Solar Eruptions: Flares & Coronal Mass Ejections

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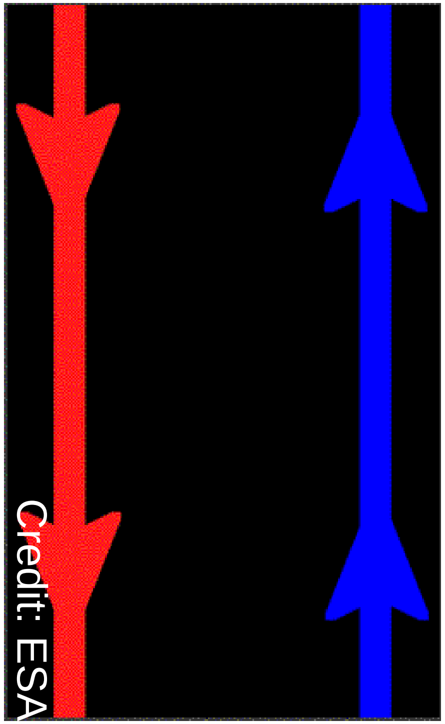
Overview

- Flares
- CMEs
- Flare CME relationship
- Summary

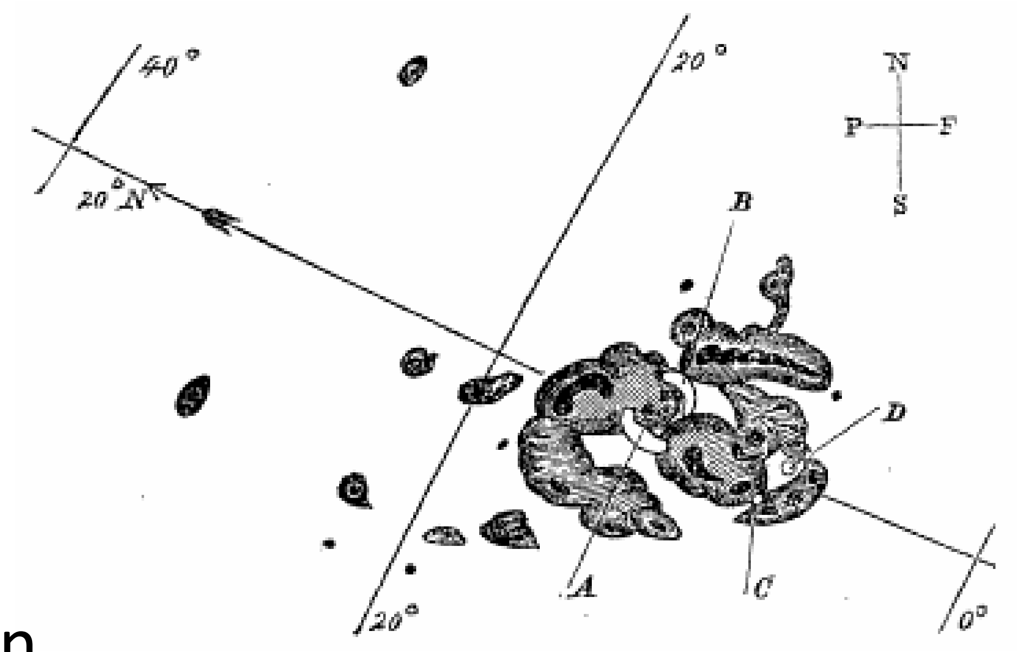
Solar Eruptions represent…

- Flares (enhanced electromagnetic emission)
- mass motion (coronal mass ejections, CMEs)
- Both are accompanied by particle acceleration
- electrons: radio emission, X-ray emission
- protons: gamma rays
- Solar Energetic Particles: detected in situ
- Acceleration mechanisms: reconnection (flares) & shock (CMEs)
- type III, type IV, type V: electrons from reconnection
- Type II bursts: electrons from shock acceleration
- radio bursts: diagnostic for the medium & agent



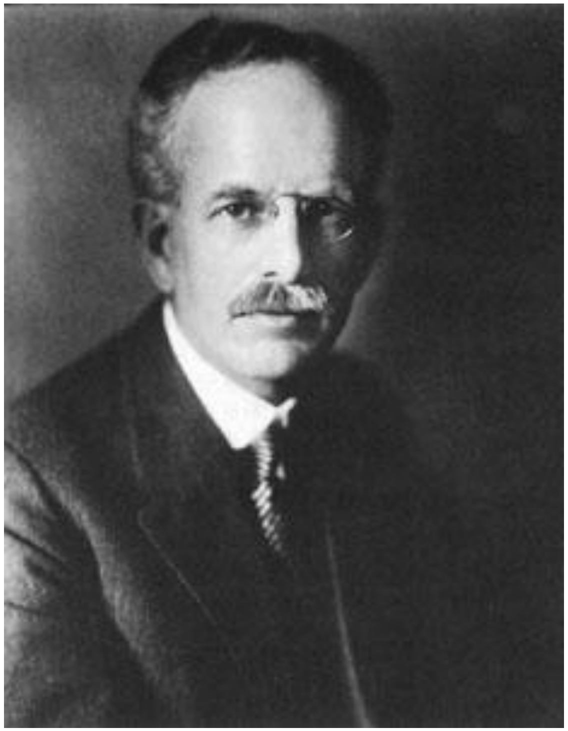
Discovery of Solar Flare

- September 1, 1859
- Independently observed by R. C. Carrington and R. Hodgson
- Magnetic storm commenced early on September 2



Drawing by Carrington

Solar Eruption and Space Weather



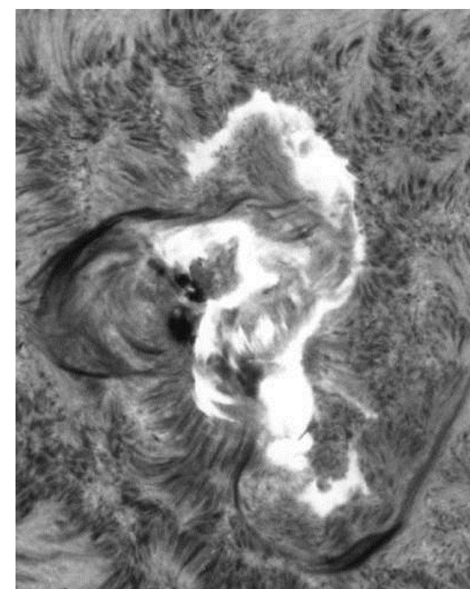
G E Hale 1868 - 1938

- Brought flares to central position via his paper in 1931:

"The spectrohelioscope and its work, Part II: Solar eruptions and their apparent terrestrial effects"

Astrophys. J. 73, 379, 1931

Big Bear Solar Observatory: 7 August 1972 Flare observed in H-alpha

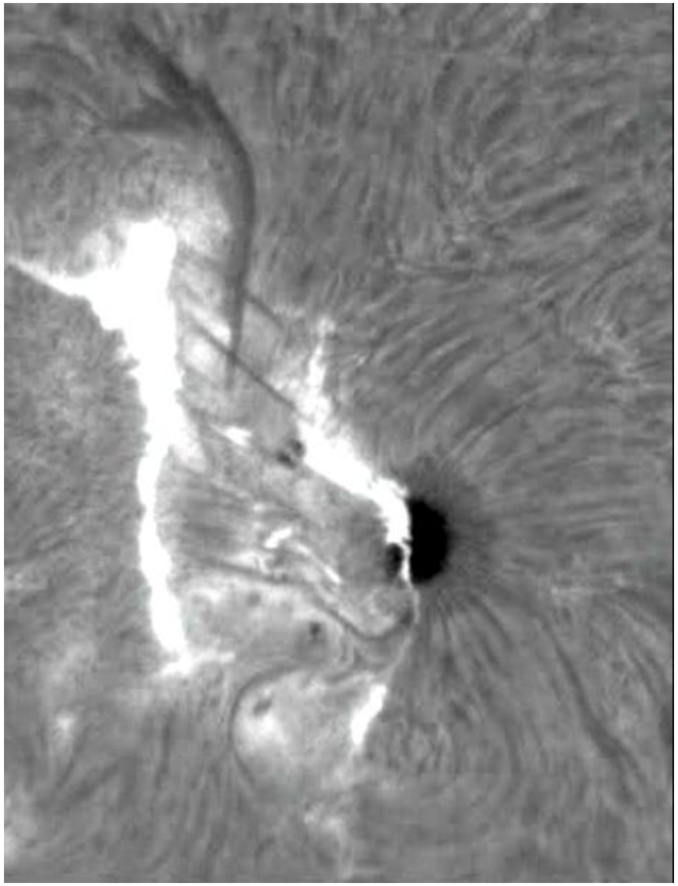


1943 Newton studied flare – geomag storm connection
-estimated the angular extent of the plasma stream
to be ~90 deg (similar to modern interplanetary CME)

H-alpha flares

- 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 < $3x10^8$ 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 ~$3x10^6$ 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

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



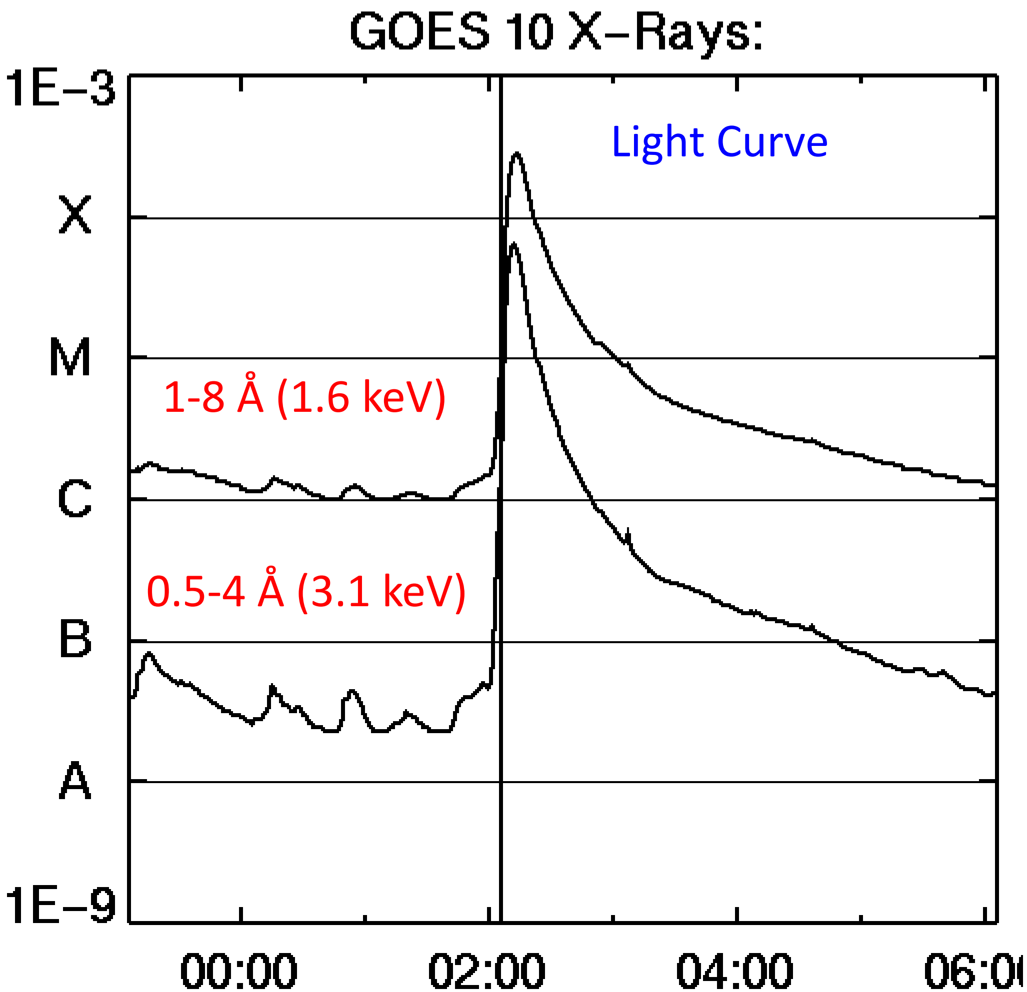
Dark loops connect the ribbons. The whole structure is referred to as flare arcade

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})

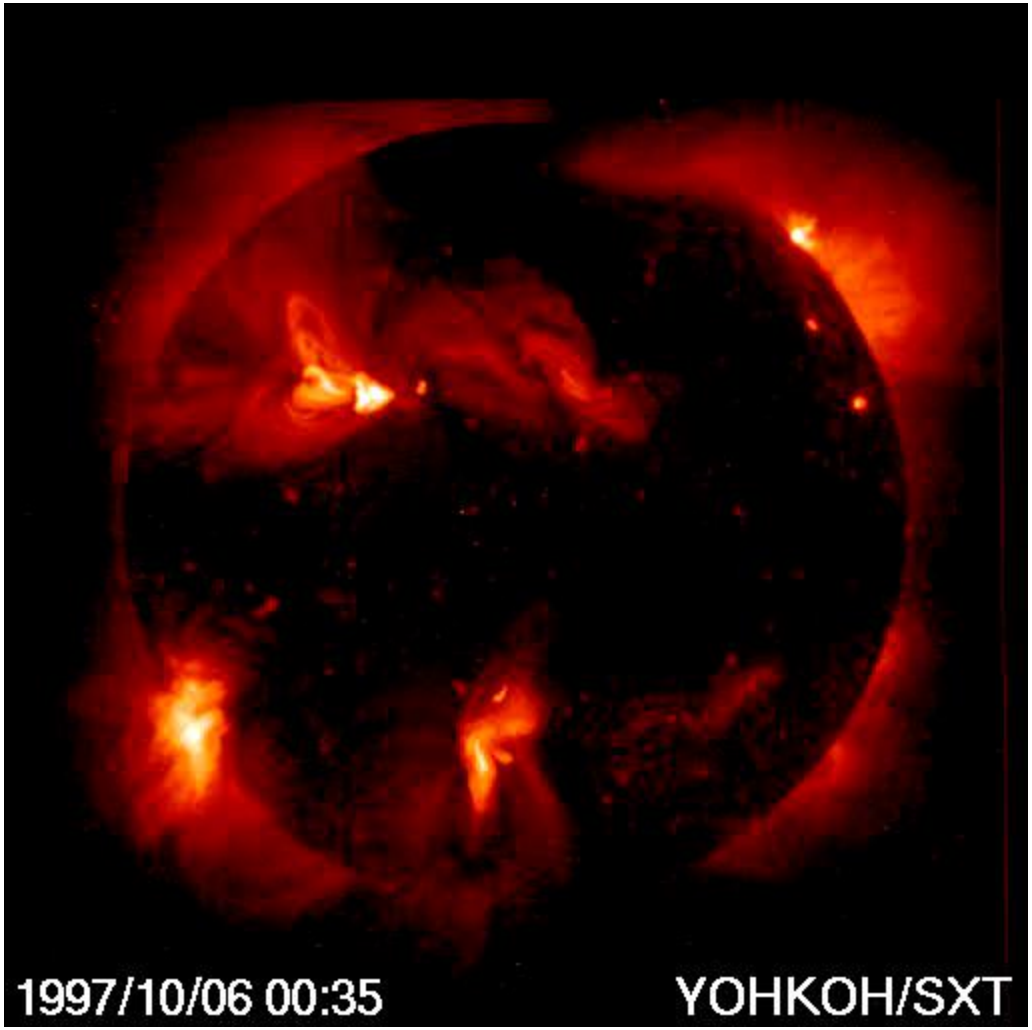
B, A added later to denote weaker flares

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

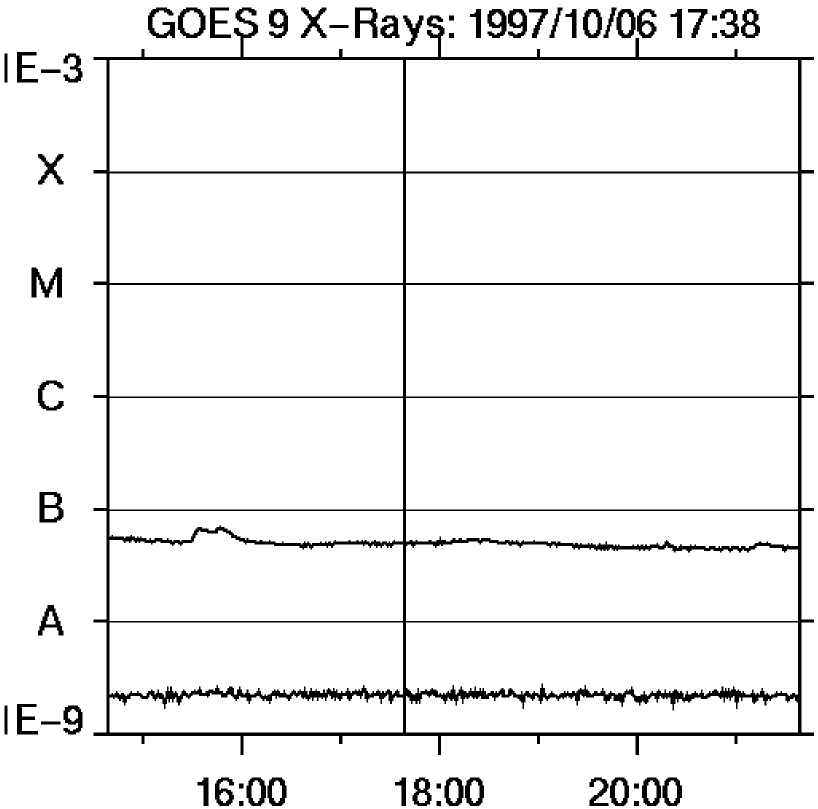
Importance class	Peak flux in 1-8 Å W/m^2
A	10^{-8} to 10^{-7}
B	10^{-7} to 10^{-6}
C	10^{-6} to 10^{-5}
M	10^{-5} to 10^{-4}
X	$>10^{-4}$

Very weak flare

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

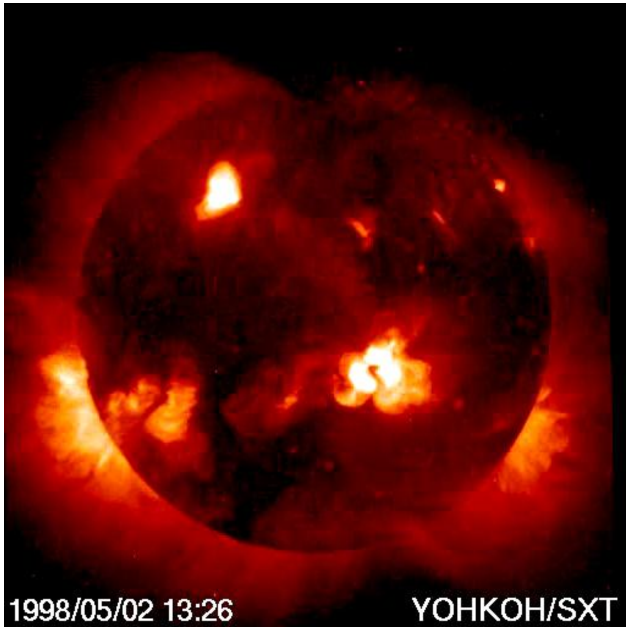


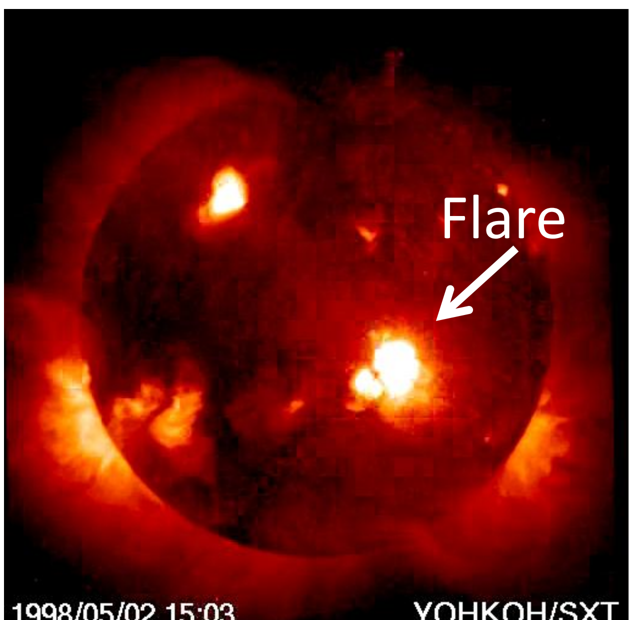
A-class flare barely seen in the soft X-ray light curve

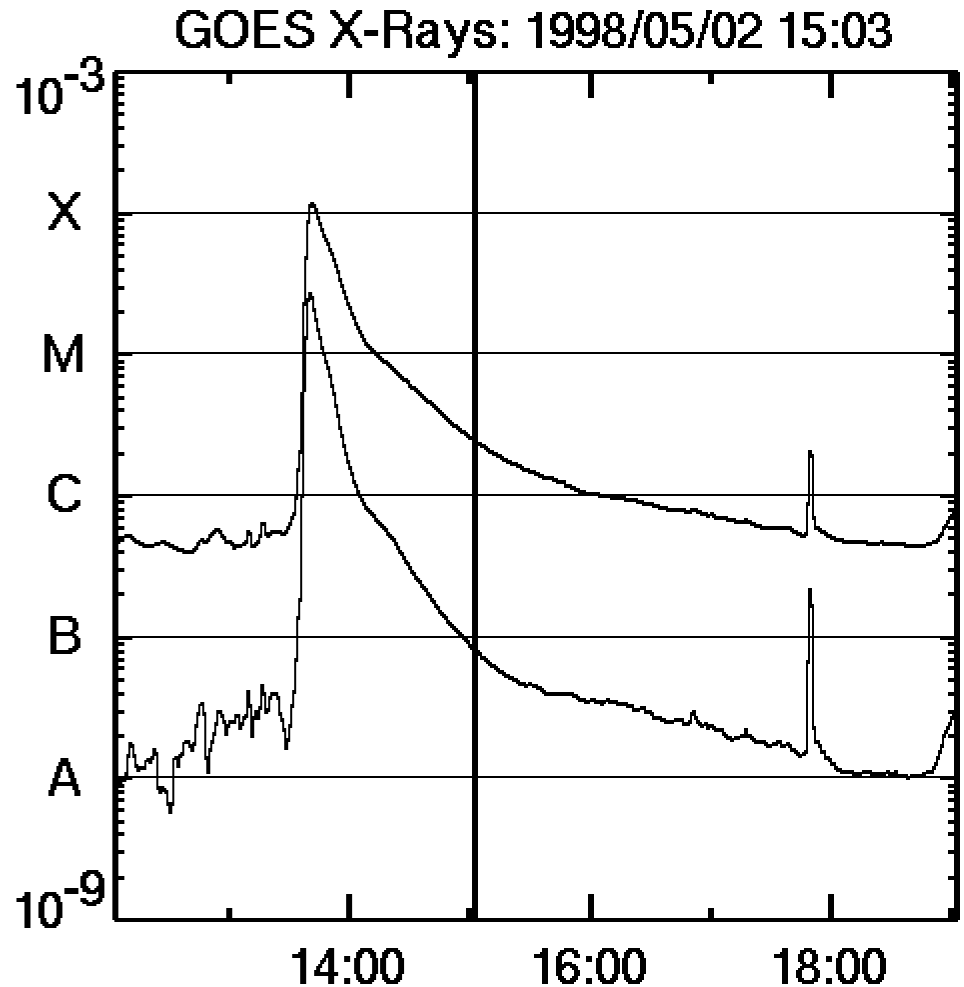


The image obtained in the energy channel 0.25 – 4 keV (2 – 50 Å)

A Large Flare & its Image

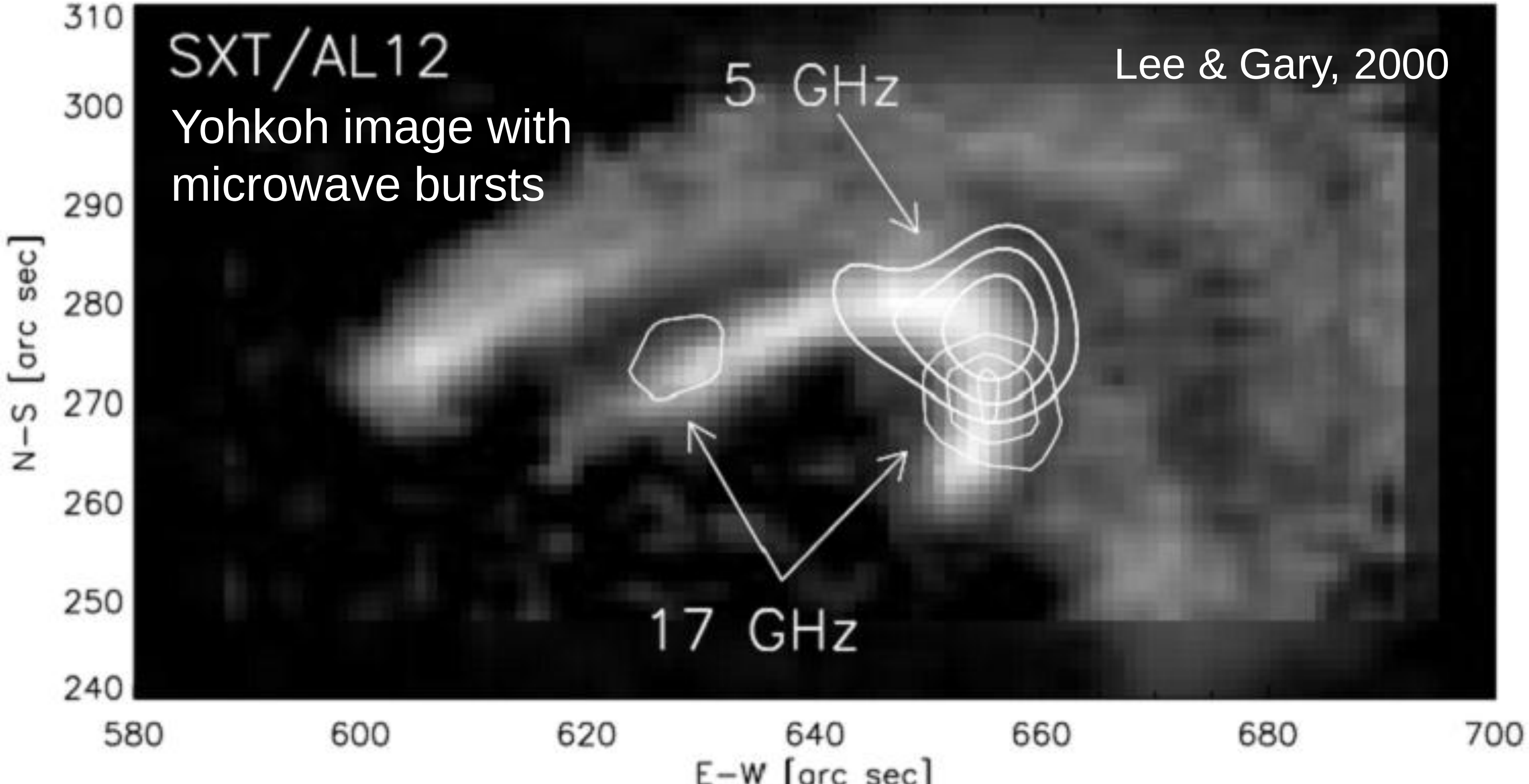






A Flare in Soft X-rays & Microwaves

soft X-rays: thermal emission (represents heating during the flare)
microwaves: nonthermal emission due to electrons accelerated during flare



Microwave (5 GHz, 17 GHz): due to gyrosynchrotron emission from 100s of keV electrons accelerated during the flare; emission occurs at10-100 harmonics of gyro frequency ω= eB/mc. B = magnetic field, e-charge, m-mass, c-light speed

H-alpha Flares and Microwave Flares: Scale comparison

Flare Area msh (Square degree)	faint	normal	brilliant	radio flux at 5 GHz (sfu)
<100 (2.06)	SF	SN	SB	<5
100-250 (2.06-5.15)	1F	1N	1B	30-1300
250-600 (5.15-12.4)	2F	2N	2B	1300-23000
600-1200 (12.4-24.7)	3F	3N	3B	23000 - 30000
>1200 (>24.7)	4F	4N	4B	>30000

msh = millionths of solar hemisphere

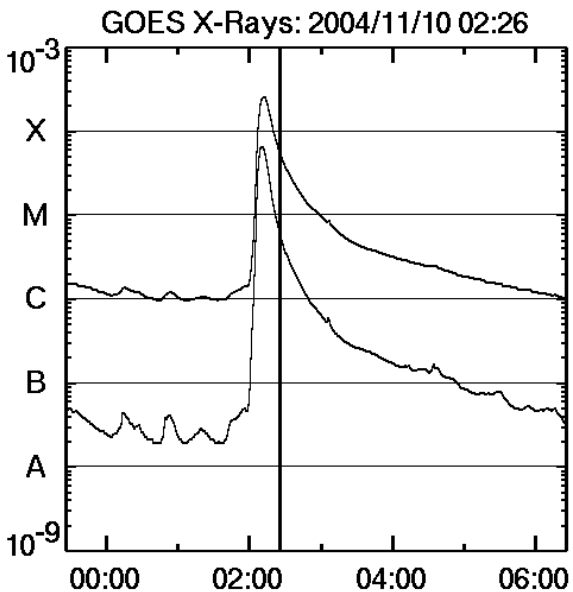
Imp = log S – 0.5; S radio flux in sfu (10^{-22} $Wm^{-2}Hz^{-1}$); Imp = H-alpha area

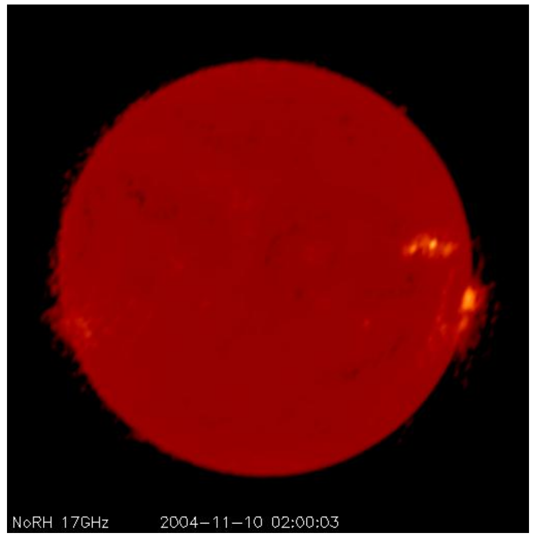
Big H-alpha flares also produce large microwave bursts

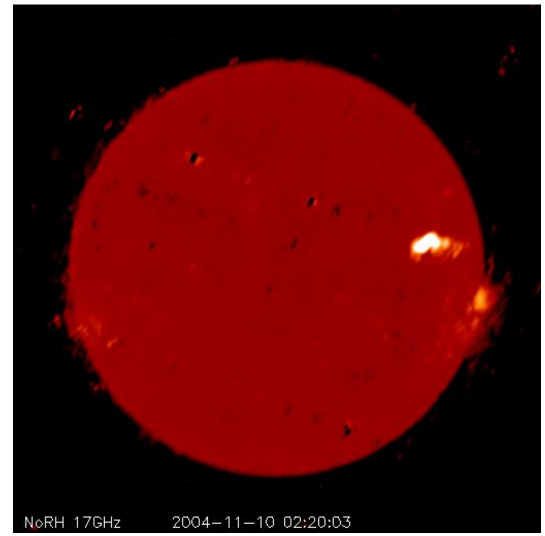
Both emissions are related to particles accelerated during the flare

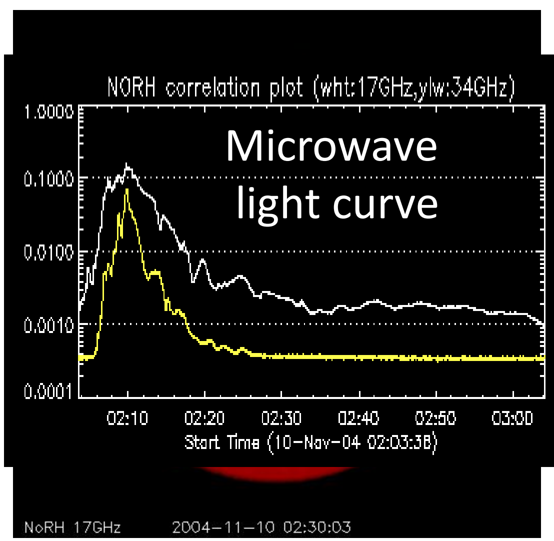
Images of a microwave flare (17 GHz)

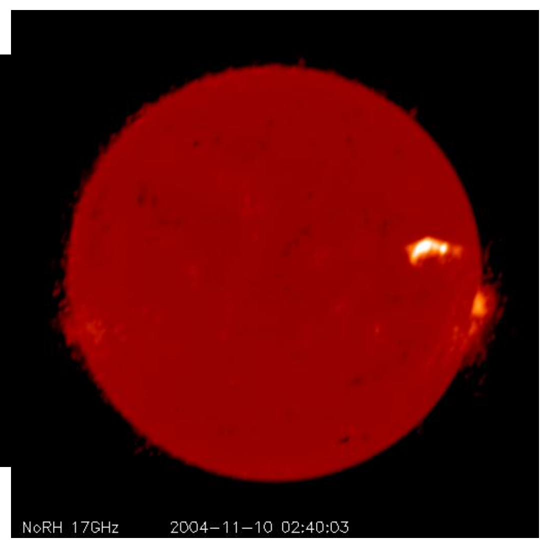
Nobeyama radioheliograph in Japan images the sun at 17 & 34 GHz

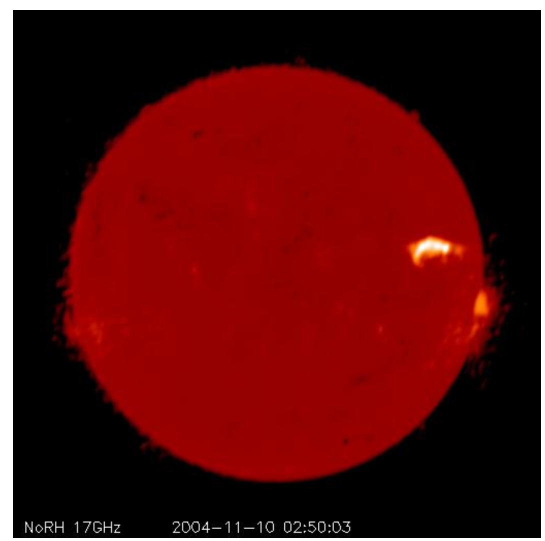






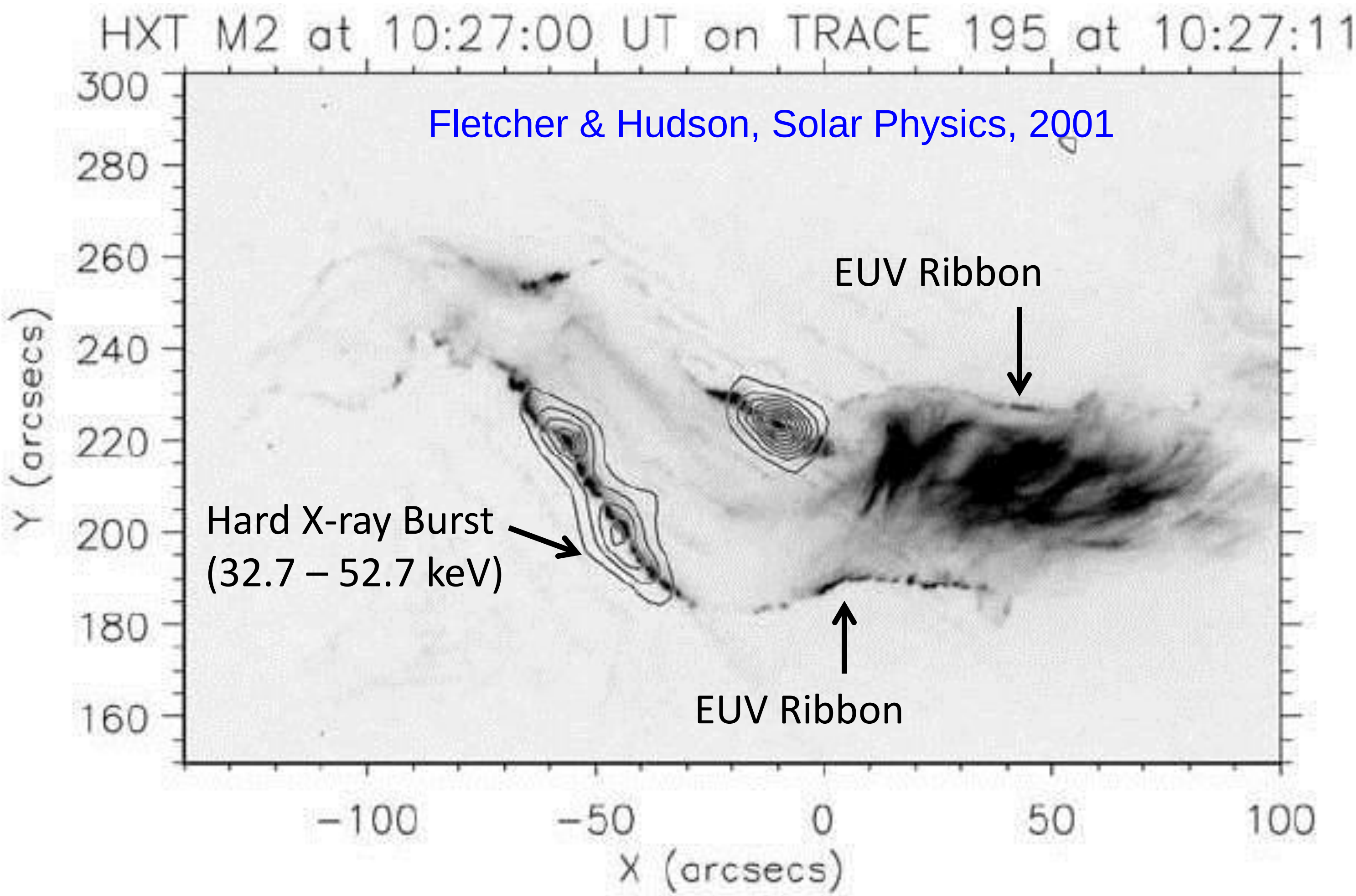






Flare Ribbons and Hard X-Rays

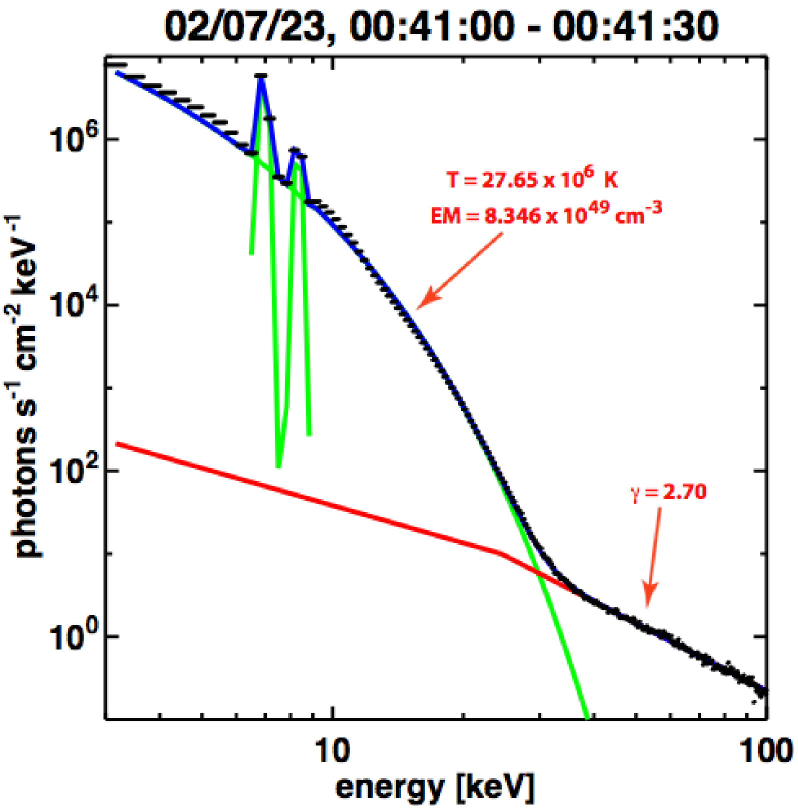
Hard X-rays are photons at higher energies than soft X-rays



