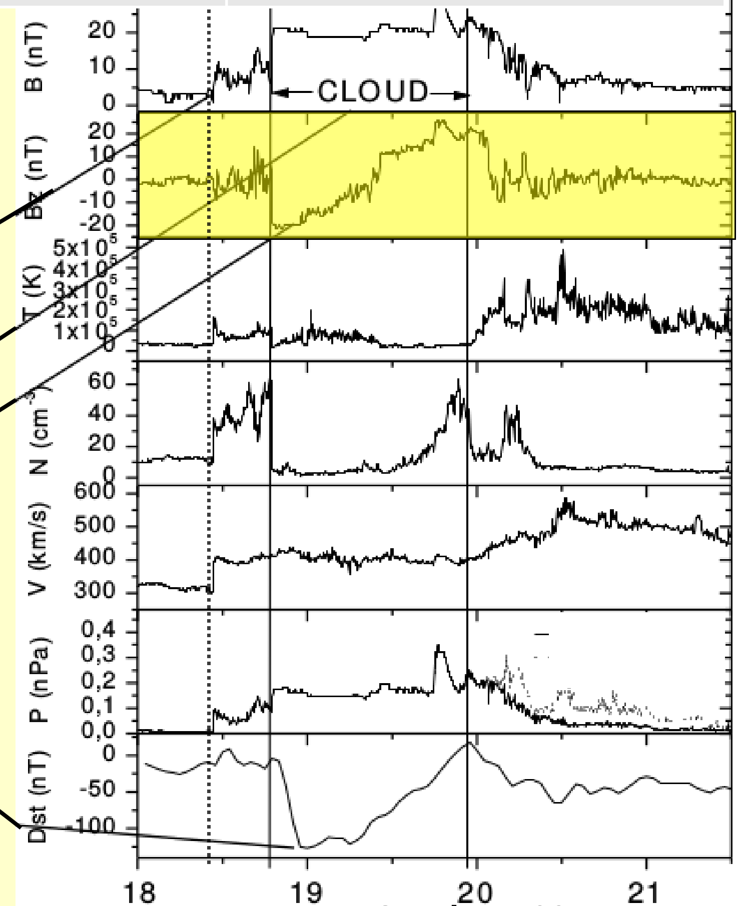
Remote sensing observa-tions



In situ observ ations

CME Arrival at Earth





October 1995

Gonzalez & Tsurutani 2005, Gopalswamy 2006

Space Weather prediction involves

Prediction of two important parameters

(a) Prediction of the magnitude of the resulting geomagnetic storm

Involves direction of propagation & prior Bz knowledge

(a) The arrival time of the CME at the Earth

Requirement

1. Identification of solar sources (CMEs /CIRs)
2. Understanding of the propagation of CMEs in IP medium
3. Identification of key interplanetary (IP) parameters
4. Relation of IP parameters with the solar parameters
5. Relationship of the strength of the geomagnetic storm with the IP parameters.

Status of Space weather prediction efforts

In-situ Observations based:

Existing Prediction Schemes (Based on the original formula of Burton et al. 1975):

O'Brien and McPherron (2000)

Feldstein (1992)

Feinrich and Luhmann (1998)

Schemes are reliable and depend on IP characteristics i.e. solar wind velocity and Bz component of the IMF

Problem: Warning time of 45 minutes to 1 hour!

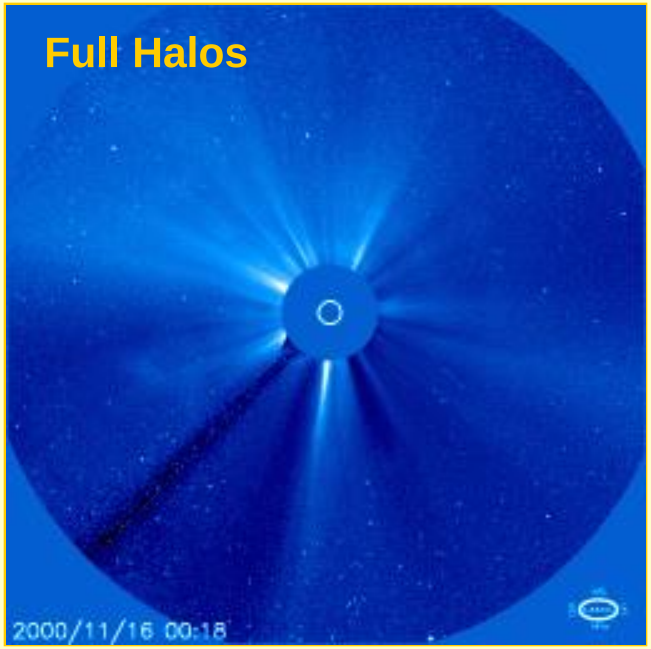
For advance prediction in time: Solar parameters required.

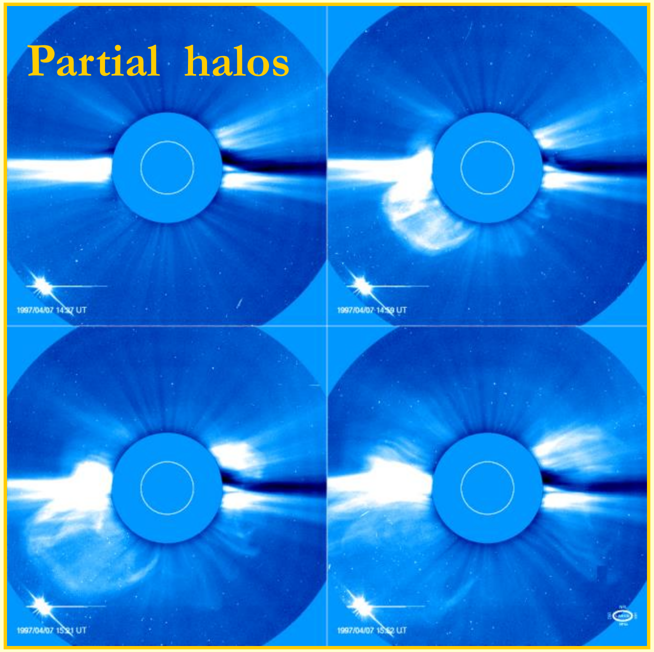
Status with solar inputs using halos: Schwenn et al. 2005

A significant number of magnetic storms cannot be predicted : 'missing alarms' (20%)

Similarly some of predicted events never occur 'false alarms' (15%)

Solar Sources: Halo-CMEs



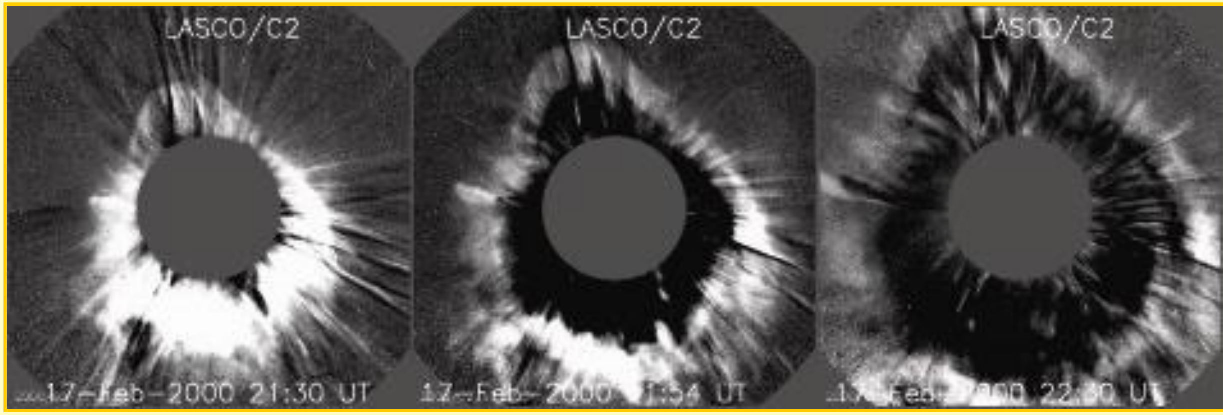


Fast moving halos important

(Gosling et al. 1990, Srivastava & Venkatakrishnan 2002, Zhao and Webb, 2003)

Asymmetric halos

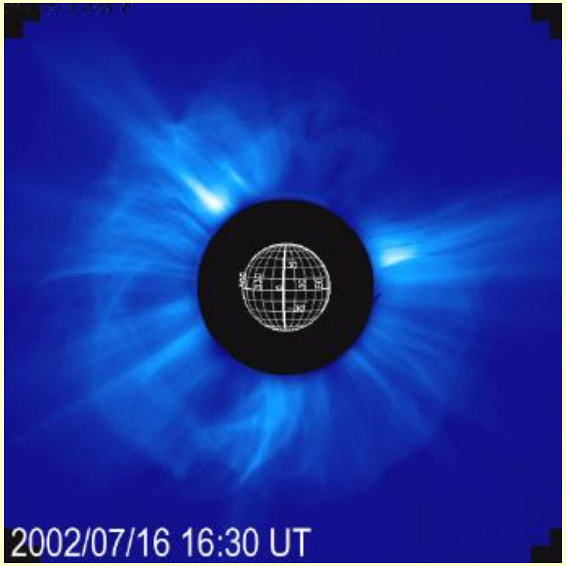
Schwenn et al. 2005



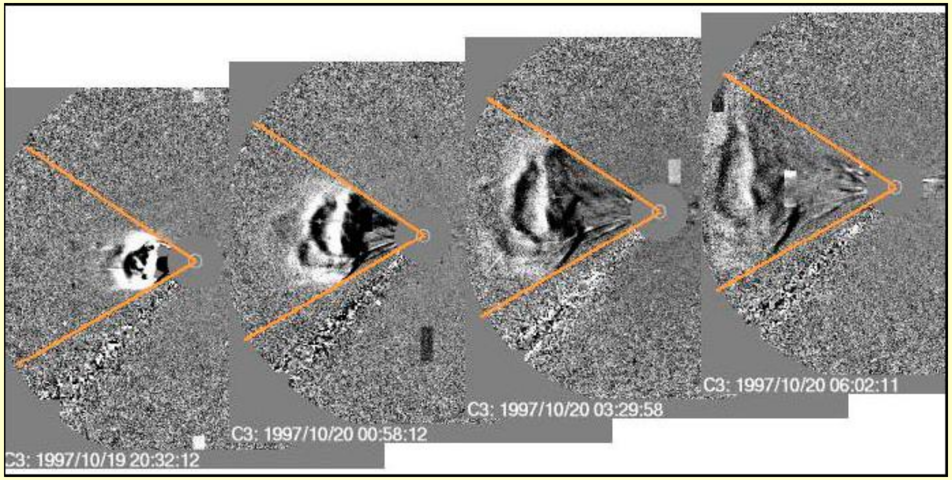
The key problem in space weather forecasting:

Infer the the CME speed component V_{rad} along the line-of-sight

(Schwenn et al. 2005)



