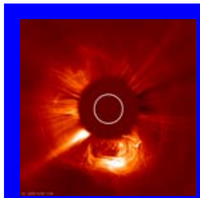
Coronal Mass Ejections: An Introduction

Angelos Vourlidas
Naval Research Laboratory

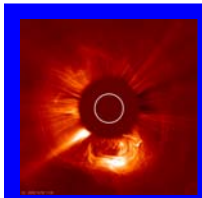
Contributions from
R.A. Howard
T. Zurbuchen



Lecture Outline

- **Related Lectures:**
  - **Overview**: Space Weather, future instrumentation
  - **Basic Physics**: Intro to flares, MHD, Magnetic Reconnection, Plasma Physics
  - **CME/SEP Obs & Models**: SEPs, Coronal/IP Shocks
  - **Practicum**: In-situ measurements, Radio instrumentation

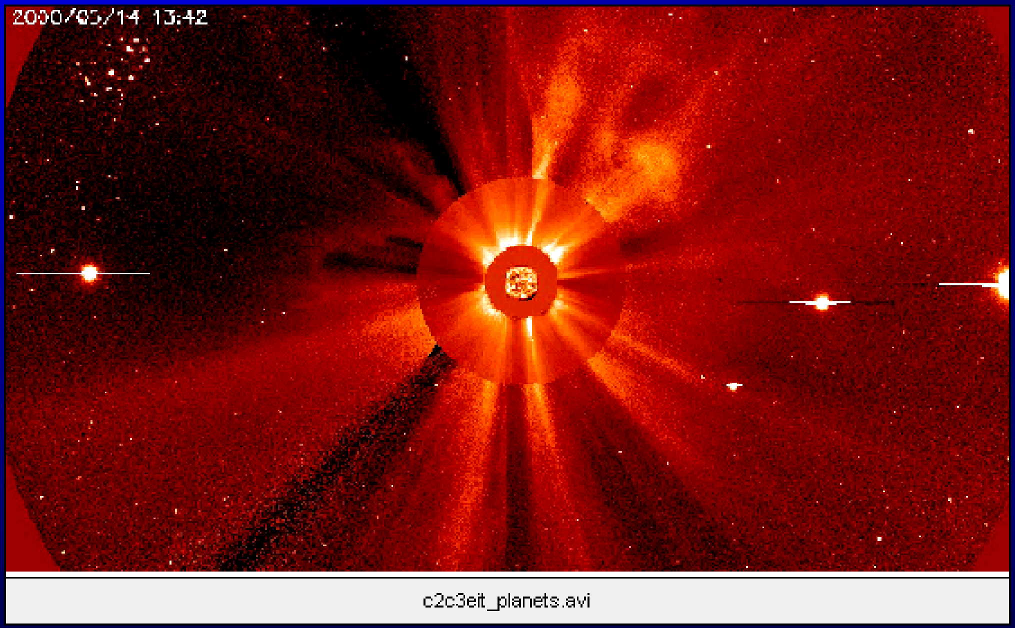
- **Outline:**
  - **A short history**
  - **Theory of white light observations**
  - **Connections to the lower atmosphere & outer heliosphere**
  - **Open questions/research topics**
  - **Review**

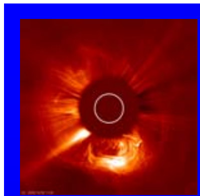


A Typical “Day” at the Office

- The (Visible) Solar Corona offers fascinating research.
- It is extremely active. The most spectacular activity are the

Coronal Mass Ejections (CMEs)



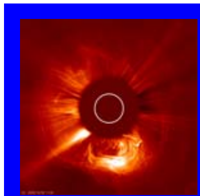


Early Solar Wind Concepts

- 17th Century, Discussion of the Origin of Aurora Begins
  - De Mairan (1731) related the return of the aurora to the return of sunspots after the Maunder Minimum

- 19th Century, Recognition of the Geomagnetic Field
  - September 1, 1859 White Light Flare
    - Lord Carrington was observing sunspots when he saw a white light flare
    - Immediately afterward, geomagnetic field was disturbed
    - 18 hrs later a major geomagnetic storm (2300 Km/s)

it was obvious that a disturbance propagating from the sun to earth had caused this aurora

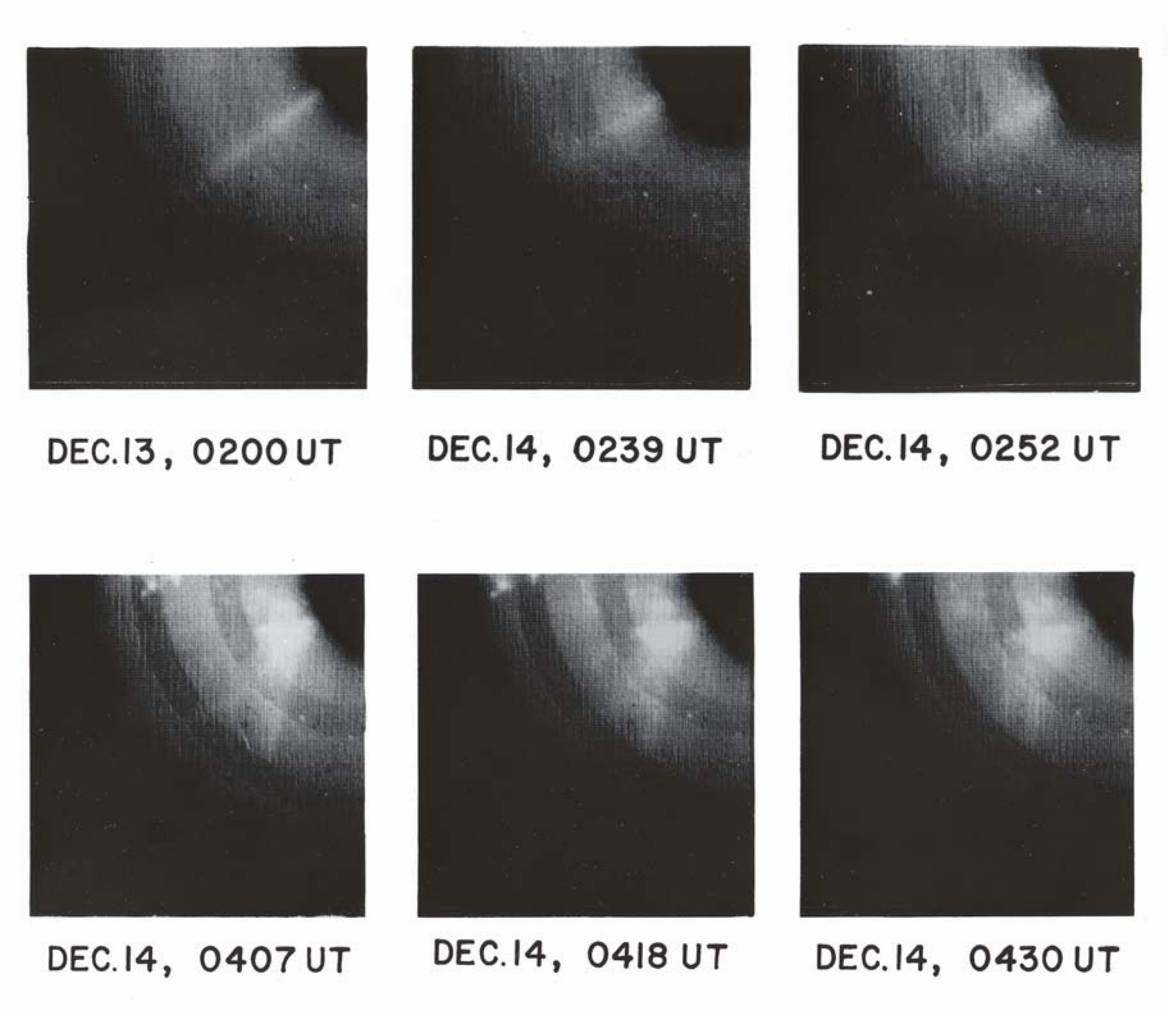


Early Indications for Solar Eruptions

- 1930s, Chapman & Ferraro proposed an intermittent solar wind that occurred only during active times.
- 1940, Pettit studied several filament eruptions/surges
- 1969, type-IIs from Culgora

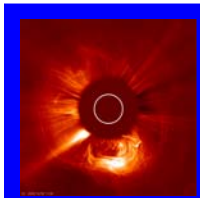
However, until the late 1960's the visible corona was considered a stable, gradually evolving (…and boring) region of the sun.

First CME Detection



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

Tousey et al. 1973

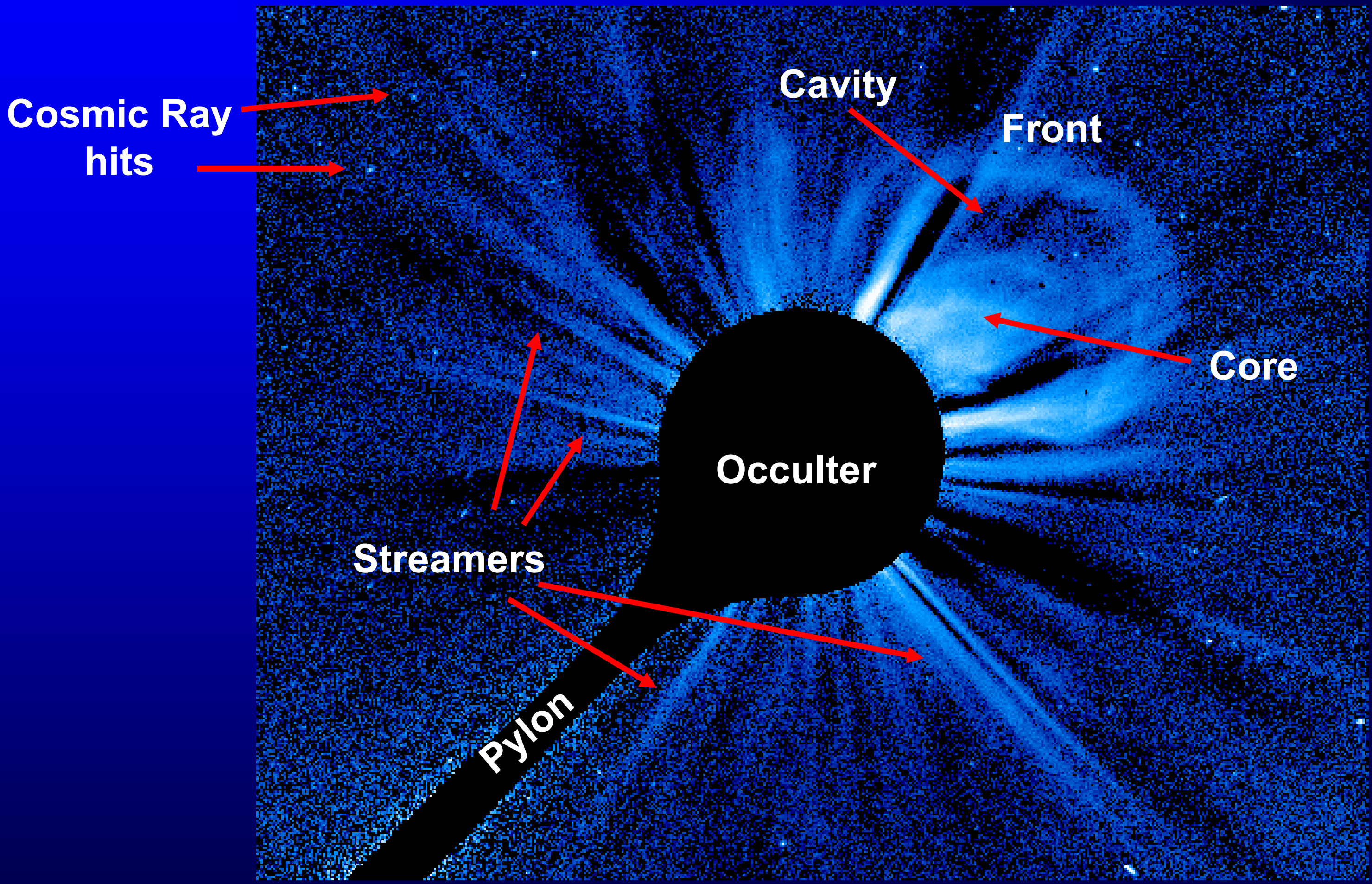


Space-borne Coronagraphs

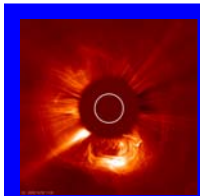
	Field of View (Rs)	Spatial Resolution (“)	CMEs	Key Results
OSO-7 (1971-73)	3 – 10	180	30	1st detection
Skylab (1973-74)	2 – 6	5	100	Beauty, Importance
Solwind (1979-85)	2.5 – 10	180	~1000s	Statistics, Halo, Shocks
SMM (1980, 84-89)	1.6 – 6	30	~1000s	3-part, Statistics
LASCO (1995 -)	1.1 – 32	5.6 – 60	>10,000	Initiation, Fluxrope, Geo-effects
STEREO/SECCHI (July 2006)	1.5 – Earth	8 – 270	?	?

See corona_history.pdf for more info on the history of CME observations

Defining the CME Vocabulary



A “typical” CME



What is recorded in the images?

- **Observations are almost always made in visible light**
  - **Sometimes in Ha (6535A), "Green line" (FeXIV, 5303A), "red line" (FeX)**

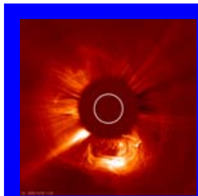
- **Coronagraphs record photospheric light reflected by electrons in the corona**

- **Emission process is Thomson scattering**

- **Emission is optically thin and polarized**

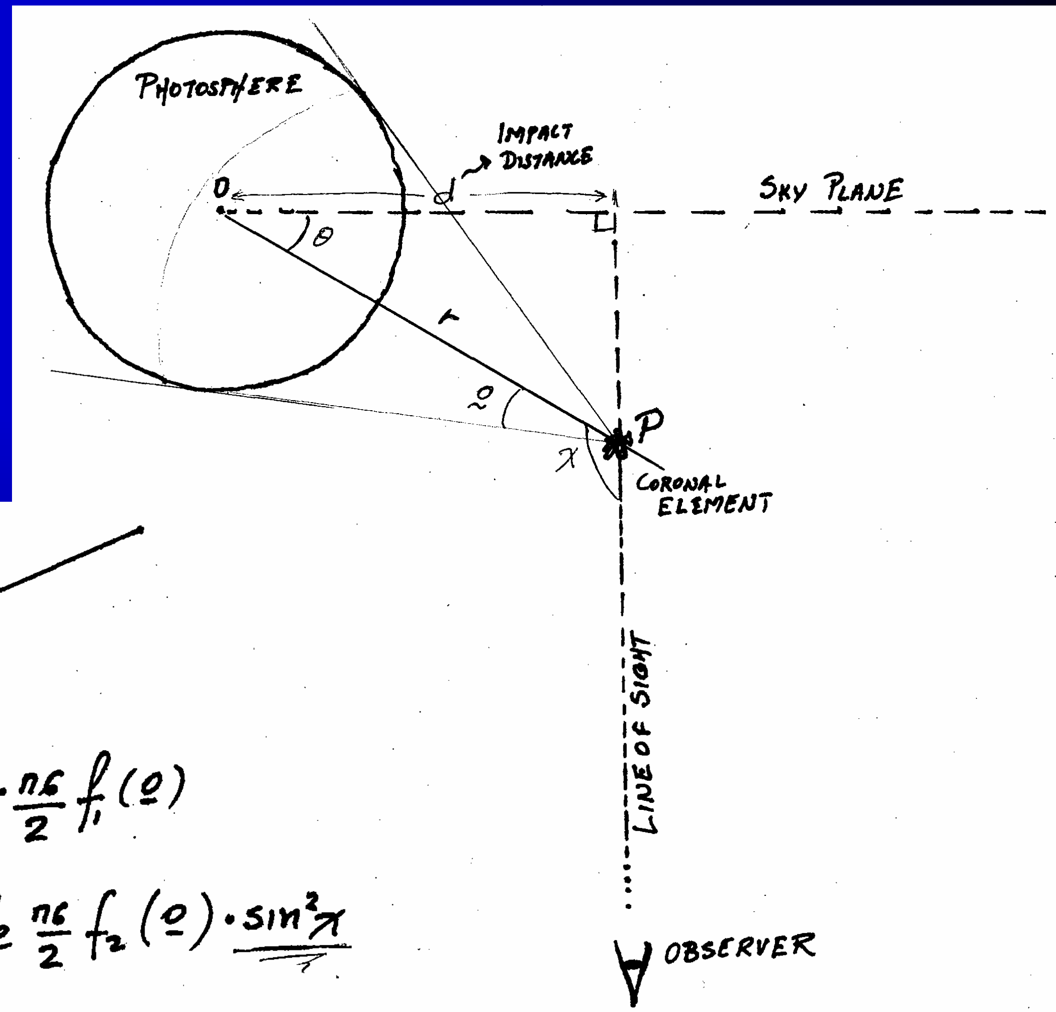
- **Our discussion applies to the quiet corona & CMEs**

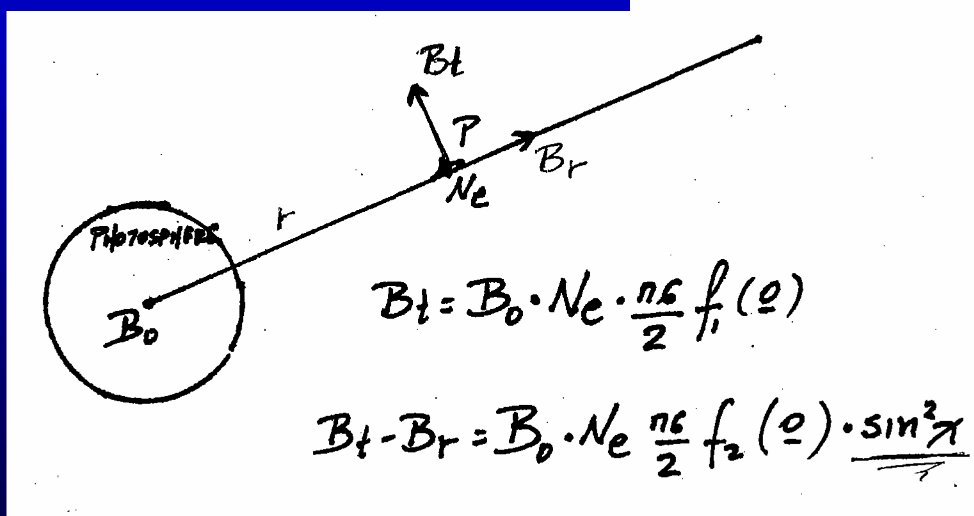
See corona_review.pdf for more info on the quiet corona



