Explosive Solar Phenomena

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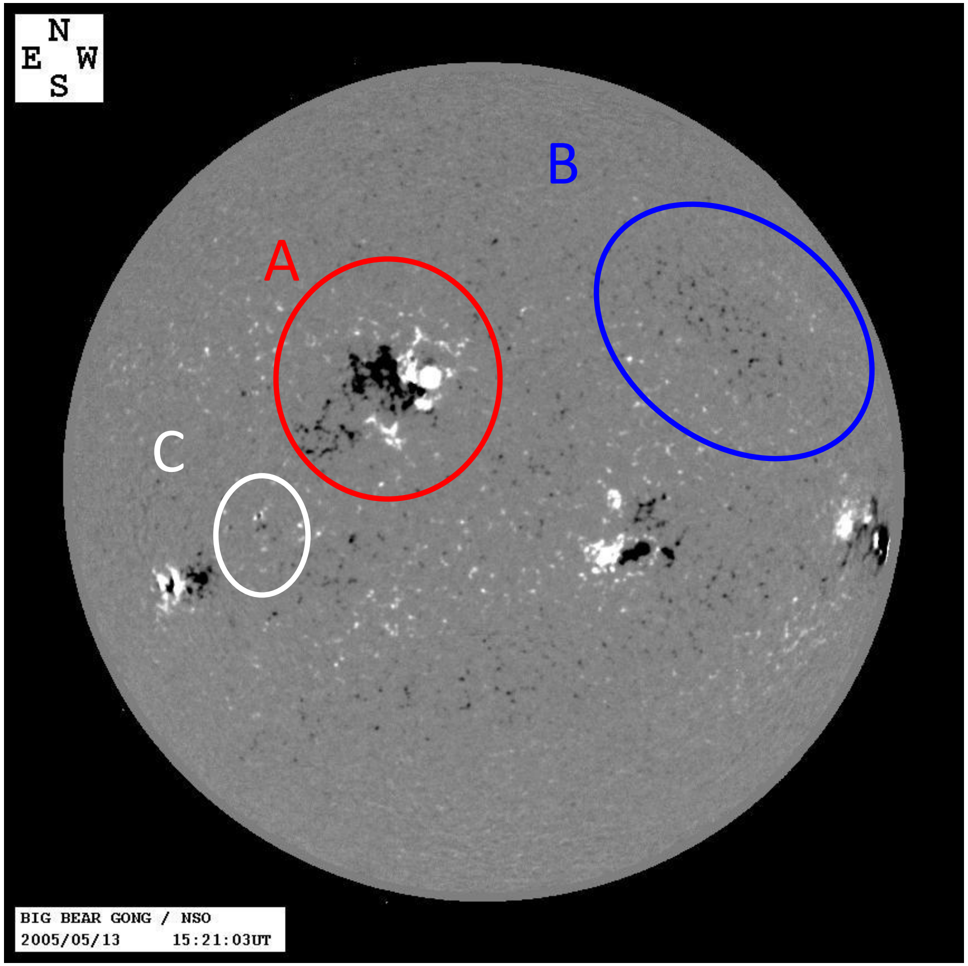
What are explosive phenomena?

- These phenomena represent sudden release of energy on the sun, confined in time and space
- The phenomena can occur at various time and spatial scales – from tiny bright pint flares to huge eruptions from solar active regions
- The source of energy for the explosions is magnetic. Therefore, these explosions occur in closed magnetic regions on the Sun
- The closed field regions can be simple bipolar region to highly complex and multipolar regions

Solar Source Regions of Explosive Events



This is a Magnetogram of the Sun.
White - positive polarity – field lines pointed away from the Sun
Dark: negative polarity: filed lines point toward the Sun

A – a large complex magnetic region. This is known as an active region
B – a large bipolar region with weak magnetic field
C – a tiny bipolar region

Energy is stored in the field lines when field lines are stresses by photospheric jostling

The stored energy is released explosively when the region cannot hold any more energy

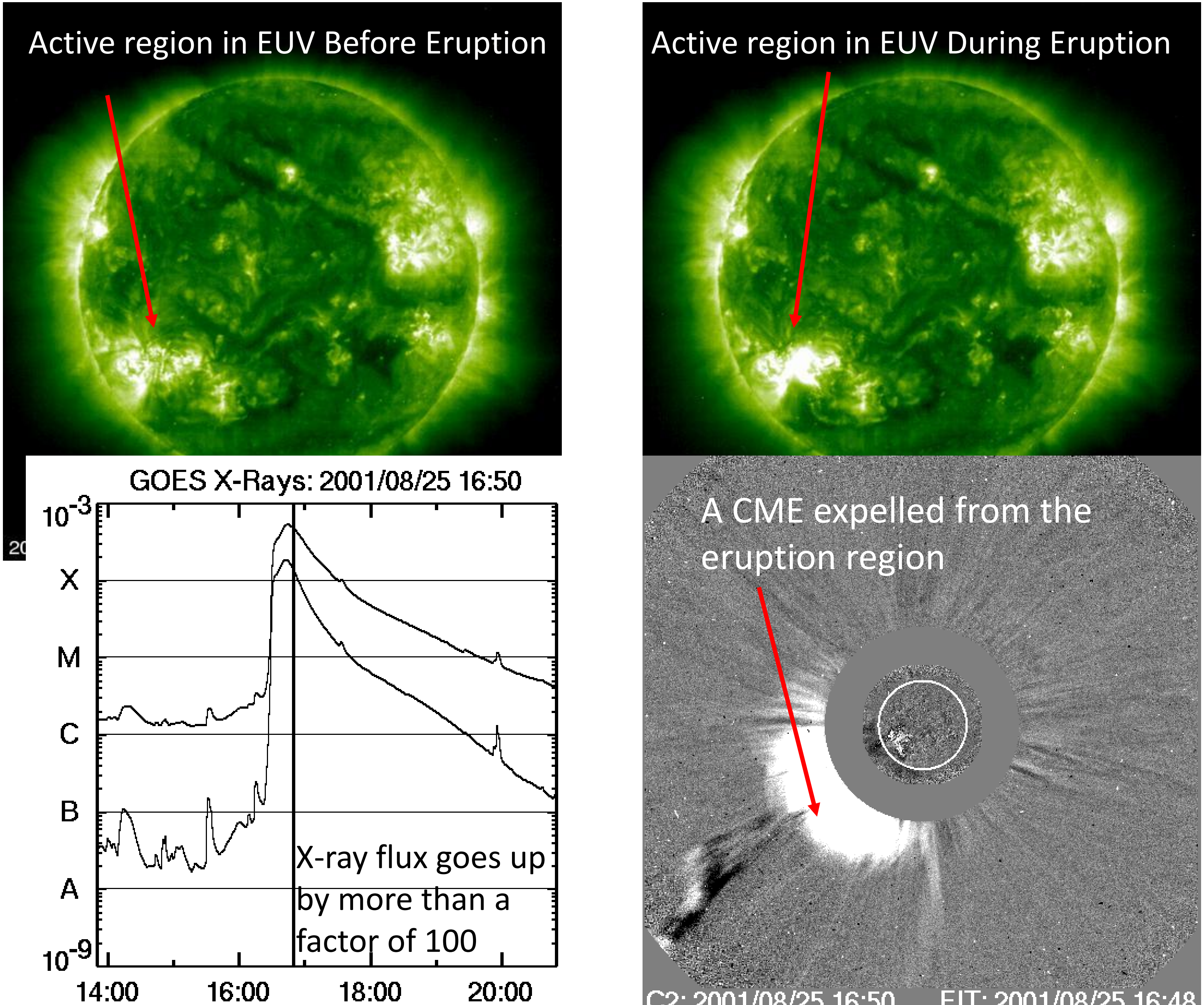
Flares and Coronal Mass Ejections

- When the energy released is large, say, $>10^{27}$ erg, they affect space in the sun's surroundings.
- Explosive energy can go into heating the plasma in the source region, into kinetic energy of plasma expelled from the explosion and into particle radiation (electrons, ions)
- Flare heating results in enhanced X-ray and EUV emission, which can increase the conductivity of the ionosphere
- Particle radiation can affect spacecraft, airplane crew and passengers, and ionospheric conductivity
- Coronal mass ejections (CMEs) can attain kinetic energies as high as 10^{33} erg.
- CMEs carry both mass and magnetic field. When CME magnetic field reconnects with Earth's magnetic field, huge geomagnetic storms can occur
- Large flares and CMEs (solar eruptive events) are of interest because they affect Earth's space environment

Observational Tools

- Optical: White light, H-alpha images
- EUV images
- Infrared: He 10830 Å images
- Microwaves (mm, cm)images , light curves
- Hard X-rays images, spectra
- Soft X-rays: images
- Gamma rays
- Decimeter to km radio waves: images,

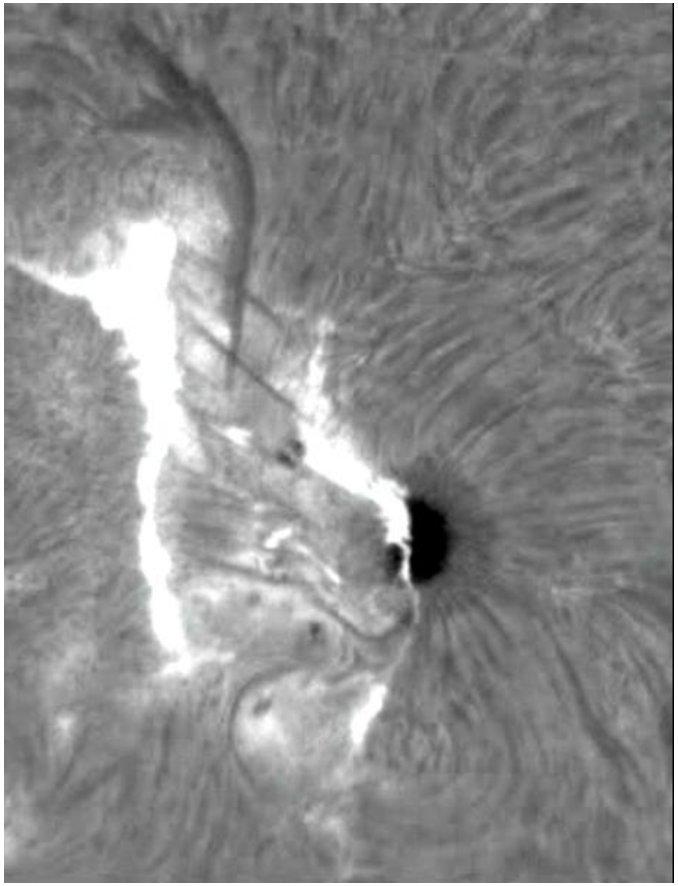
Thermal & nonthermal phenomena
Ground and space-based observations


Active region in EUV Before Eruption
Active region in EUV During Eruption
GOES X-Rays: 2001/08/25 16:50
10^{-3}
X
M
C
B
A
10^{-9}
14:00
16:00
18:00
20:00
X-ray flux goes up by more than a factor of 100
A CME expelled from the eruption region
C2: 2001/08/25 16:50
EIT: 2001/08/25 16:48

H-alpha flares

The two bright outer edges are known as H-alpha flare ribbons

- Temporary emission within dark Fraunhofer line
- In spectroheliograms, flares appear as brightening of parts of the solar disk
- Area > 10^9 km^2 for large flares
- Area < 3×10^8 km^2 for subflares
- H-alpha flare area has been used as the basis for optical flare importance
- Area at flare peak measured as number of square degrees (1 heliographic degree = $2\pi R/360$ = 12500 km with R = solar radius = 696000 km)
- Also measured as millionths of hemisphere (msh): 10^{-6} $2\pi R^2$ or ~3×10^6 km^2
- A scale of 0-4 is used with additional suffix for brightness (faint F, normal N, brilliant B)
- 4B is the highest importance; SF is the lowest



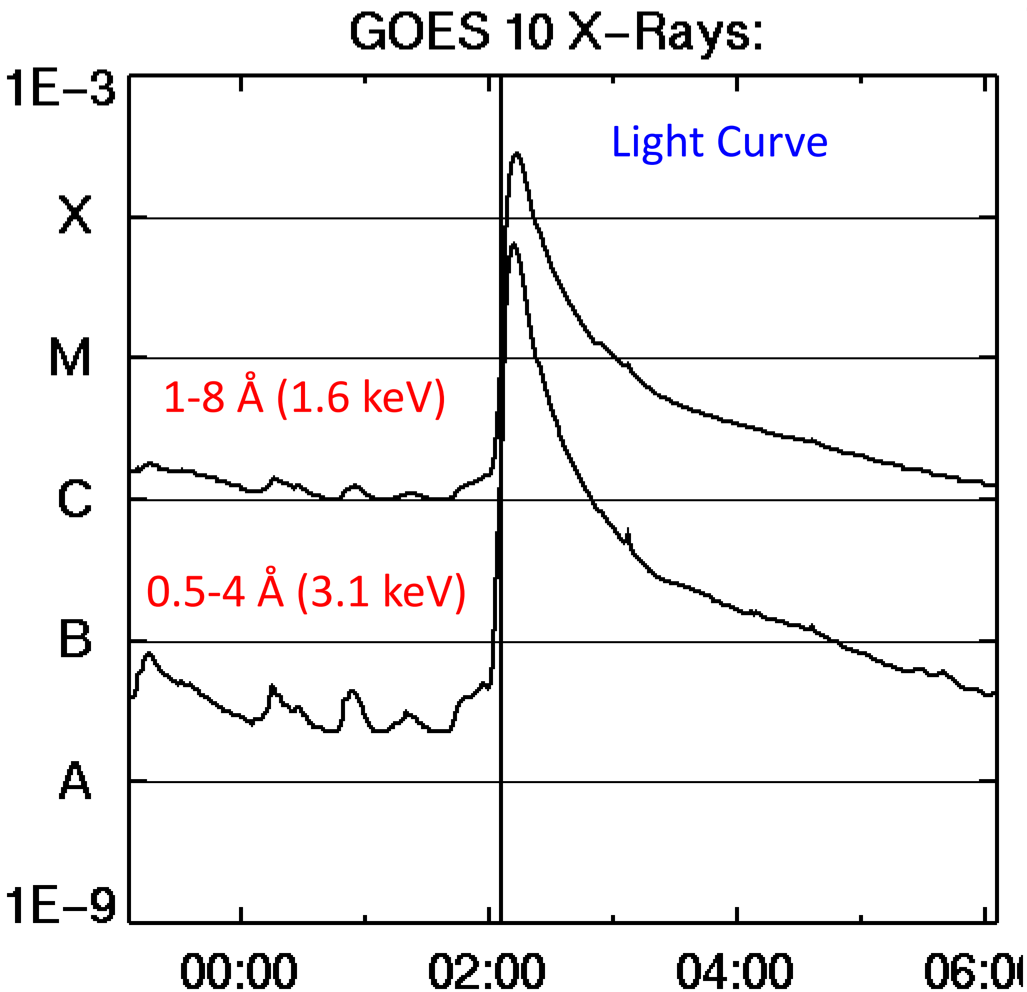
Dark loops connect the ribbons. The whole structure is referred to as flare arcade

H-alpha Flares

Flare Area msh (Square degree)	Faint	Normal	Brilliant
<100 (2.06)	SF	SN	SB
100-250 (2.06-5.15)	1F	1N	1B
250-600 (5.15-12.4)	2F	2N	2B
600-1200 (12.4-24.7)	3F	3N	3B
>1200 (>24.7)	4F	4N	4B

msh = millionths of solar hemisphere
Double Scale: 1-4 Area
1-3 Brightness (FNB)

Soft X-rays



1 Å = 10^{-8} cm = 10^{-10} m = 0.1 nm

Global photon output in the 1-8 Å band
Originally C, M, X used to indicate the flare size (e.g., X2.5 = 2.5×10^{-3} wm^{-2})

B, A added later to denote weaker flares

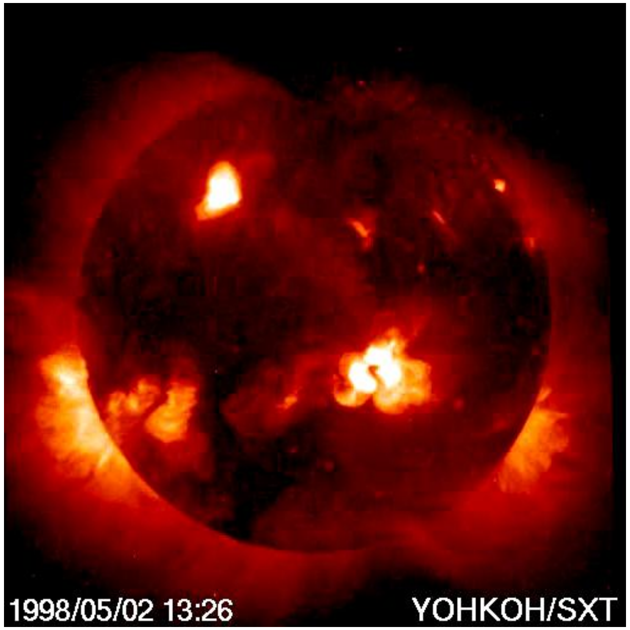
Flares larger than X10 - simply state the multiplier, e.g. X28

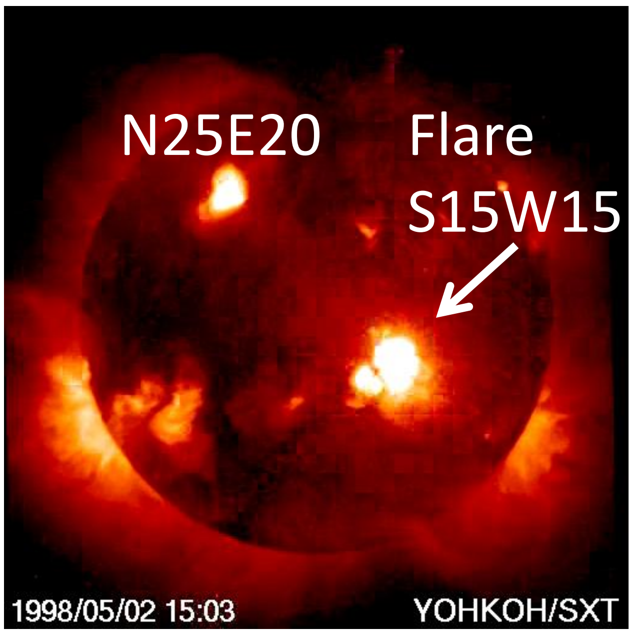
Importance class	Peak flux in 1-8 Å W/m^2
A	10^{-8} to 10^{-7}
B	10^{-7} to 10^{-6}
C	10^{-6} to 10^{-5}
M	10^{-5} to 10^{-4}
X	$>10^{-4}$