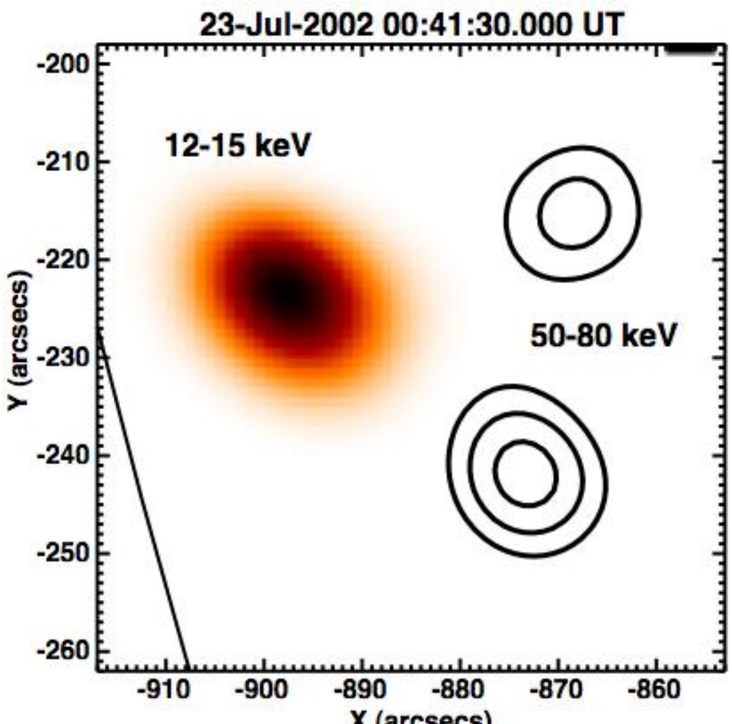
Like in H-alpha, the flare arcade can also be observed in EUV. The EUV image was obtained by TRACE satellite (gray-scale image). The contours are obtained by the hard x-ray telescope (HXT) on board the Yohkoh satellite. Note that the hard X-ray bursts are located on the ribbons

Another Hard X-ray Flare

Observations from the RHESSI satellite. Images at both soft and hard X-rays



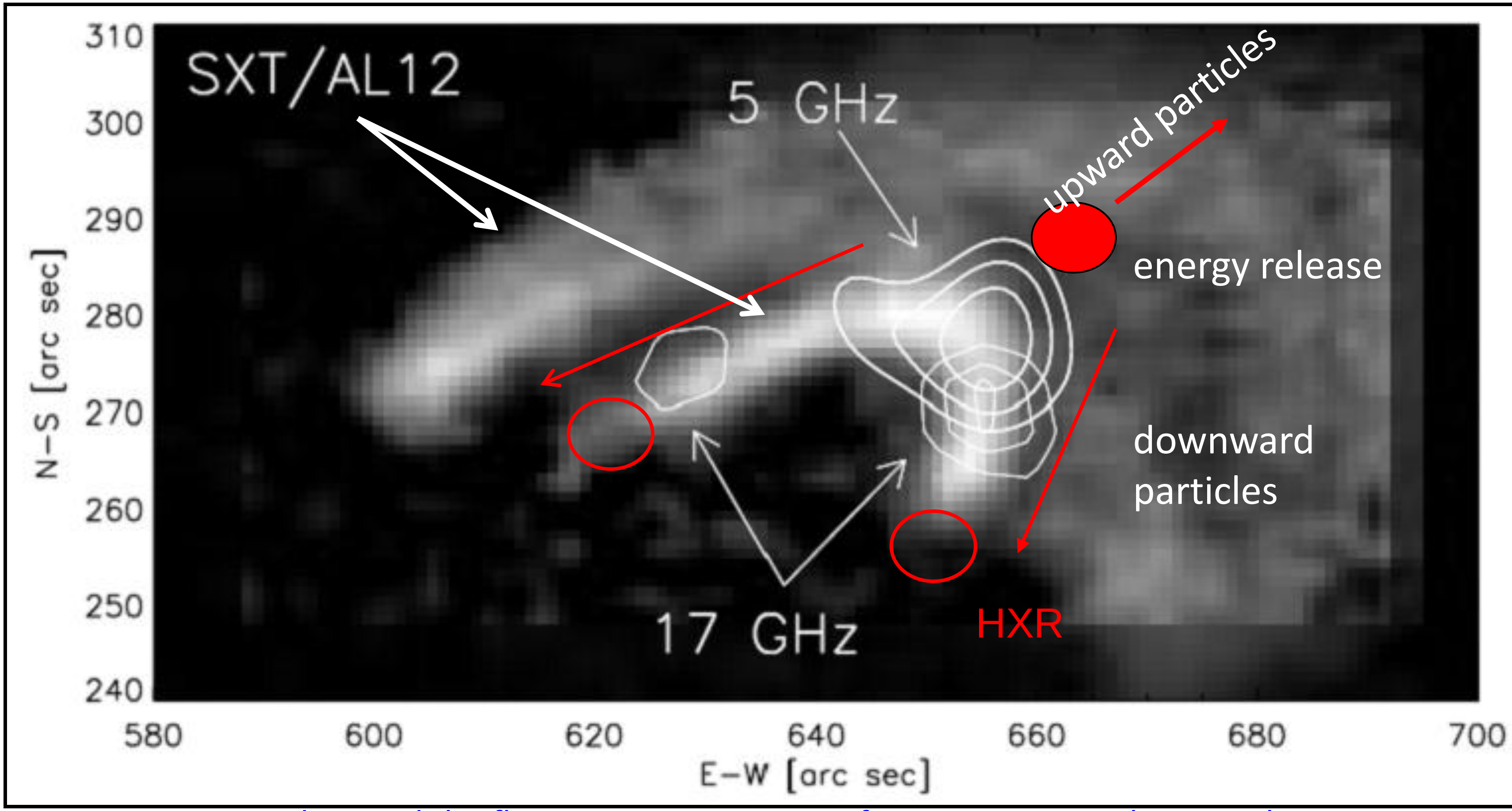
Caspi & Lin, 2005



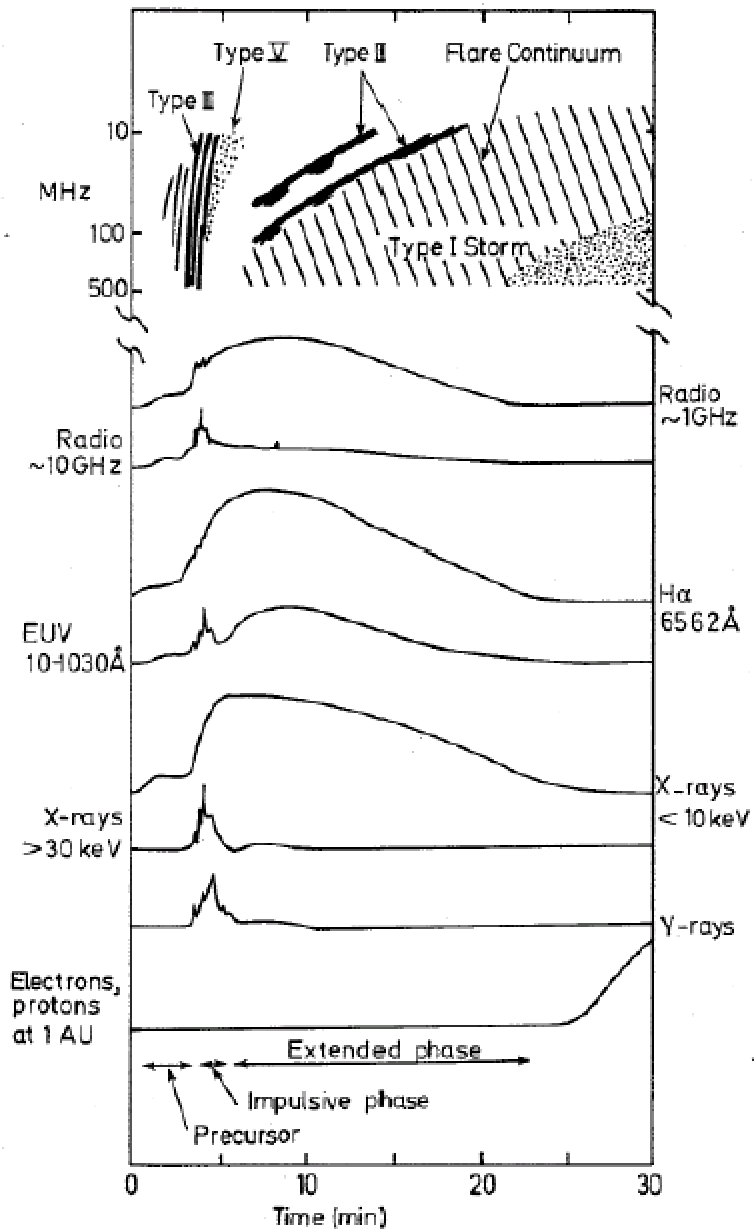
The X-ray emission can be modeled as a combination of thermal and nonthermal emissions. The thermal emission is from 27 MK plasma. The hard x-ray photons are due to energetic electrons interacting with the chromospheric protons (bremsstrahlung)

A section of the southeast quadrant of the Sun. Note that the soft X-rays (color) from higher up in the corona; hard X-rays from the surface

Upward & Downward electrons



We can now understand the flare process as starting from an energy release in the corona in which the magnetic free energy goes into accelerating electrons and ions. The accelerated particles flow down magnetic loops. Higher energy electrons trapped in the loops produce microwave bursts. Lower energy electrons reach the atmosphere and produce hard-rays and excite H-alpha emission. The heated atmospheric plasma fills the loops emitting soft X-rays. Some heating also occurs at the energy release site.



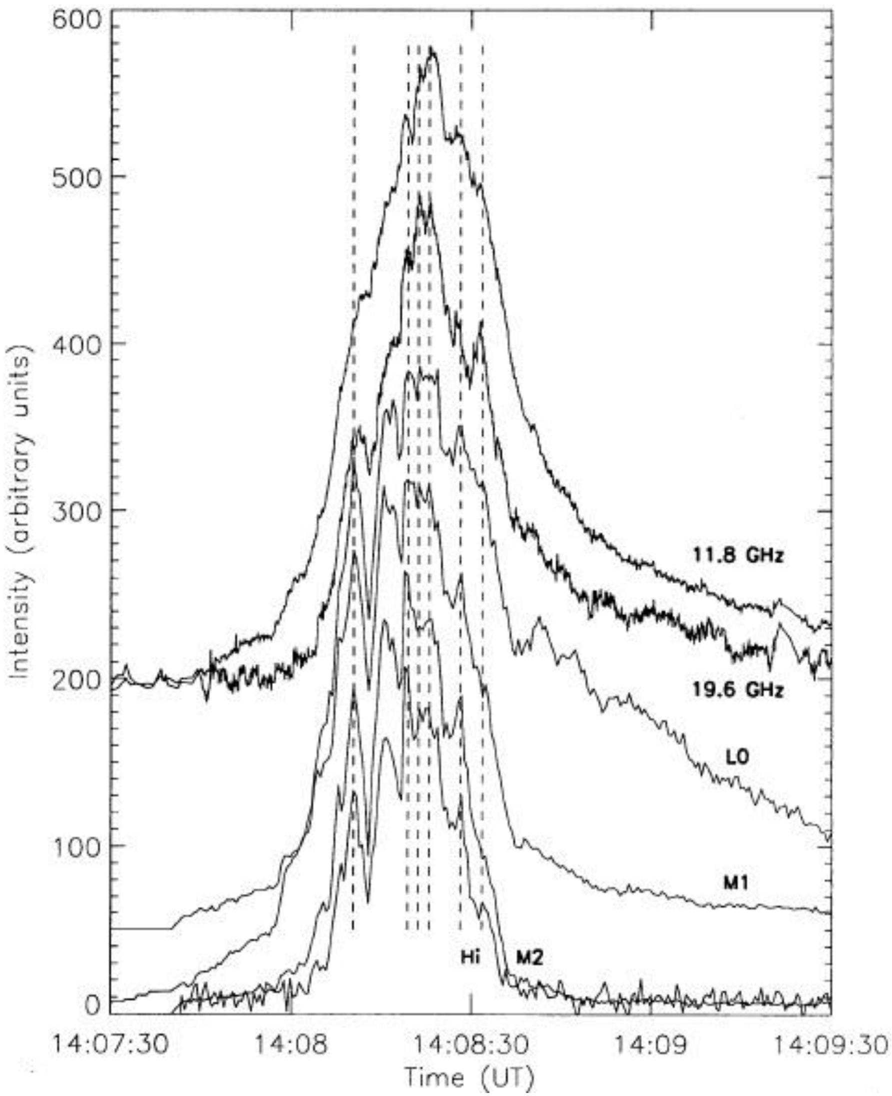
A generic Flare

Type III – due to flare accelerated electrons
Type II – due to shock accelerated electrons
flare continuum due to electrons trapped in flare loops
1 GHz radio bursts due to lower energy electrons
10 GHz radio bursts due to higher energy electrons accelerated in the flare site
H-alpha due to hydrogen atoms excited by particles precipitating in the chromosphere
soft X-rays, EUV due to heated flare plasma
Hard X-rays (>30 keV) due to accelerated electrons interacting with photospheric ions (bremsstrahlung)
gamma rays: due to particles precipitating on the Sun

electrons and ions observed in the interplanetary medium: particles escaping from the flare site, similar to the ones causing type III bursts
Some of these particles are from the CME-driven shock associated with the flare

Thermal and nonthermal components

Hard X-ray and Microwave Flares



Two microwave frequencies
Three Hard X-ray energy channels

There is one-to-one correspondence between hard X-ray and microwave peaks
The energetic electrons are accelerated in the corona at the same time
Hard X-ray: precipitating electrons
microwave: trapped electrons

Lo: 13.9 –22.7 keV
M1: 22.7 – 32.7 keV
M2: 32.7 – 52.7 keV
Hi: 52.7 – 92.8 keV

Type III & Type II Radio Bursts

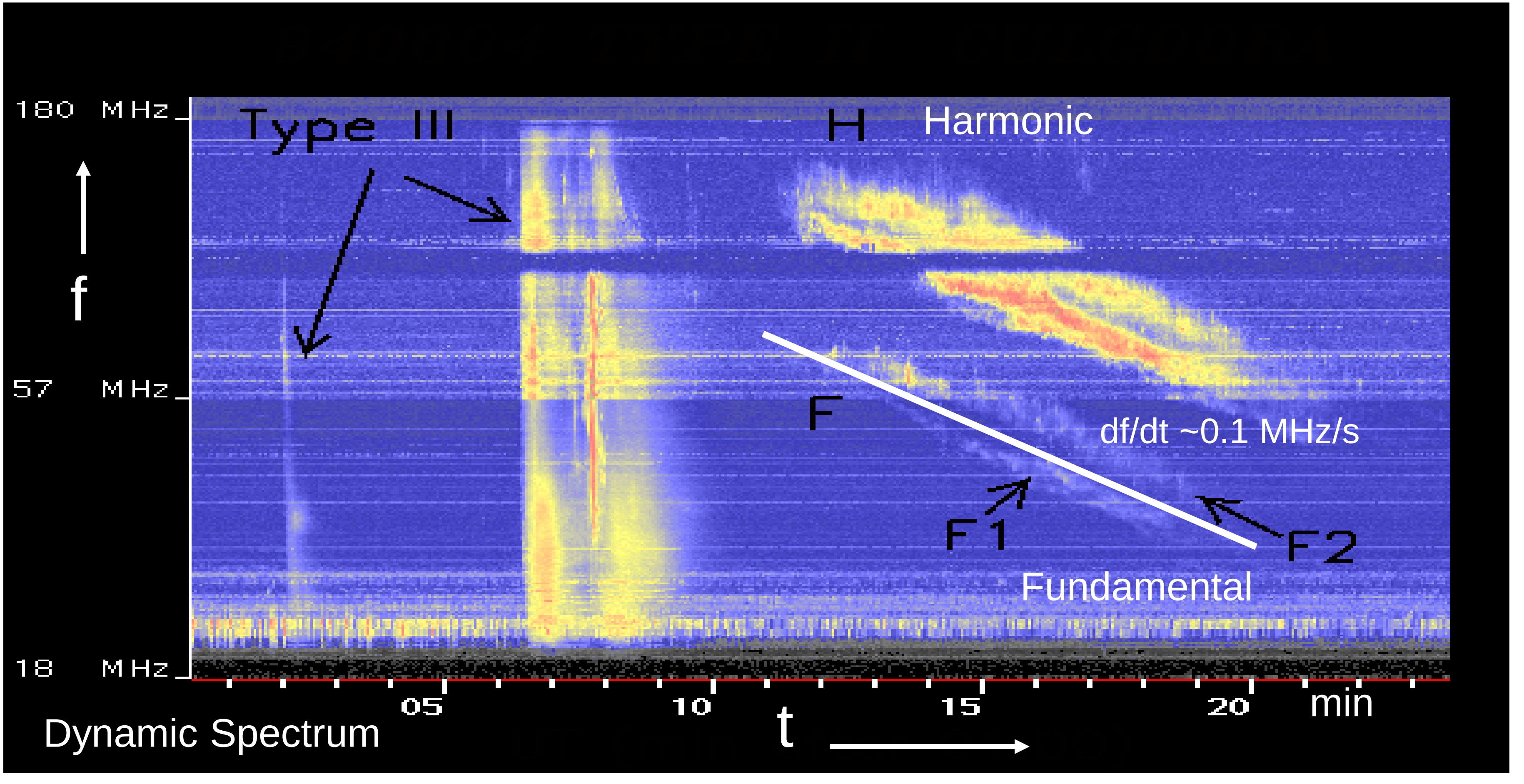
Type III (electron beams) v ~ 0.3 c

Type II (shocks) v ~ 600 km/s

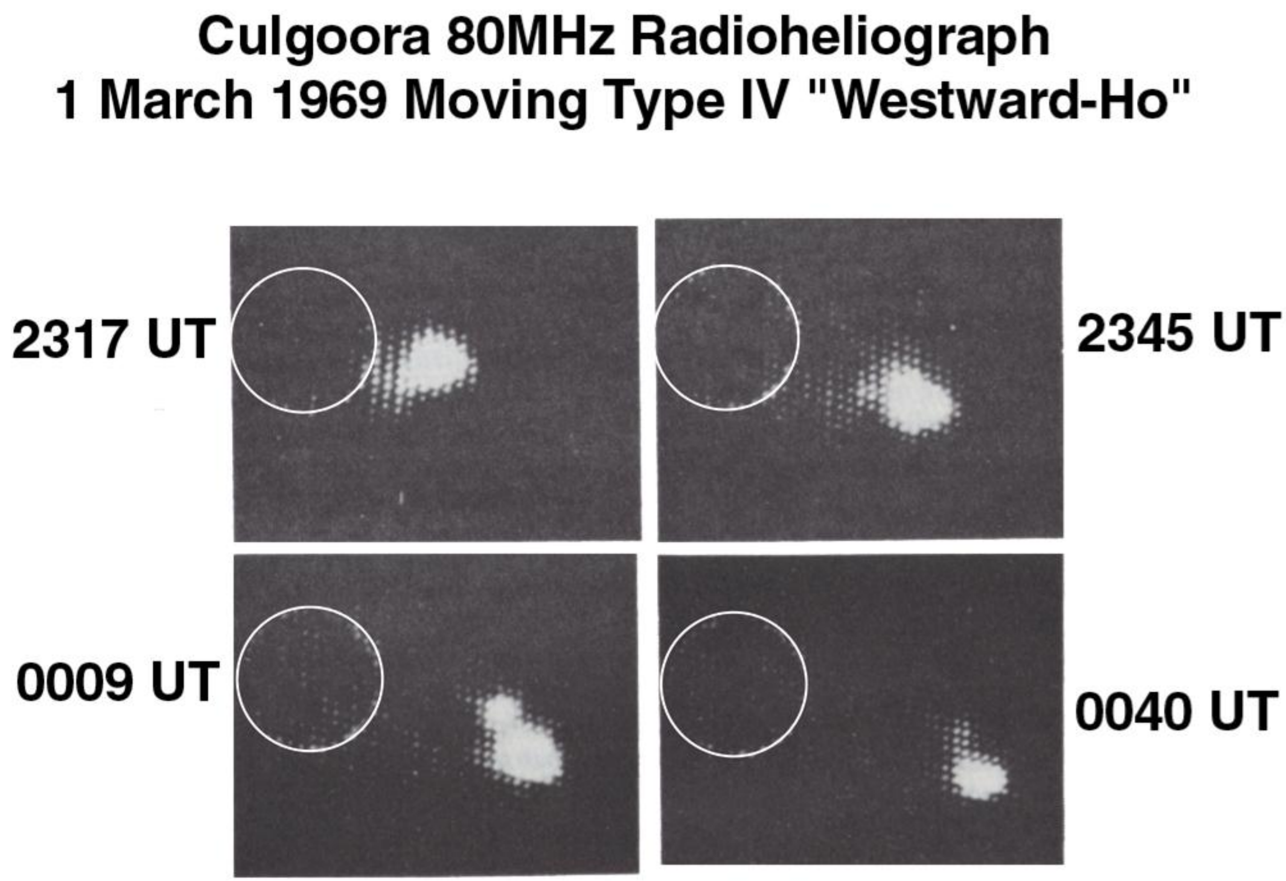
$df/dt = df/dr.dr/dt = (V/2)\, f\, n^{-1}(dn/dr)$

$V = 2L(d\ln f/dt)$

$f \sim n^{1/2}$ (plasma frequency)

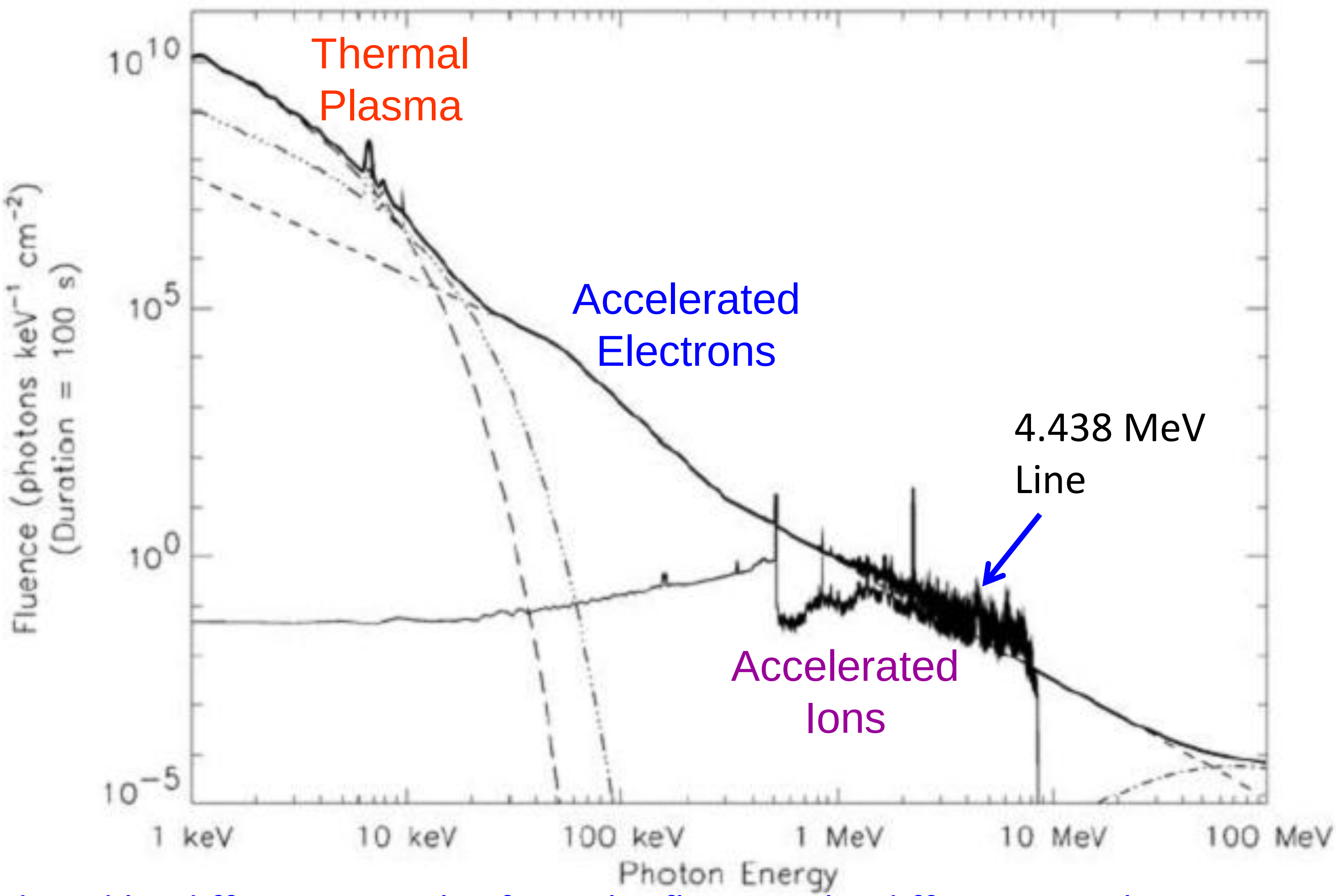


Moving type IV burst



Accelerated electrons trapped in moving magnetic structures associated with the CME

Composite Spectrum from a Large Flare



Produced by different particles from the flare site by different mechanisms (next slide)

Contributions from flare-accelerated electrons and ions to the flare spectrum

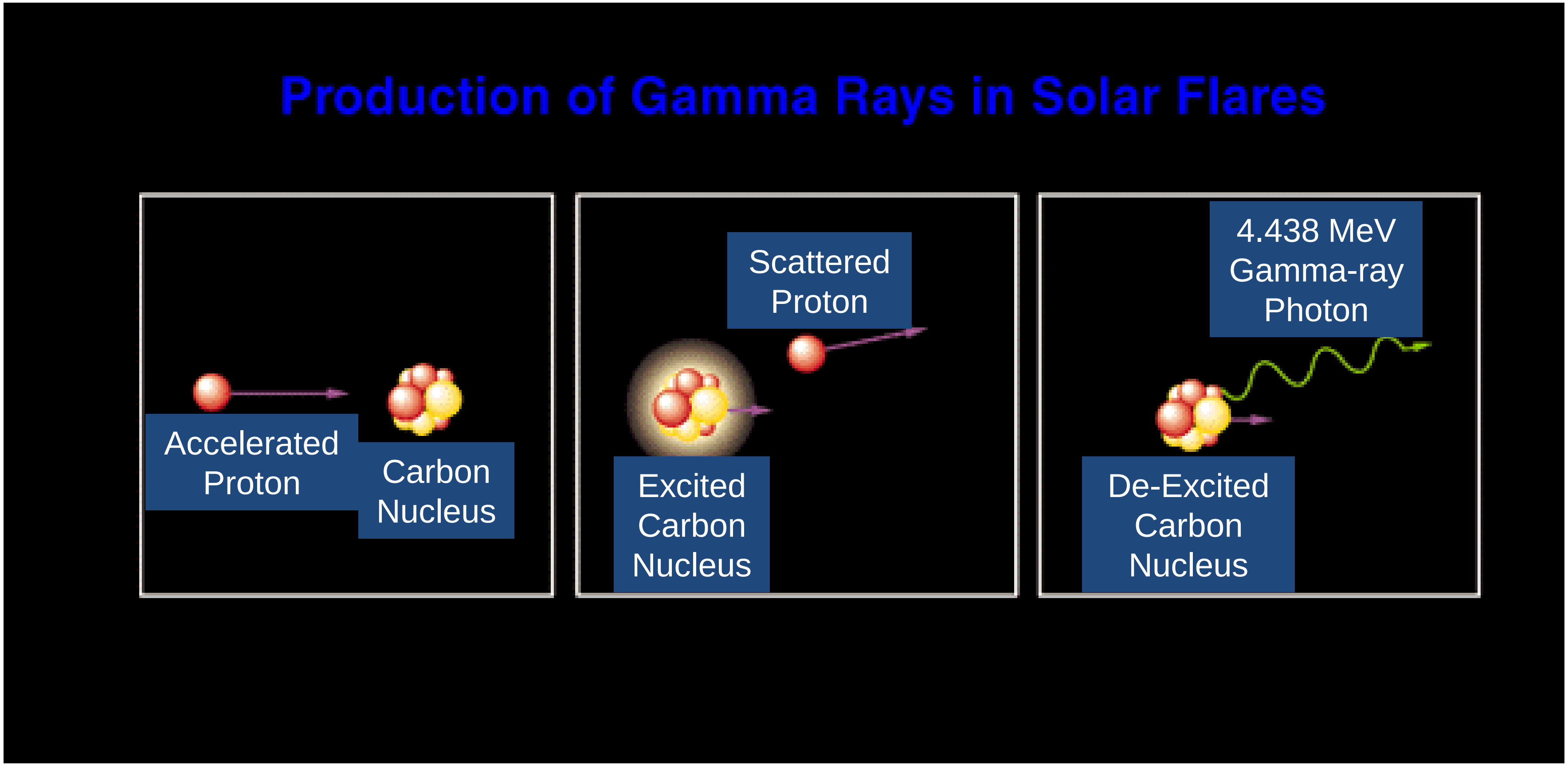
- Electrons

- X-ray and gamma-ray continuum

- Ions

- excited nuclei → gamma-ray line radiation (1-8 MeV)
- Radioactive nuclei → positron + gamma
- Pions → electrons, positrons, neutrinos, gamma
- neutrons
- - Escape to space (direct detection by neutron telescopes)
- - Capture on H to produce 2.223 MeV line
- upward protons detected by in situ particle detectors

Nuclear De-Excitation



Confined vs. Eruptive Flares

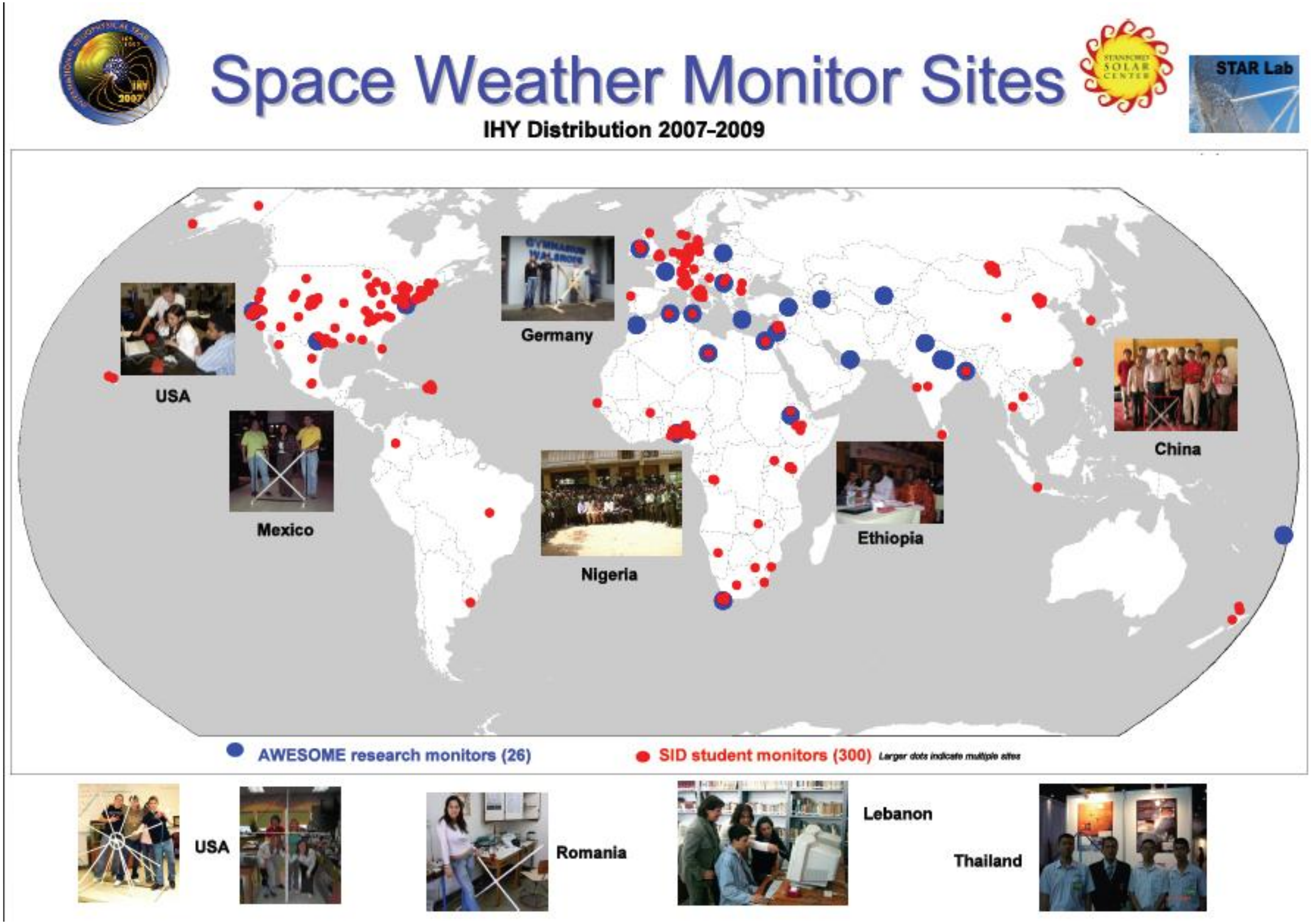
- Confined: generally a single loop
- Eruptive:
- associated with erupting prominence
- CME
- type II radio burst
- two - ribbon flares
- Post-eruption arcade