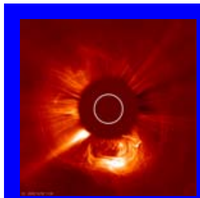
Emission Geometry & Definitions

- **Total Brightness:**
  $B = B_t + B_r$
- **Polarized Brightness:**
  $pB = B_t - B_r$

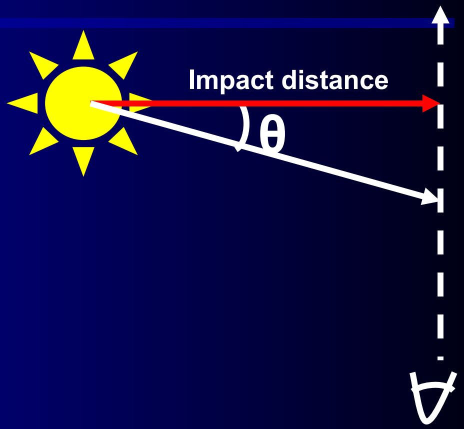




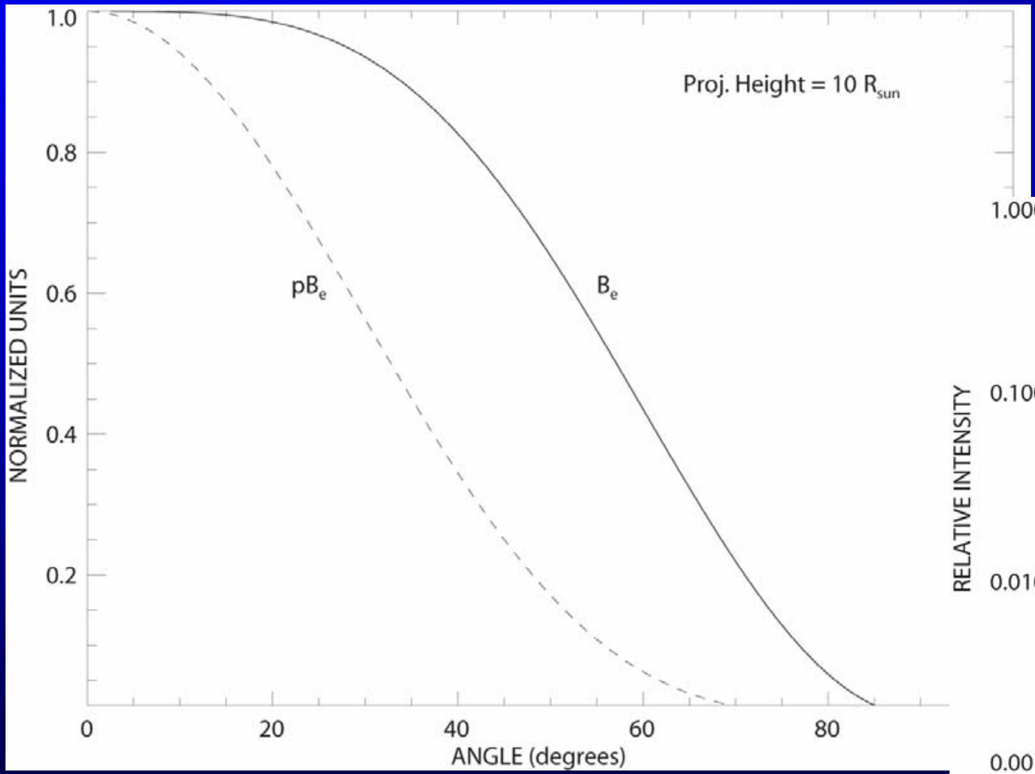
For complete treatment, see Billings (1966)

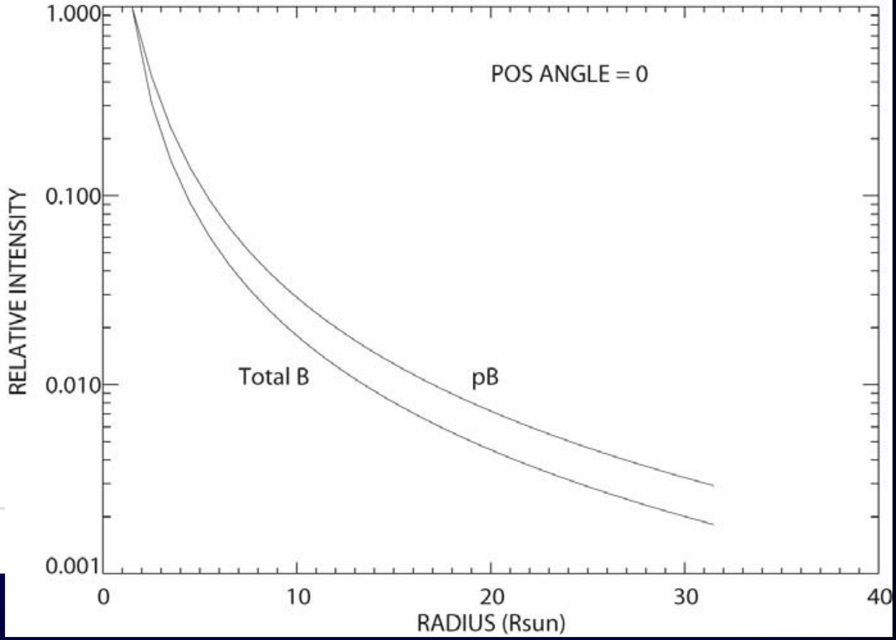


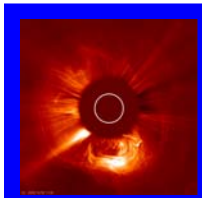
Emission Fundamentals (1)



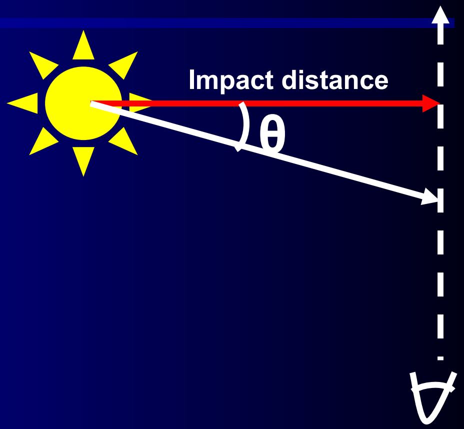
- **Intensity of signal weakens with**
  - **Angular distance from plane of maximum scattering**
  - **Linear distance from the Sun**



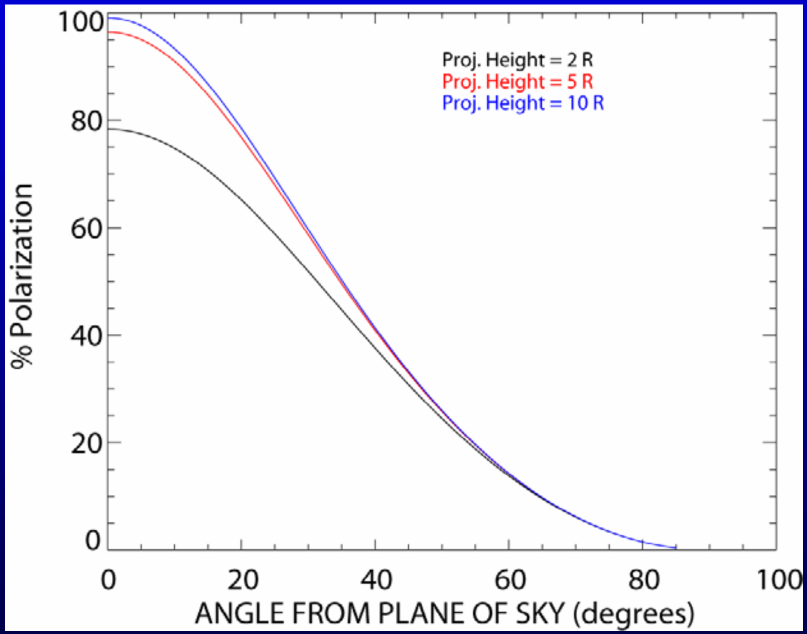


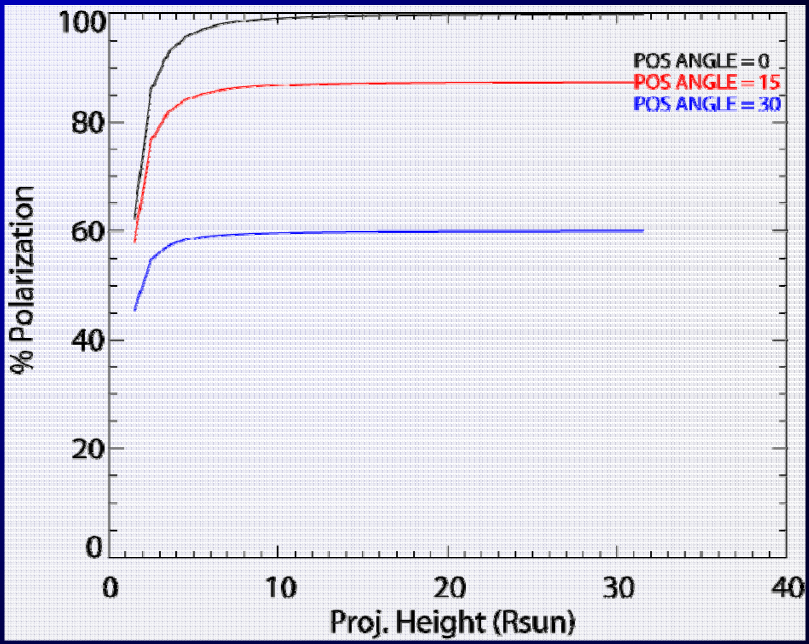


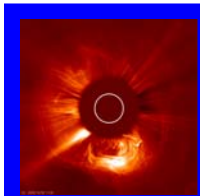
Emission Fundamentals (2)



- **Polarization of the signal:**
  - **Weakens with angular distance from plane of maximum scattering**
  - **Remains constant with radial distance**





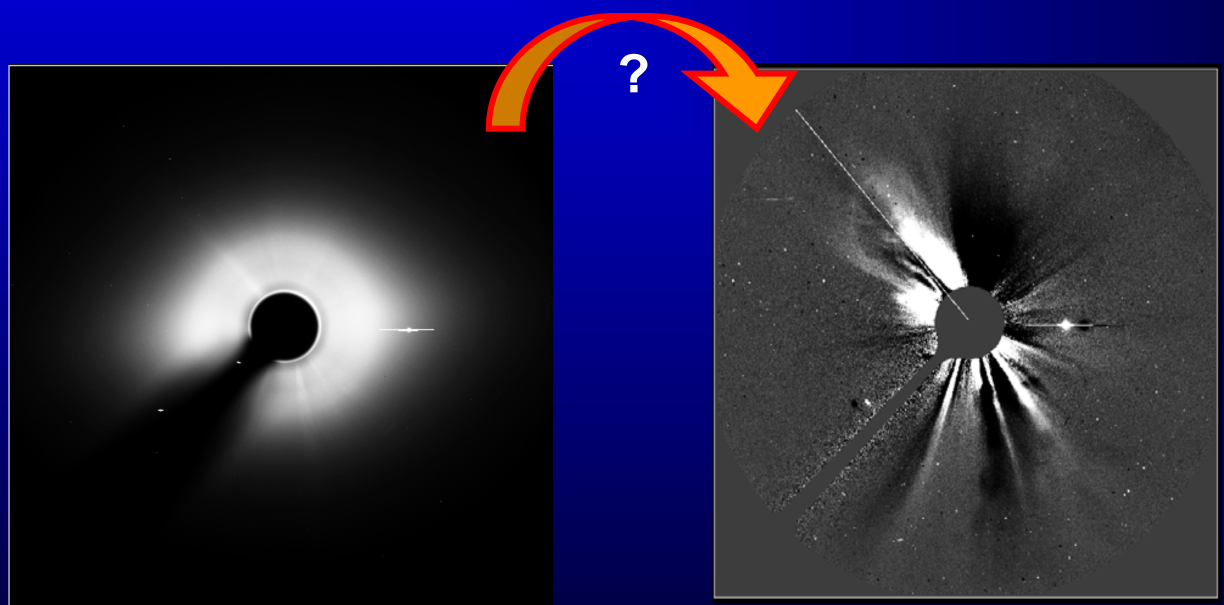


How do we interpret the images?

- **A feature can be <u>bright</u> because:**
  - **It is extended ALONG the line of sight (many electrons)**
  - **It has mass (many electrons)**
  - **It is close to the plane of max. scattering**
  - **Line emission inside instrument bandpass (e.g., Ha)**
- **A feature is <u>polarized</u> because:**
  - **It is close to the plane of max. scattering**
  - **AND is very narrow**
- **A feature <u>disappears</u> because:**
  - **It was carried away (in a CME)**
  - **It was pushed AWAY from plane of max. scattering**

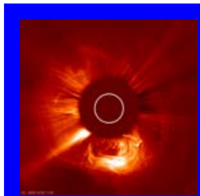
From raw to beautiful images

- **Raw images contain much more than the corona:**
  - **Stray light**
  - **F-corona (reflection from IP dust)**
  - **Stars/planets**
  - **Instrumental effects (i.e., vignetting)**



Raw C3 Image

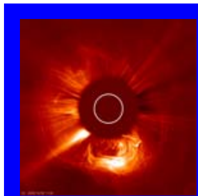
Calibrated C3 Image (Difference)



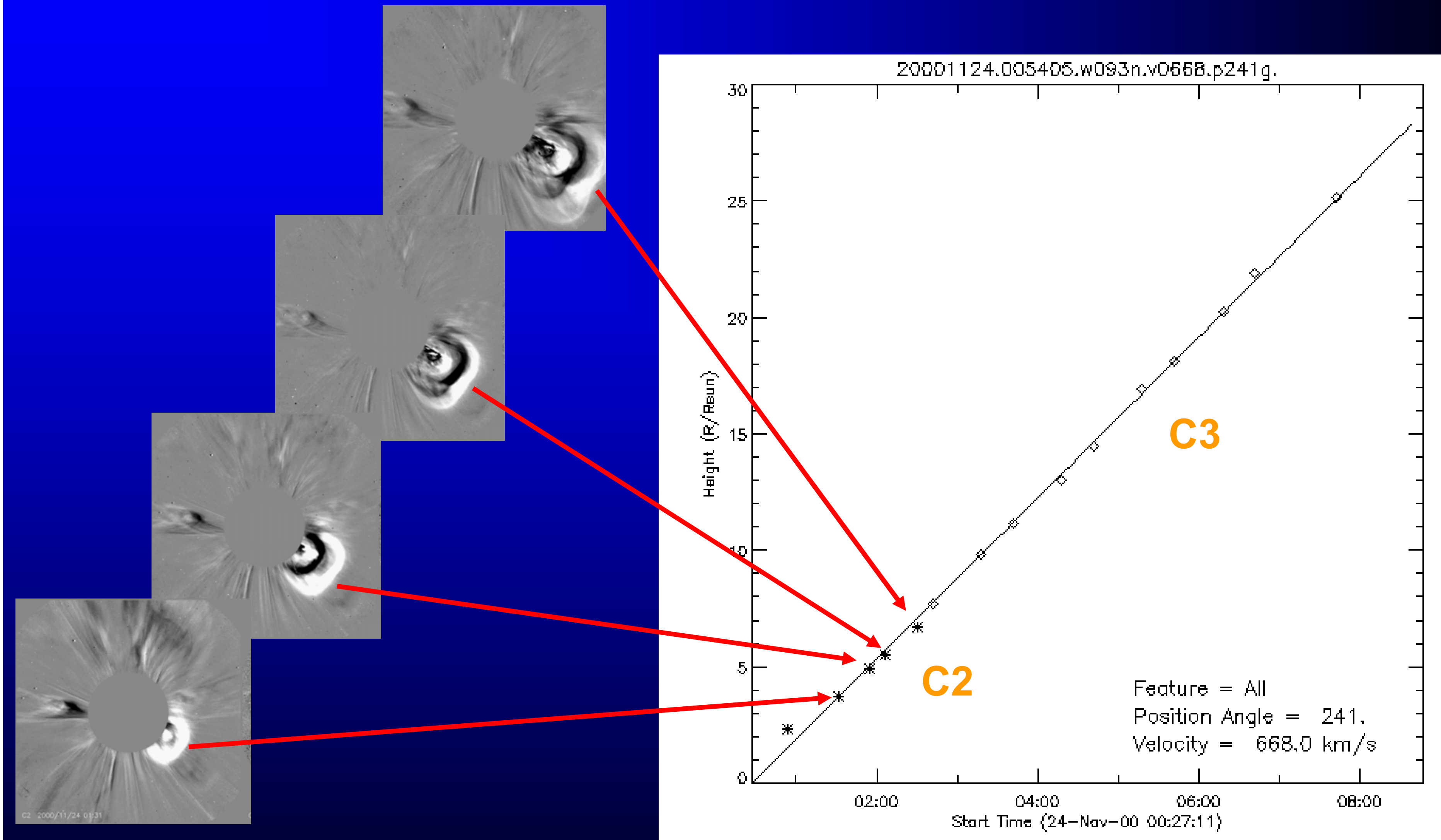
CME Analysis Tools

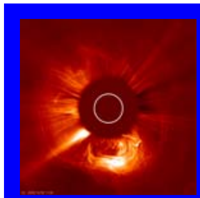
CMEs are highly dynamic events. To analyze them, we need their time-series → movies