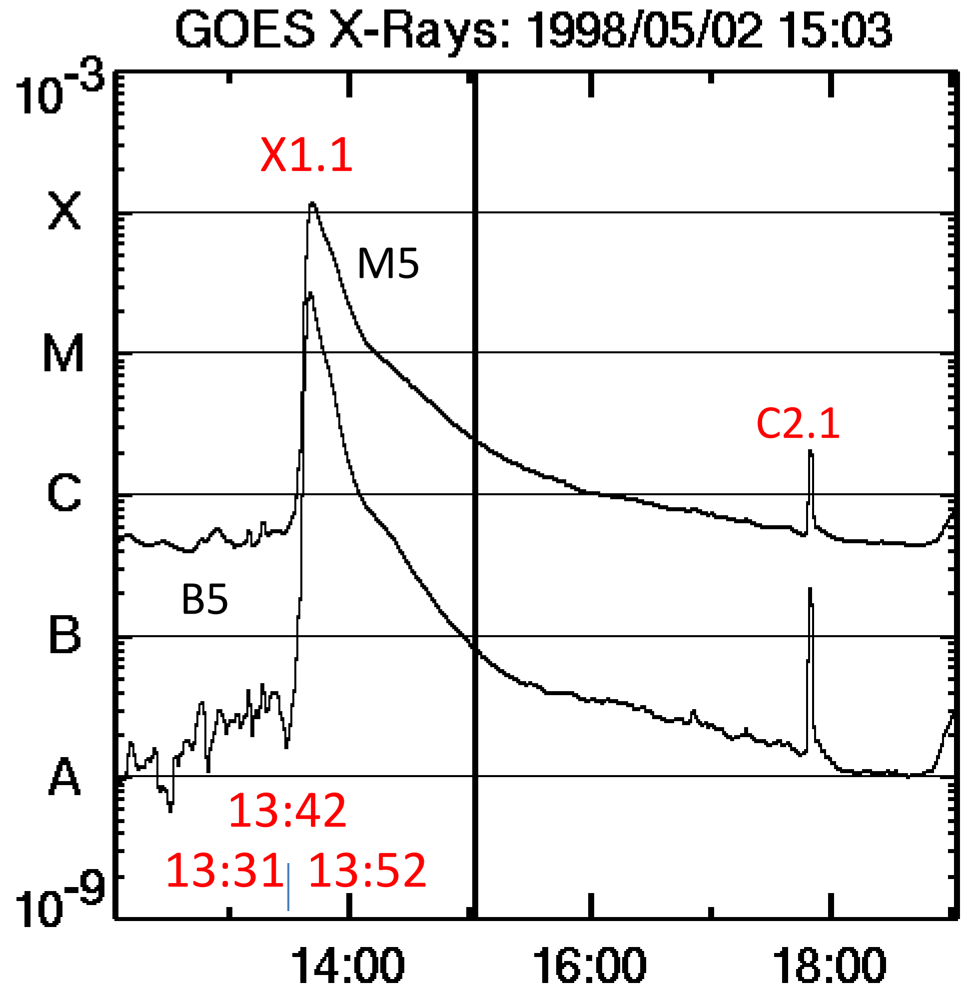
Time Marks of X-ray Flares

- Start: the first minute, in a sequence of 4 minutes, of steep monotonic increase in 0.1-0.8 nm (1-8 A) X-ray flux
- Max: the minute of the peak X-ray flux
- End: the time when the flux level decays to a point halfway between the maximum flux and the pre-flare background level.
- Details: http://www.swpc.noaa.gov/ftpdir/indices/events/README

A Large Flare & its X-ray Image



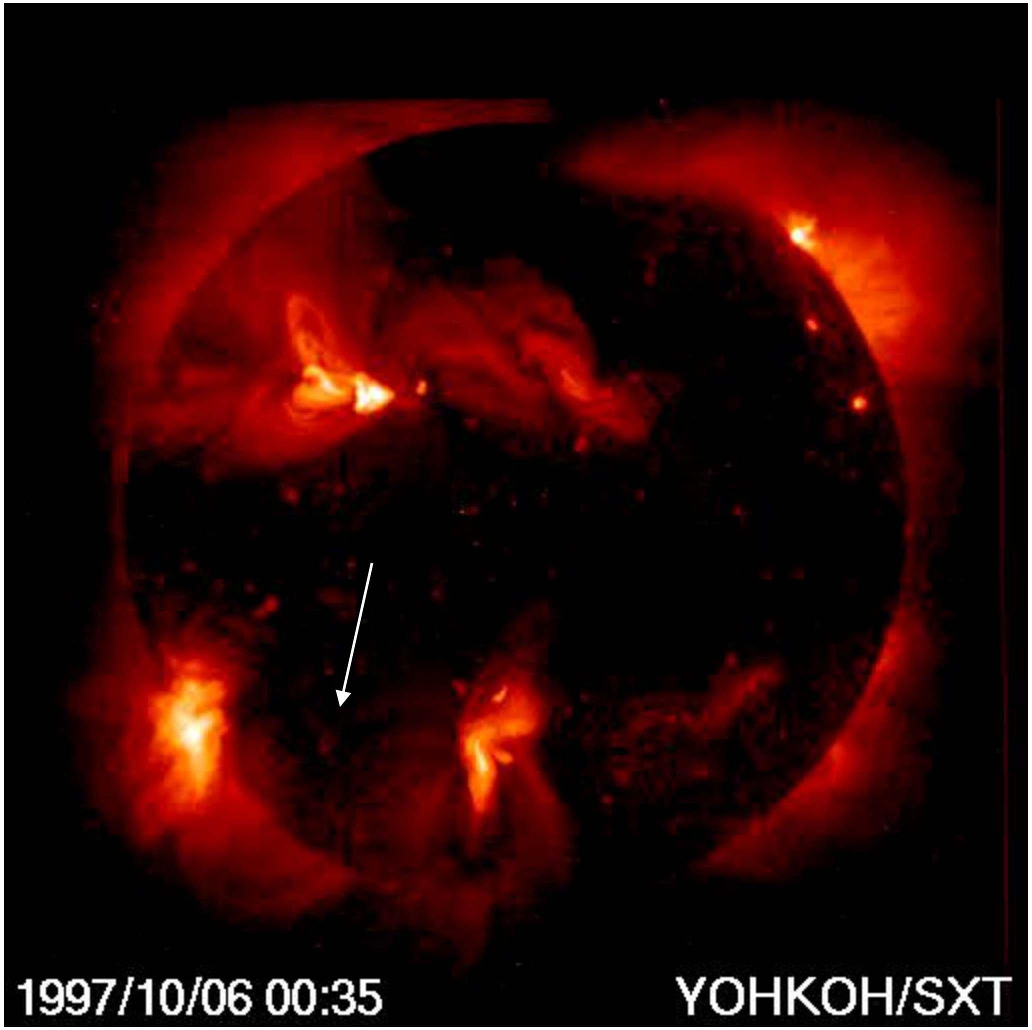




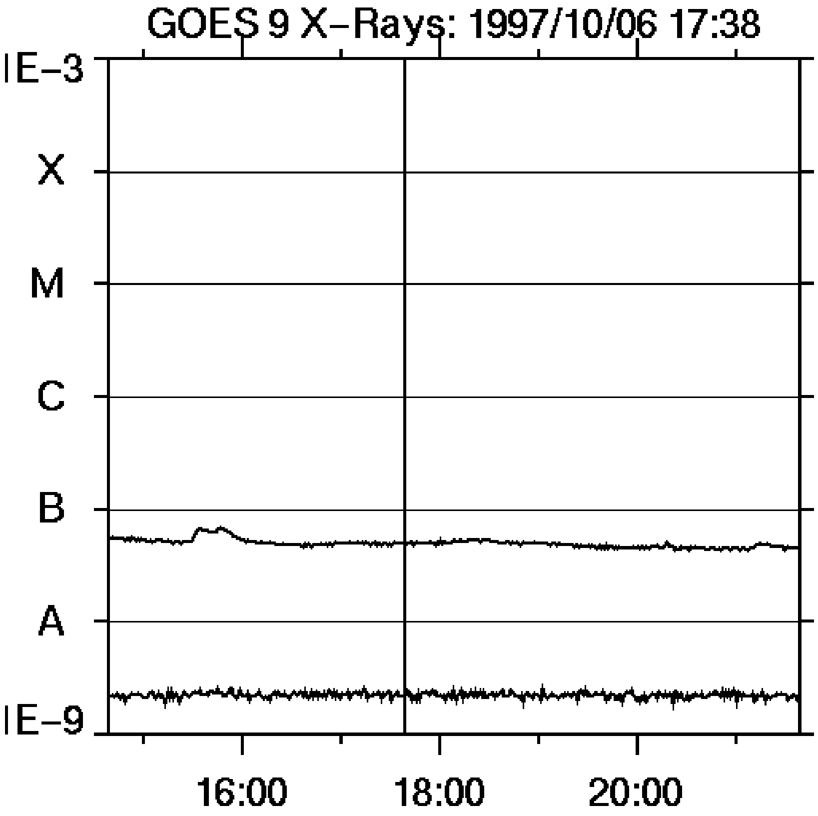
http://www.swpc.noaa.gov/ftpdir/indices/events/README

Very weak flare

Flare seen as an extended structure in soft X-ray images. Note the brightening in the southeast quadrant



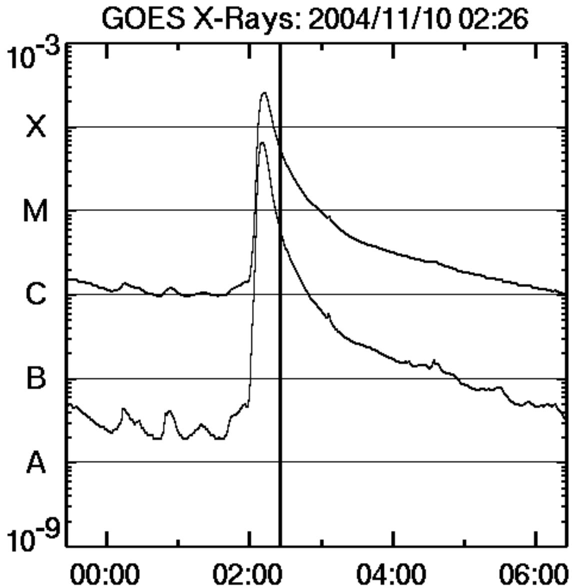
A-class flare barely seen in the soft X-ray light curve

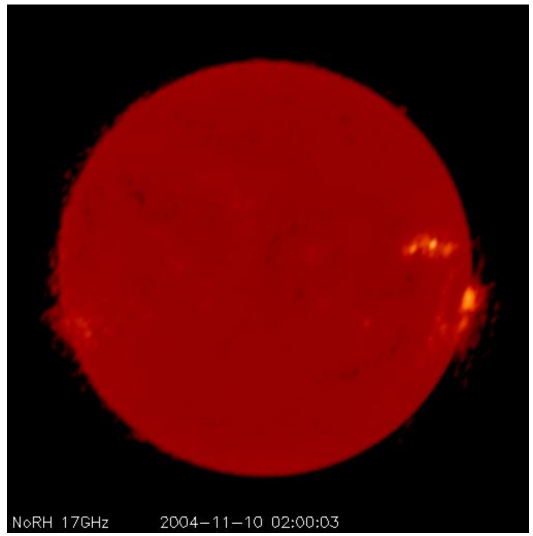


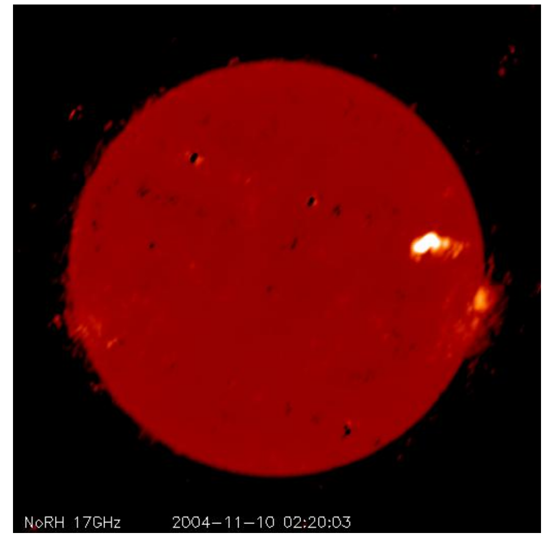
The image obtained in the energy channel 0.25 – 4 keV (2 – 50 Å)

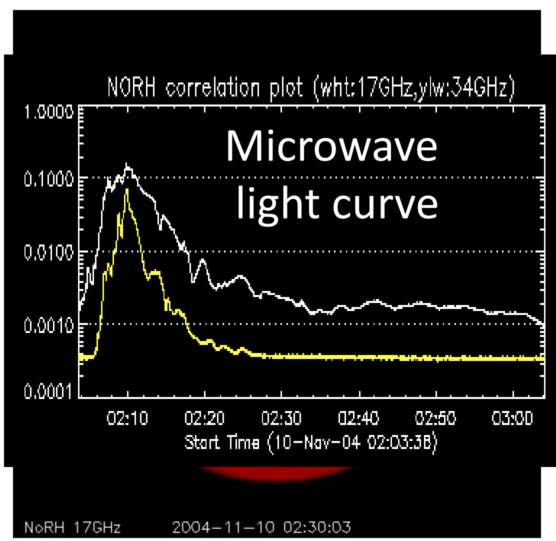
Images of a microwave flare (17 GHz)

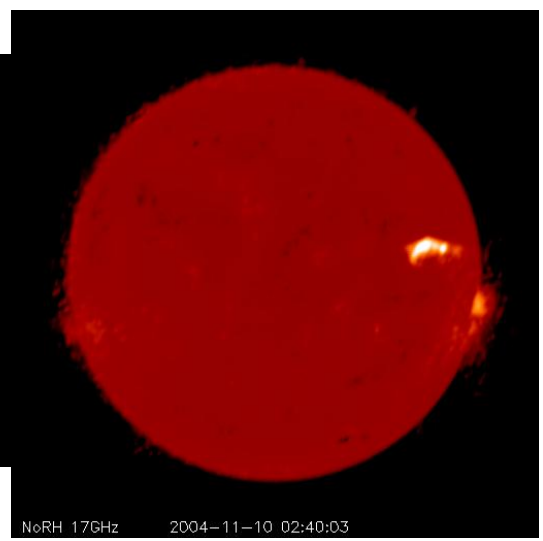
Nobeyama radioheliograph in Japan images the sun at 17 & 34 GHz

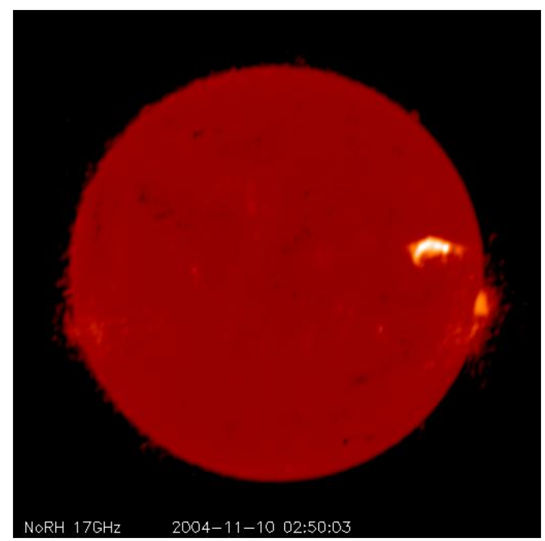












Flare Ribbons and Hard X-Rays

Hard X-rays are photons at higher energies than soft X-rays

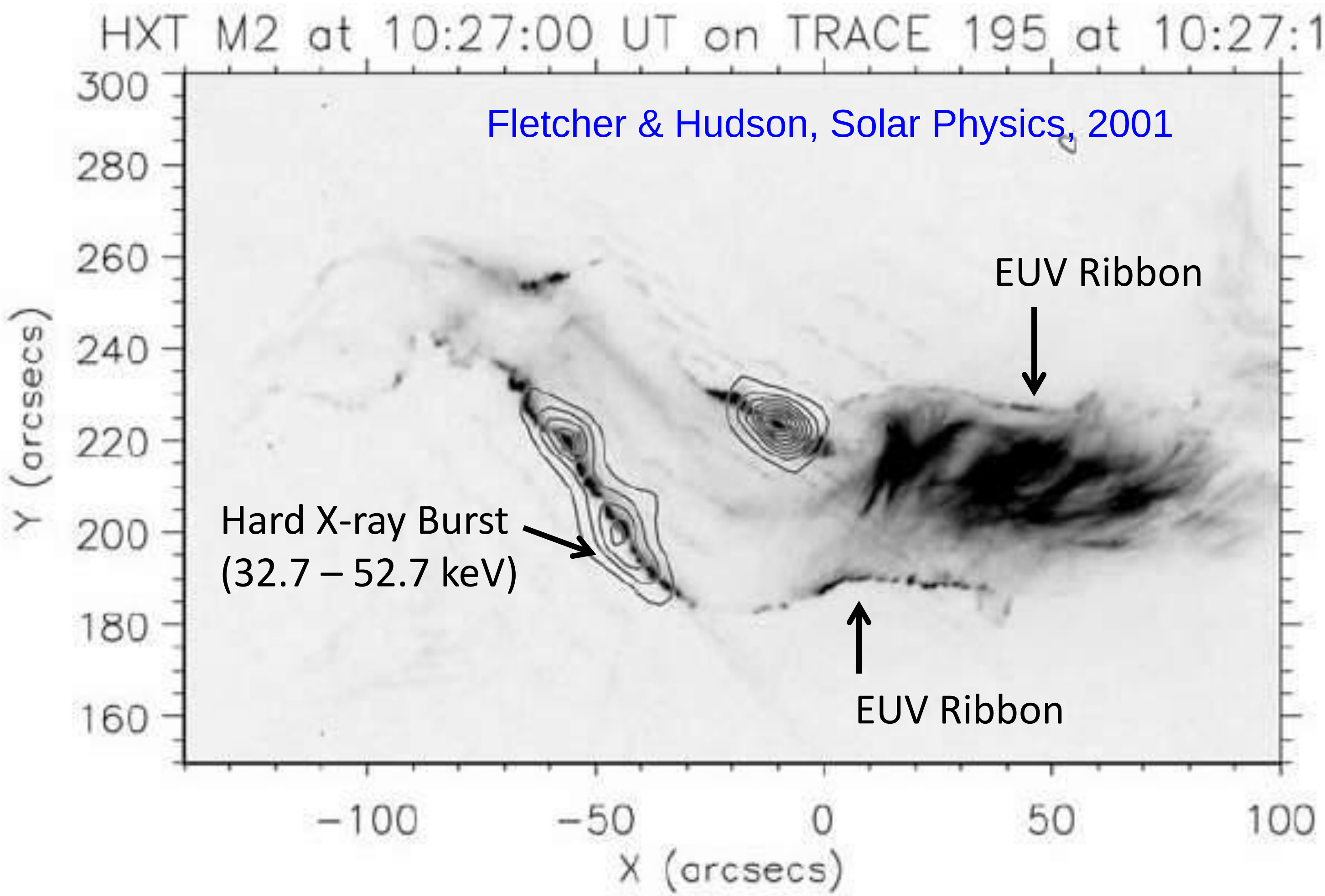


Image scale is negative: dark regions are considered more intense

Like in H-alpha, the flare arcade can also be observed in EUV. The EUV image was obtained by TRACE satellite (gray-scale image). The contours are obtained by the hard x-ray telescope (HXT) on board the Yohkoh satellite. Note that the hard X-ray bursts are located on the ribbons

