Coronal Mass Ejections

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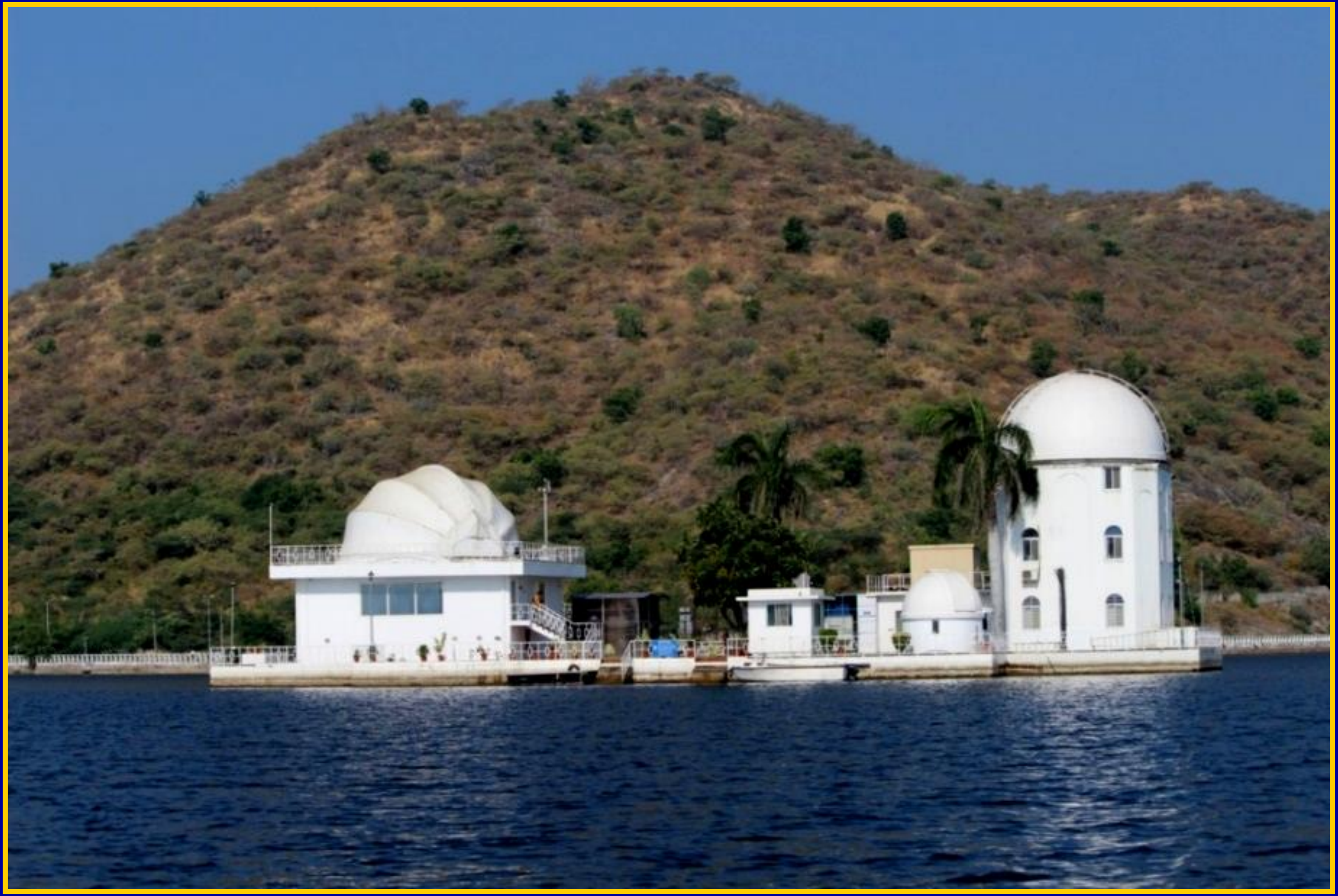
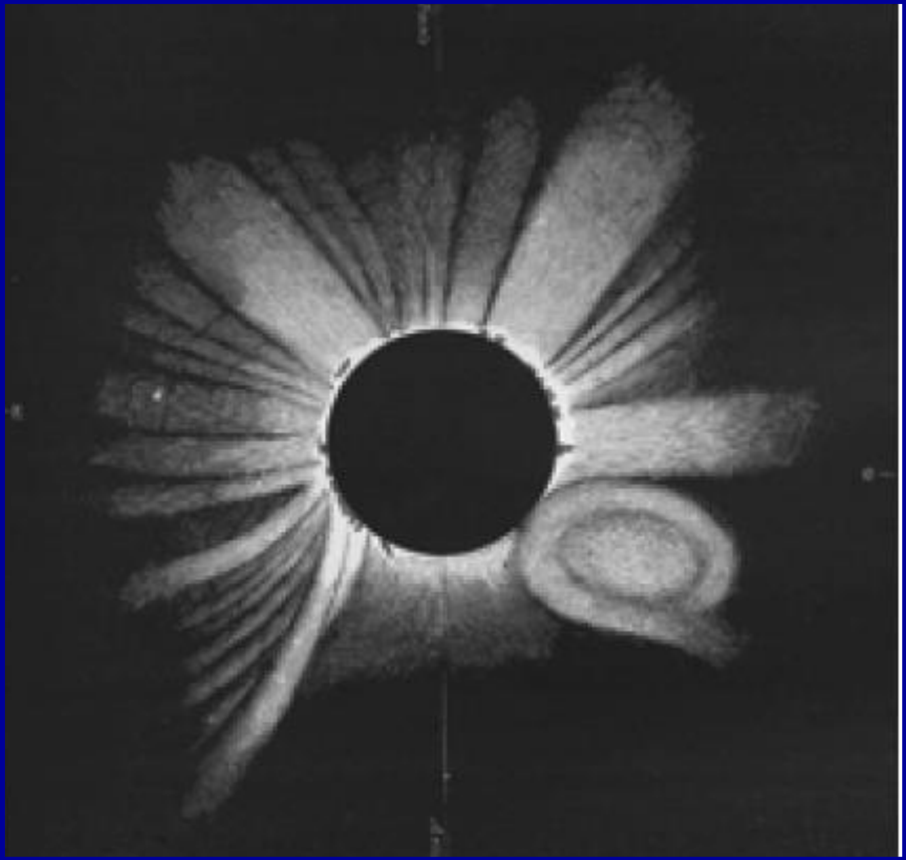


COSPAR Workshop, Samarkand, August 20, 2024

Earliest record of a CME

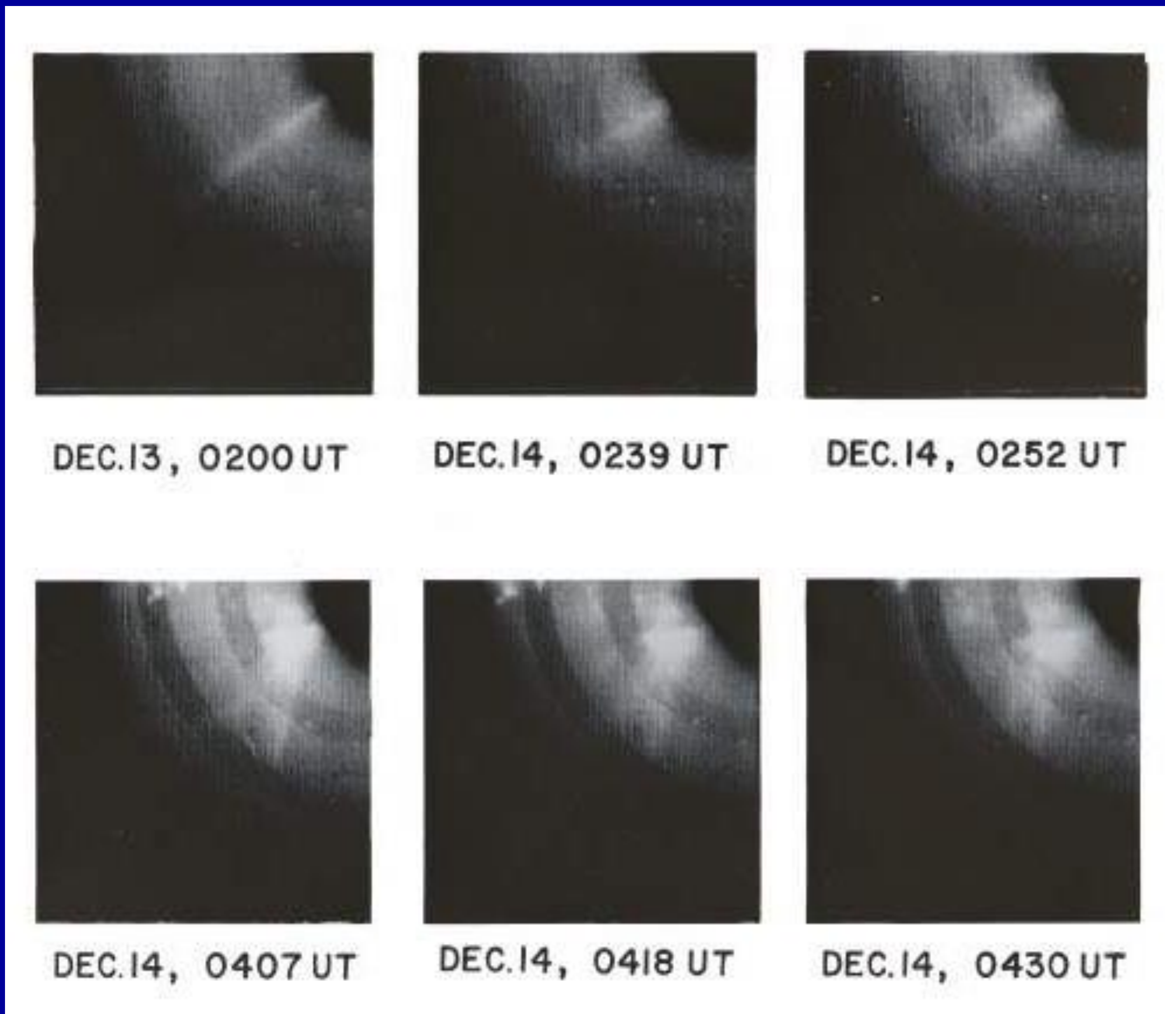


July 18, 1860 Eclipse

Sketch by Tempel (Torreblanca, Spain) in Eddy (1974)

CMEs known as large scale expulsion of plasma clouds from the Sun

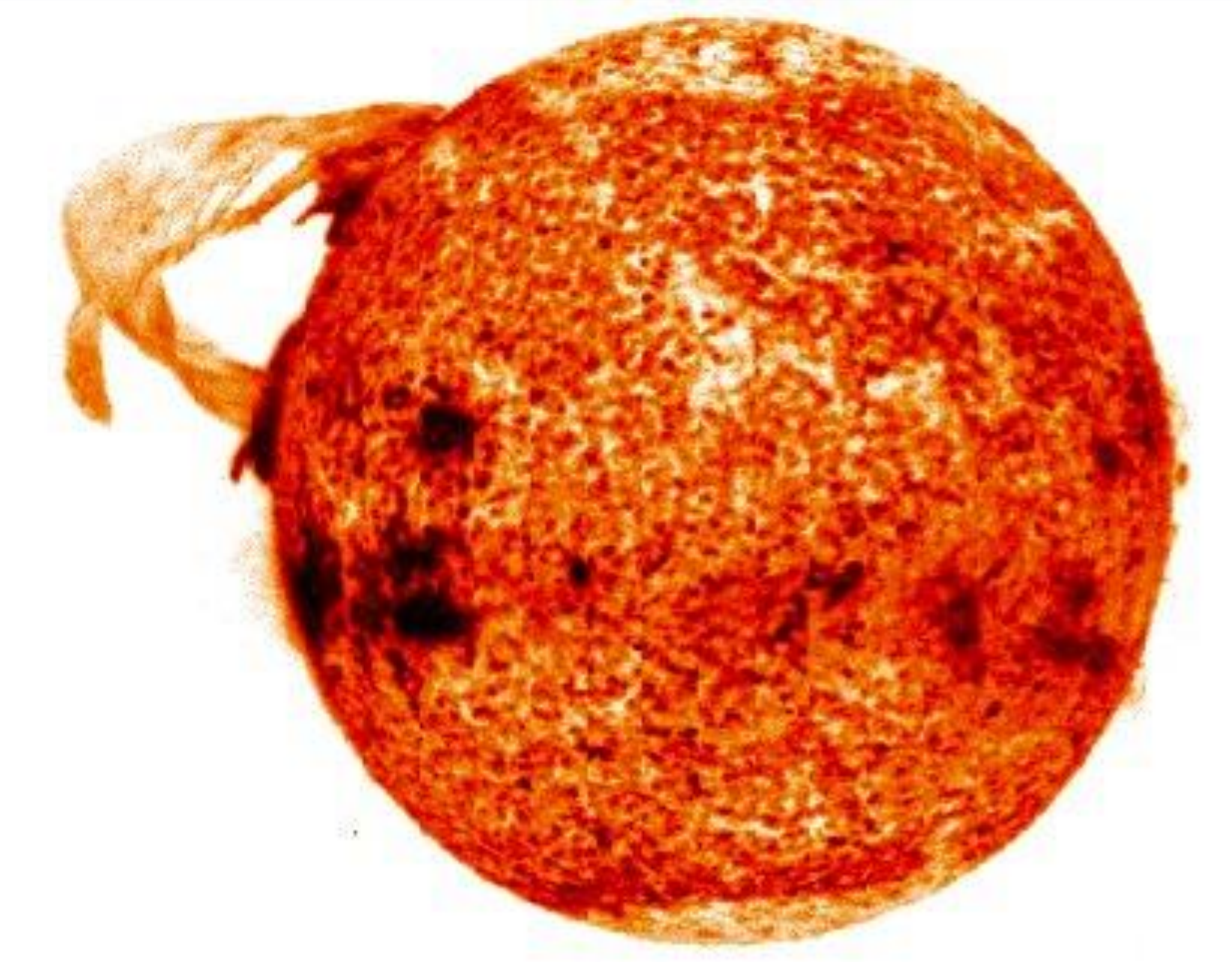
First CME Detection



Tousey et al. 1973

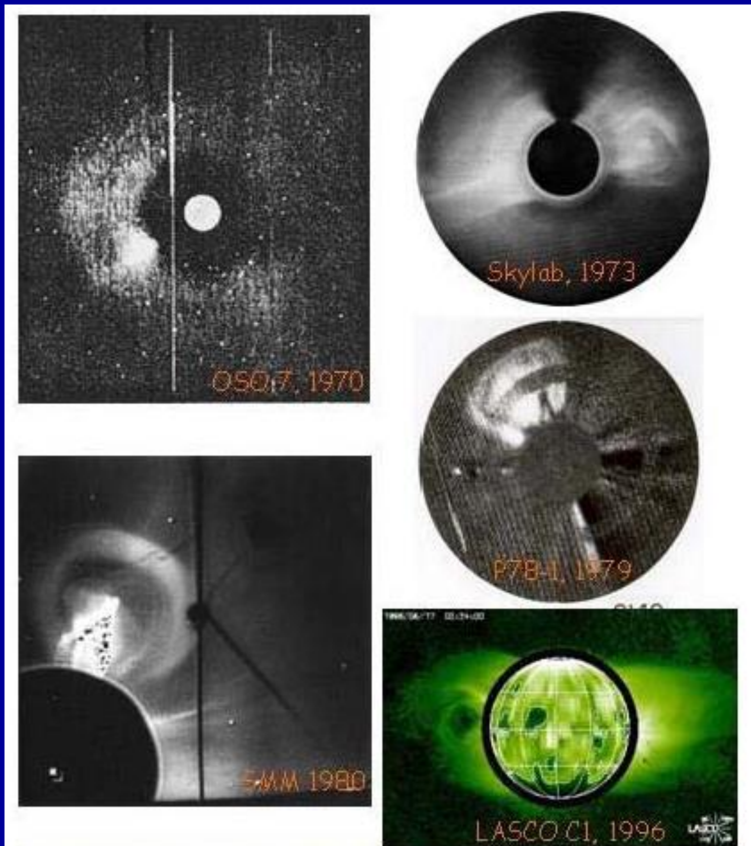
CORONAL TRANSIENT EVENT, RECORDED BETWEEN 3 AND 10 $R_{\odot}$, DEC.13-14, 1971.
NAVAL RESEARCH LAB EXPT ON NASA OSO-7

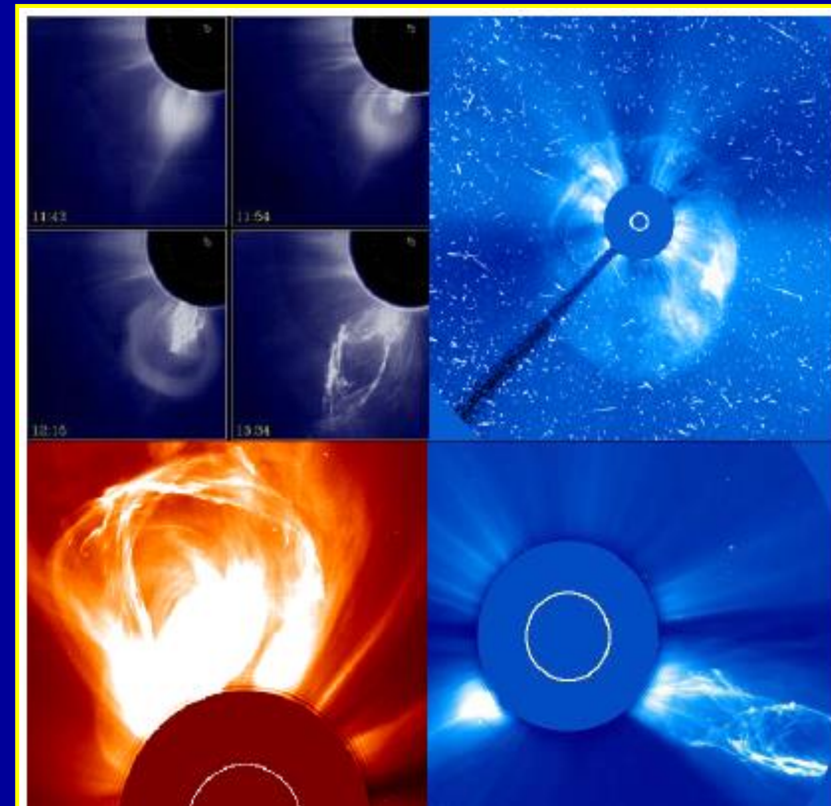
Skylab in 1973 initiated CME research



a huge eruptive prominence, seen in the He line (30.4 nm)

Modern Observations





Definition: A Coronal Mass Ejection (CME) is "...an observable change in coronal structure that
1) occurs on a time scale of a few minutes and several hours and
2) involves the appearance and outward motion of a new, discrete, bright, white-light feature in the coronagraph field of view"

Hundhausen (1984), Schwenn (1996)

A look into the history of some terms:

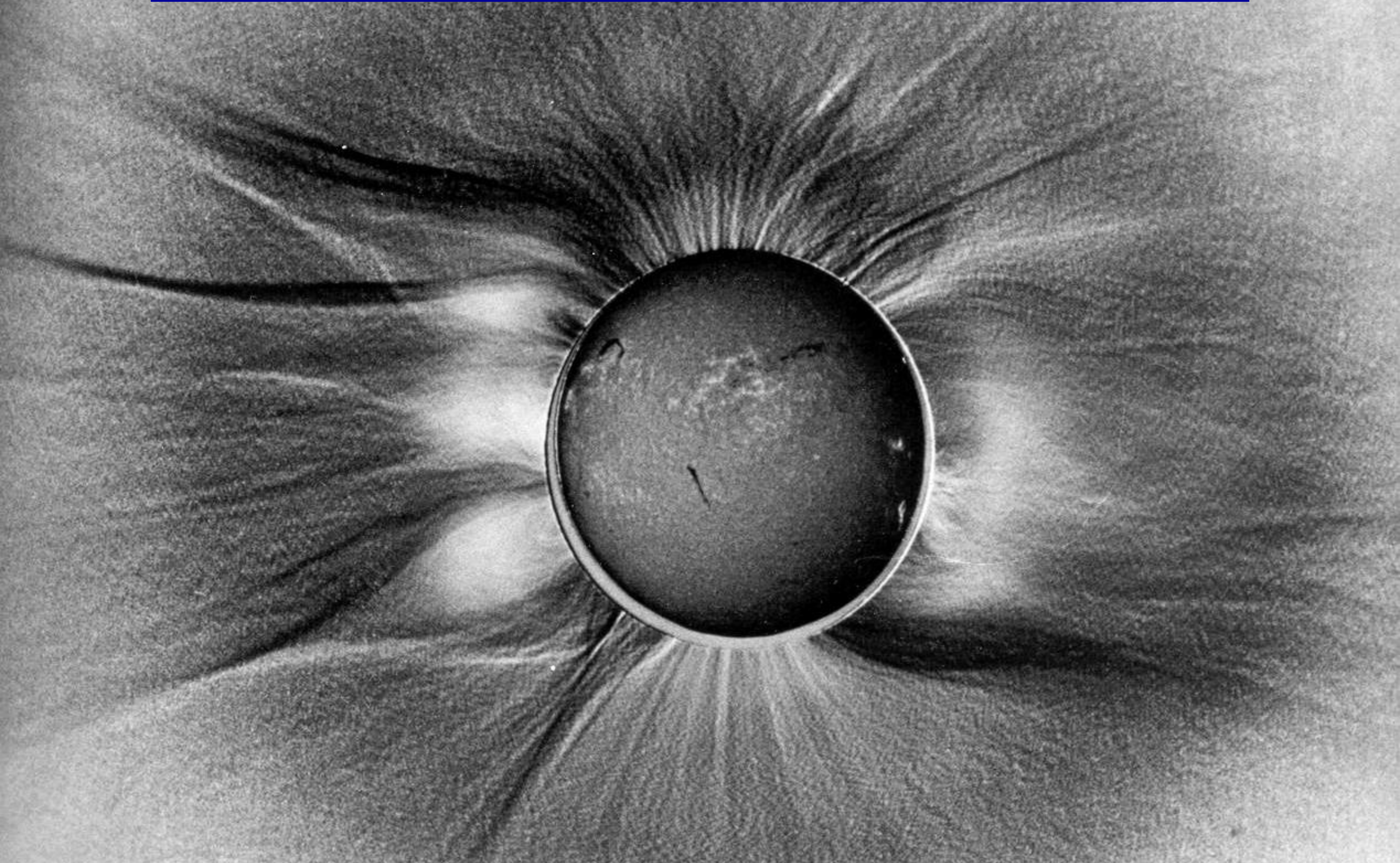
Morrison, 1954	diffuse **clouds** of ionized hydrogen bearing a turbulent magnetic field
Piddington, 1958	ejected **magnetic clouds**
Gold, 1959	magnetized clouds, "Gold's bottles"
Parker, 1959	plasma clouds
Schatten, 1970	coronal magnetic bottle
Brueckner et al., 1972	bright plasma clouds (**from OSO 7**) coronagraph
Pinter, 1973	dense plasma cloud within a closed magnetic loop
Tousey, 1973	electron clouds leaving 10 Rs
Stewart et al., 1974	white light cloud
MacQueen, 1974	**coronal transient** phenomena (from **Skylab** coronagraph)
Gosling et al., 1974	mass ejections from the sun
Gosling et al., 1975	coronagraph observed mass ejections, **coronal mass ejection events**
Hildner et al., 1975	mass ejection coronal transients
Gosling, 1976	**solar mass ejection events**
Burlaga et al., 1978	CME for Cold Magnetic Enhancement **(!)**
Munro et al., 1979	mass ejection events
Michels et al., 1980	solar mass ejections
Burlaga et al, 1981	magnetic loop, magnetic cloud
Burlaga et al., 1982	**CME for Coronal Mass Ejection**
Hundhausen et al., 1984	definition of coronal mass ejection

The term "CME" was not introduced until 10 years after their discovery!