- **Most common analysis tasks:**
  - **Height-time plots (ht-plots) → velocity, acceleration**
  - **Size & position measurements**
  - **Mass/energetics → mass, density, kinetic/potential energy**
- **Analysis software available in SolarSoft (i.e., LASCO tree)**

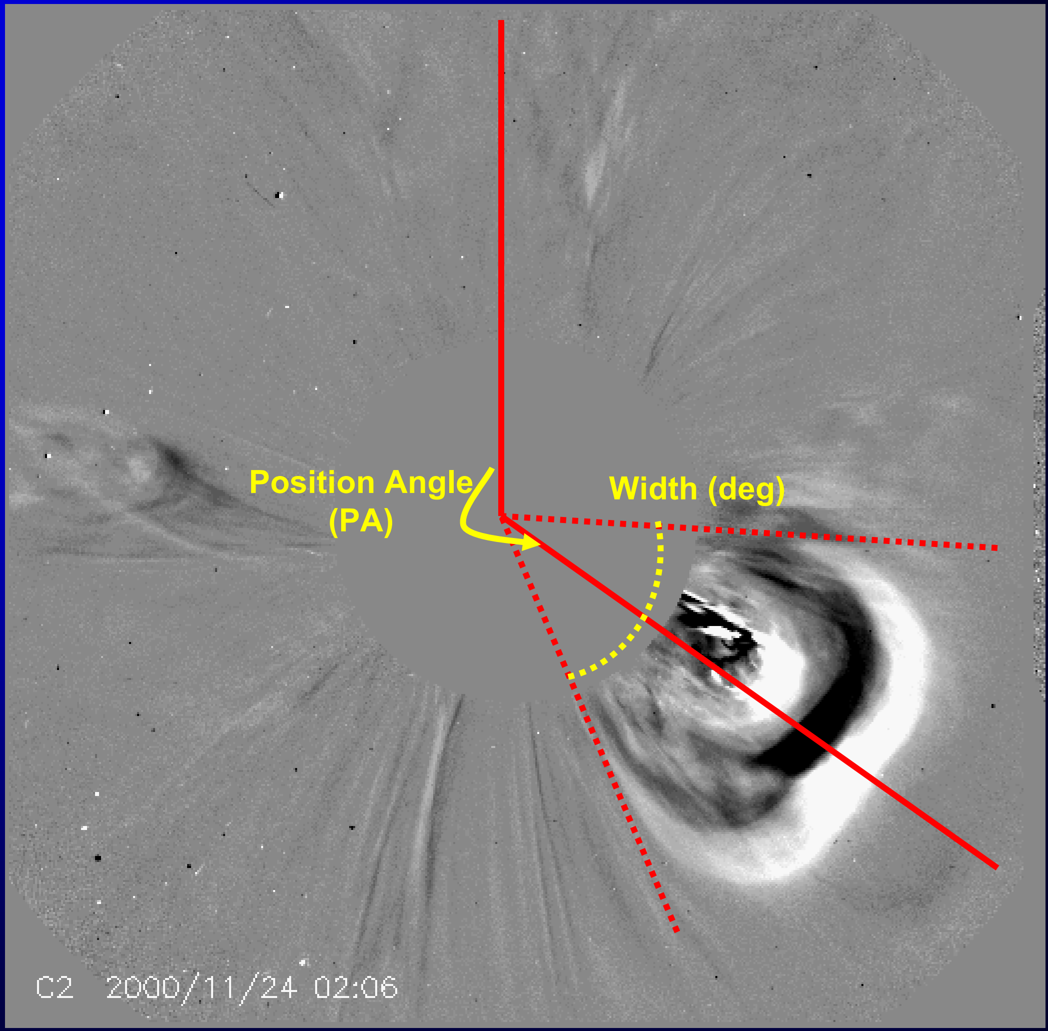


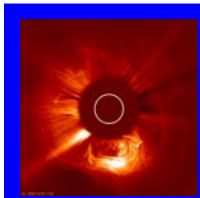
Height-Time Plots





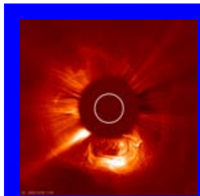
Size/Position Measurements



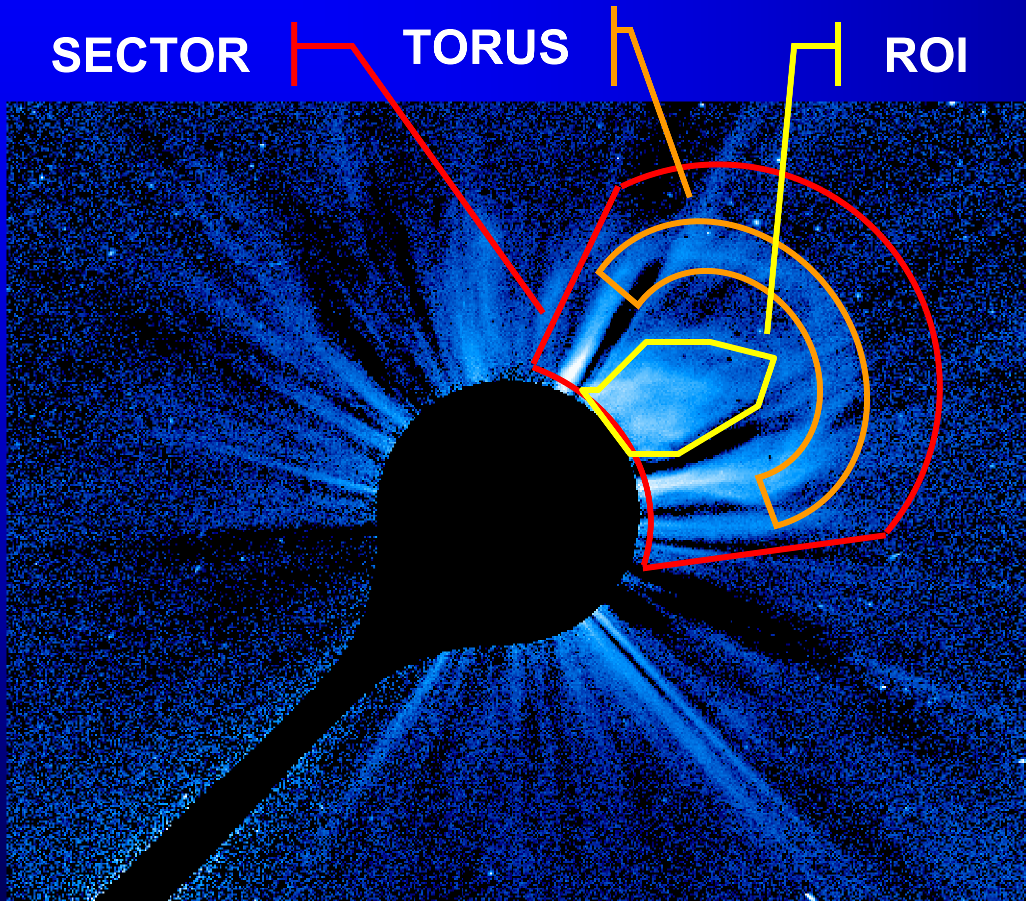


(Excess) Mass & Energy

- **Preevent image is subtracted**
- **Need CALIBRATED images (gr/pix)**
- **Sum over appropriate features**



Mass Calculation Methods



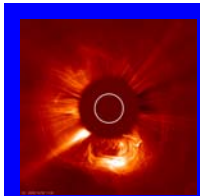
"Typical" C3 Mass Image

- **Several ways to obtain a "mass" for an event.**
- **The choice depends on the objectives:**
  - **After the whole event?**
  - **After specific features (i.e., core)?**
  - **Flow measurements?**

Best for flow calculations: Position at fixed distance

Most common: Avoid streamers, planets, other CMEs

Extent & Upper boundary from CME lists/ht measurements

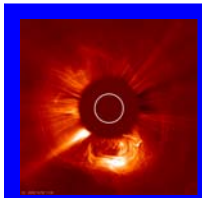


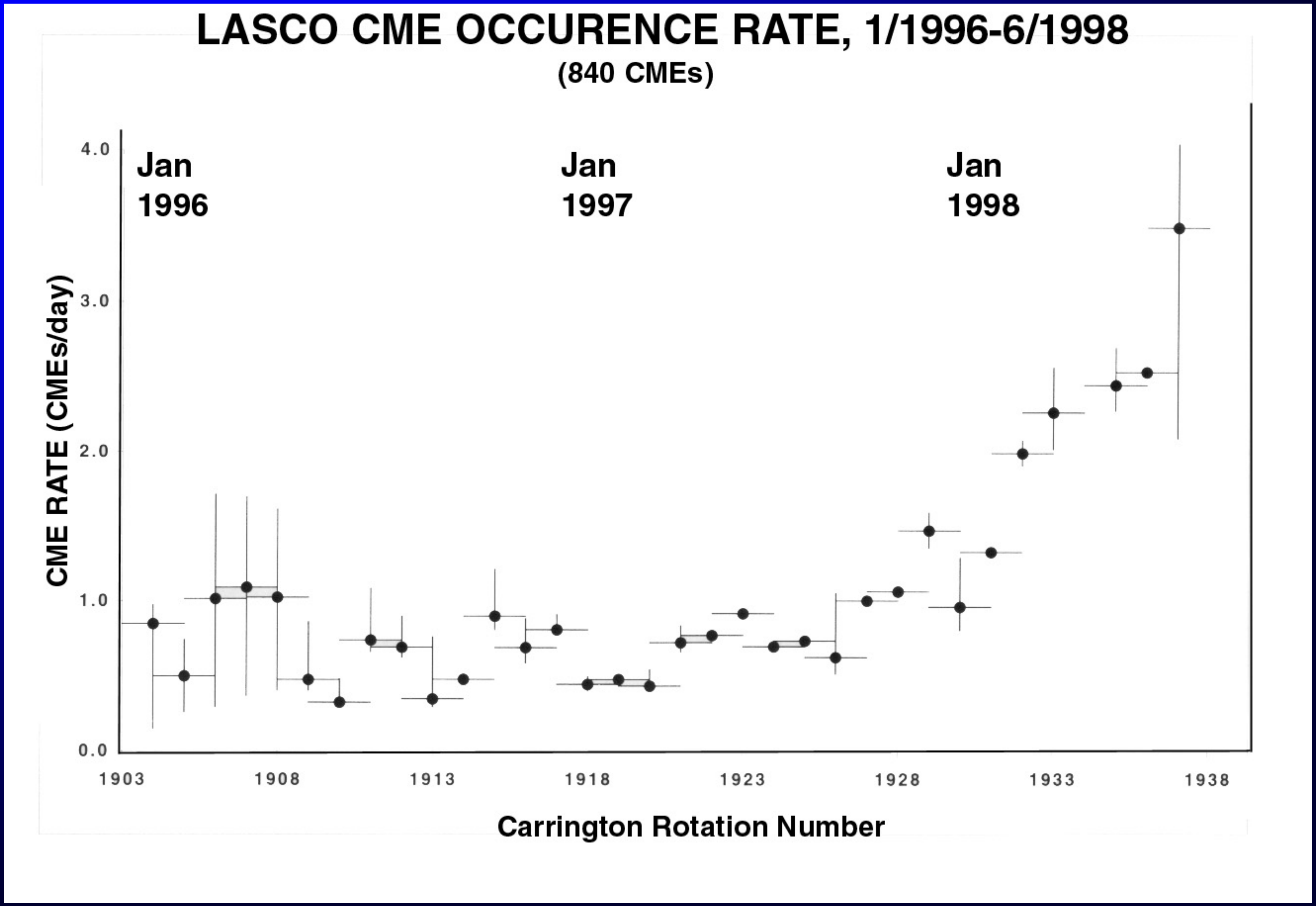
What do we know about CMEs?

- **10,000s of CMEs have been observed and measured.**

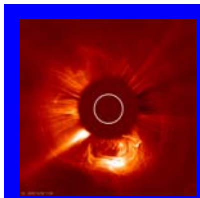
- **We know quite a lot about their properties:**
  - **Rates**
  - **Speeds**
  - **Masses/Energies**
  - **Association with type-II, flares, solar energetic particles (SEPs)**

CME Rates

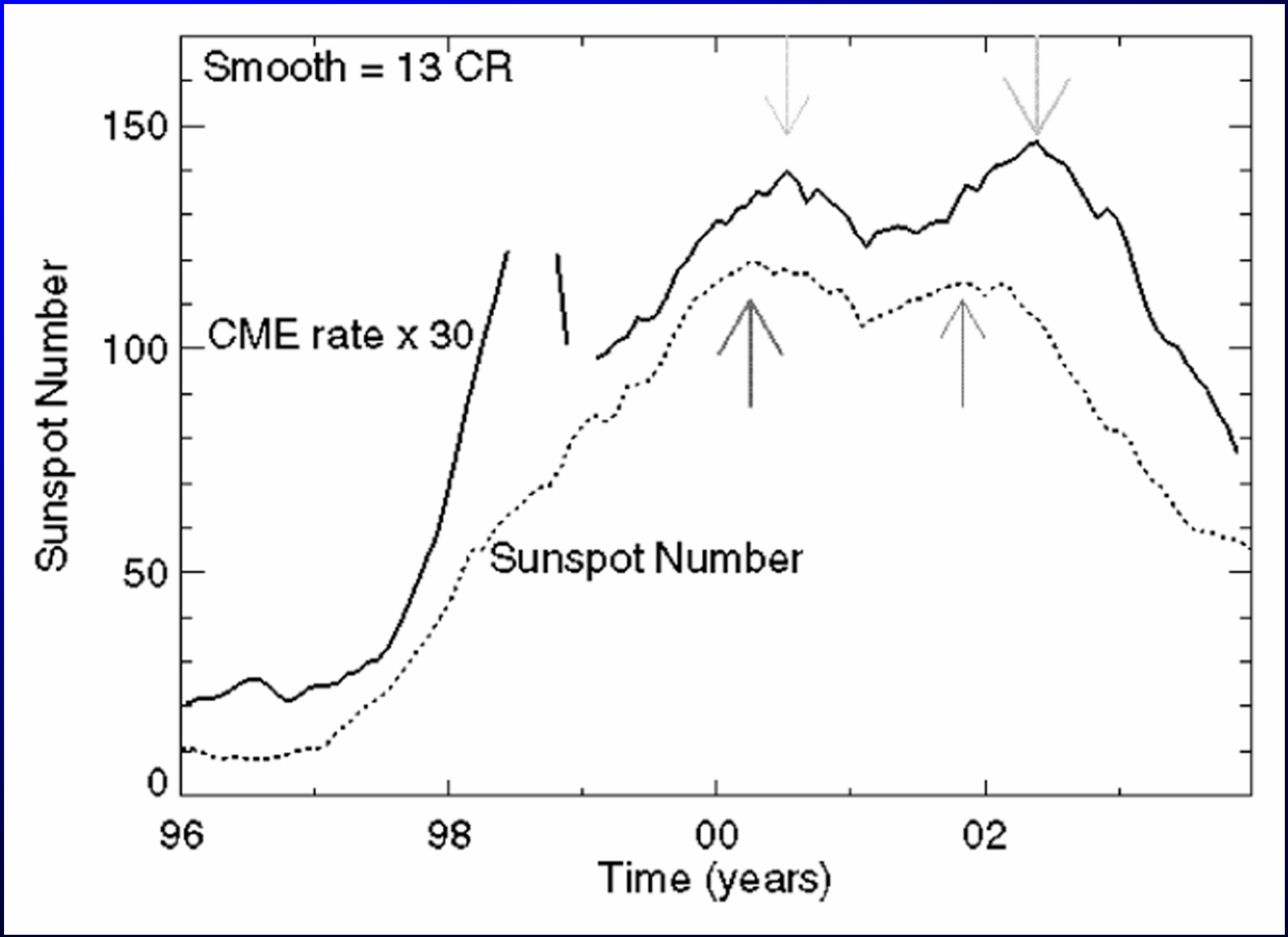




LASCO CME OCCURENCE RATE, 1/1996-6/1998
(840 CMEs)
Jan 1996
Jan 1997
Jan 1998
CME RATE (CMEs/day)
4.0
3.0
2.0
1.0
0.0
1903
1908
1913
1918
1923
1928
1933
1938
Carrington Rotation Number

