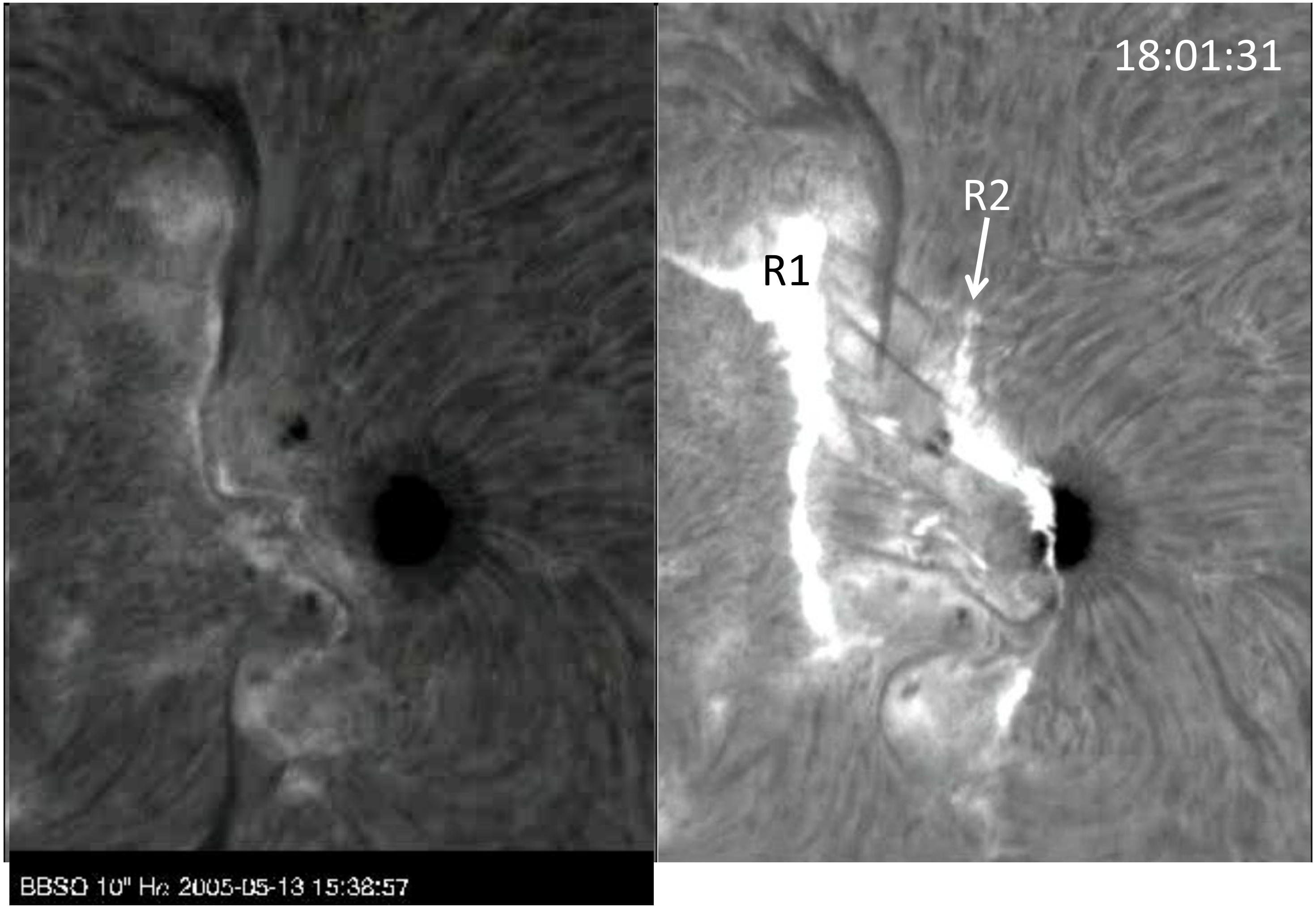
The Sunspot Region "A" Erupts

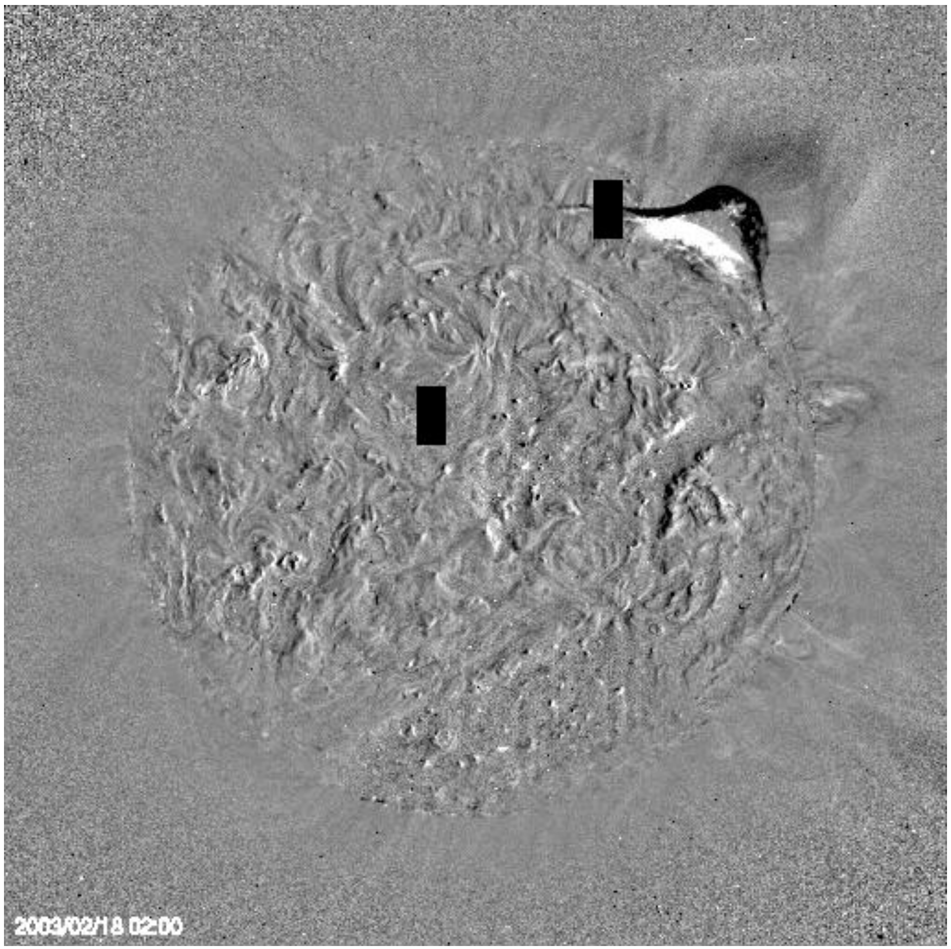


There is also wave going away from the eruption region. Part of the filament disappears