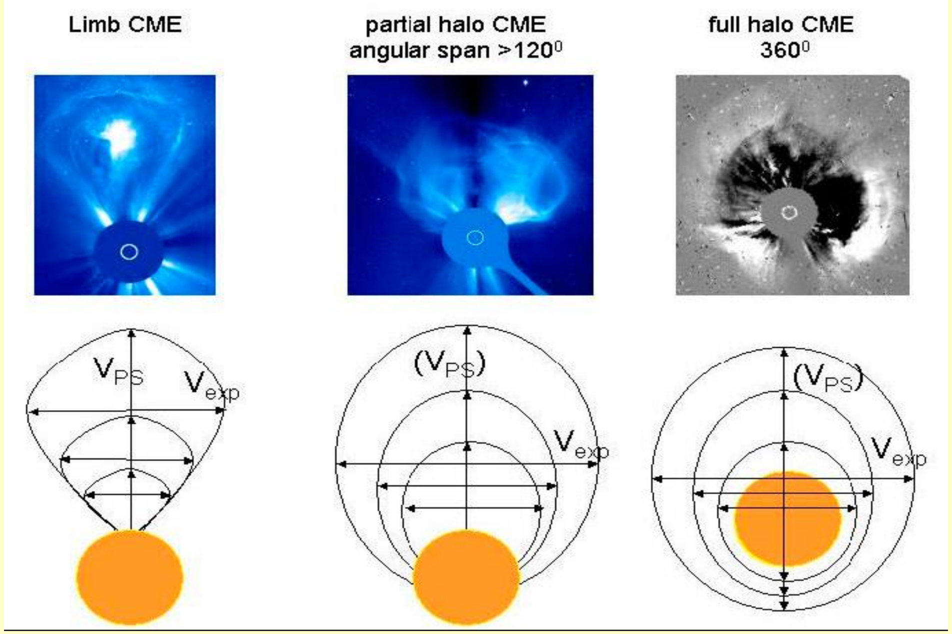
Self-similarity of CMEs



The cone angle and the general shape of CME is maintained.

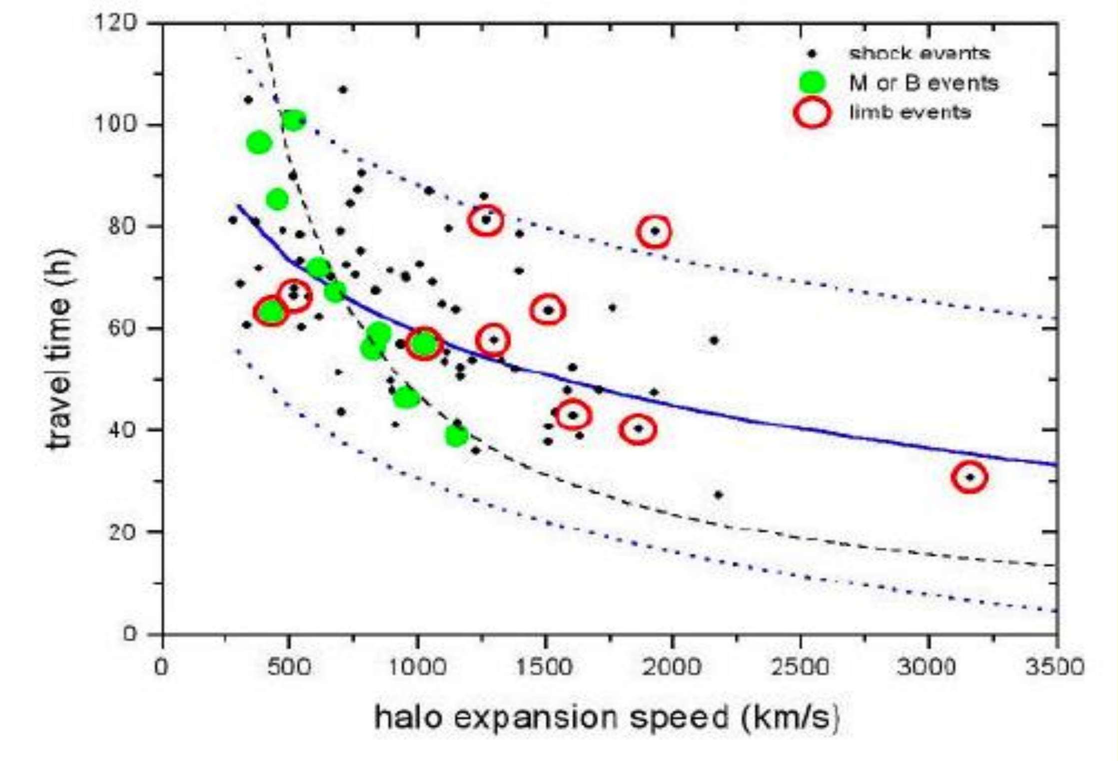
Ratio between the lateral expansion and radial propagation remains constant.

$$V_{rad} = 0.88 \times V_{exp}$$



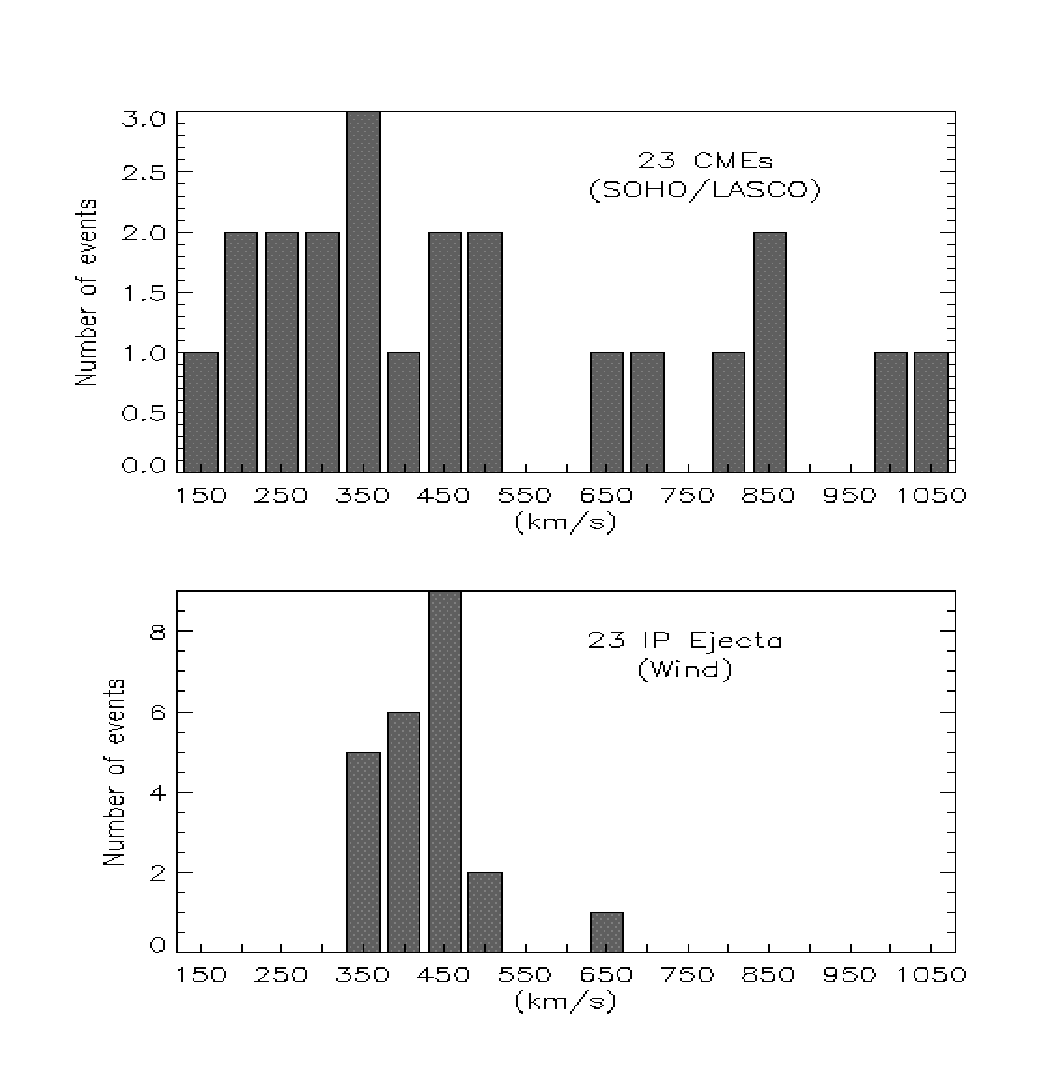
Travel Time Estimation

$$T=203 - 20.77 \ln V_{exp}$$



Schwenn et al. 2005

Propagation of CMEs



Influenced by Interaction of the CME with the Solar Wind

Close to the Sun

CME Initial speed 200-2000 km/s, vary by a factor of 10

Close to the Earth

ICME speed vary by a factor of 3

Gopalswamy et al., 2000

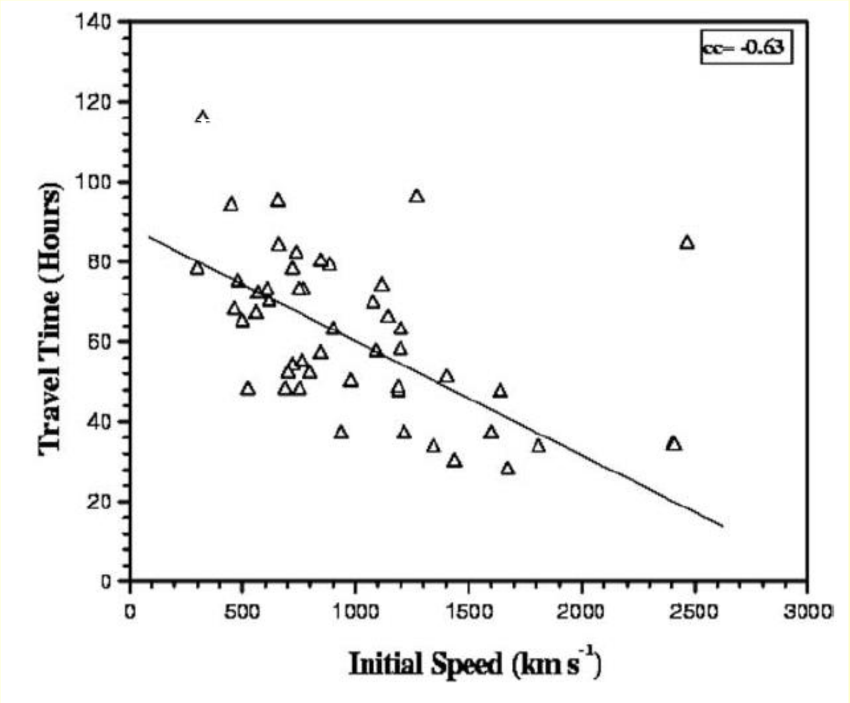
Arrival time prediction of CMEs

:

Arrival time= T_{CME}-T_{STORM}

Prediction poor due to lack of observations in the region between near sun and near earth

Empirical models based on 2 point measurements obtained from SoHO data.