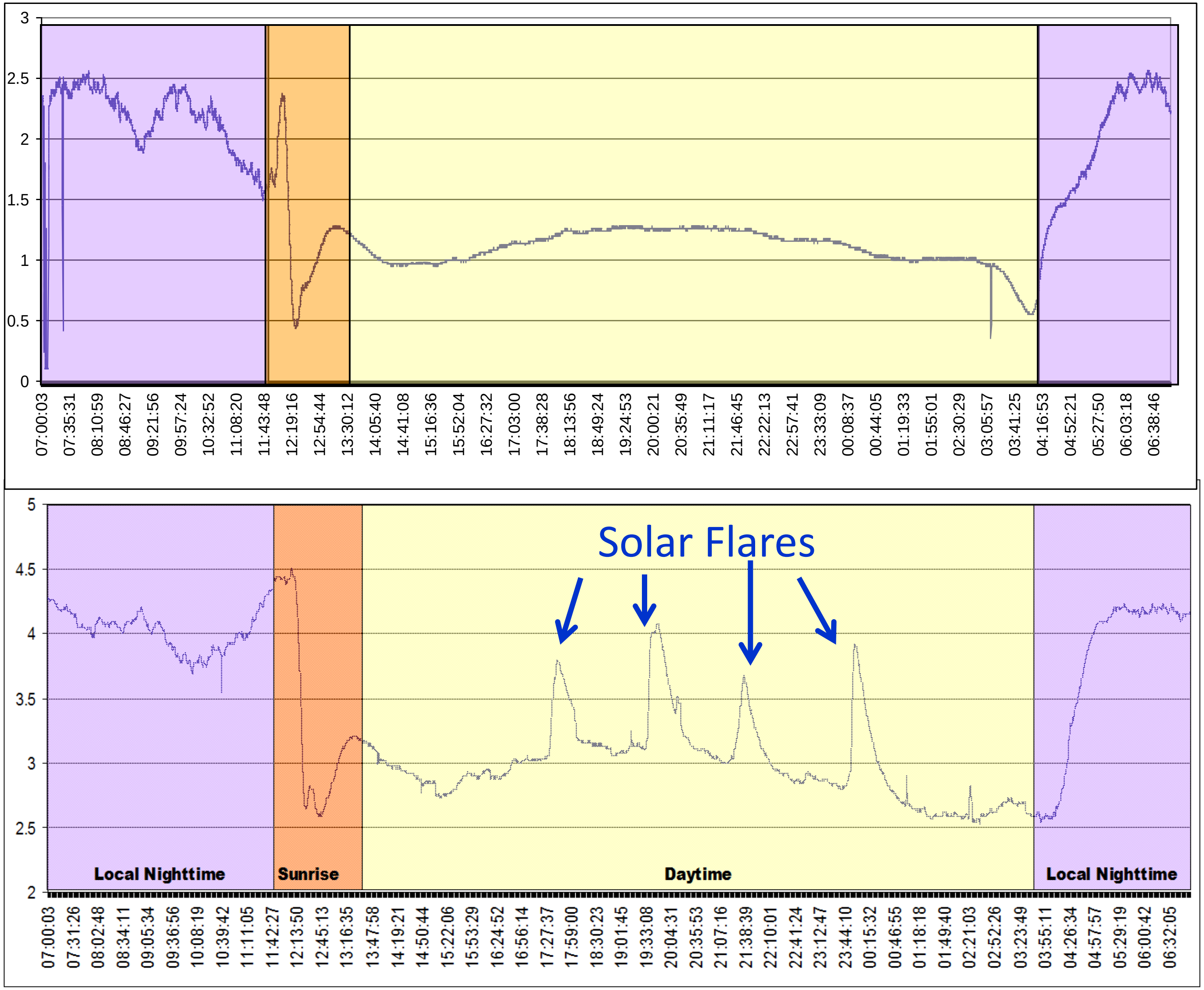
Flare Photons in the Ionosphere

- Atmospheric Weather Electromagnetic System for Observation Modeling and Education (*AWESOME*) Monitor and Sudden Ionospheric Disturbance (SID) Monitor are ISWI instruments (radio receivers) that monitor VLF signals that bounce between Earth surface and the ionosphere
- Solar flare photons increase the ionization and hence change the conductivity of the ionosphere
- This causes change in amplitude and phase of the VLF signals

Sudden Ionospheric Disturbance (SID) Event

Quiet Day

Active Day



NLK
24.8 kHz

Courtesy
Ray
Mitchell

The VLF signal amplitude and phase are modified when flare photons modify the ionosphere

Confined vs. Eruptive Flares

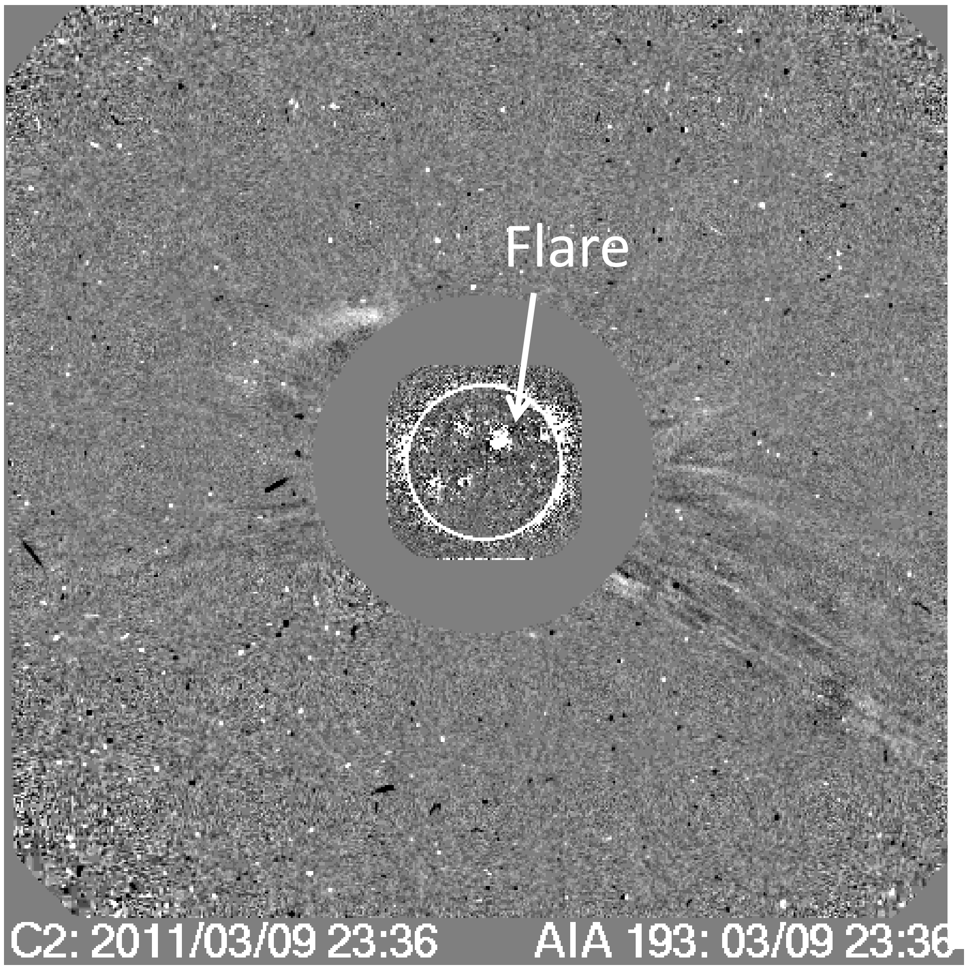
- Confined: generally a single loop
- Eruptive:
- associated with erupting prominence
- CME
- type II radio burst
- two - ribbon flares
- Post-eruption arcade

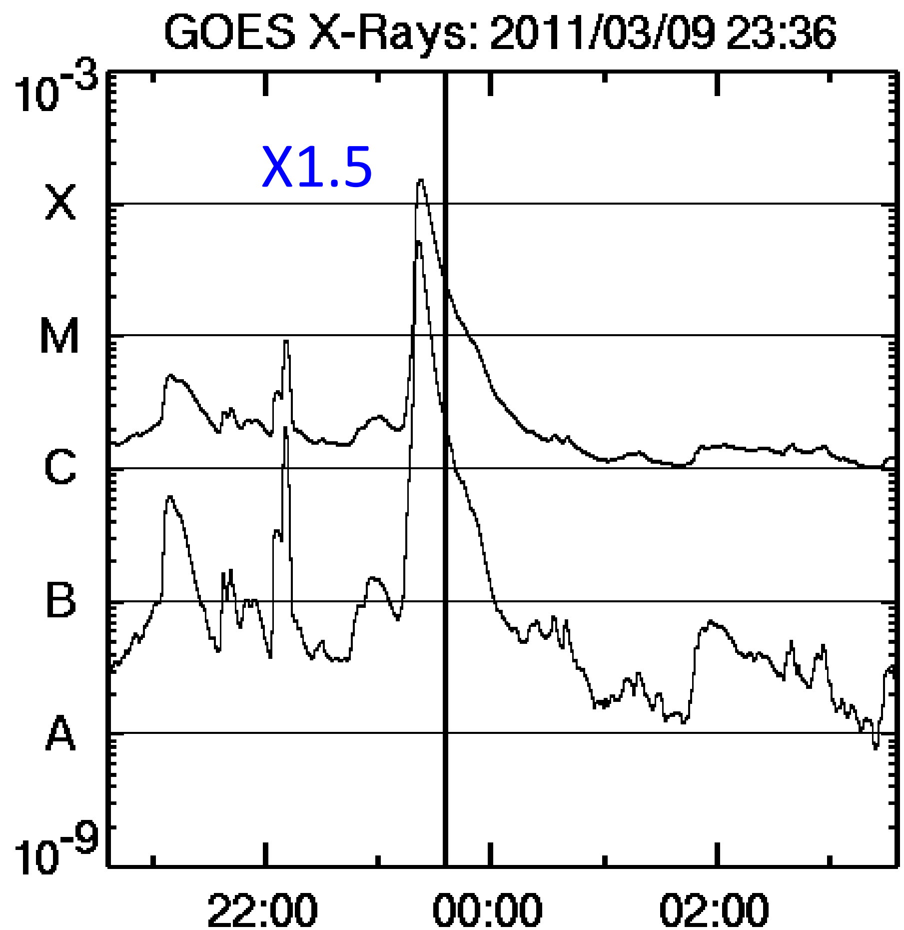
- Impulsive and gradual flares

Confined Flares

- ~ 20% of ≥M5.0 flares are not accompanied by mass motions
- Confined flares are hotter than eruptive ones
- Both confined and eruptive flares produce hard X-ray and microwave bursts
- No EUV waves found in confined flares
- No upward energetic electrons (lack of metric or longer wavelength type III, type II bursts) in confined flares

Confined Flare: No CME

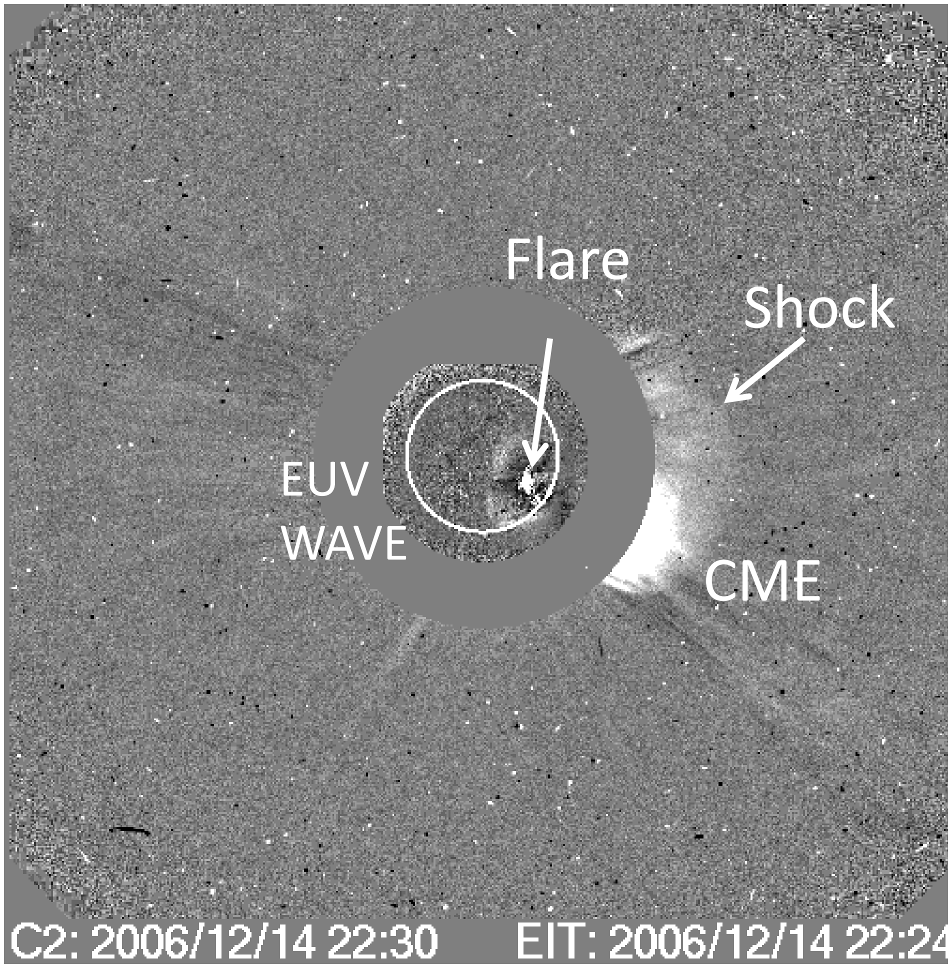




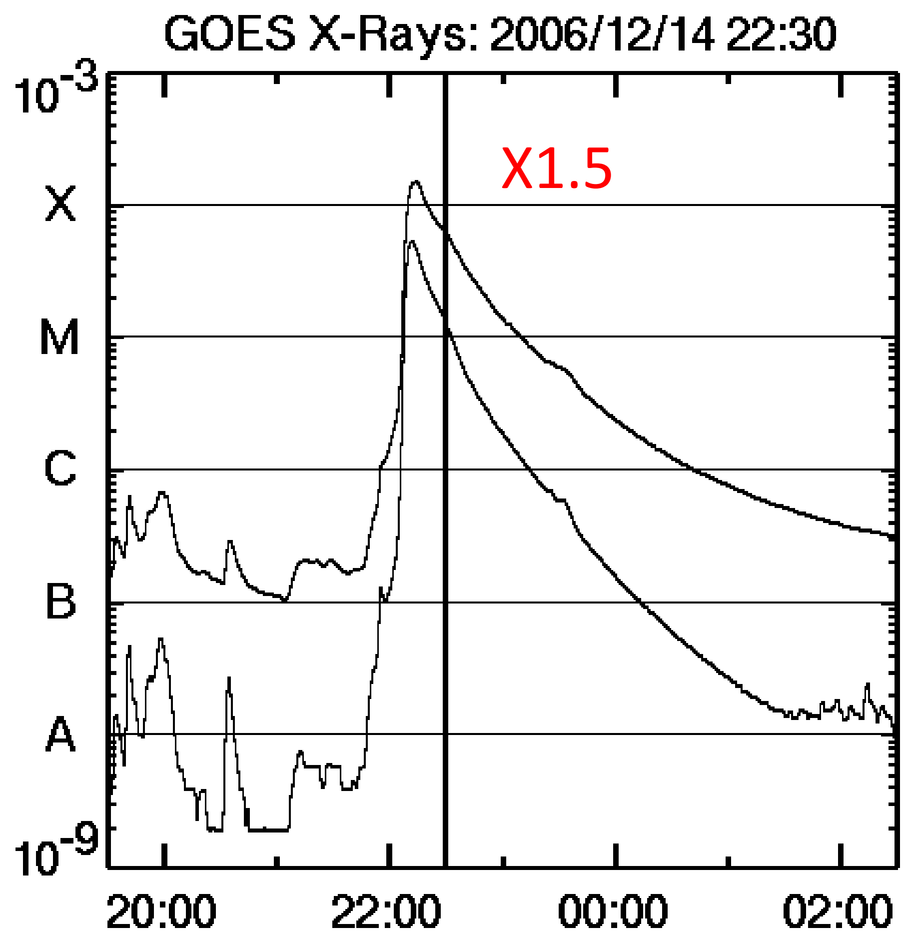
Confined flares just produce excess photons