- Impulsive and gradual flares

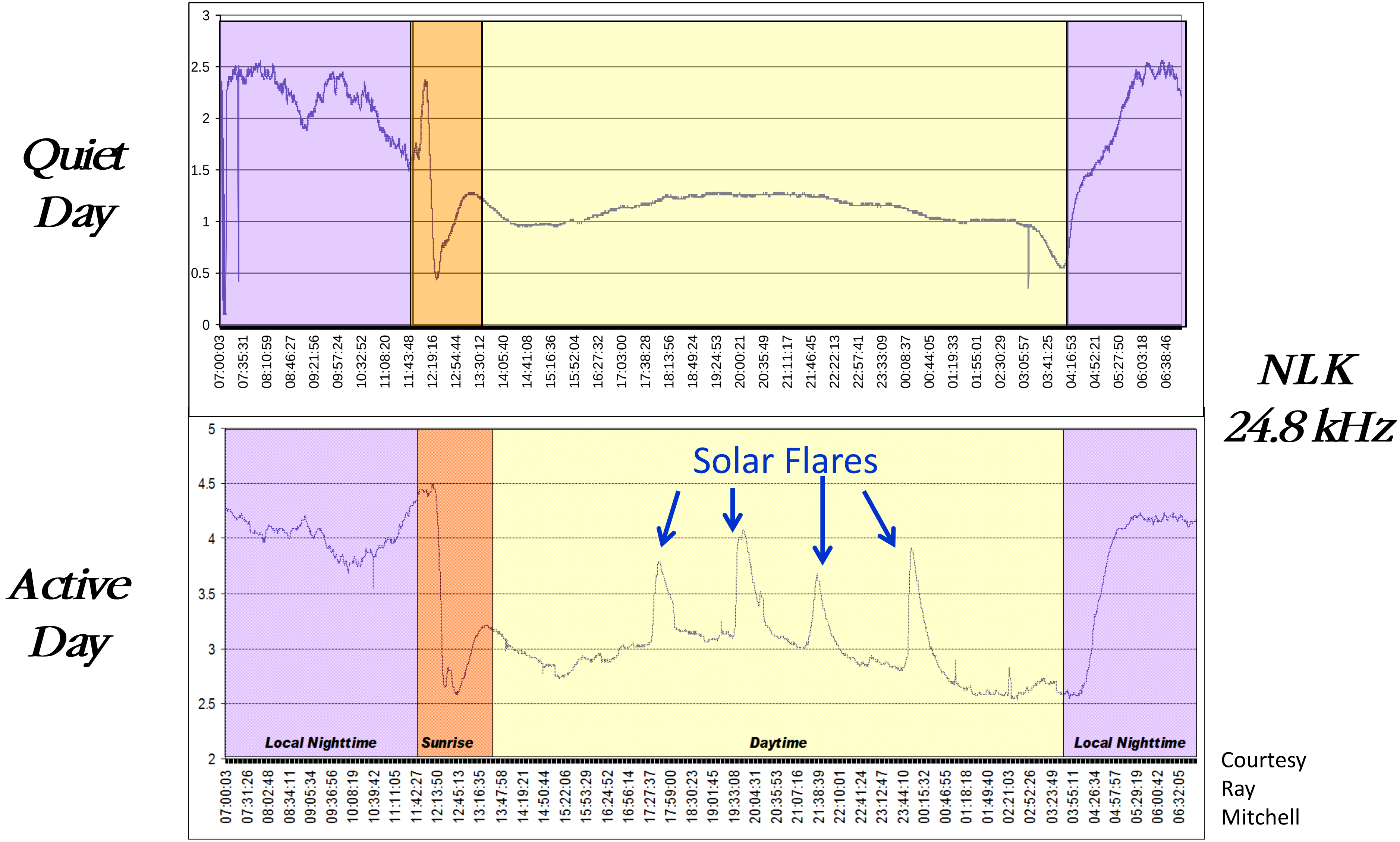
One of the Consequences of Flare Photons in the Ionosphere

- 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

Worldwide AWSOME & SID Sites



Sudden Ionospheric Disturbance (SID) Event



Courtesy Ray Mitchell

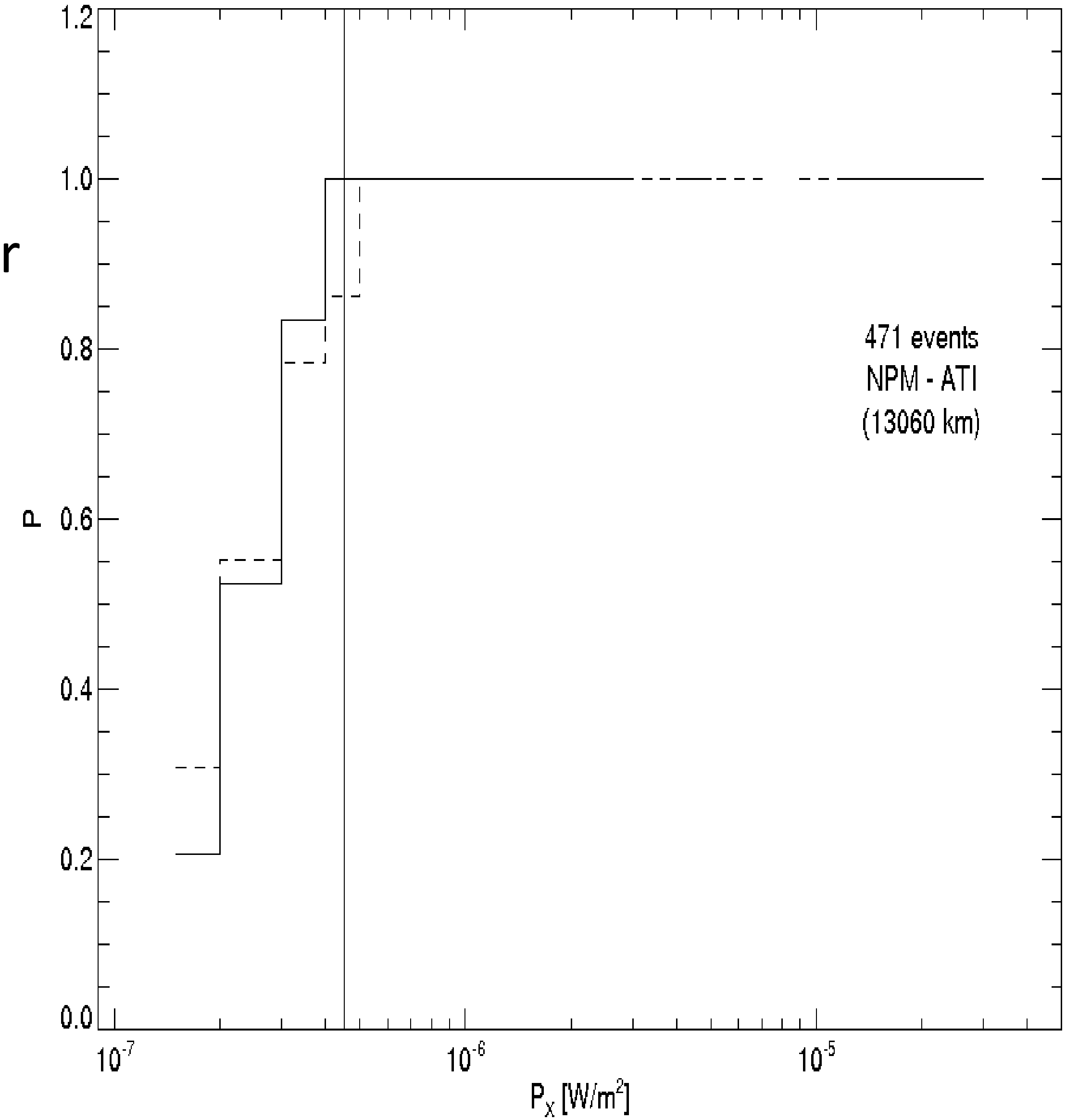
The VLF signal amplitude and phase are modified when flare photons modify the ionosphere

SENSITIVITY OF THE LOWER IONOSPHERE

The South American VLF network (SAVNET) is another VLF receiver network. SAVNET detects 100 % of ≥ B4 Class solar flares

VLF Signatures of GOES flares

(Raulin et al. 2010)

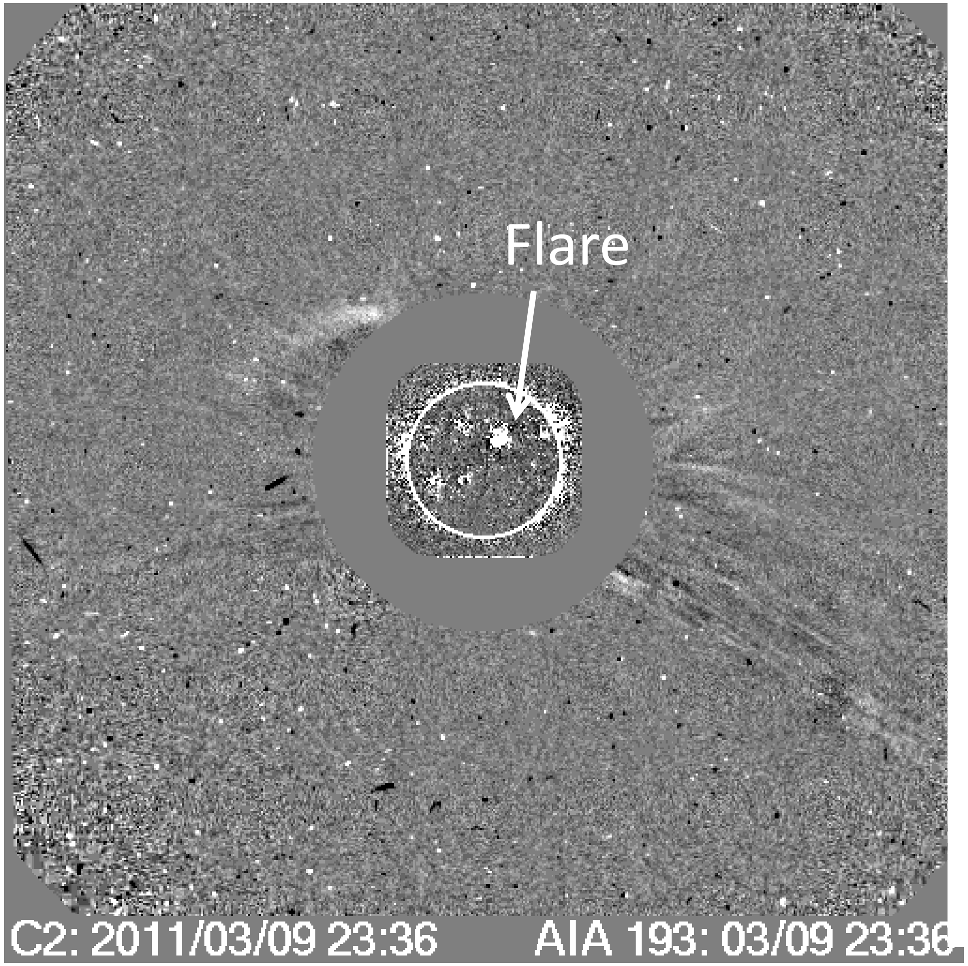


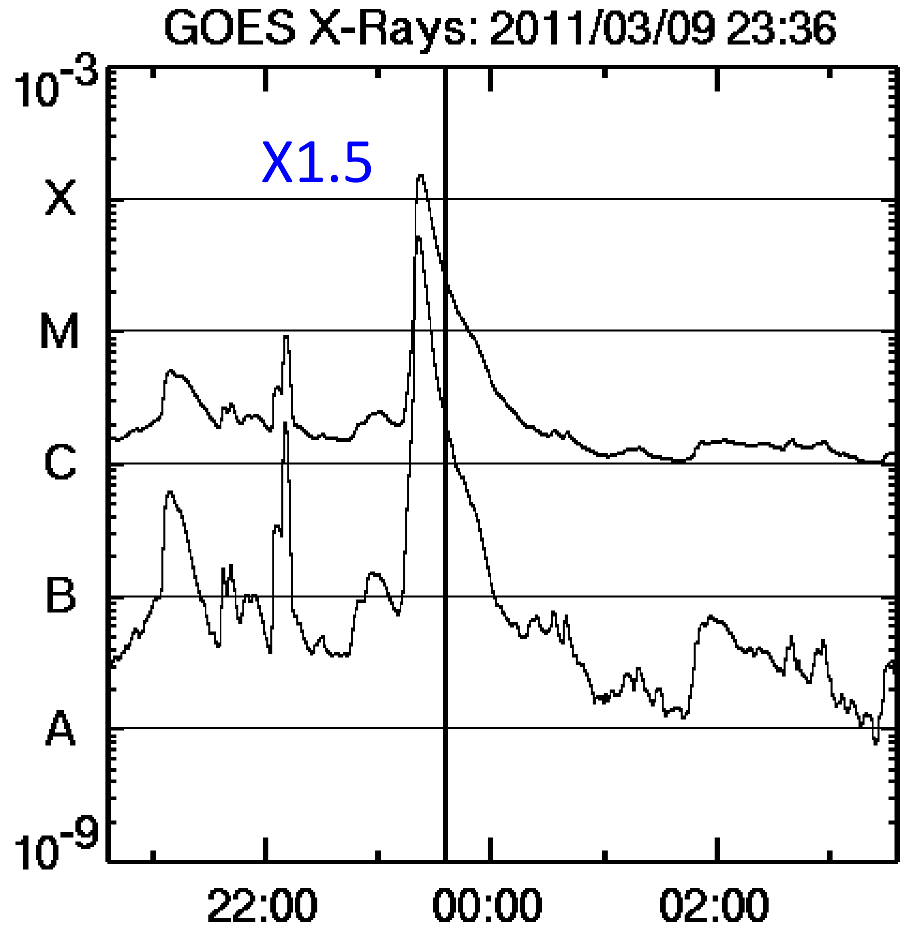
Eruptive and Confined Flares

Confined Flares

- ~ 20% of ≥M5.0 flares are not accompanied by CMEs
- 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 mass motion

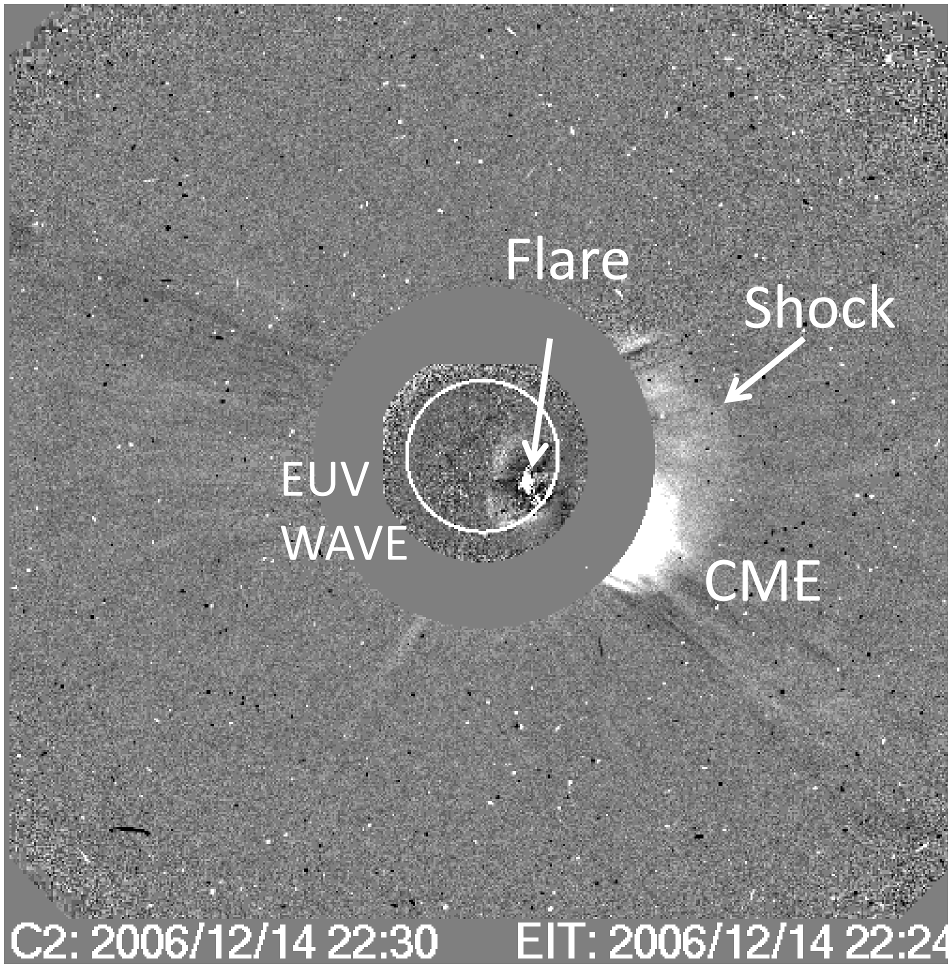




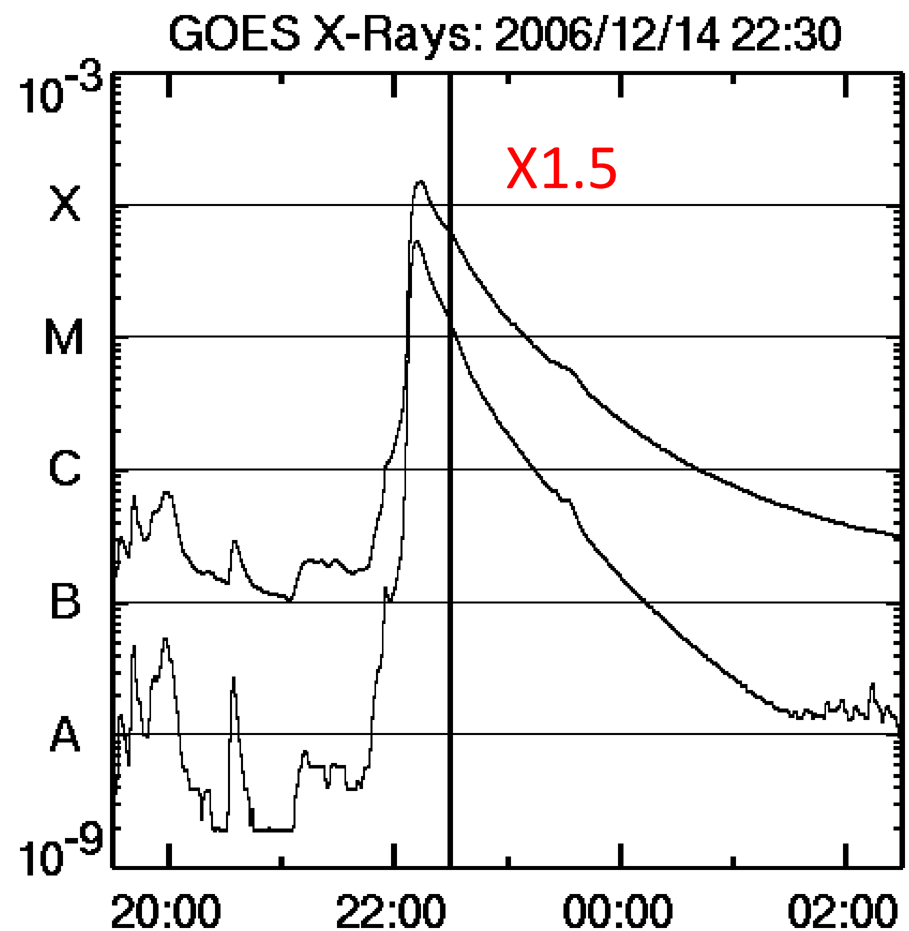
Confined flares just produce excess photons

CME is an Eruptive Event

Flares have prompt effect on the ionosphere



SOHO/LASCO & EIT Difference Images overlaid



Coronal Mass Ejections (CMEs)

Brief history

- Mass Ejections known for a long time from radio bursts, H-alpha prominence eruptions (e.g, Payne-Scott et al., 1947)
- 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)

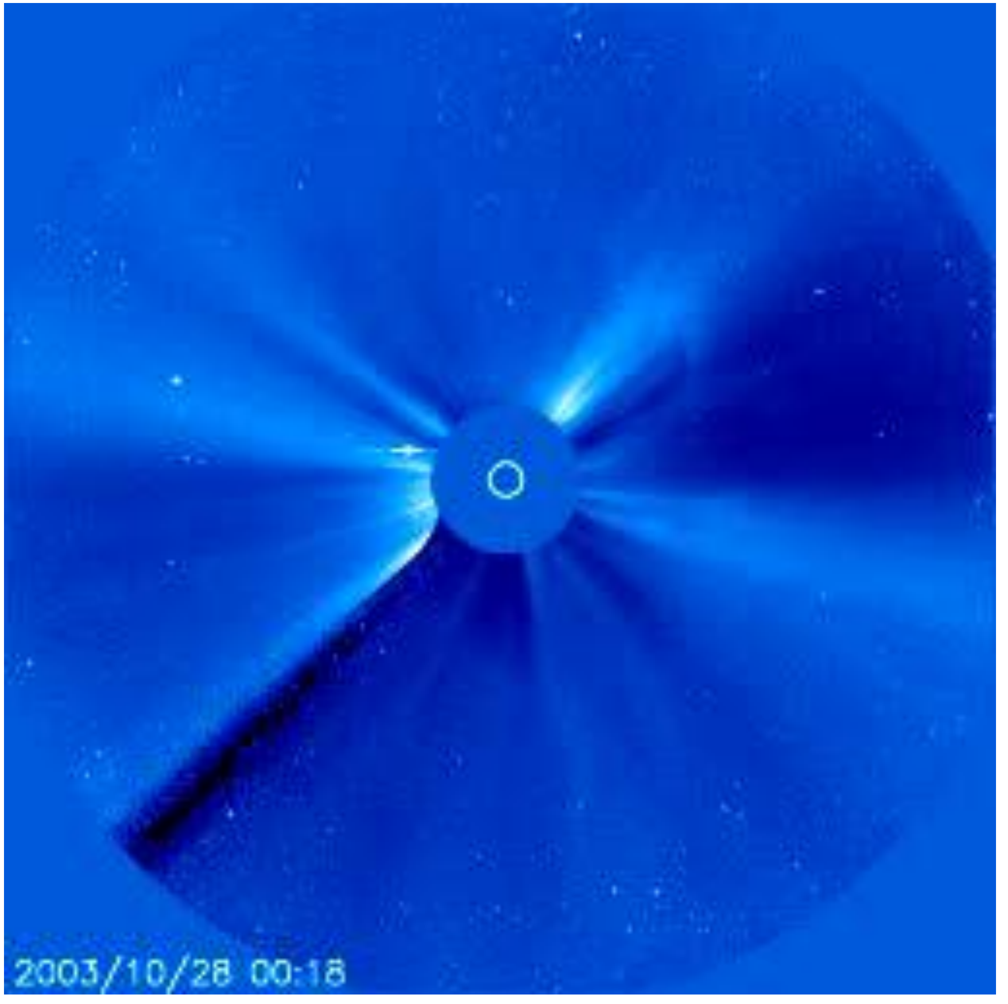
High Energy Plasmas & Particles

Solar Wind

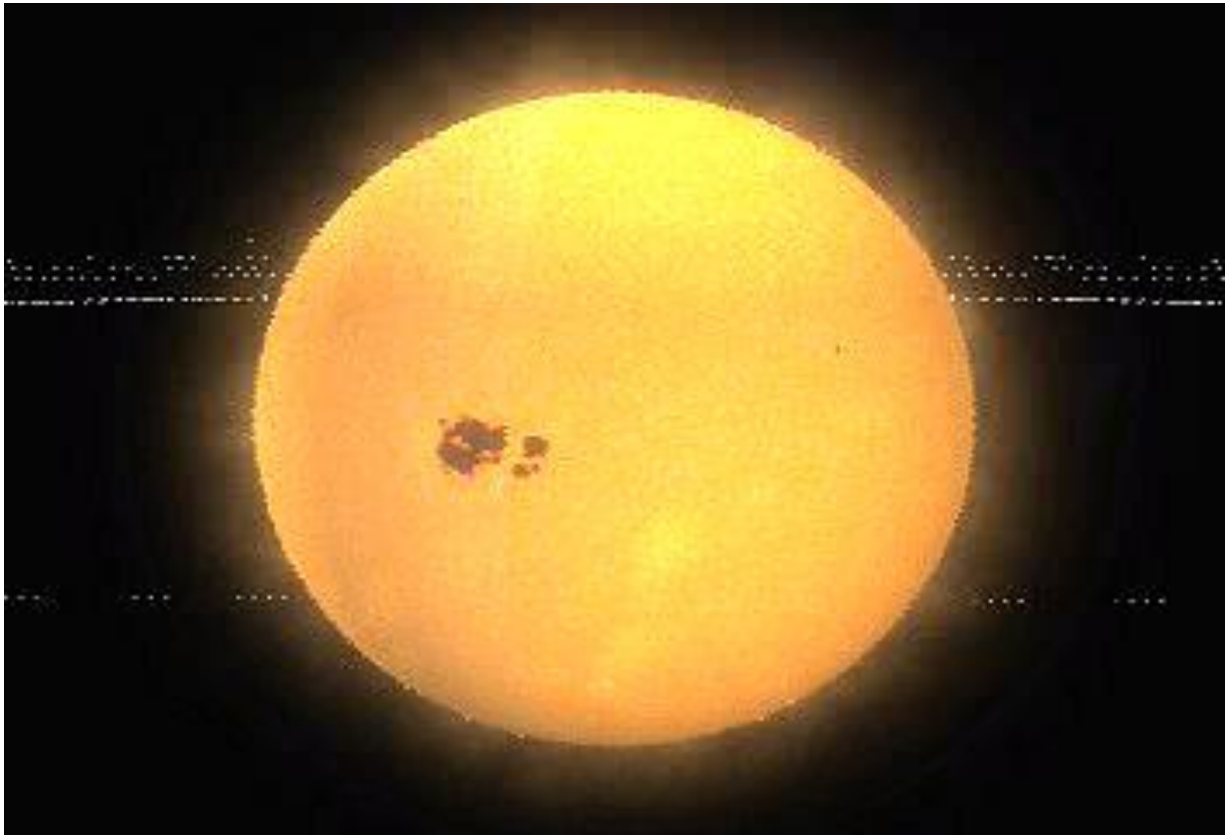
Plasma Ejected from the Sun
(Coronal Mass Ejections – CMEs)

Energetic Particles

SOHO coronagraph movie showing two CMEs



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.

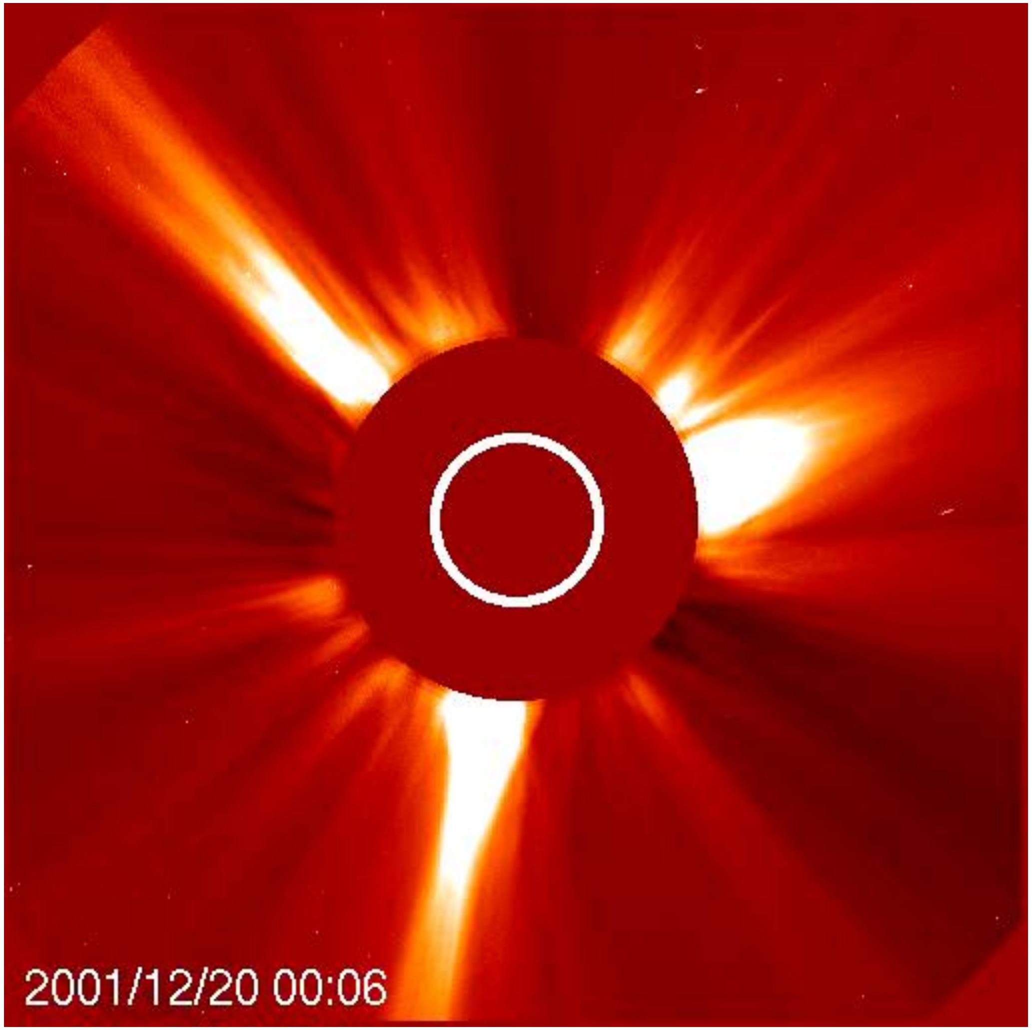
CMEs represent the most energetic phenomenon in the heliosphere

What is a CME?

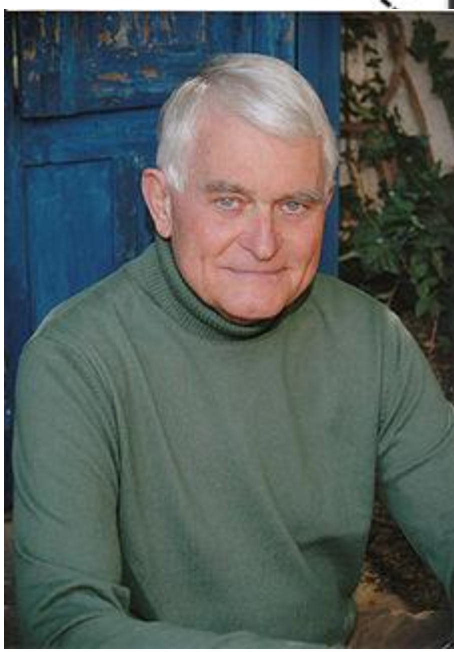
CME can be defined as the outward moving material in the solar corona which is distinct from the solar wind

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

SOHO Coronagraph movie



CME in Old Eclipse Pictures: 1860 July 18



J. A. Eddy (1931 – 2009)

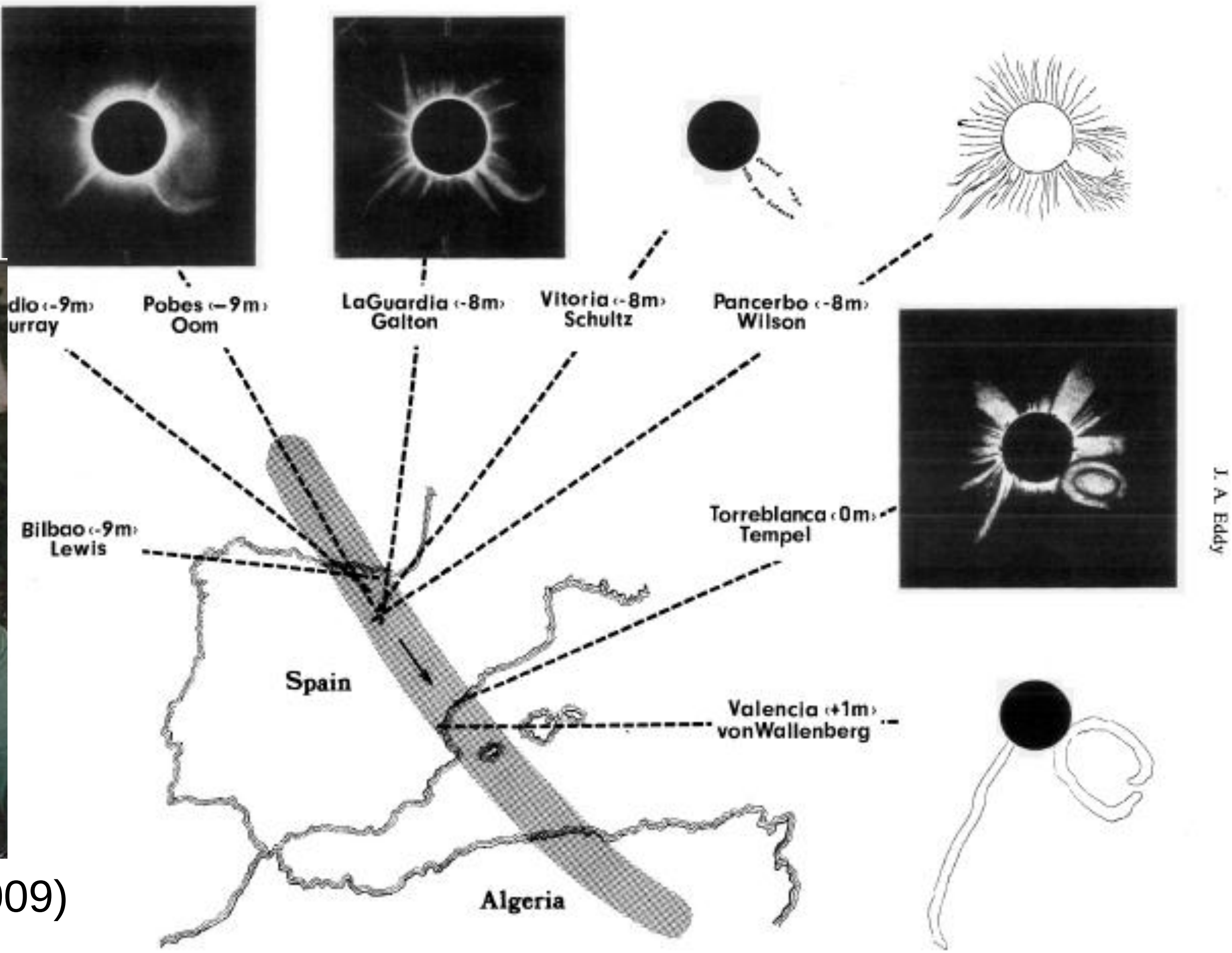
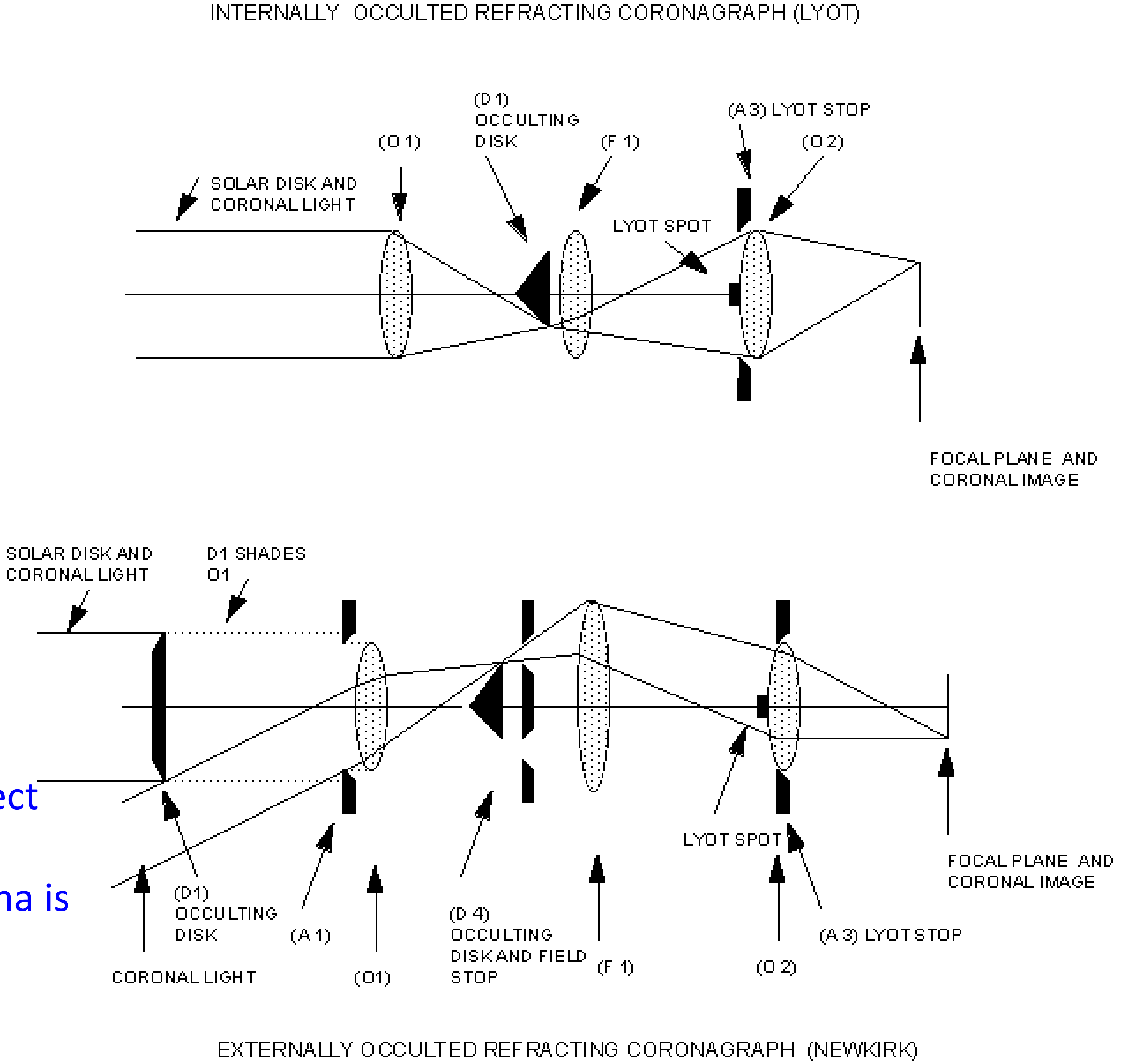