Models used

• Arrival time =80 hours [Brueckner et al. 1998]

• T=96- (V/21) [Zhang et al. 2003]

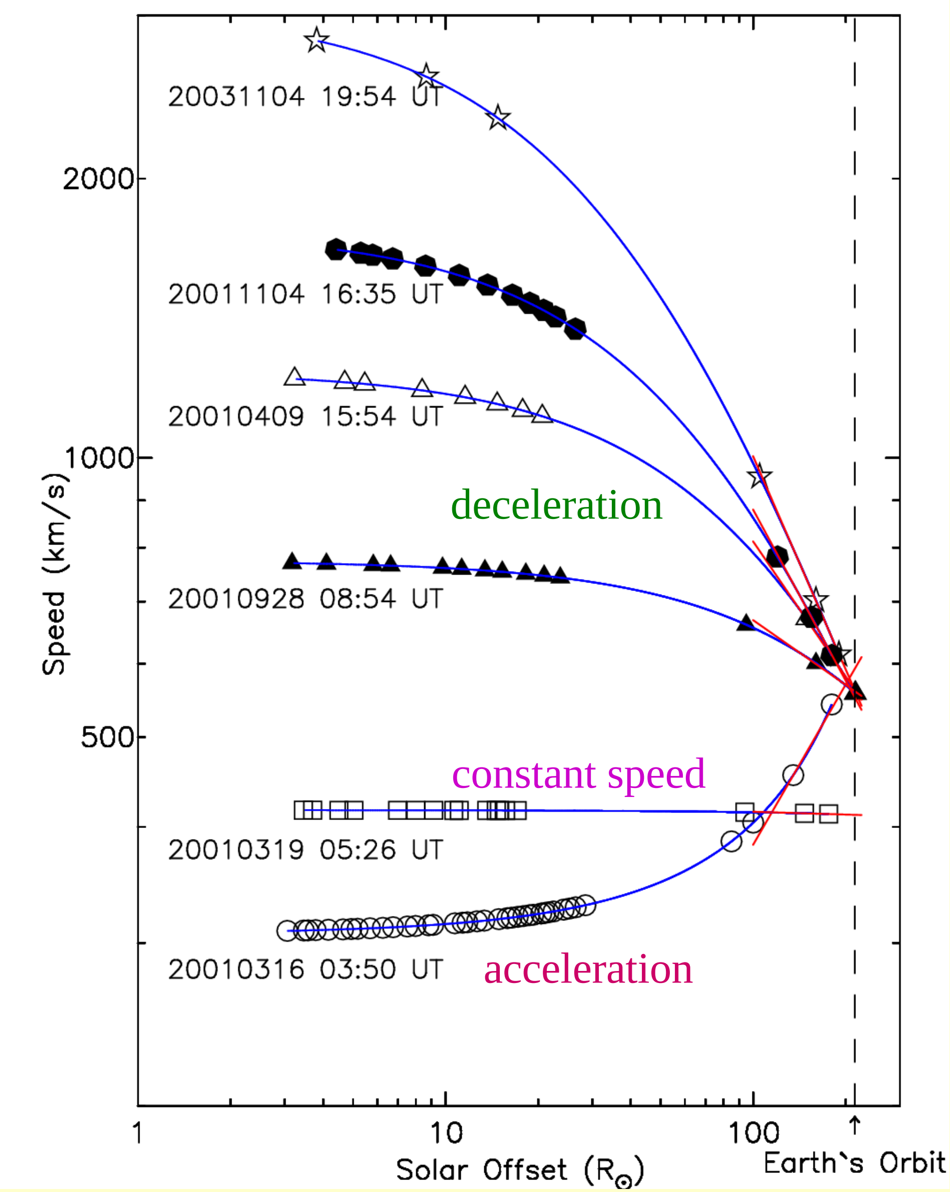
•T=27.98 + (2.11x 10^4 /V) [Wang et al. 2003]

•T=86.9 -0.026 V [Srivastava & Venkatakrishnan 2004]

What have we learnt from LASCO/SOHO observations?

1. Front-side halos potential candidates for geoeffectiveness.
2. Their initial speeds decide their time of arrival at the earth & magnitude of resulting geomagnetic storm. (Srivastava and Venkatakrishnan, 2002, Gonzalez et al.2004, Yurchyshyn et al. 2004
3. First step towards prediction: Projected plane-of-sky speeds give a "crude" estimate of their arrival time.

Speed Profiles: $V_{CME}(R)$ LASCO & IPS



Manoharan 2006

- Include constant speed, accelerating and decelerating events
- $V_{CME}(R)$ can be represented by power-law

  $V_{CME}(R) \sim R^{-\beta}$ $R < 50\ R_\odot$

  $V_{CME}(R) \sim R^{-\alpha}$ $R \sim 100 - 200\ R_\odot$

- at $R < 70\ R_\odot$: $-0.3 < \beta < +0.06$
- at $R > 70\ R_\odot$: $-0.76 < \alpha < 0.58$

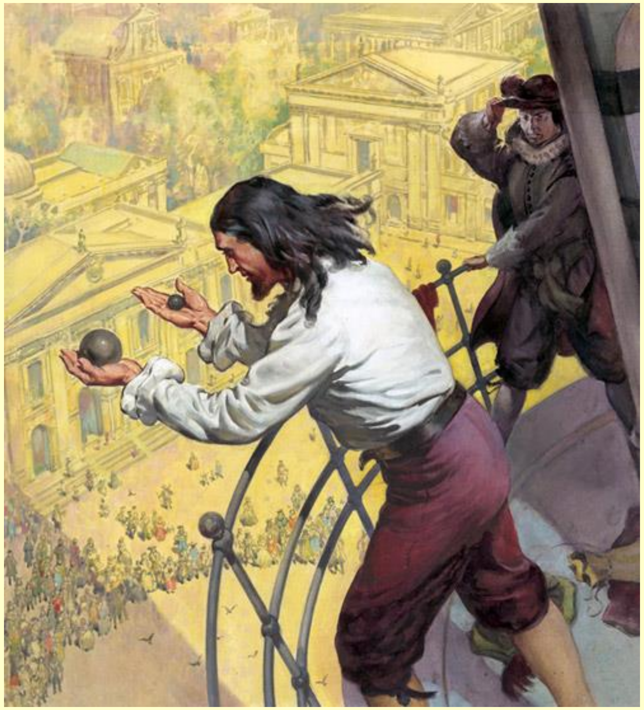
•Up to a distance of ~80 $R_\odot$, the internal energy of the CME dominates.

•At larger distances, the interaction of CME with the solar wind takes control.

Arrival Time of CMEs: Scenario prior to STEREO

"A number of CMEs be dropped from La Torre di Pisa and their drag force be directly measured!"

Reiner et al. 2003



Safe statement to make:

•For an isolated undisturbed front side halo CME the shock/ICME arrival time at the earth can de derived.

•There is a 95% probability that the shock will arrive within ±24 hrs around that predicted time.

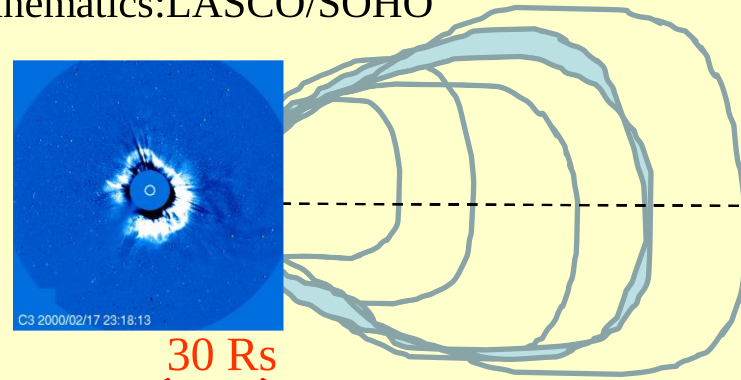
Schwenn et al. 2005

"Thus, each CME has a unique evolution trajectory and to predict the CME arrival at 1AU, multi-point measurements are essential."