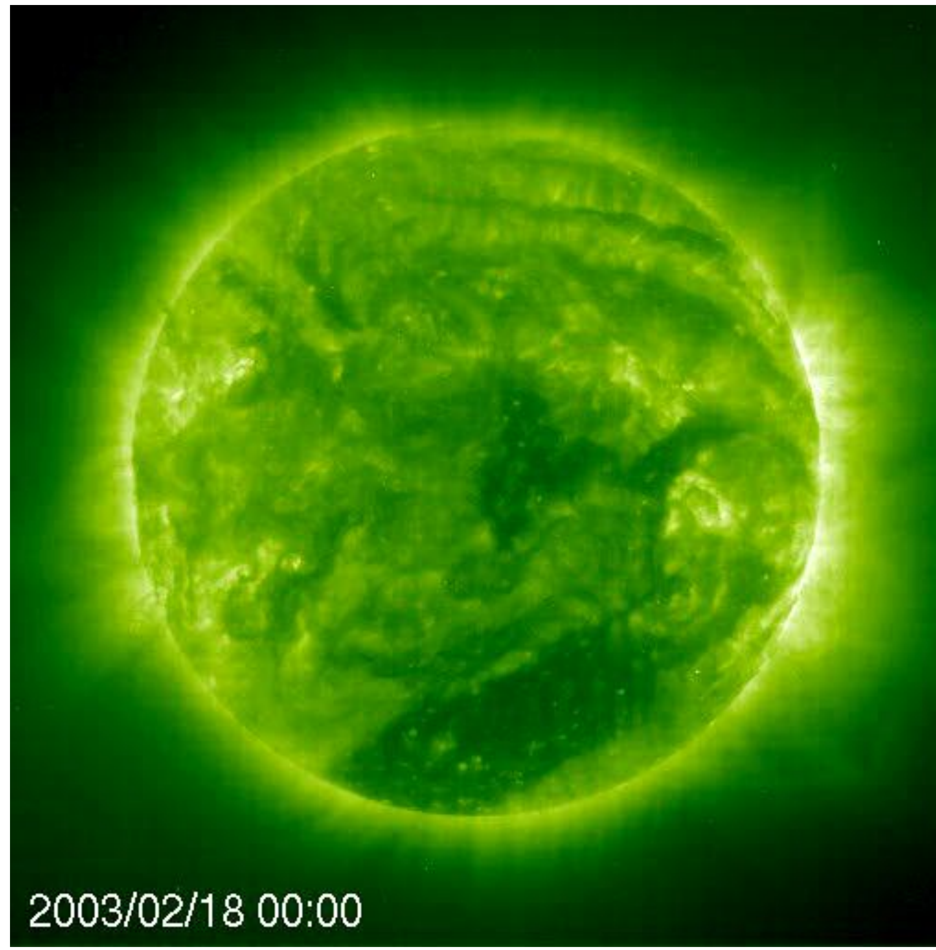
Flare arcade

Filament eruption

Difference image (SOHO/EIT)