CME is an Eruptive Event

Flares have prompt effect on the ionosphere



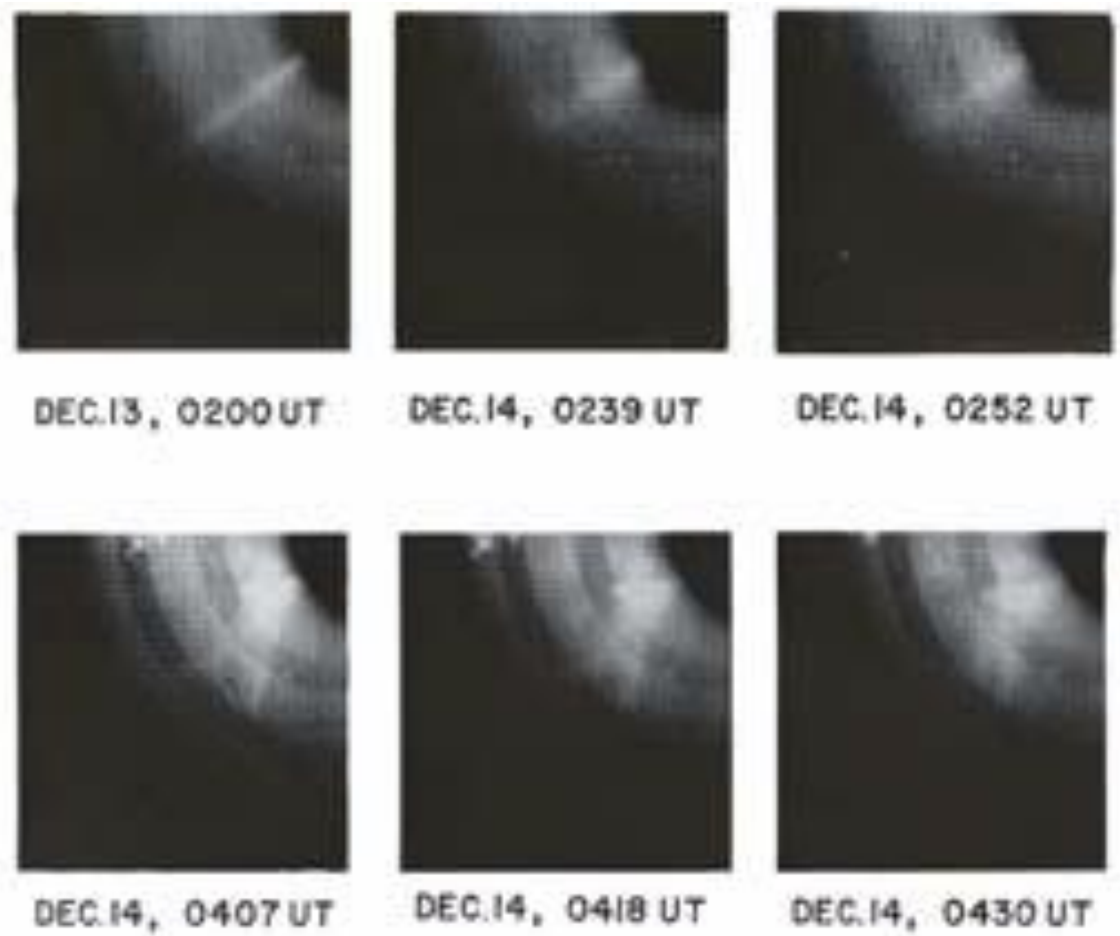
SOHO/LASCO & EIT Difference Images overlaid



Brief history

- Mass Ejections known for a long time from H-alpha prominence eruptions, type II radio bursts (e.g, Payne-Scott et al., 1947), and type IV radio bursts (Boischot, 1957)
- The concept of plasma ejection known to early solar terrestrial researchers (Lindeman, 1919; Chapman & Bartels, 1940; Morrison, 1954; Gold, 1955)
- CMEs as we know today were discovered in white light pictures obtained by OSO-7 spacecraft (Tousey, 1973)
- OSO-7, Skylab, P78-1, SMM, SOHO, and STEREO missions from space, and MLSO from ground have accumulated data on thousands of CMEs
- CME properties are measured in situ by many spacecraft since the 1962 detection of IP shocks (Sonett et al., 1964)

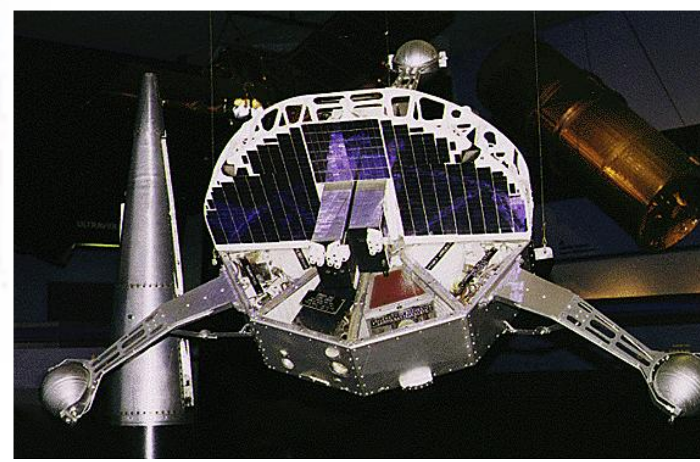
The first white-light CME from OSO-7



David Roberts, the electronics engineer noticed the change and thought his camera was failing…

Tousey, 1973
reported on the 13-14 Dec 1971
coronal transient (1000 km/s)

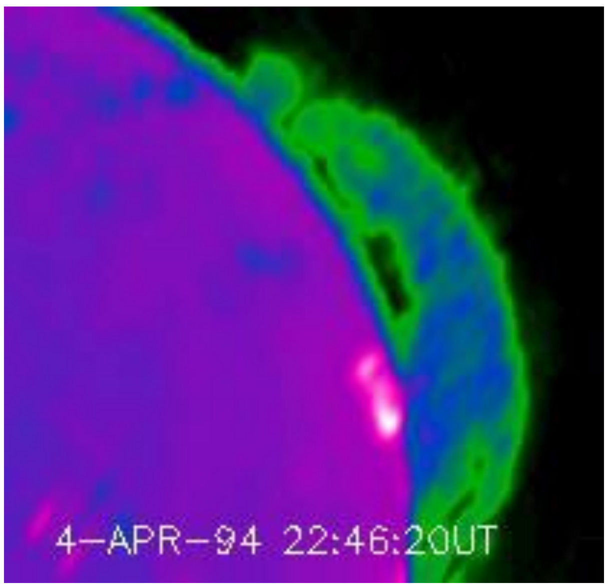
Skylab
Solwind on P78-1
Coronagraph/Polarimeter on SMM
SOHO/LASCO ←
STEREO/SECCHI
MLSO Mark IV K -Coronameter



NASA's OSO-7

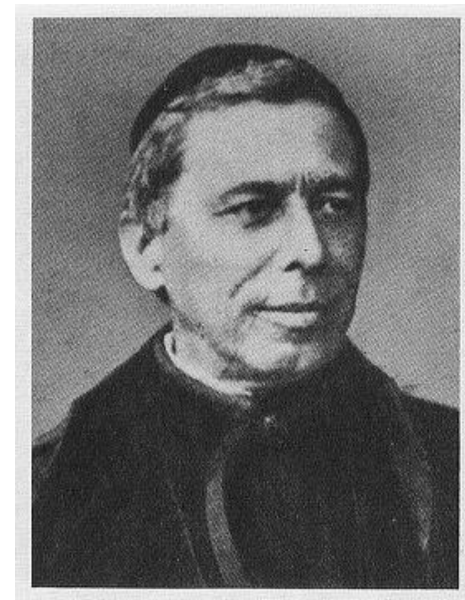
Prominences Understood by the end of 19^{th} Century

17 GHz Nobeyama radioheliograph



Gopalswamy & Hanaoka, 1998

Angelo Secchi

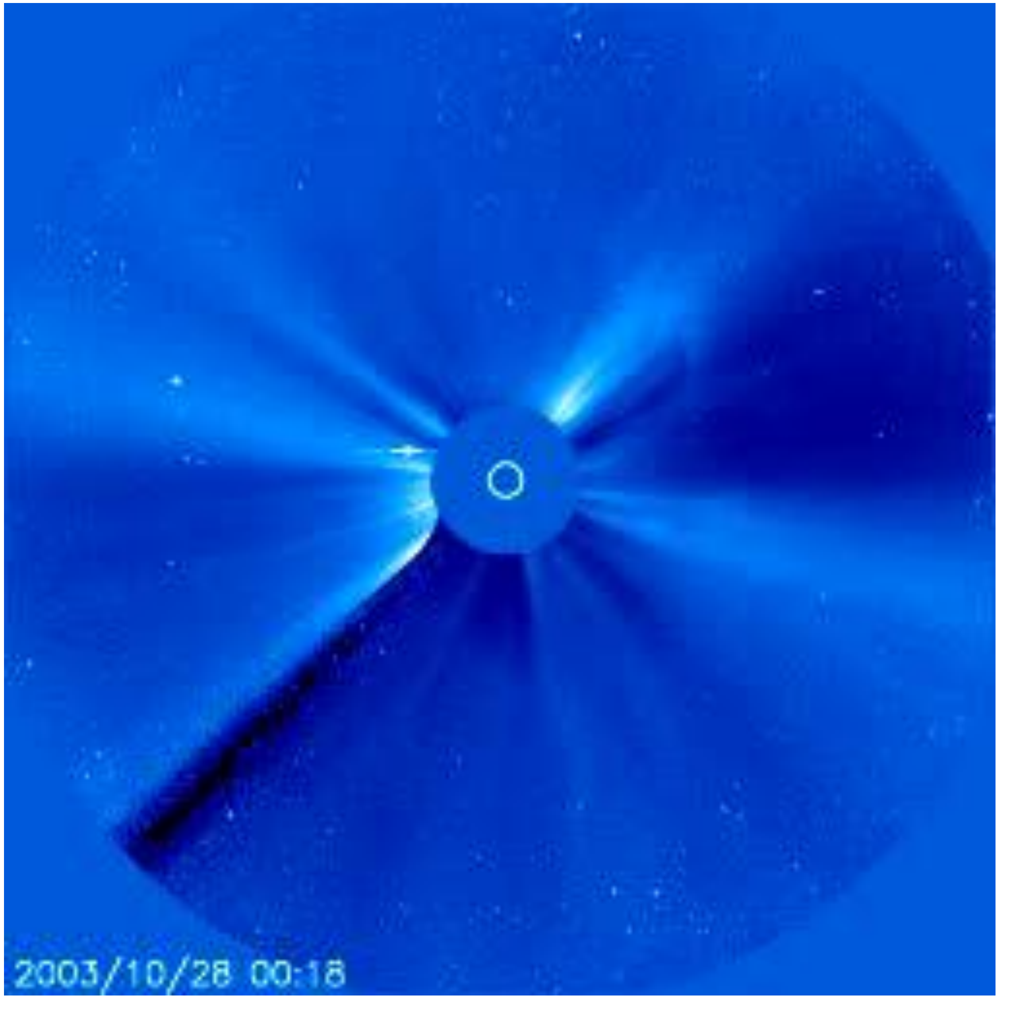


1868: Janssen & Lockyer demonstrated that prominences could be viewed outside of eclipses using spectroscope

1871: Secchi classified active and quiescent prominences
Prominence eruptions with speeds exceeding 100s of km/s became well known (Fenyi, 1892)

A big CME that affected Earth in 2003

SOHO coronagraph movie showing two CMEs

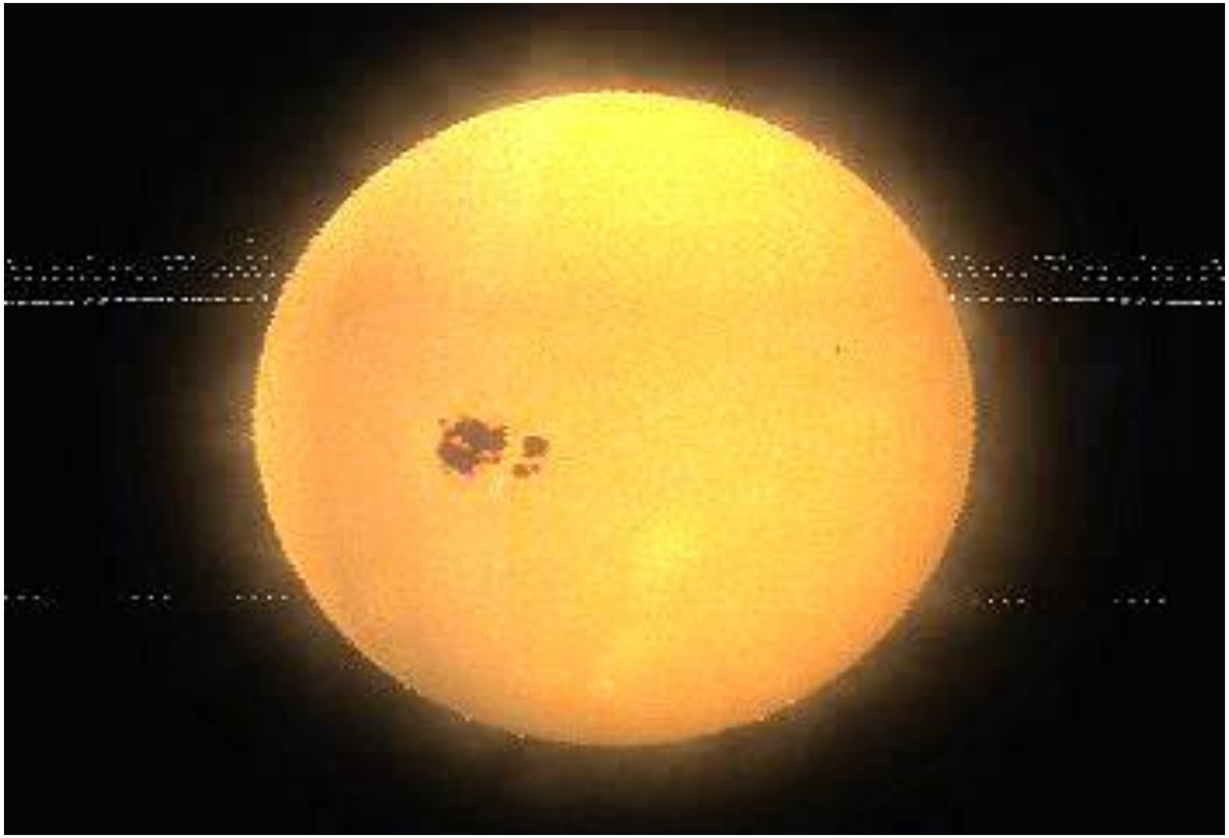


Solar Wind

Plasma Ejected from the Sun
(Coronal Mass Ejections – CMEs)

Energetic Particles

Animation of Halloween 2003 CMEs



Consequences of the CMEs were observed at Earth, Jupiter, Saturn and even at the edge of the solar system where the Voyagers were located. The CMEs took 6 months to reach the termination shock.

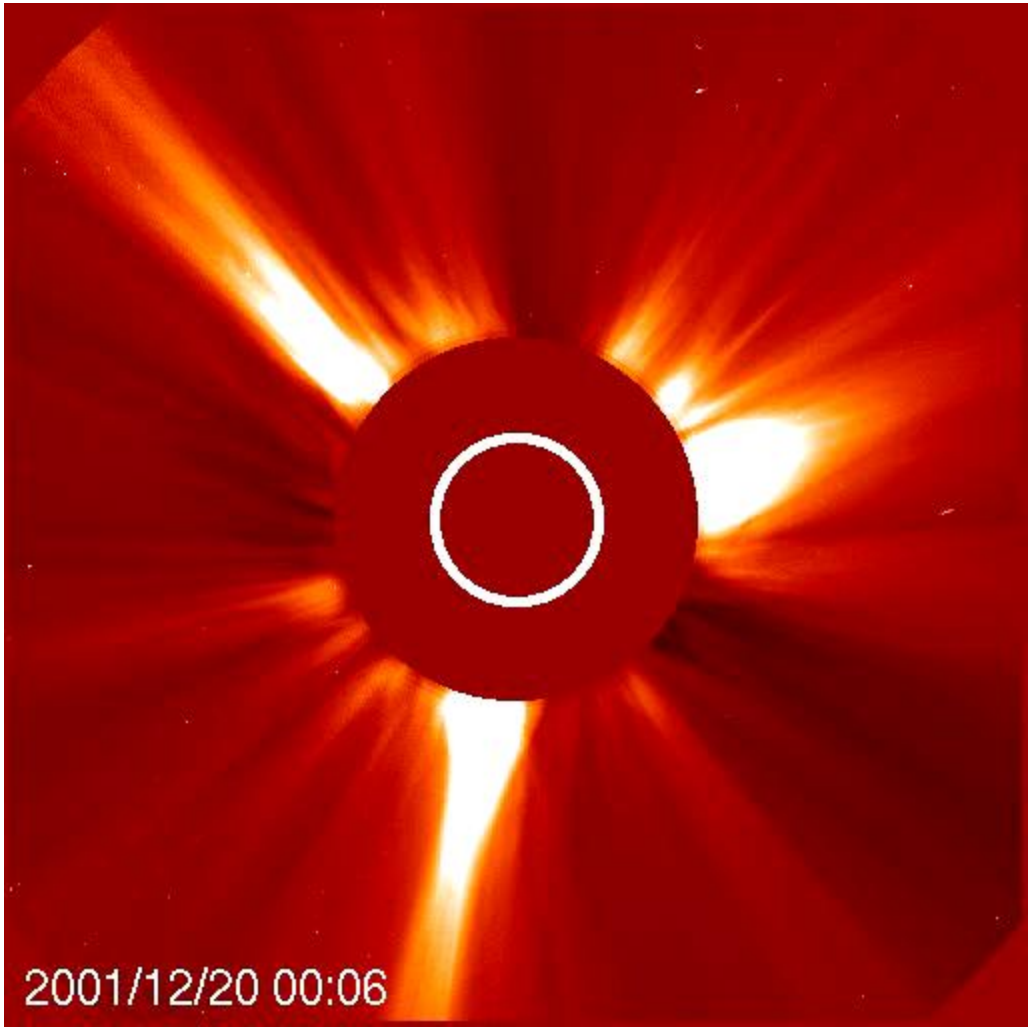
CMEs represent the most energetic phenomenon in the heliosphere

What is a CME?