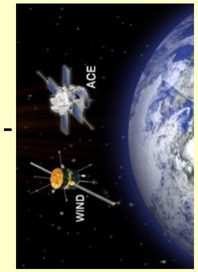
Manoharan 2006

CME propagation

Projected morphology & kinematics:LASCO/SOHO



In situ data: Single point, 1D



e.g. Drag Based Model

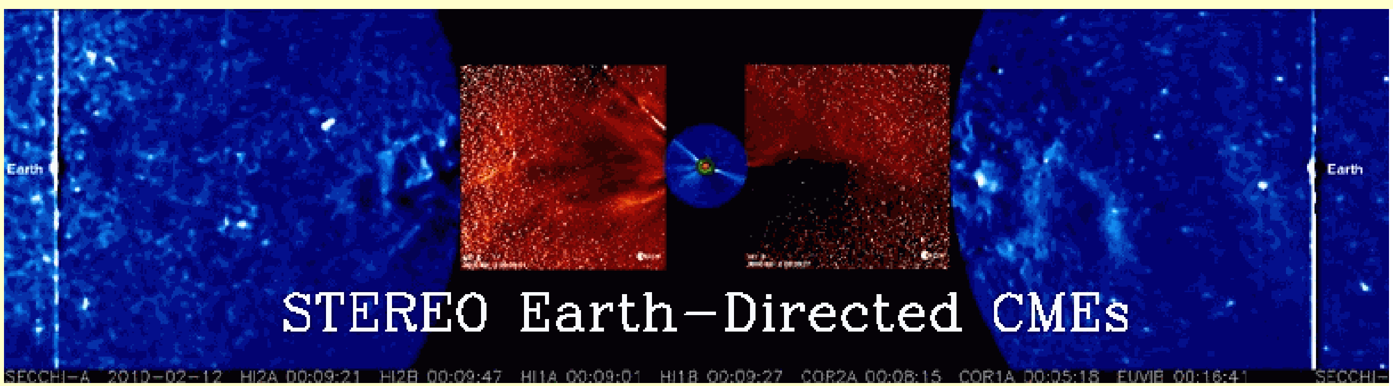
Use of models to fill the gap

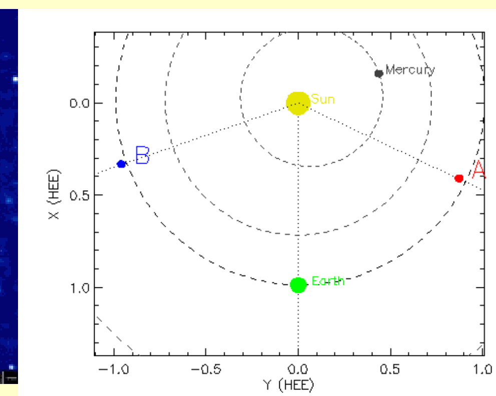
Error= ± 24 hr

30 Rs

~ 215 Rs

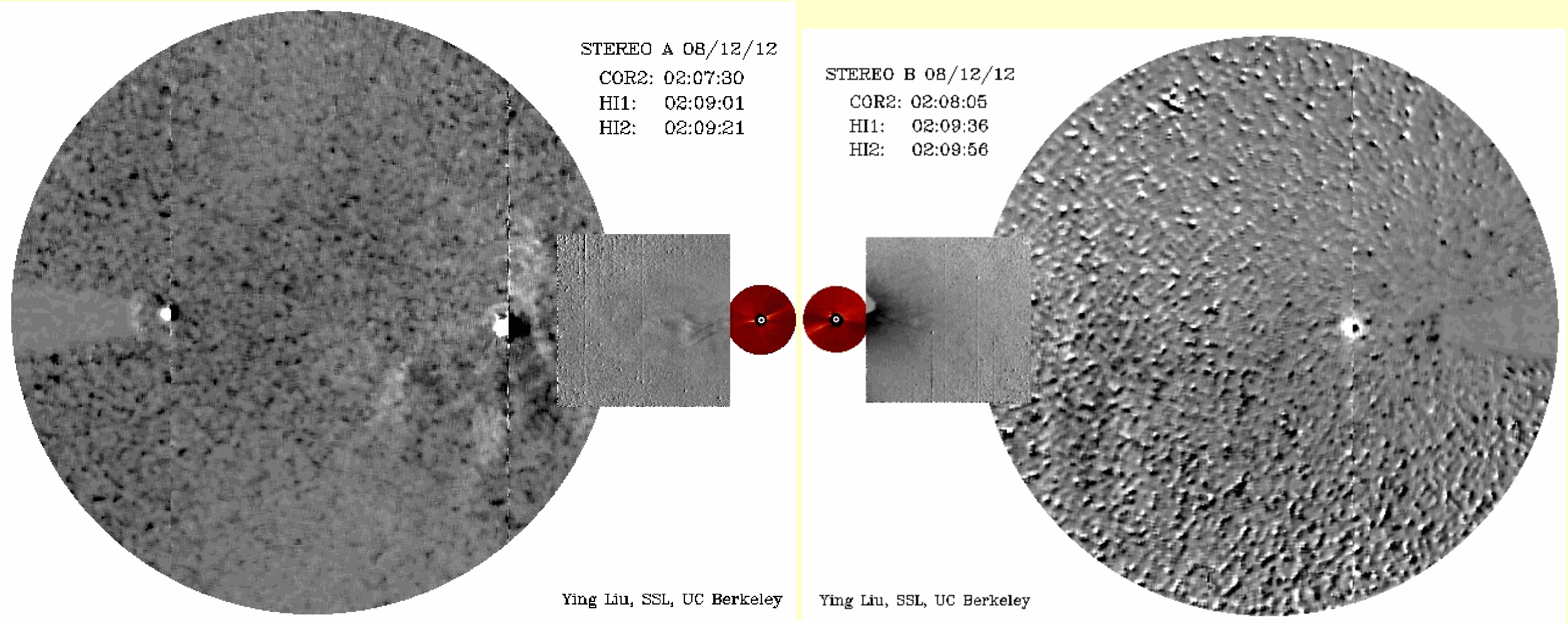
Since 2007, stereoscopic observations (from STEREO A & B) are available:



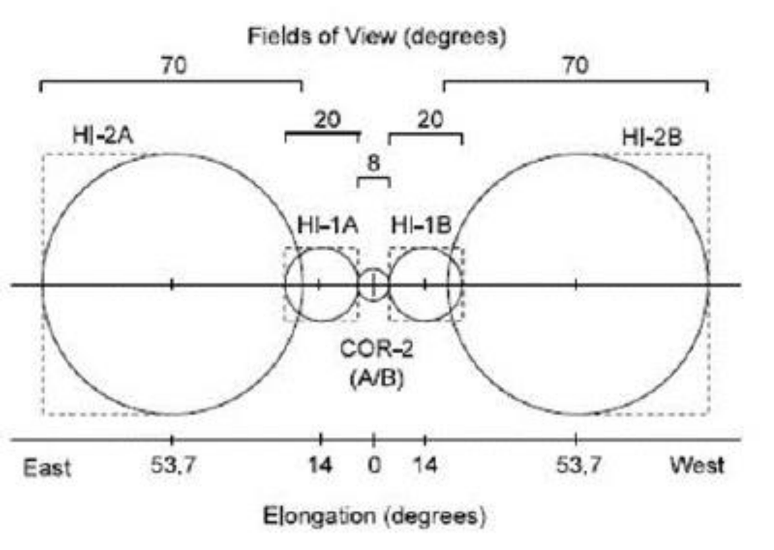


The Sun-Earth-Connection Coronal and Heliospheric Investigation (SECCHI)

STEREO -View



12 December 2008
CME –STEREO A



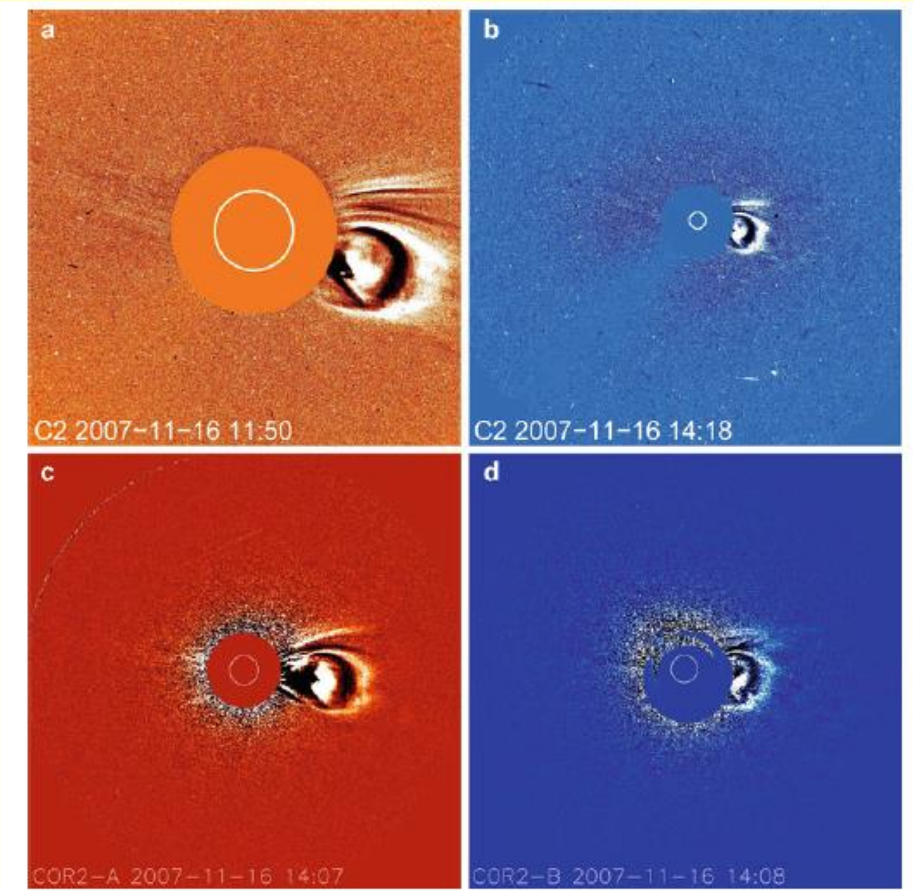
12 December 2008
CME –STEREO B

- Coronagraphs:

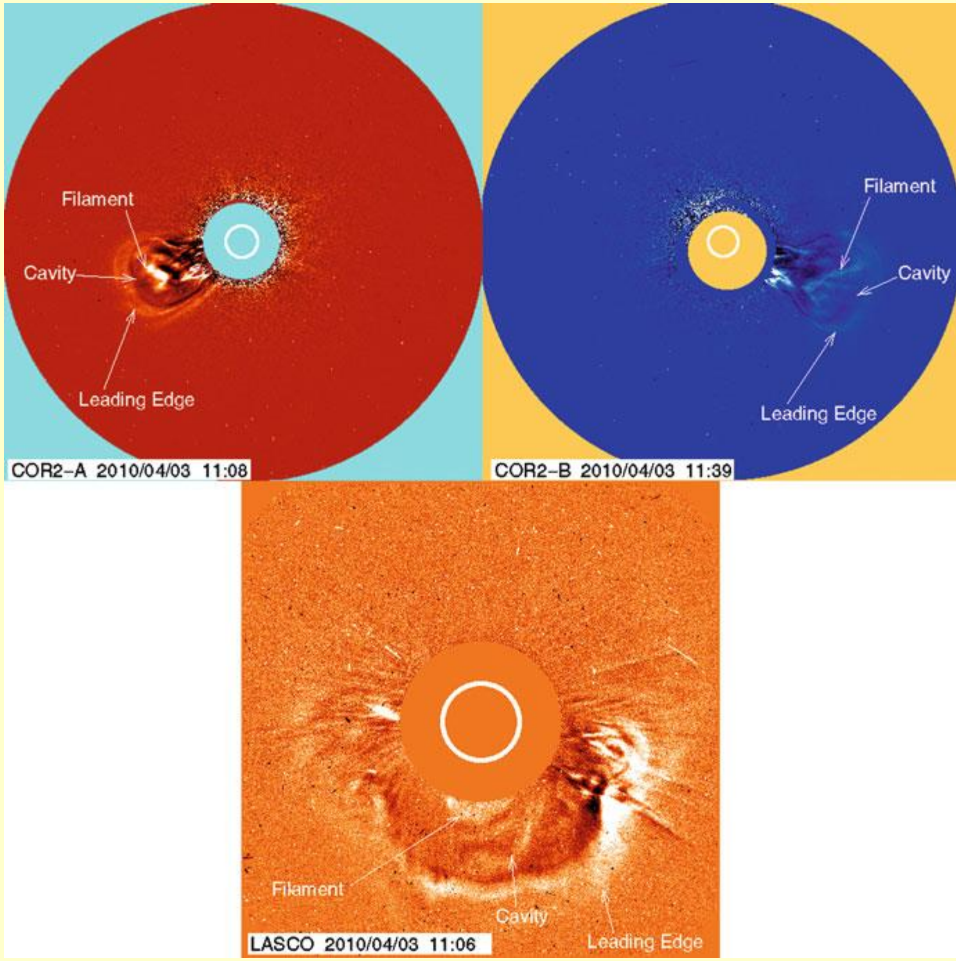
  COR1 (1.4 – 4 $R_\odot$)
  COR2 (2.5 – 15 $R_\odot$)
- Heliospheric Imager (HI)
  HI-1 (12 – 88 $R_\odot$)
  HI-2 (66 – 330 $R_\odot$)

Different views of same CME

Limb CME in 2007 (<40^0)

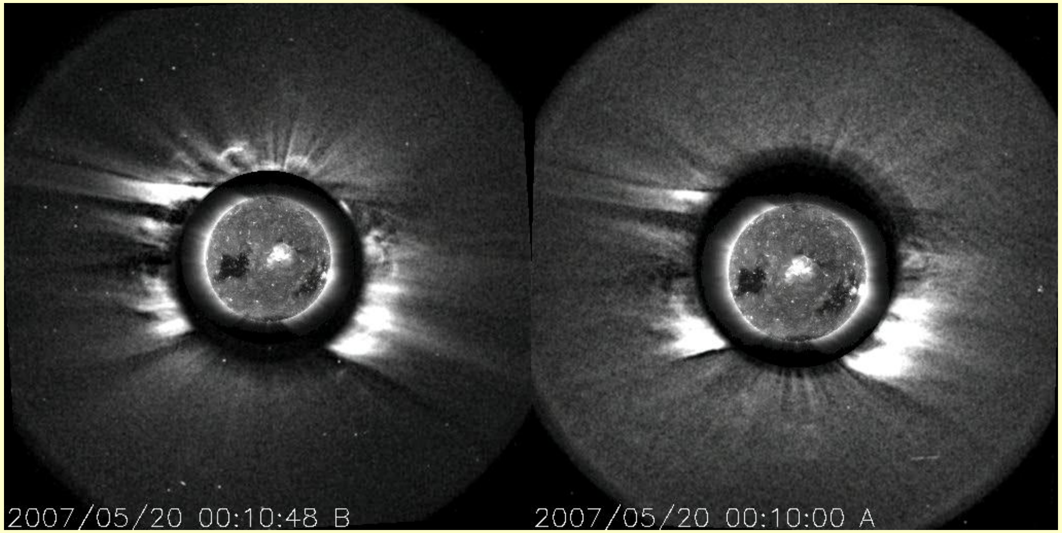


Earth-directed CME in 2010 (>90^0)