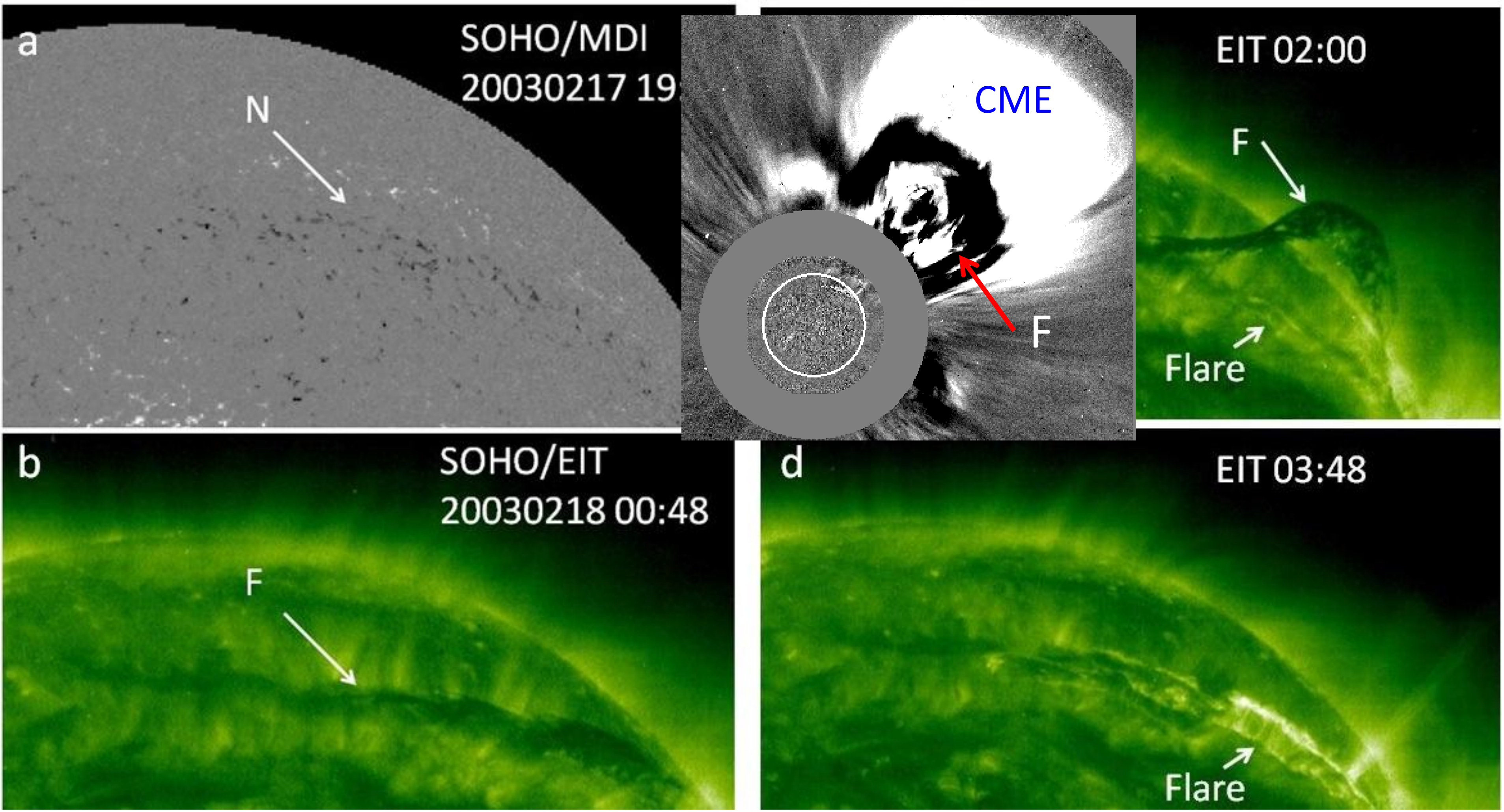


Flare from a non-sunspot region



Note the CME overlying the filament in EUV

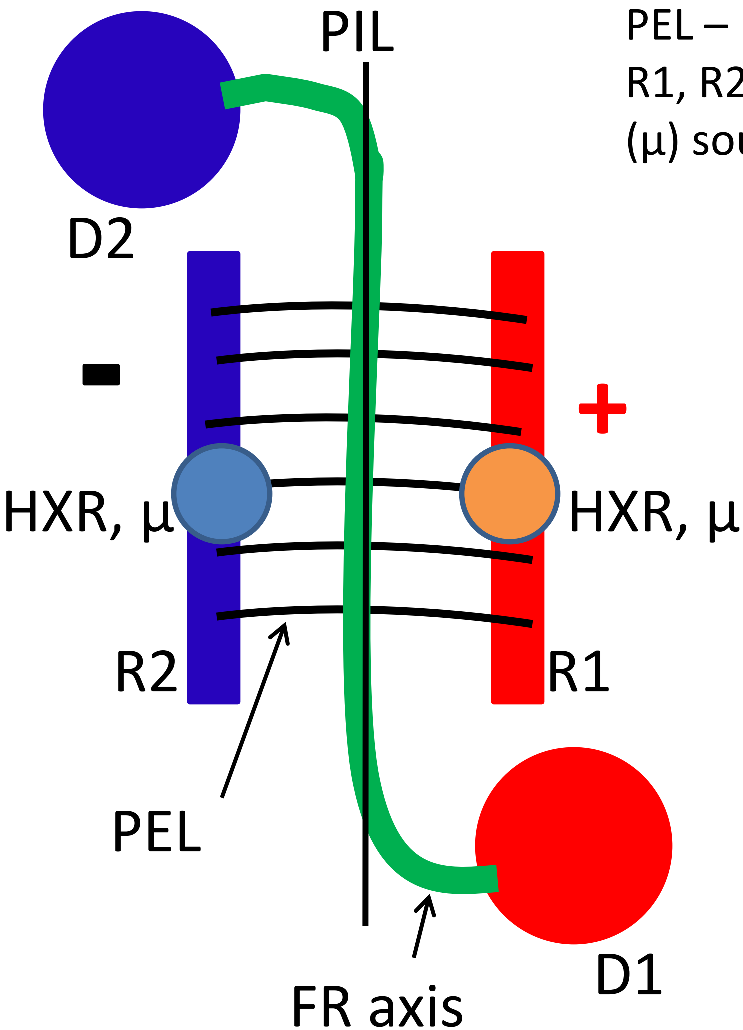
Filament Eruption in EUV

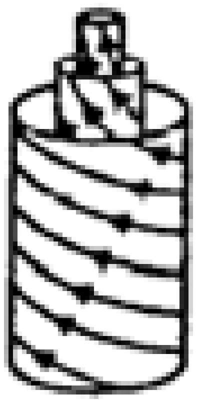


Filament (F) along neutral line (N). Flare loops under F; F becomes substructure of CMEs