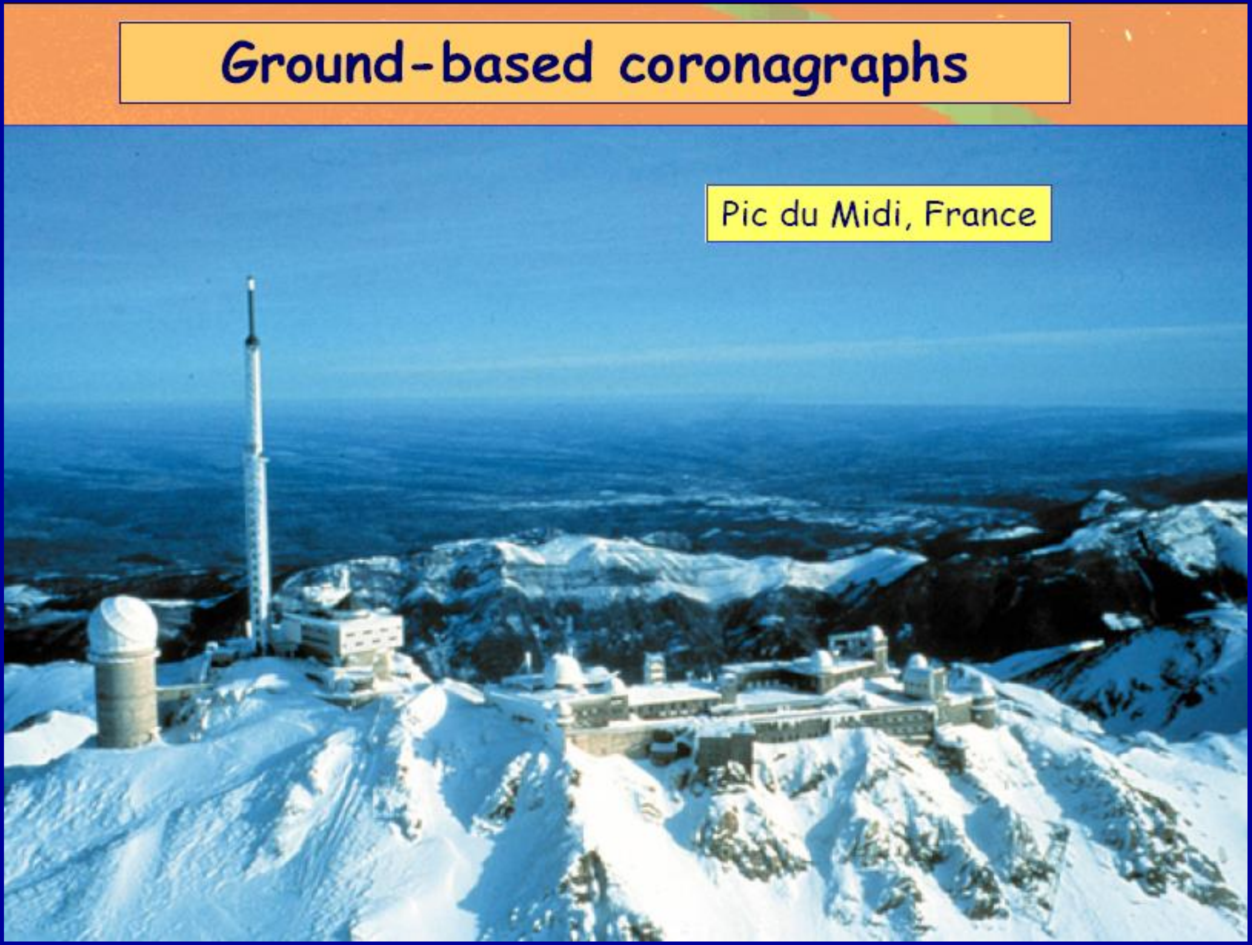
How to Observe the Corona?

Eclipses

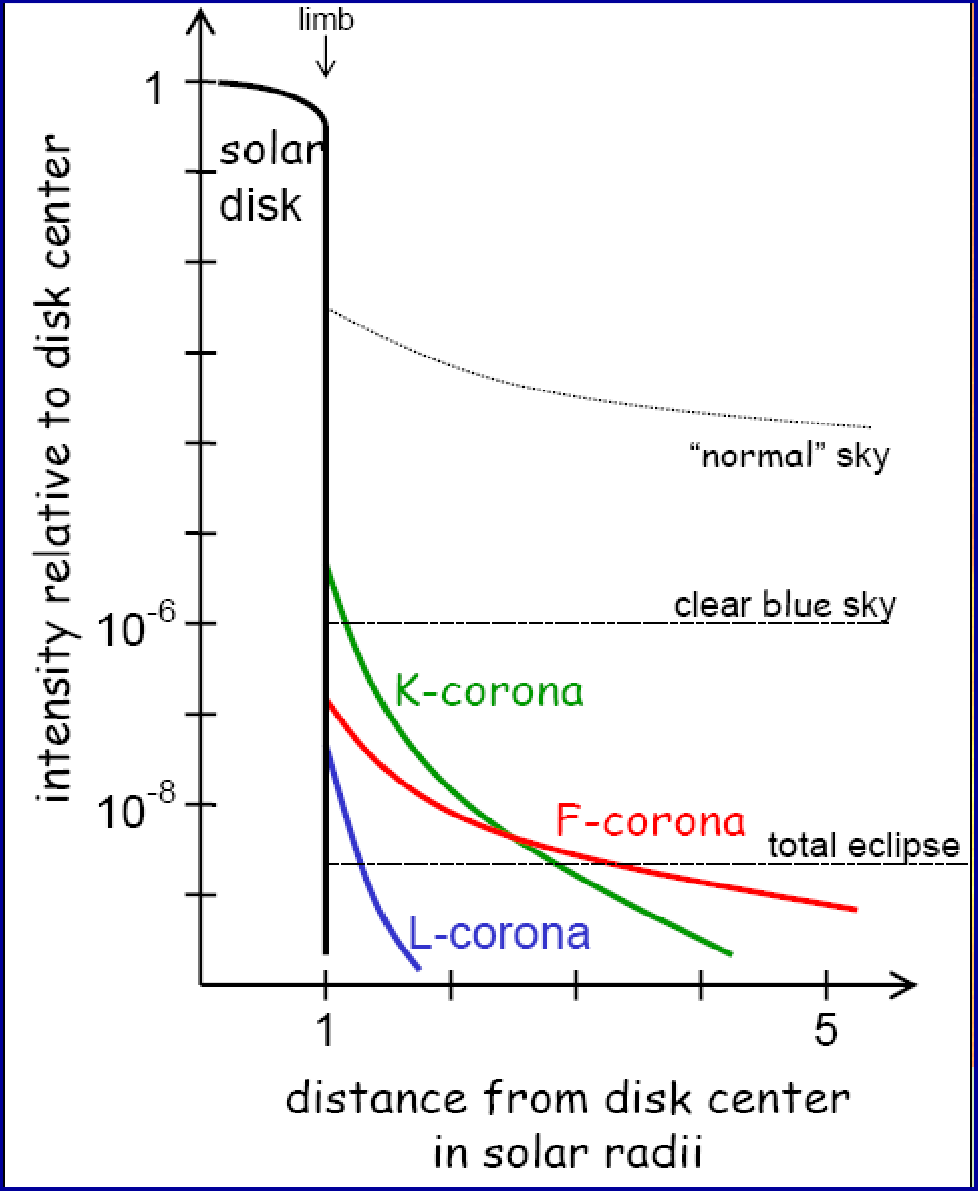
Eclipses reveal an extended corona



The eclipse of 30.6.1973, recorded and processed by S. Koutchmy.



Lyot put the first coronagraph in 1930s



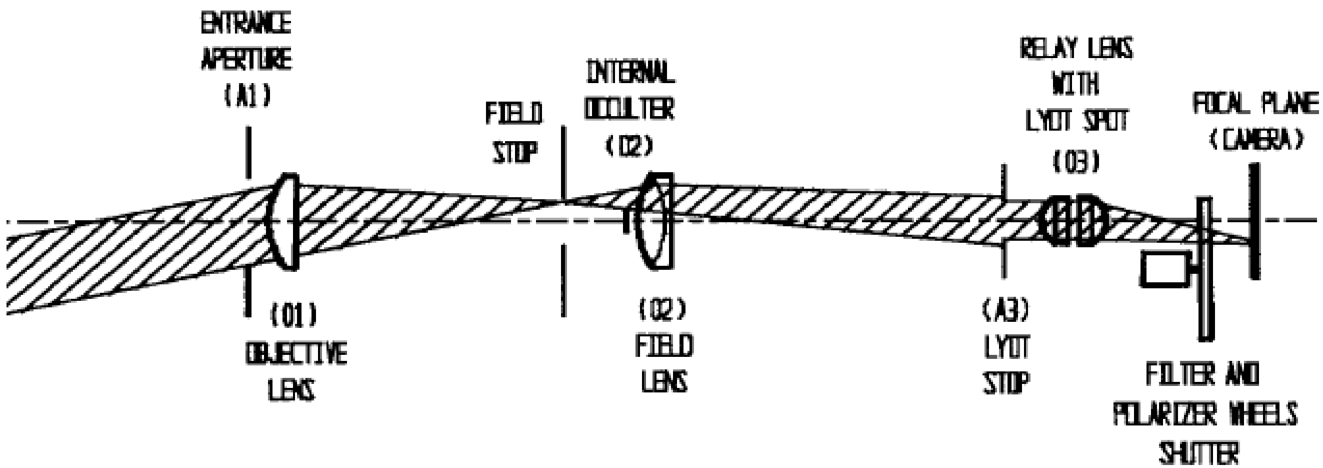
K –Continuuum corona

F-Fraunhofer Corona

L : Line Corona

How to suppress the Sun and solar straylight?

„Internal occultation" cuts out the solar image inside the instrument, at the location of the first focal plane. Problem: Straylight from fully illuminated front lens and aperture.



„External occultation" (like moon!) avoids direct sunlight on the objective lens. Problem: Diffraction limit of spatial resolution.

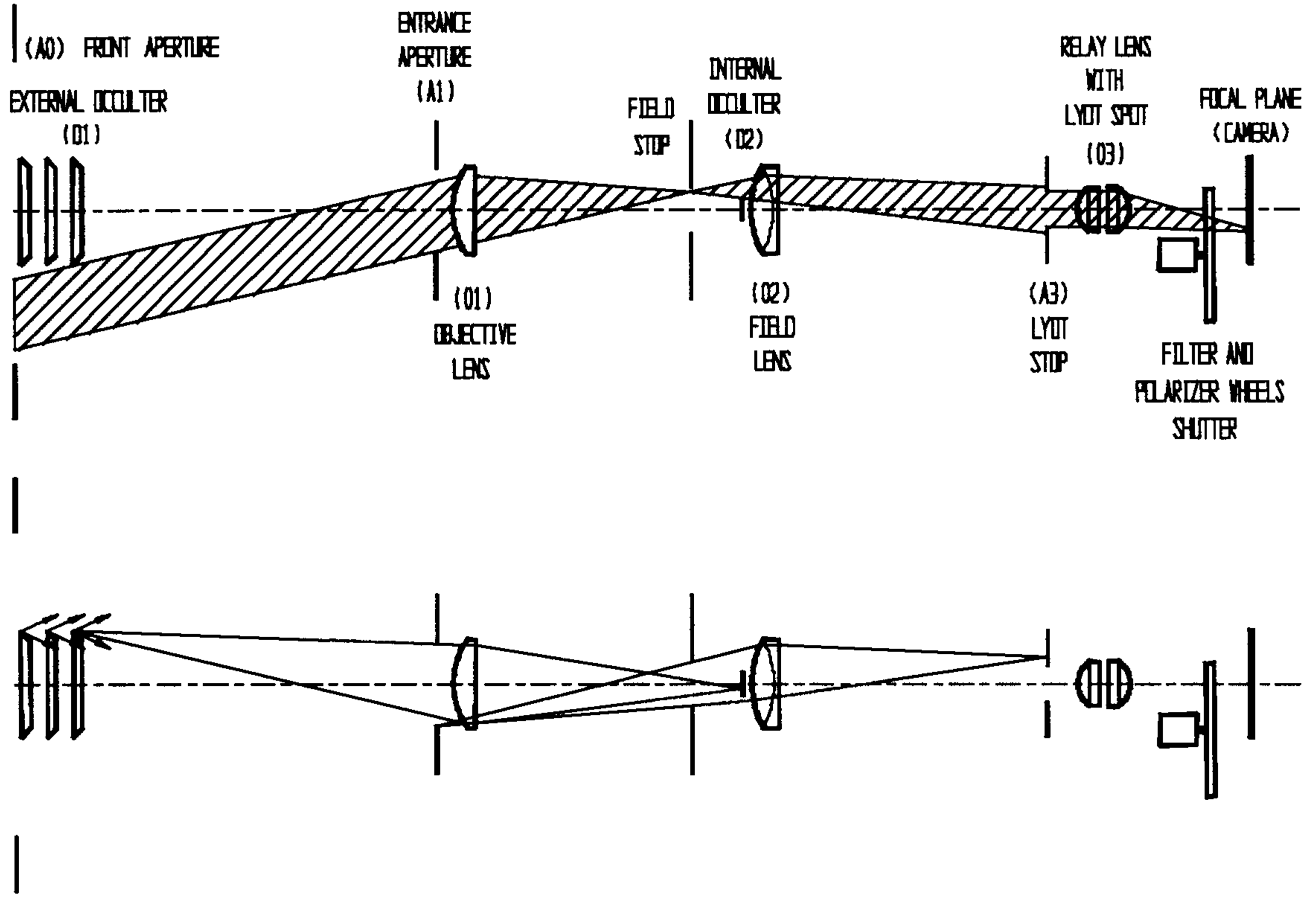


Figure 6-1: Conceptual diagram of the C3 coronagraph. The top diagram illustrates the image paths, and the bottom diagram the supression of stray light.

External occultor system is perfect to view the very outer corona, but near the inner edge it suffers from vignetting and allows no more resonable spatial resolution

Techniques of Observations

- Coronagraphic Observations: White light & Emission lines
- Non-Coronagraphic Observations

  Radio Observations

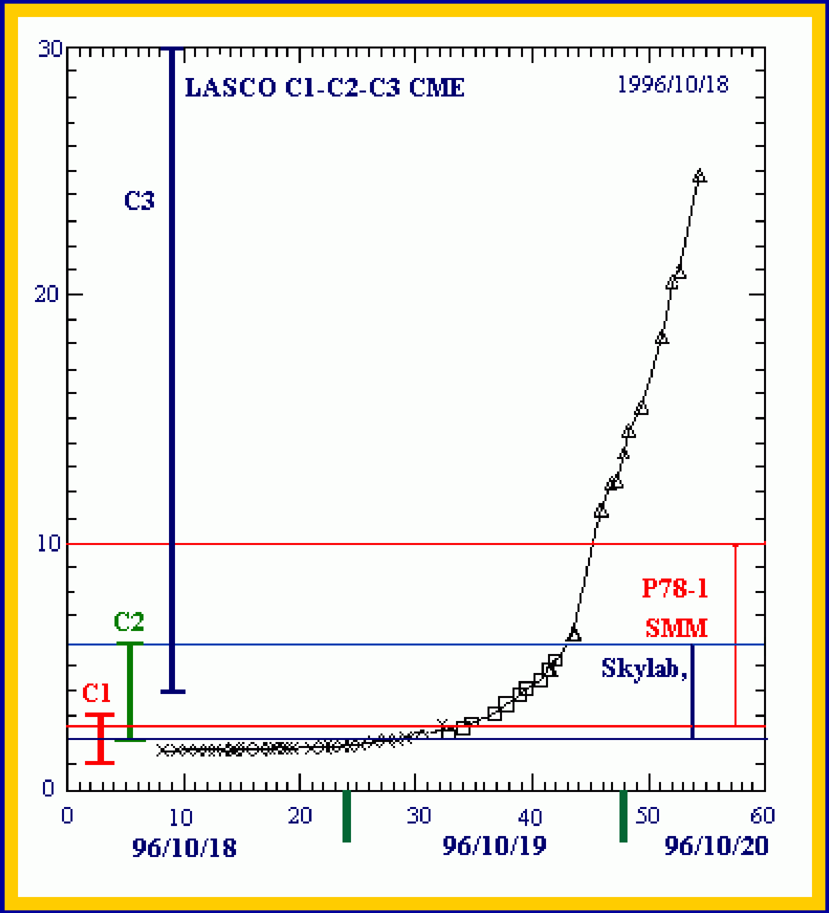
  Optical/UV

  EUV/X-ray

  Interplanetary & In-situ

Large datasets available from SoHO/STEREO

Coronagraphs: External & Internal occulted



Field of view of previous coronagraphs in contrast with LASCO

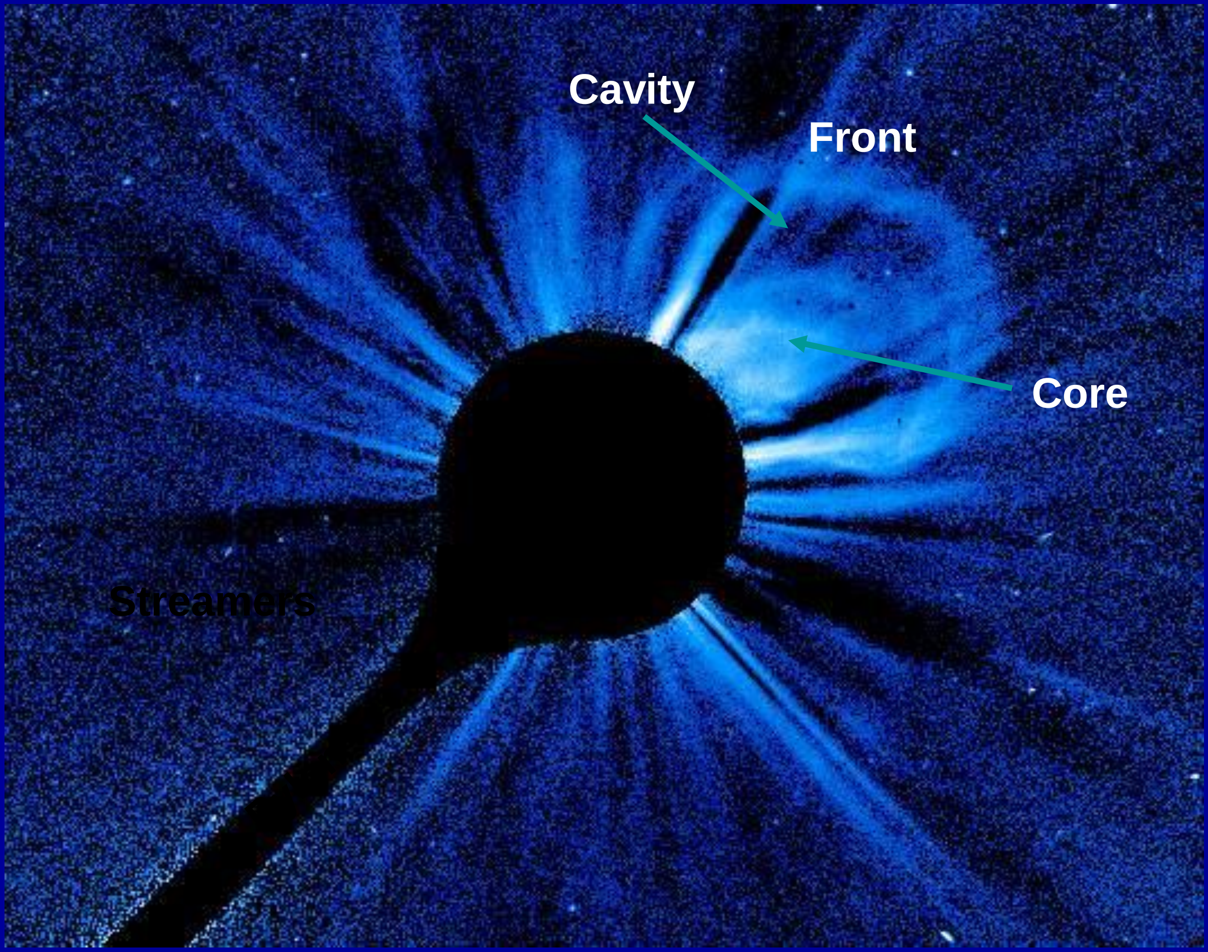
Skylab: 2-6 Rs

SOLWIND: 2.5 -10 Rs

LASCO: C1:1.1-3, C2: 2-6, C3: 3.7 to 32 Rs

MKIII: 1.15-2.24 Rs

Typical Coronagraphic Image



CME Analysis Tools

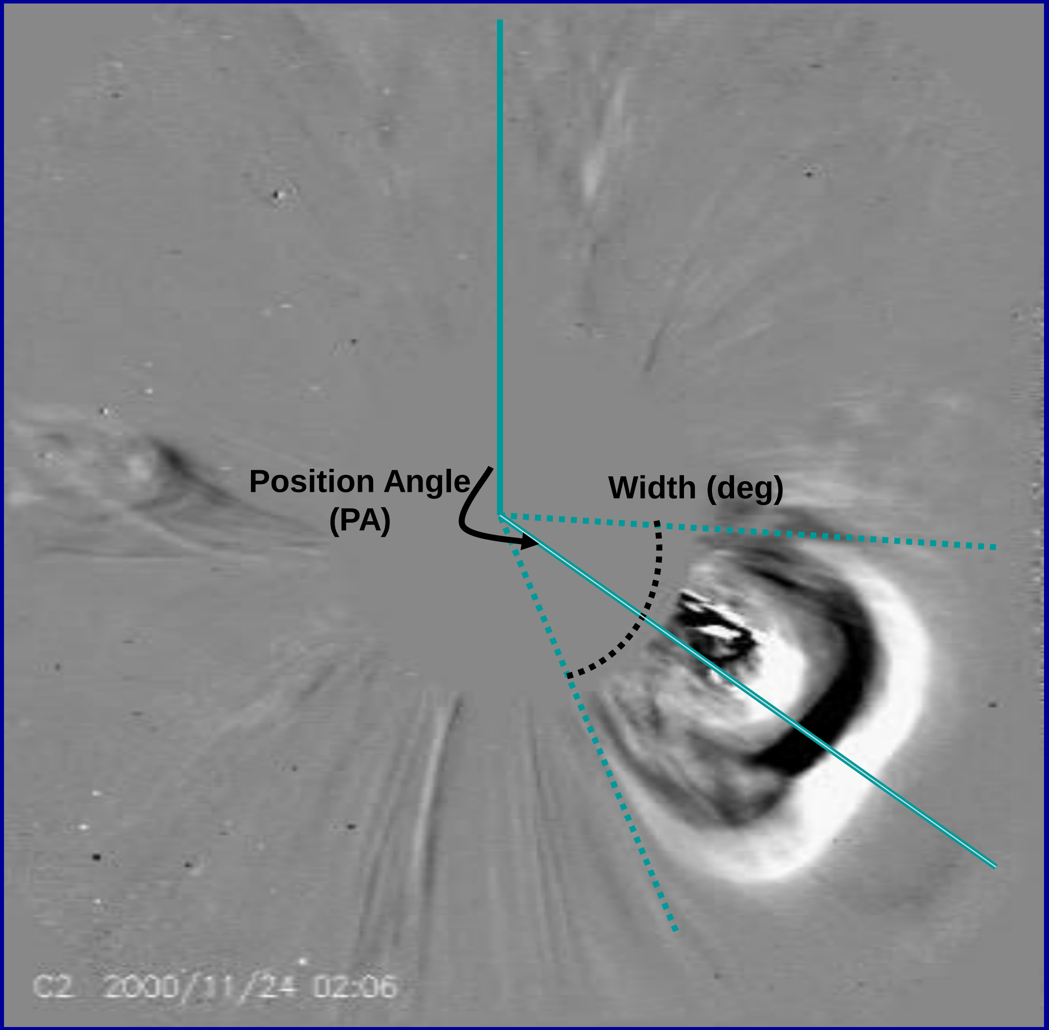
CMEs are highly dynamic events.