Howard, 2011

Reconstruction of the LE of Partial Halo CME May 20, 2007

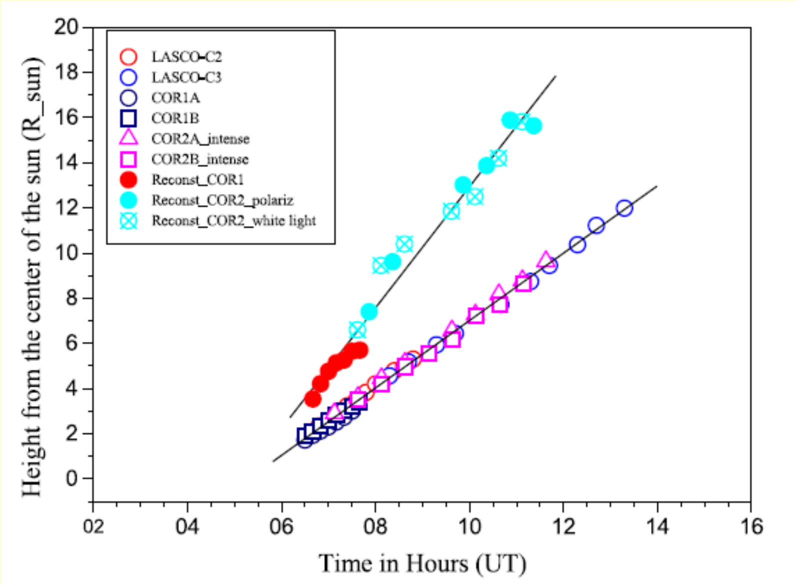


Reconstructed leading edge at different times (using tie-pointing technique) plotted in COR1 field of view.

projected speed of the LE; **285 km/s**

reconstructed speed of the LE; **510 km/s**

the mean speed from the travel time along the Sun-observer line; **535 km/s**



Srivastava et al. 2009

Estimating arrival time of CMEs using Drag -Based Model

- The key role of solar wind in the propagation of CMEs beyond the 20 R_s is well established.

(Vrsnak et al., 2010, 2012)

$$a_d = -\gamma(v-w)\,|\,v-w\,|$$

Drag acceleration

$$\gamma = \frac{c_d A \rho_w}{m}$$

γ lies in the average range of $0.2 \times 10^{-7} – 2.0 \times 10^{-7}$ km^{-1}.

where

$$A = \prod\left(\frac{\phi}{2} r\right)^2$$

v ~ CME speed
w ~ ambient SW speed
c_d ~ dimensional drag coefficient
A ~ cross sectional area of CME
ϕ ~ CME cone angular width
ρ_w ~ ambient solar wind density
m ~ CME mass

3D Speed: Using tie-pointing method on COR2 observations alone:

CME dates	Actual arrival time (UT) of CME leading edge at L1	Error in predicted arrival time	Measured velocity of CME leading edge at L1	Velocity (Km s^{-1}) in COR2 FOV
12 Dec 2008	17 Dec 04:39	-26.9	365	453
07 Feb 2010	11 Feb 12:47	-21.8	360	480
12 Feb 2010	16 Feb 04:32	-41.5	310	867
14 Mar 2010	17 Mar 21:19	+27	450	335
03 Apr 2010	05 Apr 13:43	-2.3	800	816
08 Apr 2010	12 Apr 02:10	-9.5	410	478
26 Oct 2010	31 Oct 06:30	-46.7	365	600

Mishra, and Srivastava, 2013

Arrival Time Estimates

kinematics of 8 CMEs: Using GT technique on HI observations

CME dates	Actual T_{arr} (Peak density time)	Error in predicted T_{arr} at L1 (hr)		Actual v1 at L1 (km s^{-1})	Error in predicted v1 at L1 (kms^{-1}) [γ = 0.2 – 2.0 (10^{-7} km^{-1})]
		Kinematics + Drag Based Model [γ = 0.2 – 2.0 (10^{-7} km^{-1})]	Distance + Polynomial fit		
12 Dec 2008	16 Dec 23:50	-3.4 to -3.9	+6.5	356	-25 to -18
07 Feb 2010	11 Feb 02:05	-4.3 to -3.2	-1.2	370	+72 to +23
12 Feb 2010	15 Feb 23:15	-8.7 to -7.9	-7.1	320	+122 to +81
14 Mar 2010	17 Mar 21:45	-0.6 to +3.2	-5.4	453	-16 to -75
03 Apr 2010	05 Apr 12:00	+5.5	-3.0	720	-96
08 Apr 2010	11 Apr 14:10	-4.4 to -1.2	-7.6	426	+85 to -24
10 Oct 2010	15 Oct 06:05	+5.5 to +5.6	-7.2	300	+54 to +53
26 Oct 2010	31 Oct 03:30	-3.7 to -4.0	-18.9	365	-24 to -22

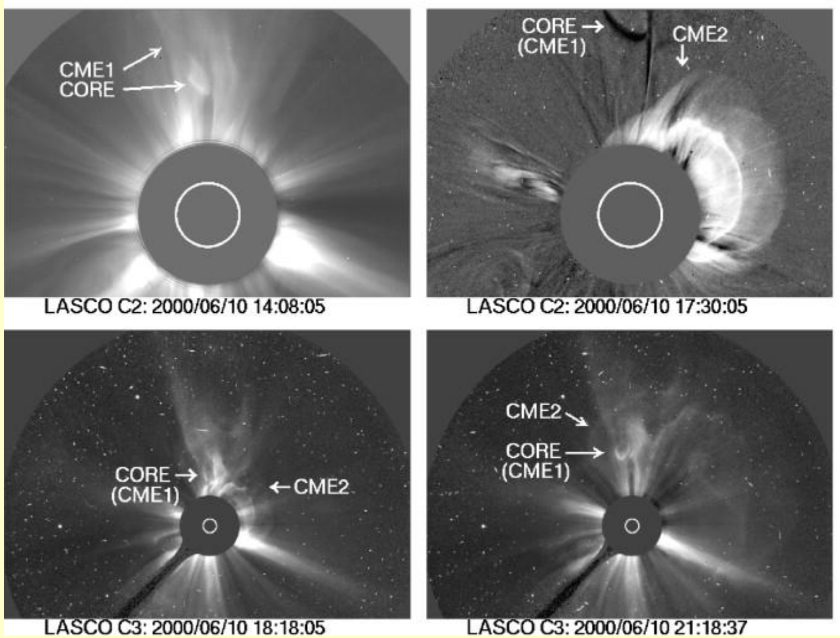
- GT technique + DBM is better (within 3 to 9 hr) than using only 3D speed in COR2 observations.

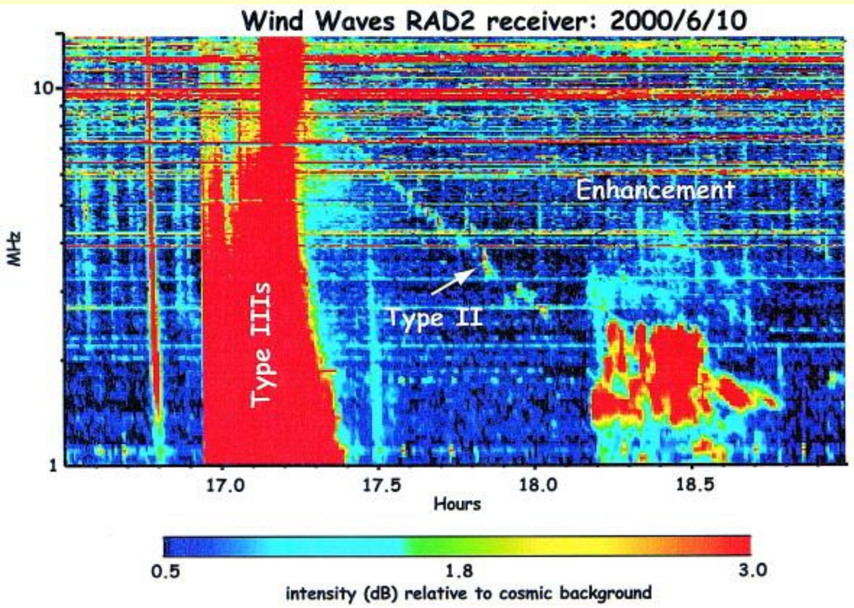
Propagation speed altered by CME-CME interactions

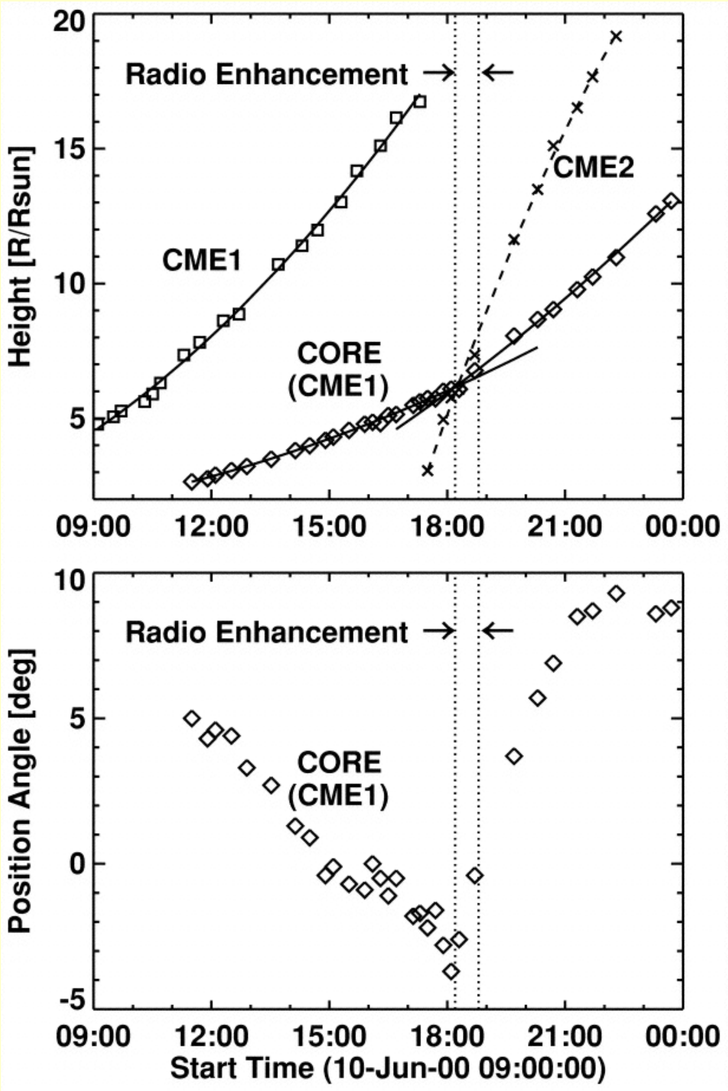
Average travel time of CMEs: 1 to 4 days
Launch rate: ~ 5 around solar maximum → CMEs in quick succession →
Collision or merging (depends on kinematics)