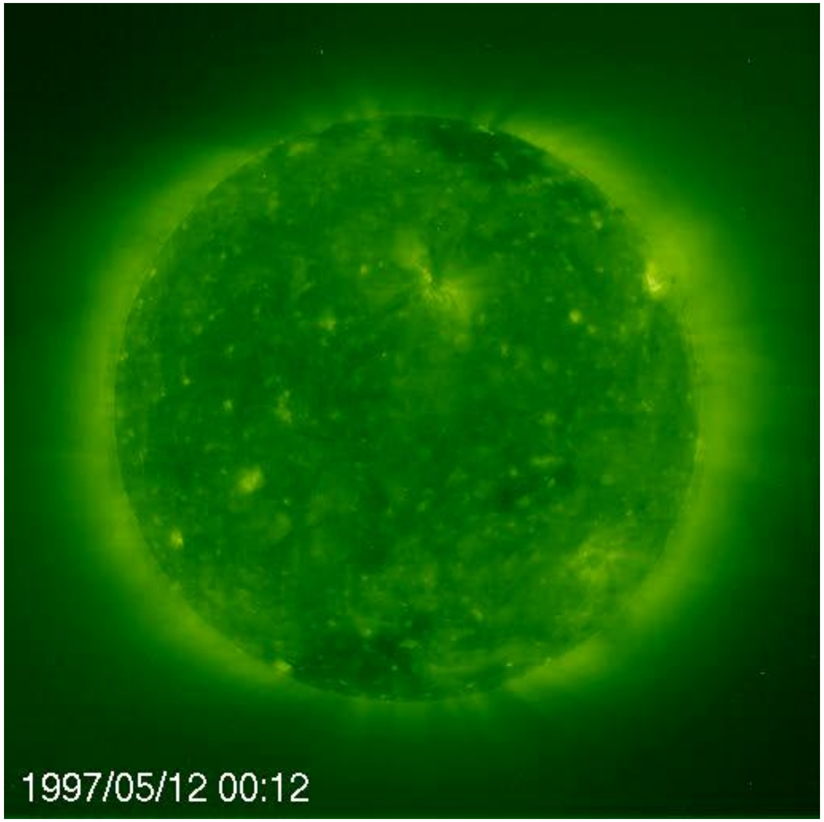
Coronal Dimming and Eruption Geometry

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.