CME can be defined as the outward moving material in the solar corona which is distinct from the solar wind

This image shows three main CMEs from The solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO)

SOHO Coronagraph movie

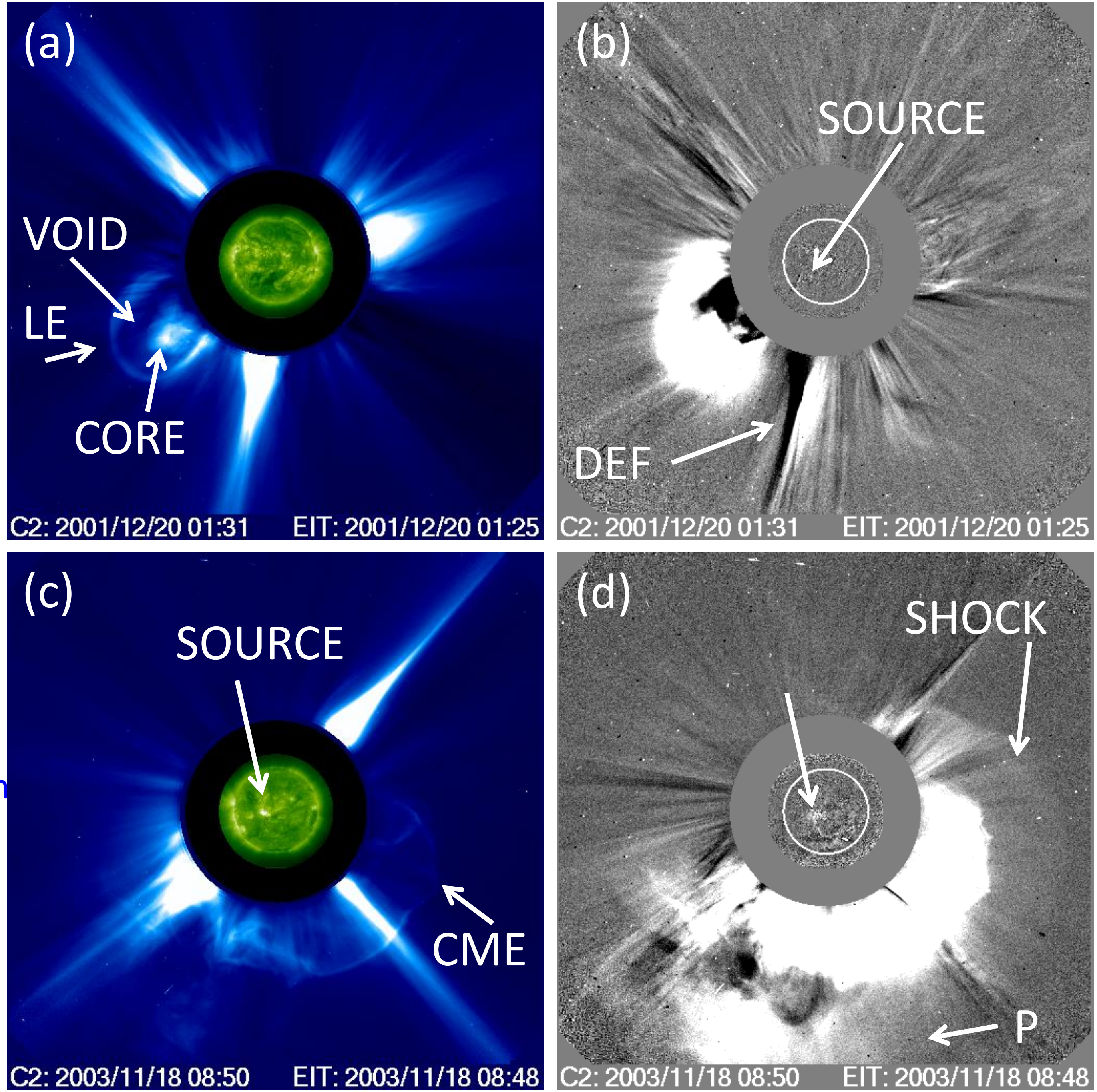


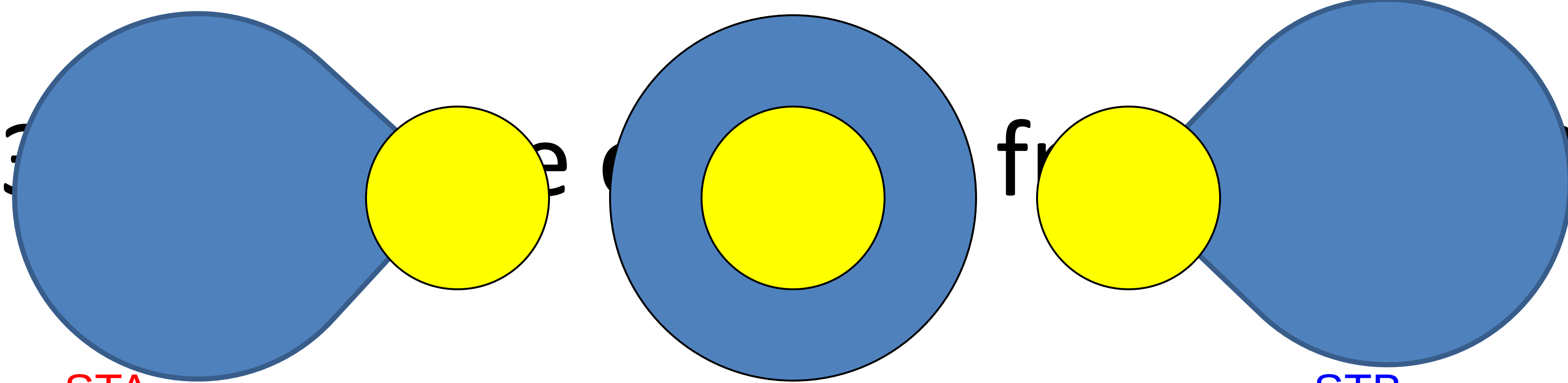
Morphological Properties

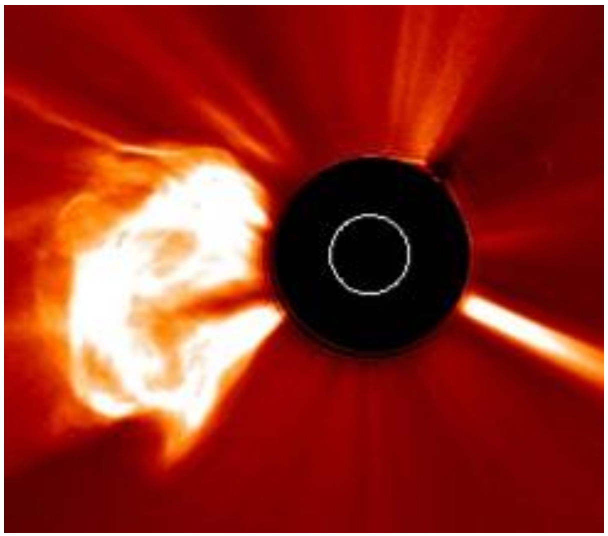
CMEs have spatial structure:
bright front, dark void, & prominence core

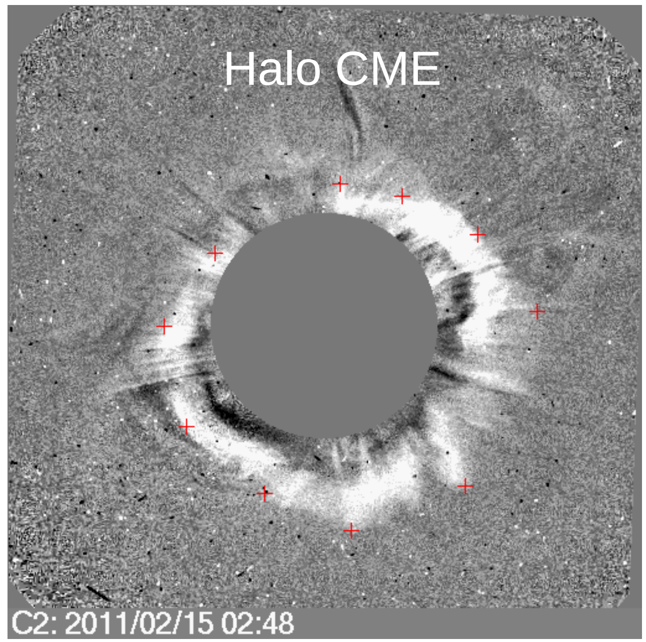
When the CMEs are fast, they drive fast mode MHD shock

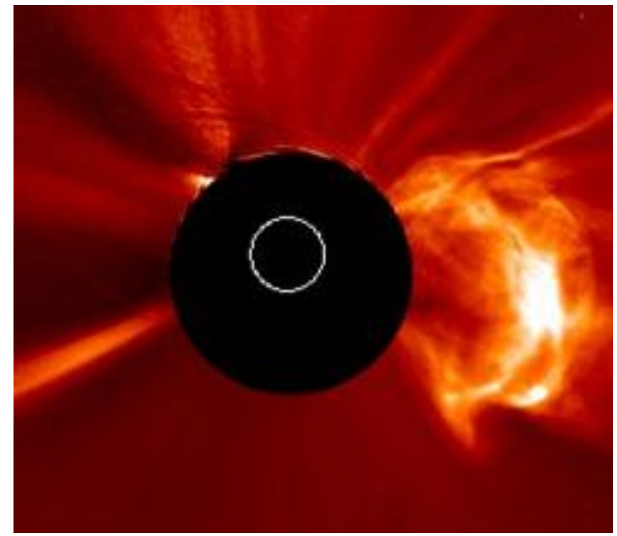
The shock can accelerate particles and produce sudden commencement when arriving at Earth





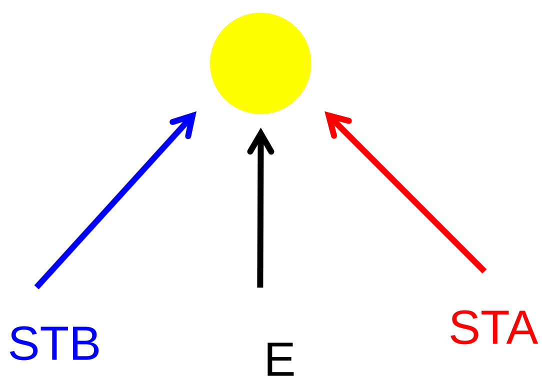






Limb CME

Limb CME



3-D Structure of CMEs: look like a balloon as is clear from three views

STEREO-A & B and SOHO coronagraphs

Physical Properties

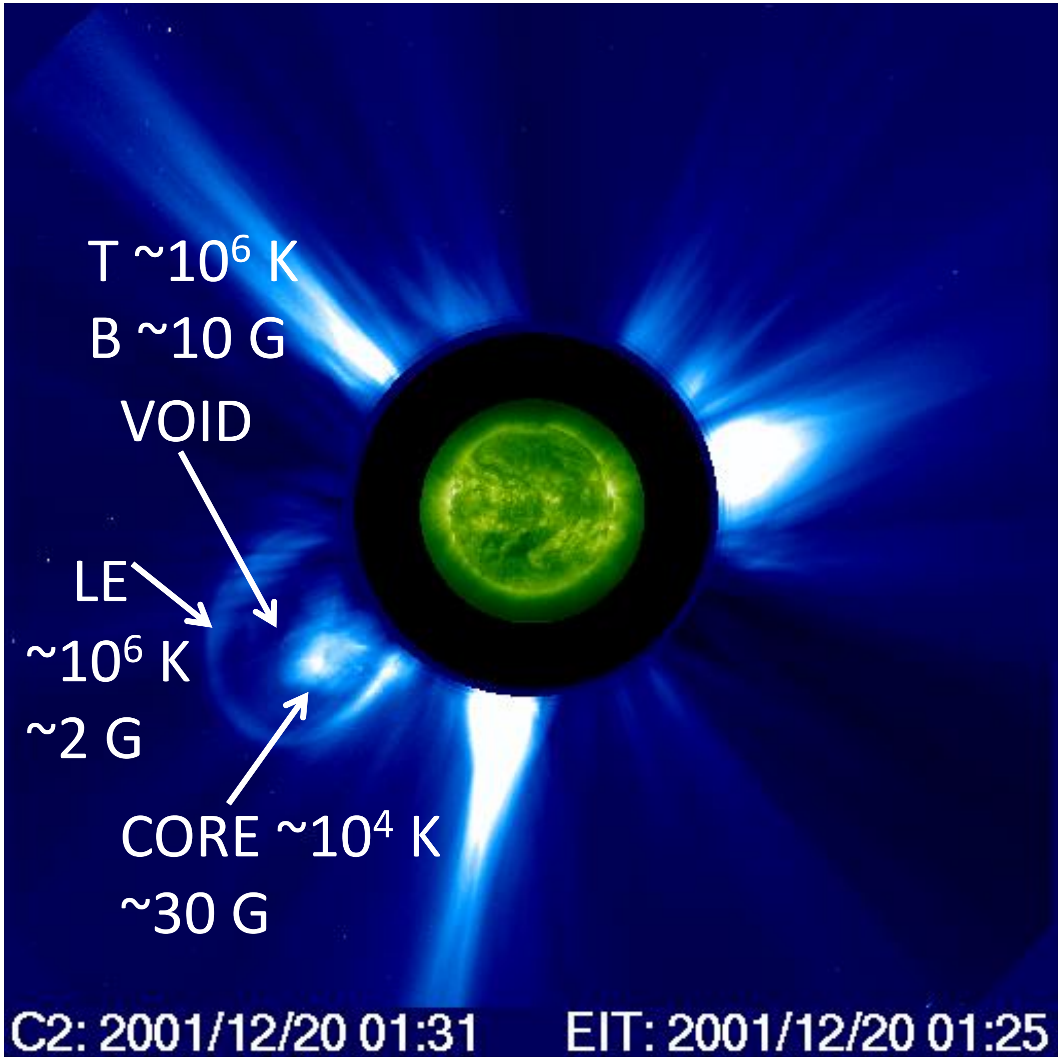
Three-part structure
Illing & Hundhausen, 1986

Four-part structure when shock driving

The bright front is thought to be material compressed by the flux ropes (dark void). Both are at coronal temperature but they have different densities

temperature and densities of various structures are shown

Coronagraph image + EUV image combined



Kinematic Properties

- Based on height-time measurements of CMEs at the leading edge.
- The measurements refer to the sky plane, so they may be subject to projection effects
- Linear fit to the height-time data points gives average speed within the coronagraphic field of view
- Quadratic fits give acceleration

Basic Attributes of a CME:

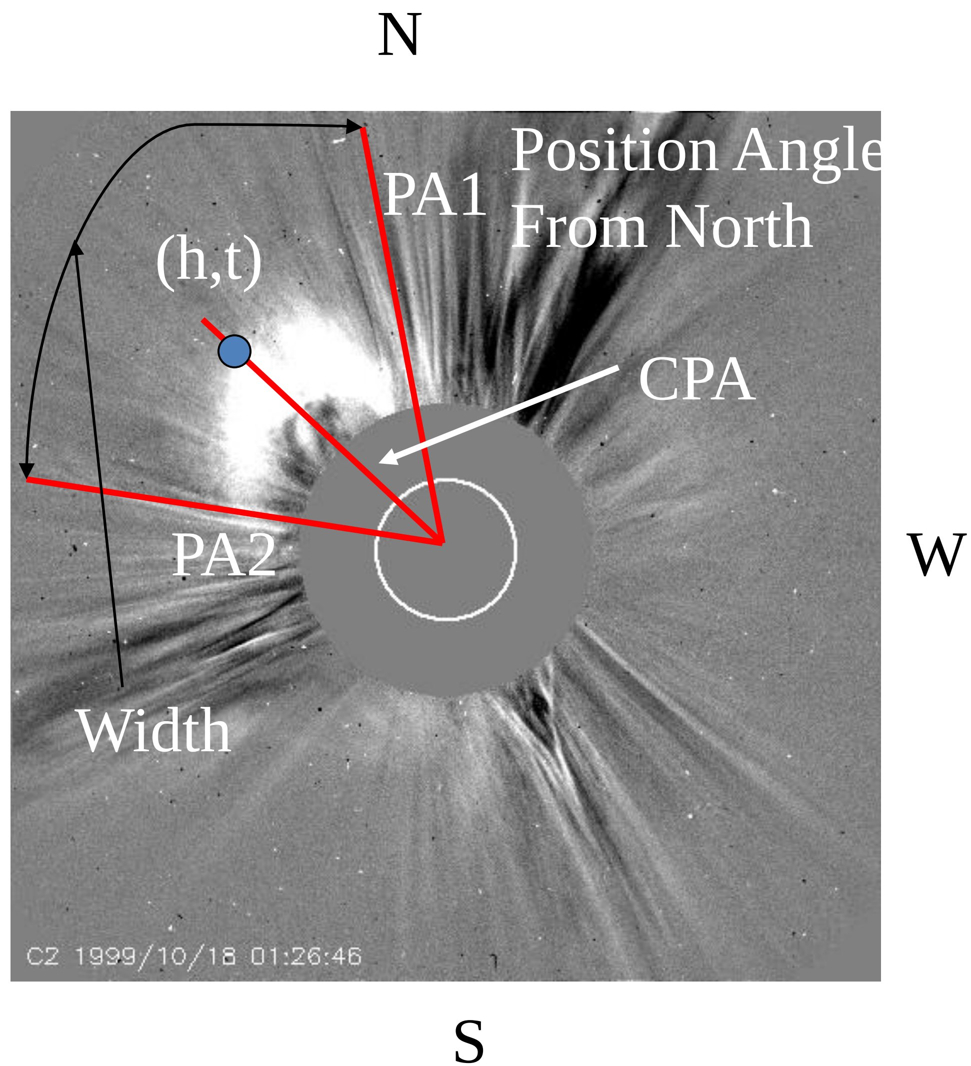
Speed, Width & CPA

Base Difference: $F_n - F_o$
Running Difference: $F_n - F_{n-1}$
F_n, F_{n-1}, F_o are images at times t_n , t_{n-1} and t_o