Fig. 4. Selected drawings of the corona (from Ranyard, 1879), made by different observers along the path of totality in Spain during the 1860 eclipse. Times are relative to mid-totality at Tempel's station at Torreblanca

Eddy, 1974 estimated the CME speed to be 200-500 km/s

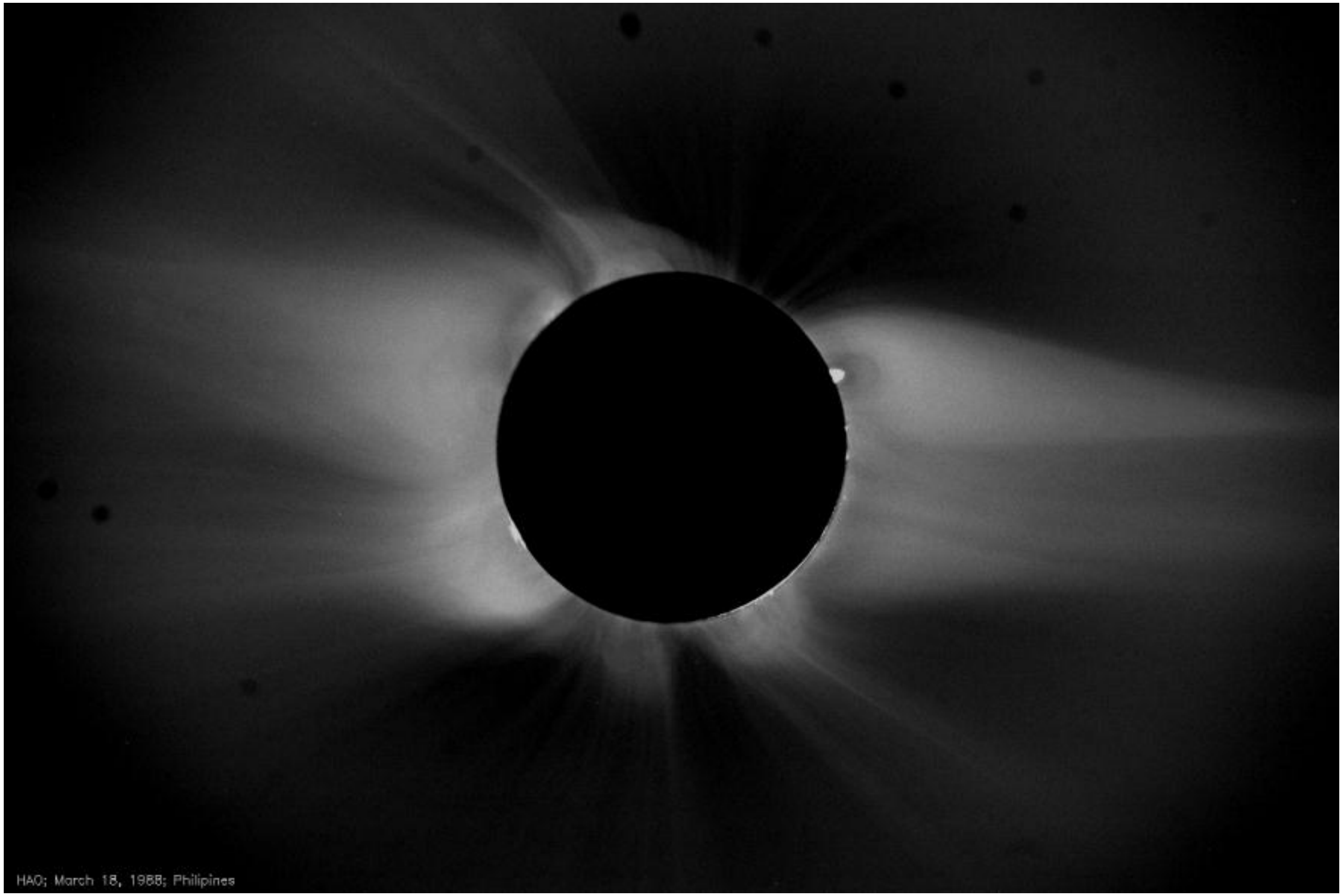
Coronagraphs

Bernard Lyot (1939)



The occulting disk prevents direct photospheric light from falling on the objective lens. The corona is about a million times dimmer than the photosphere

Moon is a natural occulting disk



Courtesy: HAO

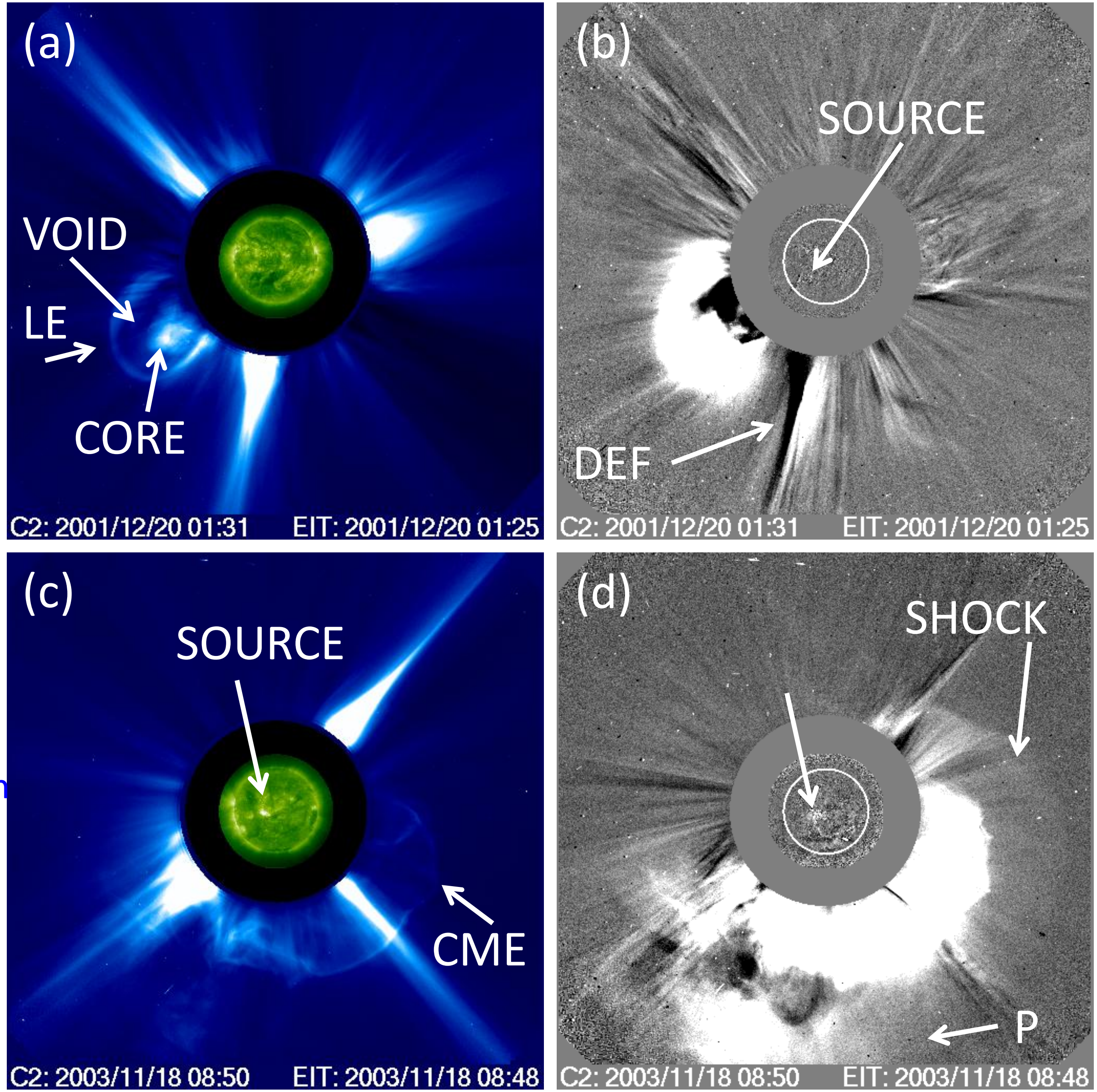
Prominence, coronal cavity and overlying streamer: Look like a CME before taking off!

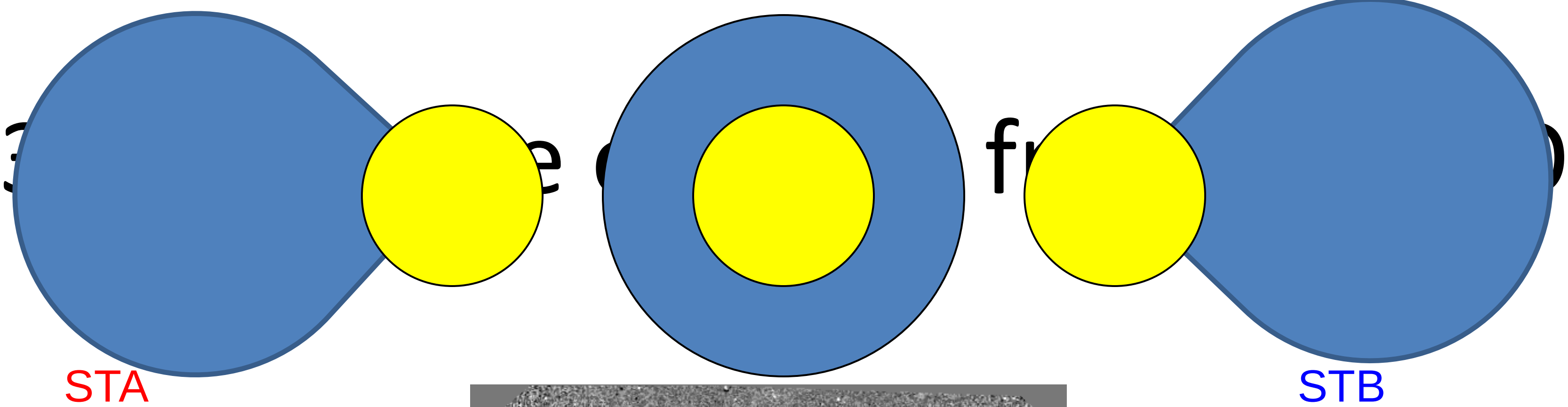
Morphological Properties

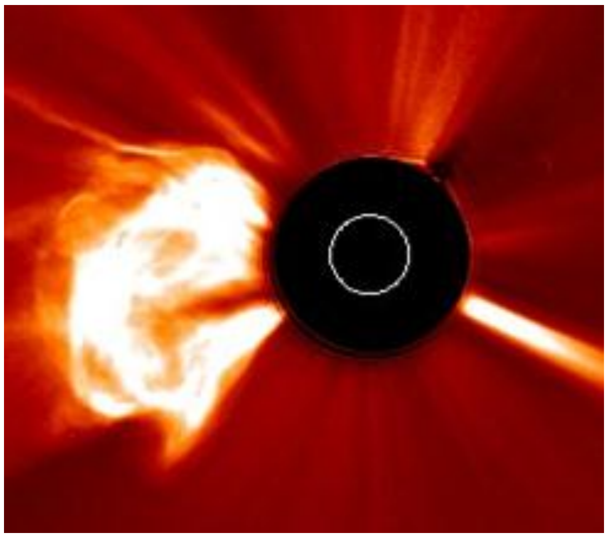
CMEs have spatial structure: bright front, dark void, & prominence core

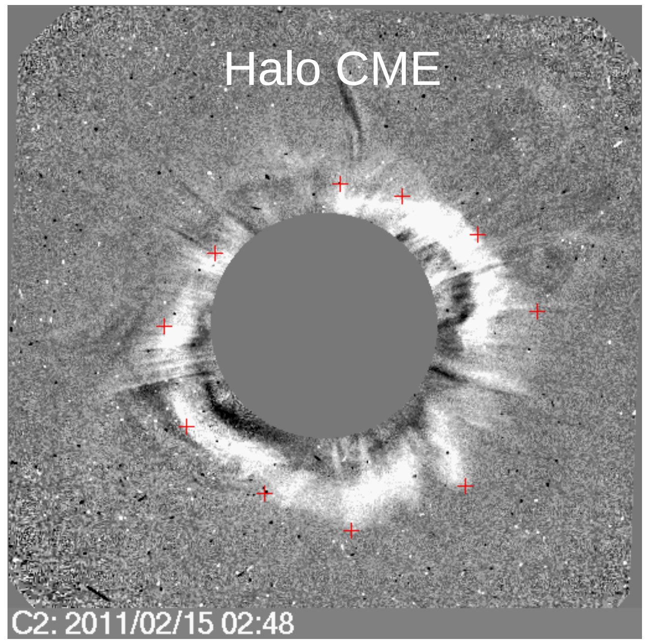
When the CMEs are fast, they drive fast mode MHD shock

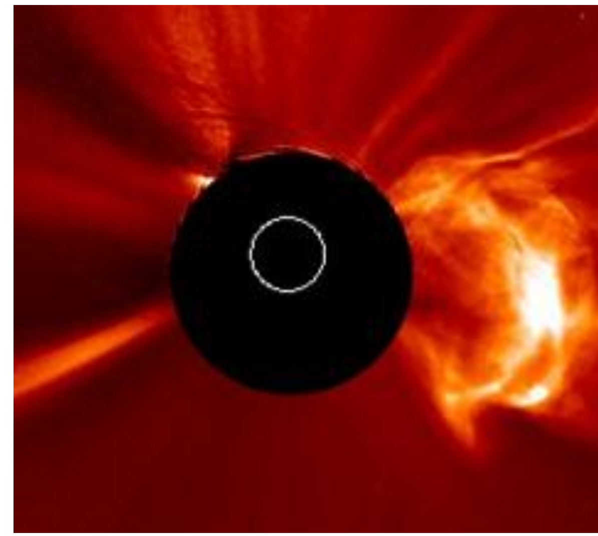
The shock can accelerate particles and produce sudden commencement when arriving at Earth





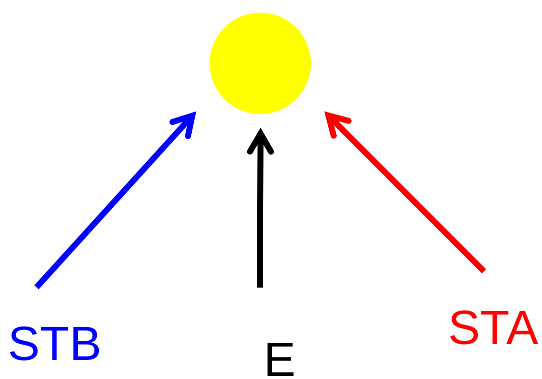






Limb CME

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

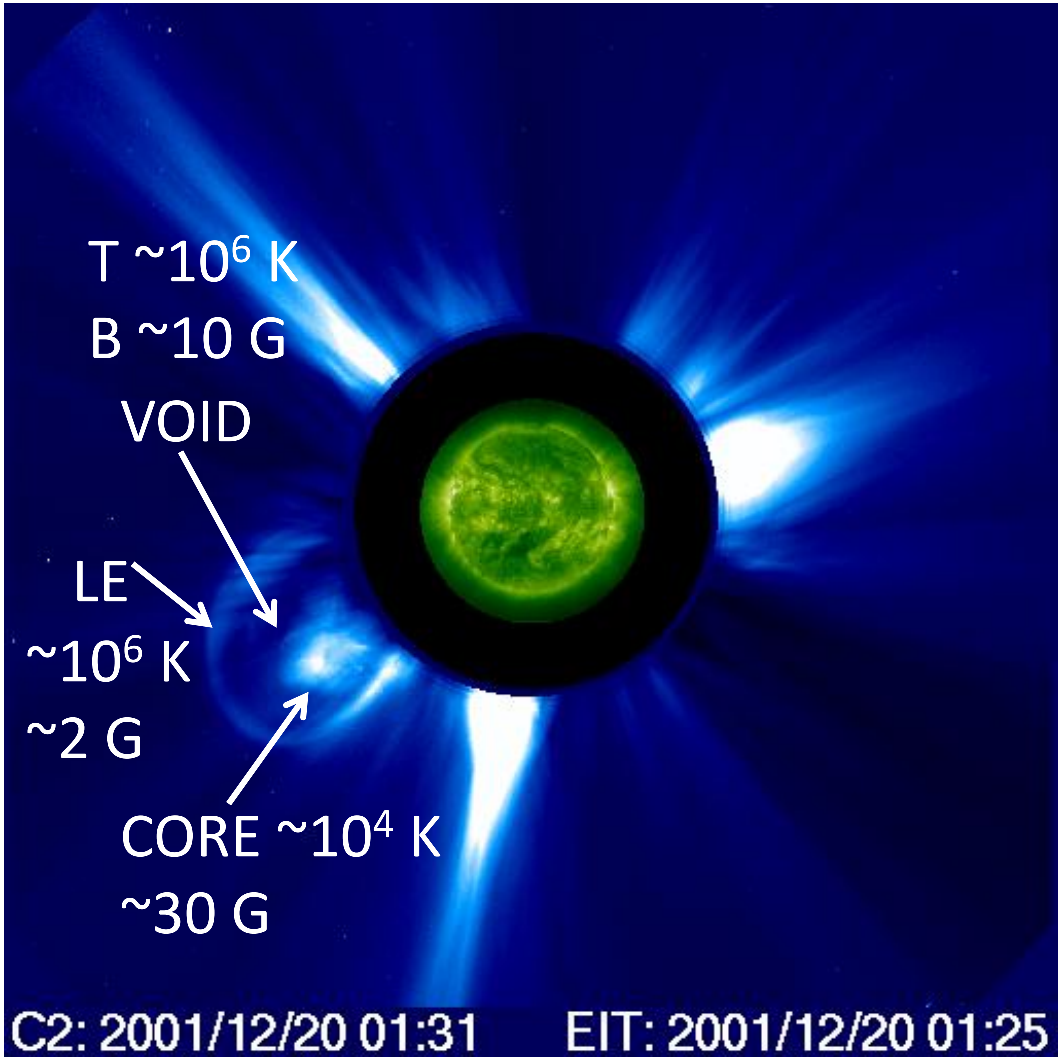
Three-part structure
Illing & Hundhausen, 1986

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

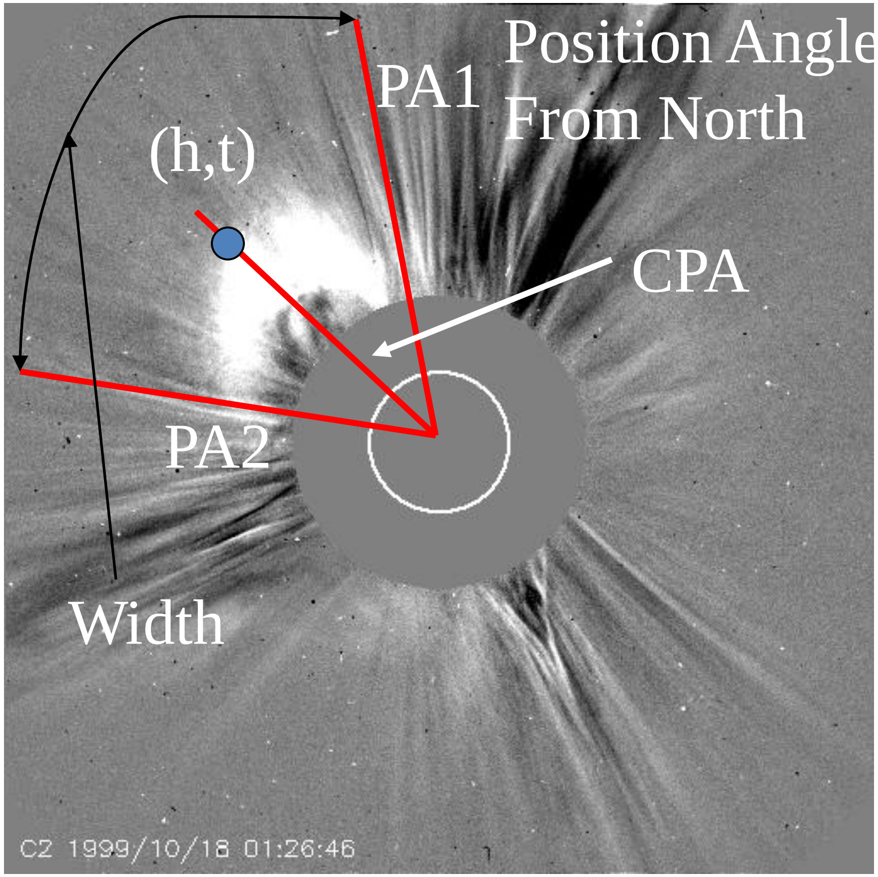
Base Difference: $F_n - F_o$
Running Difference: $F_n - F_{n-1}$
F_n, F_{n-1}, F_o are images at times t_n , t_{n-1} and t_o

CPA = Angle made by CME apex with Solar North

Width = PA2 – PA1

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

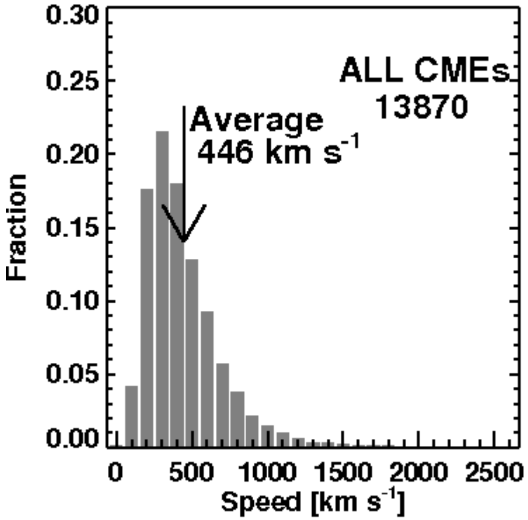
N

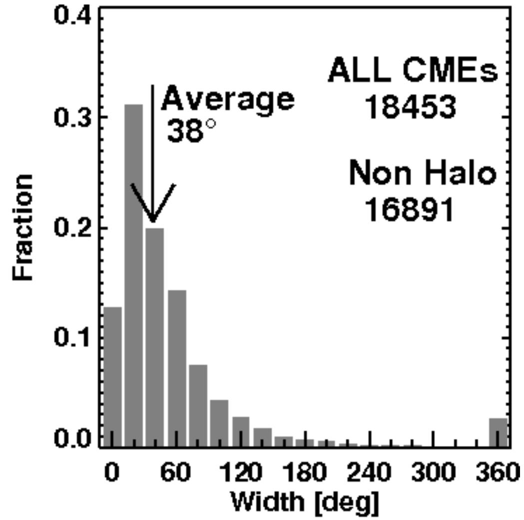


W

S

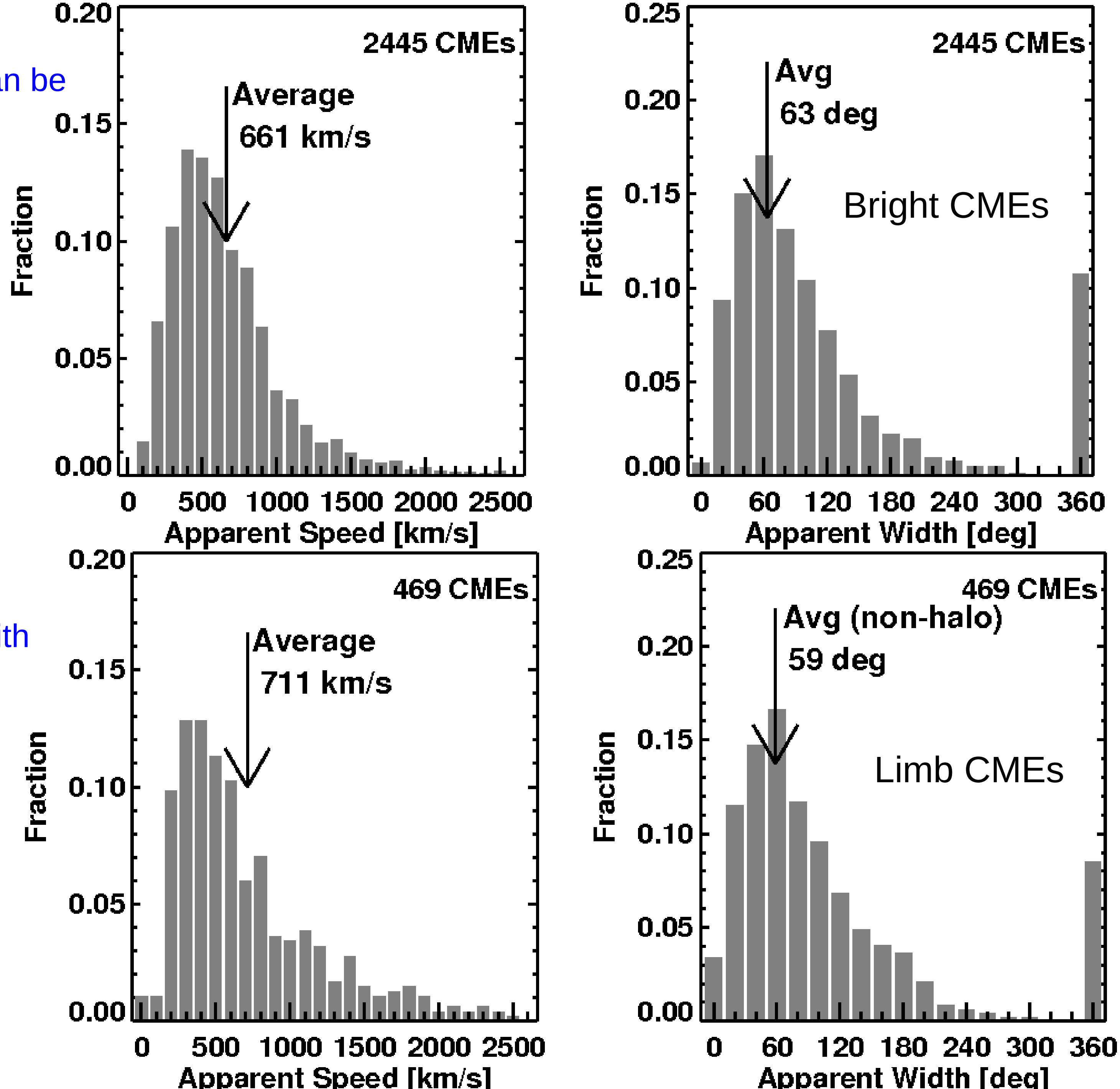
Kinematic Properties: Speed & Width



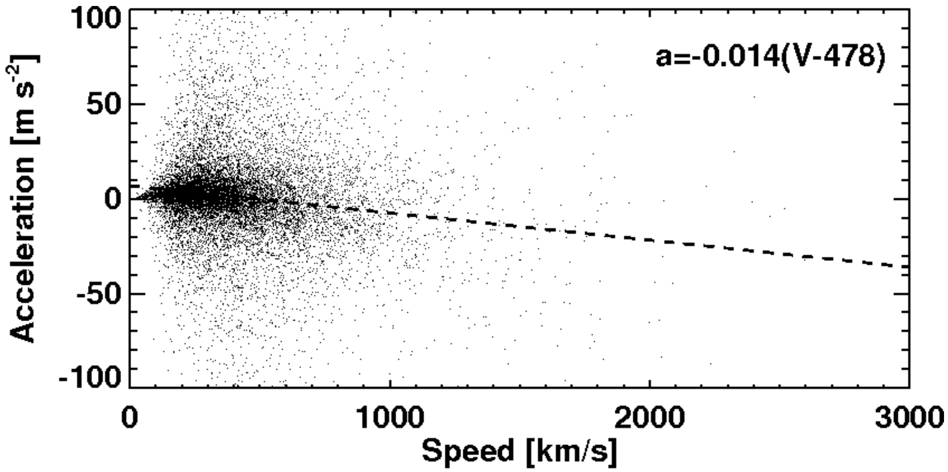


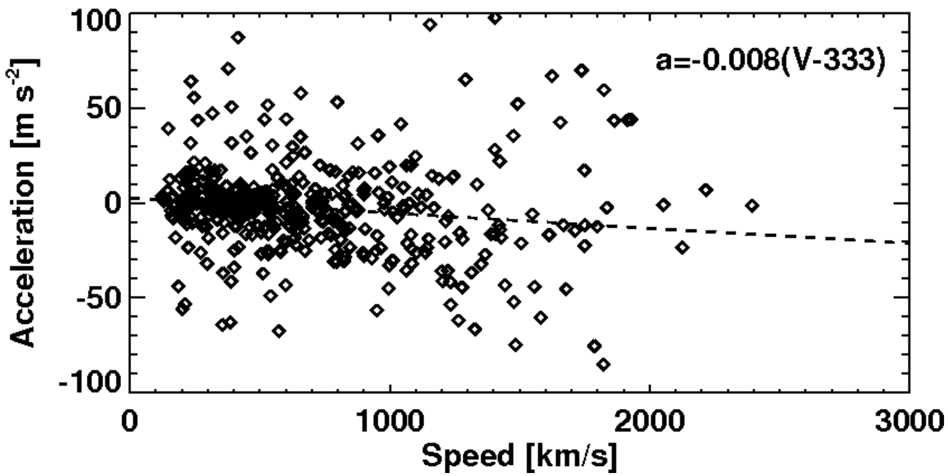
CMEs that can be Measured to >20 Rs

Limb CMEs associated with ≥C3.0 flare



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

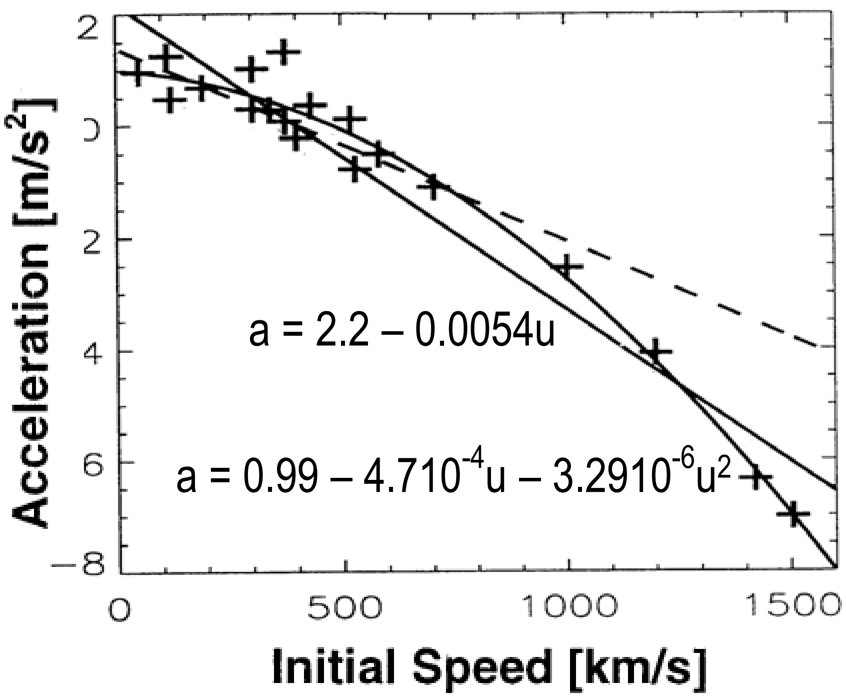
So, the measured acceleration is therefore mostly due to aerodynamic drag:
$a = -a_d$
and is referred to as residual acceleration

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

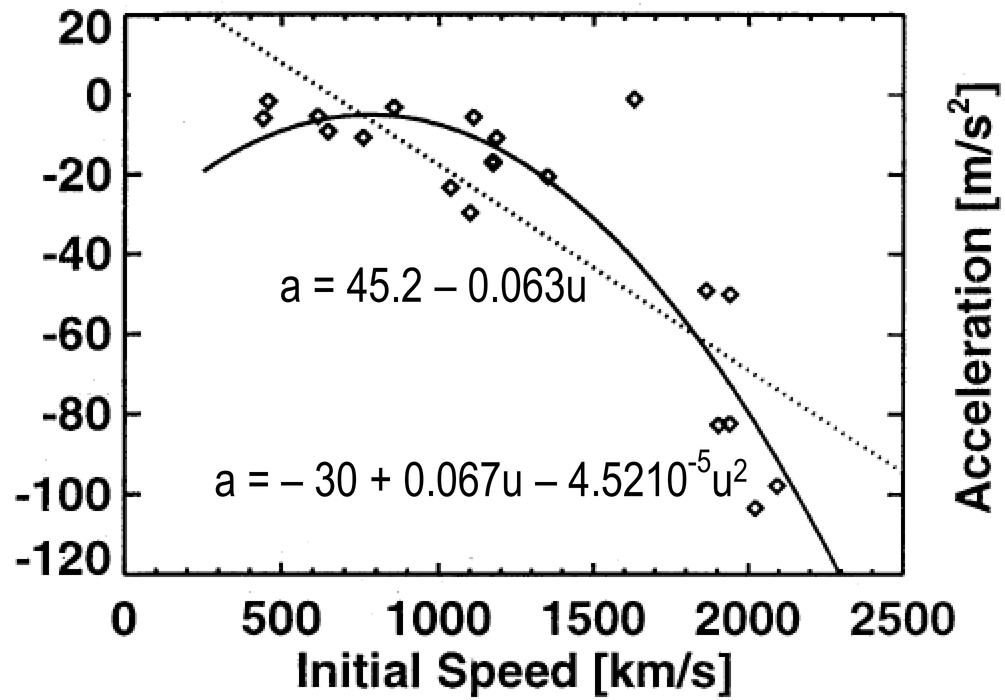
IP Acceleration

The average acceleration of a CME over the Sun-Earth distance can be obtained from the coronagraphic and in situ speed measurements

(a) Helios/PVO Data



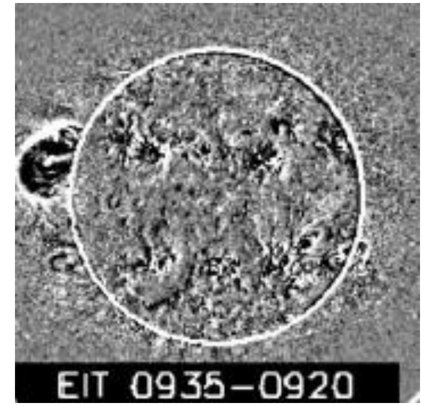
(b) SOHO/LASCO Limb CMEs



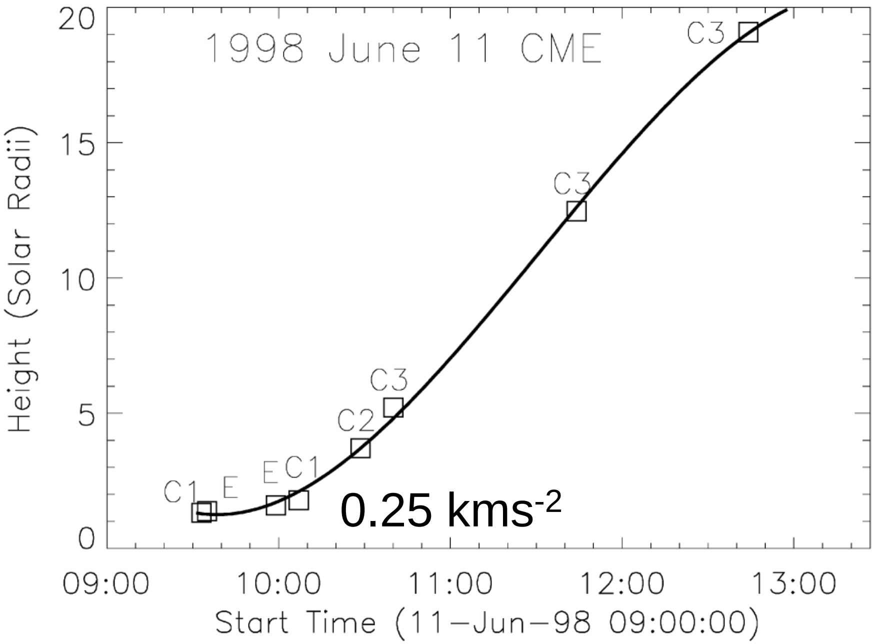
useful for predicting Sun-Earth travel time of CMEs based on initial speed