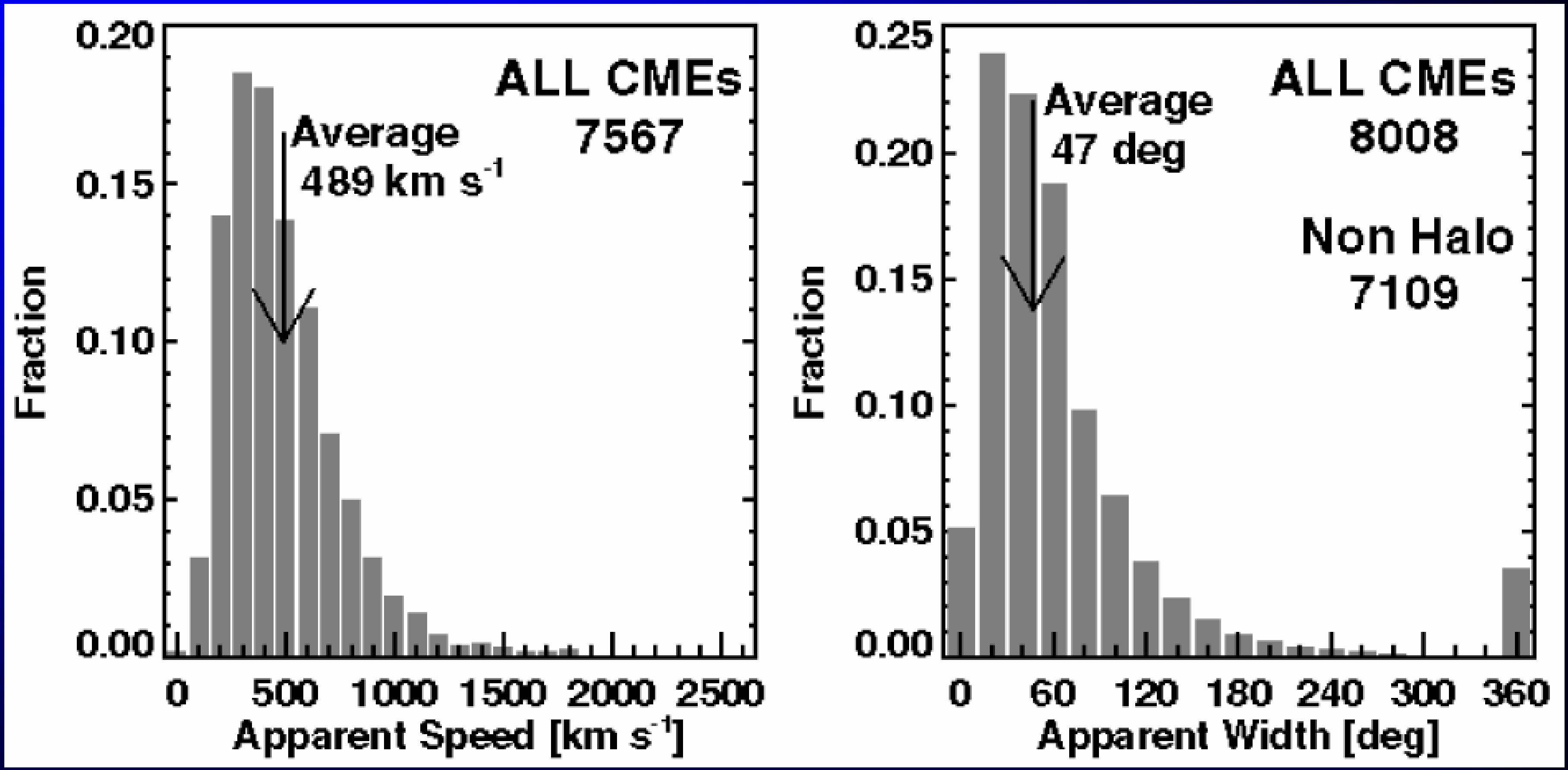


Comparison of CME Rate with Sunspot Number

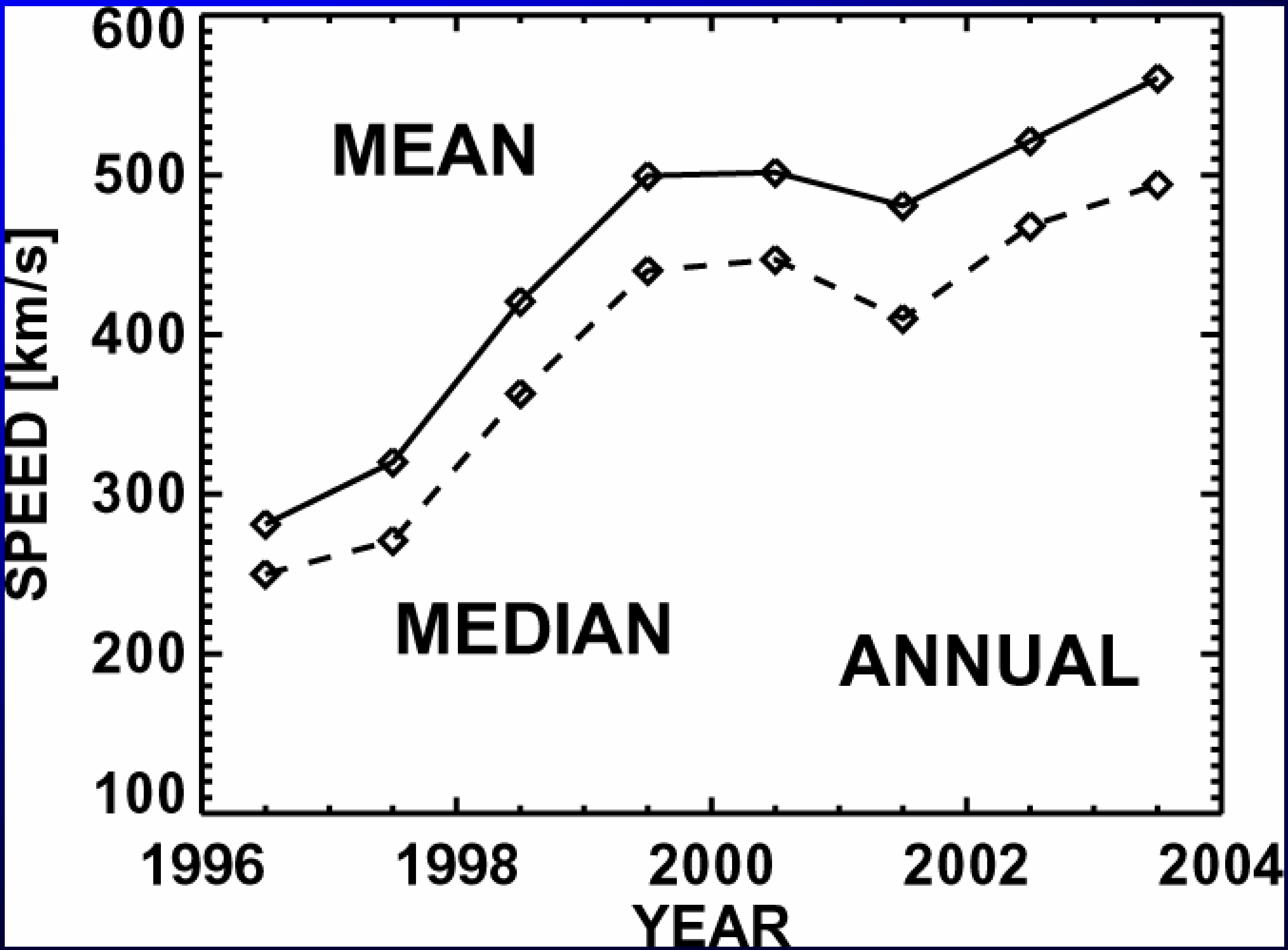


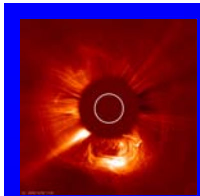
CME Properties (speed, width)