Launch rate: ~ 1 in 3 days, around minimum → Unlikely

LASCO (white-light) and Wind/Waves (radio) observations
Gopalswamy et al. (2001)





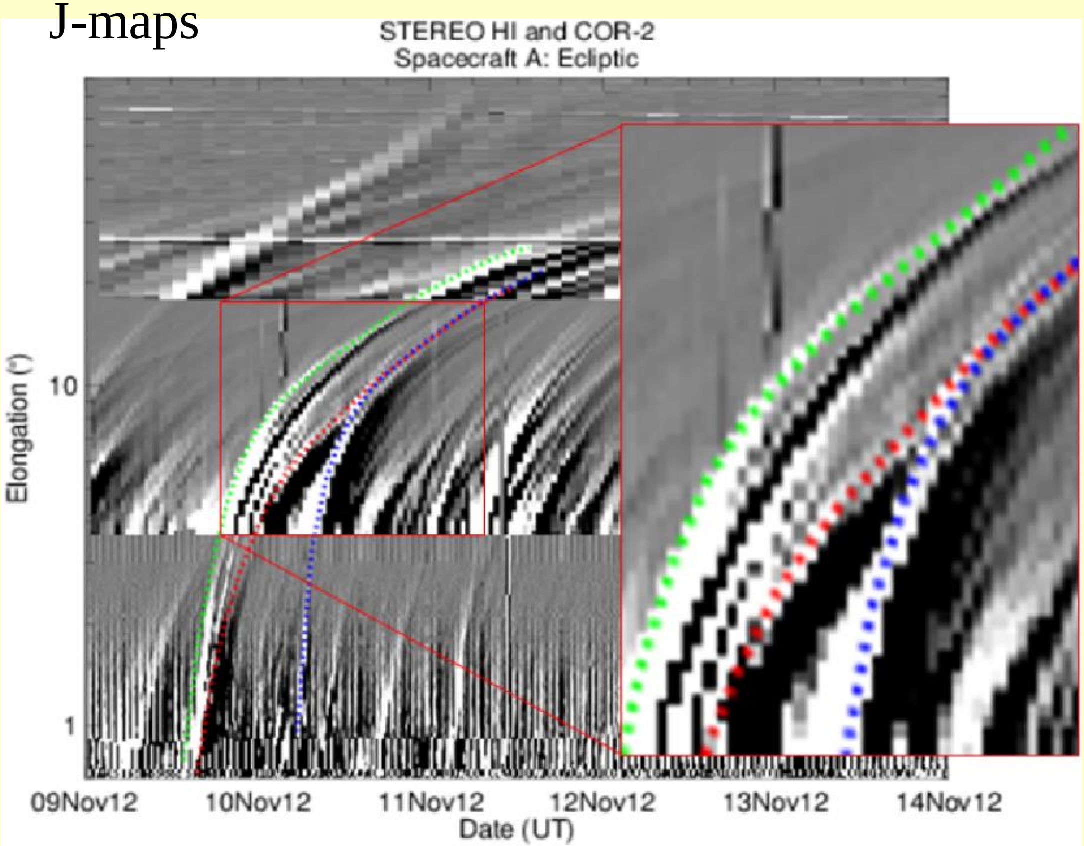


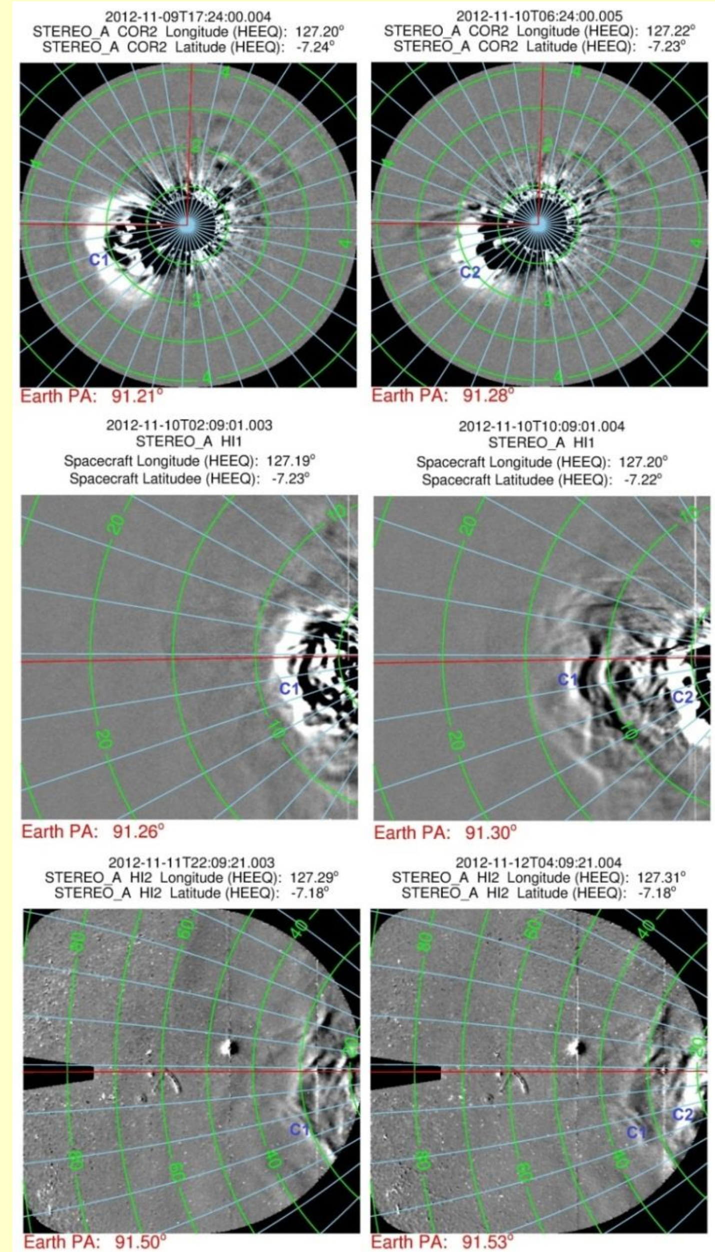
Radio Enhancement & Change in direction

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.