CPA = Angle made by CME apex with Solar North

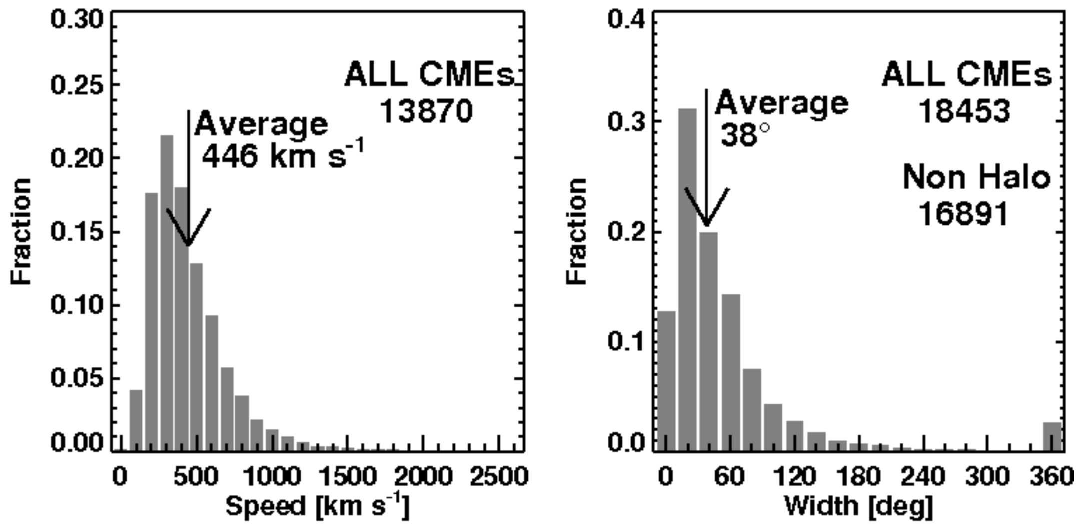
Width = PA2 – PA1

Speed = dh/dt
Acceleration = d^2h/dt^2

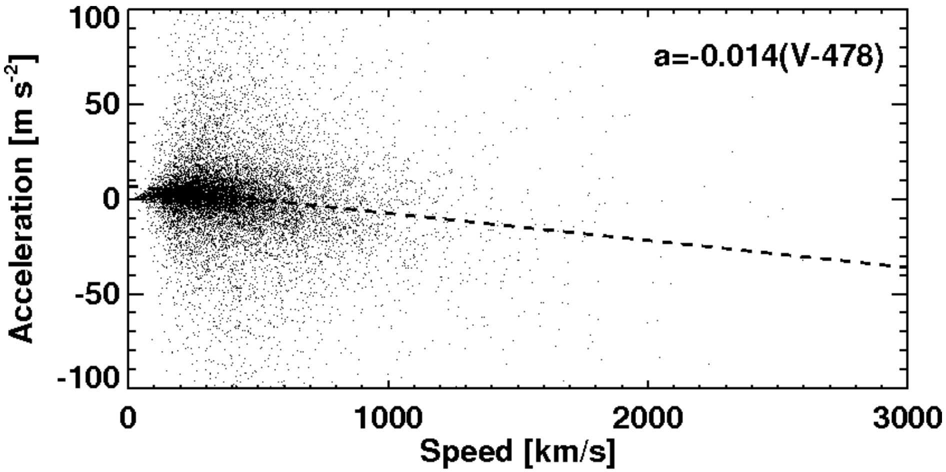


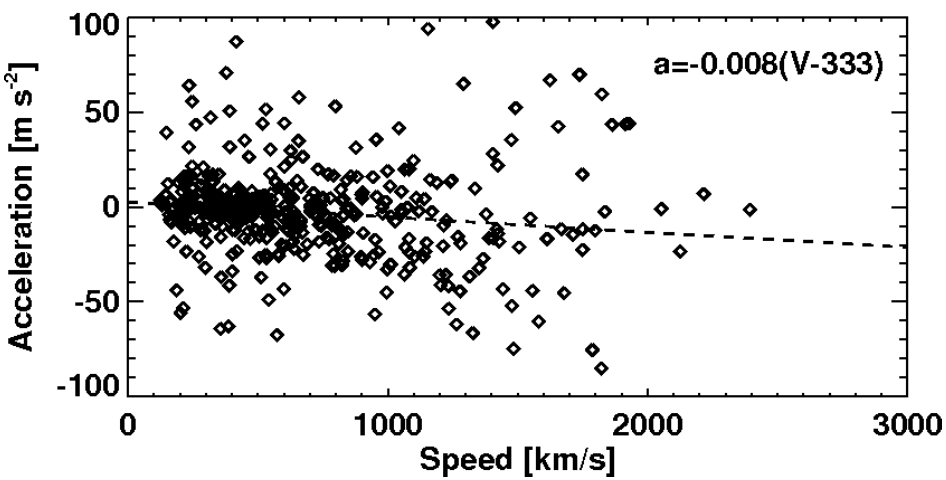
In the exercise session you will measure the speed and width of two CMEs

Kinematic Properties: Speed & Width



Acceleration in LASCO C2/C3 FOV





The measured acceleration is a combination of accelerations due to the propelling force, gravity, and aerodynamic drag.

$a = a_p - a_g - a_d$

In the SOHO coronagraph, the measurements are made beyond 2.5 solar radii

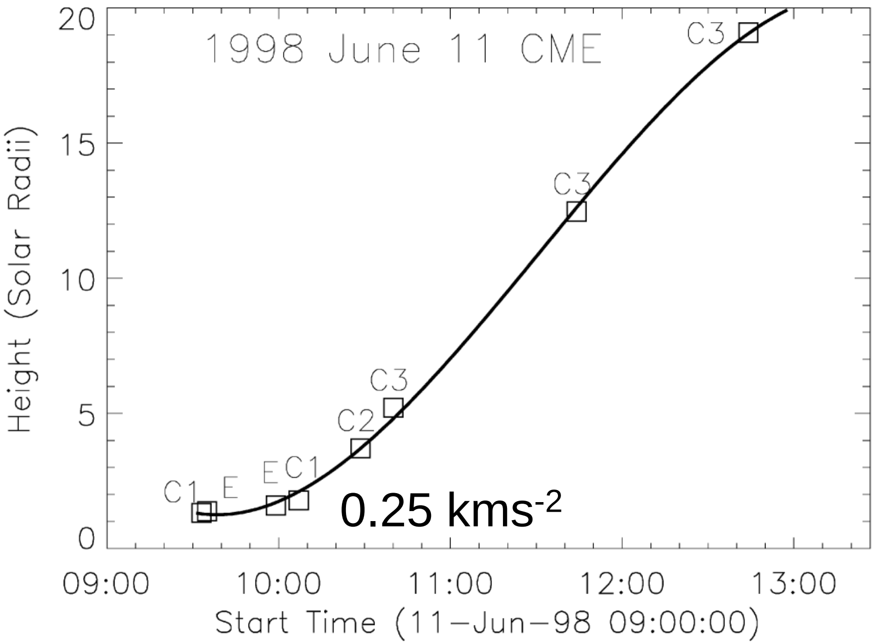
By this distance a_p and a_g are weakened significantly

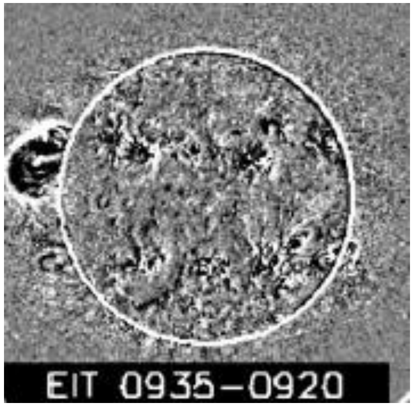
So, the measured acceleration is therefore mostly due to aerodynamic drag:
$a = - a_d$
and is referred to as residual acceleration

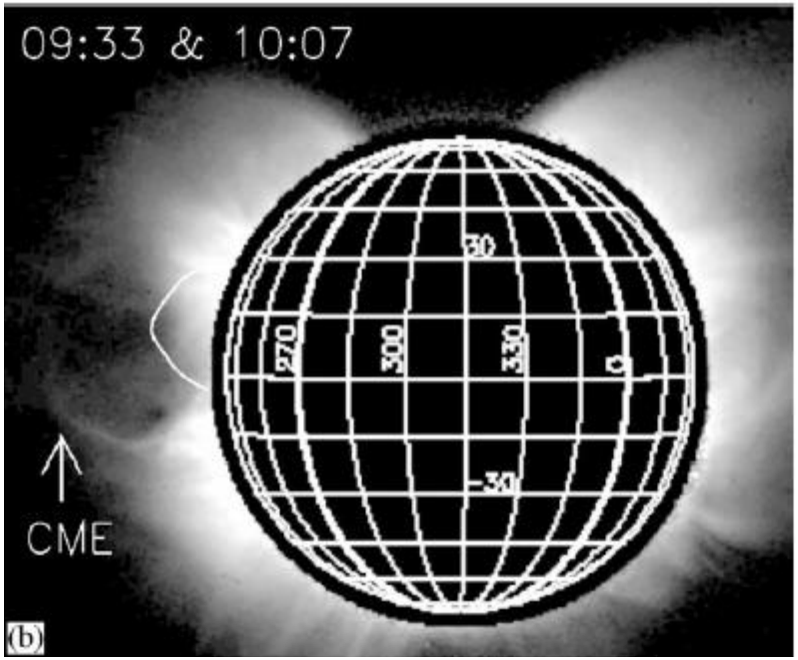
a_p can be 2-3 orders of magnitude higher than the residual acceleration.

Acceleration from LASCO C1, EIT

Gopalswamy & Thompson 2000





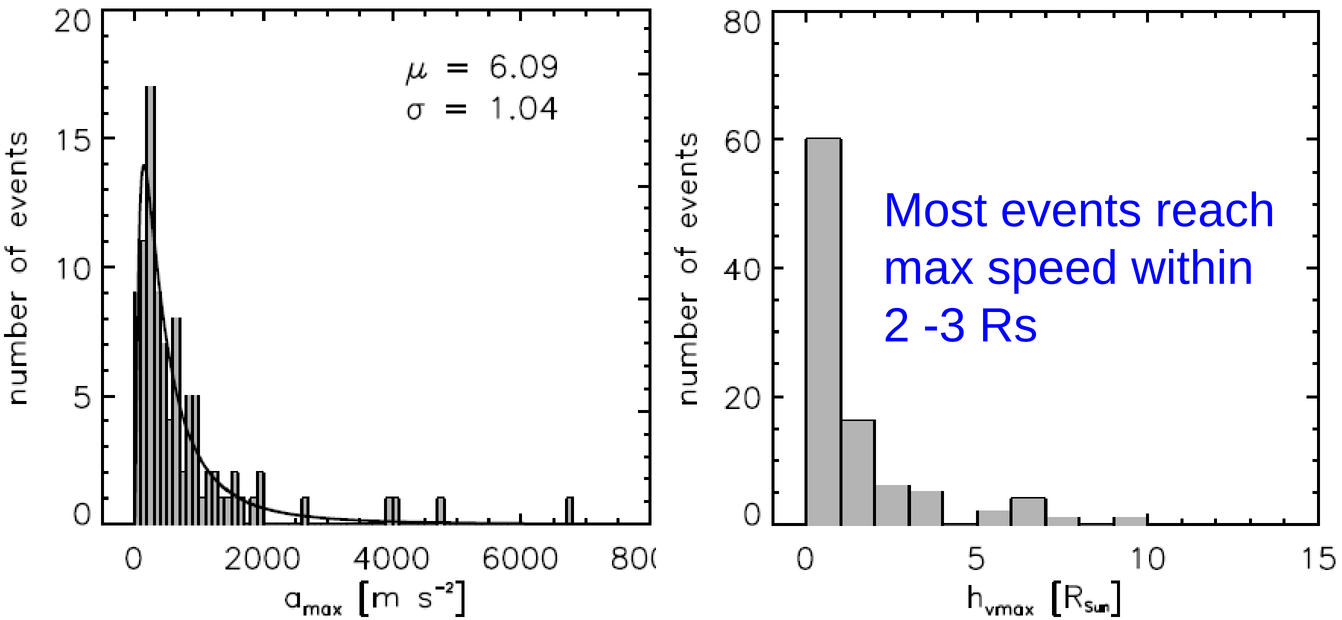


$h = 3.1 – 0.1t + 1.5\times10^{-3}t^2 – 3.4\times10^{-6}t^3$

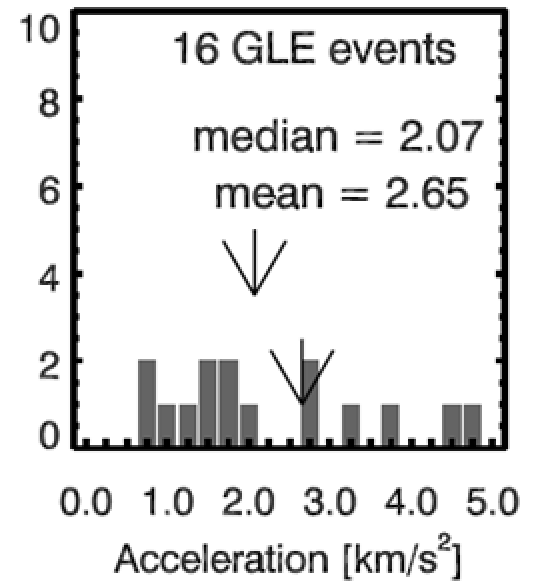
Before June 1998, SOHO had inner coronagraph that measured CMEs close to the surface. The height-time measurement can be fit to a 3rd order polynomial indicating early acceleration and later deceleration (a_p = 0.25 kms^{-2} and residual acceleration = -36 ms^{-2})

Initial Acceleration of CMEs

Bein et al., 2011



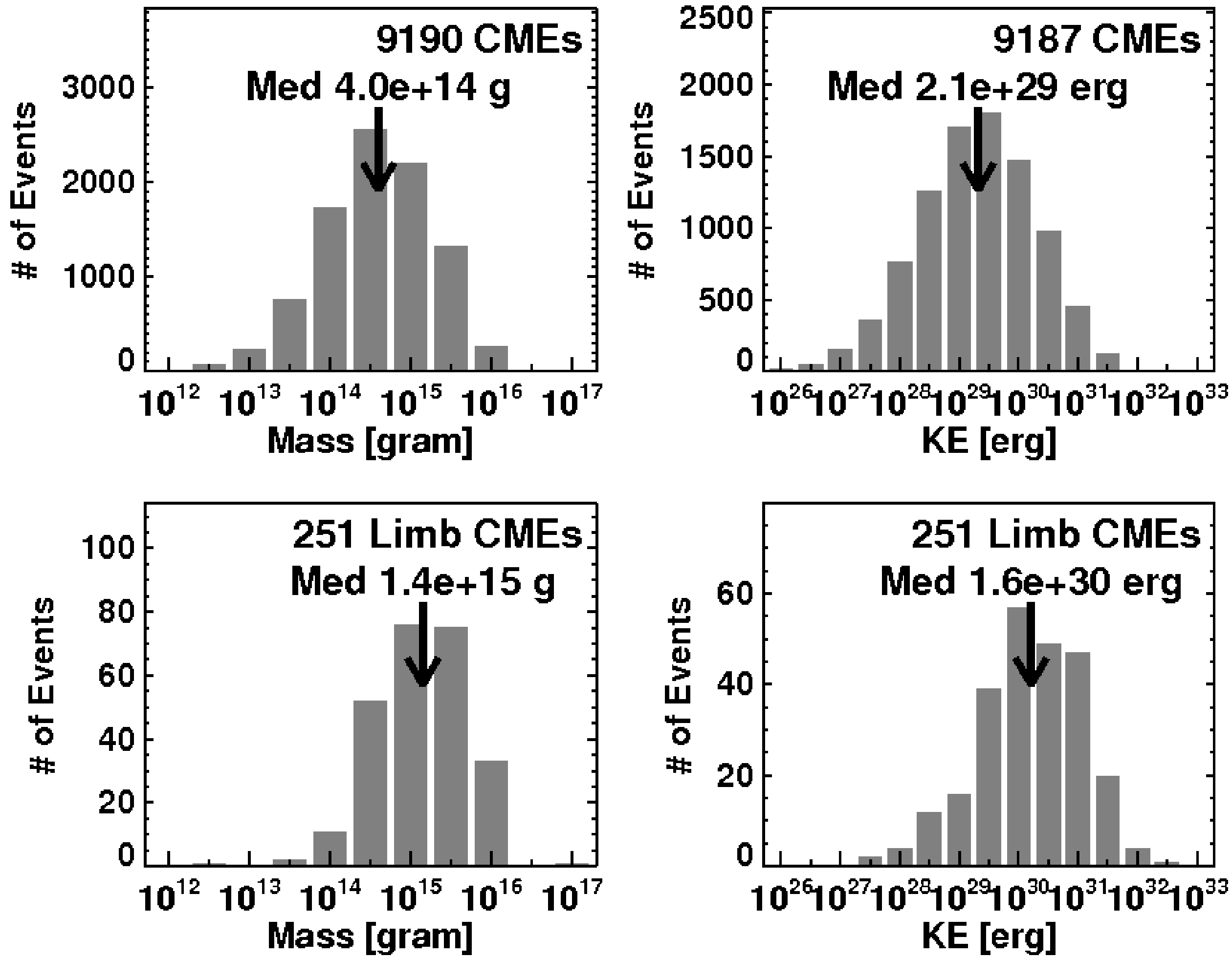
Gopalswamy et al. 2011



- STEREO/EUVI COR1
- 95 CMEs
- a_{max}: 0.02 to 6.8 kms^{-2}
- Height at Vmax: 1.17 to 11 Rs

- Ultrafast CMEs
- CME acceleration = Flare acceleration
- a: 0.5 to 7.5 kms^{-2}

Mass & Kinetic Energy



The CME mass can be determined from the excess brightness due to the CME and how many electrons are needed to produce this brightness. Once the mass and speed are known, the CME kinetic energy can be determined. Limb CMEs give the true distribution because they are not subject to projection effects

Solar Cycle Variation

- CMEs come from closed field regions on the Sun (e.g. Sunspot regions).
- CME speed and rate in phase with sunspot number (CME rate SSN are well correlated)
- There are exceptions especially during solar maximum phase
- Cycle 23 and 24 (when good CME observations are available) give details of this correlation

CME Rate & Speed (Rotation Averaged)

#CMEs per year
~10^3

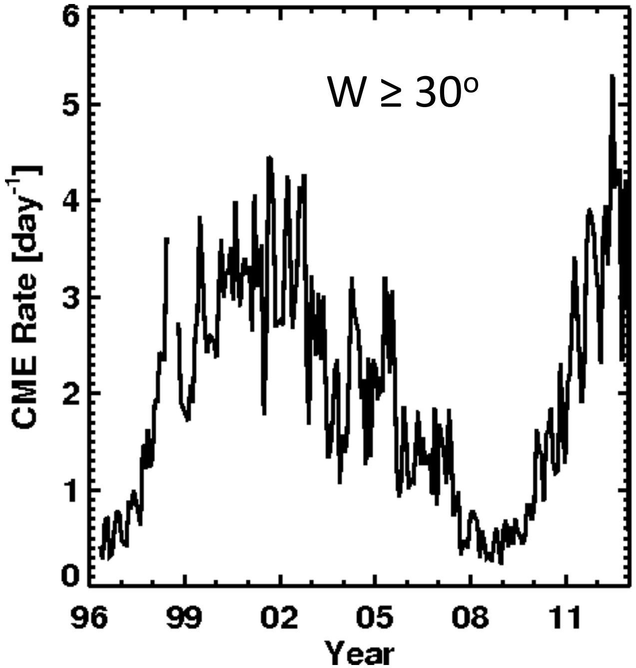
Mass per CME
~$4x10^{14}$ g

Mass loss due to CMEs
~$4x10^{14}$ kg.yr^{-1}
= $2x10^{-16}$ Ms. yr^{-1}

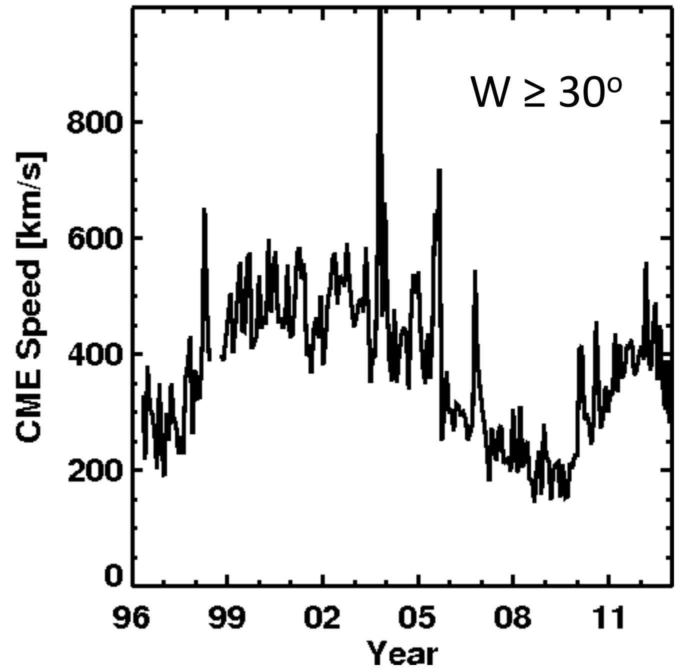
Solar wind mass loss:
~$2x10^{-14}$ Ms. yr^{-1}