For analysis, time-lapse images & movies required

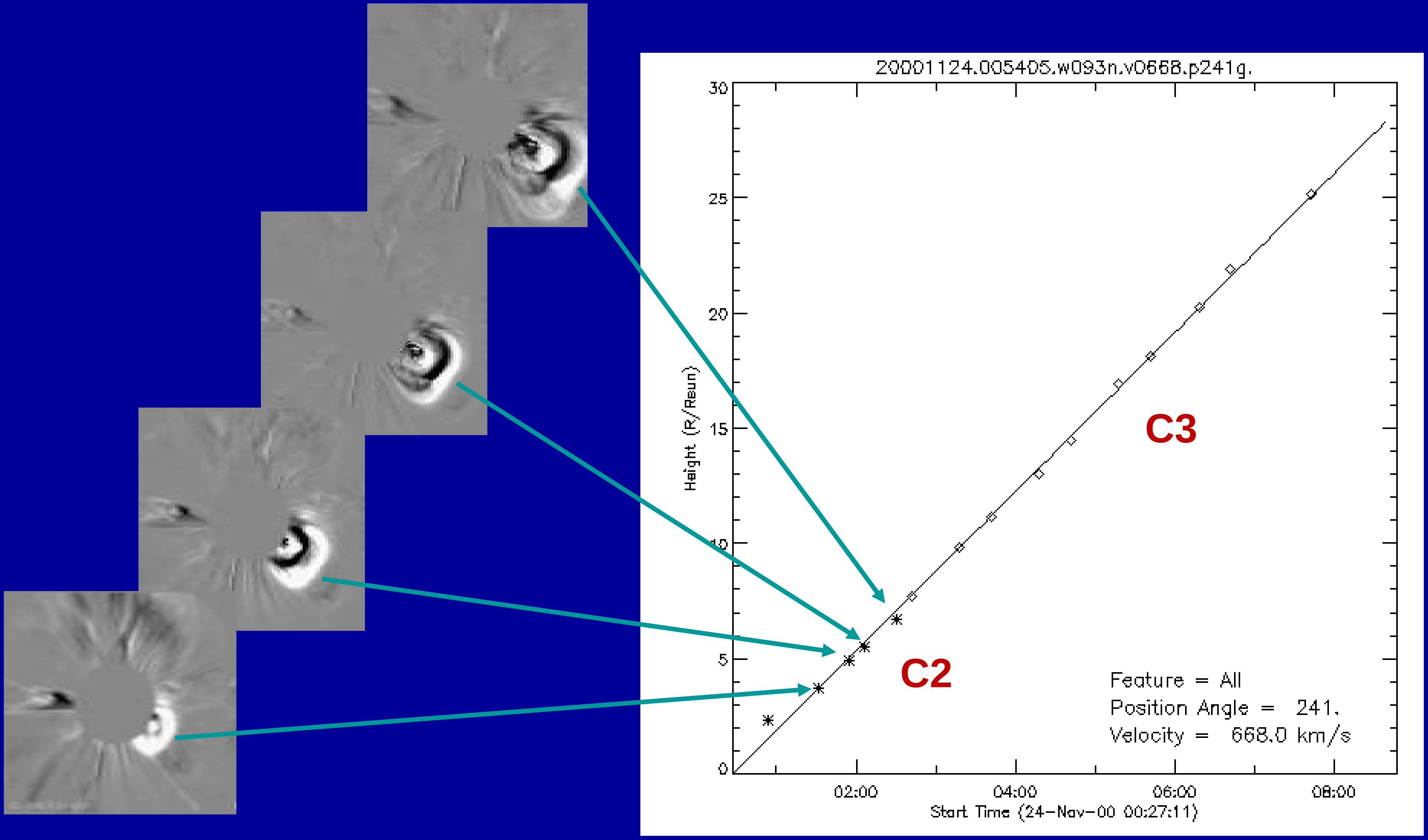
- Height-time plots (ht-plots) → velocity, acceleration
- Size & position measurements
- Mass/energetics → mass, density, kinetic energy

• Analysis software available in SolarSoft (i.e., LASCO tree)

Size/Position Angle Measurements



Height-Time Plots- for CMEs



LASCO-SOHO CME Catalog

http://cdaw.gsfc.nasa.gov/CME_list/.

https://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2017_09/univ2017_09.html

https://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2017_09/univ2017_09.html

CME heights (with respect to the disk center) are measured at the fastest segment of the leading edge.
PA= Position Angle measured from Solar North in degrees (counter-clockwise)
Halo CMEs are indicated in the "Central PA" column. The letters ("S", "BA", "OA") in the brackets show type of halo CMEs. See examples.
Click on date to view Java script movie of the CME.
Click on time to see height-time measurements as a text file.
Click on speed to view height-time plots of the CME.
Beware of data gaps. Check for LASCO/C2 data gaps here.

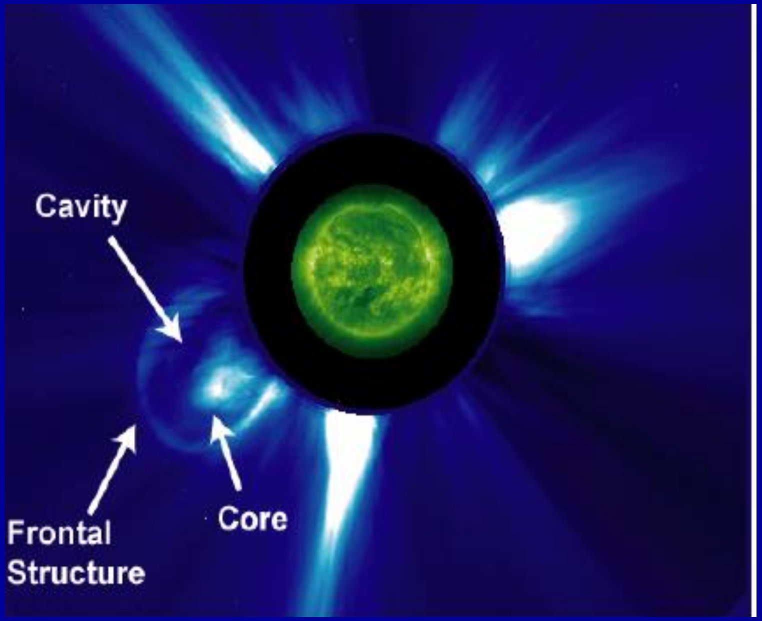
A complete description of the catalog
Click here to search the entire catalog.

First C2 Appearance Date Time [UT]		Central PA [deg]	Angular Width [deg]	Linear Speed [km/s]	2nd-order Speed at final height [km/s]	2nd-order Speed at 20 Rs [km/s]	Accel [m/s^2]	Mass [gram]	Kinetic Energy [erg]	MPA [deg]	Movies, plots, & links	Remarks
2017/09/01	01:36:13	104	27	102	105	151	0.5*1	2.2e+14	1.1e+28	104	C2 C3 PHTX DST Java Movie	Poor Event; Only C2
2017/09/01	02:00:05	276	59	87	0	0	-10.8*1	1.2e+14	4.6e+27	286	C2 C3 PHTX DST Java Movie	Poor Event; Only C2
2017/09/01	10:48:05	237	43	409	476	547	7.8*1	1.0e+14	8.7e+28	238	C2 C3 PHTX DST Java Movie	Poor Event
2017/09/01	22:00:05	286	41	192	243	615	15.0*1	3.4e+12	6.3e+26	285	C2 C3 PHTX DST Java Movie	Very Poor Event; Only C2
2017/09/02	15:48:05	269	94	705	761	744	5.1	5.8e+15	1.4e+31	276	C2 C3 PHTX DST Java Movie	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	C2 C3 PHTX DST Java	[illegible]

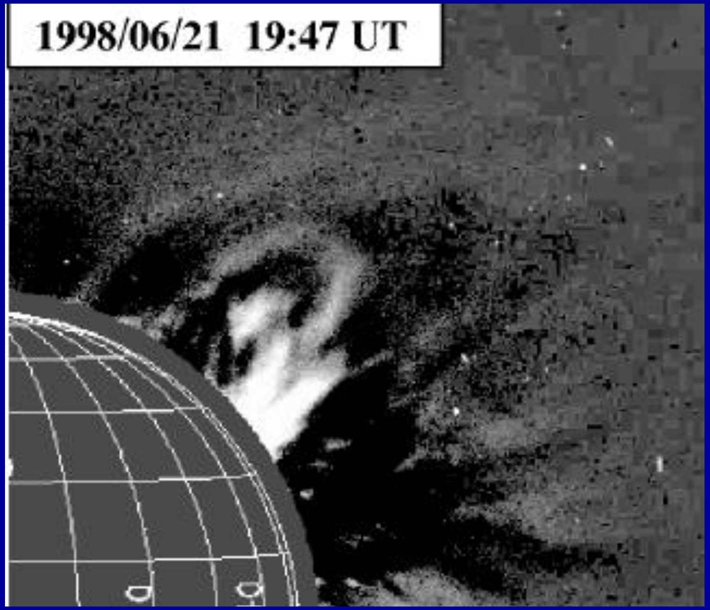
Yashiro et al. 2004

Morphological Properties

- Three part Structure
- Bright Leading edge contains frontal material
- Dark cavity has low density
- Bright Knot has mostly dense prominence material

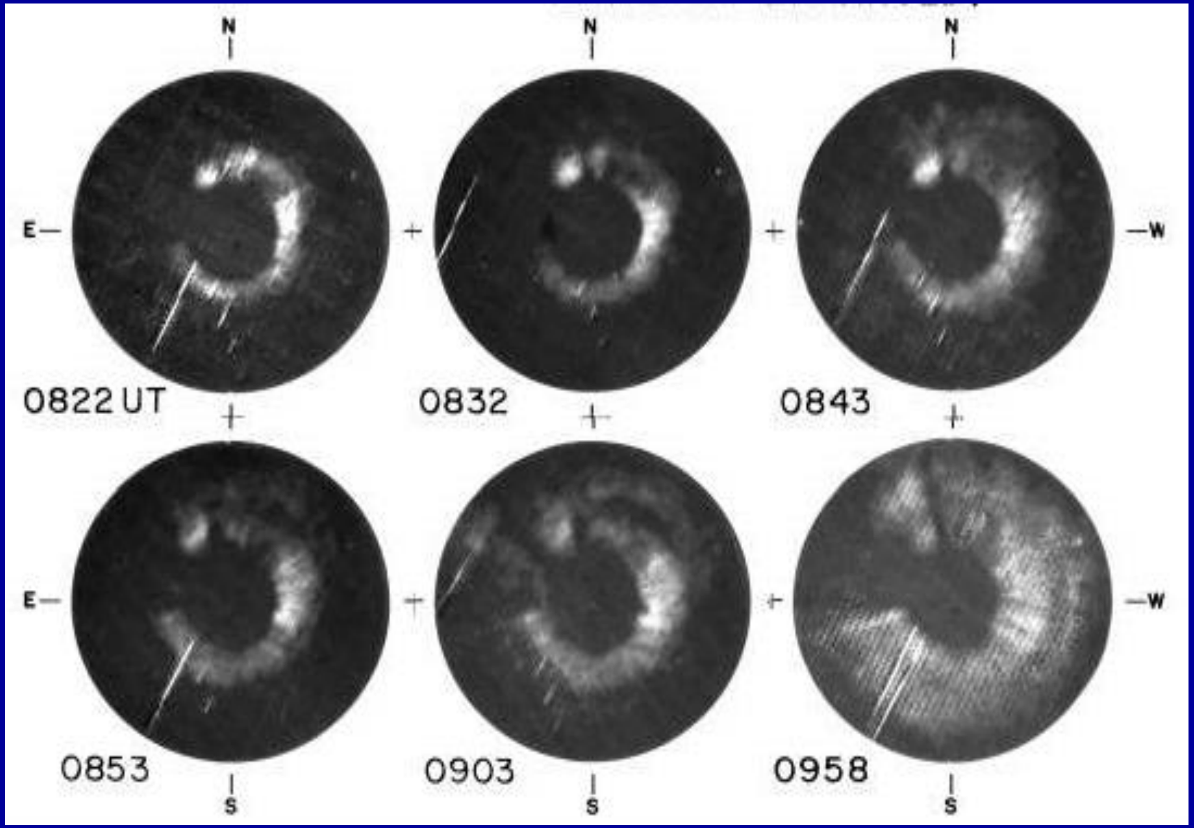


White light (Gopalswamy et al. 2006)



FeXIV –LASCO-C1, Srivastava et al. (2000)

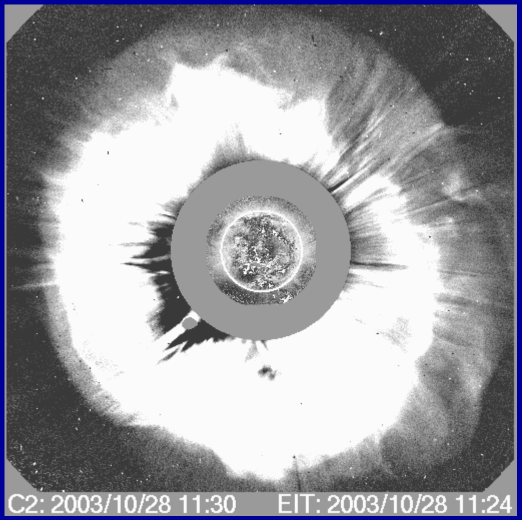
First Halo-CME Detection



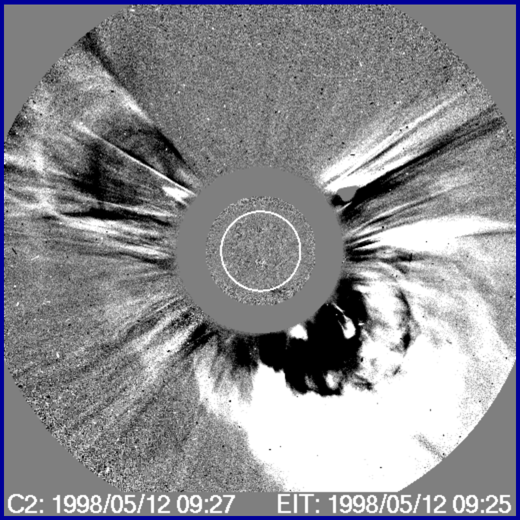
27 NOV '79 "HALO" CORONAL TRANSIENT
(PRE-EVENT IMAGE SUBTRACTED,
CONTOURS ENHANCED)

Types of CMEs

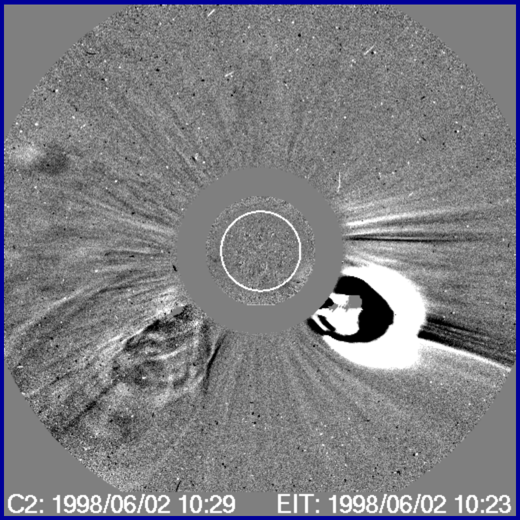
Full halo

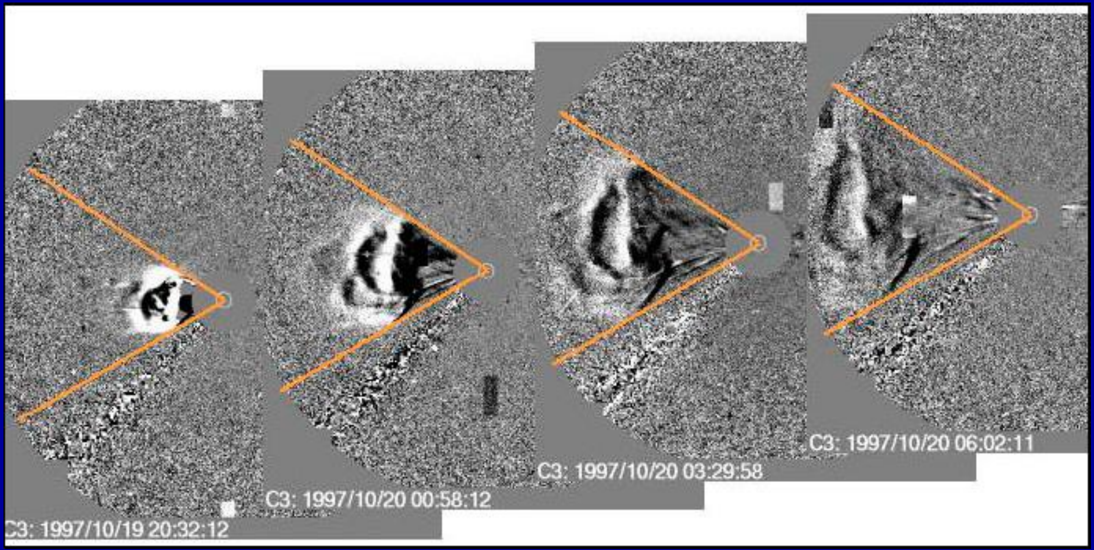


Partial halo



Limb CME





Full -360^0

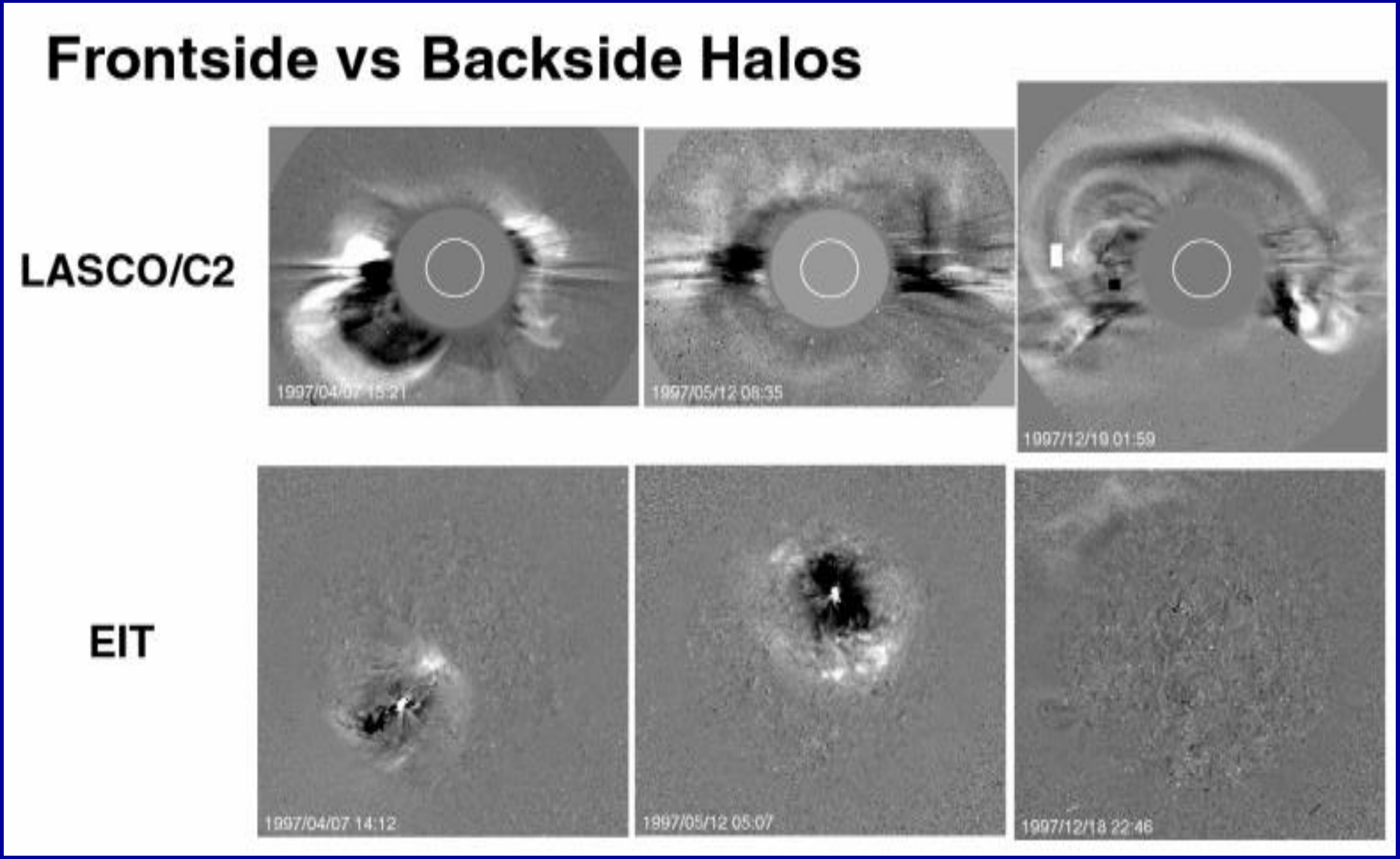
Partial: 120-360^0

Limb: <120^0

The cone angle and the general shape of CME is maintained (Plunkett et al. 1998, Schwenn et al. 2005). Ratio between the lateral expansion and radial propagation remains constant.