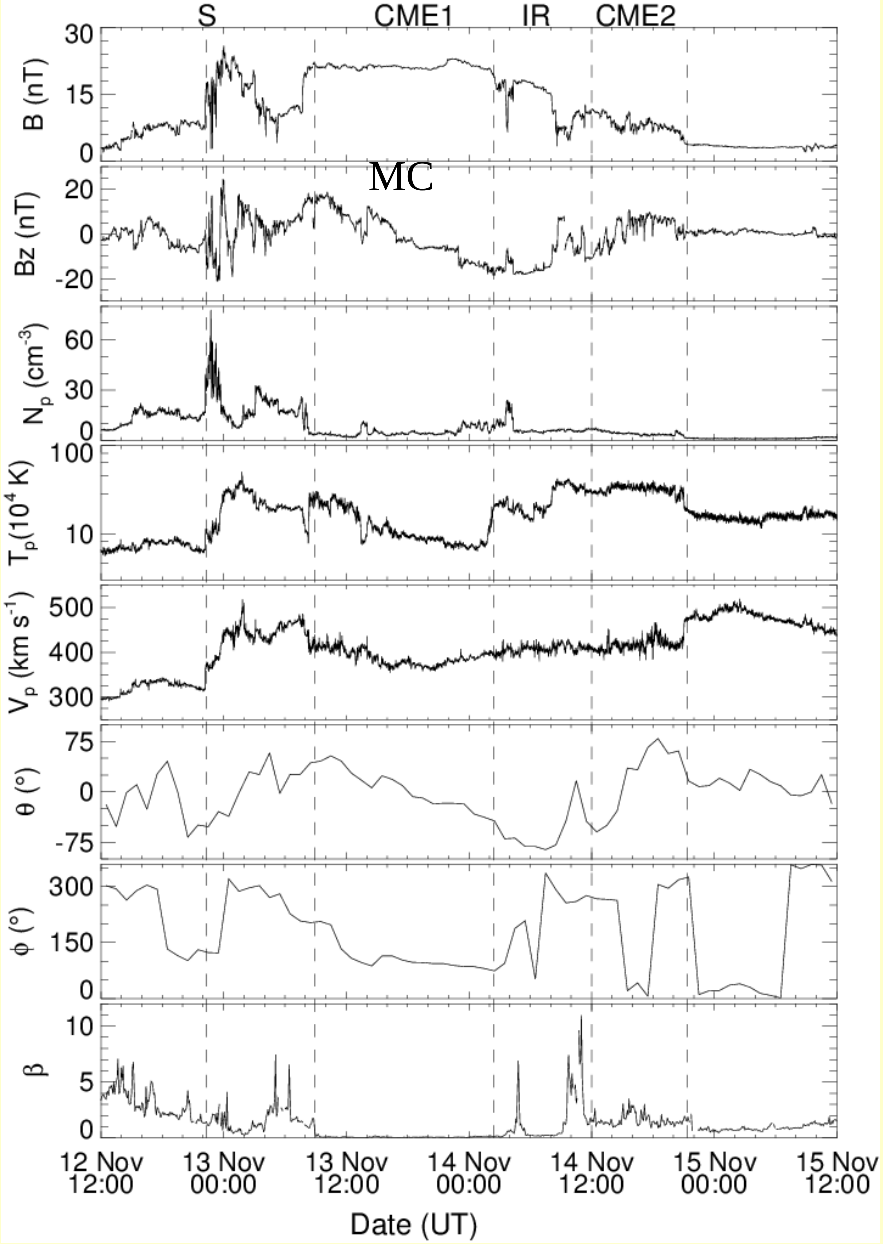
J-maps

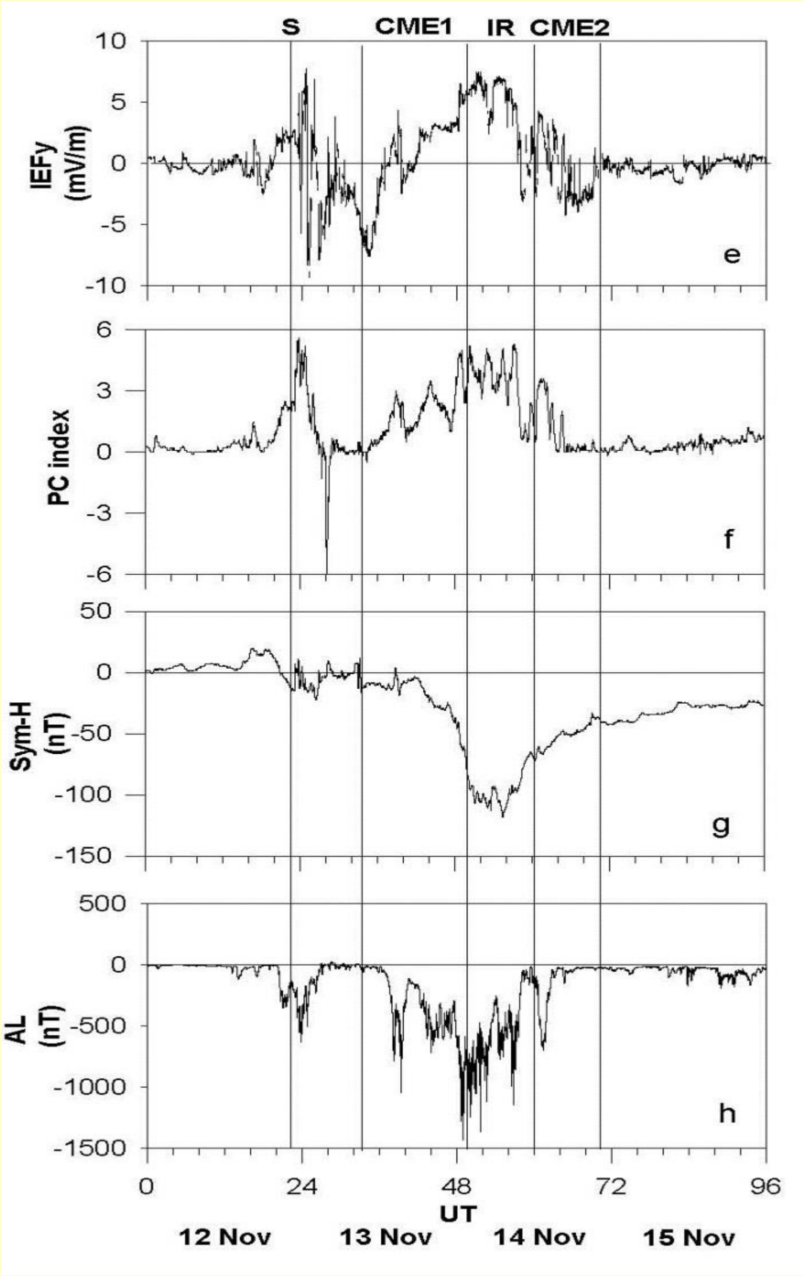




Green: CME1 Leading edge (LE),
Red: CME1 Trailing edge (TE), Blue: CME2 LE

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





Mishra, Srivastava, and Chakrabarty, 2015

Observed cases of Interacting CMEs (STEREO/SECCHI observations)

Interacting CMEs	CME1 Source Location, NOAA No.	CME2, Source Location, NOAA No.	propagation direction of CME1 &2 (longitude)	Interaction location (Rsun)	Collision Type	Mass ratio (M2/M1)	Momentum exchange	Dst (nT)
August 3 &4, 2011	11261, N16W30	11261, N19W36	14.8^0, 19.2^0	157	perfectly inelastic	1.38		-113
January 18 & 19, 2012	11401 N19E38	11402, N32E22	-2^0,-7^0	85	perfectly inelastic	3.2	74%, -11%	-69
March 4 &5, 2012	11429, N19E61	11429,N17E52	-28^0, -32^0	~185	inelastic (0.2)	3.2	36%, -40%	-95
September 25 &28, 2012	11575, N08W04	11575, N09W30	-19.5^0, -6^0	Merging at the Earth (215 & beyond)	elastic (0.86)	5.54	195%, -38%	-119
February 14 &15, 2011	11158,S20W04	11158,S20W10	6^0,-3^0	25	elastic (0.89)	1.08	68%, -35%	-30
November 9 &10, 2012	Near 11608, S20E09	11608,S21W04	-10^0, -2^0	35	perfectly inelastic	0.48	23%, -31%	-108
May 23 & 24, 2010	N19W12	N18W26	11^0, 28^0	45	Inelastic (0.2)	0.5	27%, -35%	-85
June 13 & 14, 2012	11504, S16E18	11504, S17E06	-7^0, -3^0	90	perfectly inelastic	1.1	57%, -24%	-71
October 25, 2013	11882, S08E73	11882, S06E69	-77^0, -71^0	40	perfectly inelastic	1.23	42%, -19%	-55

Interacting CMEs

- Interaction of CMEs observed close to the sun as well as near the Earth. The closest distance is 25 solar radii (one event). Other interactions occur at a distance beyond 35 solar radii. Therefore, only few interactions have been reported in SOHO era.

- Interaction is more probable when the CMEs are launched from the same source region, in the same direction within a few hours (less than a day). Since the re- build-up and release of energy takes a finite time, it is more likely that in general, CMEs will interact in the heliosphere in the HI field of view at a distance close to the Earth.

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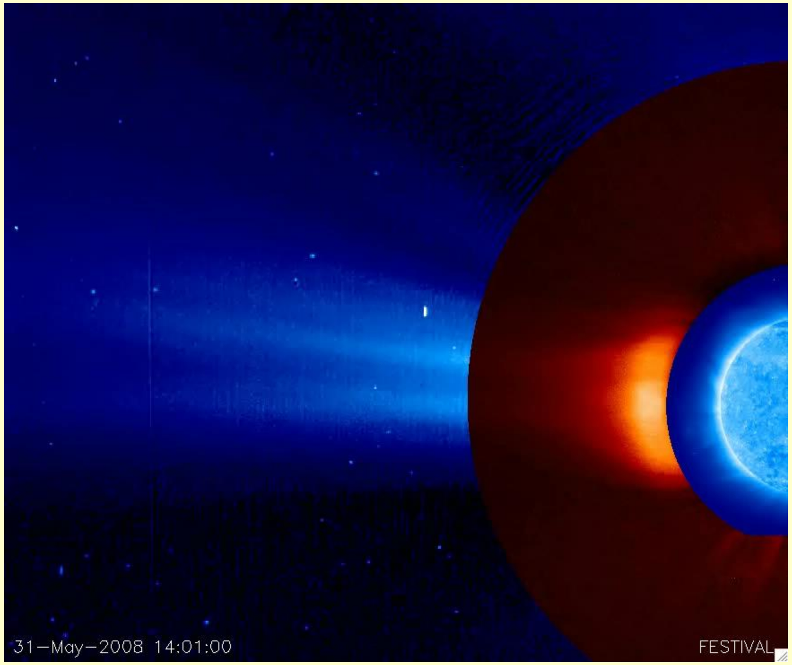
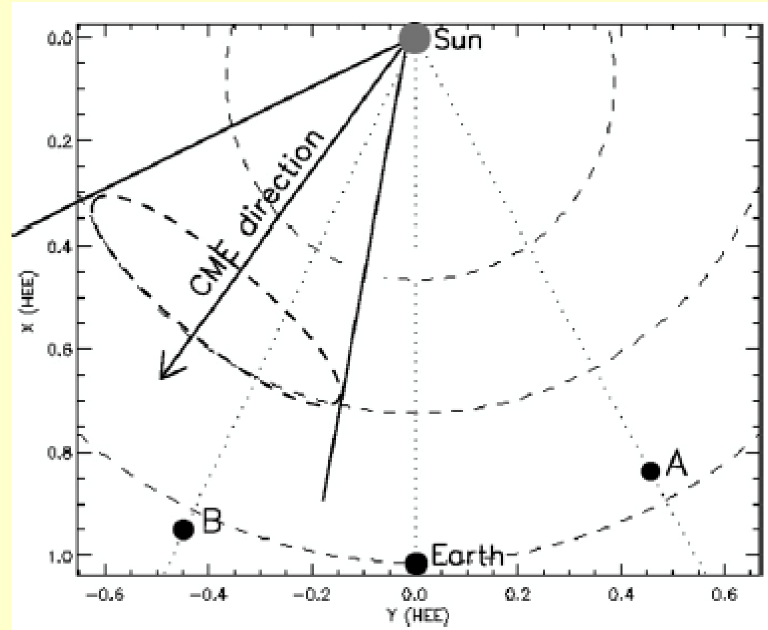
- Merging of CMEs probable when CME-CME interaction occurs closer to the Sun than the earth. This is possible when the events are fast and/or occur close in time. The merged structure generally leads to a single step storm.

- Two step storm signatures observed when the interaction occurs close to the Earth or events occur far in time and/or are slower in speed.

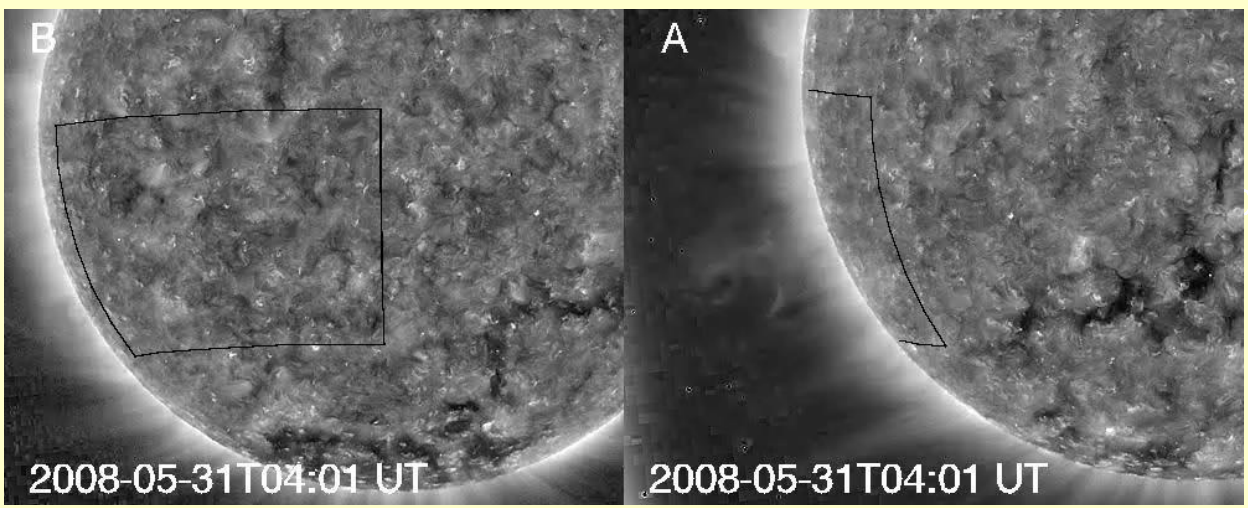
- Using the post-interaction speeds of CMEs participating in interaction, the arrival time estimates (several hours) are improved.

Challenges: Stealth CMEs (No Trace Left Behind)





Robbrecht et al. 2009



A slow eruption is seen in limb view (STA).

In disk view (STB), no signatures were seen indicative of a CME (e.g. eruption, dimming, EUV wave, post-erupion arcade (PEA), etc.

Stealth CMEs – Basic Properties and Why Do We Care?

- Diffuse CME
- Slow CME
- In limb view, CME identifiable only above ~1.5 Rs (heliocentric distance).
- Reminiscent of streamer blowouts (R. Howard et al. 1985).
- Possible source region near a filament channel (Pevtsov et al. 2013).