Gopalswamy et al., 2001

Acceleration from LASCO C1, EIT



Gopalswamy & Thompson 2000

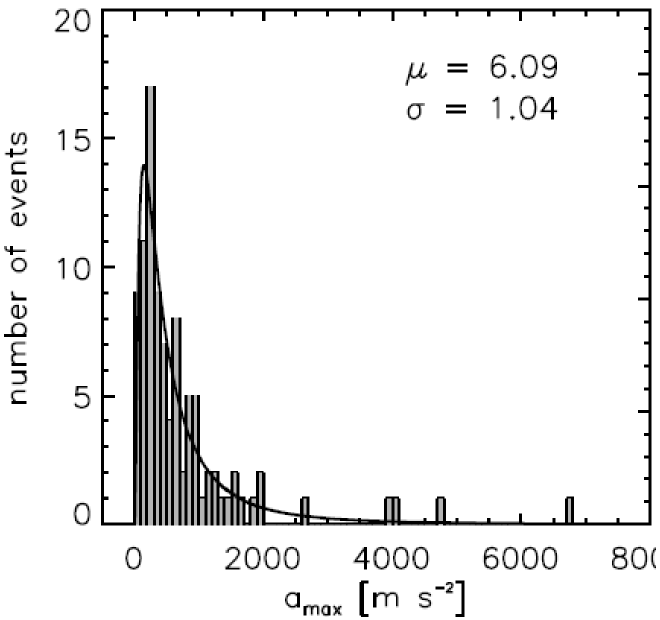


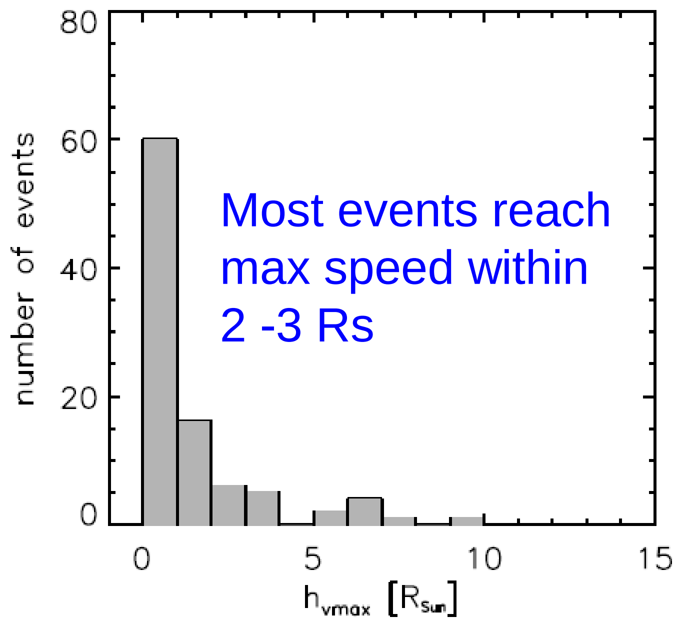
$$h = 3.1 - 0.1t + 1.5\times10^{-3}t^2 - 3.4\times10^{-6}t^3$$

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})

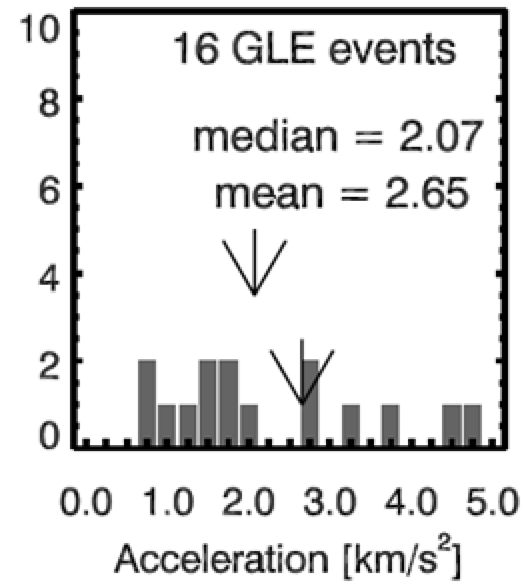
Initial Acceleration of CMEs

Bein et al., 2011





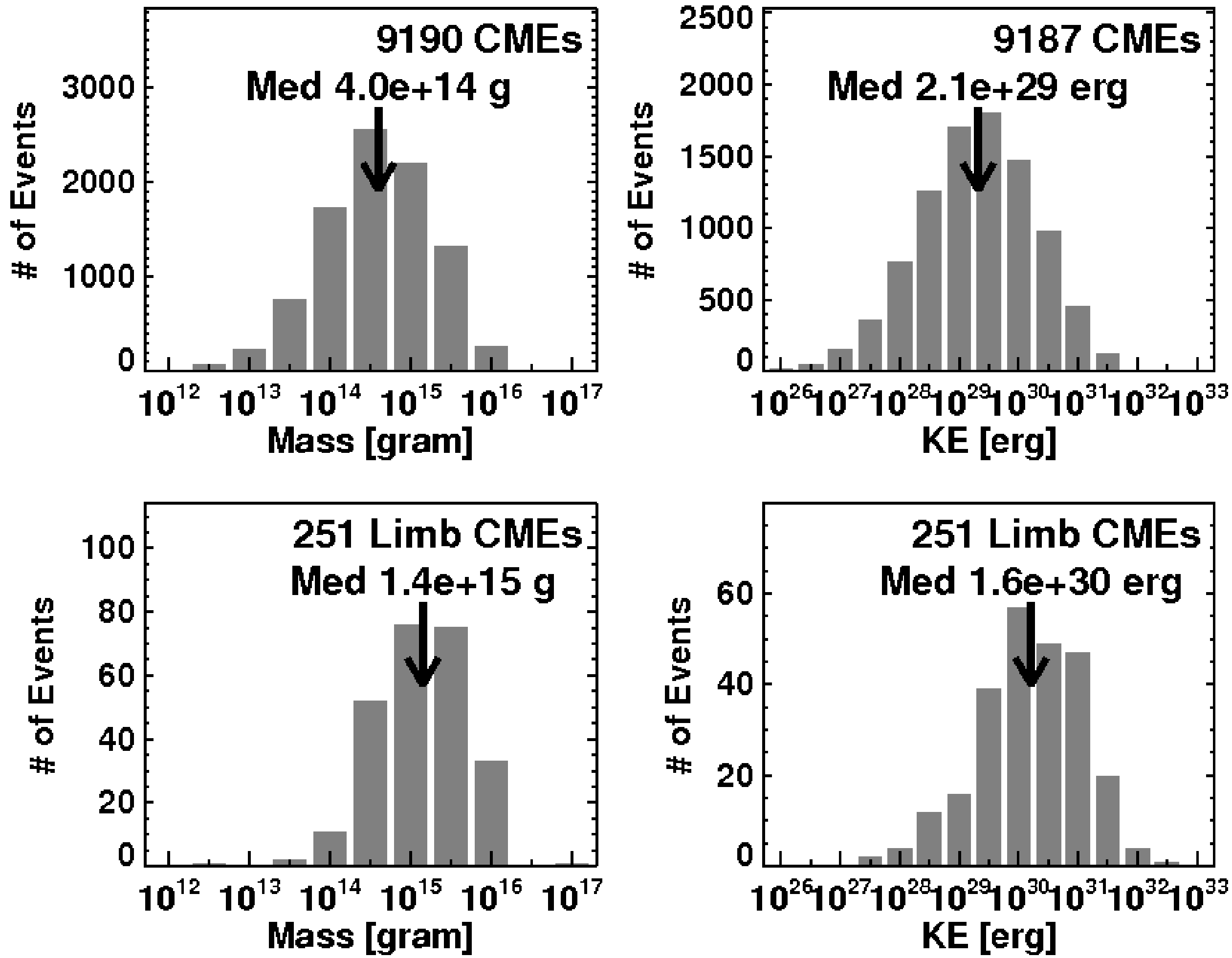
Gopalswamy et al. 2011



- 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 accel = Flare accel
- 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)

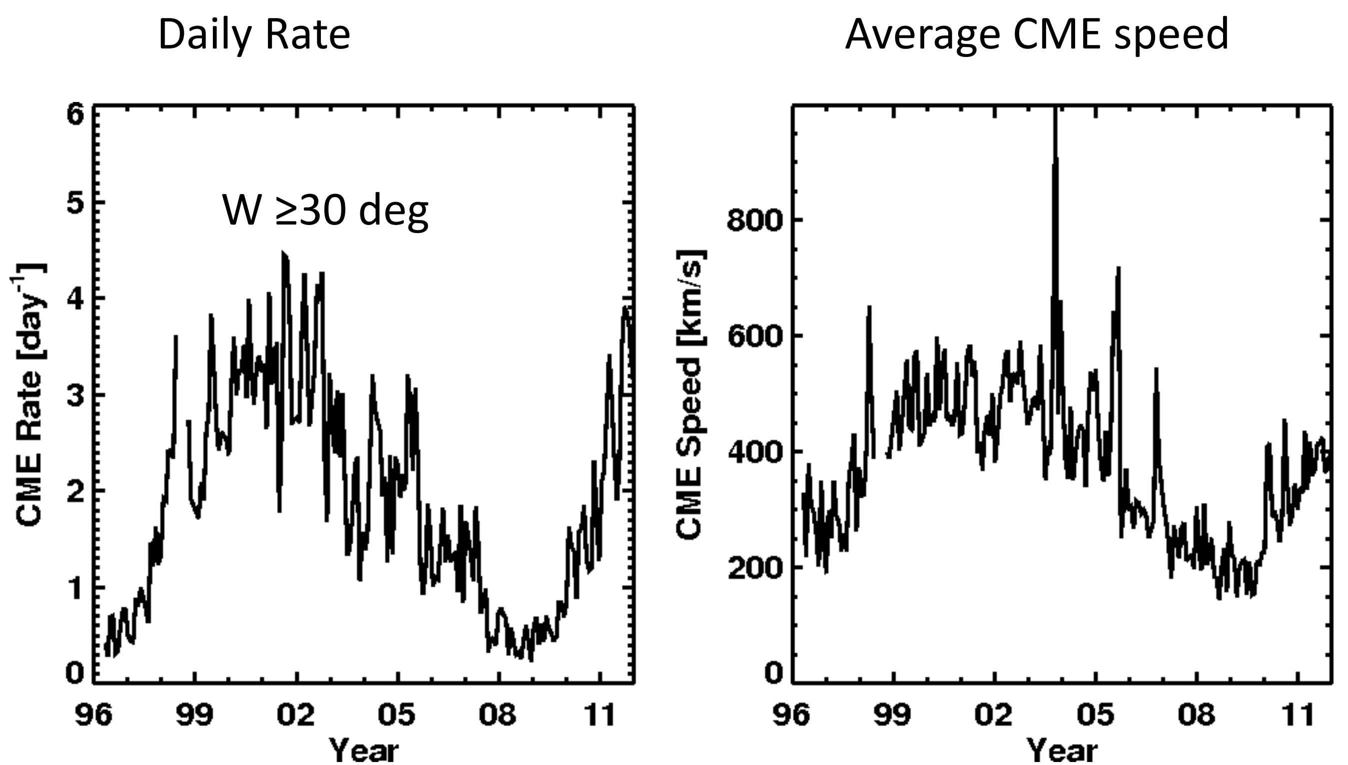
#CMEs per year
~10^3

Mass per CME
~4×10^{14} g

Mass loss due to CMEs
~4×10^{14} kg.yr^{-1}
= 2×10^{-16} Ms. yr^{-1}

Solar wind mass loss:
~2×10^{-14} Ms. yr^{-1}

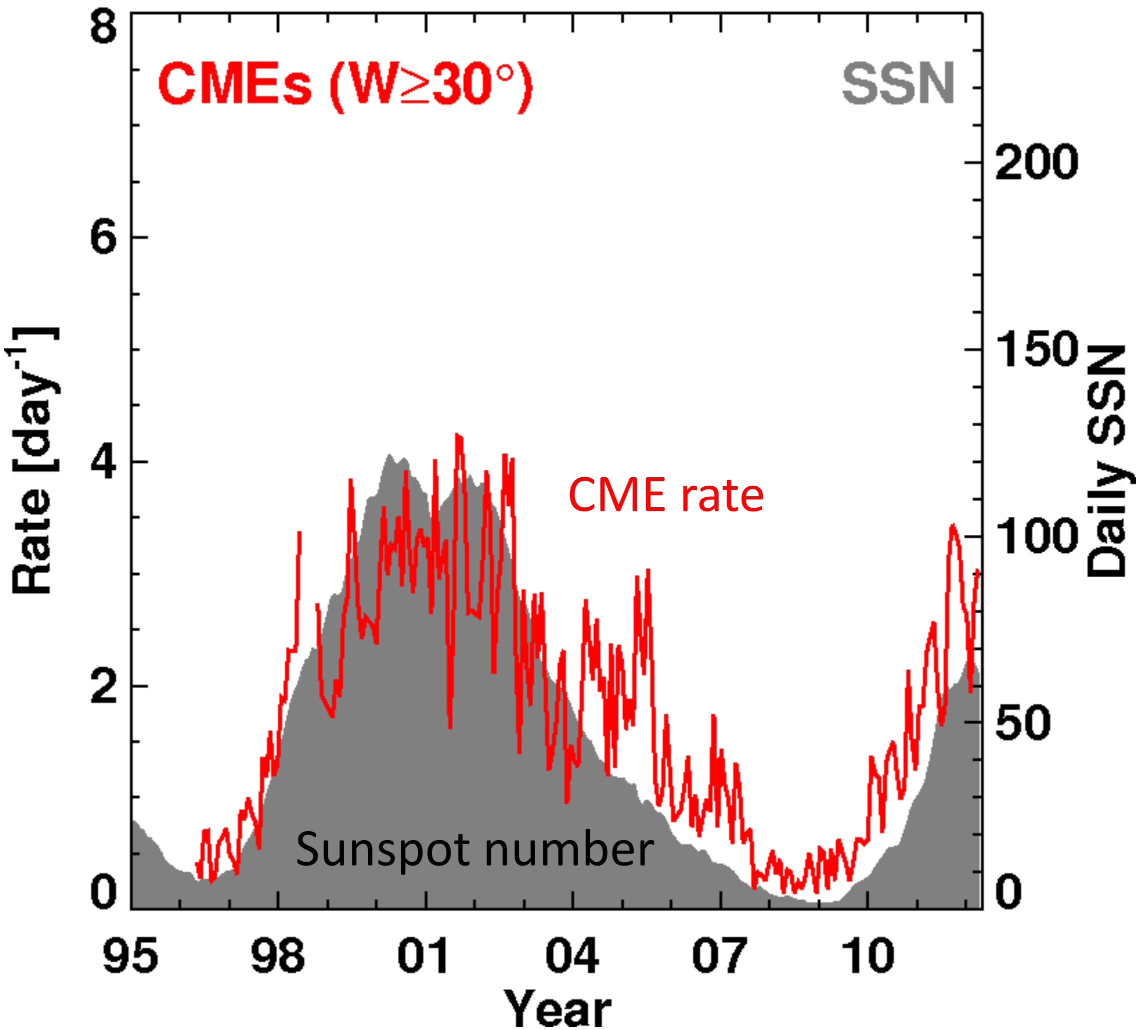
During solar maximum, CME mass loss up to 10% of solar wind flux



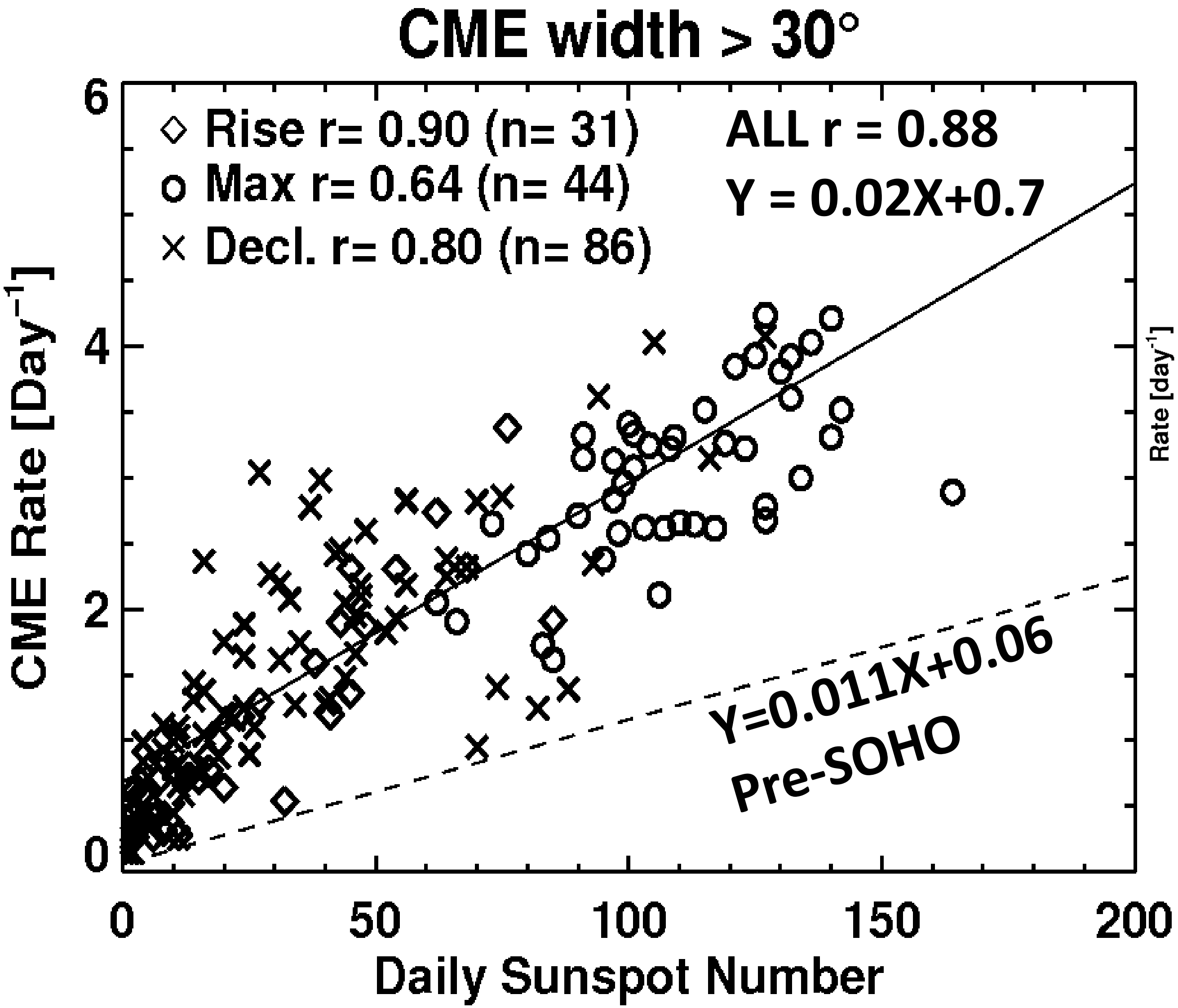
The rate is ~0.5 per day during the solar minimum and exceed ~4 per day during solar maximum

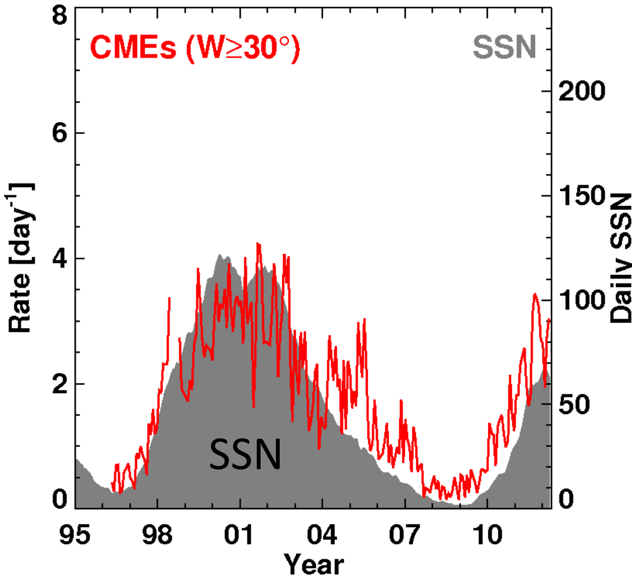
The CME speed also varies with solar cycle: CMEs are generally faster during solar maxima

CME Rate Compared with Sunspot Number (SSN)



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

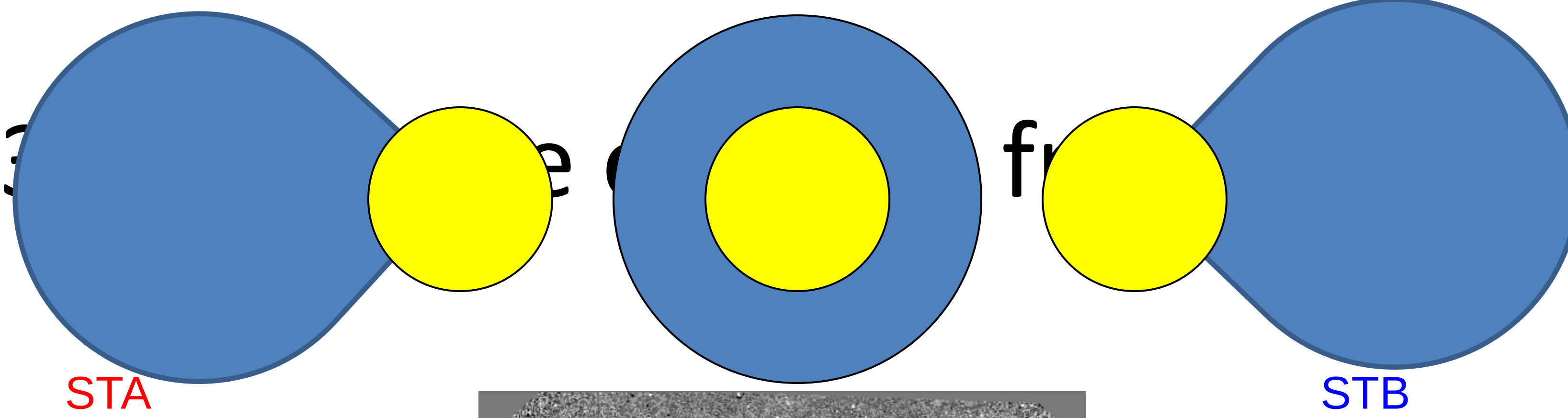
- CMEs that appear to surround the occulting disk in sky-plane projection

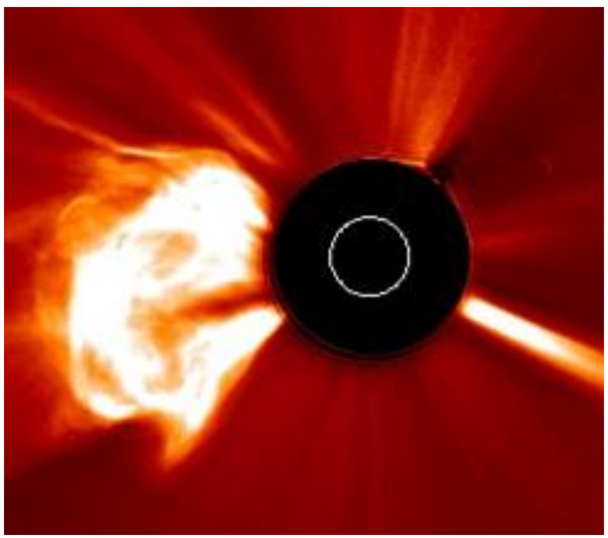
- Halos are no different from other CMEs, except that they must be faster and wider on the average to be visible outside the occulting disk

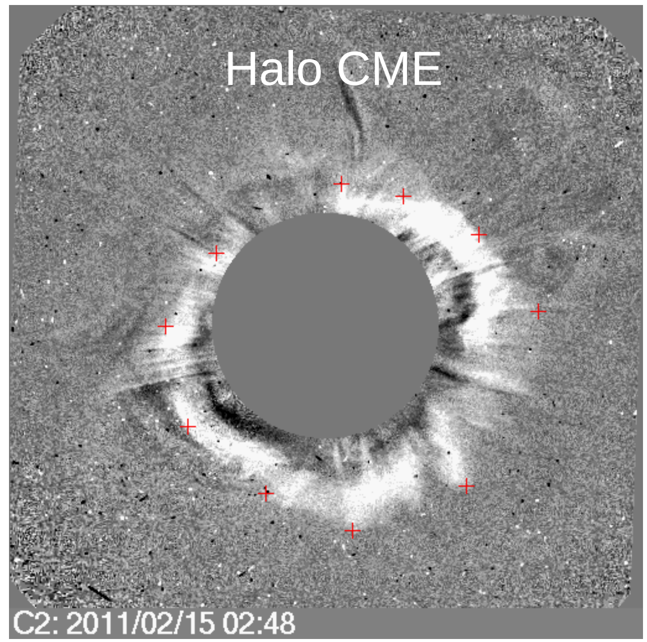
- Halos affect a large volume of the corona

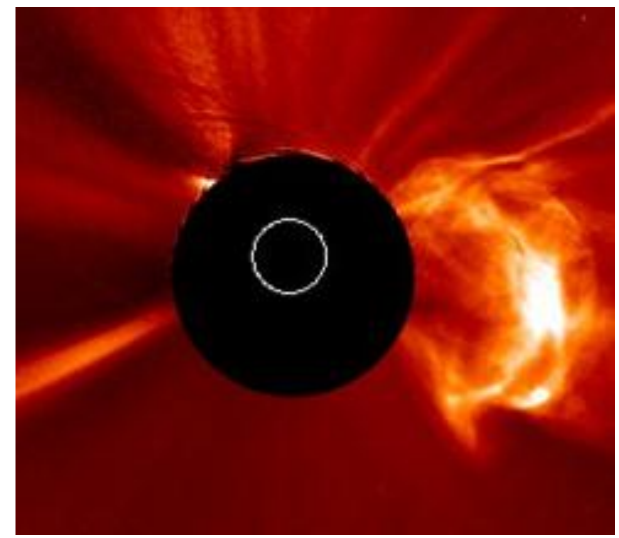
- Most of the halos may be shock-driving

- Halos can be heading away or toward Earth. Those heading toward Earth are important for space weather





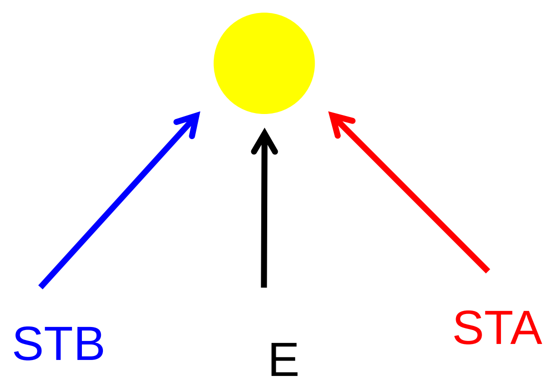




Limb CME

Limb CME

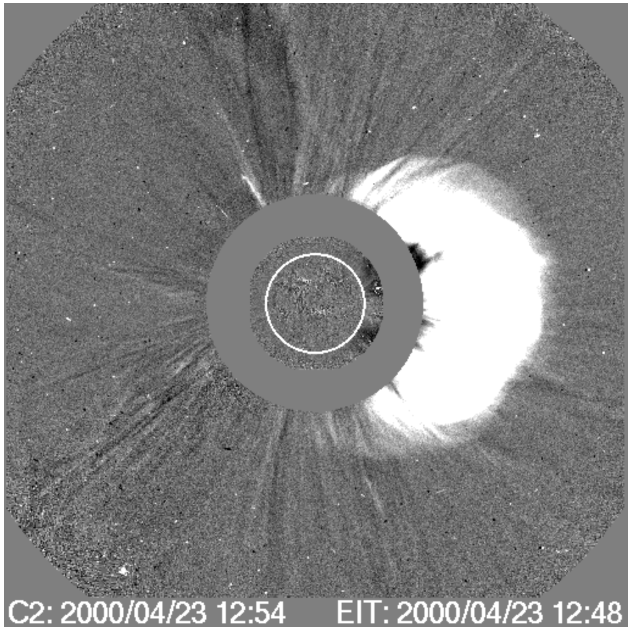
3-D Structure of CMEs

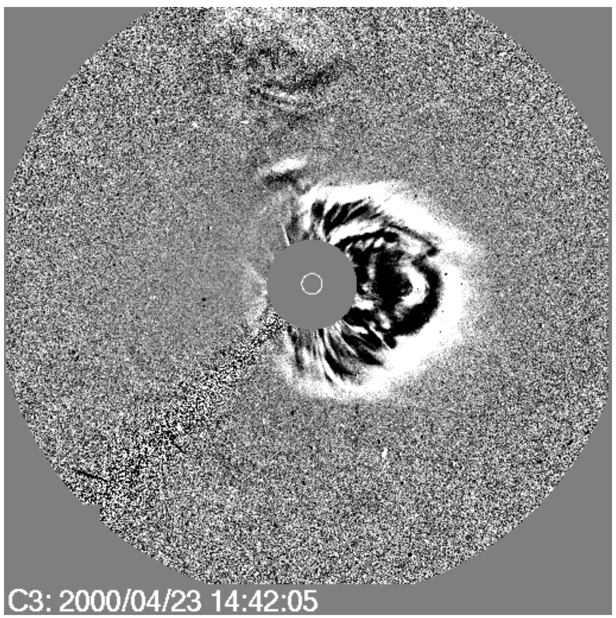


demonstration that halo CMEs are normal CMEs

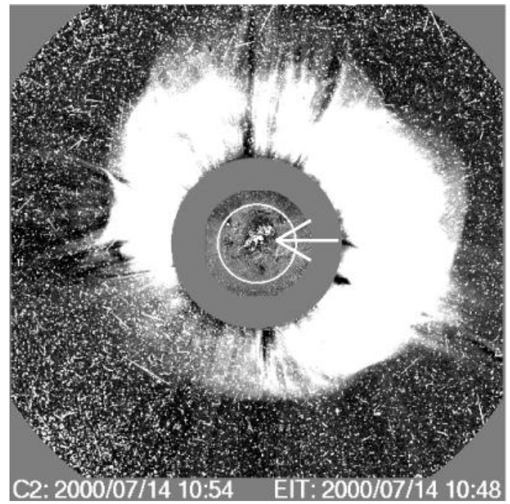
Halo CMEs

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

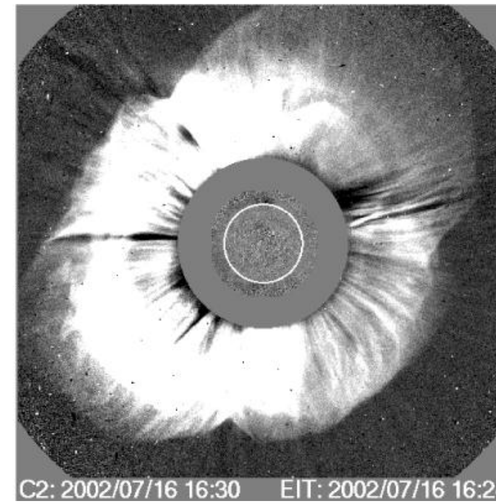




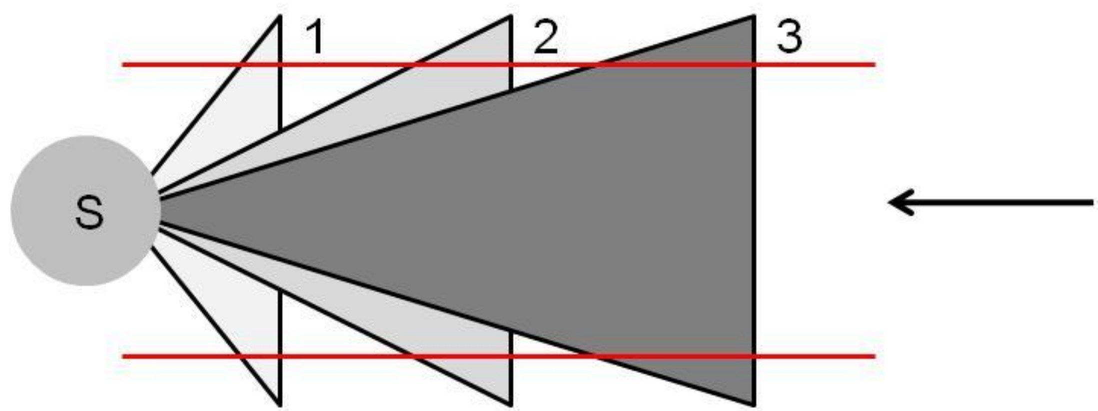
Partial halo becomes asymmetric halo



Front-side halo



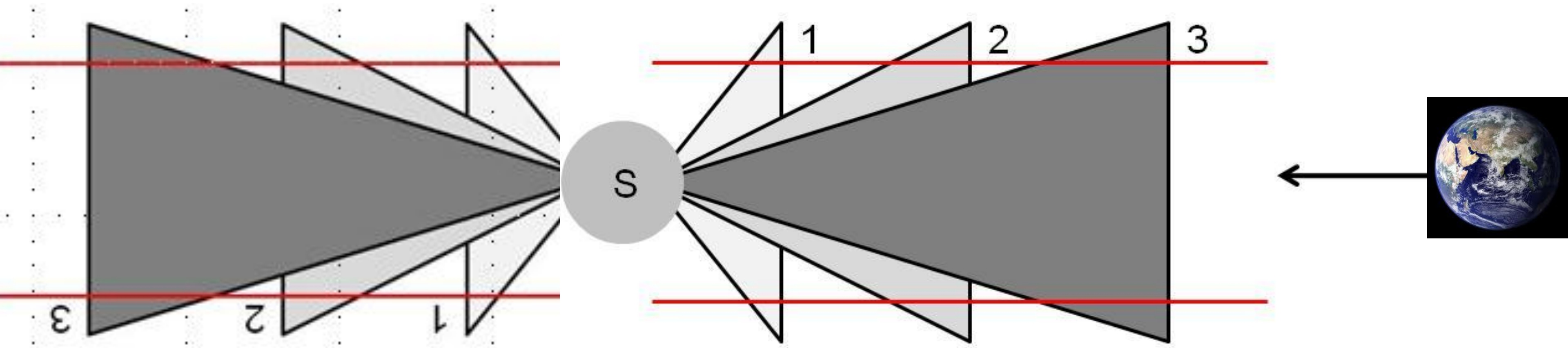
back-side halo



Halo CMEs are generally wide

The three cones 1, 2, 3 represent 3 CMEs

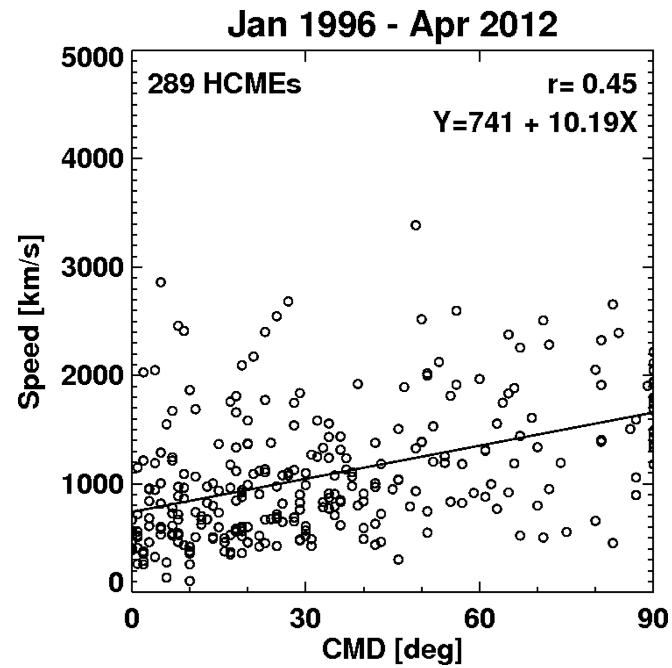
Frontside halos (earth-directed)