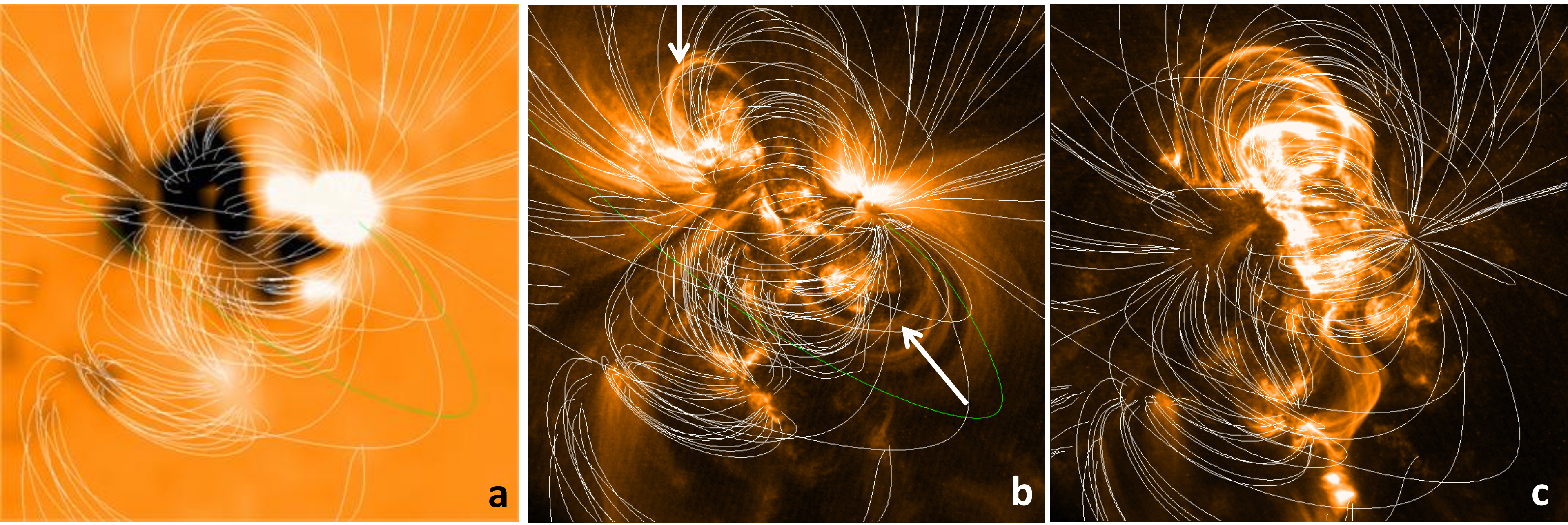
FR



Dimming: Sites of flux rope legs?

Where does the energy come from?

Extrapolated field lines on TRACE coronal images



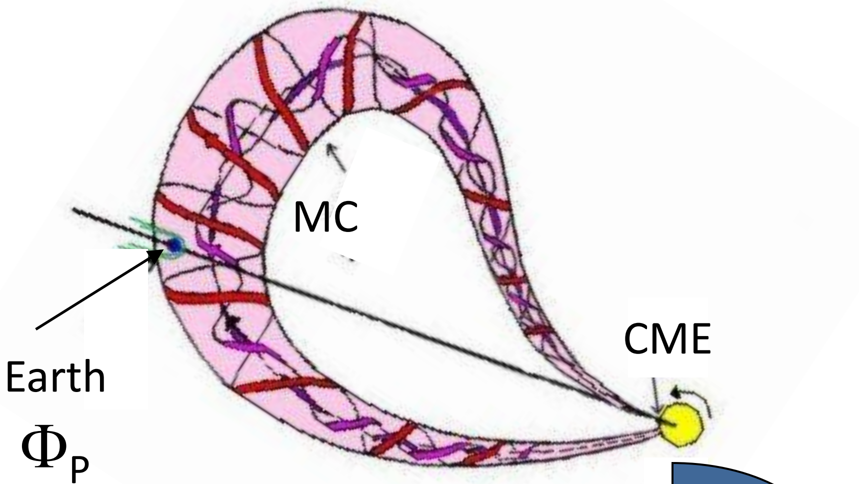
2005/05/13 14:56:00 | 2005/05/13 15:25:56 | 2005/05/13 21:26:36