- Under certain circumstances, these events can be geoeffective.

- Zhang et al. (2007) showed 10 out of 88 major geomagnetic storms ($Dst \lesssim -100$ nT) in solar cycle 23 had no clear source on the disk.

3-Nov-2000 15:42:43 3-Nov-2000 20:11:43

- Kilpua et al. (2014) included a G2 (Kp=6) geomagnetic storm from a CME of unknown solar origin.

- We need to know where the CME comes from in order to understand or predict the ICME magnetic field.

Textbook Case: Solar Eruption ⟷ ICME at 1 AU

No Ambiguity

12-14 July 2012

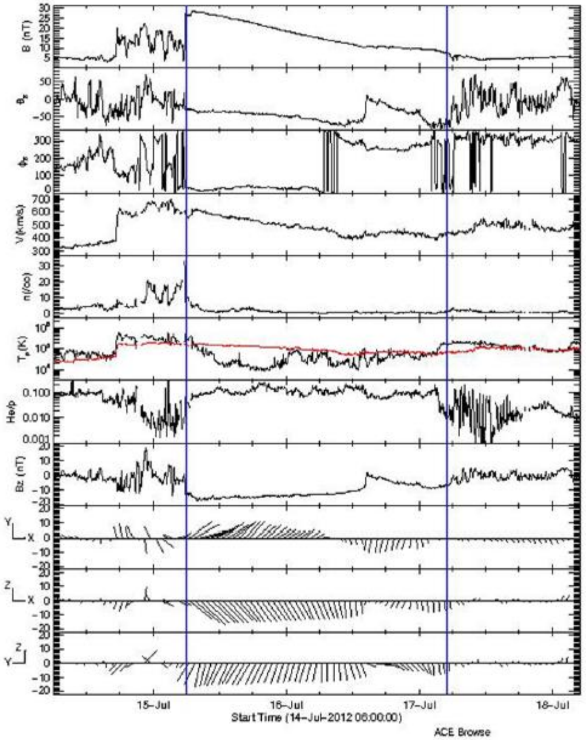
ICME
In-situ (ACE, Wind)

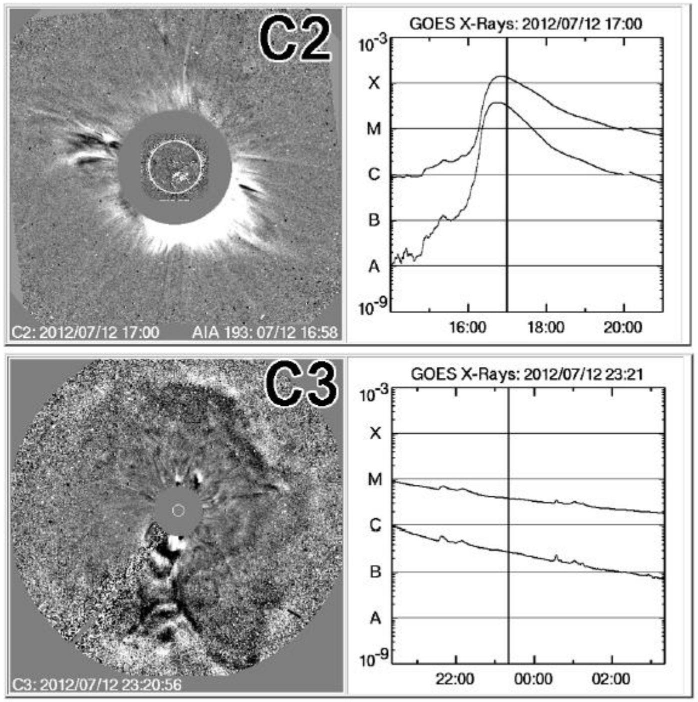
Step-1 →

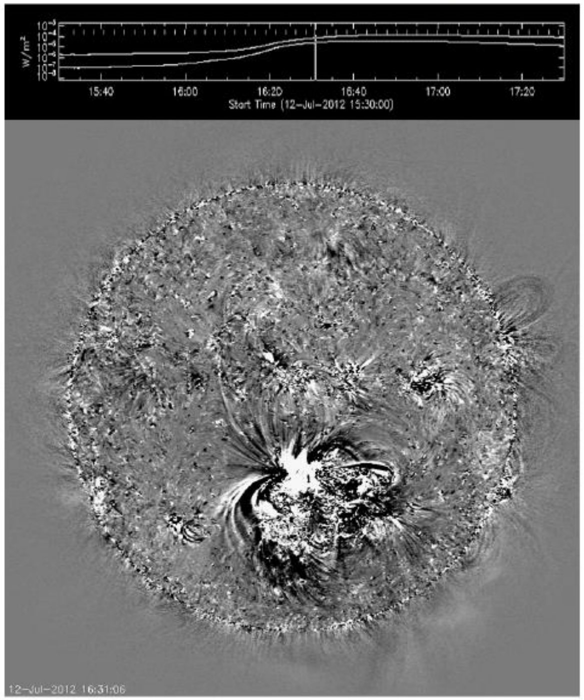
(Halo) CME
Coronagraph (LASCO)

Step-2 →

Low coronal signatures
EUV images (EIT, AIA)







From ~200 $R_\odot$ to ~30 $R_\odot$

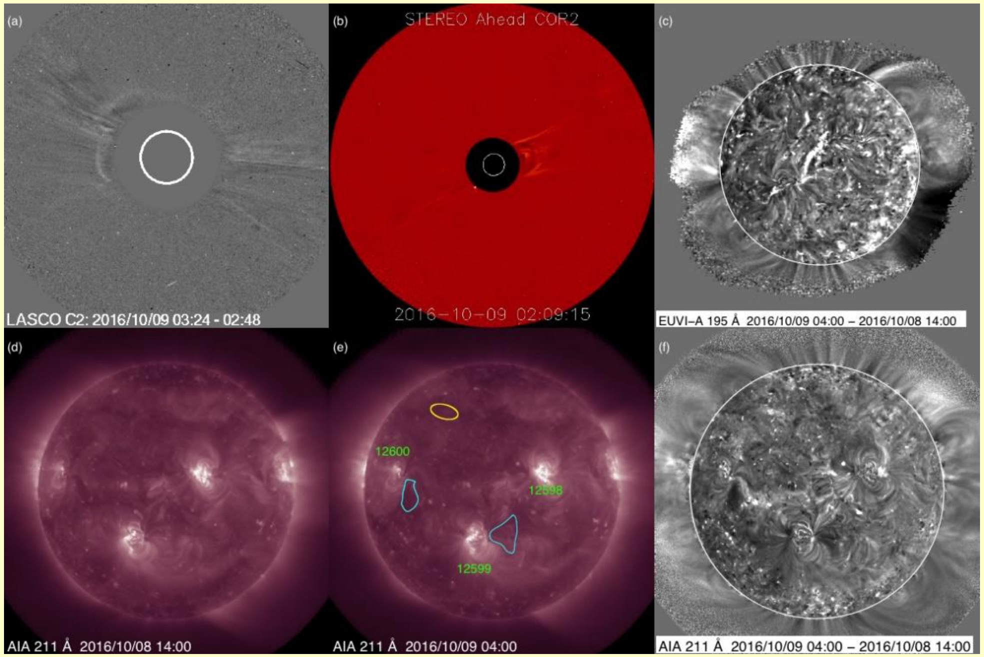
COR2 and HI1/2 of **STEREO** narrows the time range and provides side views

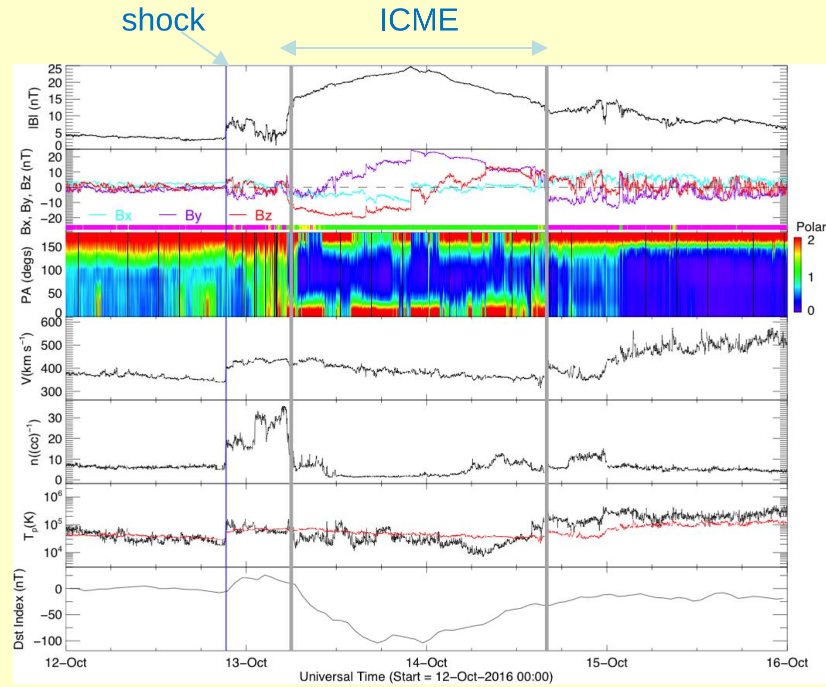
From ~2.2 $R_\odot$ to ~1.2 $R_\odot$

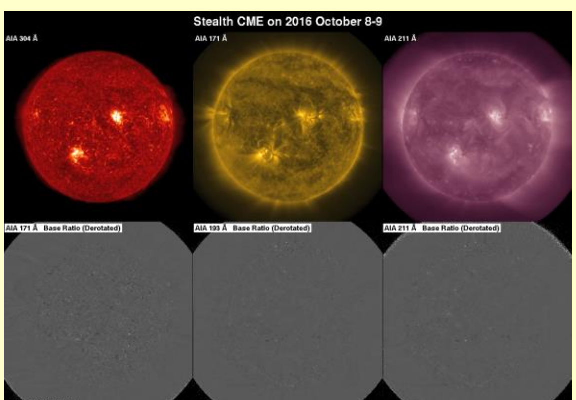
EUVI and COR1 of **STEREO** narrows the time range and provides side views

Challenging Stealth Event: 8 – 9 October 2016

CME on 8 – 9 October 2016







The CME was very diffuse. Without STEREO-A data, it could have been identified as a backside event.

A small filament eruption was seen in NE but it was too localized and early for the CME.

MAJOR SOLAR FLARE COULD HAVE BEEN LETHAL (1972)

Len Fisk: I had an interesting dinnertime conversation once with Neil Armstrong. And we were just chatting, and he said that the thing that he feared the most on the Apollo 11 mission was a solar flare.

Summary

More Observational Challenges:

- To predict a **flare, recurrent flares/CMEs**, initial CME acceleration and launch
- Future space missions and ground telescopes will drive the progress leading to a better understanding of solar sources and conditions of drivers of space weather, including the **very crucial Stealth CMEs**
- Prediction of **CME-CME interaction, possible deflection** in the interplanetary medium using the CME images in the inner and outer corona and the heliosphere
- Prediction of **impact of CMEs**
- Using the near Sun magnetic and flare properties one can **predict the Bz** component of the IMF, an important parameter for space weather.

Thanks