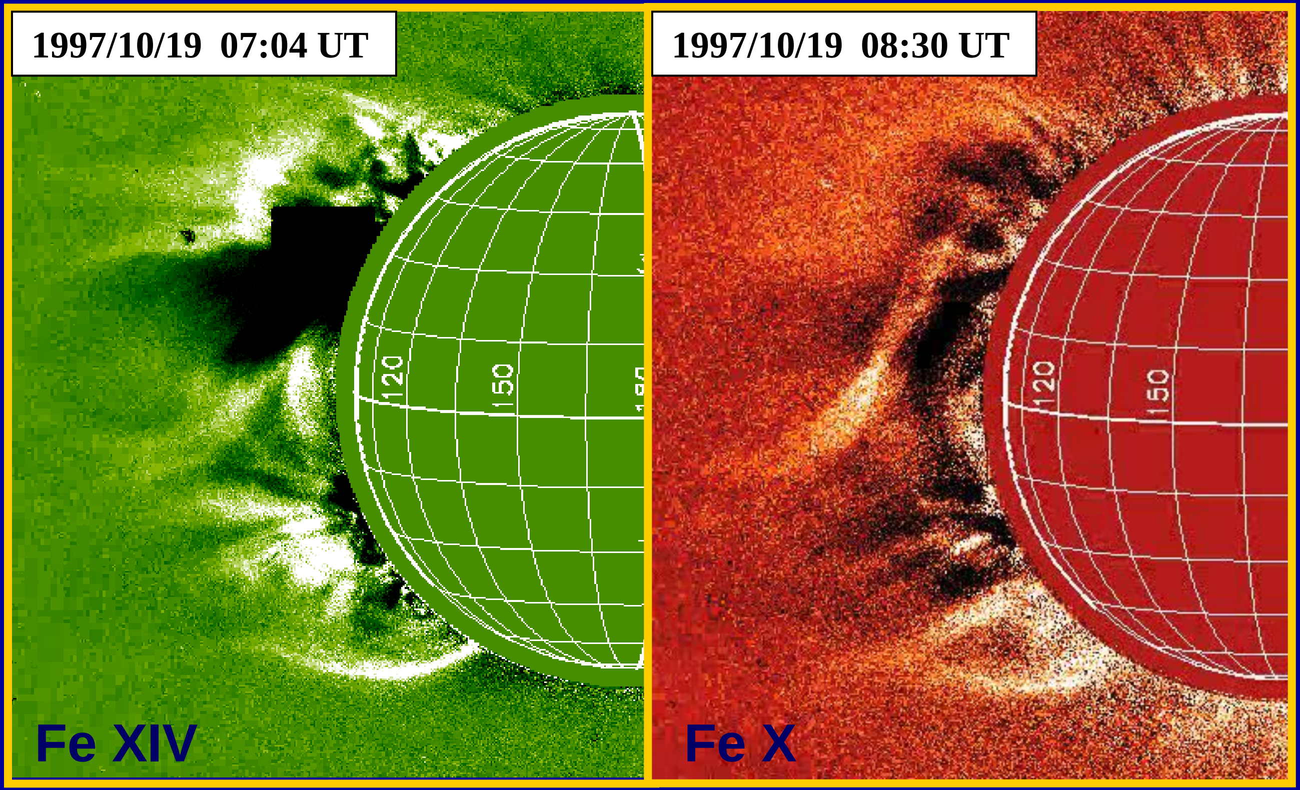
Vrad=0.88 Vexp

Halo CMEs



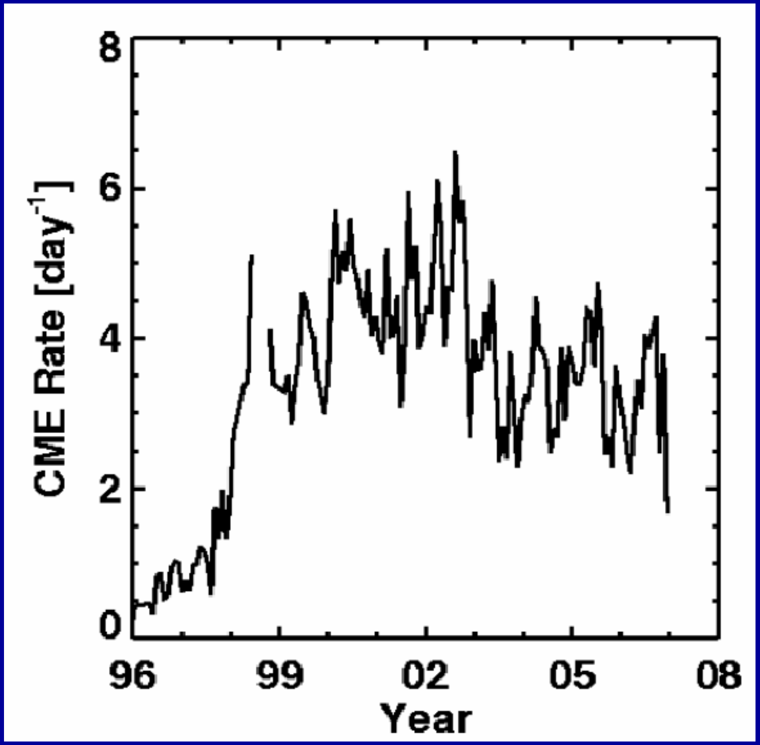
- Morphology depends on projection, coronal structure

CME mass flow in the lower corona constrained by overlying streamer geometry



LASCO - C1 observations suggest that the paths of the CMEs are defined by the geometry and the location of overlying streamers, i.e., irrespective of the latitudes at which the CME is launched (in LASCO-C1), it bends towards the apex or the stalk of the streamers, as it travels outwards.

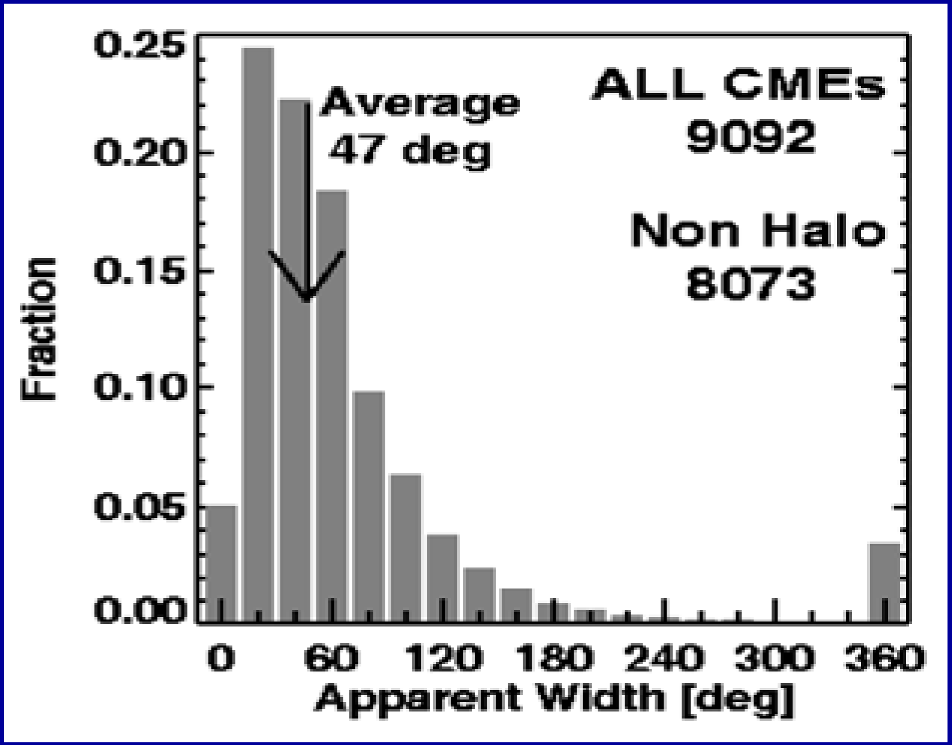
CME Occurrence Rates



Gopalswamy et al. (2009)

0.3 per day (solar min) to
5-6 per day (solar max)

Angular Size or apparent widths

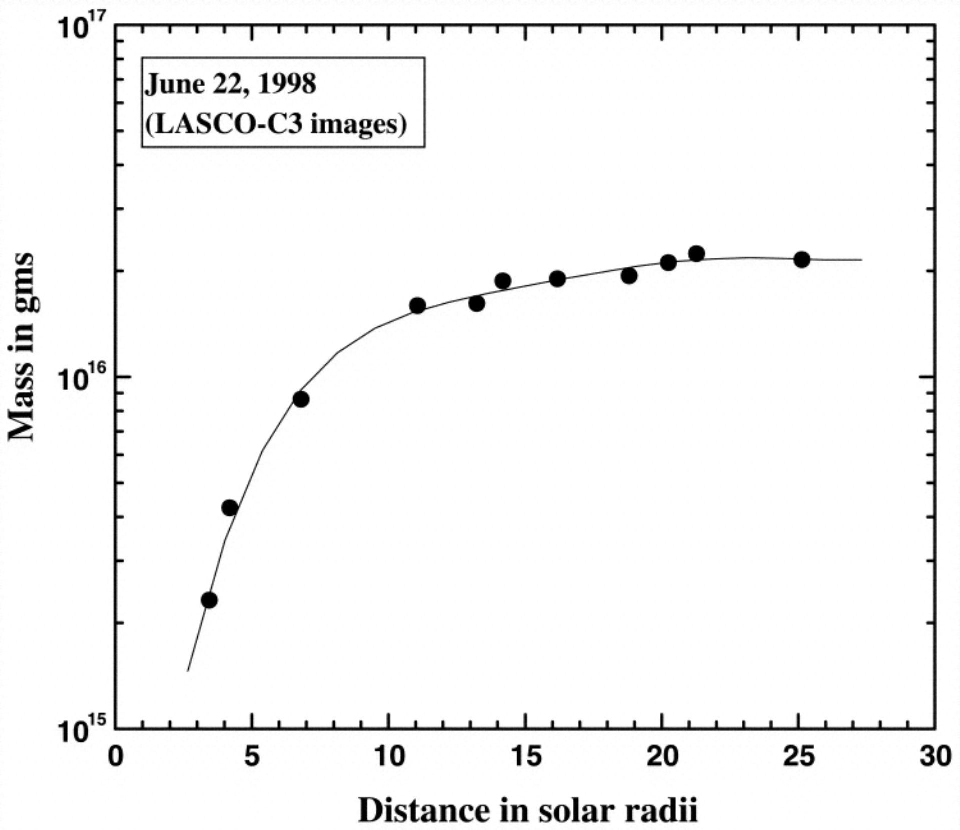


Yashiro et al. (2004)

Av width: 47^0 min

Av width: 61^0 max

CME Mass Estimates



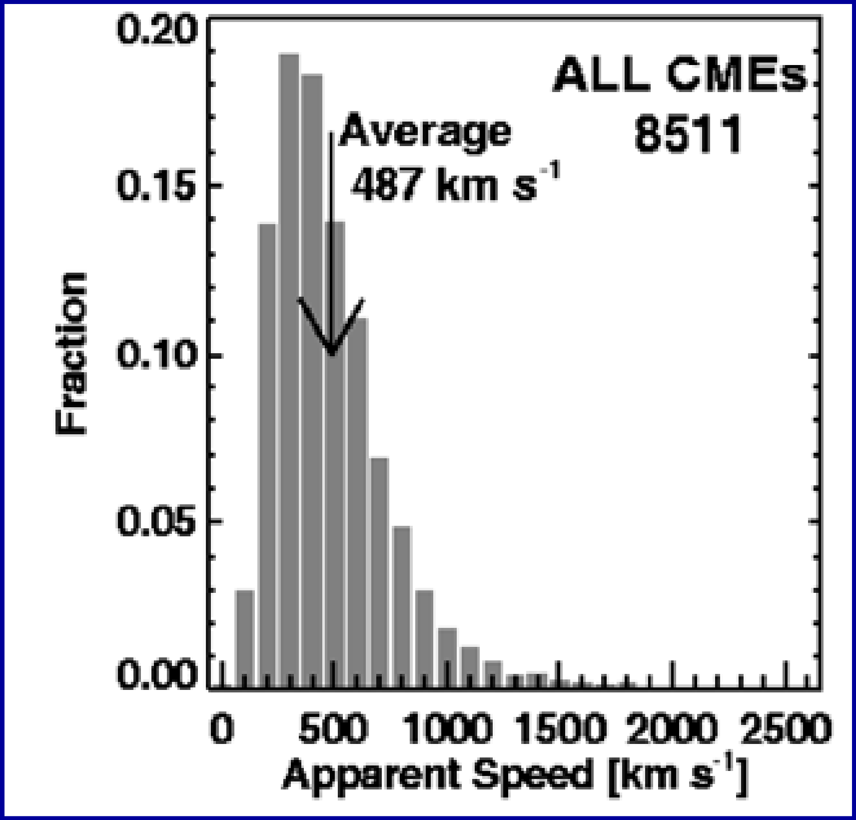
Srivastava et al. (2000)

Masses: Derived from white light images 10^{15} -10^{16} gm

•Kinetic Energy: 10^{31}-10^{32} ergs.

Similar results found with SOLWIND data.

Kinematics



Speeds
Range of speeds: 10-3000 Km s^{-1}

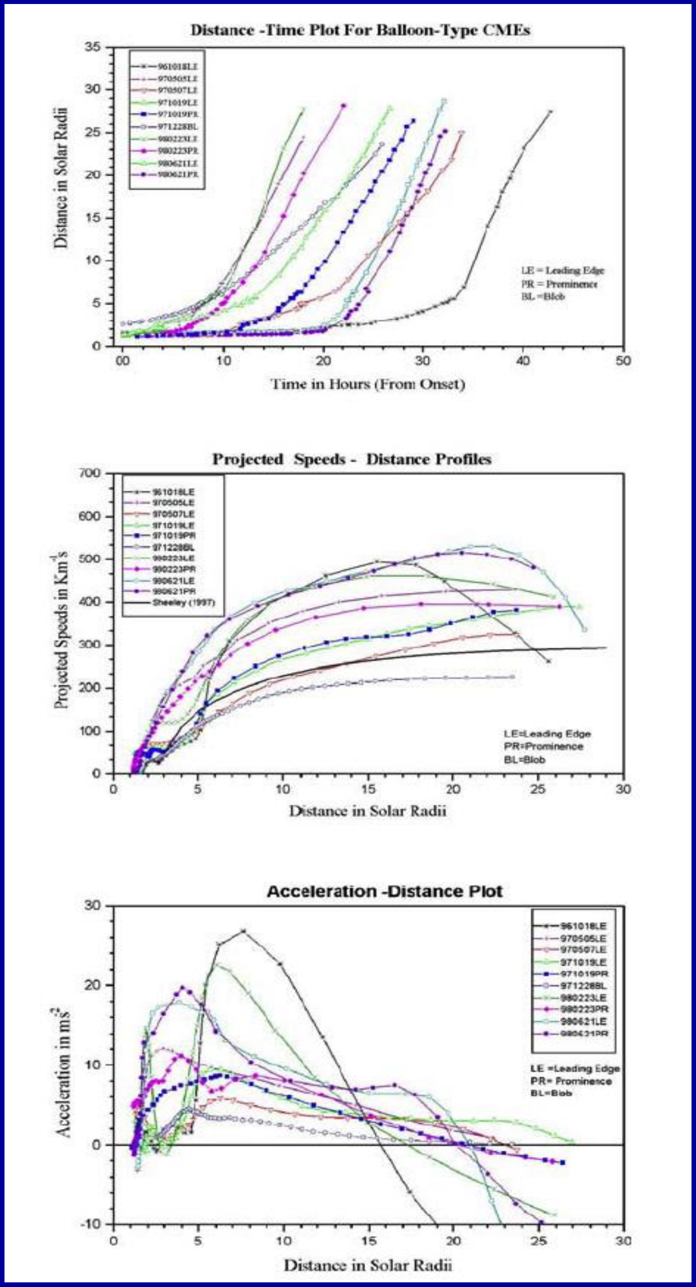
Varies with solar cycle
Speeds in descending phase lower than in the minimum
Maximum speed during maximum phase

Acceleration

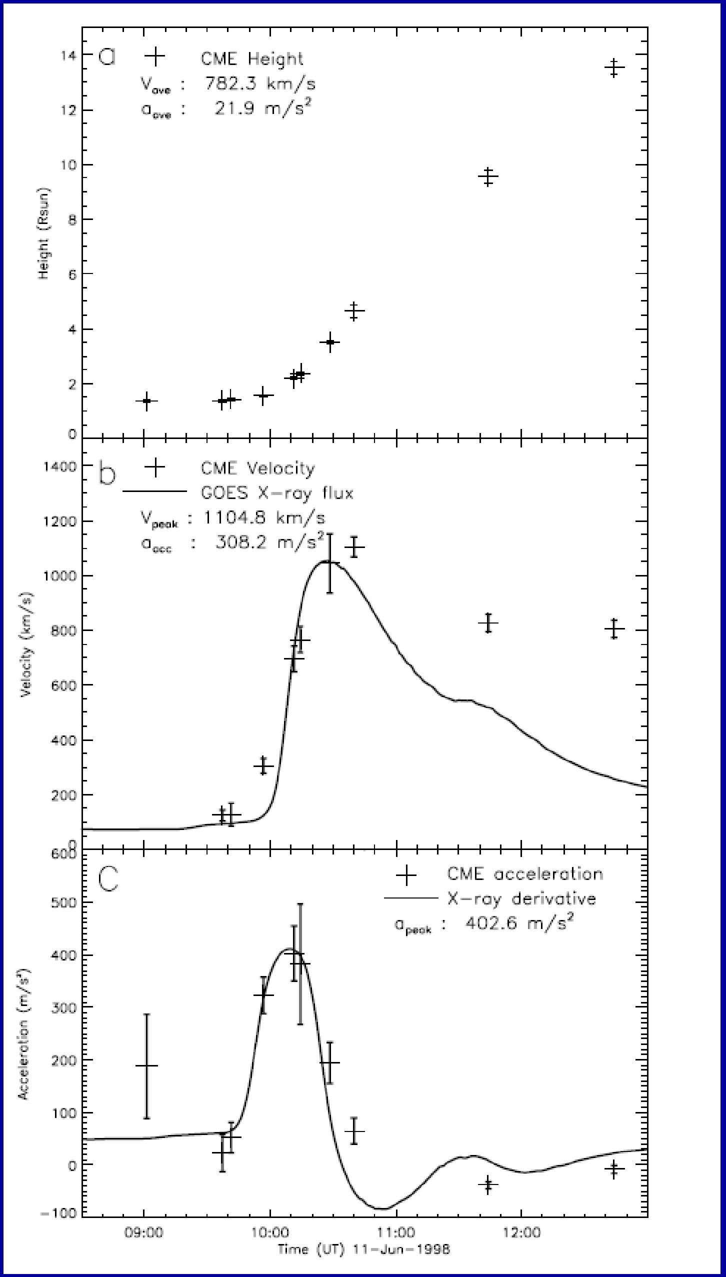
Very fast CMEs (>1000 km s^{-1})
Slow CMEs (<1000 km s^{-1})

higher values of acceleration
(0-80 cm s^{-2})