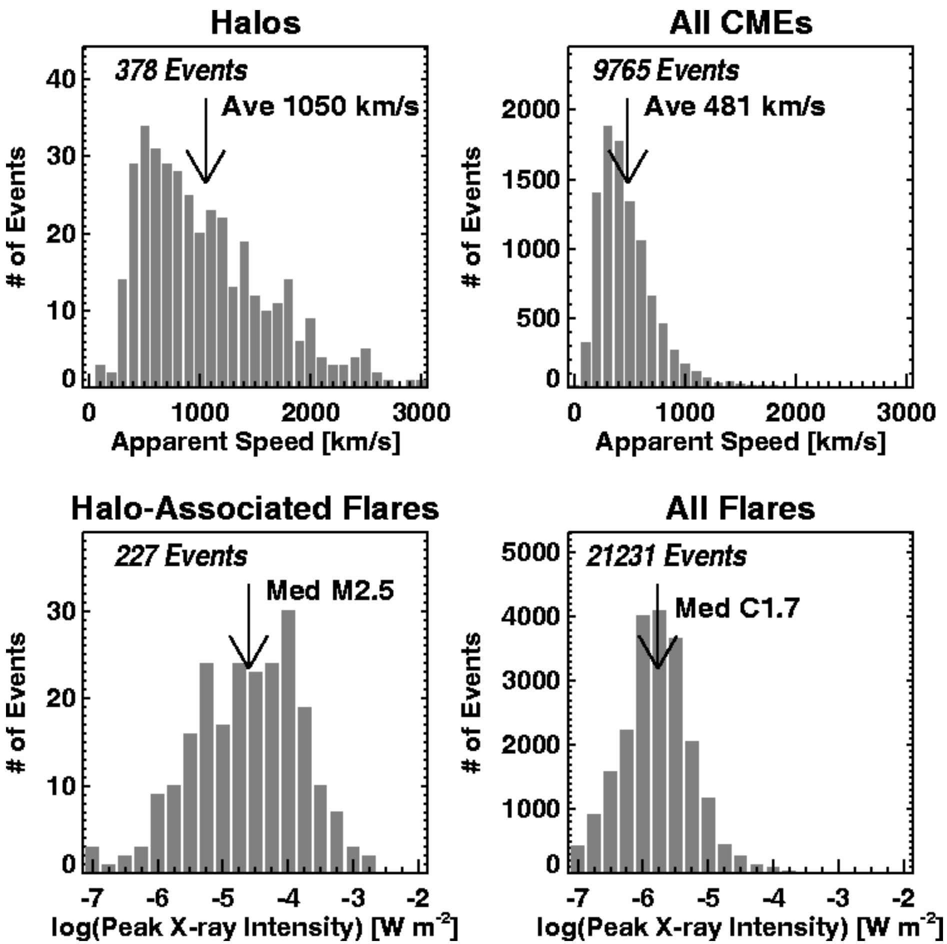


backside halos
(anti-earthward)

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

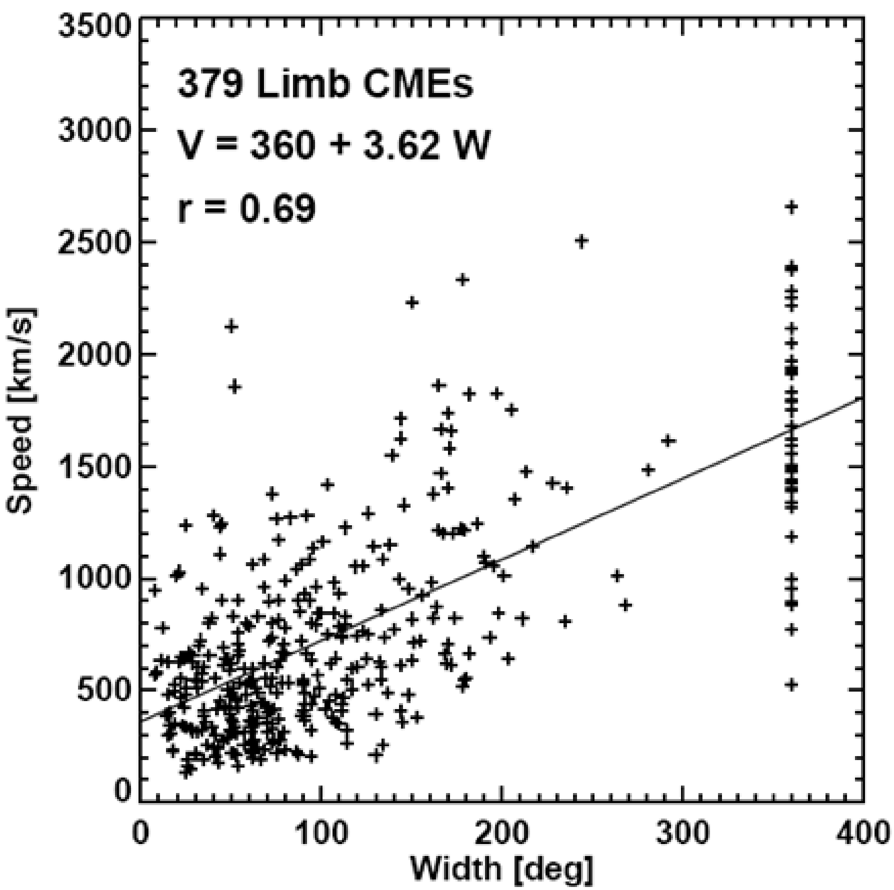
Halos are ~ 2 times faster than the average CME (halo CMEs are subject to large projection effects)

Flares associated with halo CMEs are larger

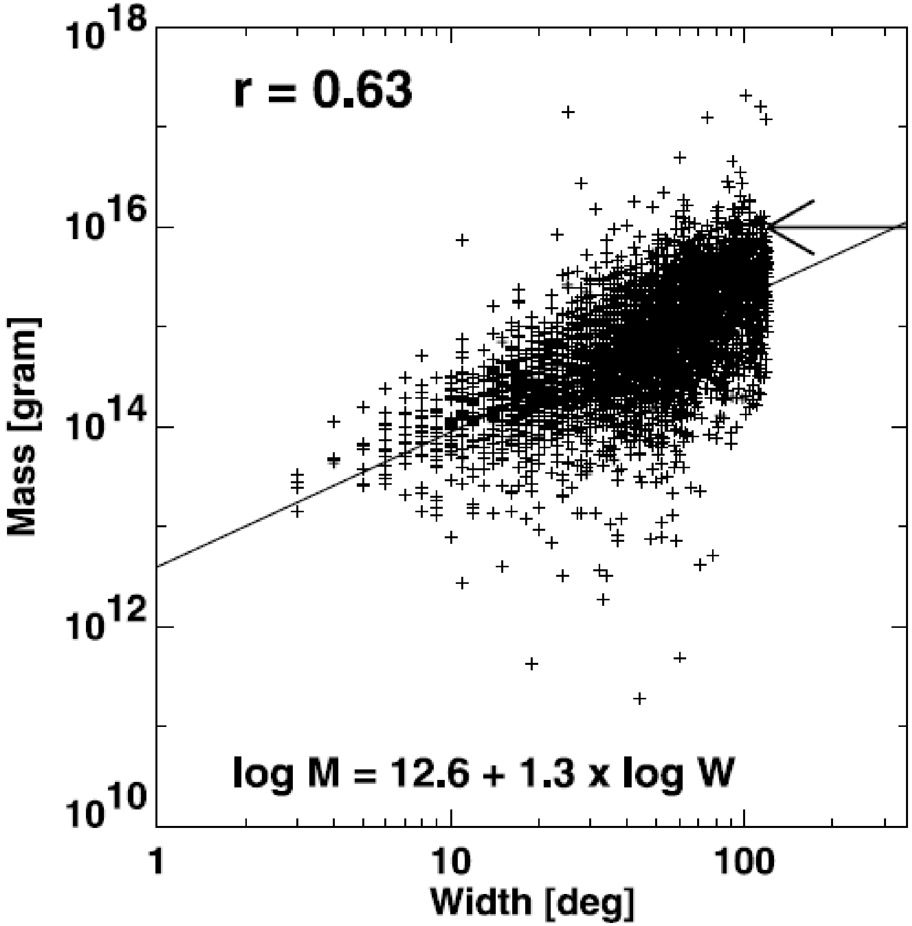
Higher kinetic energy: travel far into the interplanetary medium and impact Earth

Faster and Wider CMEs are More Energetic

Wider CMEs are faster



Wider CMEs are more massive



Halo CMEs are more energetic

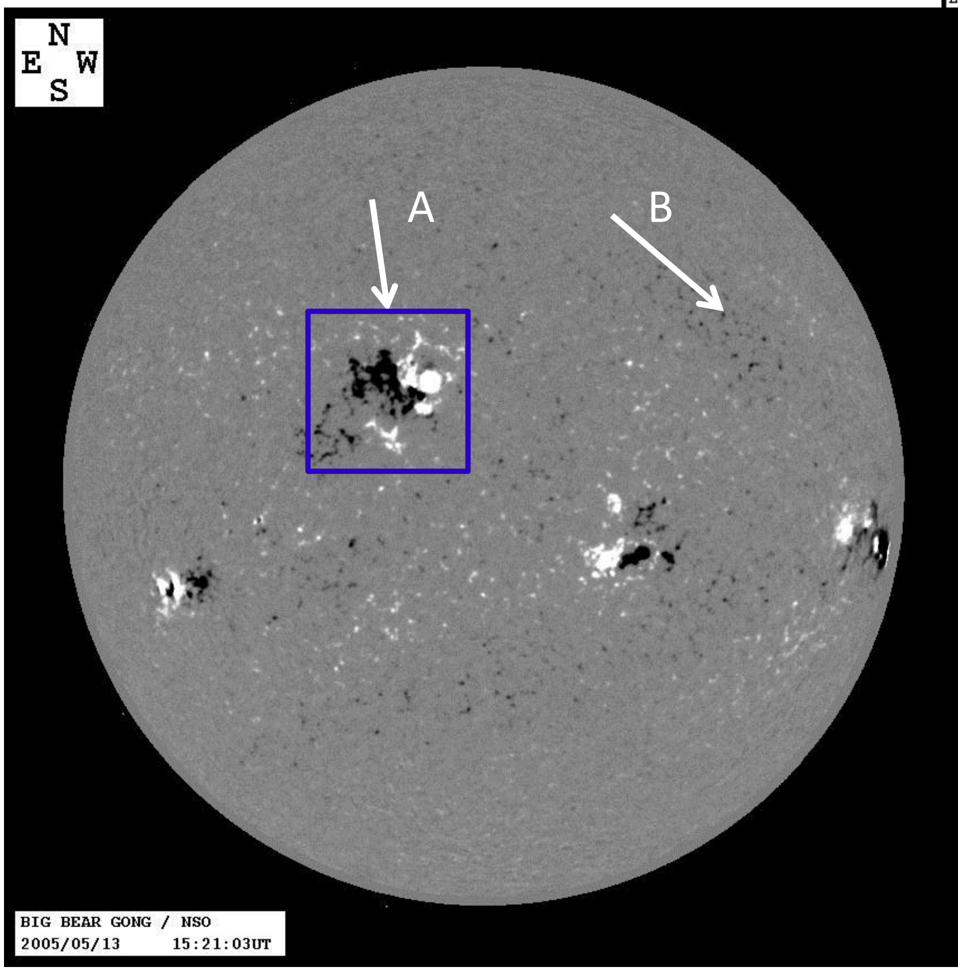
Fraction of halos is a measure of the energy of a CME population

Solar Source Regions

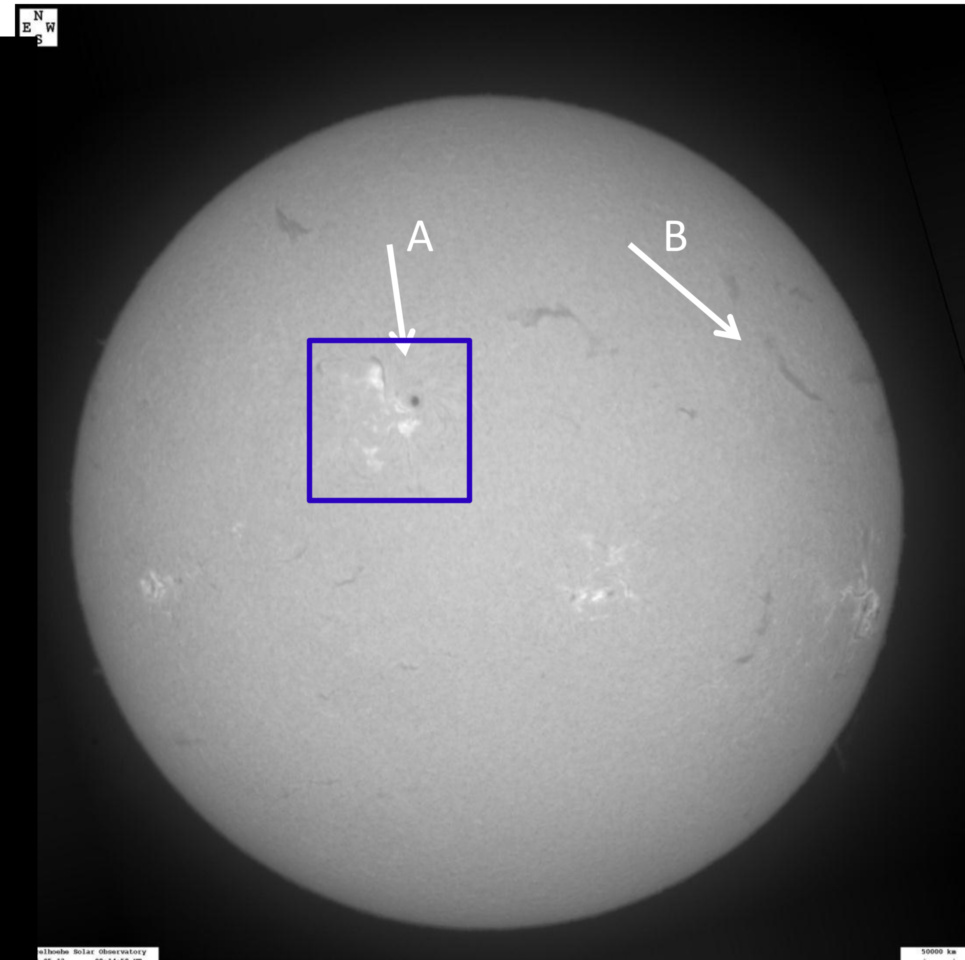
- CMEs originate from closed magnetic field regions (bipolar or multipolar configurations)
- Active regions
- Filament regions
- Loops connecting two active regions
- CME source regions are easily identified from the associated flare (close connection between CMEs and flares)

An Eruption Region

Photospheric Magnetogram



Chromosphere (H-alpha)

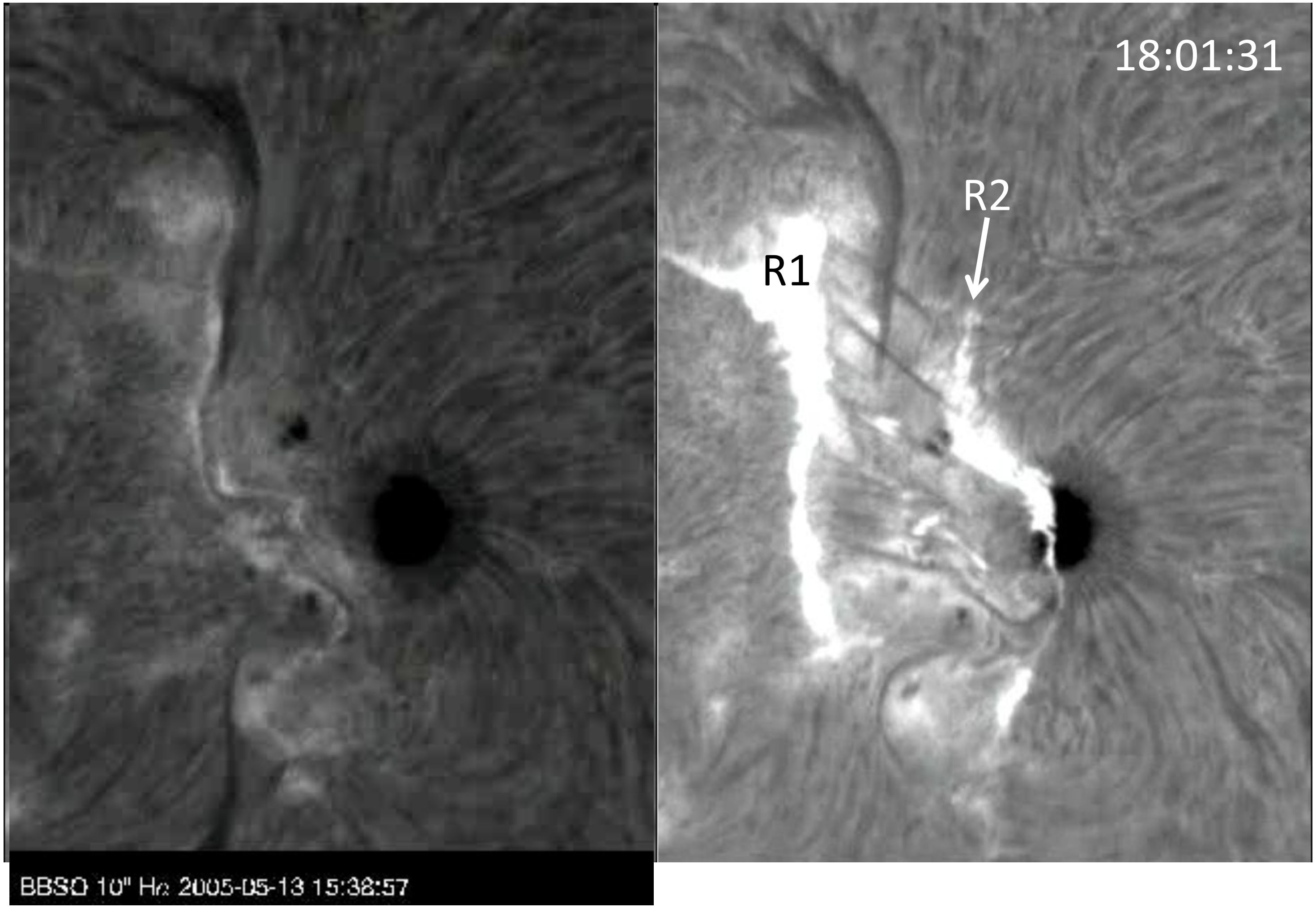


A: active region

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

Both regions have filaments along the polarity inversion line

The Sunspot Region “A” Erupts

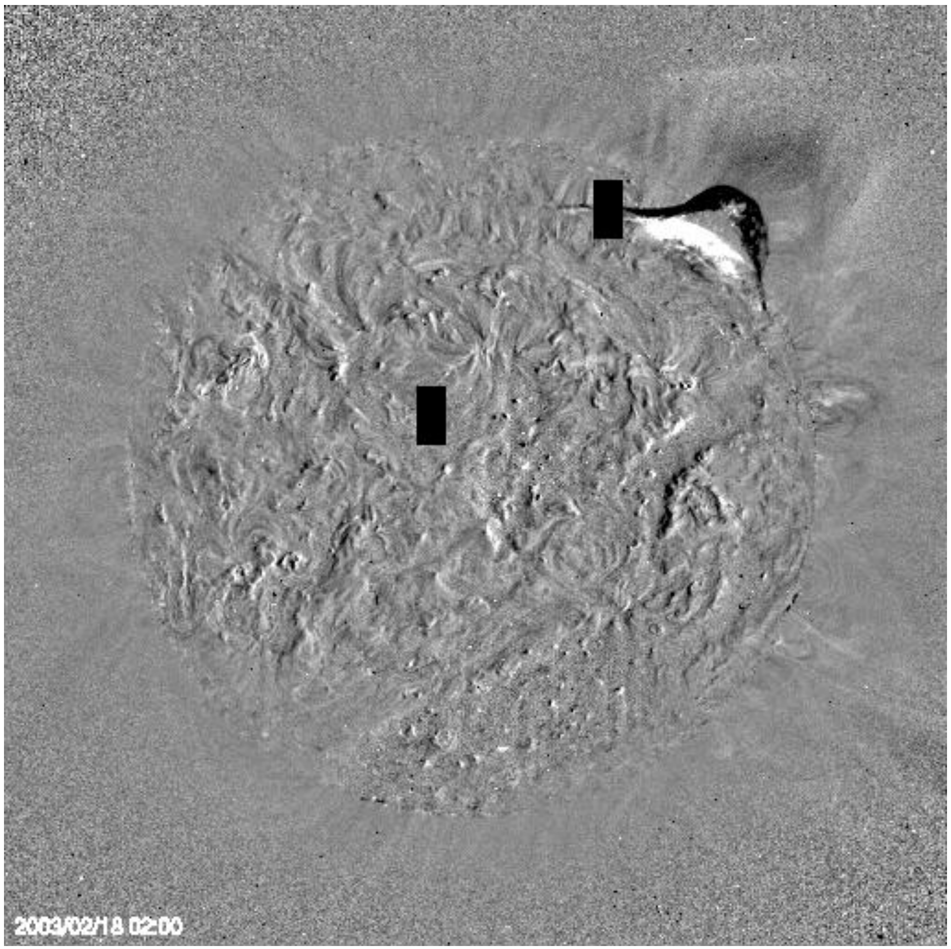


There is also wave going away from
the eruption region. Part of the filament disappears

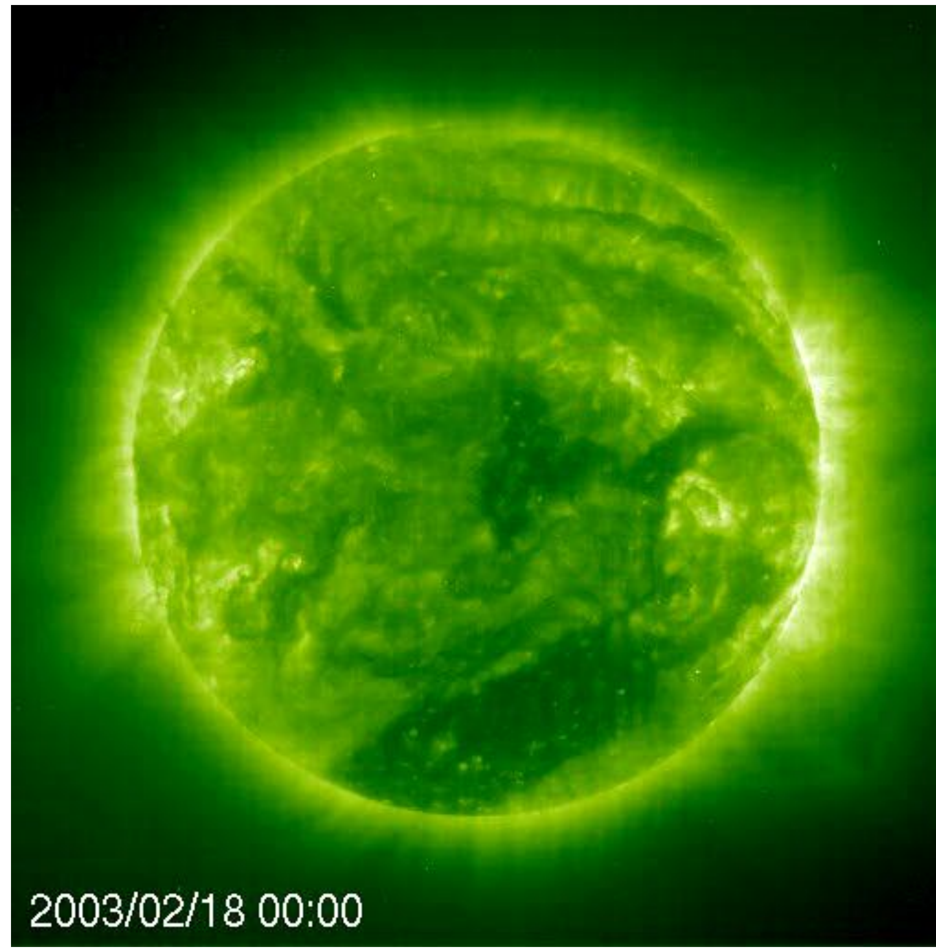
Flare arcade

Filament eruption

Difference image (SOHO/EIT)

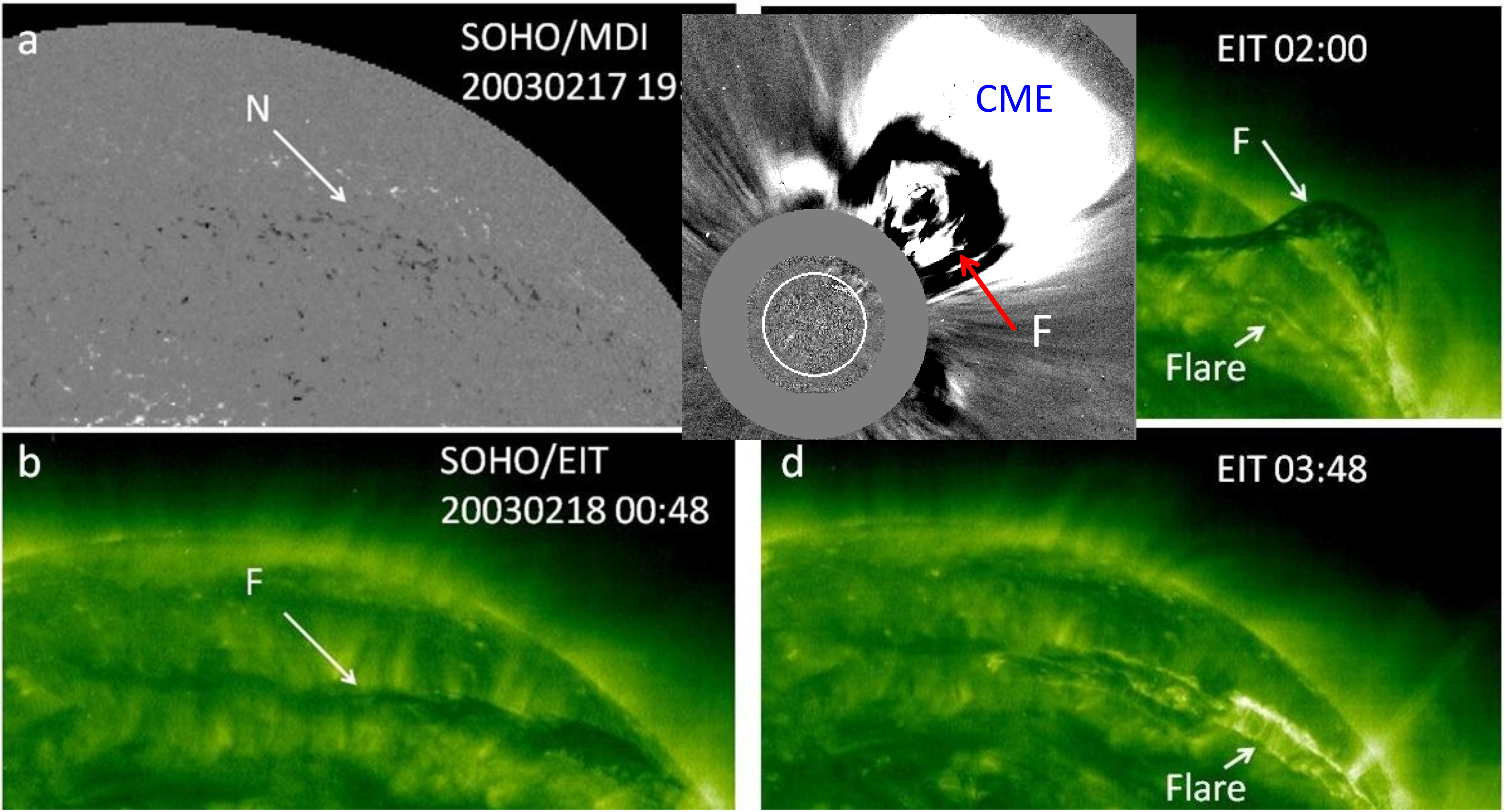


Flare from a non-sunspot region



Note the CME overlying the filament in EUV

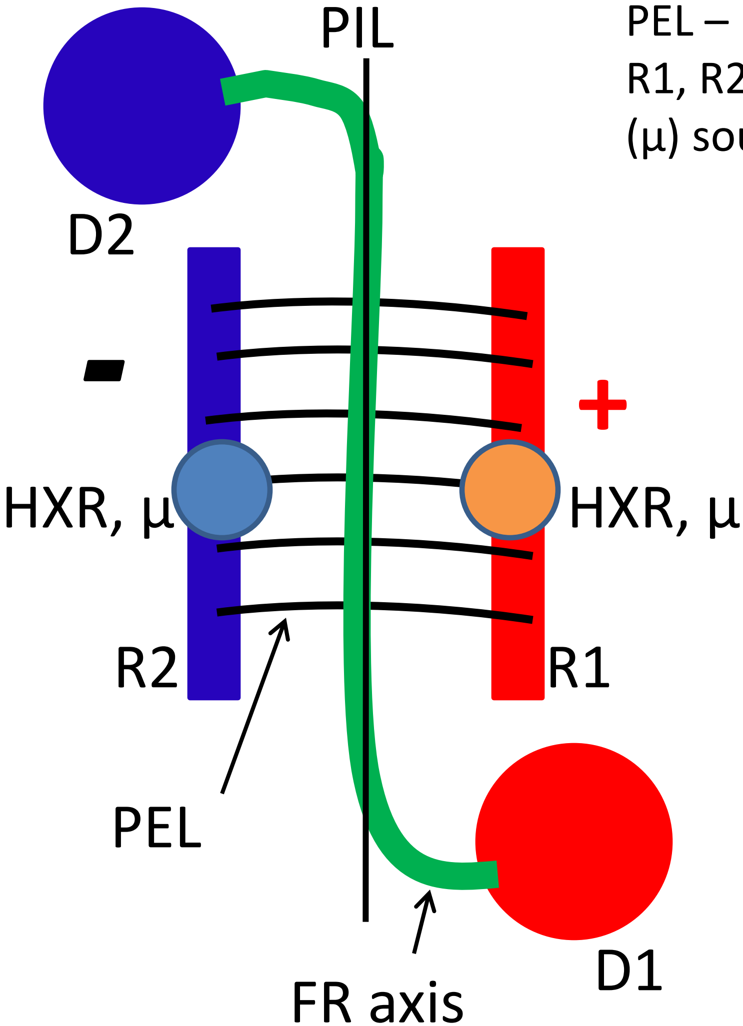
Filament Eruption in EUV

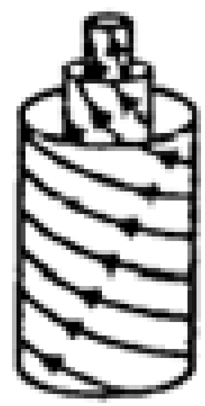


Filament (F) along neutral line (N). Flare loops under F; F becomes substructure of CMEs

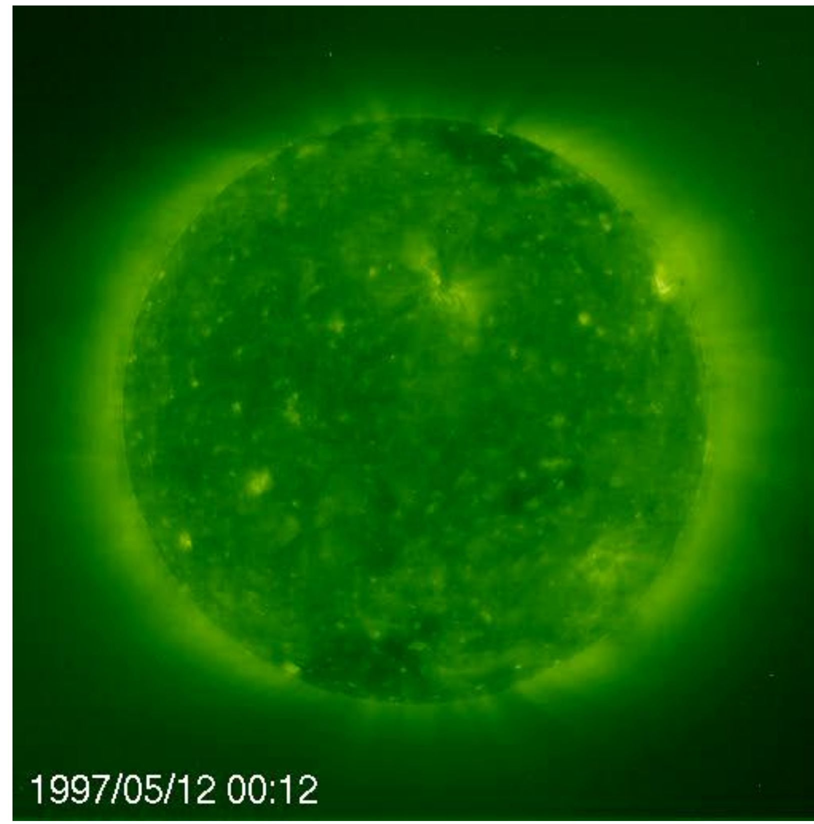
Coronal Dimming and Eruption Geometry

PIL – polarity inversion line (between + and -)
D1, D2 – dimming regions in which the flux rope (FR) is rooted
PEL – post eruption loops
R1, R2 – flare ribbons with hard X-ray (HXR) and microwave (μ) source locations.





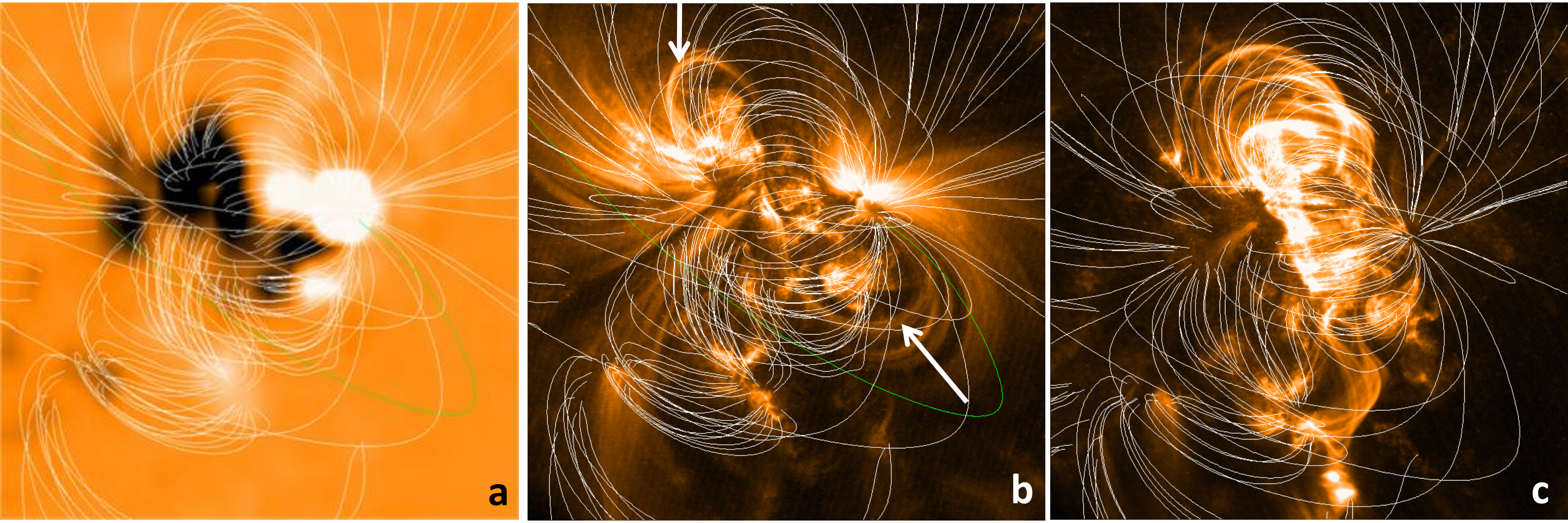
FR



Dimming: Sites of flux rope legs?

Where does the energy come from?