During solar maximum, CME mass loss up to 10% of solar wind flux

Daily Rate



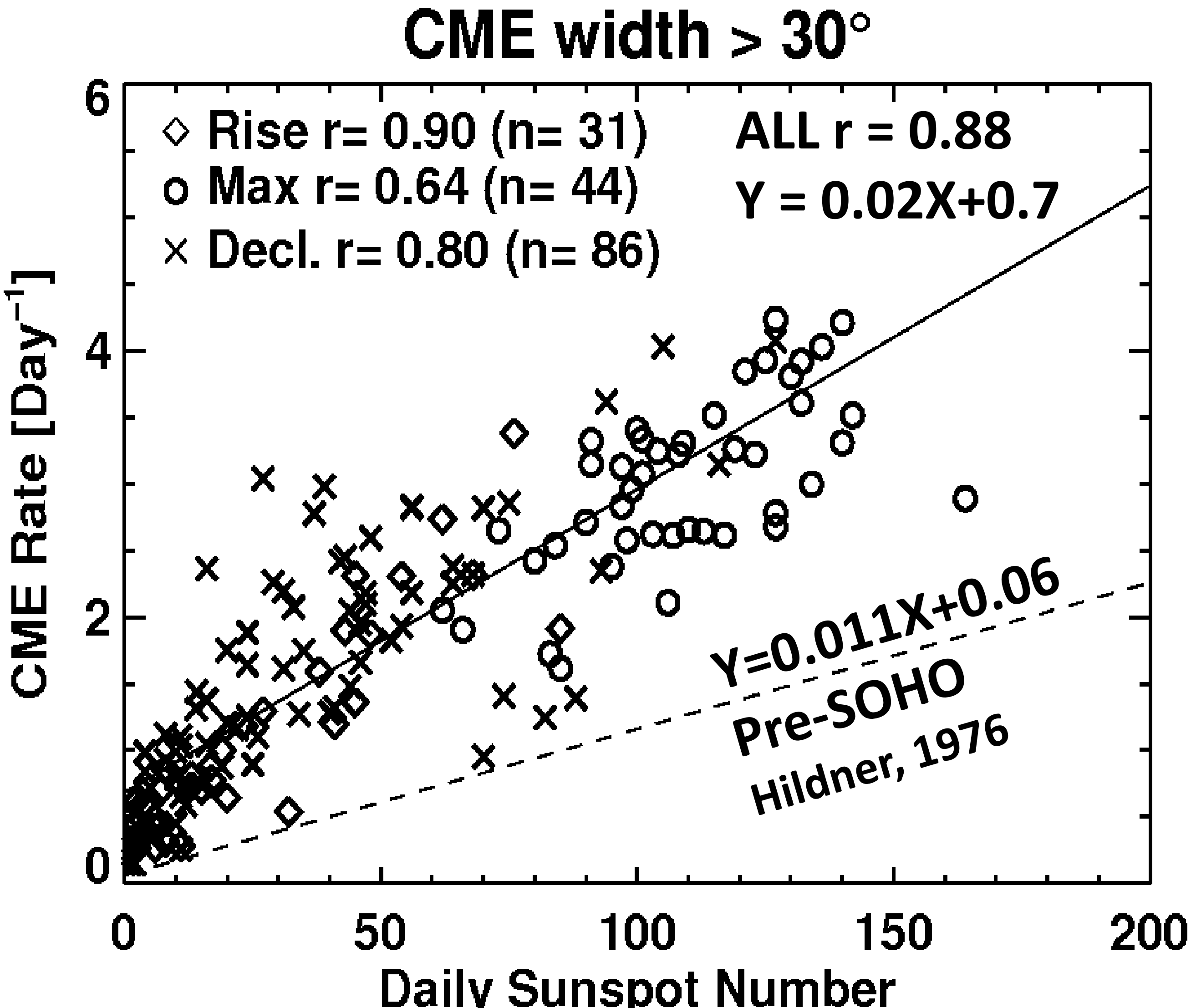
Average CME speed



The rate is ~0.5 per day during the solar minimum and exceed ~4 per day during solar maximum

The CME speed also varies with solar cycle: CMEs are generally faster during solar maxima

CME Rate well correlated with SSN

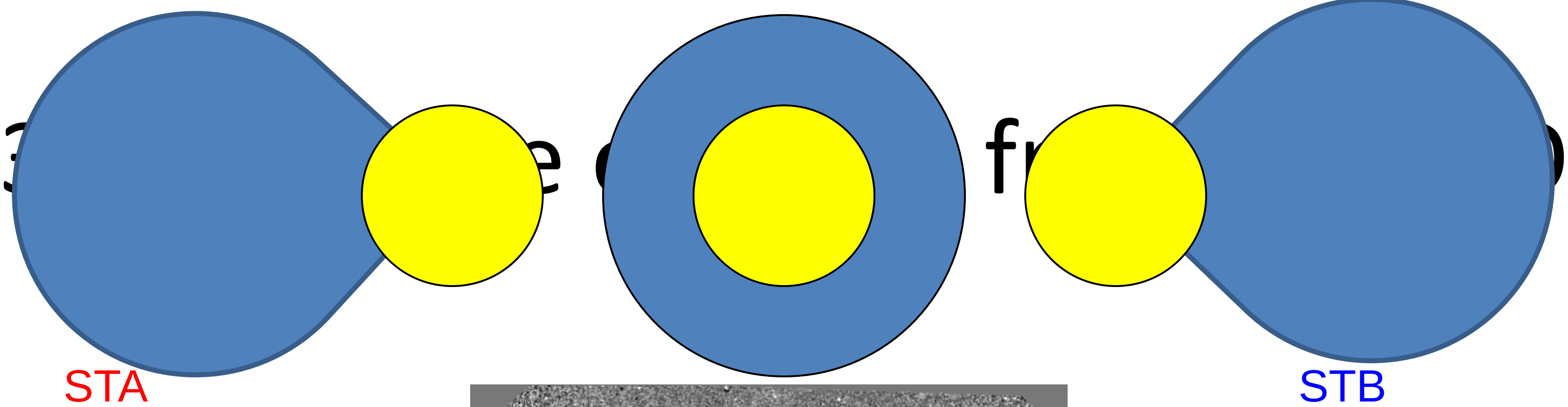


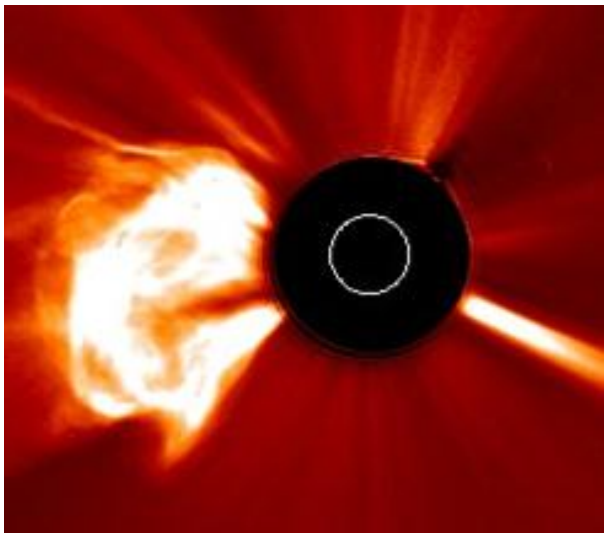
Weaker correlation during maximum phase: CMEs from outside sunspots – Polar crown filaments

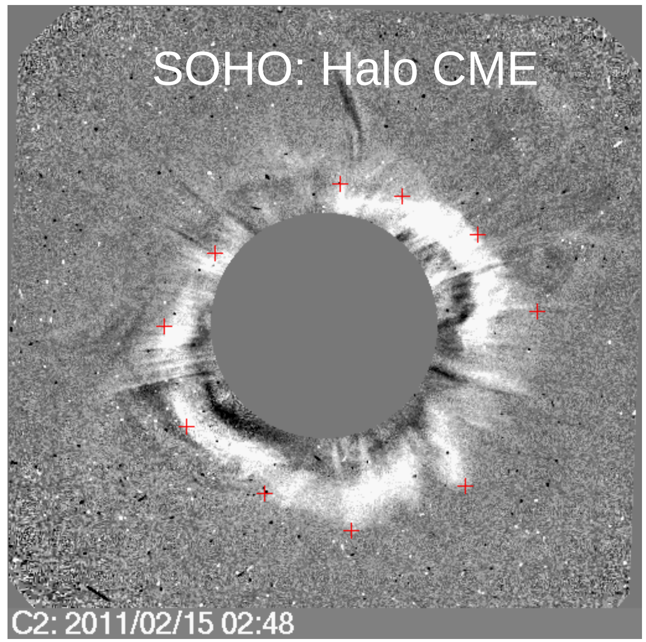
The pre-SOHO (SMM, Solwind) data indicate a smaller slope because of the lower sensitivity and smaller field of view compared to the LASCO coronagraphs.

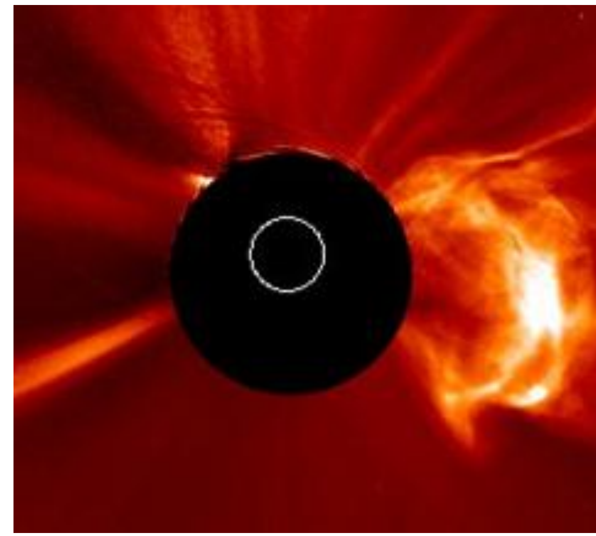
Halo CMEs

- CMEs that appear to surround the occulting disk in sky-plane projection
- No different from other CMEs, except that they must be faster and wider on the average to be visible outside the occulting disk
- Halos affect a large volume of the corona
- Most of the halos may be shock-driving
- Halos can be heading away or toward Earth. Those heading toward Earth are important for space weather



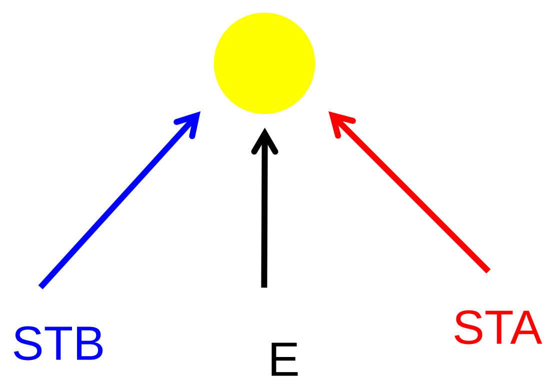






Limb CME

Limb CME

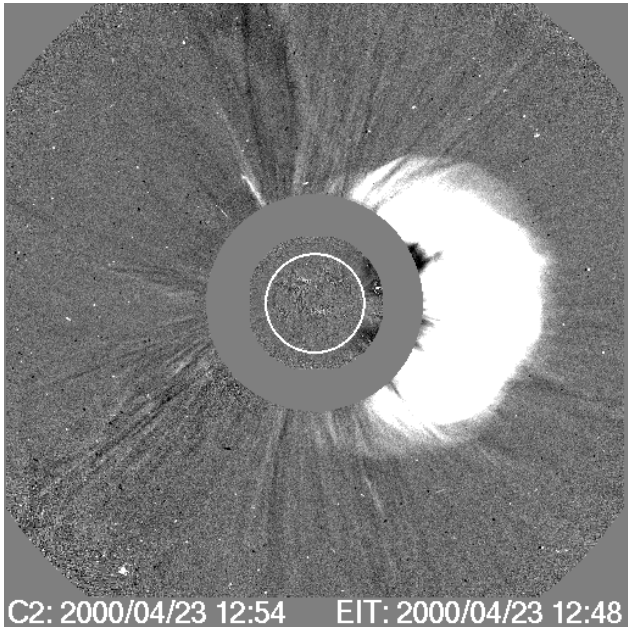


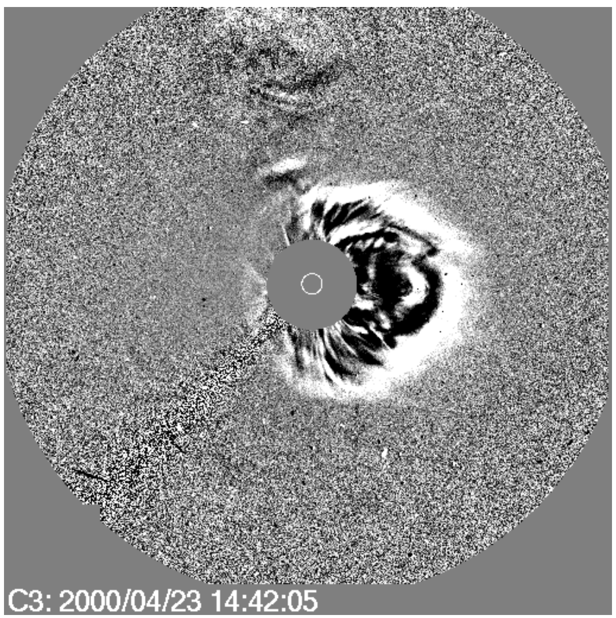
3-D Structure of CMEs

Simultaneous STEREO and SOHO observations demonstration that halo CMEs are normal CMEs

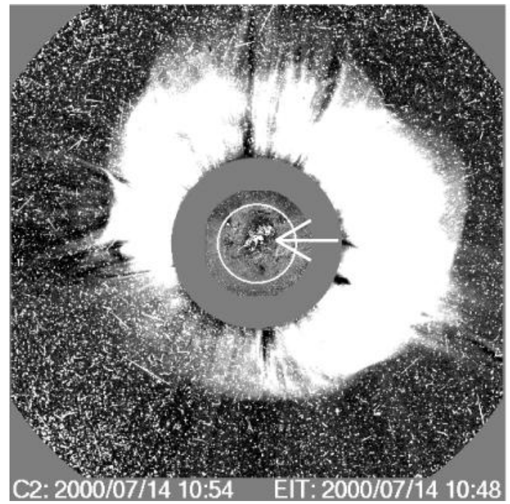
Halo CMEs

Halo CMEs, discovered in Solwind data (Howard et al. 1982), have been recognized in the SOHO era as an important subset relevant for space weather (Gopalswamy et al., 2010)