Height -Time profiles

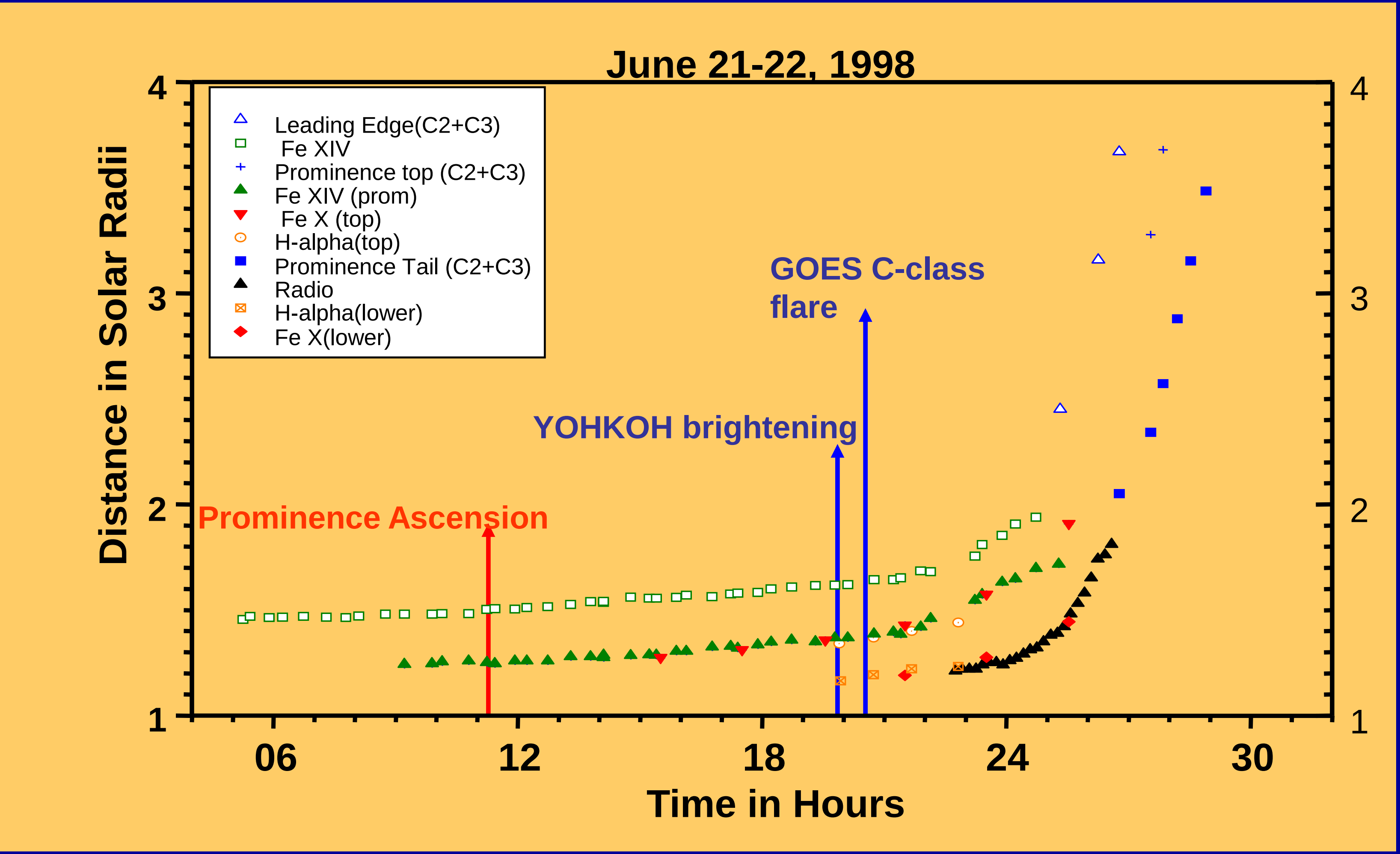


Srivastava et al. (1999)



Zhang et al. 2004

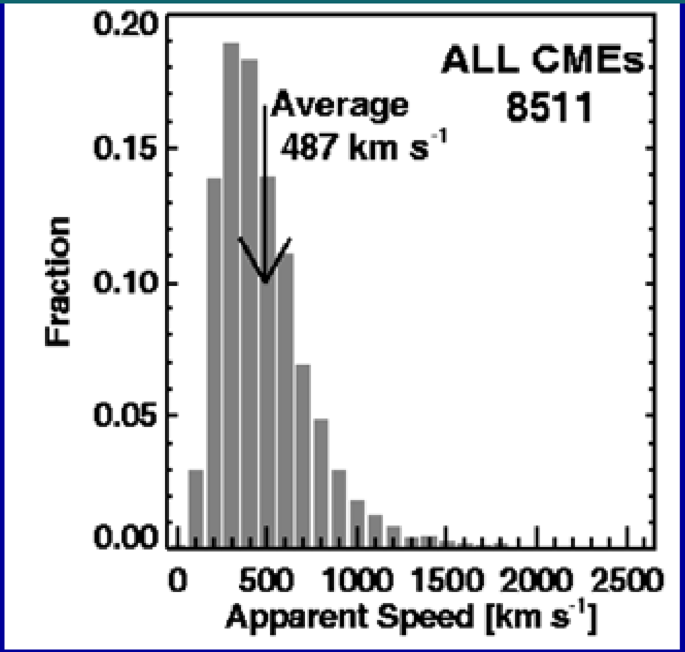
CME Initiation : Lower Corona



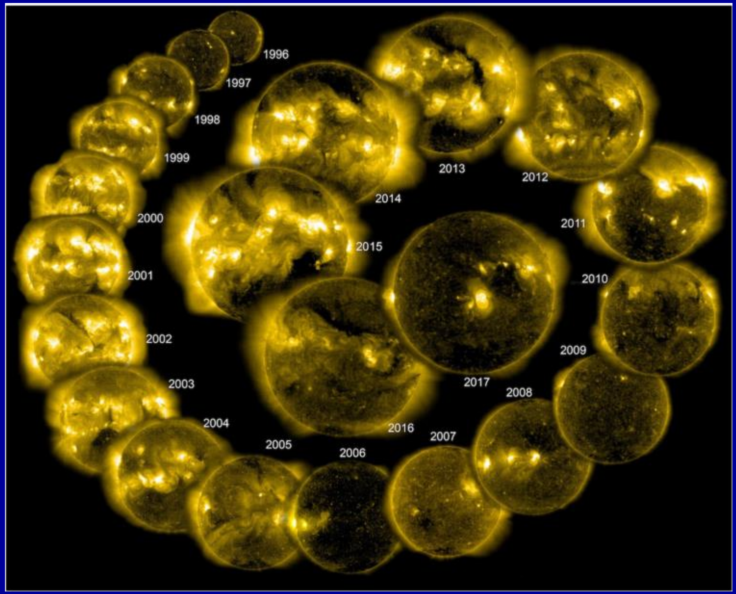
Exact Onset Time ~ Difficult to define

Srivastava et al. 2000

CME Kinematics



Solar Activity Cycle



Speeds
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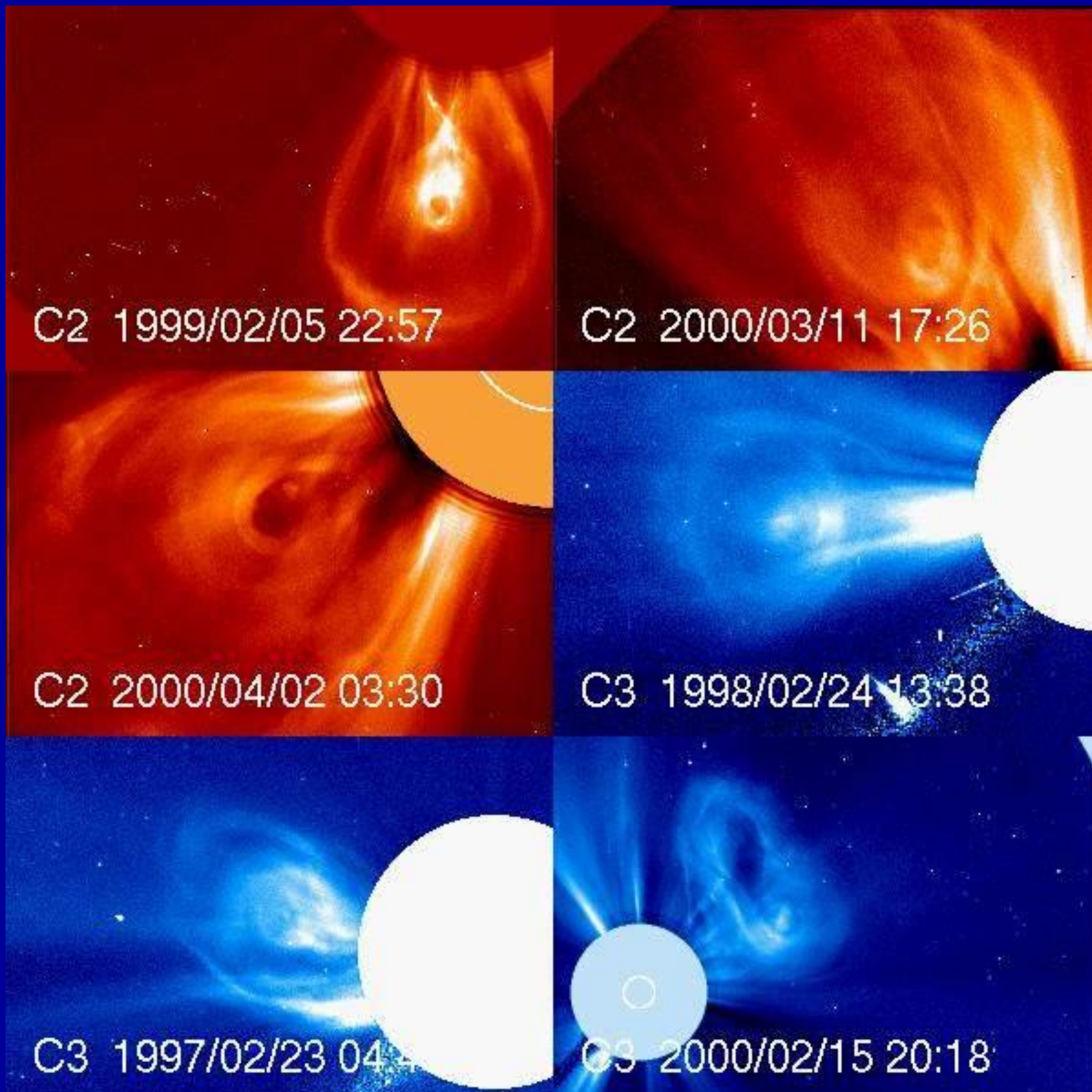
higher values of acceleration
(0-80 cm s^{-2})

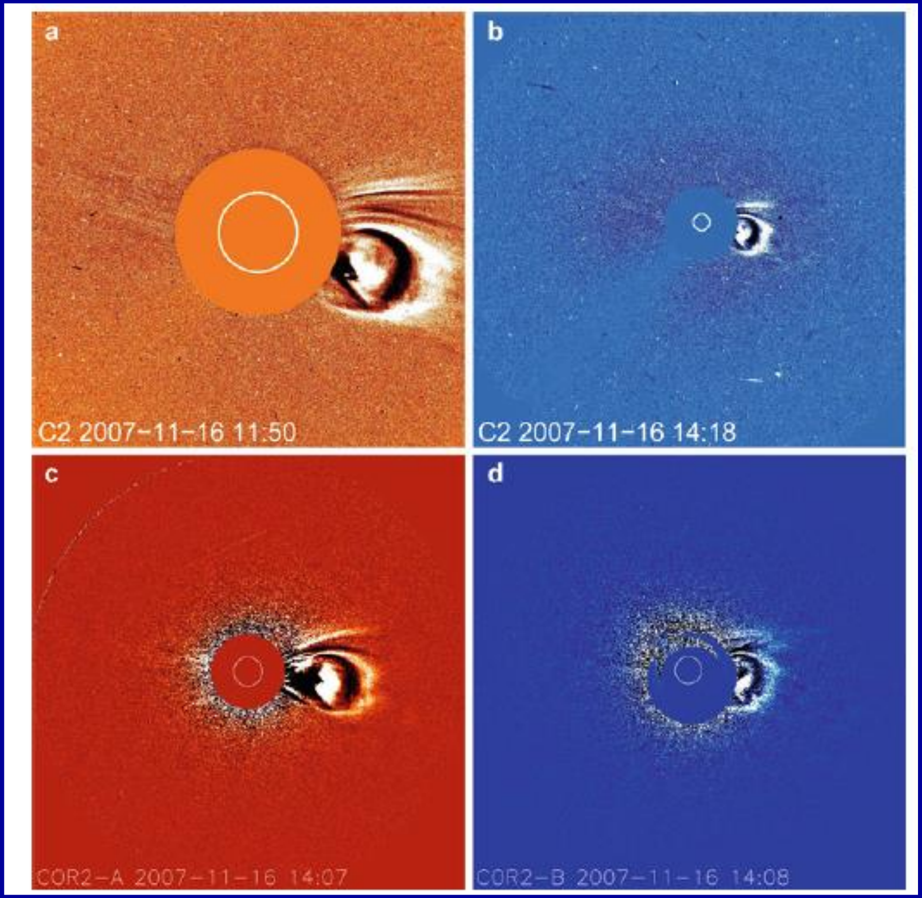
CME Structure: Flux Rope formation



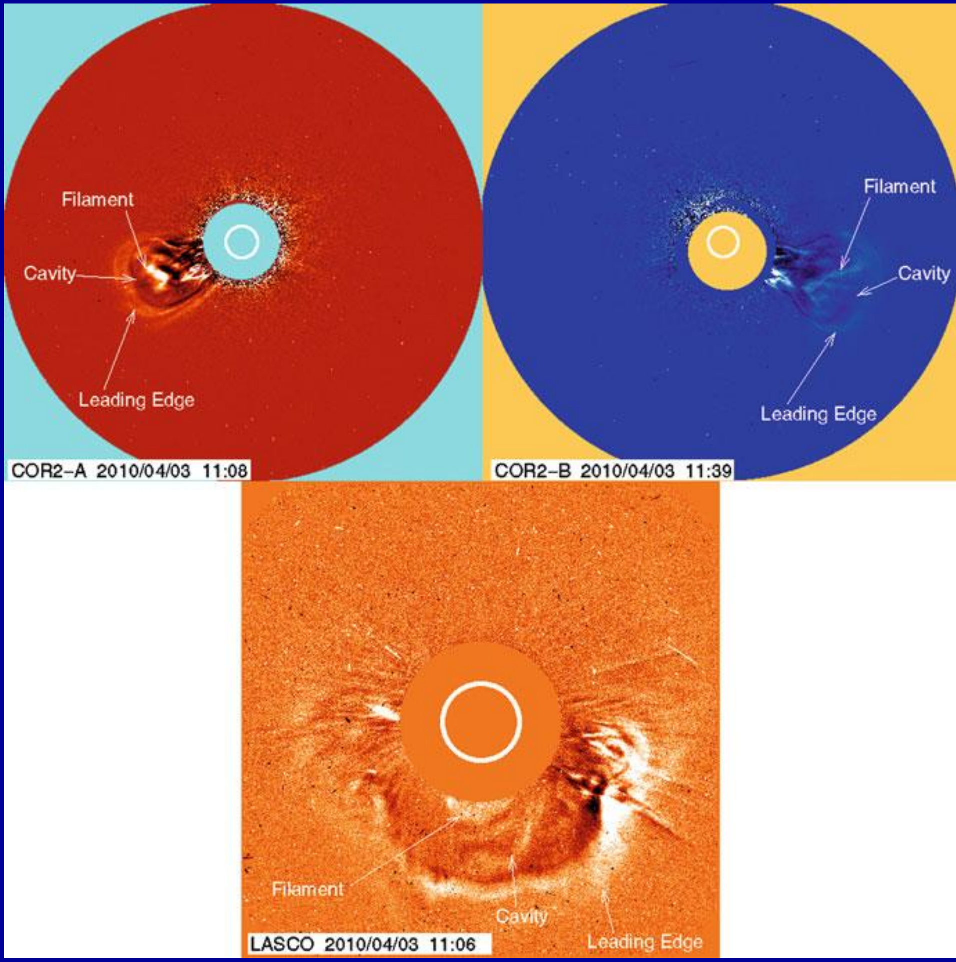
Stereoscopic Observations of CMEs

Different views of same CME

Limb CME in 2007 (<40^0)

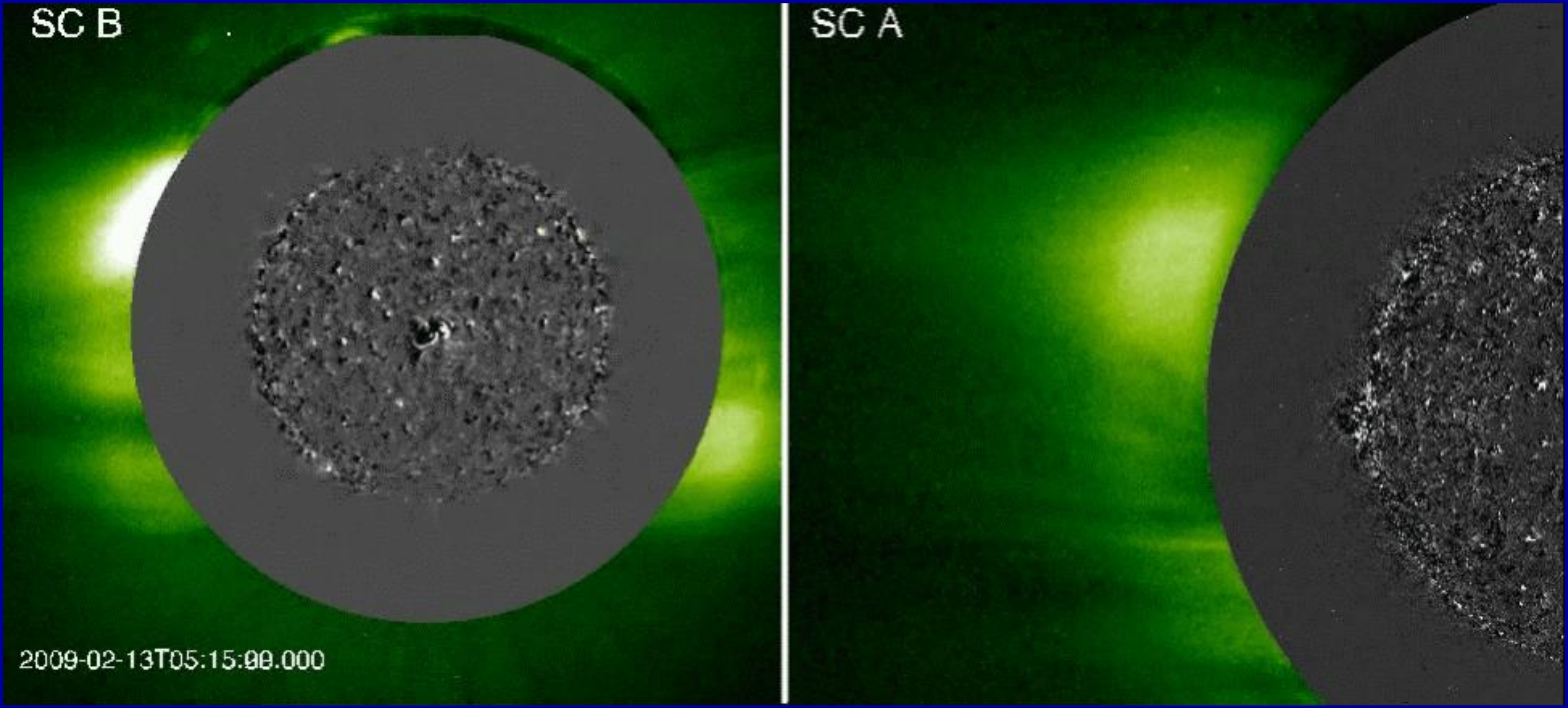


Earth-directed CME in 2010 (>90^0)



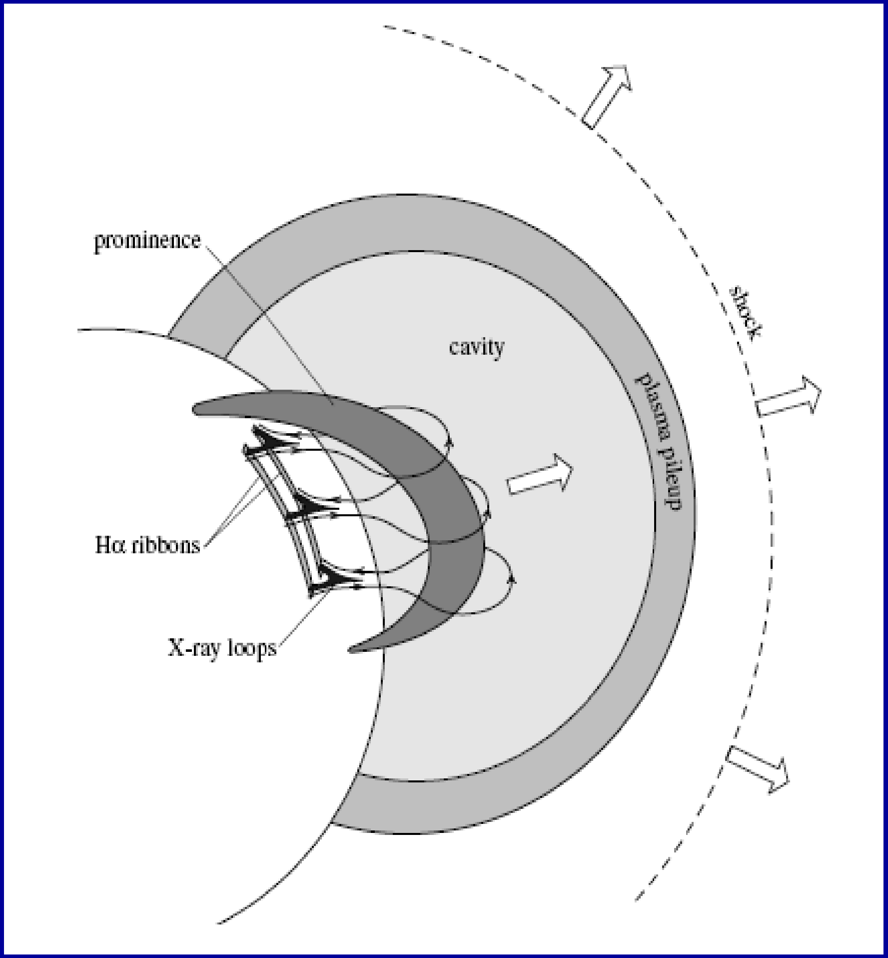
Howard, 2011

February 23, 2009 STEREO A & B



Separation angle 90 degrees

Standard model of 3 part CME



Magnetic energy storage in the corona

Energy loss by dissipative processes or loss of equilibrium

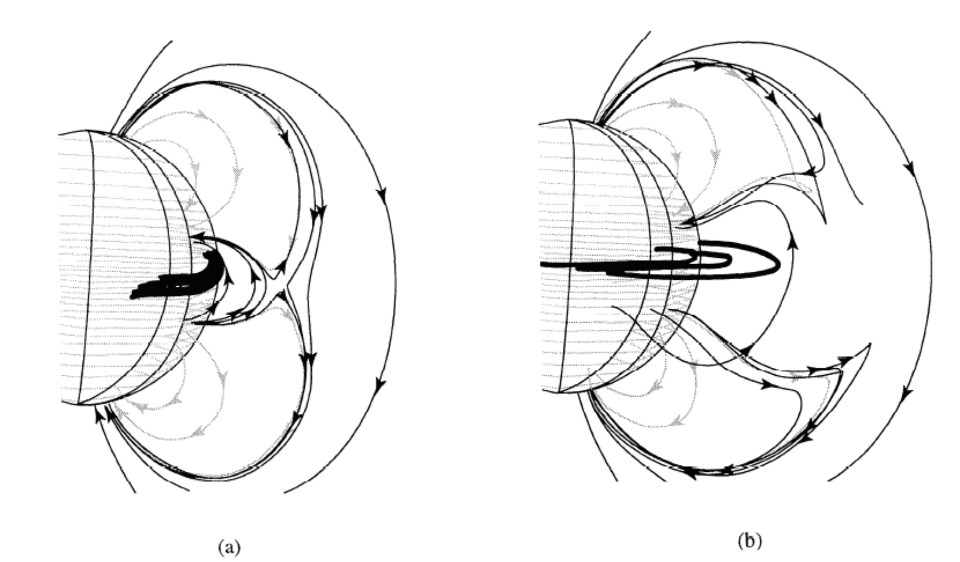
Dissipation by any of the these

•Reconnection below the erupting structure eg. Tether cutting or emerging flux

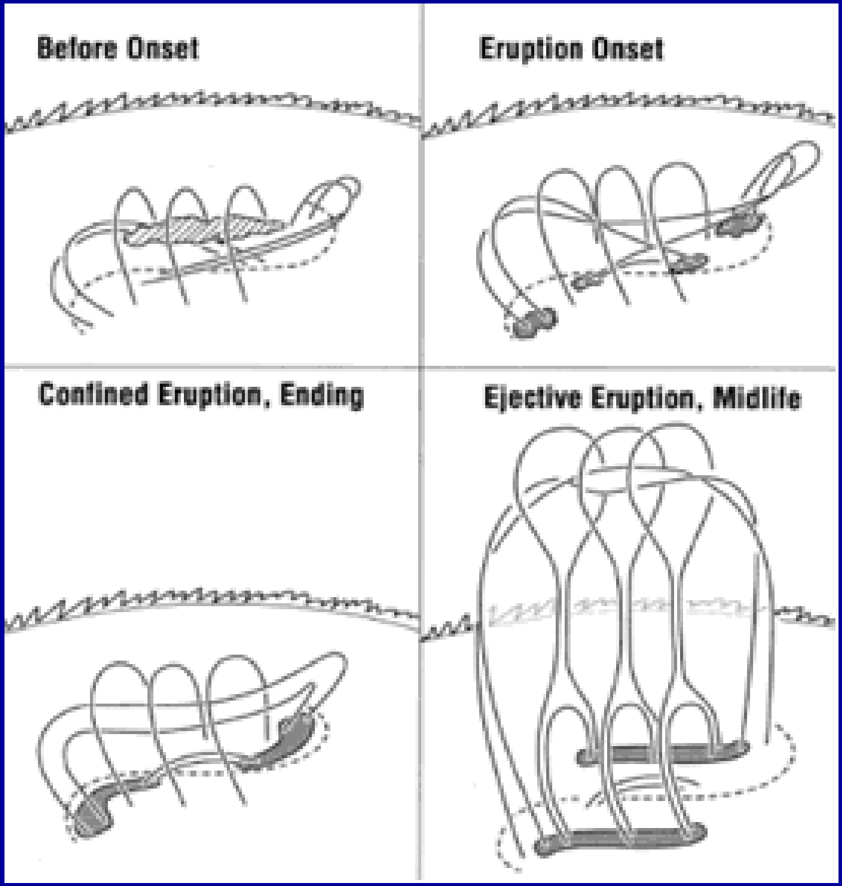
•Reconnection above : break out model

Existing models for CMEs

1. Break out model : Antiochos et al. 1999
2. Tether cutting model: Sturrock et al. 1984
3. Flux rope model: Chen et al. 1996
4. Flux-injection model: Krall, Chen and Santoro, 2000
5. Mass loading model: Low and Smith 1981