Projected Speed | **Projected Width**

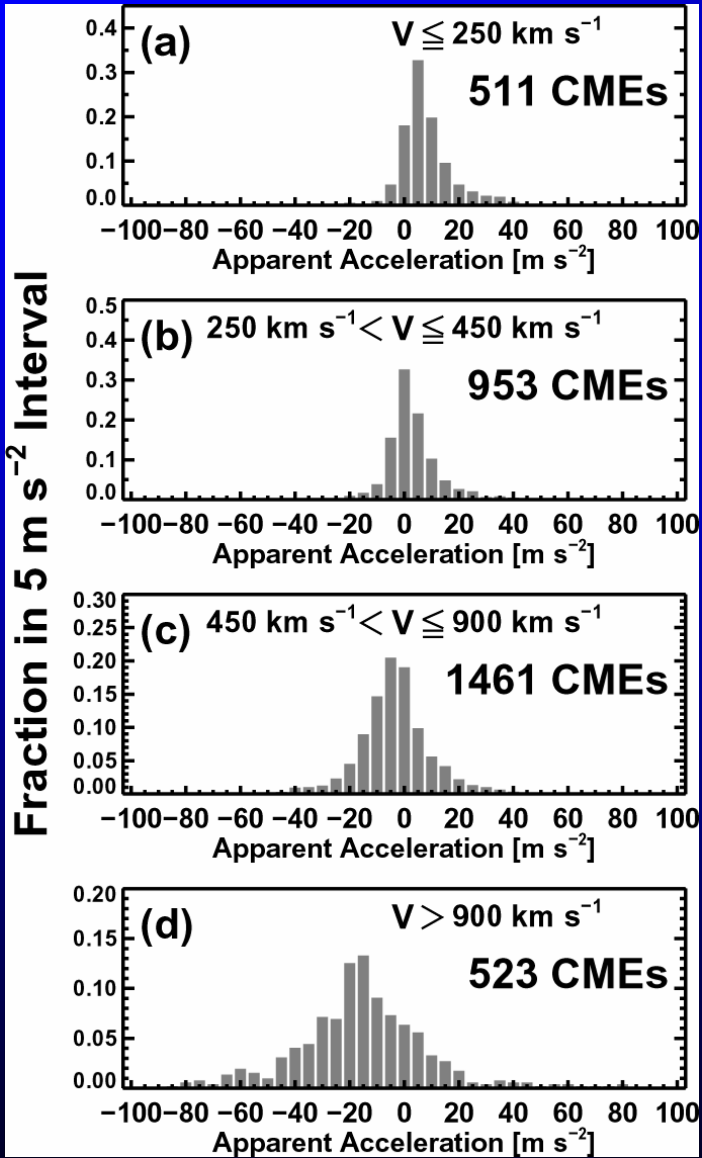


Solar Cycle Variation of Speed

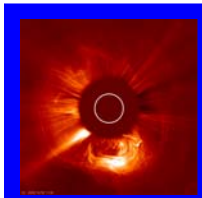




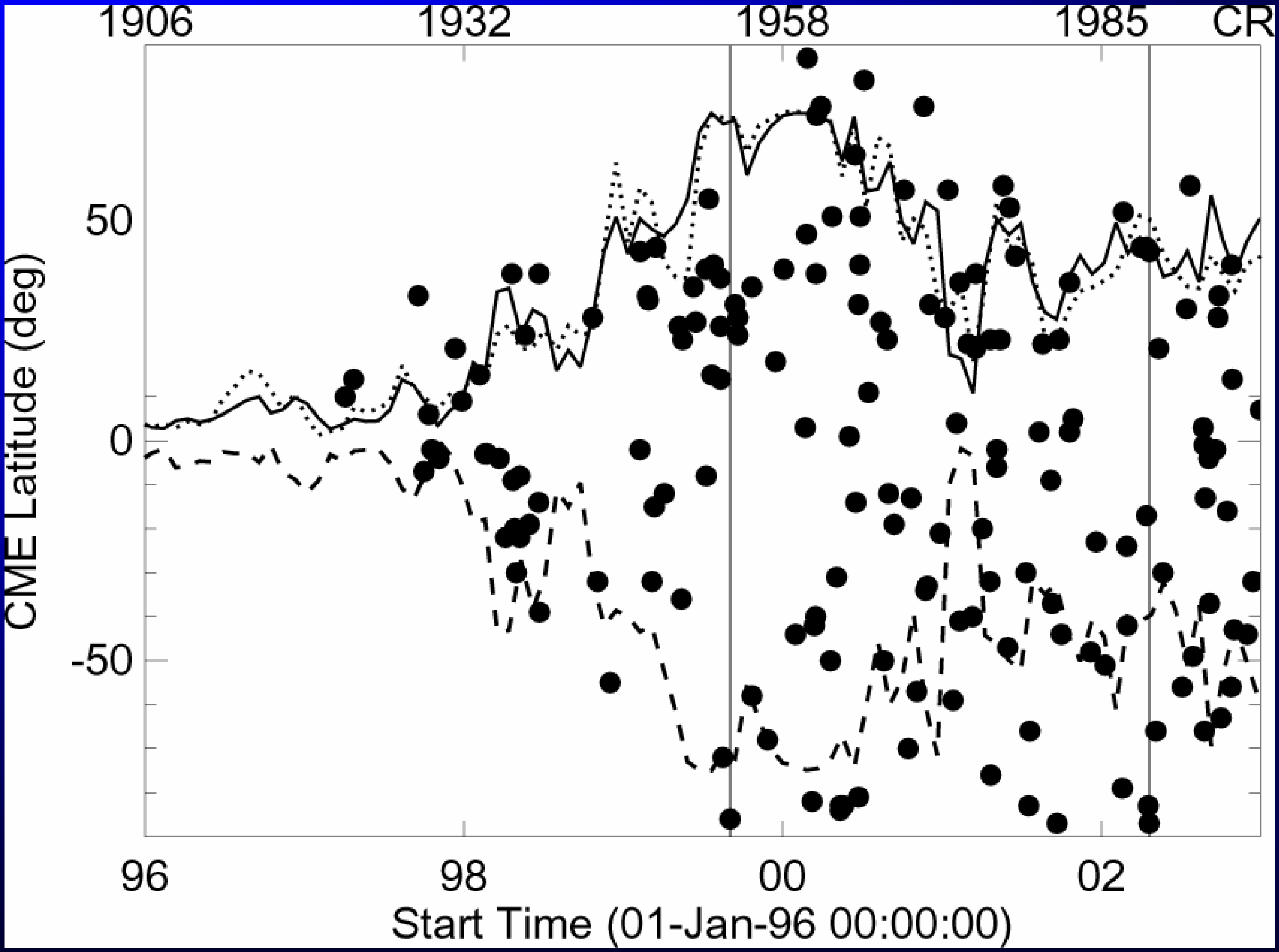
Acceleration of CMEs

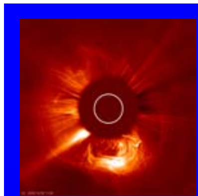


Tendency for
Slow CMEs to Accelerate
and
Fast CMEs to Decelerate

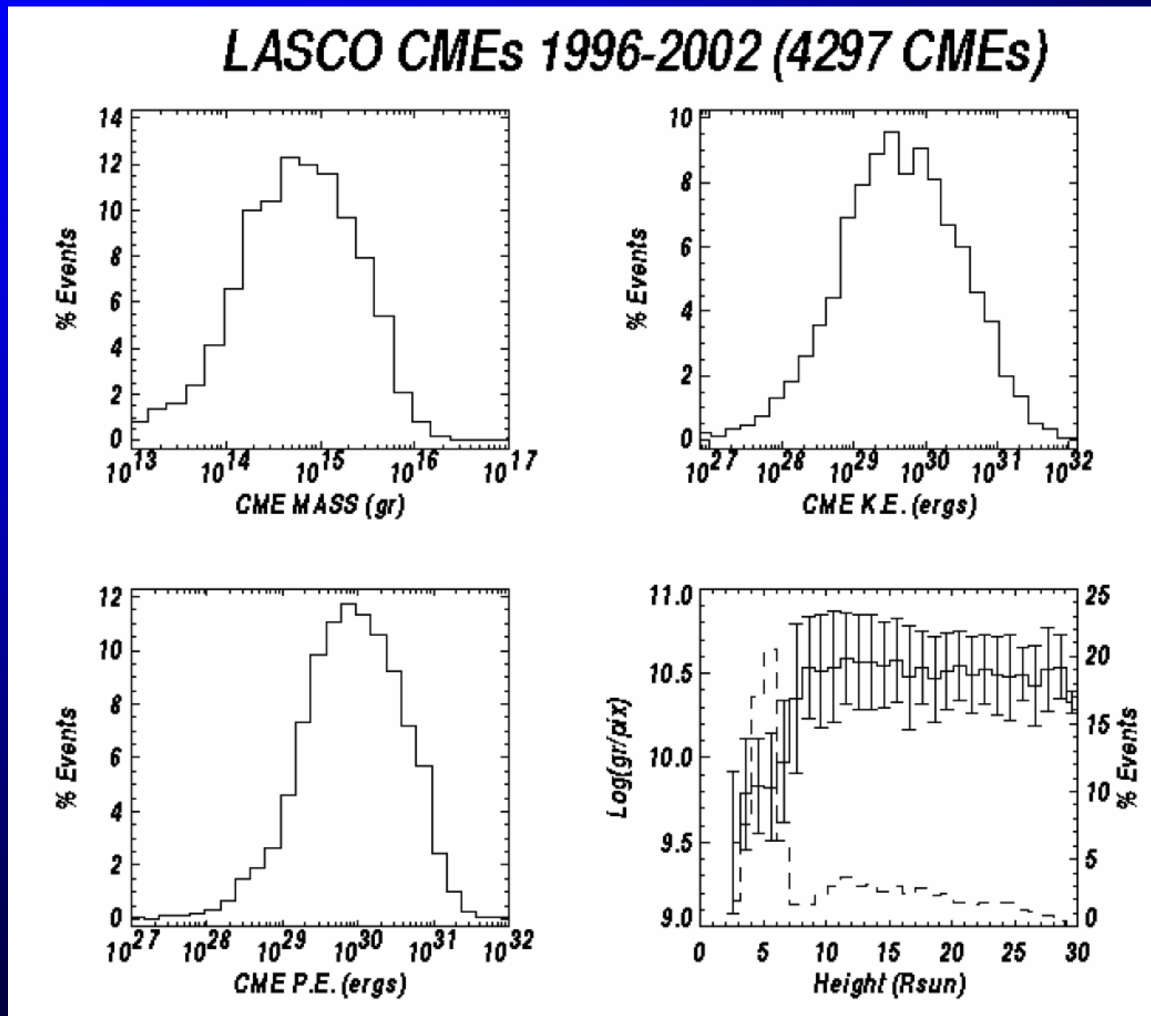


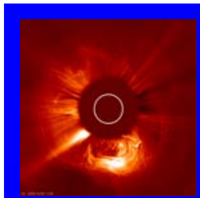
Evolution of CME Origin





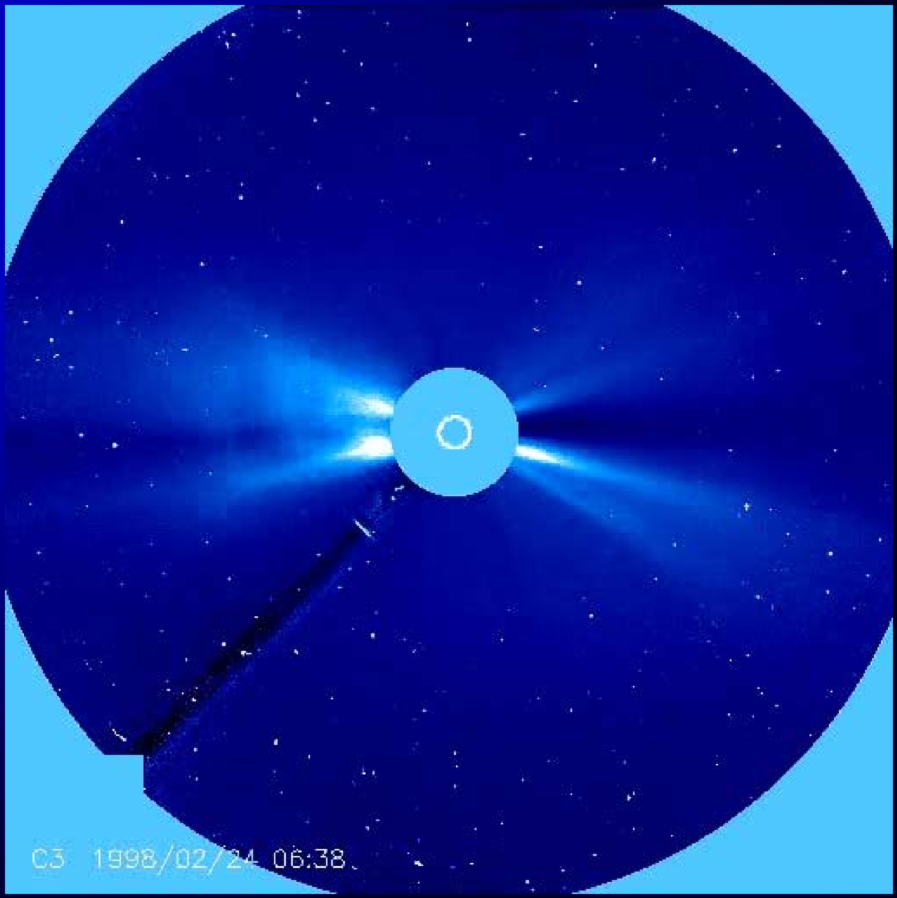
CME Mass & Energy Distributions

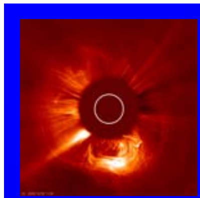




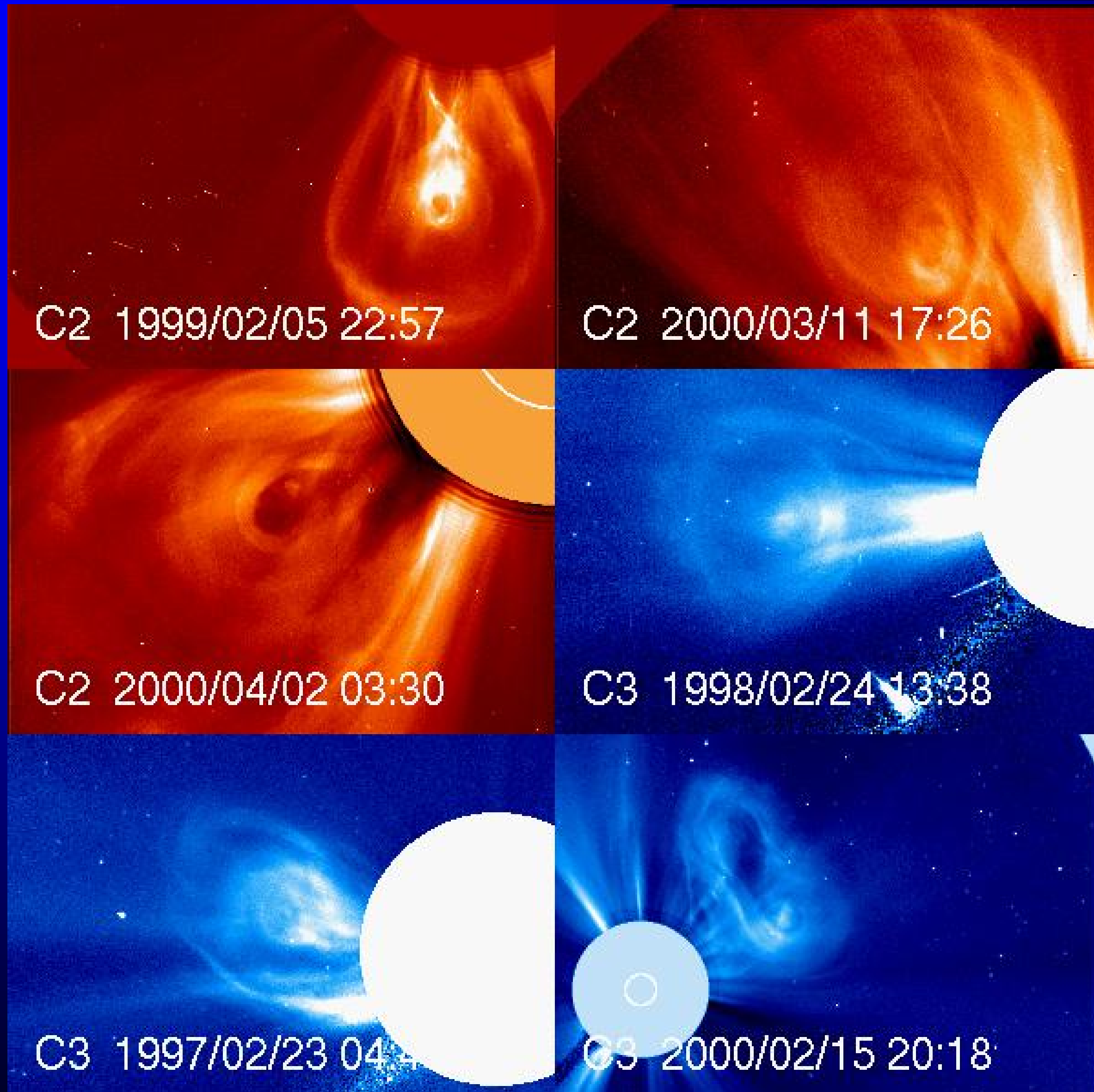
"Typical" CME Morphologies

- **Fluxrope (used to be known as 3-part CME)**
- **Halo**
- **Streamer Blowout**



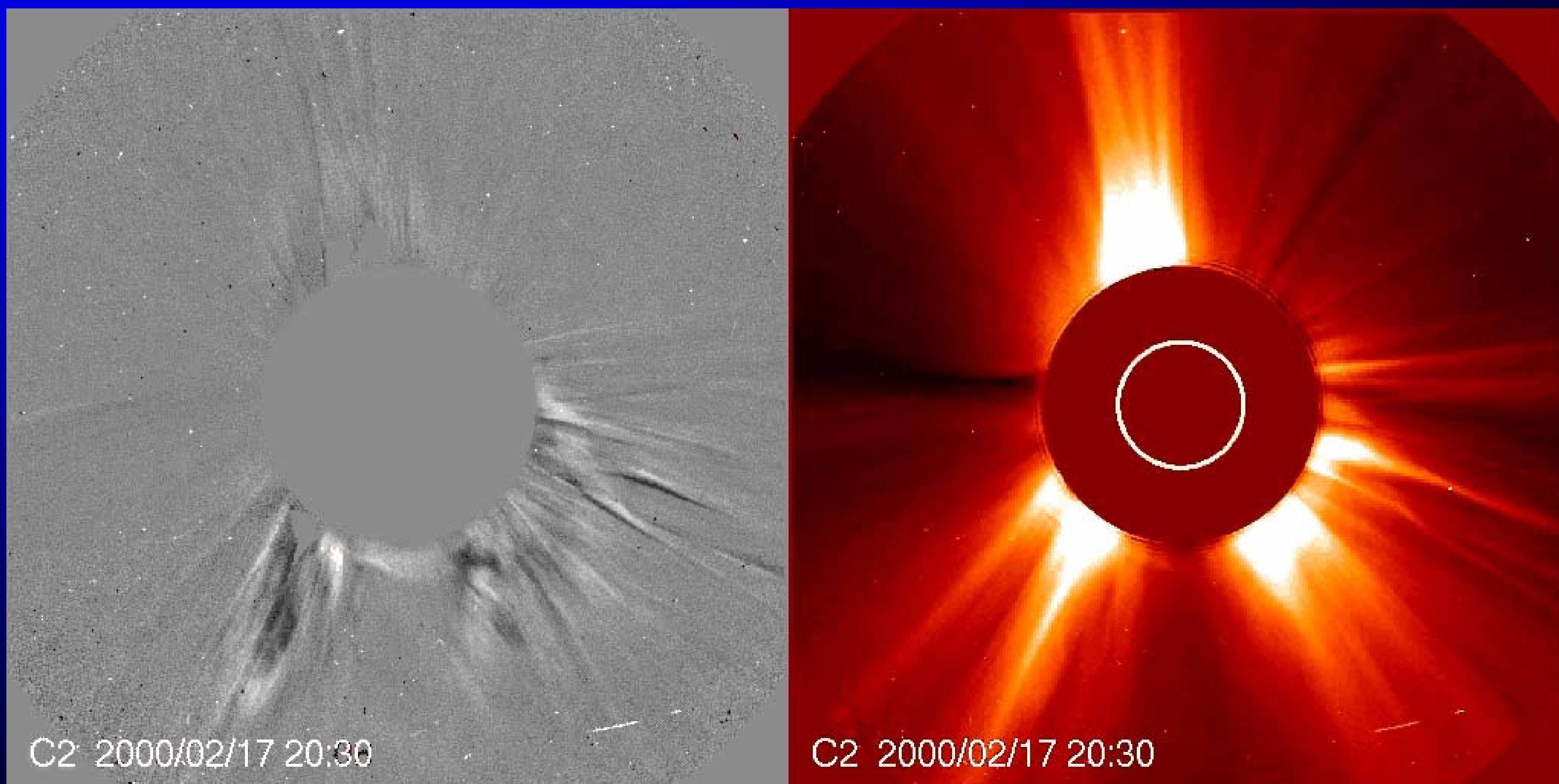


Examples of Flux Rope CMEs

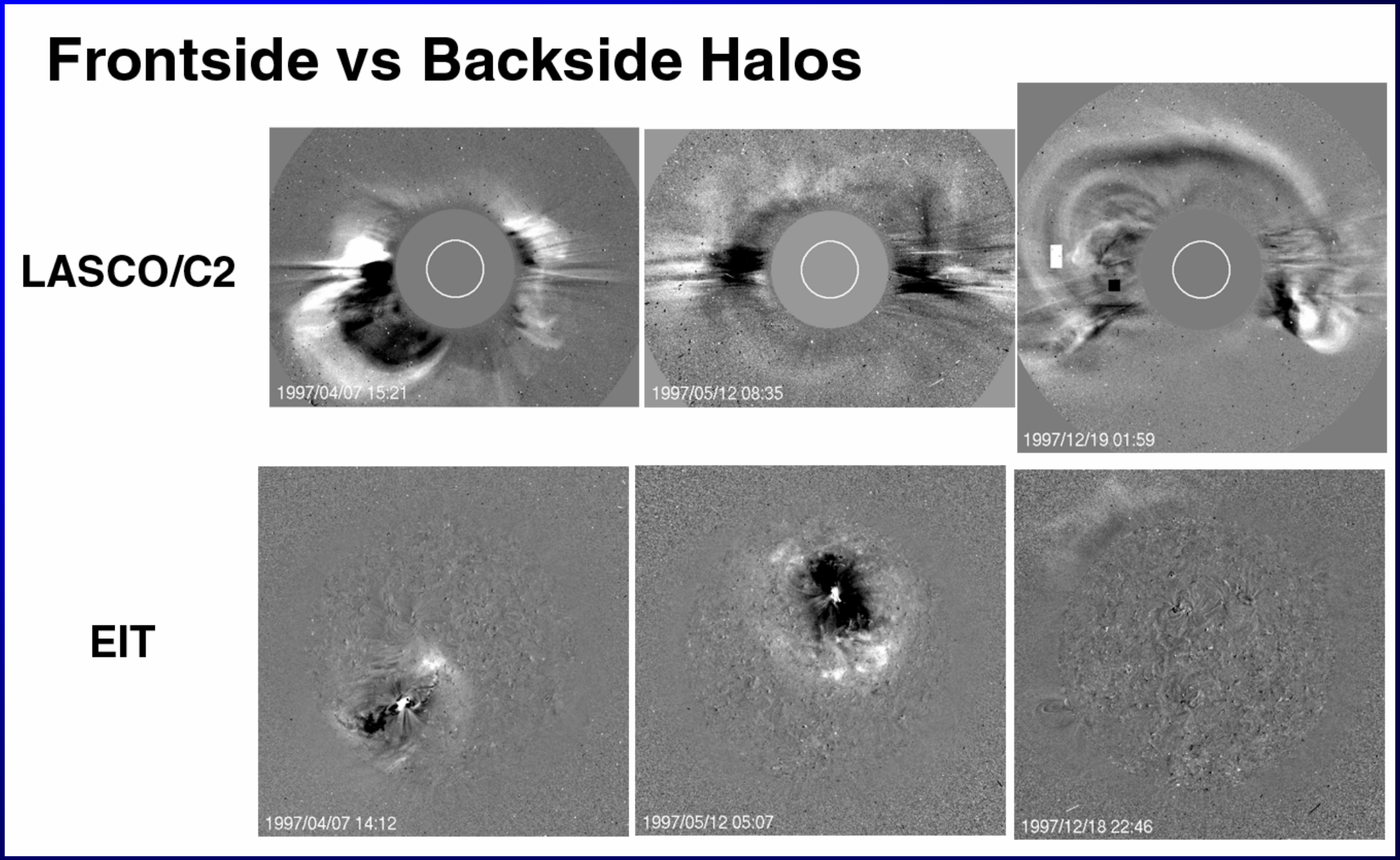


"Typical" CME Morphologies

- **Fluxrope (used to be known as 3-part CME)**
- **Halo**
- **Streamer Blowout**

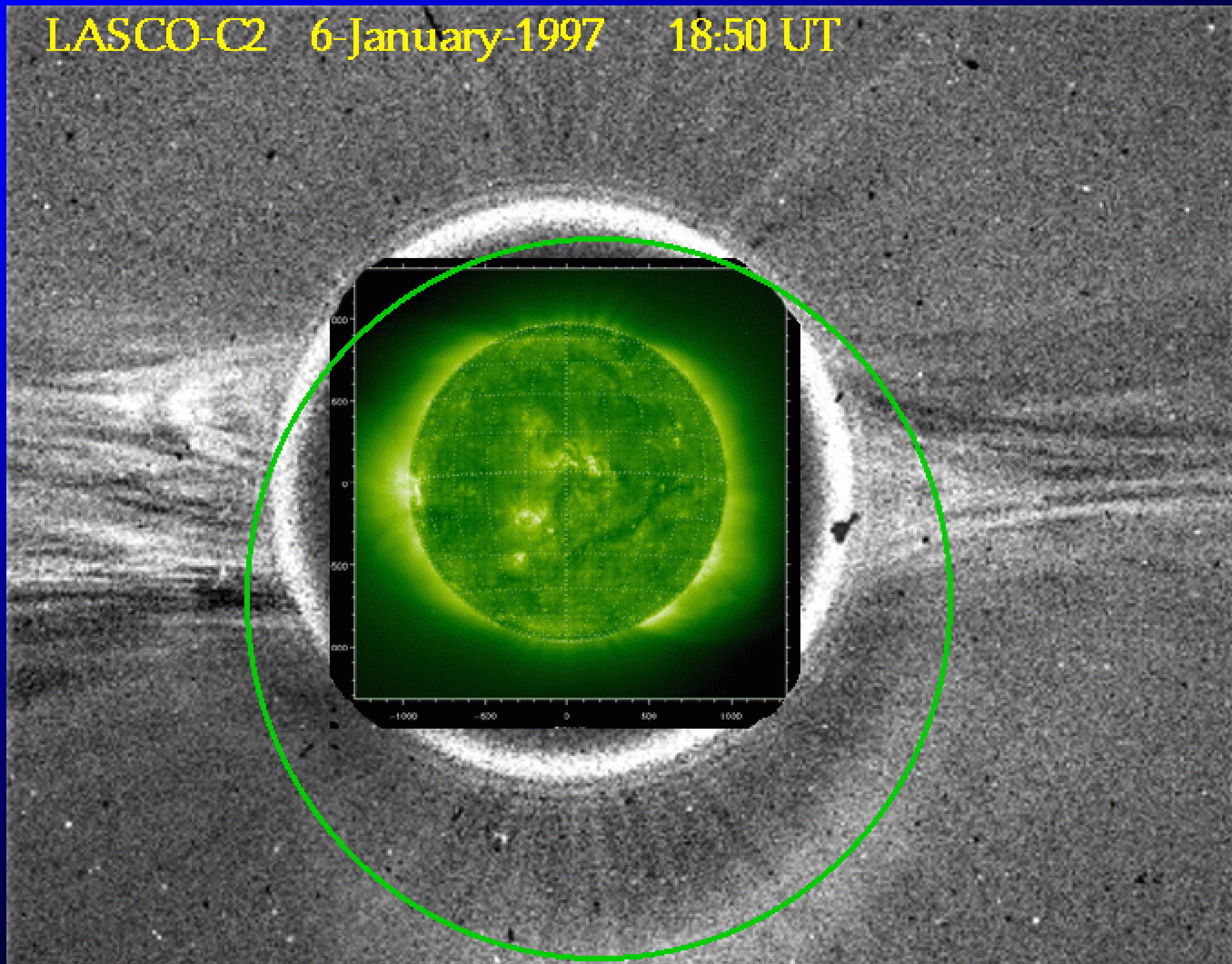


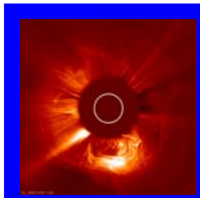
Halo CMEs



- **Morphology depends on projection, coronal structure**

Halo CME 6 Jan 1997



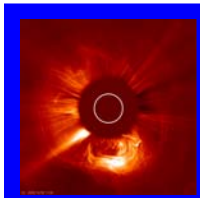


CMEs and the Lower Corona

Activity in active regions correlated with the CME:

- **EIT Waves**
- **Flares**
- **Filaments**
- **Brightenings/loop motions**

These connections became obvious thanks to the joint use of EUV imager / coronagraph in SOHO

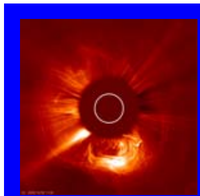


Flares & CMEs

- **FACT: CMEs & Flares occur together very frequently.**
- **QUESTION: Do flares cause CMEs or vice versa?**
  - **Both are signs of energy release & reconfiguration in the corona.**

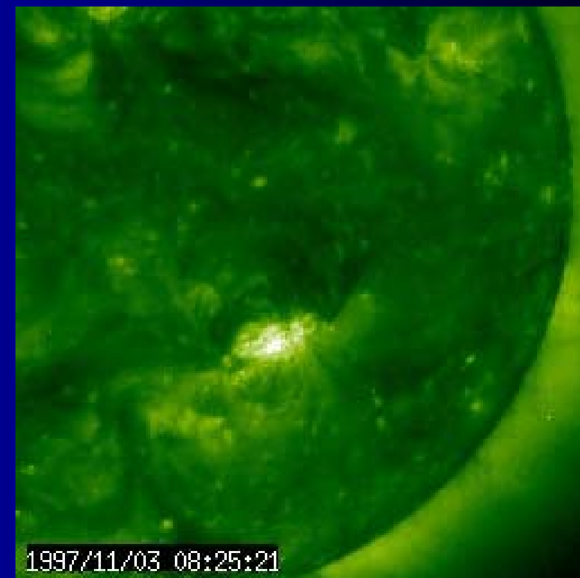
	Size	Time	Energy (ergs)	Particles	Filaments	Ejecta
CMEs	Global	Gradual	~10^{32}	Yes	Yes	Large
Flares	Local	Impulsive	~10^{32}	Yes	Yes	Small

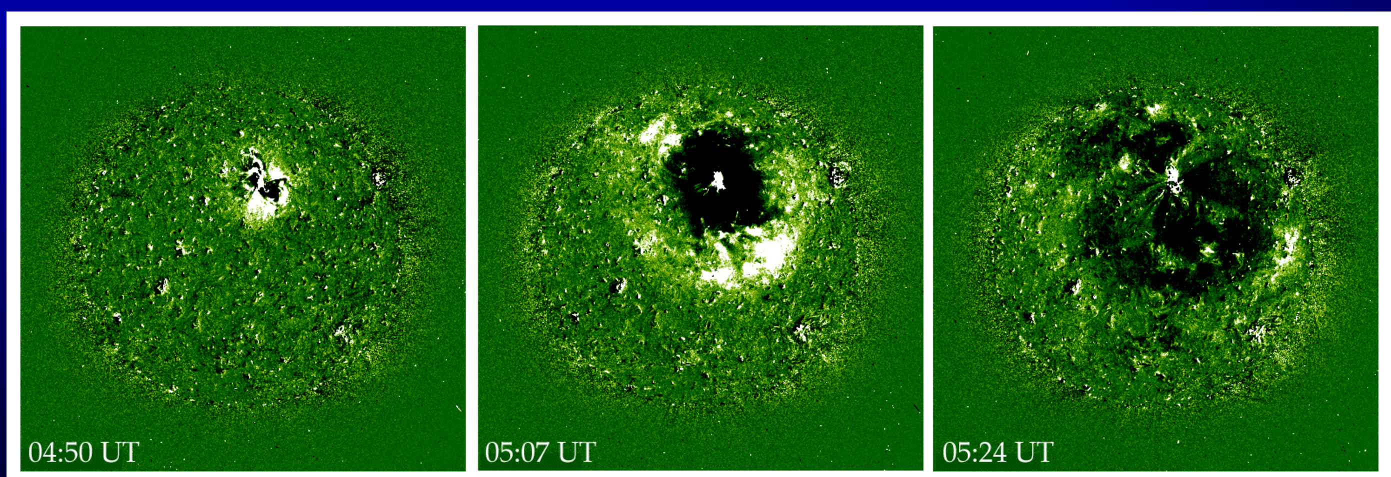
But impulsive CMEs are associated with flares
And gradual flares are associated with CMEs.

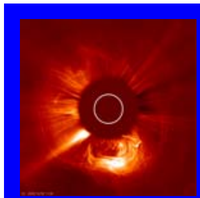


CMEs and Coronal Waves

- **The EIT wave might be the "ground track" of the CME. With it, we trace the:**
  - **Expansion of the CME**
  - **Interactions with distant regions**
  - **Relation between CME & flare**

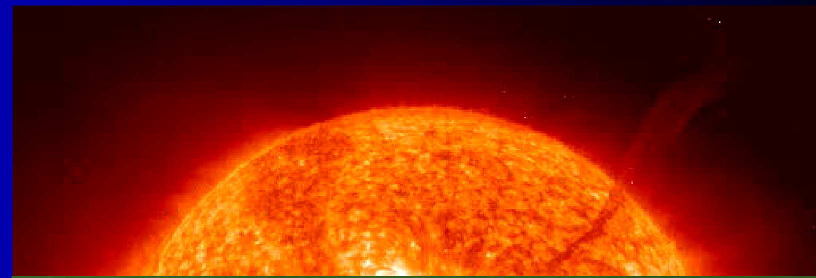


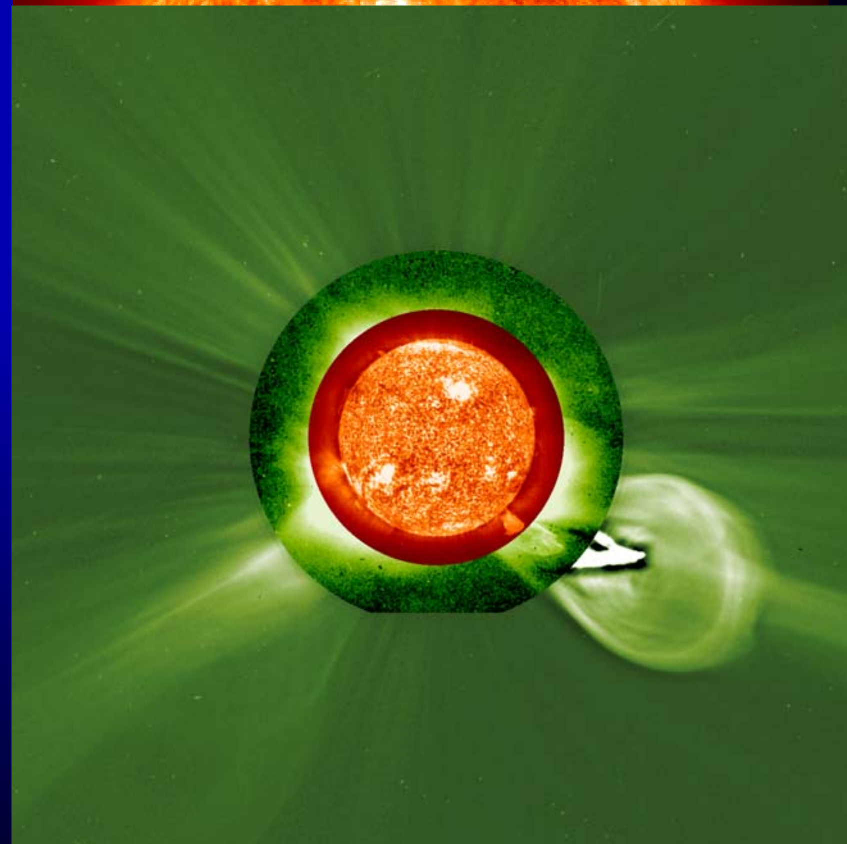


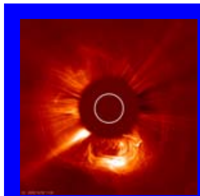


CMEs & Filaments

- **Filaments eruptions are the strongest CME signatures in the low corona.**
- **Almost all filaments erupt**
- **The majority of the mass drains down.**
- **QUESTIONS:**
  - **Do ALL CMEs contain a filament?**
  - **Do filaments play a role in the initiation or propagation?**
  - **Are *Streamer-Blowout* CMEs special?**





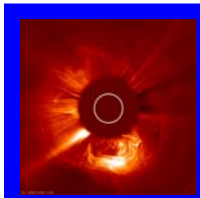


CMEs and the solar surface

- **Waves in the chromosphere: (likely) flare-driven.**
- **Waves(?) in the photosphere: flare-driven**
- **Photospheric magnetic flux changes: inconclusive**

So far, there is no ROBUST evidence of DIRECT CME signatures below the corona.

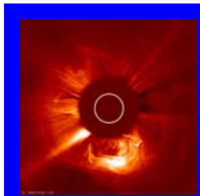
Why not ?



CMEs and the Heliosphere (1)

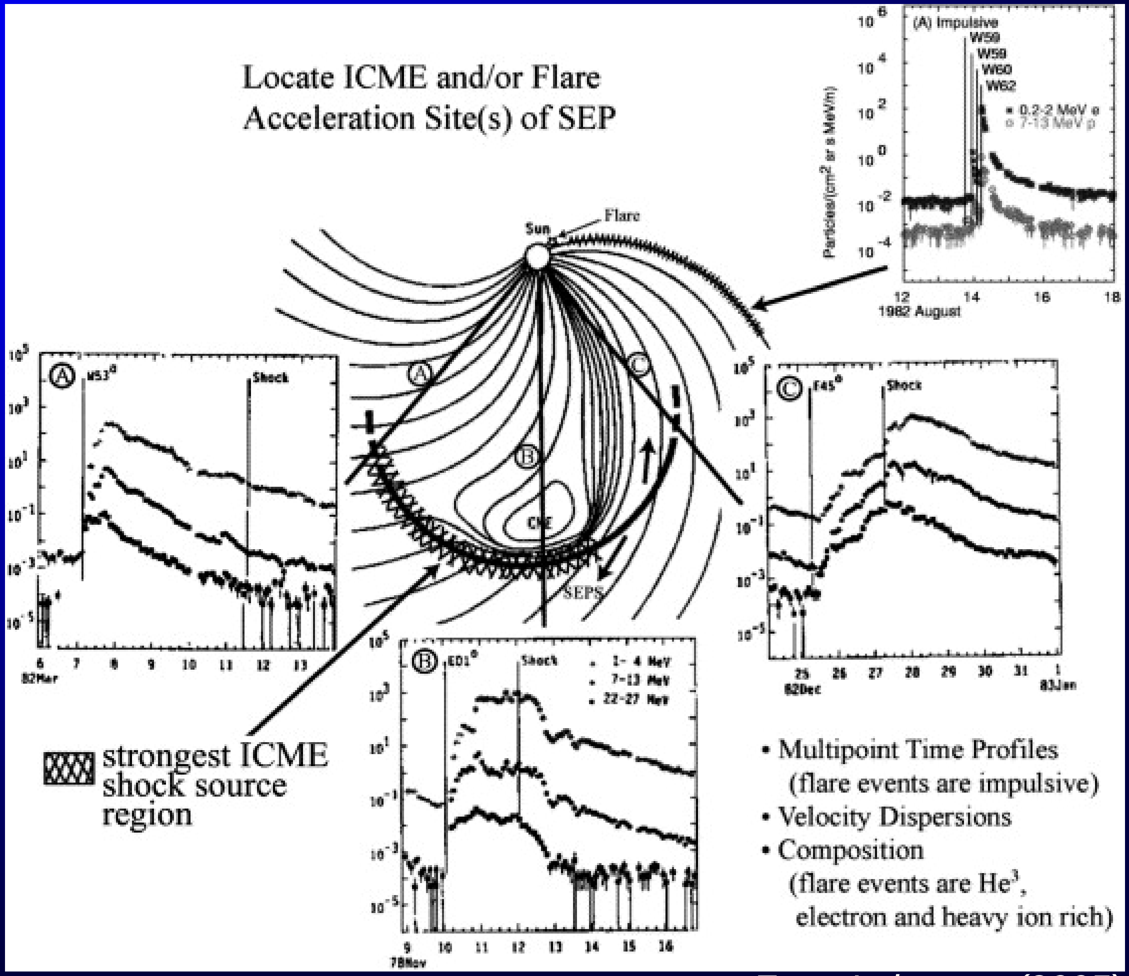
- **CME in the heliosphere = ICME (*interplanetary CME*)**
- **CME plasma are probed directly by in-situ probes.**
  - **Magnetic field (magnitude, direction)**
  - **Plasma density, composition, temperature**
  - **Particle energies (electron, protons)**
- **How do CMEs affect (are affected by) the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

More in
1. "in-situ Measurements: Particles & Fields" (Cohen)
2. "Space Weather" (Raeder)
3. "SEPs" (Cohen)

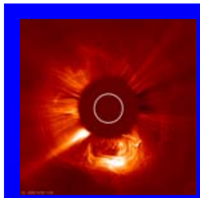


CMEs and the Heliosphere (2)

- **In-situ measurements**

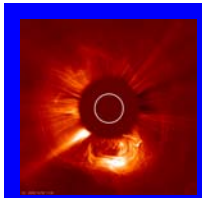


From Luhmann (2005)

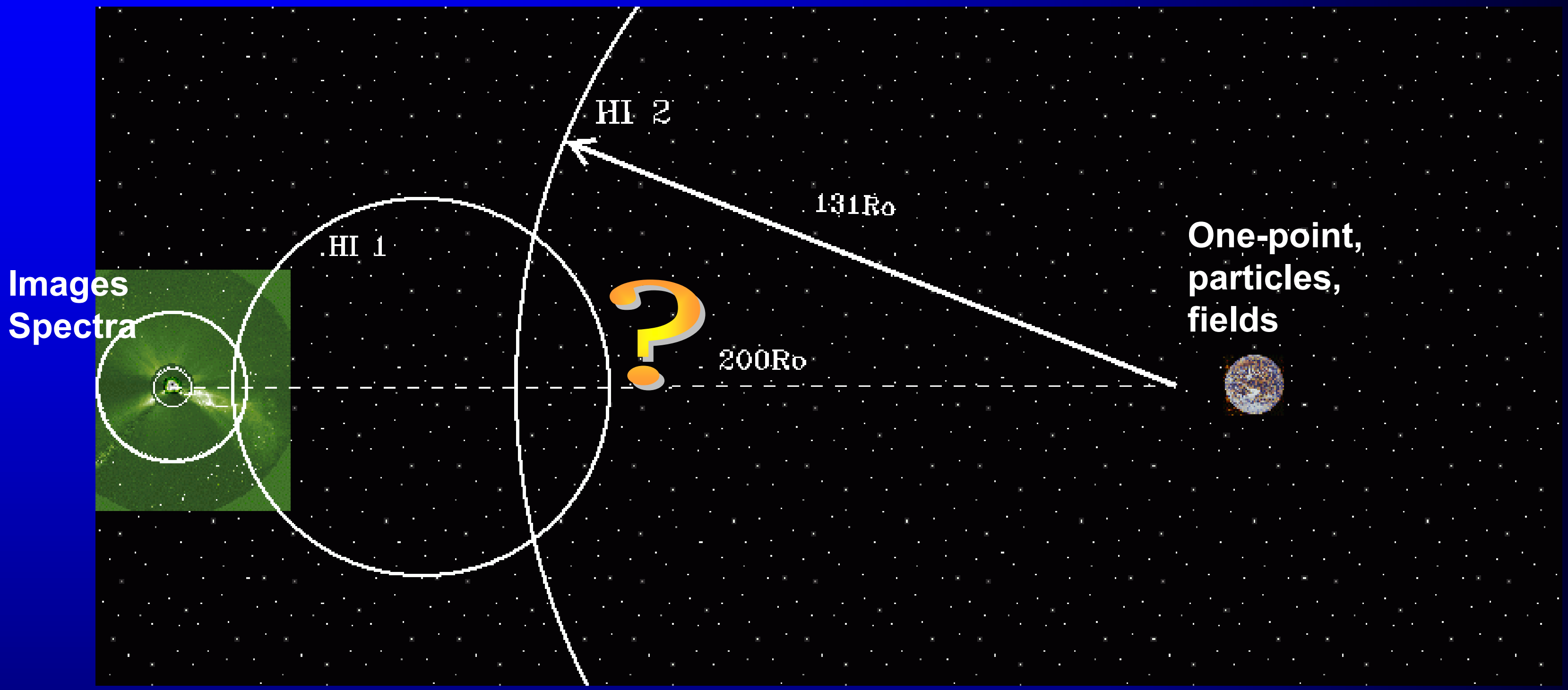


The far-reaching CMEs

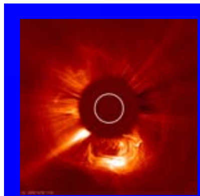
- **CMEs have been detected to the edges of the solar system (by the Voyagers).**
- **CMEs shield against from cosmic rays**
- **CMEs responsible for auroras, geomagnetic storms → space weather.**



What is the relation of CMEs to ICMEs ?