Extrapolated field lines on TRACE coronal images



2005/05/13 14:56:00

2005/05/13 15:25:56

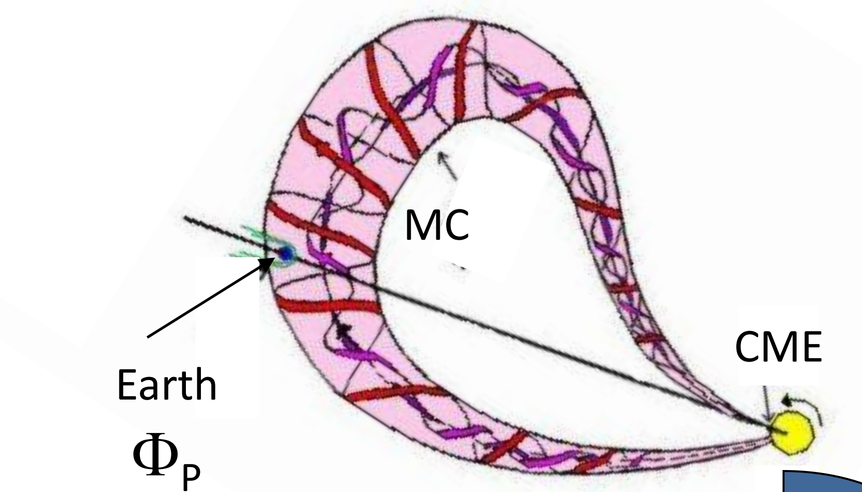
2005/05/13 21:26:36

Photospheric magnetogram with potential field extrapolation

Actual coronal structure is "distorted" from potential field → free energy (FE)
Distortion due to current J.
Lorentz force JxB propels the CME

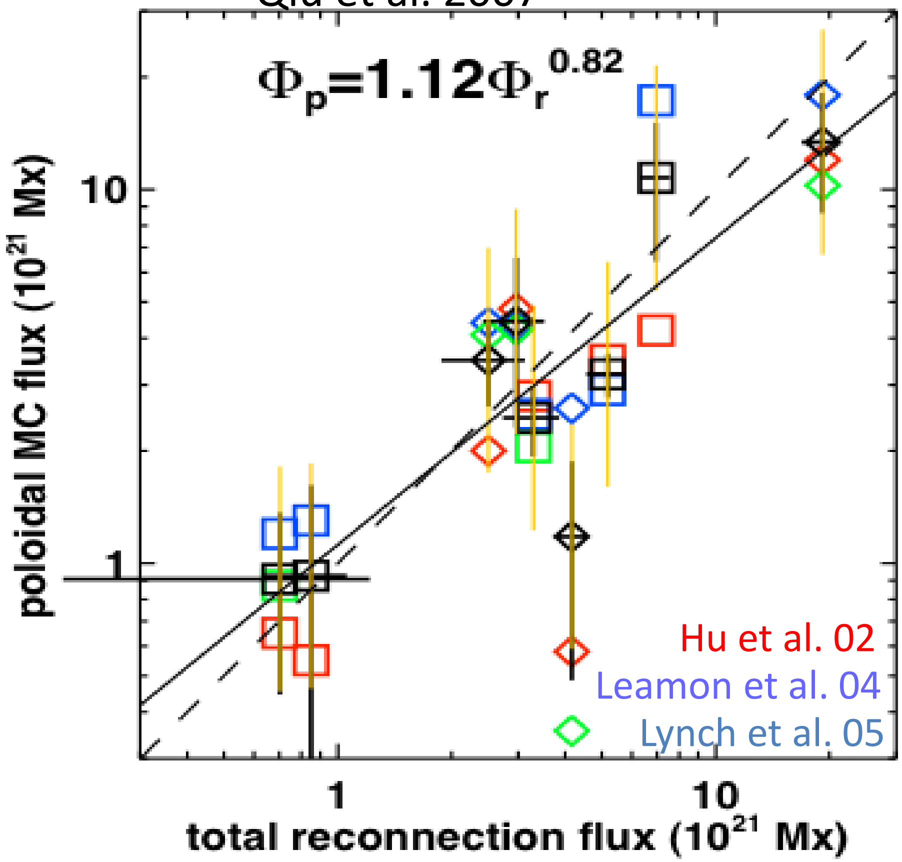
Free energy went into the CME kinetic energy
Arcade is now potential (no more current J)

De Rosa & Schrijver

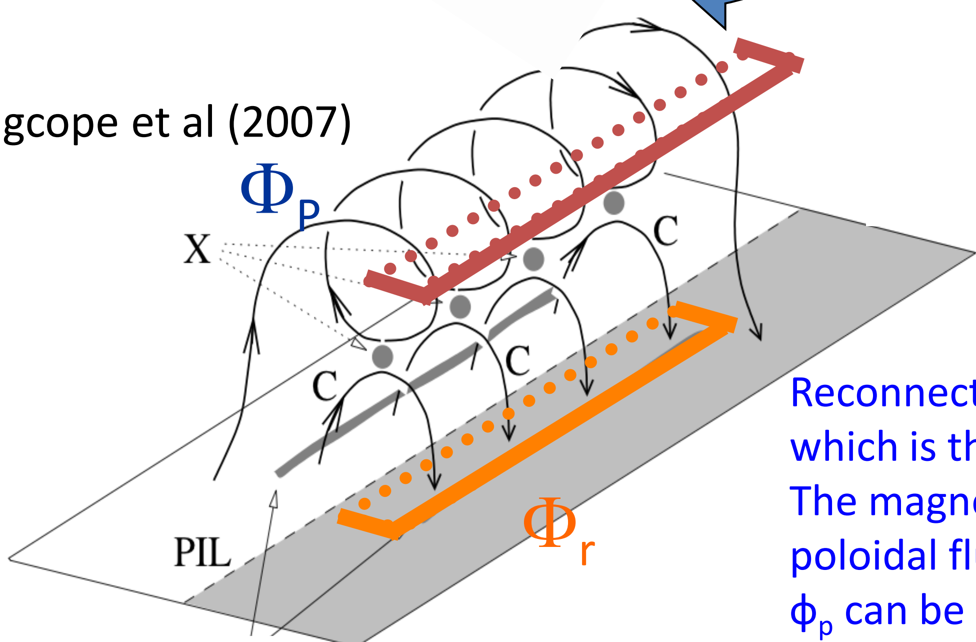


Marubashi 1997

Qiu et al. 2007

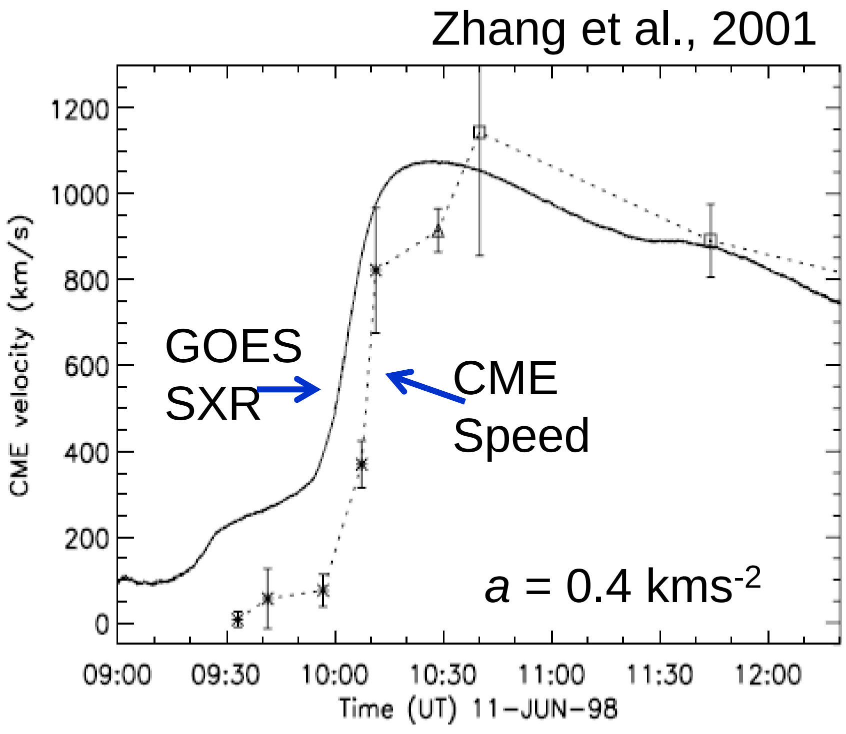


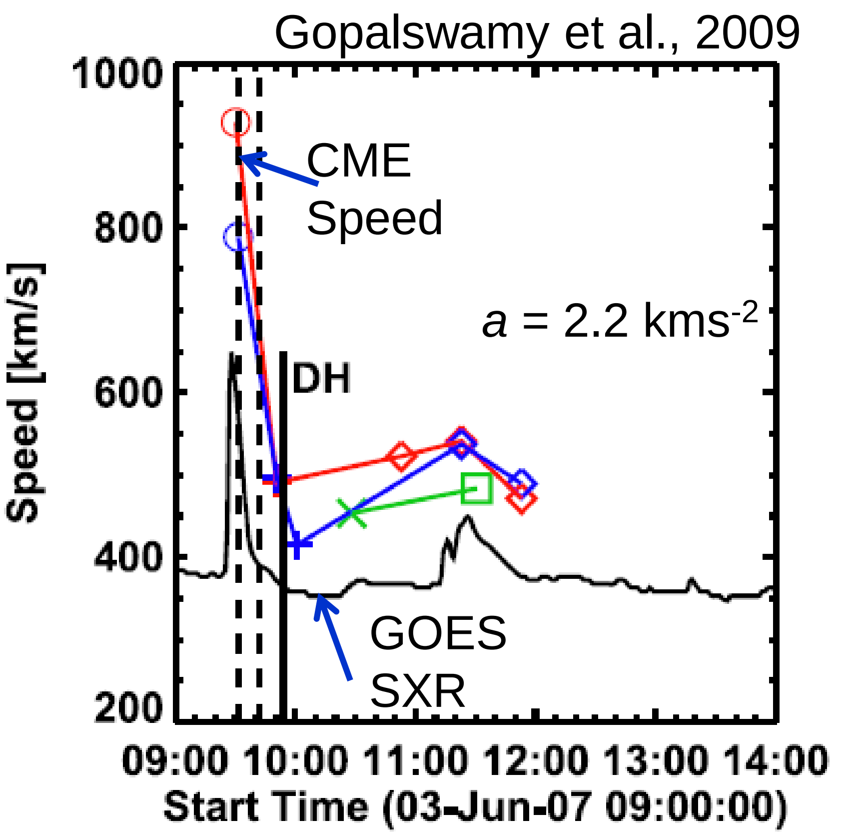
Longcope et al (2007)



Reconnection forms the flare arcade and the flux rope, which is the fundamental magnetic structure of a CME. The magnetic flux in the flare ribbons (ϕ_r) and the poloidal flux of the flux rope (ϕ_p) must be the same. ϕ_p can be measured when the flux rope reaches earth. Observations support this flare CME connection

CME speed max at Flare peak



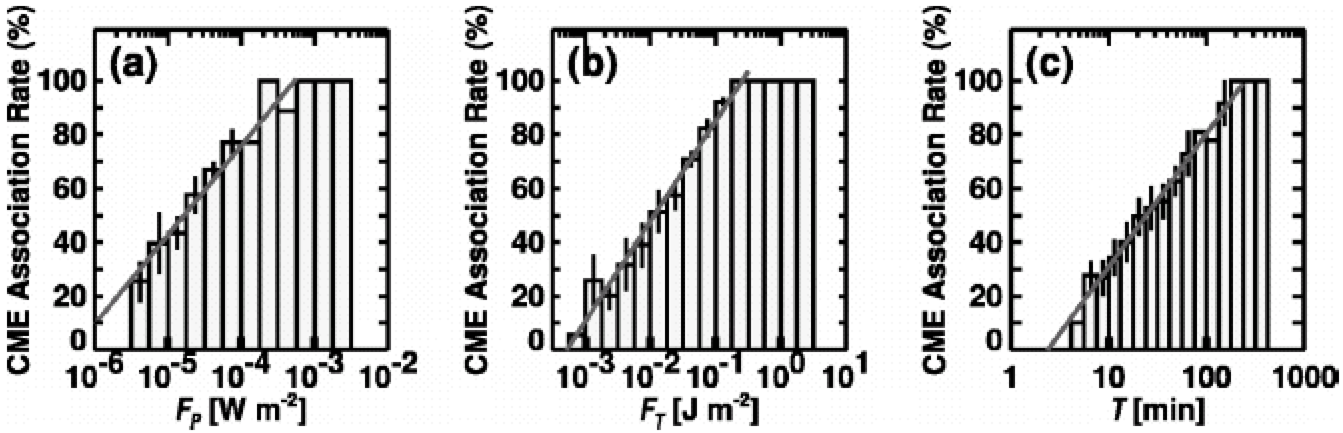


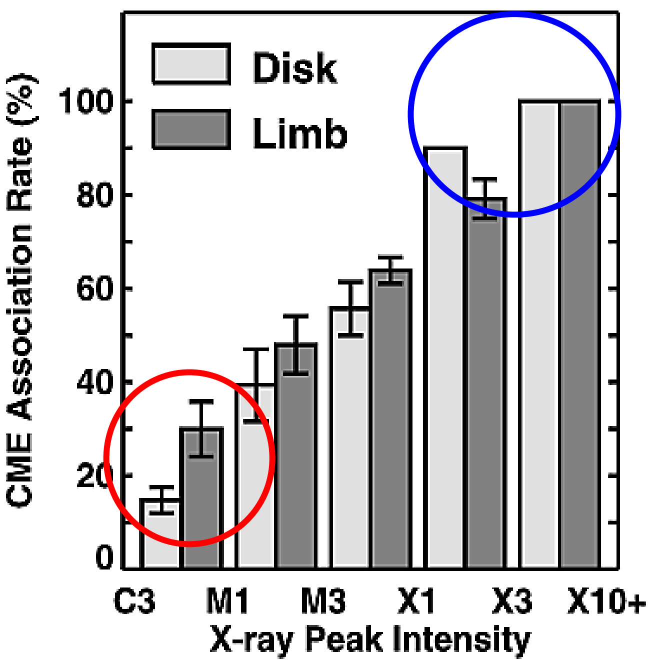
CME speed profile similar to the Flare soft X-ray profile in large and small flares CME onset ~ Flare Onset. These observations tell us that flare and CME are two manifestations of the same eruption. Flare loops stick to the Sun; the flux rope expands into the interplanetary space as the CME

CME-Flare Relationship

- Part of the same process: CSHKP model
- Flares (even X-class) without CMEs, but no CME without flare (if you count weak arcades)
- Eruptive & non-eruptive flares (Munro et al. 1979): good classification
- Prominence eruptions vs. flares: not a good classification
- Active region and non-AR CMEs?

CME-Flare Association





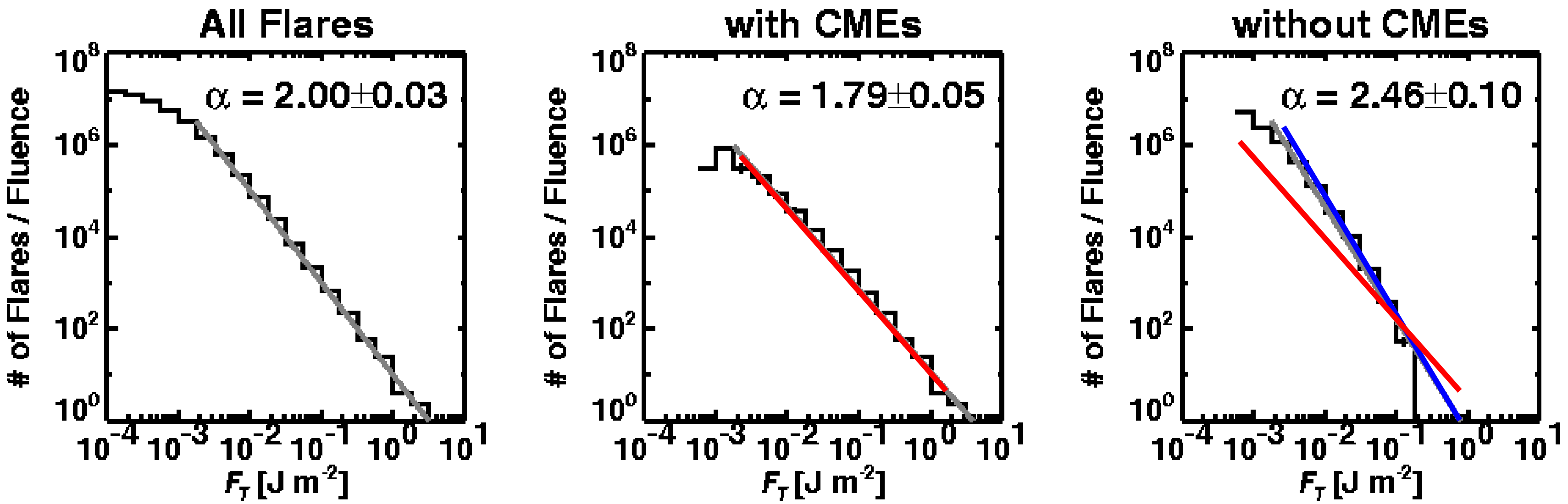
Yashiro et al. 2005 JGR

Flare size	0-30 deg	30-60 deg	60-90 deg
X	100%	100%	100%
M	84%	100%	100%
C	50%	67%	100%

Estimated CME Visibility function assuming that all limb CMEs are detected by LASCO

Flares with & without CMEs

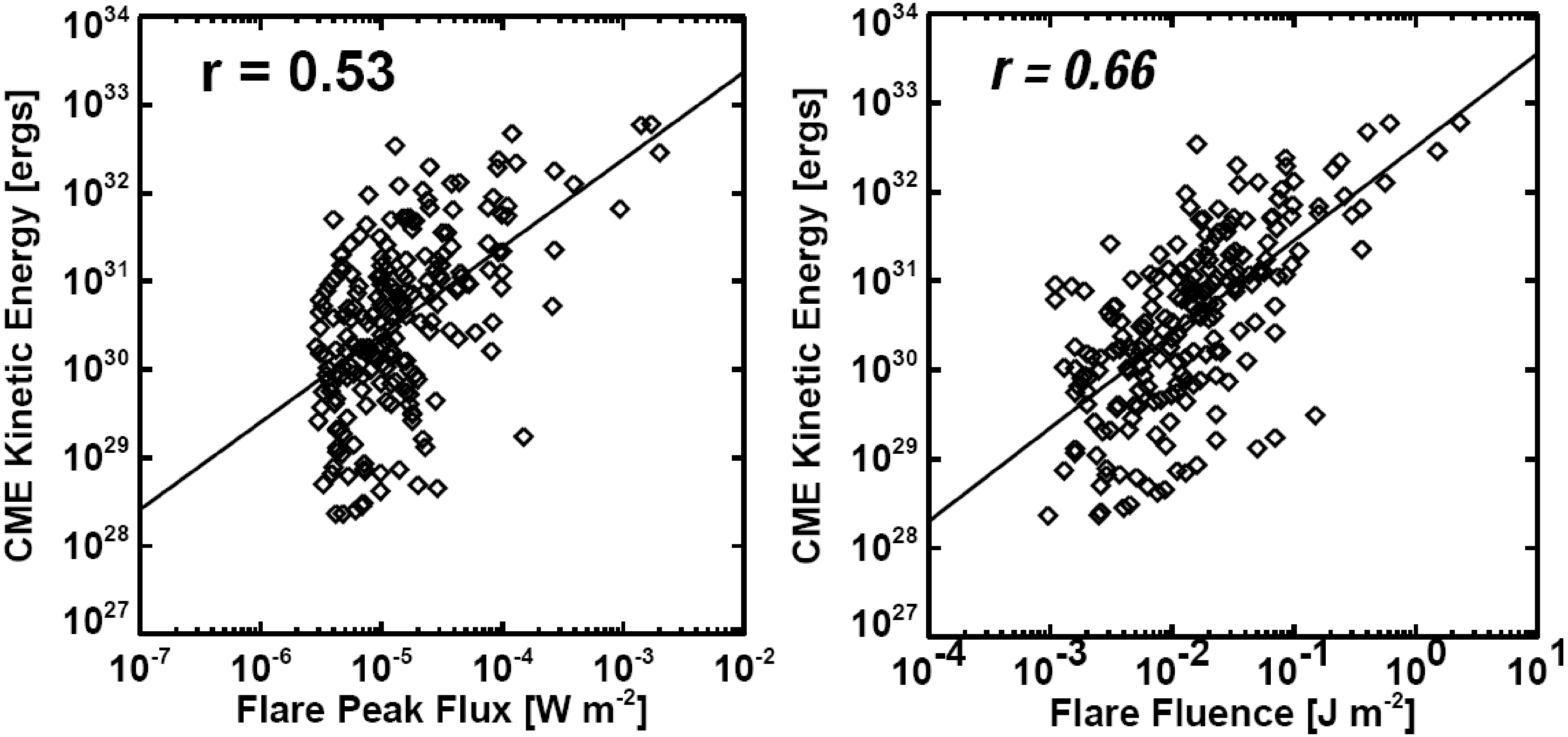
Yashiro et al. 2006 ApJL



- Flare number (N) distributions obey a power-law of the form: $dN/dX \sim X^{-\alpha}$ where X is a flare parameter (e.g. peak SXR flux)
- $P \sim \int X \, dN/dX \sim X^{-\alpha+2}$
- $\alpha > 2$ → Small X contribute to P (Hudson et al. 1991)
- The larger power-law index for flares without CMEs supports the possibility that nanoflares contribute to coronal heating.
- Consistent with the fact that flares without CMEs are hotter (Kay et al. 2003)

Flare Temp: <Tmax> [MK]: 16.4 (all) 18.7 (w/o CMEs) 11.4 (with CMEs)

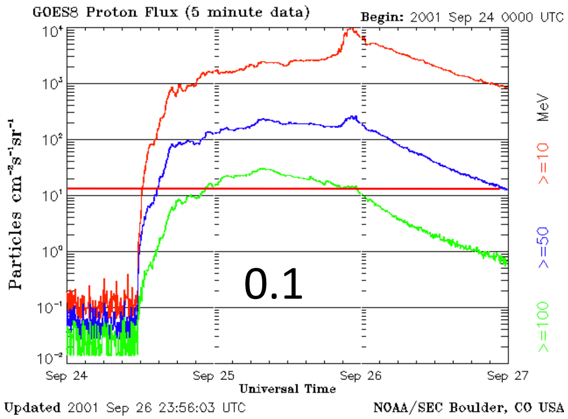
CMEs and Flares: Energy Comparison



CME kinetic energy and soft X-ray flux/fluence are reasonably correlated showing that they share the same energy release

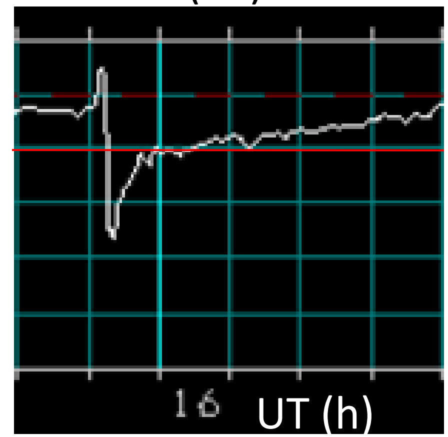
CMEs & Space Weather

10,000



0.1

Dst (nT)



0
- 100
- 200
- 300
- 400
- 500

CMEs

On the way and upon arrival

SEPs

Space systems
Airplanes
atmosphere

Shock-driving Capability is Crucial

$V_{CME} - V_{SW} > V_{MS}$

Magnetic storms

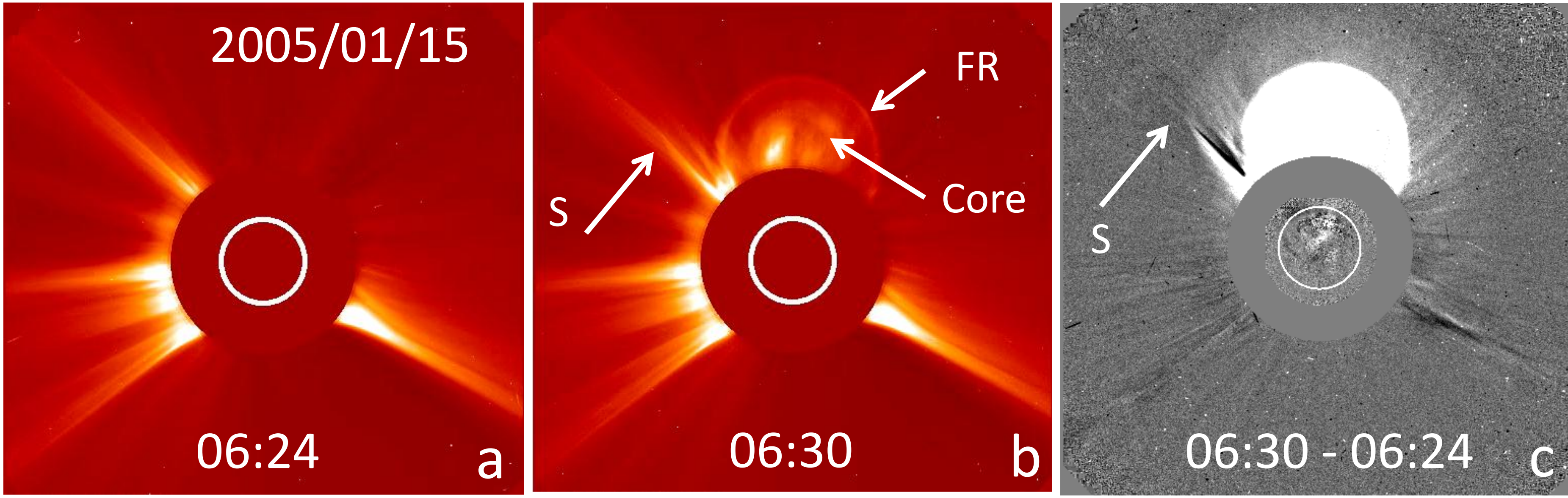
Upon arrival at Earth

Space systems
Magnetosphere
Ionosphere
Atmosphere
Ground

CME's Magnetic Structure Is Crucial
(Bz <0)

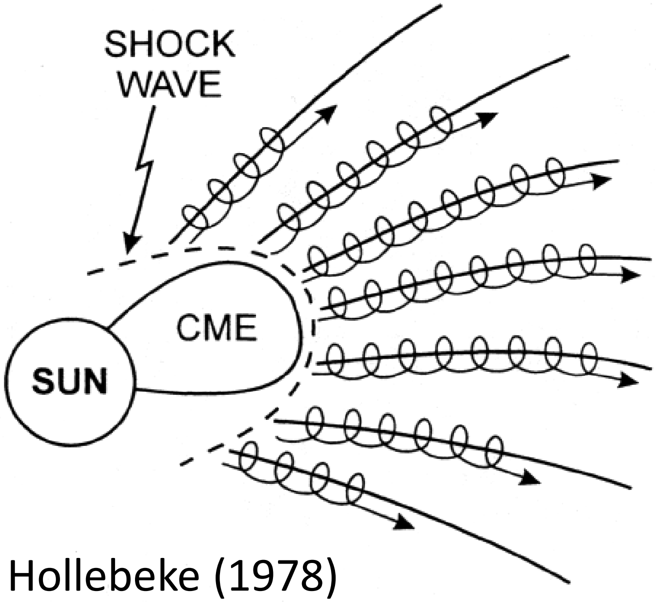
CMEs and SEPs

Large SEP Events: Shock-driving CMEs



Fast CMEs drive shocks, which accelerate particles
resulting in solar energetic particle (SEP) events
Particles travel along interplanetary field line

Particle radiation most hazardous in directly
affecting astronauts, space technology



Kahler, Hildner, & Van Hollebeke (1978)

Type II Radio Bursts are caused by electrons accelerated in the CME shock

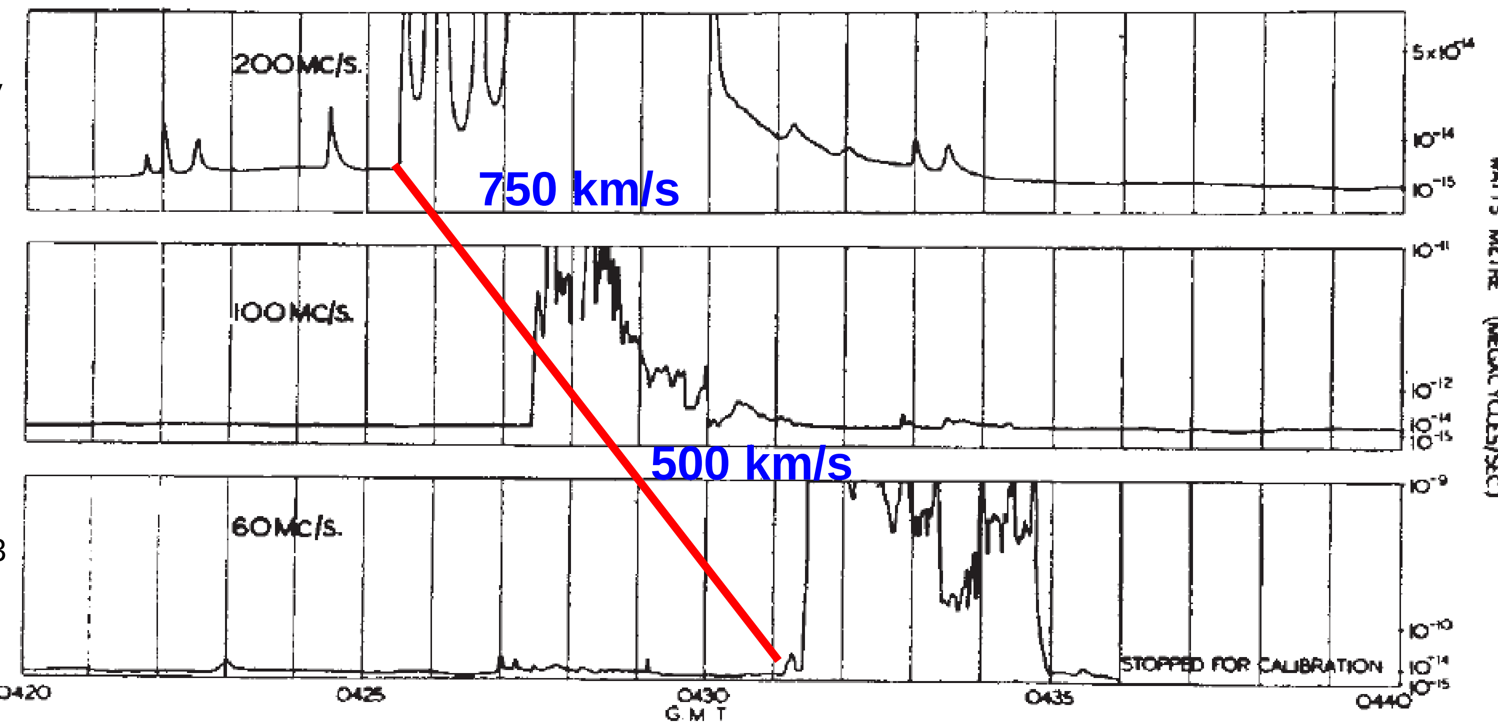
Ruby Payne-Scott
1912 – 1981

The whole pattern drifts;
140 MHz in 6 min
df/dt = 0.4 MHz/s

Plasma density
5.0×10^{8} cm^{-3}

1.2×10^{8} cm^{-3}

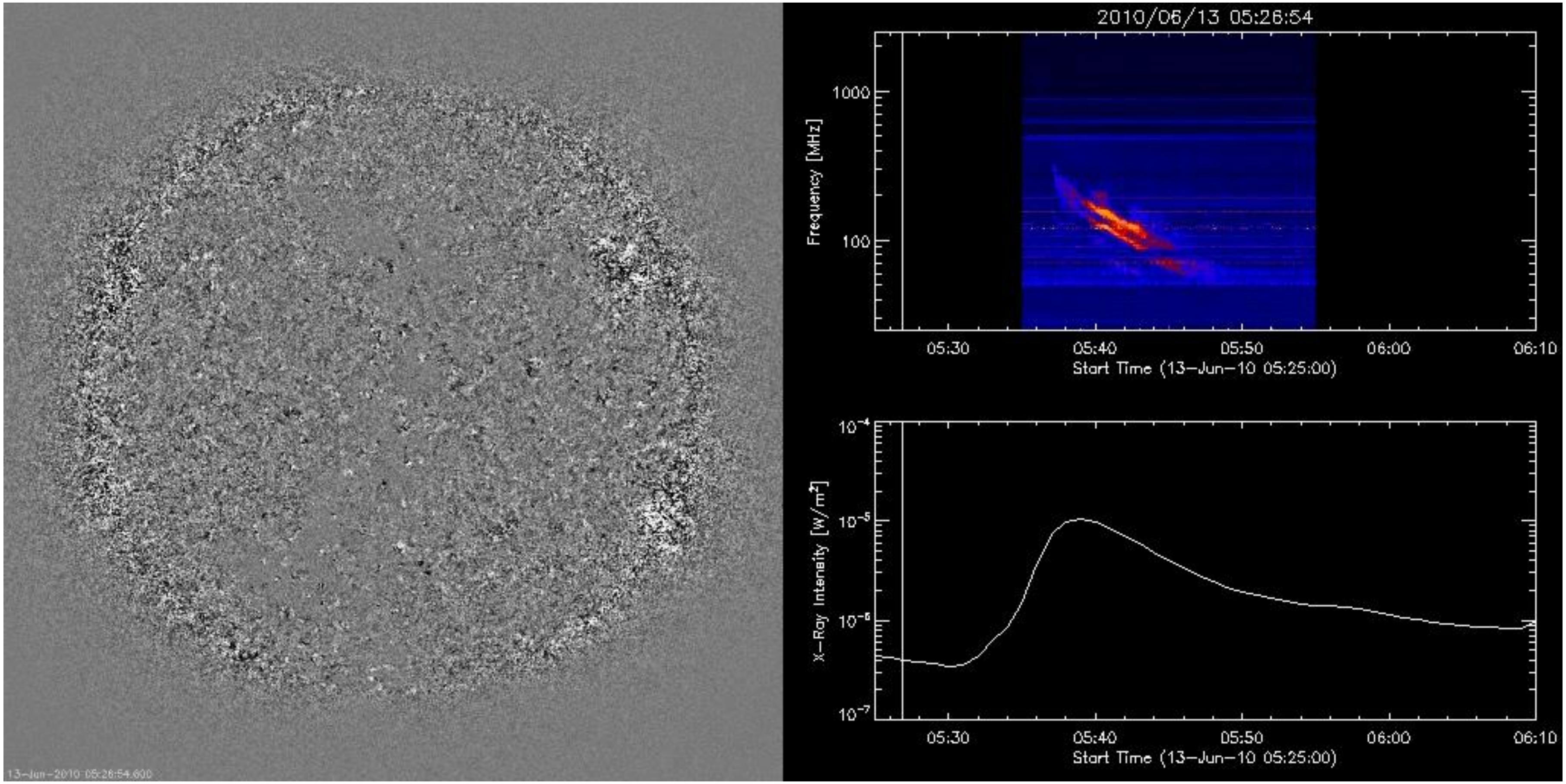
0.4×10^{8} cm^{-3}



Nature 260, 256, 1947

LARGE OUTBURST OF MARCH 8, 1947

CME and shock observed in EUV by the Solar Dynamics Observatory



CME starts at 5:34 at 1.13 Rs; Type II starts at 5:36 when the CME at 1.17 Rs; shock 1.19 Rs. Shock and type II appear simultaneously.