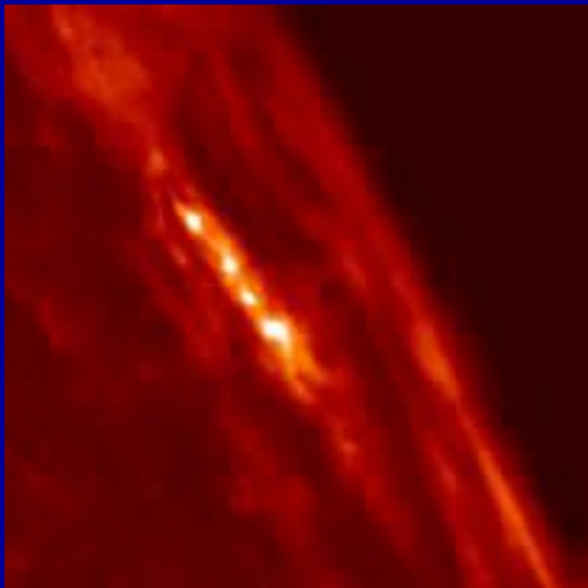


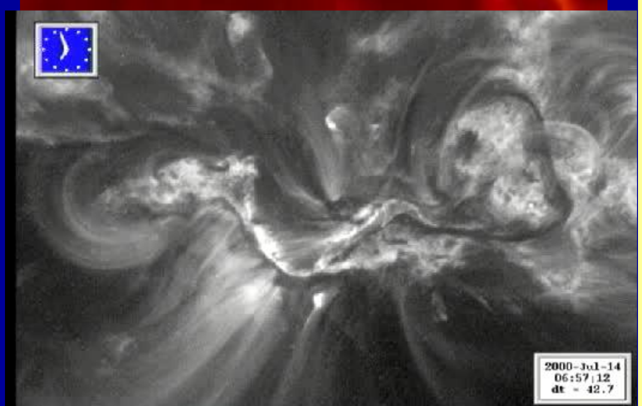
Break out model



Tether cutting model

The relationship between flares & CMEs

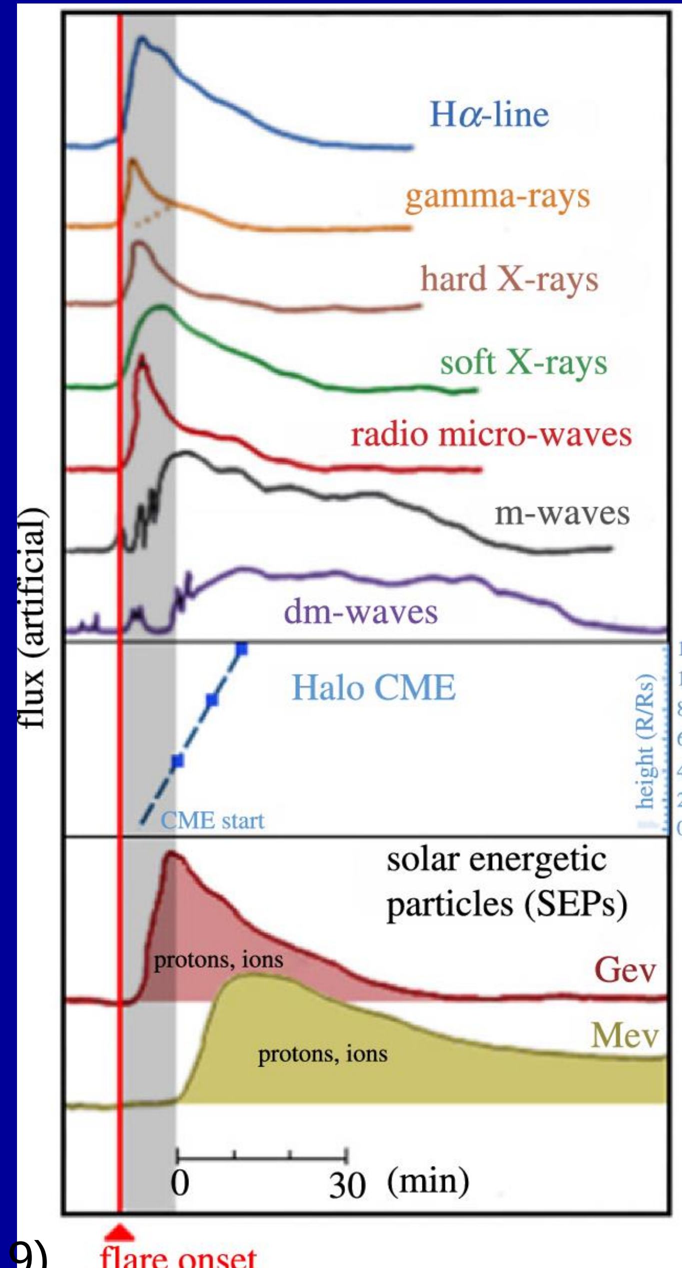




- Flares are localized short-duration explosions in the solar atmosphere, seen in visible light, EUV, X- and Gamma-rays.

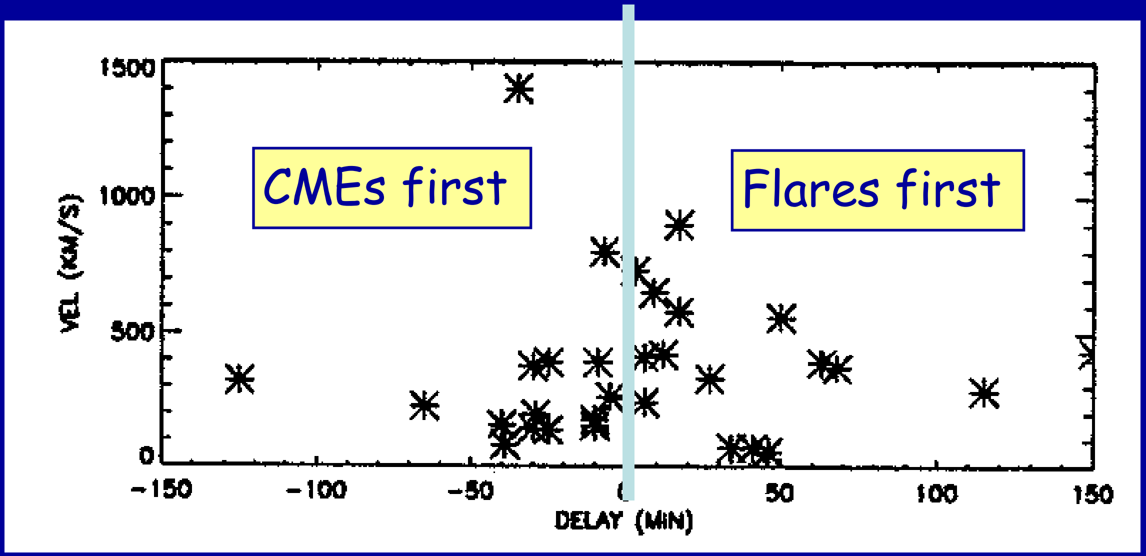
- CMEs are large-scale expulsions of huge plasma clouds that may drive shock waves.
- Flares and CMEs often occur in close temporal context.

The Bastille-day flare, on July 14, 2000



Anastasiadis et al. (2019),

CME-flare relation, a hen-and-egg situation?



Time separation between flares and correlated CMEs

The simple but important conclusions from these studies:

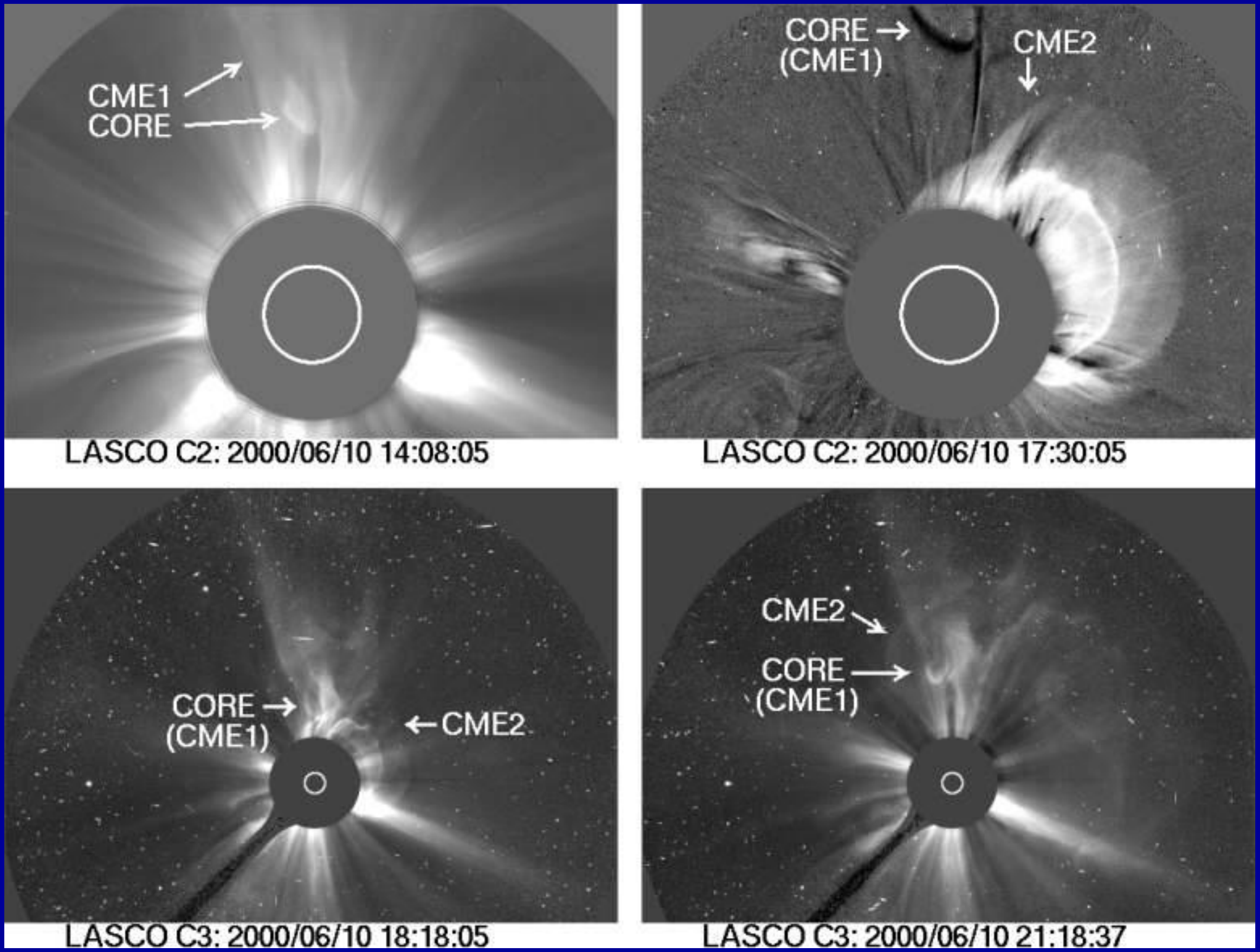
Flares occurring after their associated CMEs cannot be their cause, quite logically.

Flares and CMEs are probably symptoms of a more basic "magnetic disease" of the sun.

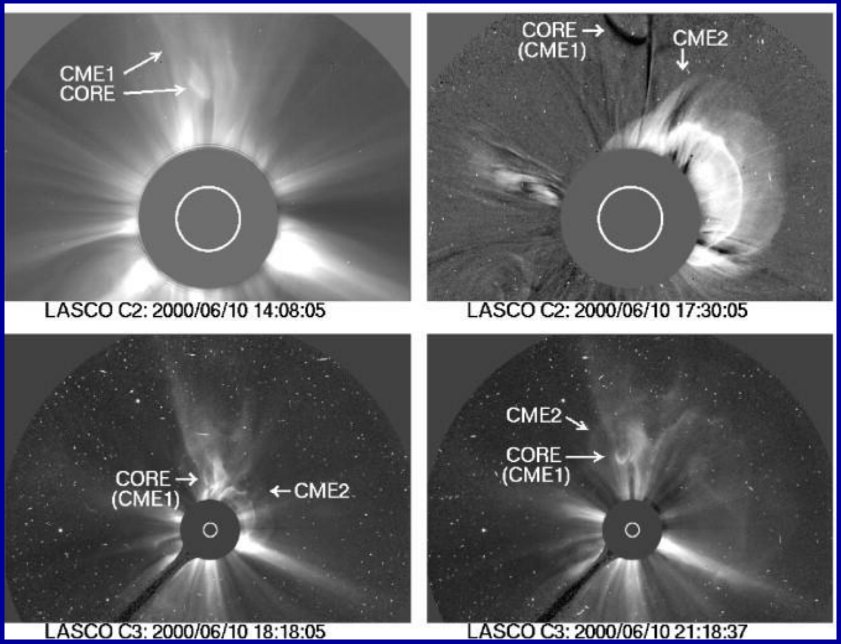
Non-coronagraphic Observations

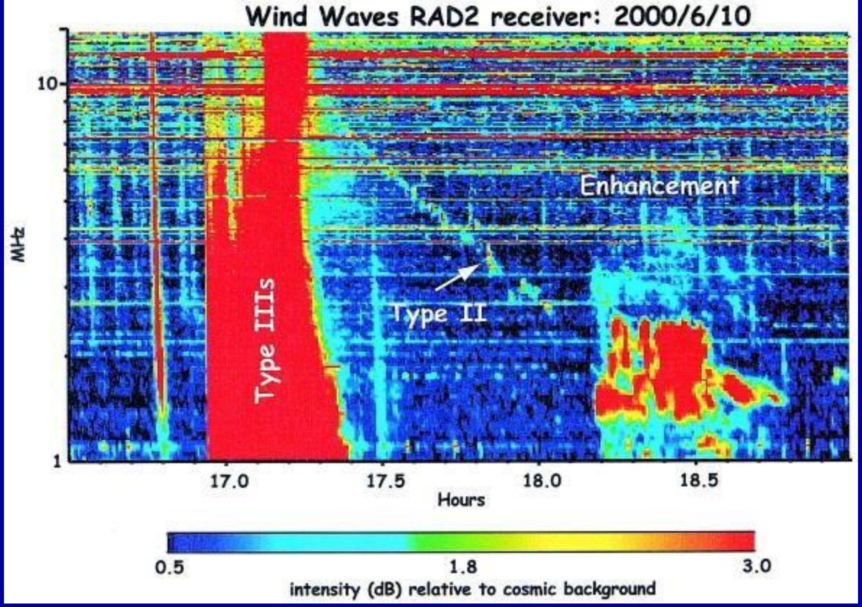
- EUV/X-ray imaging : Shows the K-corona in emission (emissivity decreases in short wavelengths). High contrast images possible in X-rays
- ICME/in-situ measurements: velocity, density, temperature, magnetic field, orientation, charge-states of the particles in the cloud.
- Radio –Large Range of radio frequencies possible from the ground

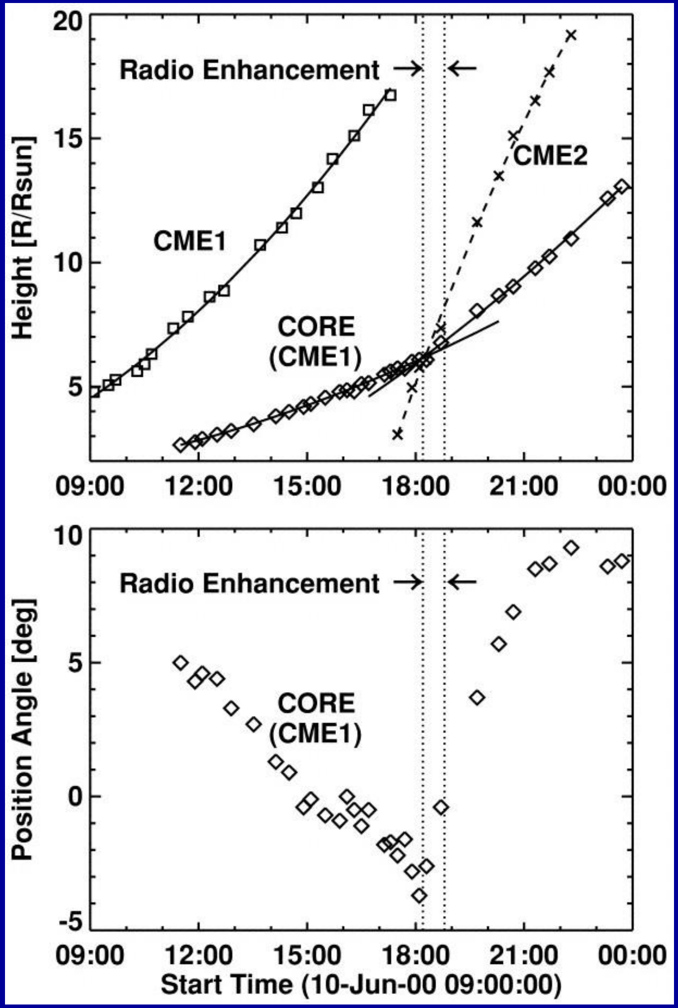
Interaction of CMEs



CME-CME Interaction







Radio Enhancement & Change in direction after interaction

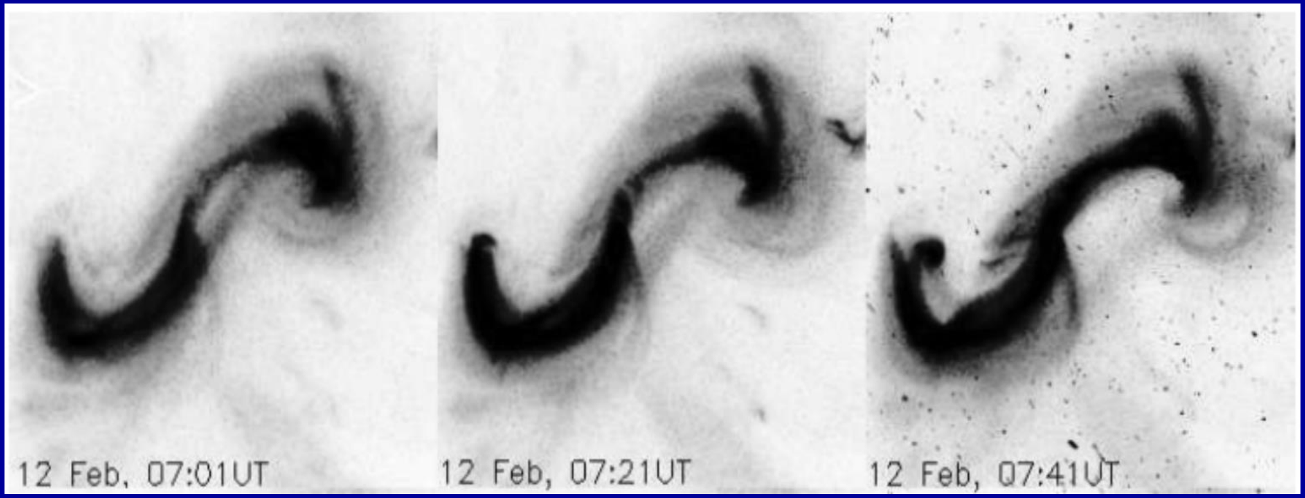
Gopalswamy et al. (2001)

Solar Energetic Particles

The main locations for electron and ion acceleration are flare sites and shock waves in the corona and in interplanetary space. The energy of these *solar energetic particles (SEPs)* reaches from a few keV of “suprathermal particles” to some GeV.