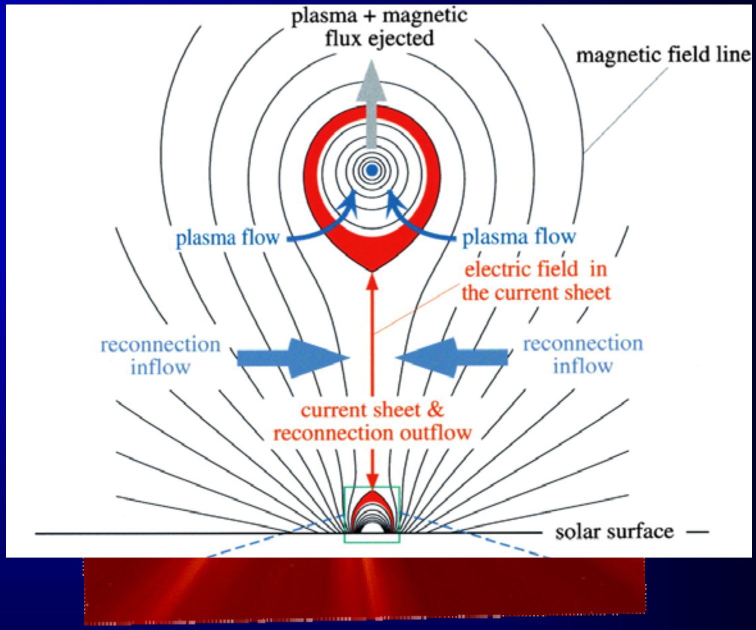


- We rely on models to fill this gap
- STEREO will obtain imaging observations.

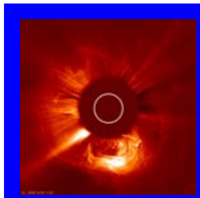


Outstanding Issues

- **Initiation**
  - **Observations cannot determine the mechanism (currently).**
  - **But there are only a few viable models (i.e., breakout, flux emergence). All rely on reconnection processes.**
- **Propagation**
  - **CME interplanetary evolution is (largely) unknown**

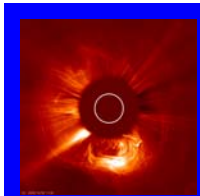


More in
1. "Reconnection" (Forbes)



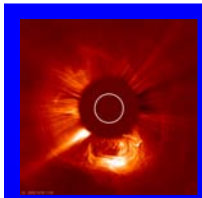
Some open questions

- **Initiation**
  - **How are CMEs initiated and why?**
  - **How do they affect the large scale corona?**
  - **What is the 3D structure of CMEs?**
  - **What is the relation between CMEs and flares/filaments?**
  - **Can we predict CMEs?**
- **Propagation**
  - **What is the role of the solar wind?**
  - **Where do shocks develop?**
  - **Can CMEs accelerate high energy particles?**
  - **Do CMEs interact?**
  - **What is the magnetic structure of CMEs?**



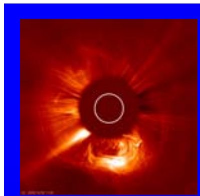
Review (1)

- **CME is**
  - **The ejection of a large-scale, organized coronal structure from the corona that escapes into the heliosphere**
- **A typical CME has**
  - **Width of ~45°, mass of ~10^{15} gr, speed of ~500 km/s, and a fluxrope structure**
- **Things to remember**
  - **The emission is optically thin, the structure along the line of sight is unknown**
  - **Most of the measured quantities are projected on the sky plane.**
  - **The morphology depends on projection effects, launch longitude**



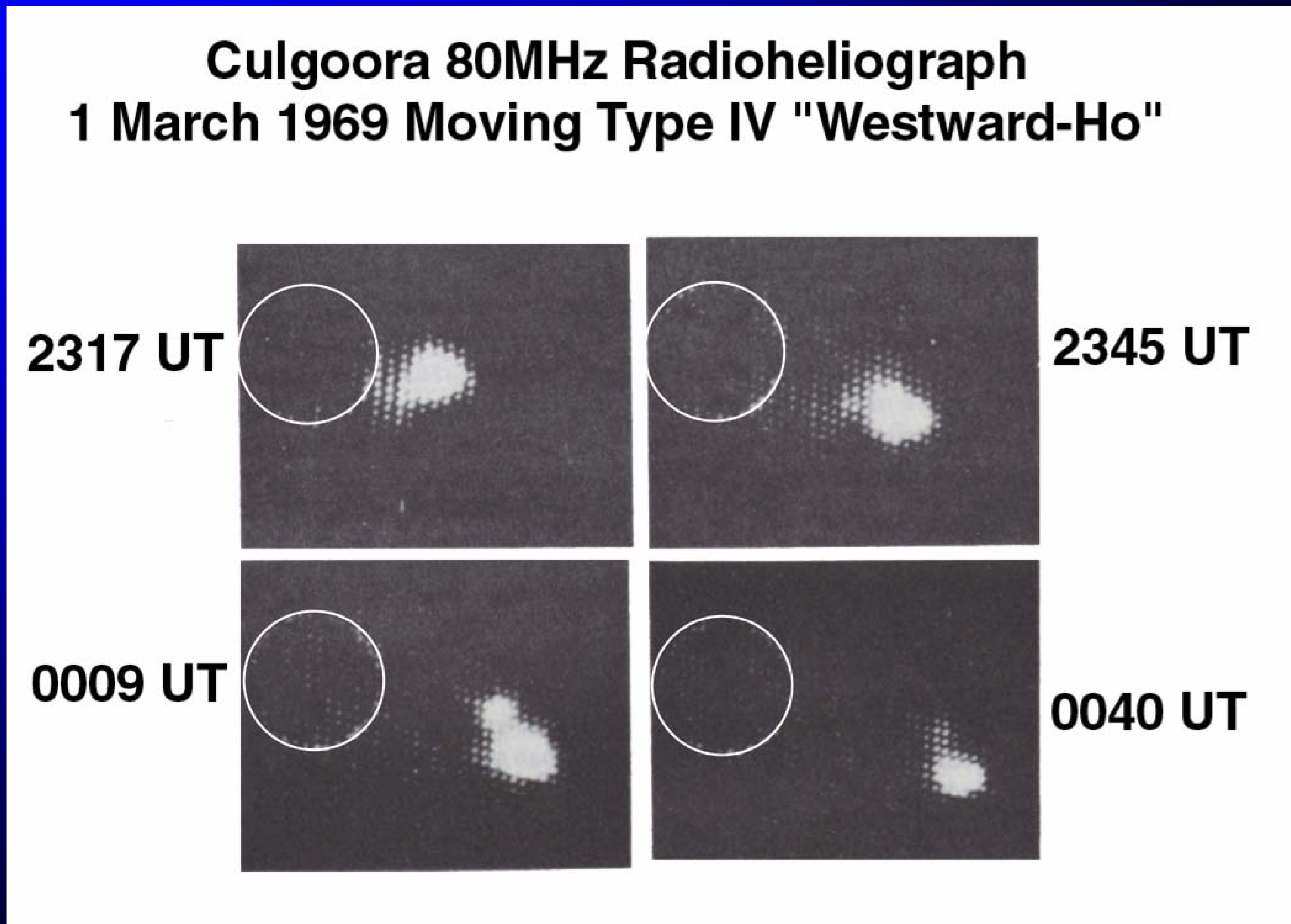
Review (2)

- **Generally, fast CMEs are associated with flares, slower CMEs with filaments**
- **CMEs are coronal phenomena**
  - **Little, if any, effects in the chromosphere or below**
- **CMEs involve the ejection of <u>plasma</u> & <u>magnetic field</u>**
- **CMEs can accelerate/transport energetic particles**
- **CMEs cause the strongest geomagnetic storms**
- **The study of CMEs involves many areas of solar physics**
  - **Physical processes (i.e., storage and release of mag. energy)**
  - **Properties of coronal plasma, heliosphere**
  - **Shock generation and particle acceleration**
  - **Interaction with Earth's enviroment (magnetosphere, ionosphere)**

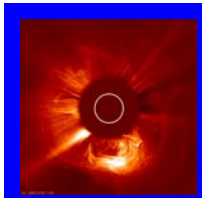


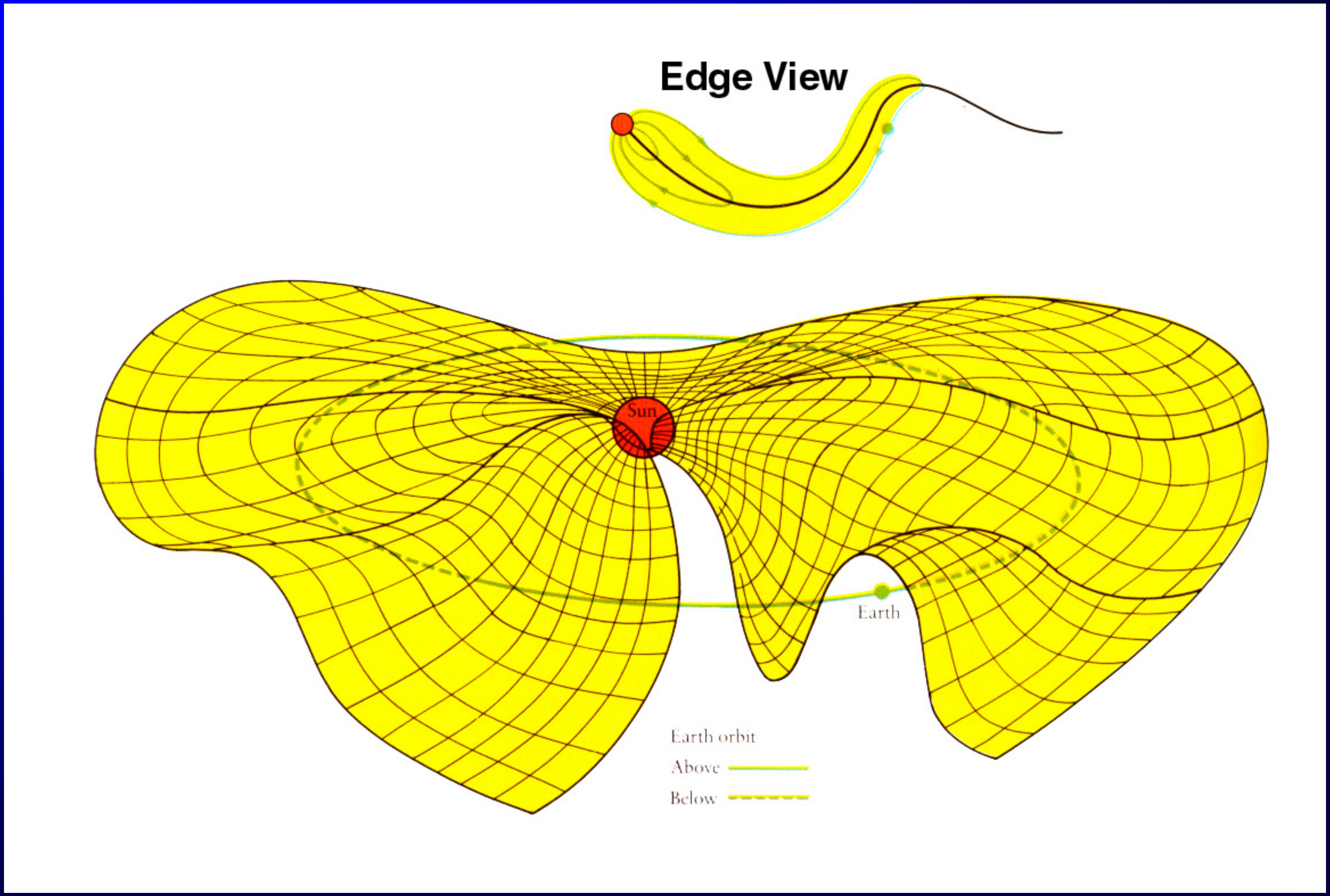
Backup Slides

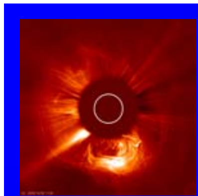
A Key Observation



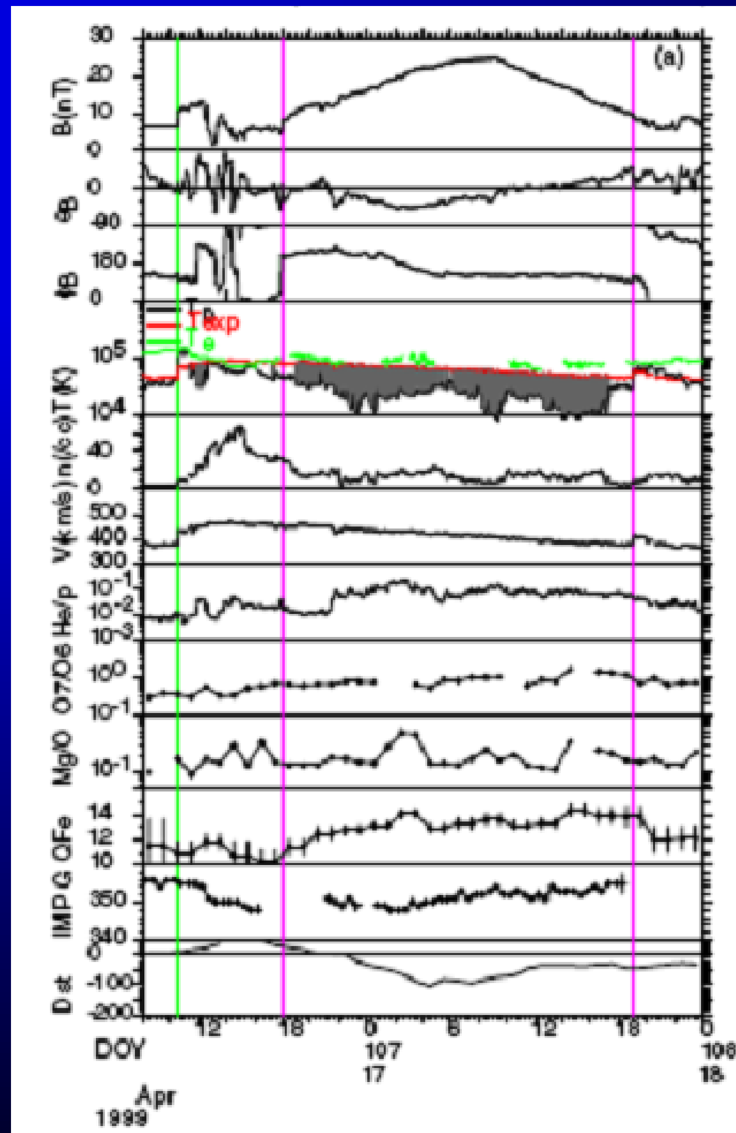
Heliospheric Plasma Sheet “Ballerina Skirt”