Coronal Alfven Speed

CMEs need to be superAlfvenic
to drive a shock

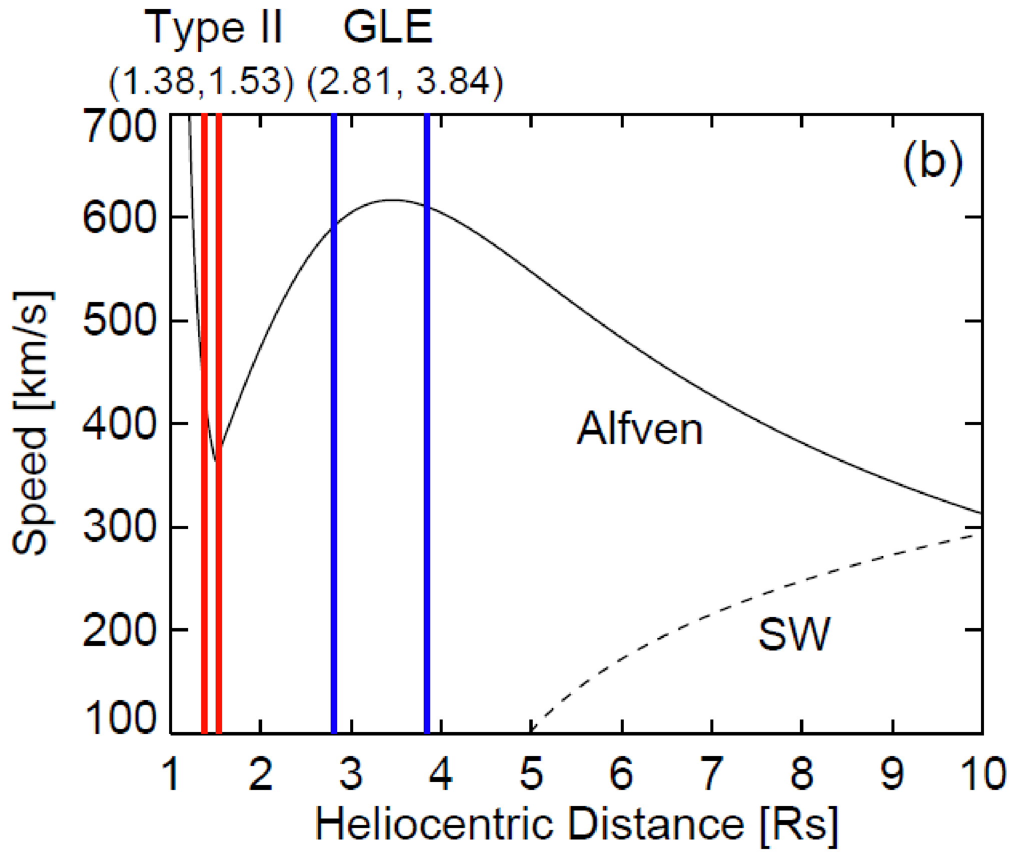
Shock formation typically happens
close to the surface
as indicated by the type II bursts

Around the time of release of SEPs,
CMEs reach a height of ~3.6 Rs,
where the Alfven speed is ~600
km/s

For Mach 2, the CME speed needs
to be 1200 km/s

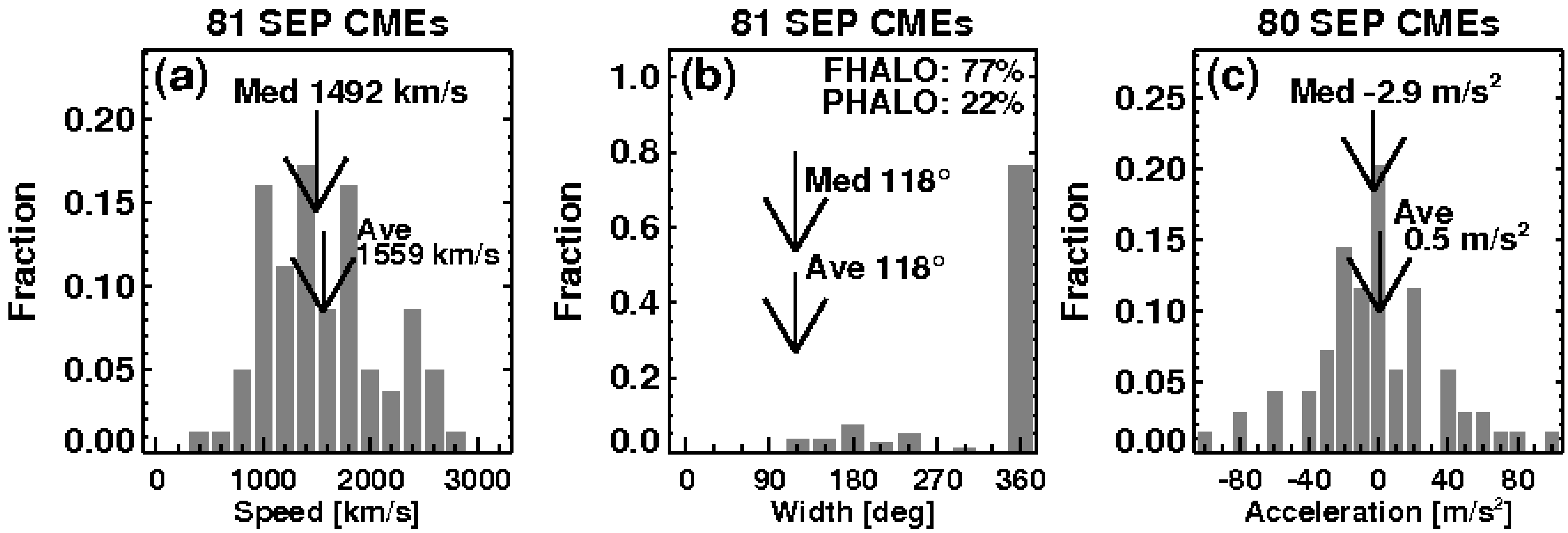
Height of
shock formation

Height of
Particle release



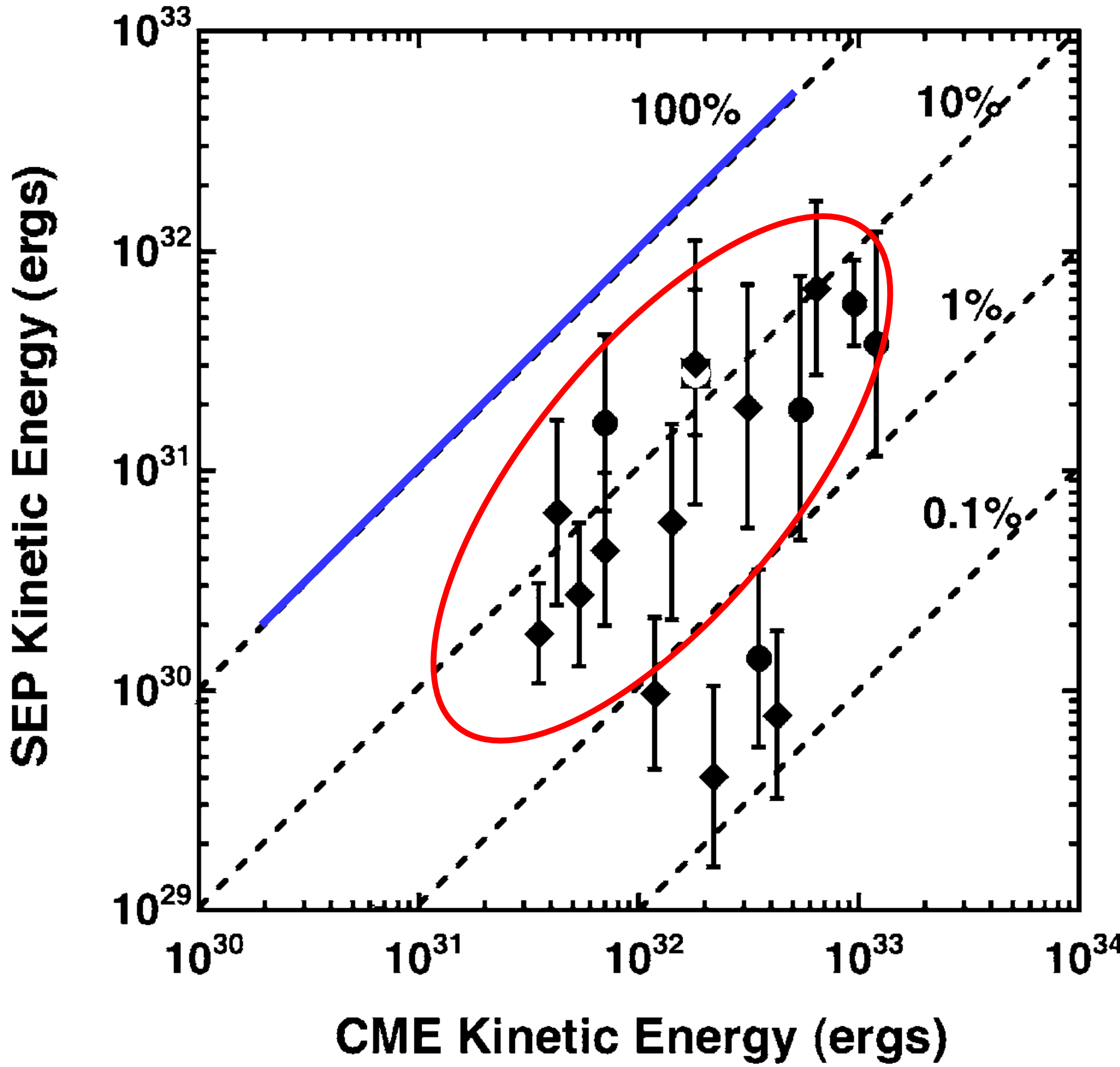
Gopalswamy et al. 2012

SEP Producing CMEs



The CMEs are very fast
Almost all CMEs are halos or partial halos
Halo CMEs are generally wide

CMEs are Efficient Accelerators

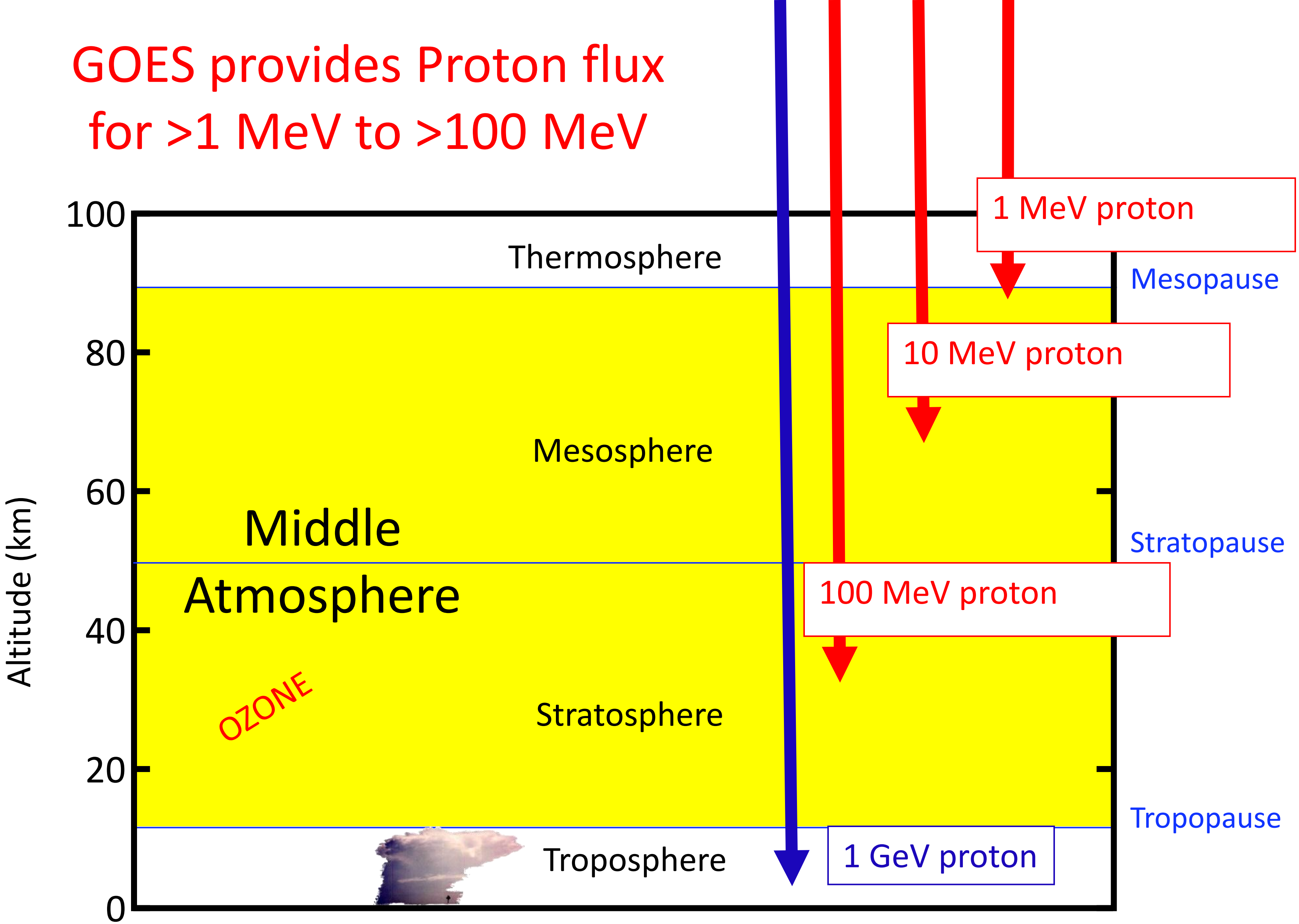


Typically about 10% of CME kinetic energy goes into SEPs

Similar to flare energy in SEPs

Mewaldt, 2006

GOES provides Proton flux
for >1 MeV to >100 MeV



Particle radiation from the Sun can destroy ozone

courtesy: C. Jackman

CMEs and Geomagnetic Storms

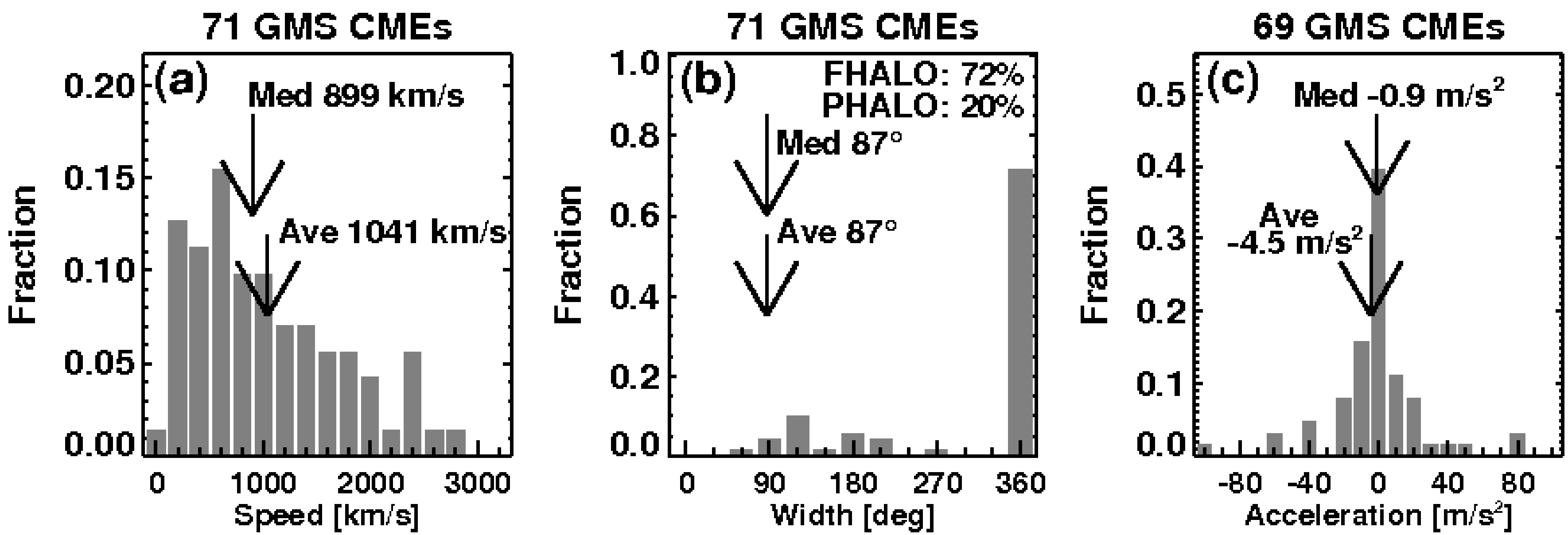
- Direct impact of CME plasma on Earth's magnetosphere
- Causes ring current enhancement
- Acceleration of electrons inside the magnetosphere
- Sudden commencement and exposure of geosync satellites to the interplanetary space

Out of the Ecliptic B from CMEs

- Normal Parker-spiral field does not have a Bz component
- CMEs with flux rope structure (magnetic clouds) naturally produce the Bz component
- Magnetic field draping in the shock sheath can also cause Bz (Gosling & McComas, 1987; Tsurutani & Gonzalez, 1988)
- Corotating interaction regions and fast wind have Alfven waves that represent Bz, but the magnitude is relatively small

CMEs Producing Geomagnetic Storms

Large Dst (≤ -100 nT) events from cycle 23 and the associated LASCO CMEs considered



The CMEs are very fast (projected speed ~1041 km/s)
Almost all CMEs are halos or partial halos (92%)

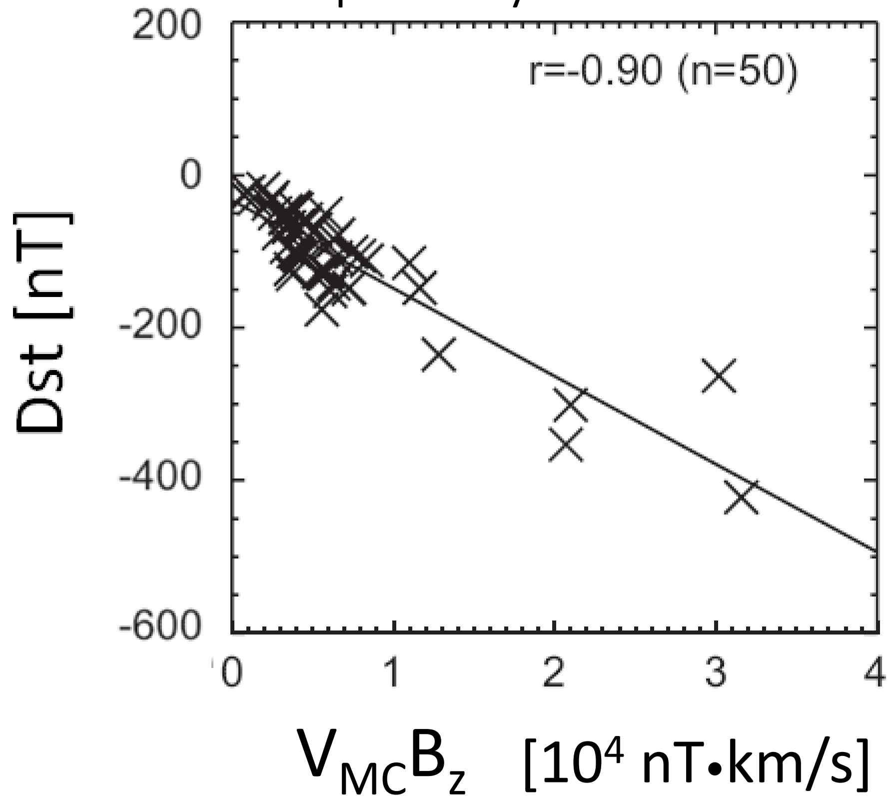
Geomagnetic Storm and CME parameters

$Dst = -0.01VB_z - 32$ nT

The high correlation suggests
That V and Bz are the most
Important parameters
(- Bz is absolutely necessary)

V and Bz in the IP medium are
related to the CME speed and
magnetic content

Gopalswamy 2008



Carrington Event: VBz = 1.6 10^5 nT•km/s
V = 2000 km/s, Dst = -1650 nT → Bz = -81 nT

Origin of V and B

$$Dst = -0.01VB_z - 32\ \text{nT}$$

Solar Wind speed
CIR Speed
CME speed

Active Region
Free energy

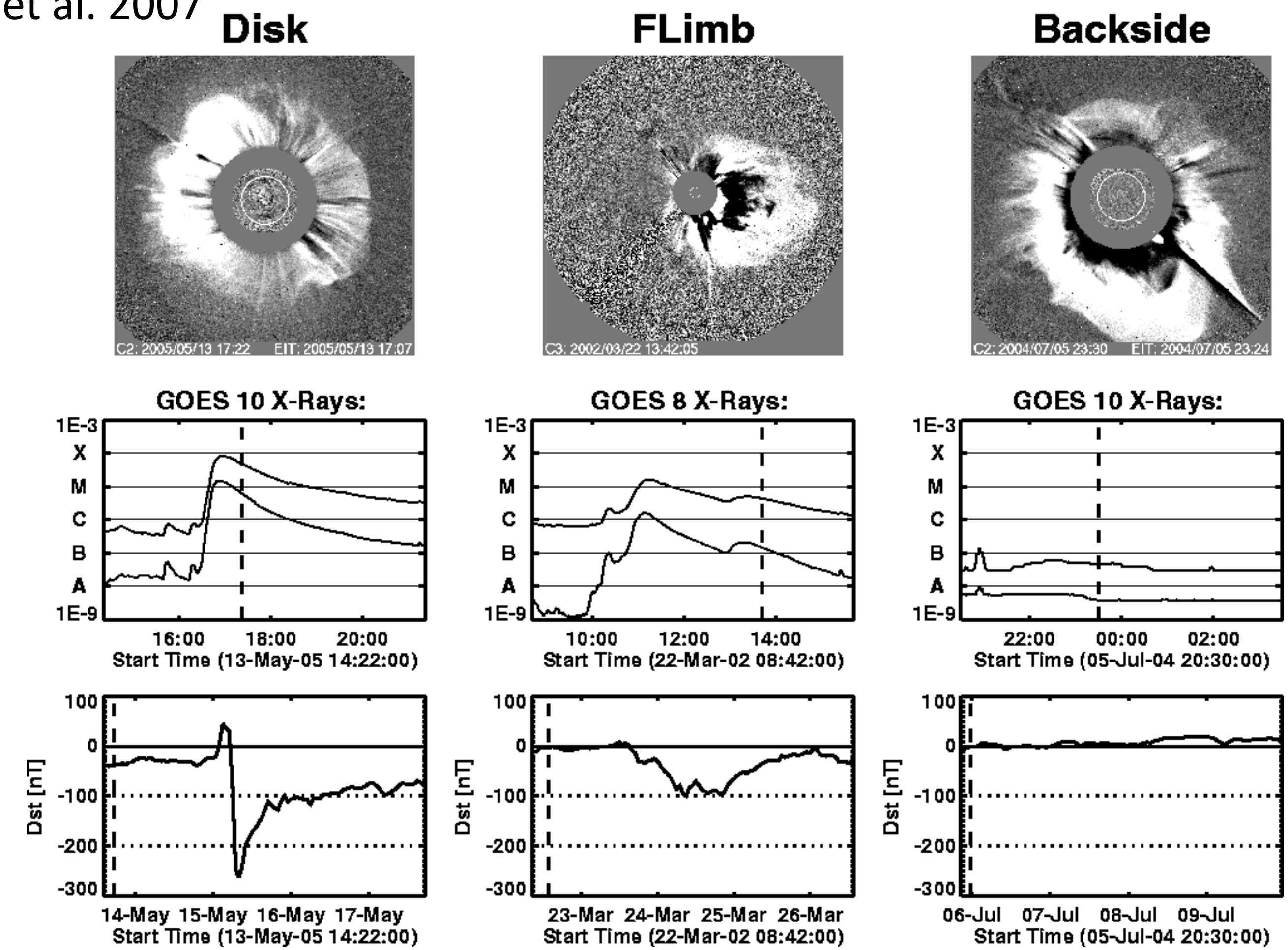
Alfven waves
CIR: Amplified Alfven waves
ICME: Sheath & Flux rope

Heliospheric
Mag Field

Active Region
Mag Field

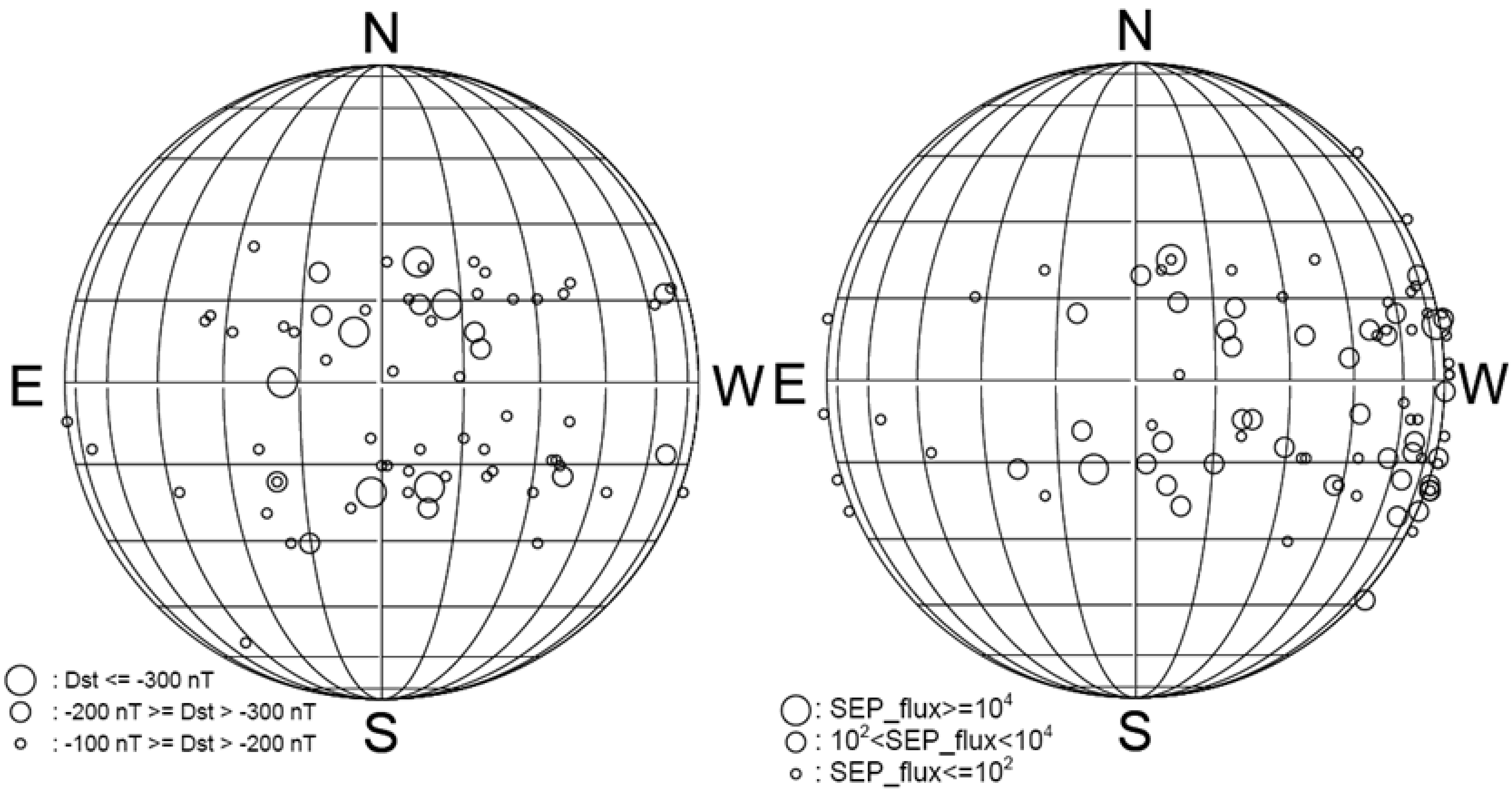
CMEs and Geomagnetic Storms: Direct impact is important

Gopalswamy et al. 2007



Direct impact Glancing impact No impact

Geoeffective & SEP-producing CME Sources



CMEs need to arrive at Earth
CMEs must contain Bz South
Similar to MC and Halo CME sources

CMEs need to drive shocks
Source region needs to be magnetically connected to Earth

Many double-whammy events

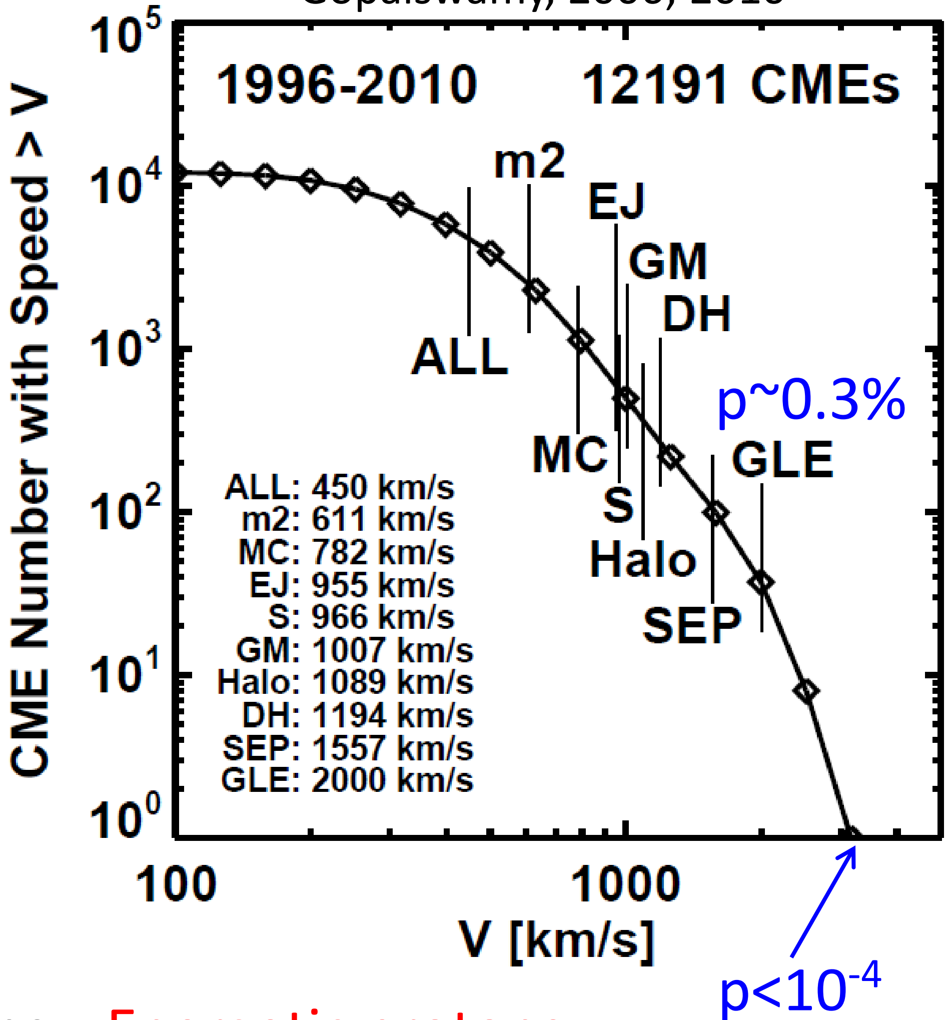
Significant CMEs & their Consequences

Cycle 23 – 24 CMEs from SOHO/LASCO

There seems to be a maximum CME speed

m2 – Metric type II
MC – Magnetic Cloud
EJ – Ejecta
S – Interplanetary shock
GM – Geomagnetic storm ←
Halo – Halo CMEs
DH – Type II at λ 10-100 meters
SEP – Solar Energetic Particles ←
GLE – Ground Level Enhancement

Gopalswamy, 2006; 2010



Plasma impact   Energetic electrons   Energetic protons

Tail of the CME Distribution

Category	Number of CMEs
All identified CMEs	18000
# CMEs with V ≥ 1000 km/s	539
# CMEs with V ≥ 1500 km/s	131
# CMEs with V ≥ 2000 km/s	39
# CMEs with V ≥ 2500 km/s	9
# CMEs with V ≥ 3000 km/s	2
# CMEs with V ≥ 3500 km/s	1
# CMEs with V ≥ 4000 km/s	0

AR Potential Field Energy ~ Free Energy

Free Energy ~ Magnetic Potential energy (Mackay et al., 1997)

Free energy is > Mag PE

by a factor 3-4 (Metcalf et al. 2005)

Max potential energy during cycle 23 ~ 4×10^{34} erg

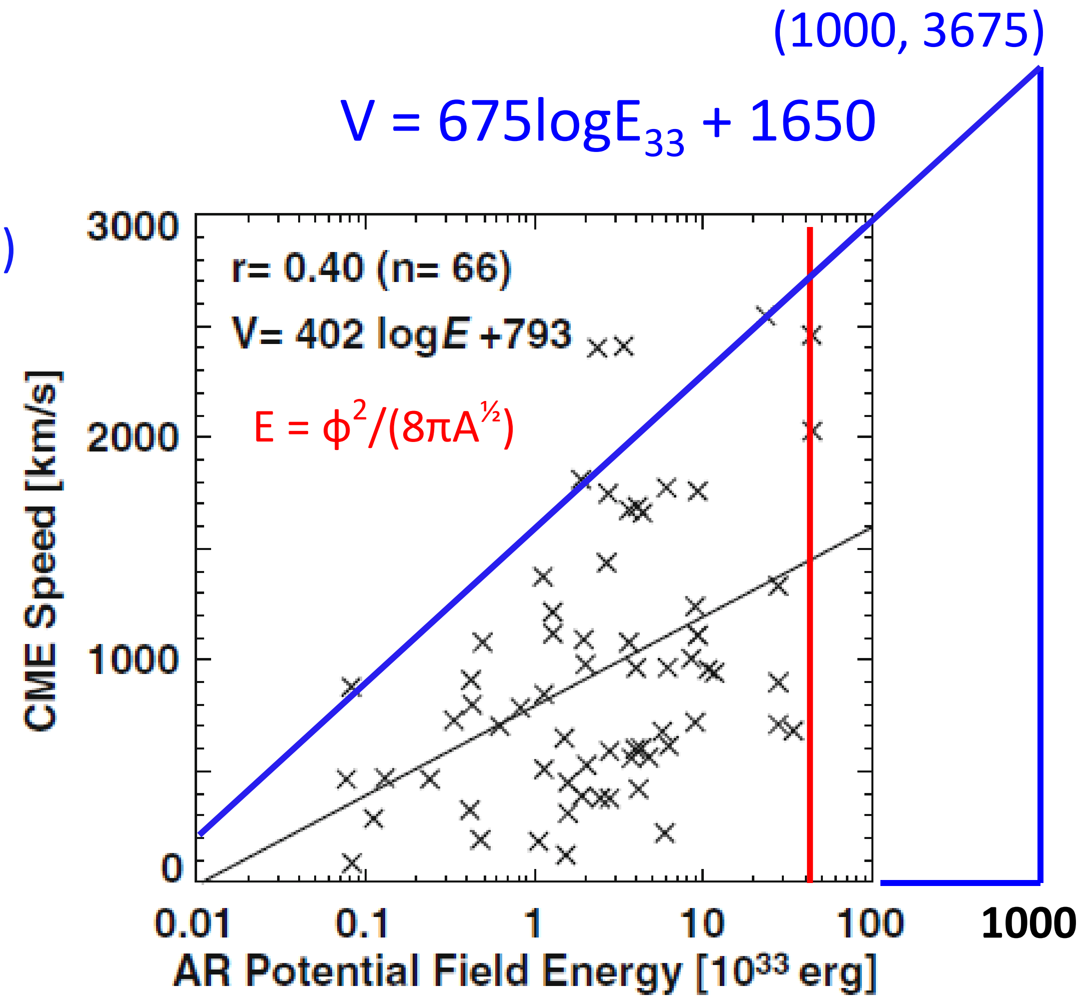
Max CME KE observed ~ 1.2×10^{33} erg

CME Speed limit → maximum energy that can be stored depending on A, B

B < 6100 G; A < 5000 msh

→ E ~ 10^{36} erg

Livingston et al. 2006; Newton, 1955



ϕ = AR flux; A = AR area; E = AR Potential energy

Gopalswamy et al., 2010

Max speed from magnetic Potential Energy (E)

- $V = 675 \log E_{33} + 1650$; $E = \phi^2/(8\pi A^{½})$ $\phi = BA$
- $E \sim 10^{36}$ or $E_{33} = 10^3 \rightarrow V = 3675$ km/s
- Transit time = 11.3 h
- But there is the solar wind → longer transit time ~12.6 h (2005 Jan 20 CME had this speed; transit time was 34 h because the source was at W60)

A Generic Eruption: Summarizes most of the observations discussed

Flare Reconnection leads to CME flux rope formation

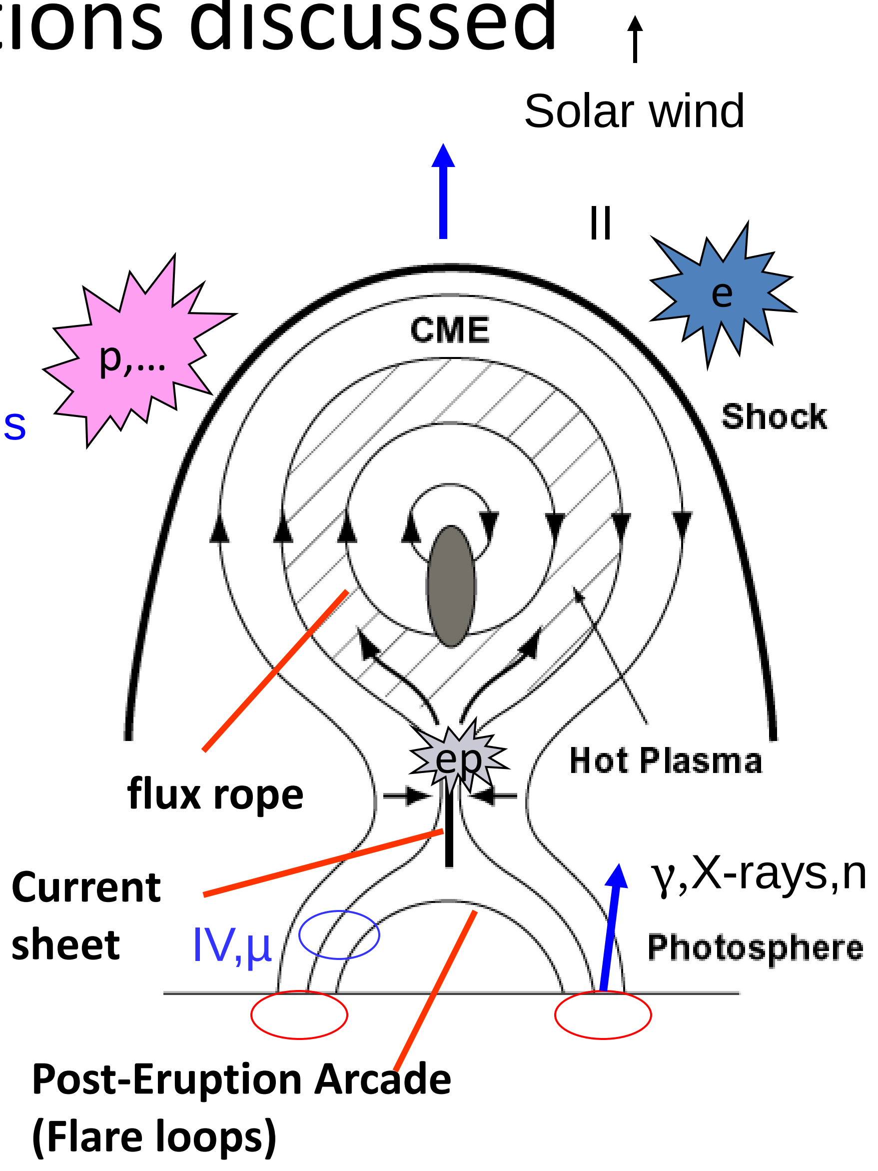
CME drives Shock

Shock accelerates electrons and protons

Flare: impulsive SEP events,
Much smaller, high charge states
CME may or may not accompany

The relative contribution from Flare & CME in a given event under debate

flux rope formation by flare reconnection is the injection of hot plasma – high charge states at 1 AU



Summary

- Solar Magnetism and its variability is ultimately responsible for space weather via flares and CMEs
- Flares and CMEs are from closed magnetic regions on the Sun (i.e., bipolar or multipolar) and are part of the same energy release
- Flares cause sudden ionospheric disturbances
- CMEs cause wide-ranging space weather effects: SEPs, geomagnetic storms and the related effects

terima kasih !

Some definitions

- Plasma: ionized gas with macroscopic charge neutrality
- Magnetic field is frozen in the plasma
- Magnetic field acts like a gas; it has pressure
- Pressure balance: use both gas and magnetic pressures
- $B^2/8\pi > NkT$: magnetic field controls
- $B^2/8\pi < NkT$: gas dominates
- Lorentz Force: JxB