Sometimes the fastest particles obtain more than half the speed of light, and they arrive at the Earth only a few minutes after the light flash. They are of particular concern in the space weather context since they can penetrate even the skins of spaceprobes traveling outside the Earth’s magnetosphere and blind or even damage sensitive technical systems.

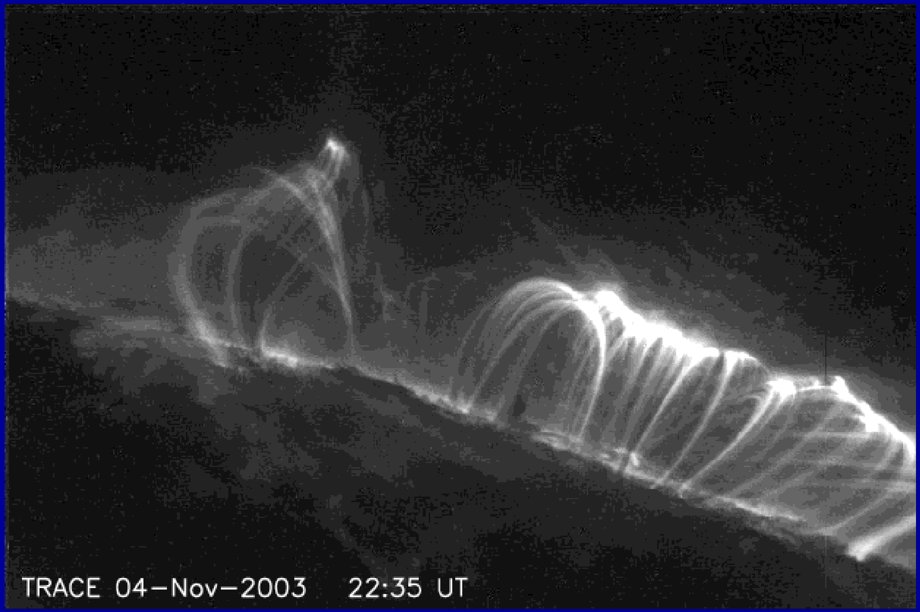
Associated phenomena



Evolution of an active region sigmoid which erupted on 12 February 2007 as observed by XRT telescope on Hinode.

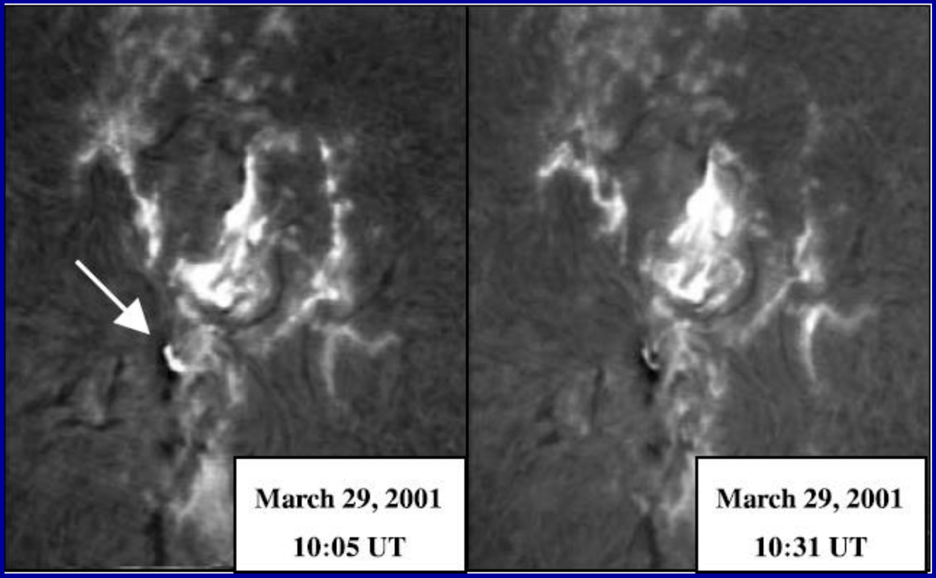
50000-150000 km

Post-eruptive arcades-EIT



A post-eruptive arcade (PEA) observed by TRACE on 4 November 2003 at 22:35 UT in EUV (195 Å) line

Solar Flare

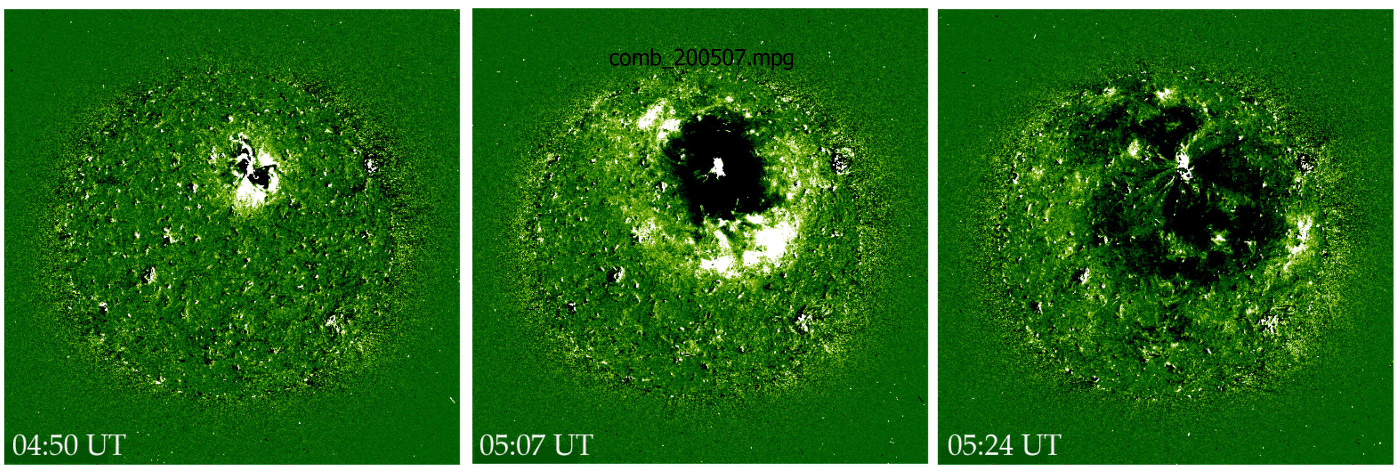


A solar flare observed on March 29, 2001 at Udaipur Solar Observatory

EIT Waves

The EIT wave might trace the CME in the lower atmosphere.

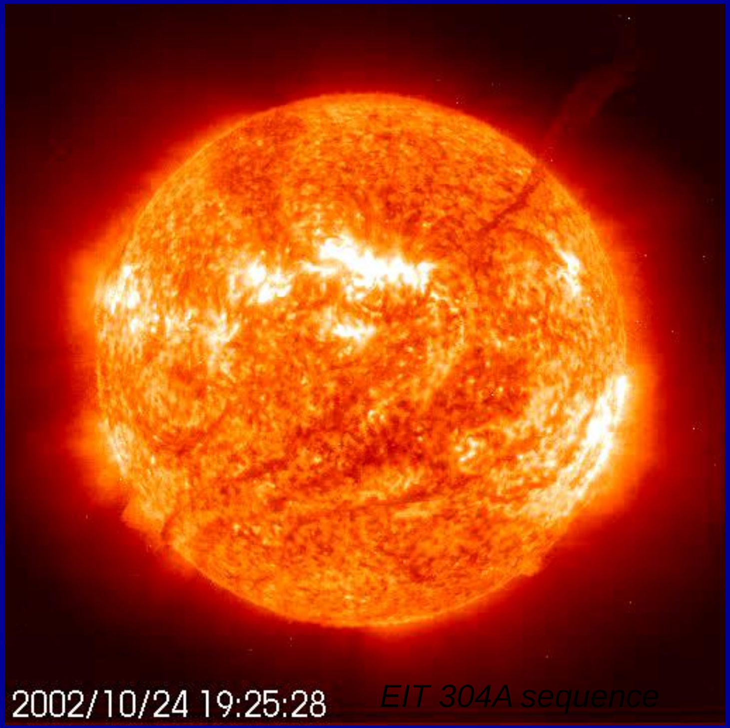
Expansion of the CME
Interactions with distant regions
Relation between CME & flare

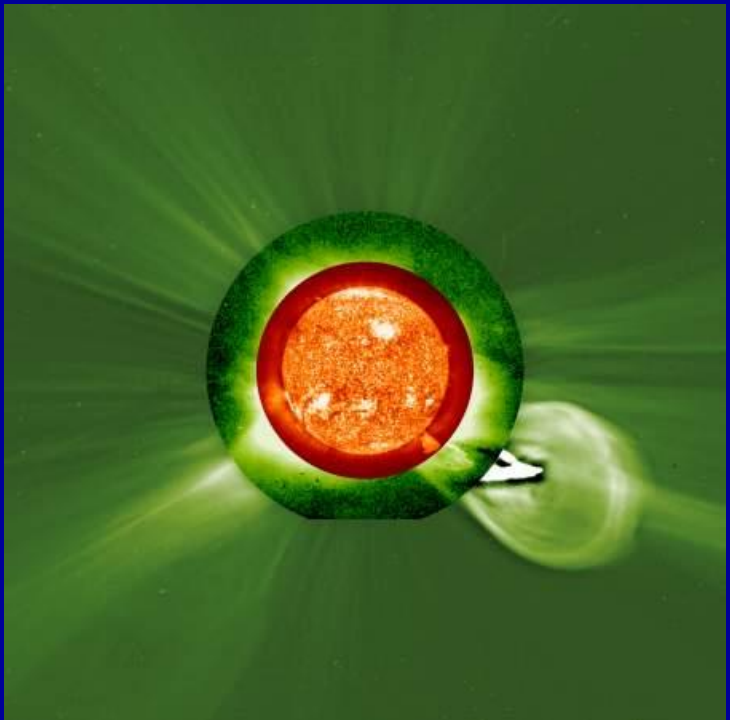


SOHO-Extreme ultraviolet Imaging Telescope (EIT)
observations of Moreton wave expanding from coronal mass ejection (CME) initiation site
1997 May 12
First differences in Fe XII 195 Å (1.5 MK)

CMEs & Filaments

- Filaments eruptions are very important CME signatures in the low corona.
  - Do filaments play a role in the initiation or propagation?
  - Are *Streamer-Blowout* CMEs special?

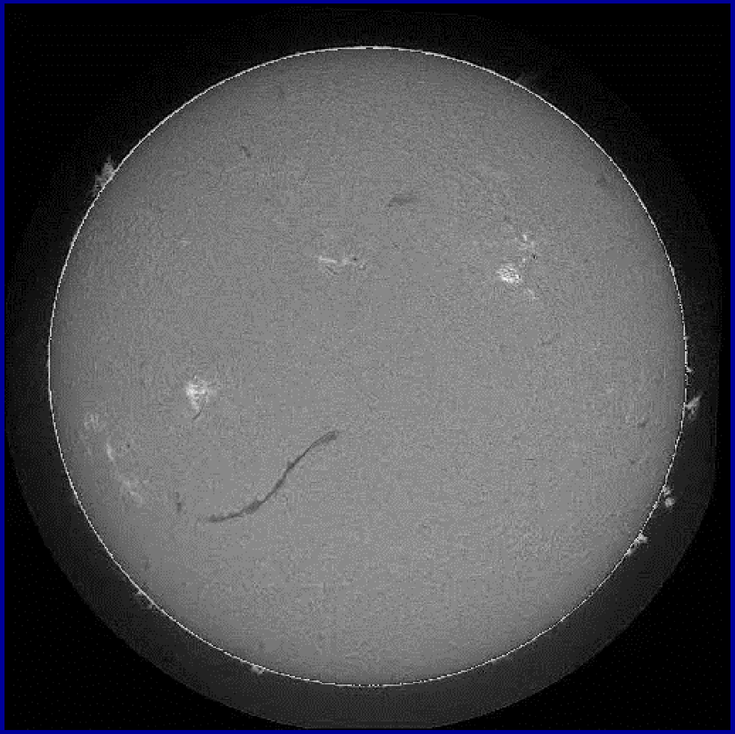




72% association with CMEs
Gilbert et al (2000)

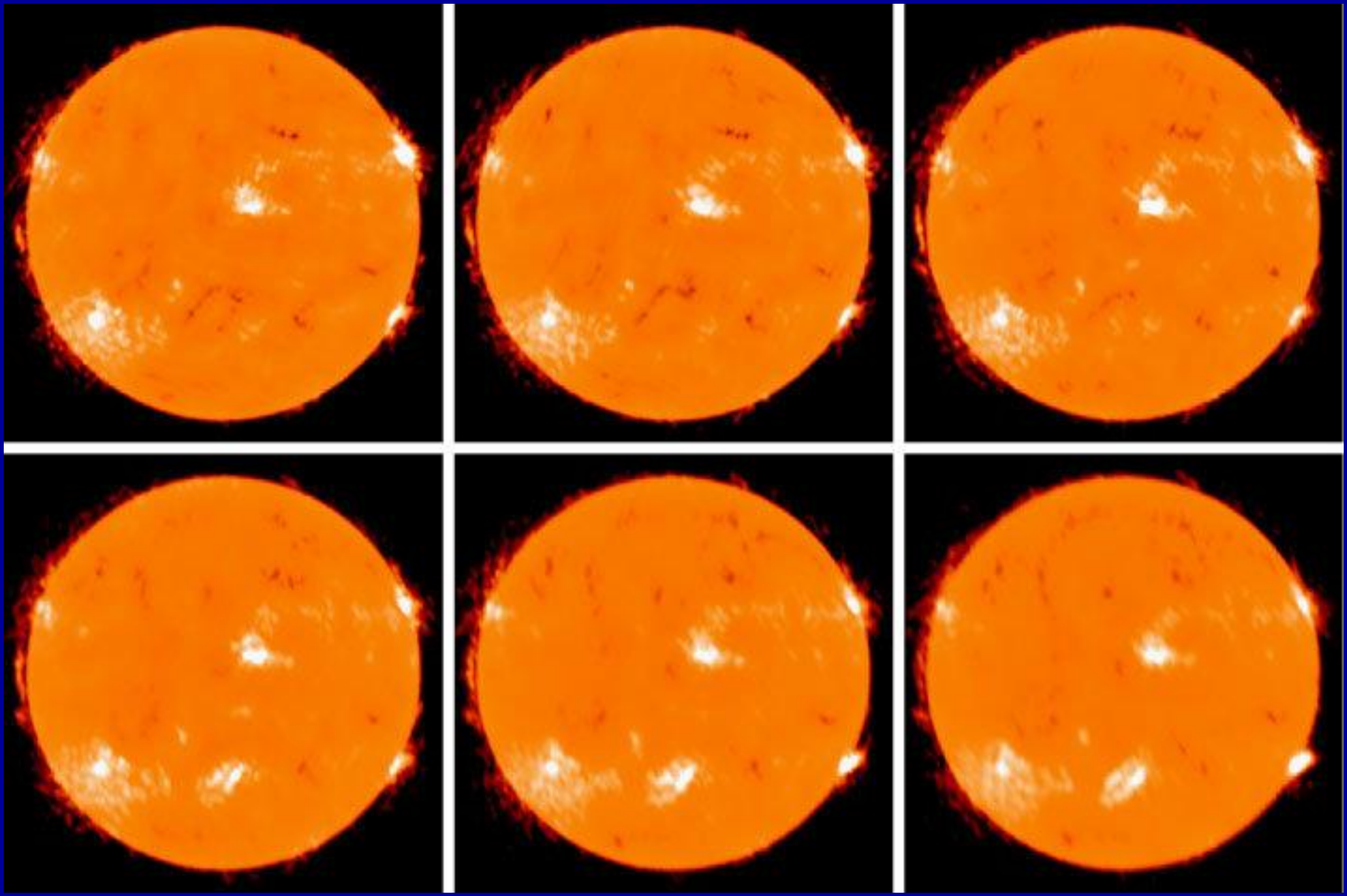
Filament eruptions- USO, Udaipur

Partial Eruption-4 Aug 2012

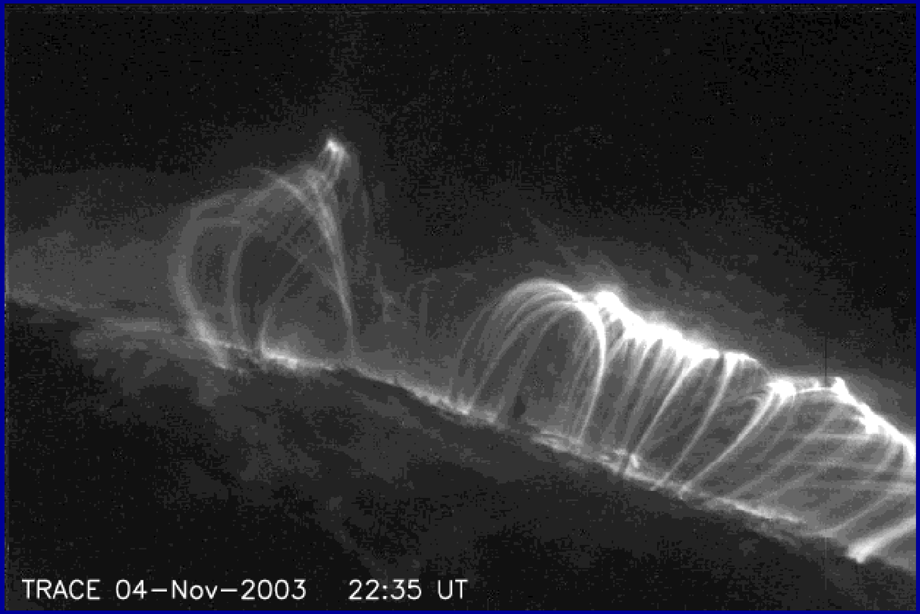


Complete Eruption- 5 Jan 2005

Nobeyama Radioheliograph Observations-filament eruption
19 September 1999

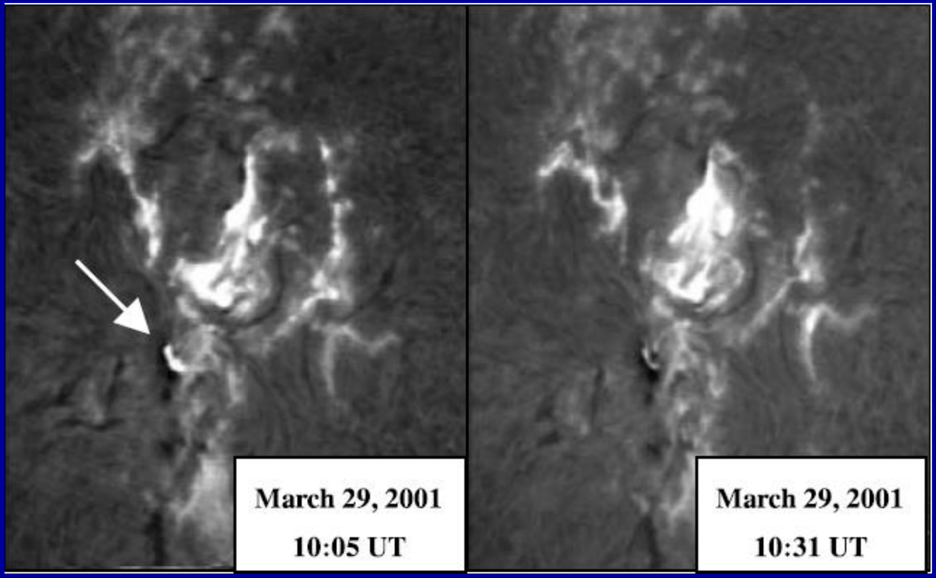


Post-eruptive arcades-EIT



A post-eruptive arcade (PEA) observed by TRACE on 4 November 2003 at 22:35 UT in EUV (195 Å) line

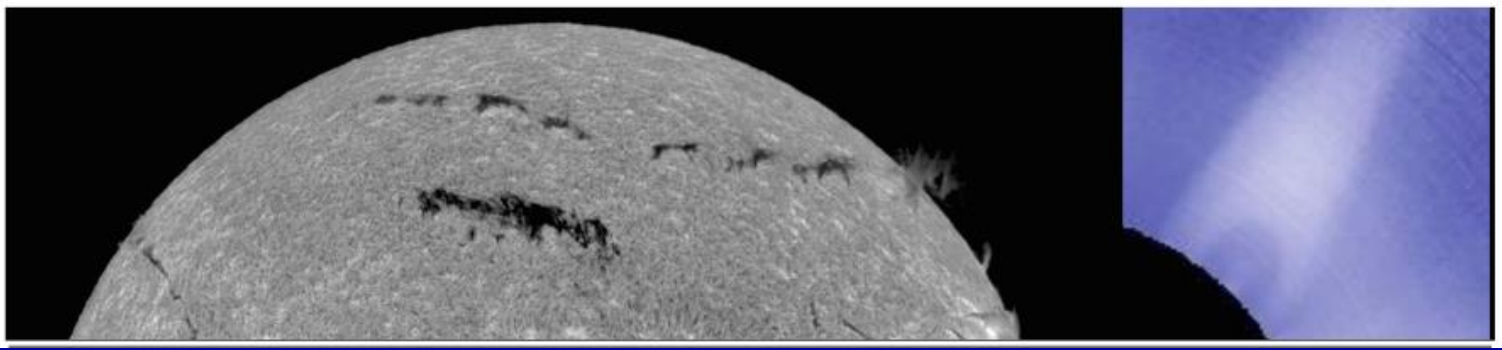
Solar Flare



A solar flare observed on March 29, 2001 at Udaipur Solar Observatory

Coronal Cavity

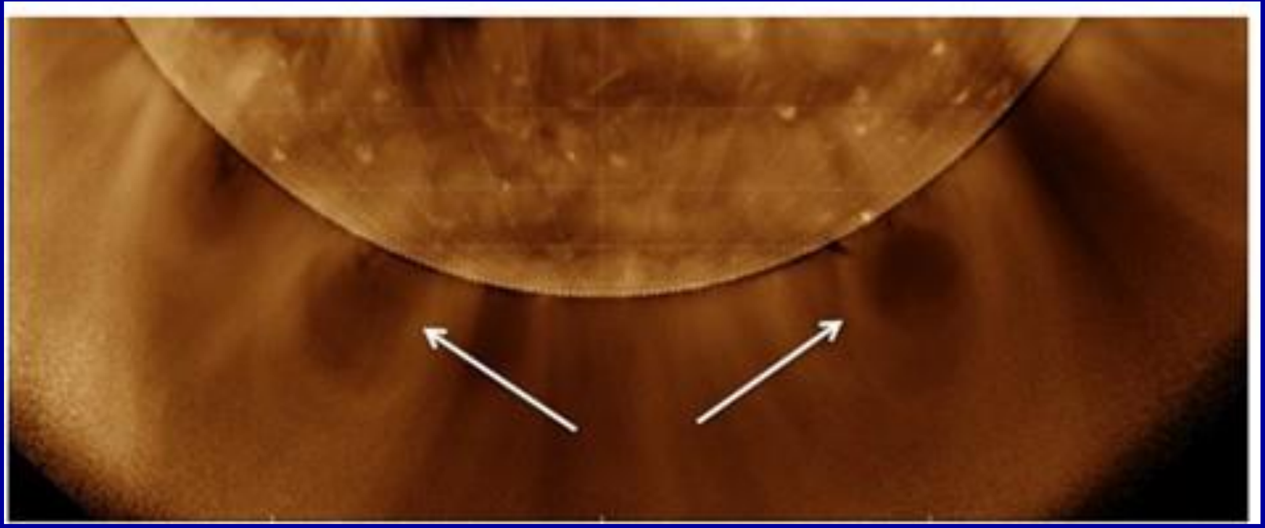
Cavities appear as dark features over the solar limb and are believed to be the density depleted cross-sections of the magnetic flux ropes, where the magnetic field strength attains a much higher value compared to the background corona. Cavities may last for days or even weeks and evolve as the dark core part of the CME during the eruptive phase.
(Low and Hundhausen, 1995; Gibson and Fan, 2006)