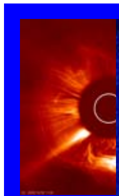


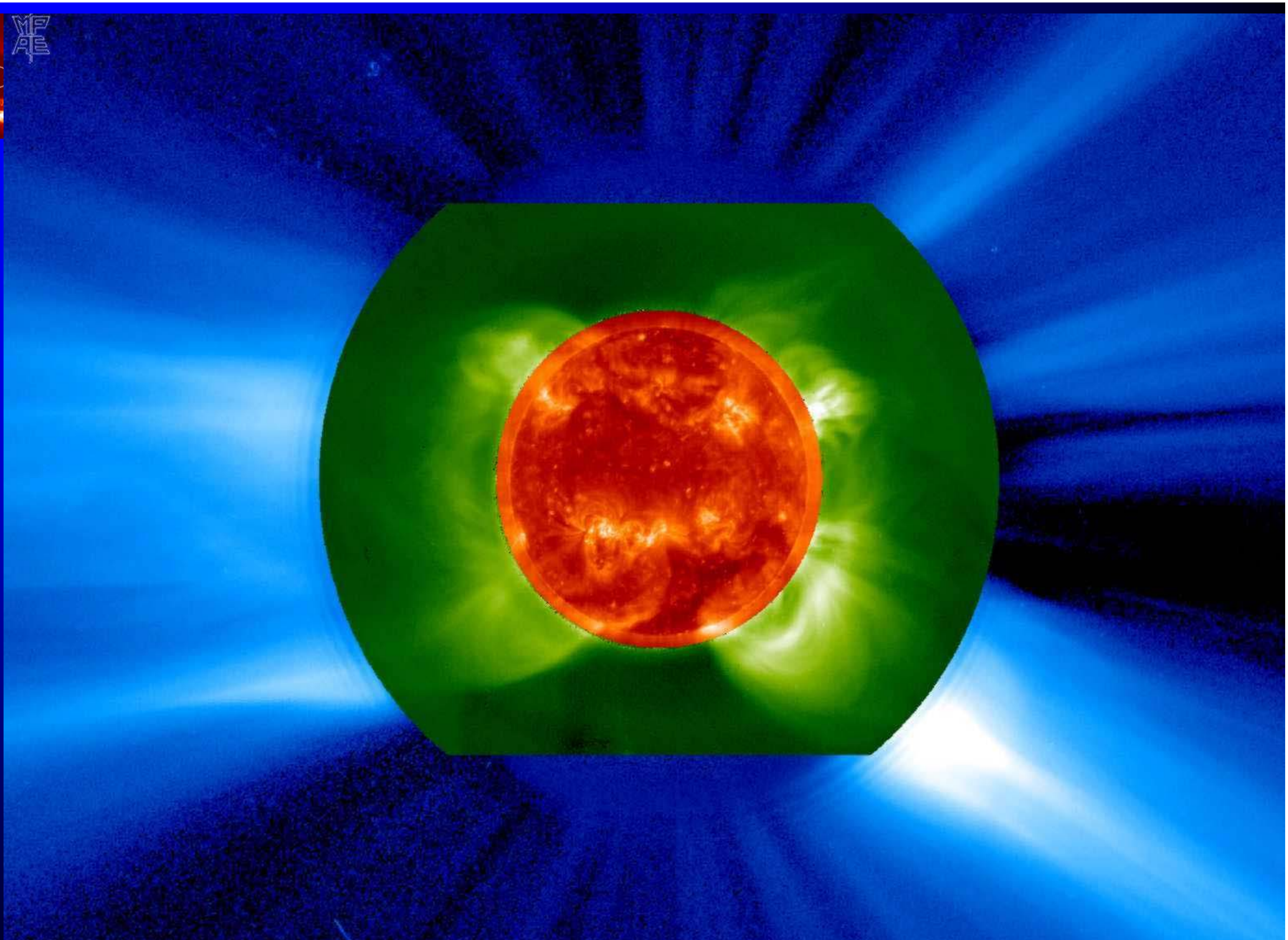


A CME “seen” in-situ

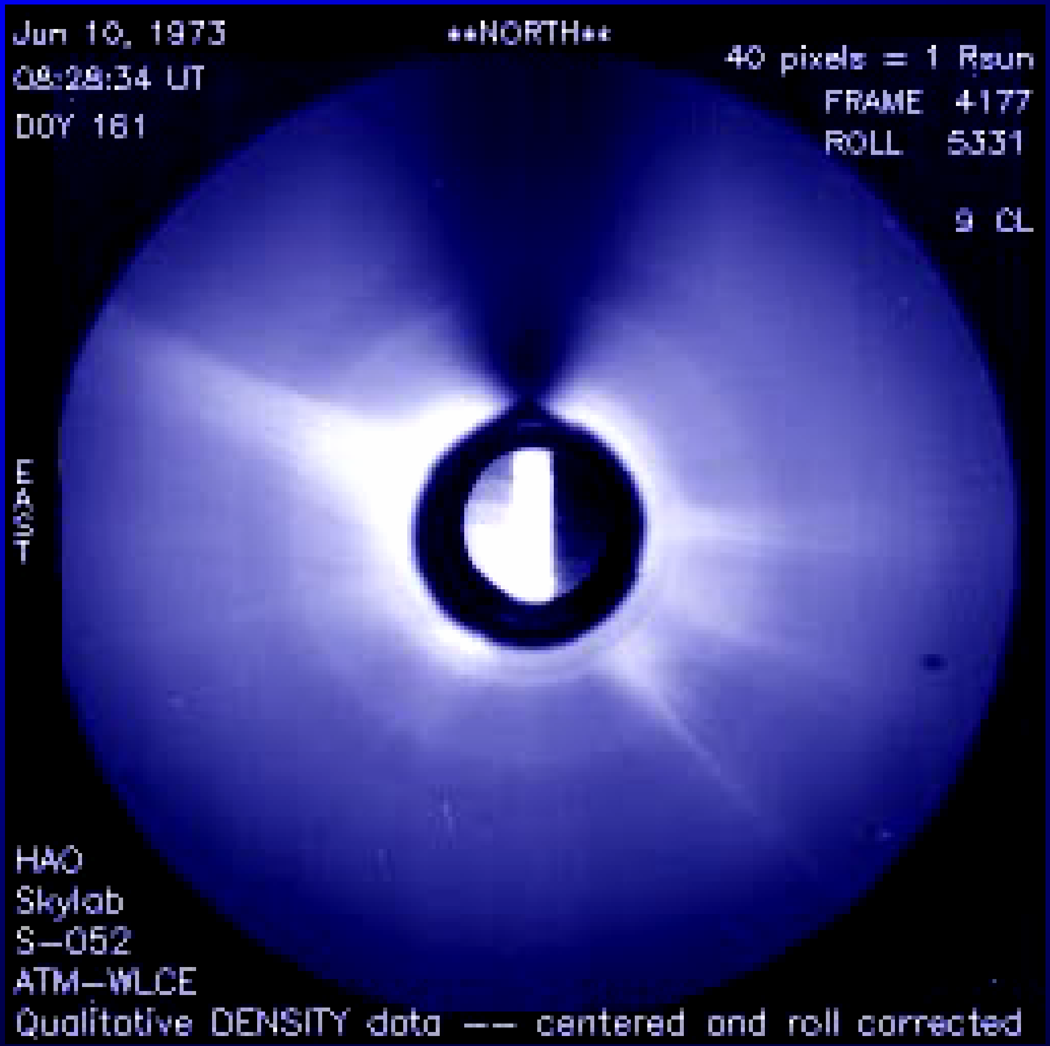


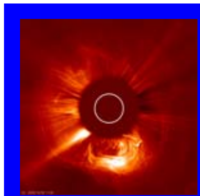
From Zurbuchen & Richardson (2004)



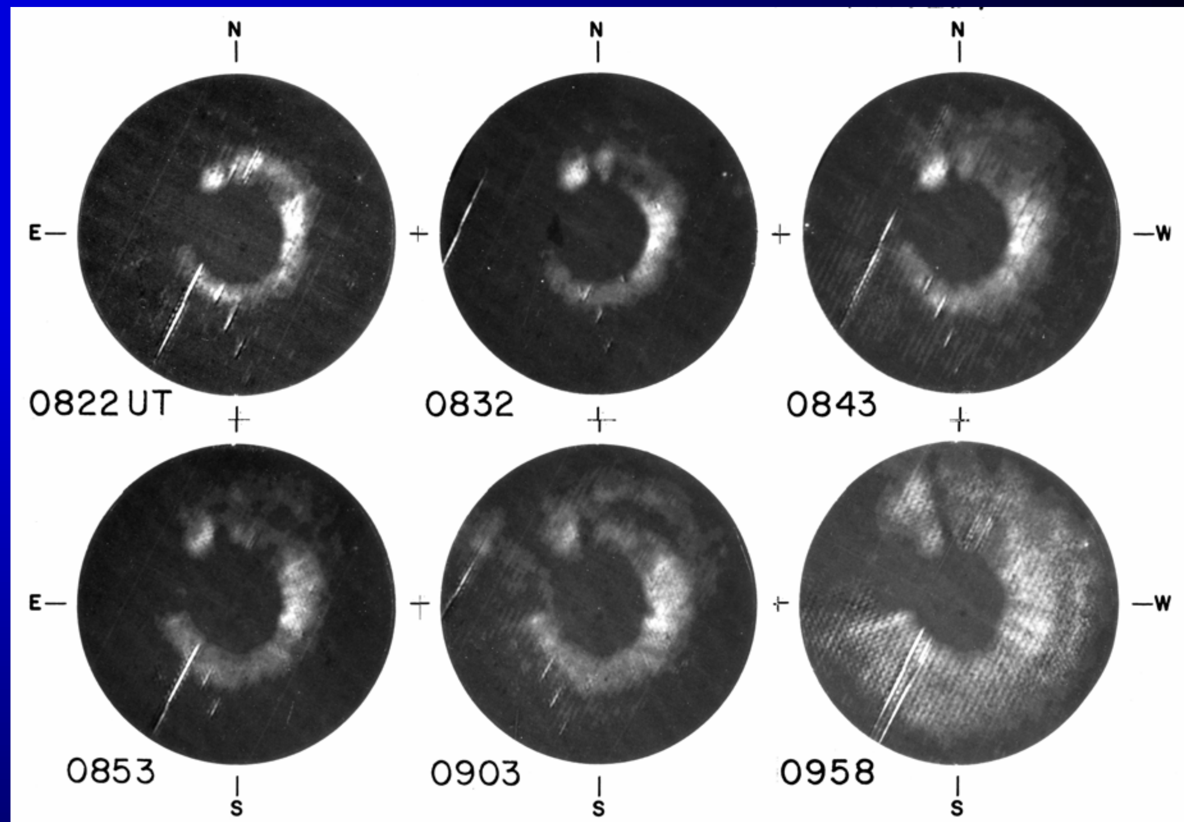


First CME from Skylab 10 June 1973

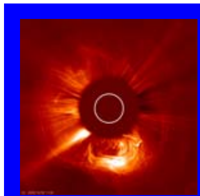




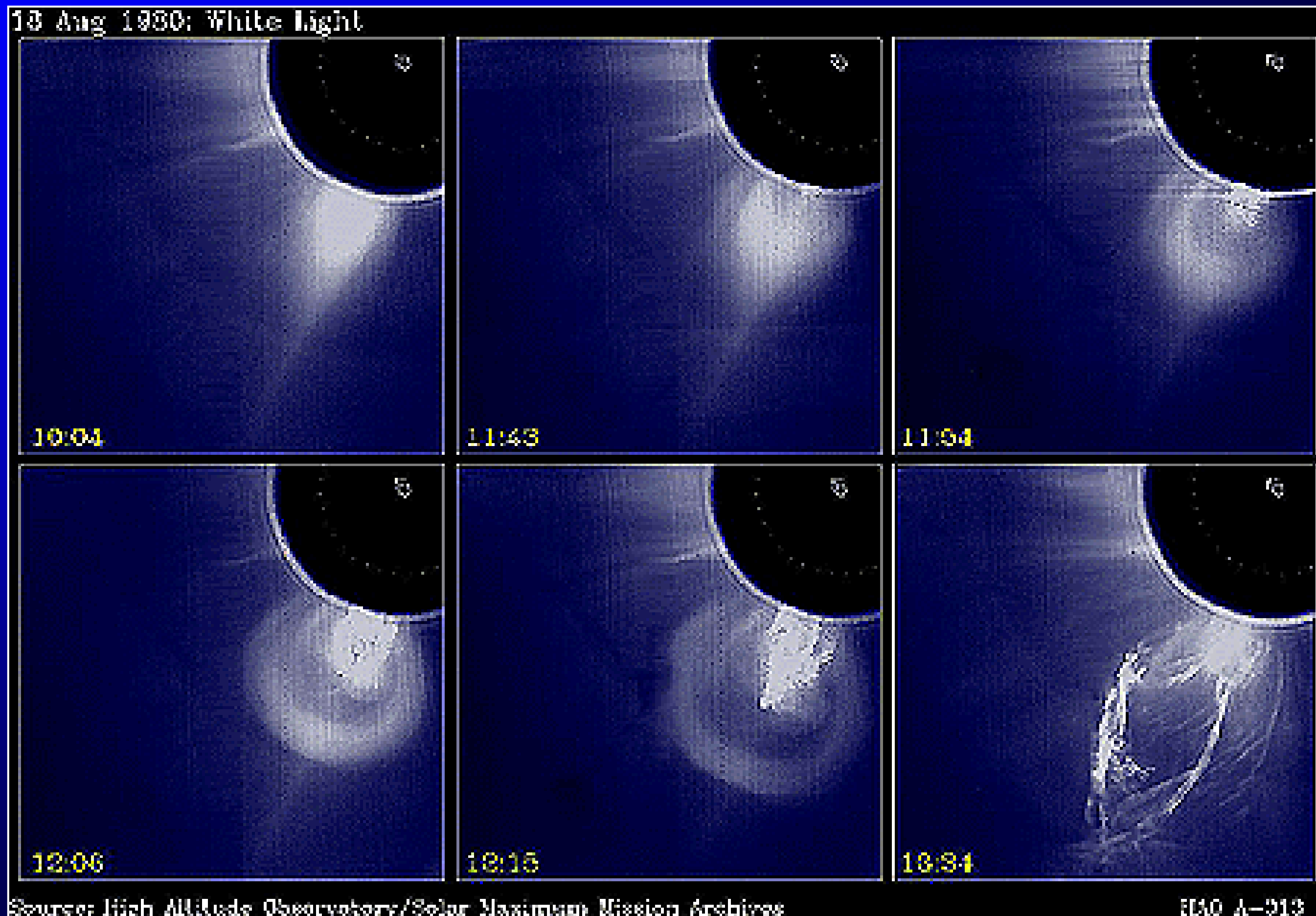
First Halo-CME Detection

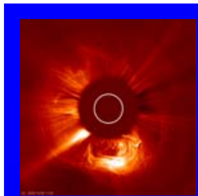


27 NOV. '79 "HALO" CORONAL TRANSIENT
(PRE-EVENT IMAGE SUBTRACTED,
CONTOURS ENHANCED)



3-Part CME


18 Aug 1980: White Light
10:04
11:43
11:54
12:06
Source: High Altitude Observatory/Solar Maximum Mission Archives

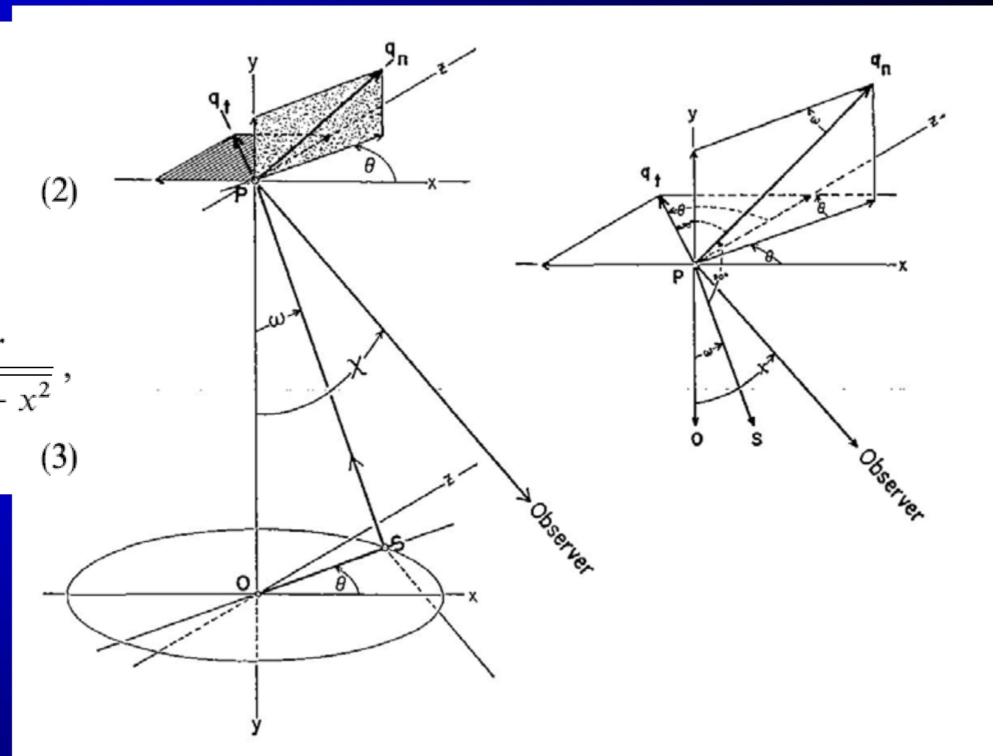


Emission Fundamentals-Details

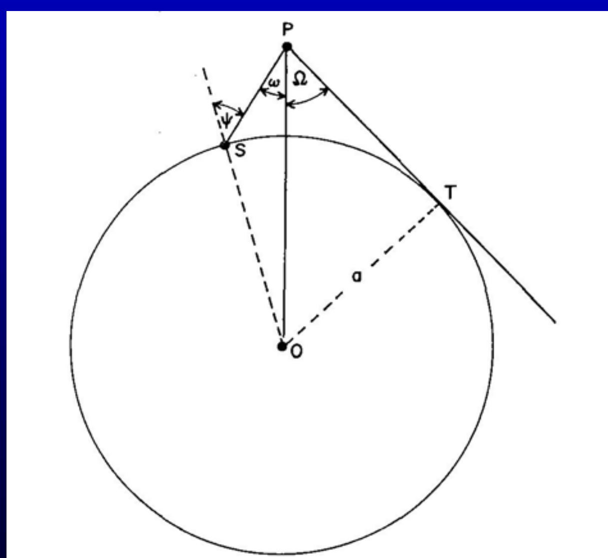
$$B = K_t(x) + K_r(x) = K(x) = C\int_x^\infty N(r)\left[\left(2 - \frac{x^2}{r^2}\right)\mathscr{A}(r) + \frac{x^2}{r^2}\,\mathscr{B}(r)\right]\frac{r\,dr}{\sqrt{r^2 - x^2}} \qquad (2)$$

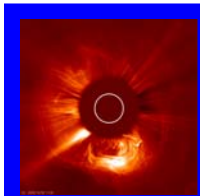
and

$$pB = K_t(x) - K_r(x) = C\int_x^\infty N(r)[\mathscr{A}(r) - \mathscr{B}(r)]\,\frac{x^2\,dr}{r\sqrt{r^2 - x^2}}\,, \qquad (3)$$



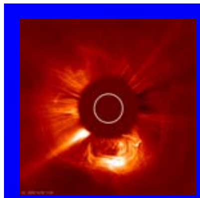
From Billings (1966)





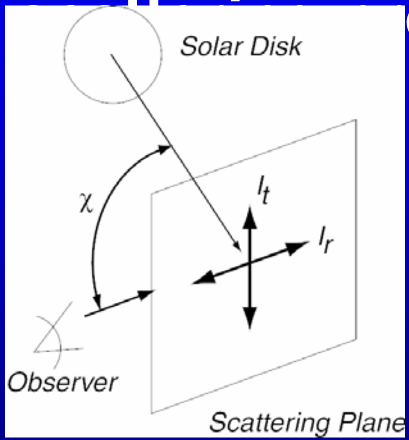
Lyot Coronagraph

- During the 1930s, Bernard Lyot analyzed the sources of scattered light and developed the "internally occulted" coronagraph
- The "externally occulted" coronagraph extension by Jack Evans in the 1960s, putting a single disk in front of the objective lens
- Triple disk external occulter assembly added by Newkirk and Bohlin achieved 10^{-6} suppression
- Purcell and Koomen suggested that a serrated external achieves the same apodization of the diffracted light as the triple disk



Electron Scattering

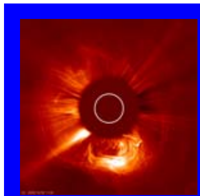
- **LASCO (C2/C3) observes photospheric light scattered by free electrons in the Thomson scattering process**



$$I_t = I_o \frac{N_e \pi\sigma}{2}[(1-u)C+uD]$$

$$I_t - I_r = I_o \frac{N_e \pi\sigma}{2} \sin^2\chi[(1-u)A+uB]$$

- **The scattering is in a plane perpendicular to the incident photon and can be divided into two components.**
- **The observed intensity is the integration along the line of sight.**



Solar Corona

- **The inner corona**
  - **The region immediately beyond the disk of the sun that rotates rigidly with the sun.**
  - **It is dominated by magnetic energy and extends to approximately 2 solar radii. Magnetic structures are very complicated.**
  - **Electron density is falling very rapidly (r^{-8}/r^{-10})**
- **The outer corona**
  - **The properties in this region are a mixture between the solar wind and the corona.**
  - **Electron density still is dropping faster than the solar wind (r^{-4}) but not as fast as closer to the sun.**
  - **The magnetic field direction is approximately radial.**