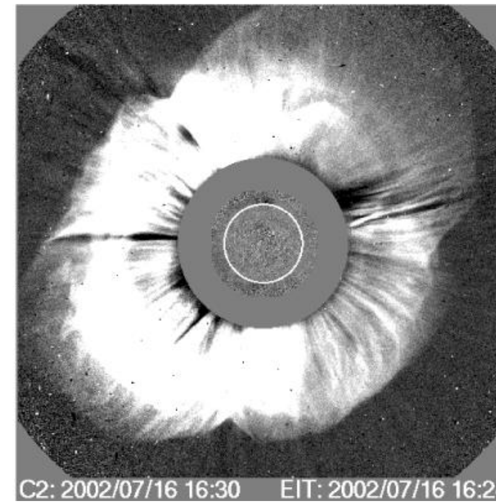




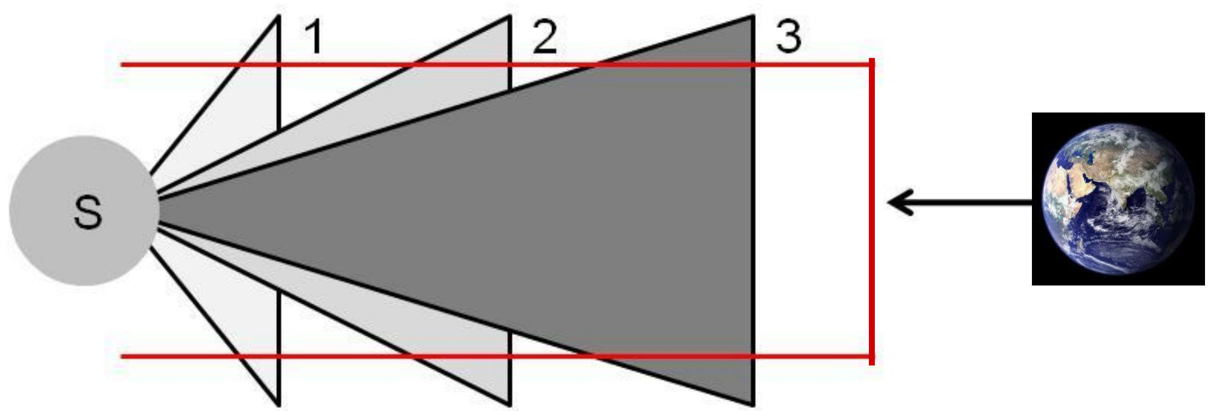
Partial halo becomes asymmetric halo



Front-side halo



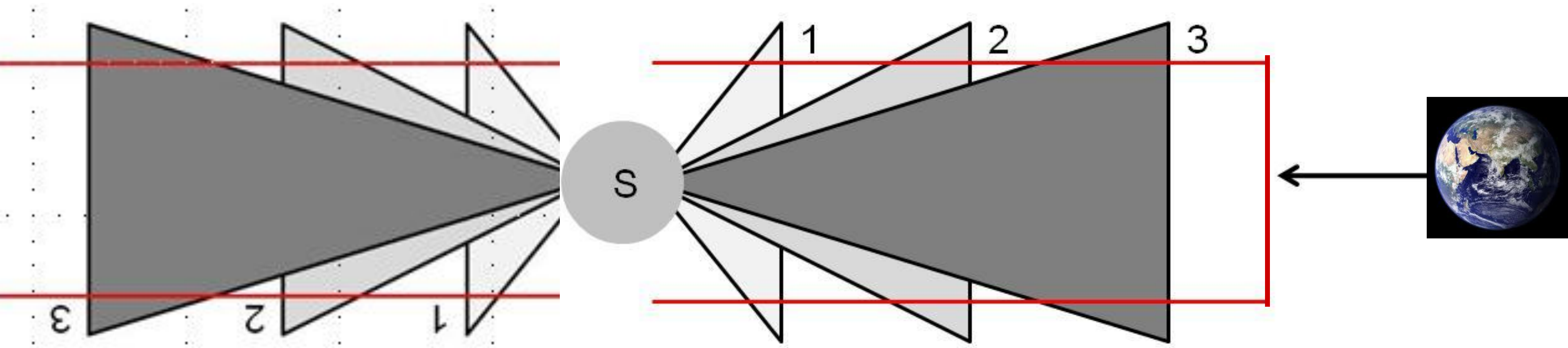
back-side halo



Halo CMEs are generally wide

The three cones 1, 2, 3 represent 3 CMEs

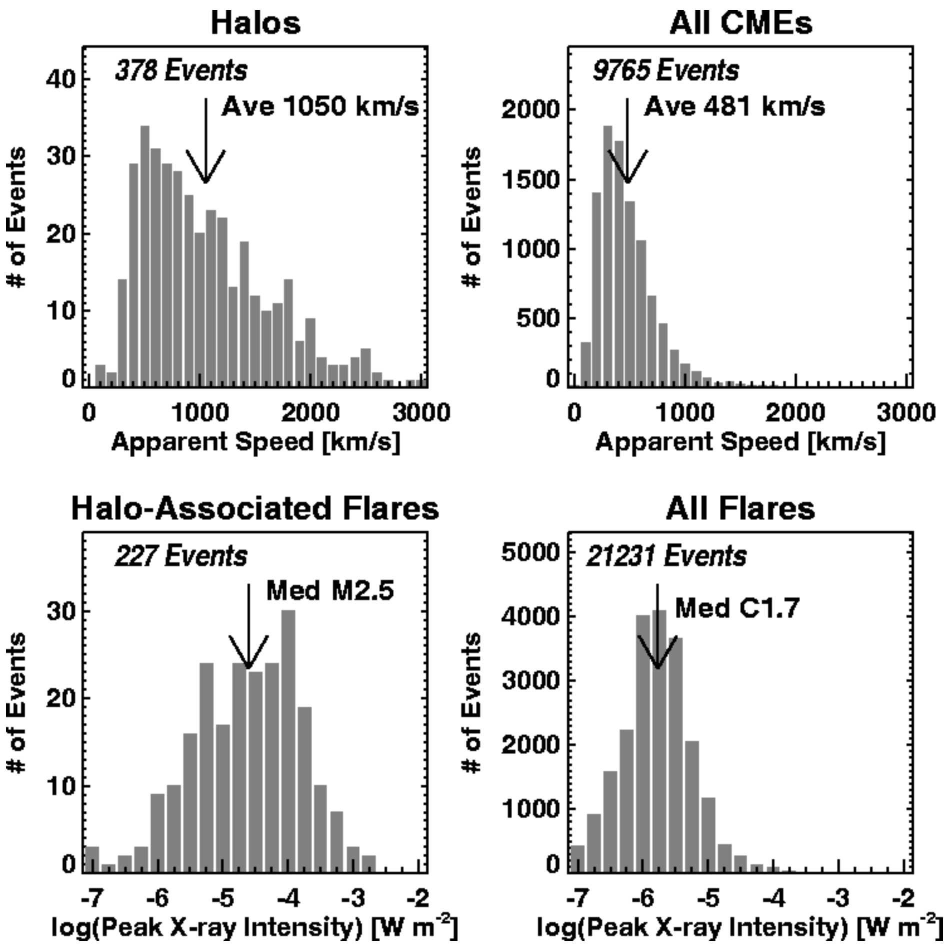
Frontside halos (earth-directed)

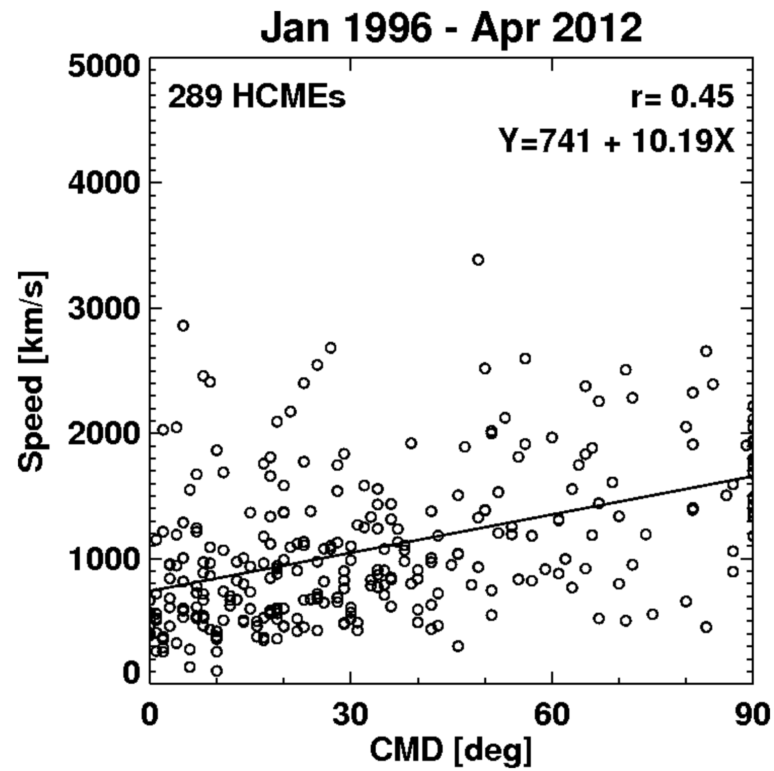


backside halos
(anti-earthward)

Portions outside the red lines appear as halos
1, 2, 3 represent three CMEs with decreasing widths. 1 will appear as halo immediately. 3 has to travel a long distance before appearing as halo. Some may never become a halo or fade out before becoming a halo.

Halo CME Properties





Only ~3.5% of all CMEs are halos

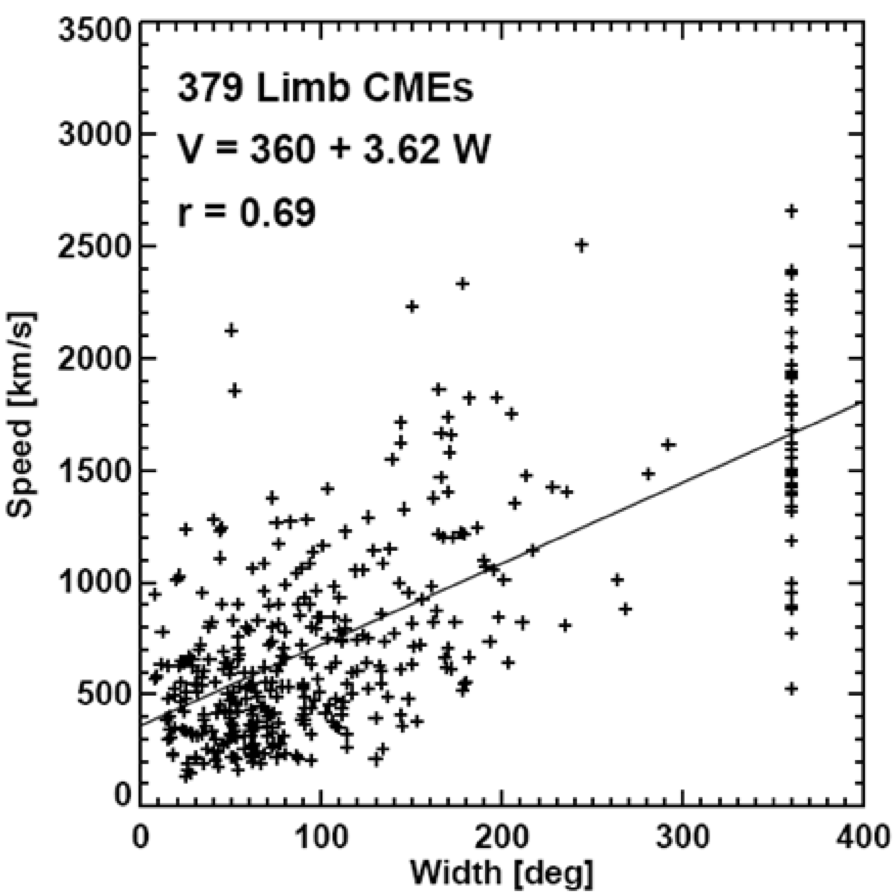
Halos are ~ 2 times faster than the average CME (halo CMEs are subject to large projection effects)

Flares associated with halo CMEs are larger

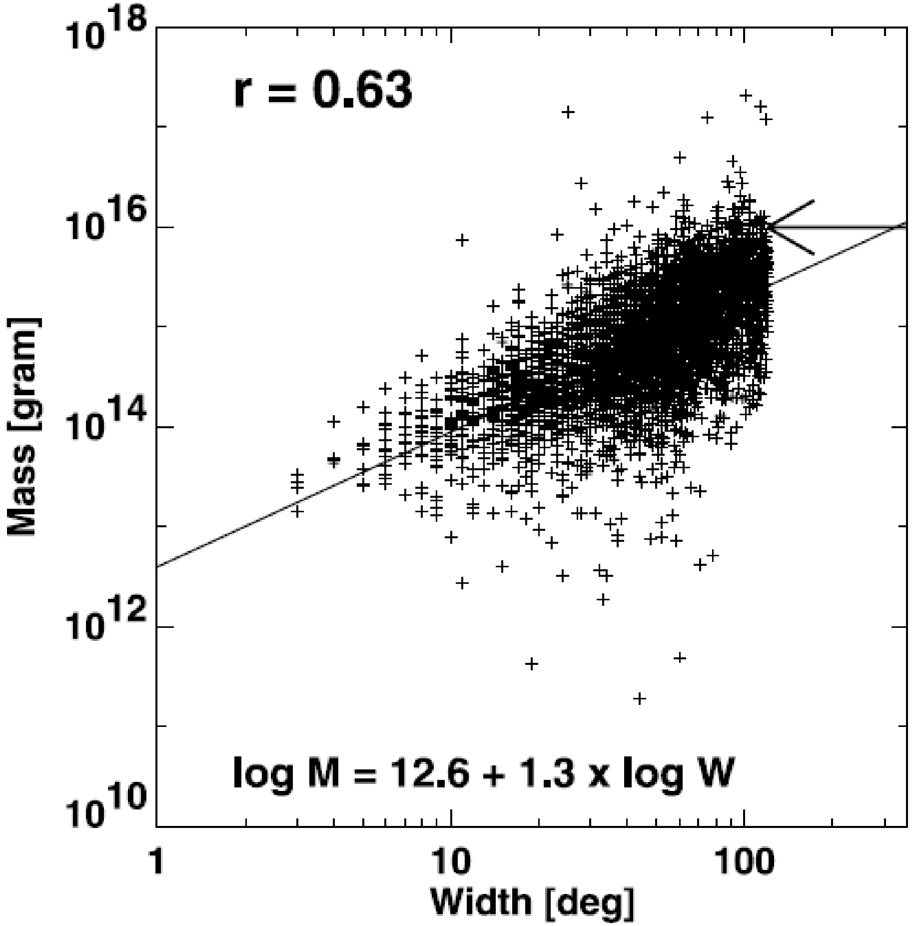
Higher kinetic energy: travel far into the interplanetary medium and impact Earth

Faster and Wider CMEs are More Energetic

Wider CMEs are faster



Wider CMEs are more massive



Halo CMEs are more energetic

Fraction of halos is a measure of the energy of a CME population

Halo Fraction of Some CME Populations

Table 1 Speed and width of the special populations of CMEs

	Halos	MCs	Non-MCs	Type IIs	Shocks	Storms	SEPs
Speed ($km\ s^{-1}$)	1,089	782	955	1,194	966	1,007	1,557
% Halos	100	59	60	59	54	67	69
% Partial halos	–	88	90	81	90	91	88
Non-halo width (°)	–	55	84	83	90	89	48

Gopalswamy et al. 2010

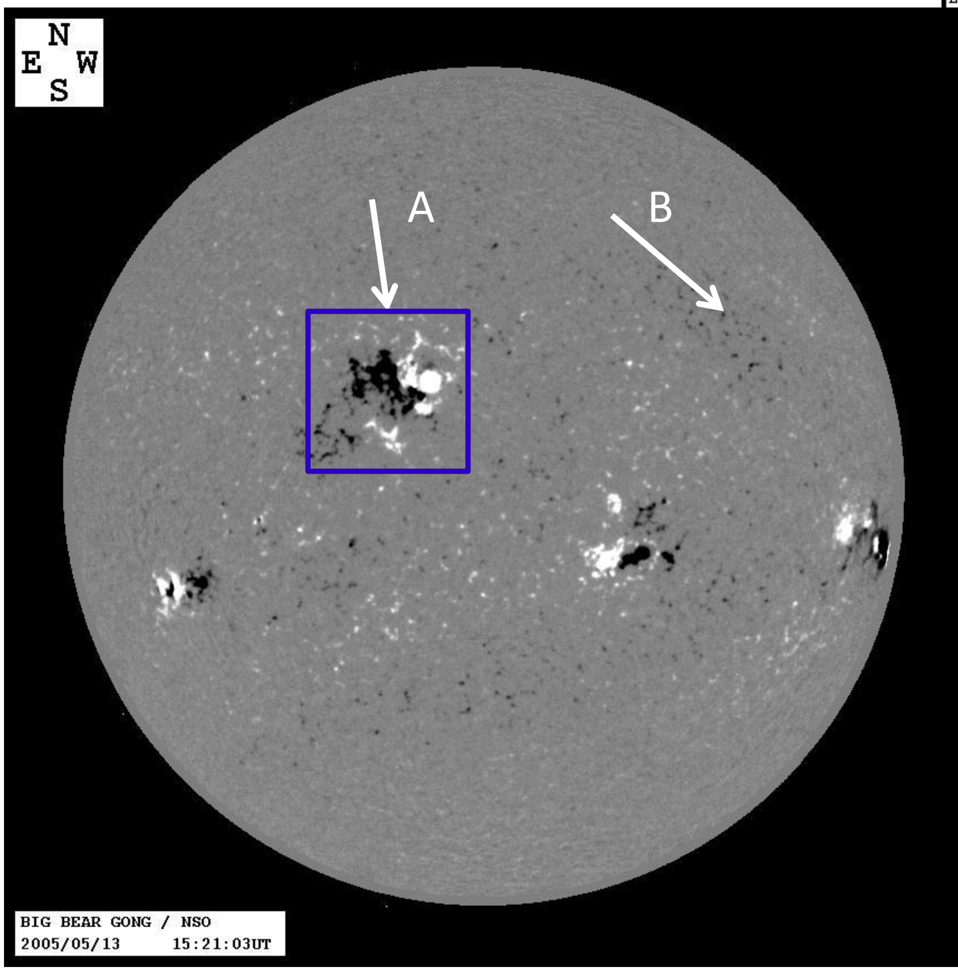
Solar Source Regions

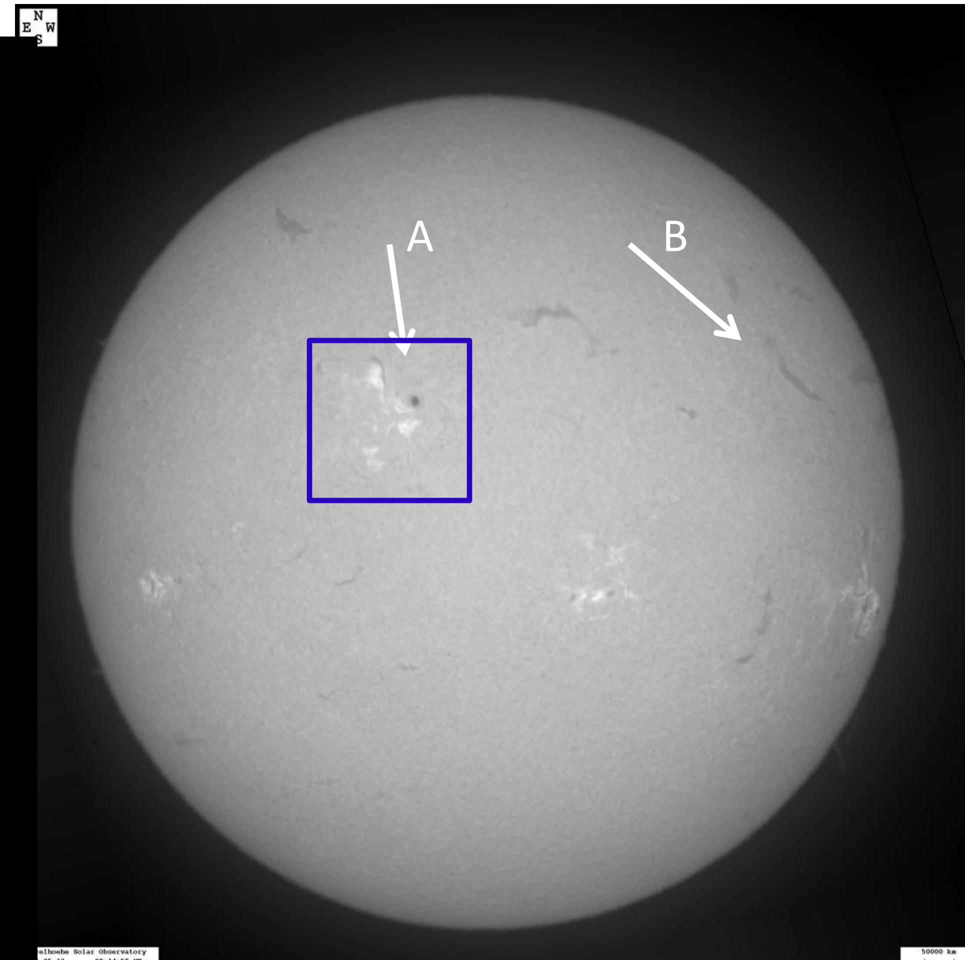
- CMEs originate from closed magnetic field regions (bipolar or multipolar configurations)
- Active regions
- Filament regions
- Loops connecting two active regions
- CME source regions are easily identified from the associated flare (close connection between CMEs and flares)

An Eruption Region

Photospheric Magnetogram

Chromosphere (H-alpha)





A: active region

B: Filament region (also bipolar, but no sunspots)

Both regions have filaments along the polarity inversion line

Part 2