PCF observed in Hα by BBSO on July 2002 (right): White light cavity observed by MLSO/MK4

[Gibson 2017]

EUV Cavity observed from AIA 193 channel
on 29 May 2013



[Karna et al. 2017]

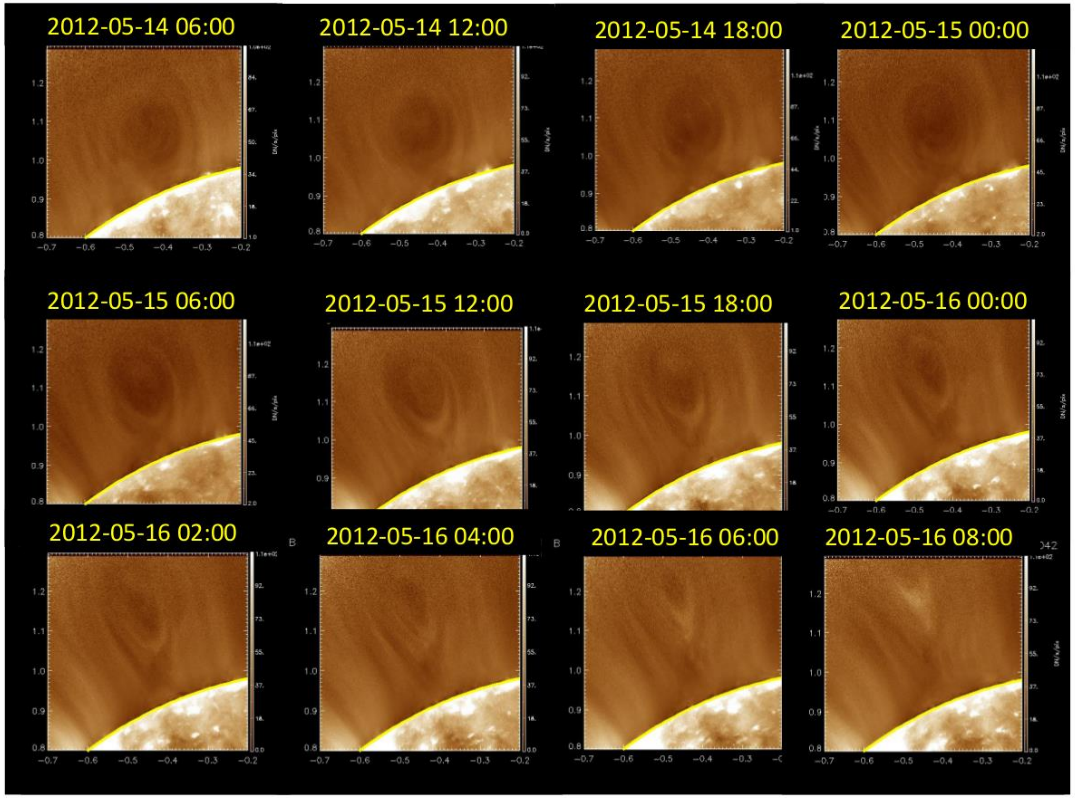
Morphological pre-cursors for cavity eruption:

Cavity morphology can be observed as semi-circular, elliptical or tear-drop shape.

Forland et al. 2013, identified 129 cavities during June 2010 to December 2019 from the data obtained from AIA 193 channel

Of these 129 cavities, 28 % were eruptive.

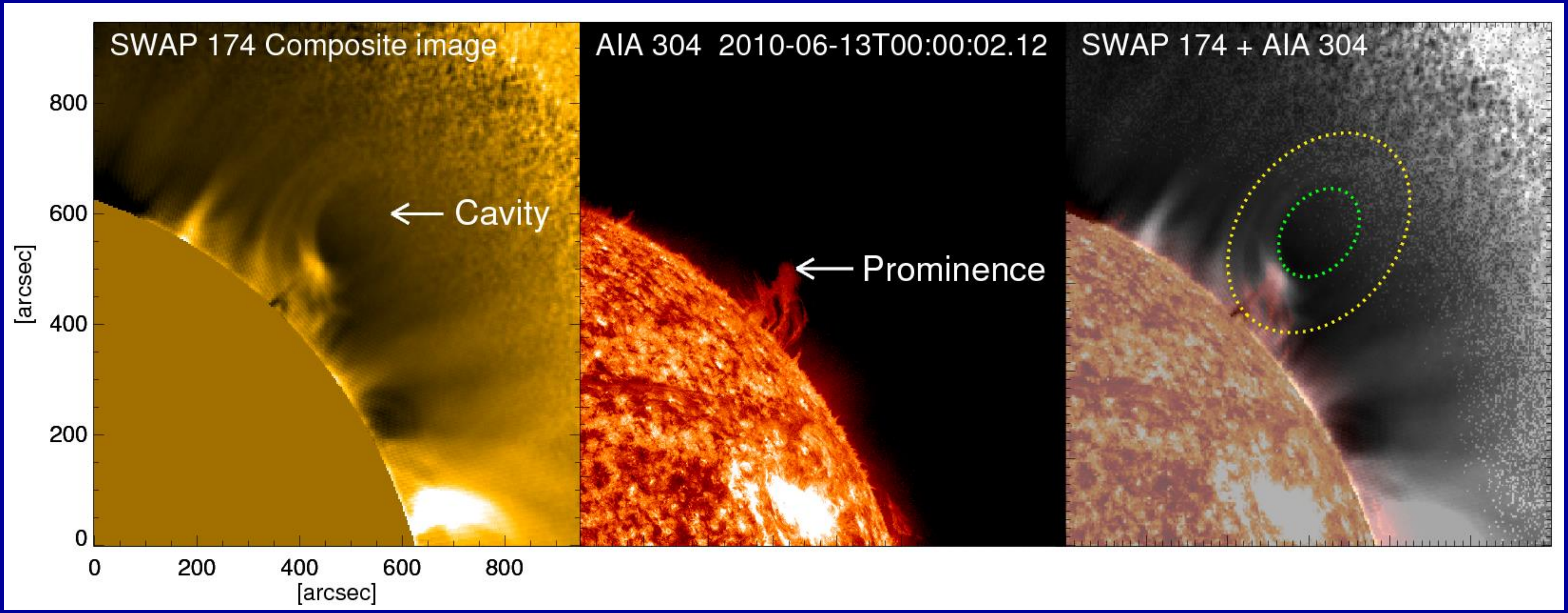
61% of all the eruptive cavities have been found to be in tear-drop shape before the eruption.



Stability study of coronal cavities:

Decay index values for the non-eruptive cavities at the height of its centroid mostly lie below the 1.0 value. (de Toma & Gibson 2018)

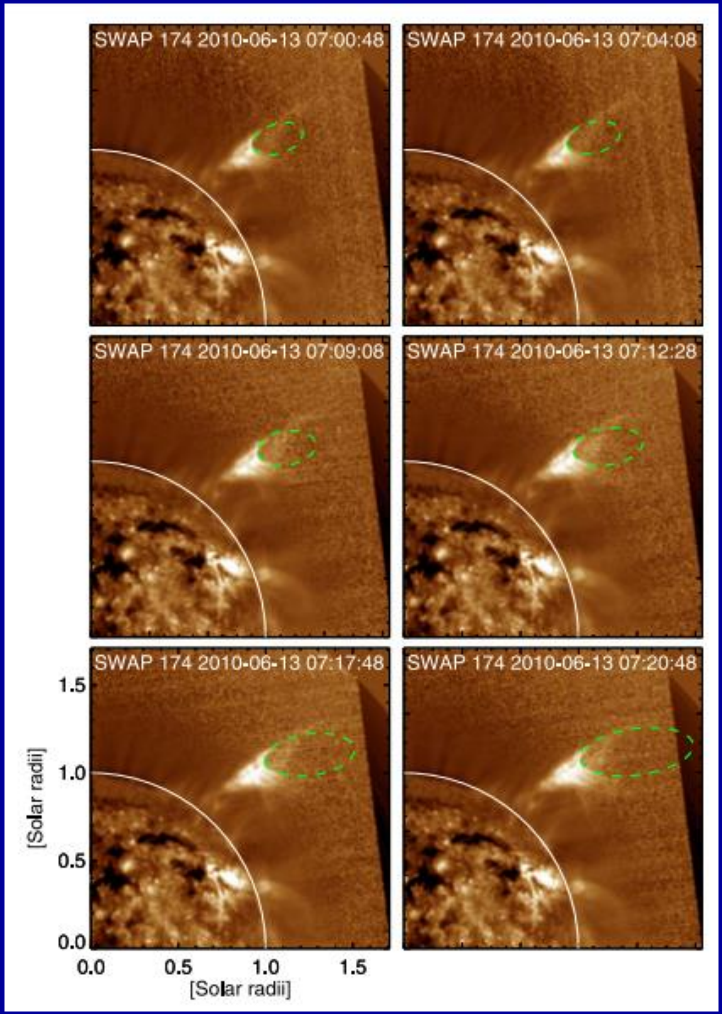
Overlap of coronal cavities seen in SWAP and the prominence material seen in AIA 304



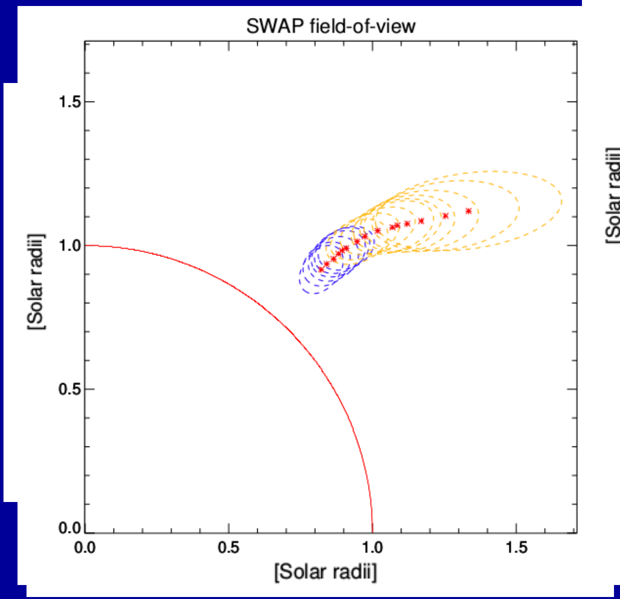
The top of the prominence material and the lower-most part of the cavity coincide well.

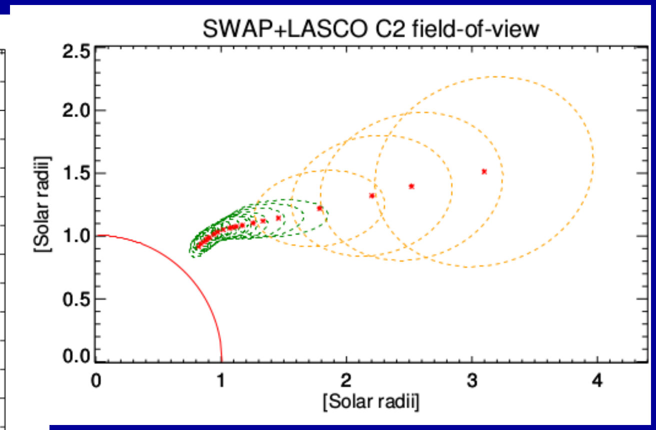
Do they maintain this trend during the eruption also ?

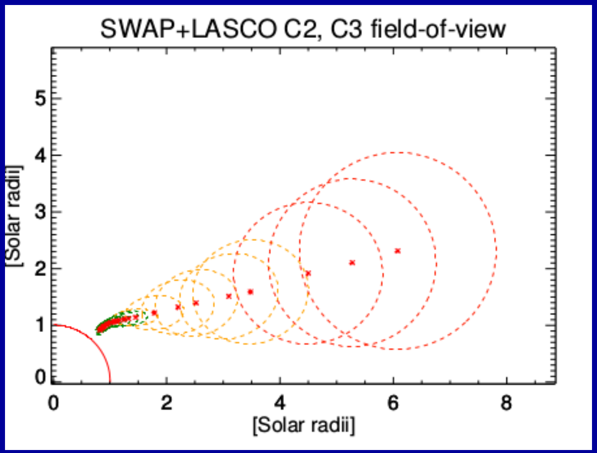
Evolution of the coronal cavity during eruptive phase

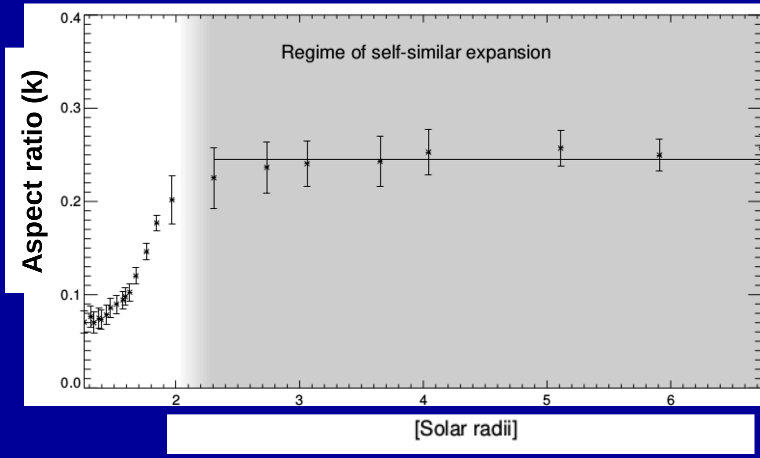


Deflection and nature of expansion of the CME









- The CME undergoes a strong deflection (≈40°) at 1.3 R_S. After that the propagation direction remains almost constant. The presence of coronal hole in the vicinity of the filament channel might have caused the deflection.
- The CME exhibits non self-similar expansion below ≈ 2.2 R_S.

Sarkar et al. 2019, ApJ

Stealth CMEs: Without Surface (Coronal) Activity

42.18

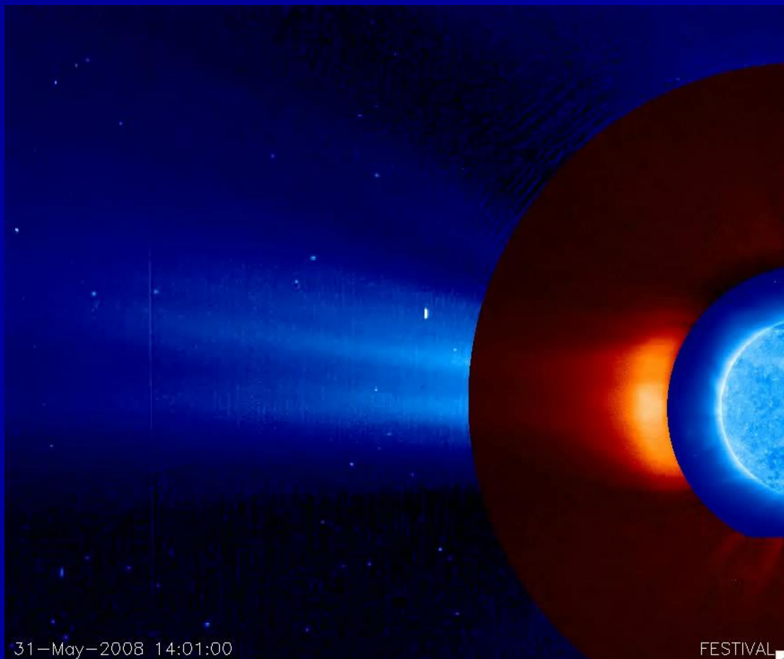
<u>Spontaneous Coronal Mass Ejections</u>

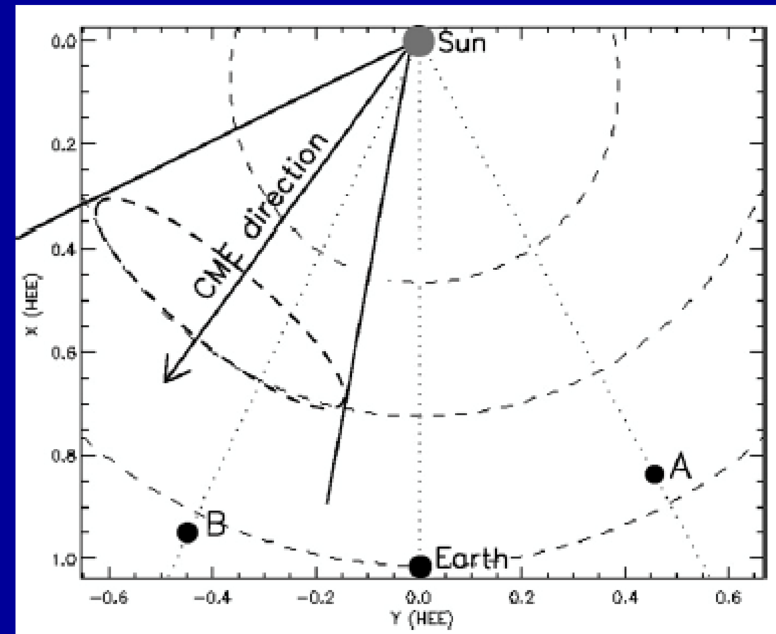
W. J. Wagner (High Altitude Observatory/NCAR)

In the Skylab period, limb flares and eruptive prominences were usually accompanied by coronal mass ejections (CMEs). Nevertheless, only about 1/2 of the 1973 CMEs could be associated with such near-surface activity. A study, relying only on statistical probabilities, investigated both Skylab and Solar Maximum Mission mass ejections, comparing time and locations of CMEs to those of H-alpha flares, erupting prominences, long-duration X-ray emission, and metric type II and IV radio bursts. I find that a considerable number of mass ejections have no associated flare, erupting prominence, X-ray or radio burst. Corrections were made for estimated behind the limb activity. The study concluded that almost 1/2 the Skylab CMEs and almost 1/3 of the Solar Maximum Mission ejections needed no energetic impulsive initiation.

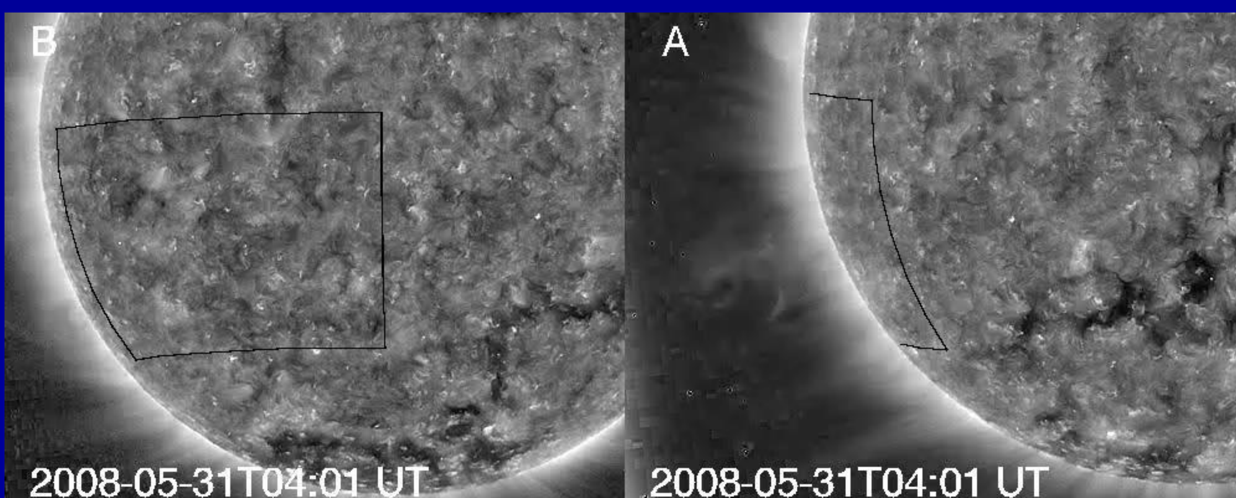
BAA, 16, 536 (1984)

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).

Space –based Coronagraphy

Coronagraph	Year	FOV	Resolution
OSO-7	1971-1973	3.0-10 Rs	3 arc-min
Skylab	1973-1974	2.0-6.0 Rs	5 arc-sec
Solwind/P78-I	1979-1985	3.0-10 Rs	Same as OSO
SMM	1980, 1984-1989	1.6-6 Rs	30 arc-sec
LASCO	1995-1998 1995-	1.1-3.0, (E-corona) 2.0-6.0, 3.7-32 Rs	11.2 arc-sec 23 arc-sec 112 arc-sec
SECCHI	2006-	1.4-4.0, 2.0-15 Rs 12-84 Rs 66-250 Rs	7.5 arc-sec 15 arc-sec

CMEs and the Heliosphere

- CME in the heliosphere known as ICME (*interplanetary CME*)
- CME plasma are probed directly by in-situ probes.
  - Magnetic field (magnitude, direction)
  - Plasma density, composition, temperature
  - Particle energies (electron, protons)
- How do CMEs get affected by the heliosphere?
  - CMEs propagate through the
    - solar wind (fast, slow regions)
    - interplanetary magnetic field (parker spiral)
  - But they remain distinct from the solar wind.

Summary

- CME research: initial acceleration and launch mechanism to be explained.
- 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