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

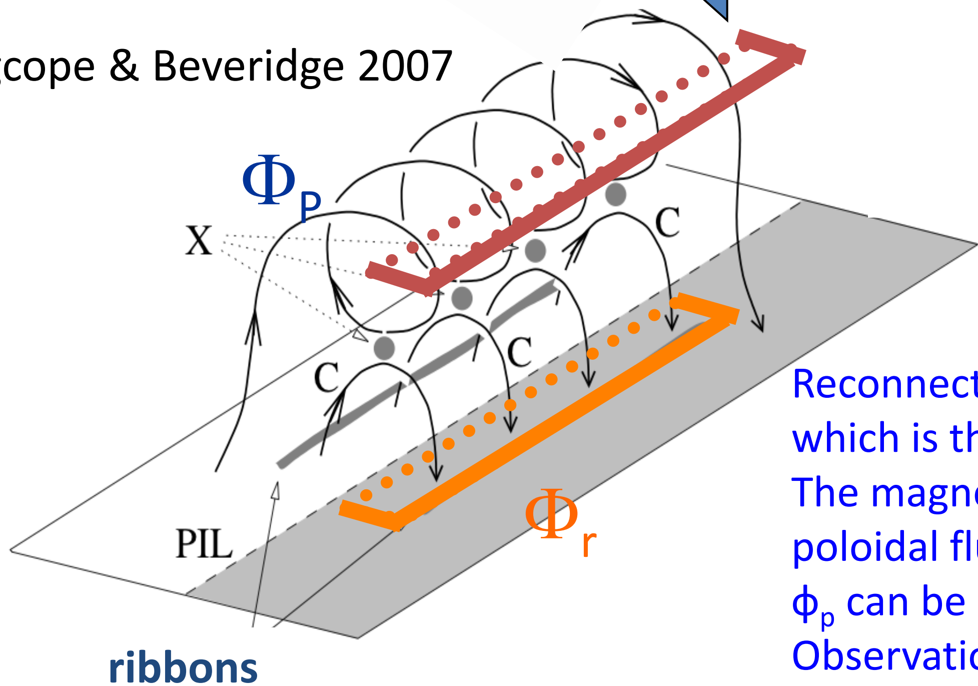
Free energy went into the CME kinetic energy
Arcade is now potential (no more current J)

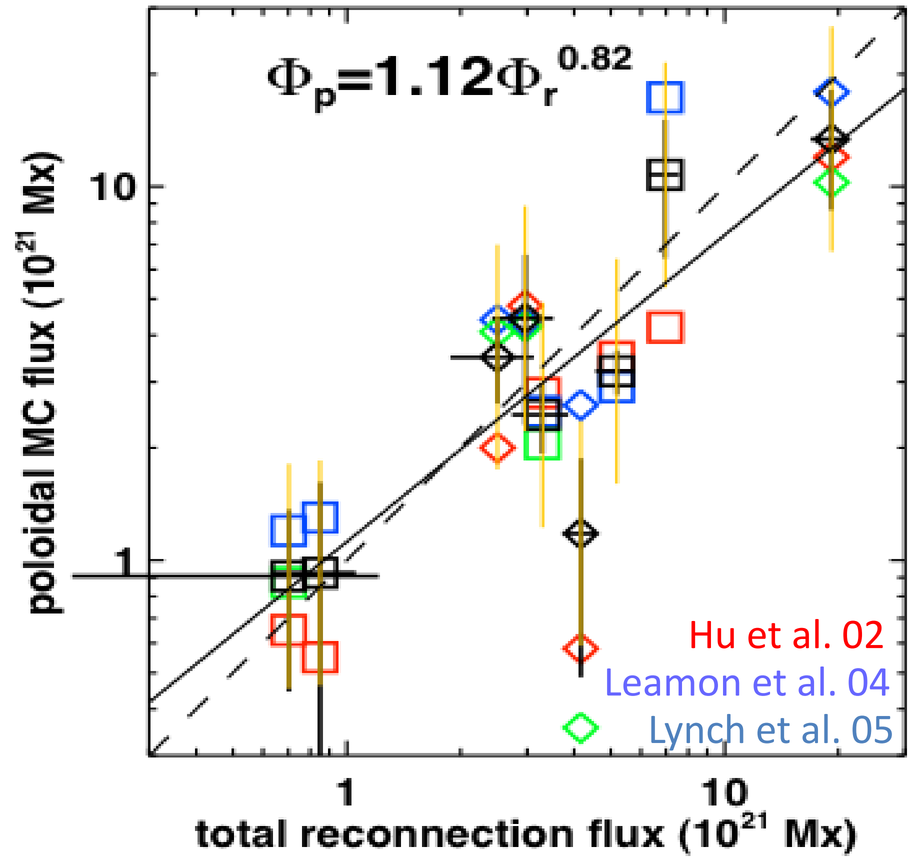
De Rosa & Schrijver



Marubashi 1997

Longcope & Beveridge 2007





Qiu et al. 2007

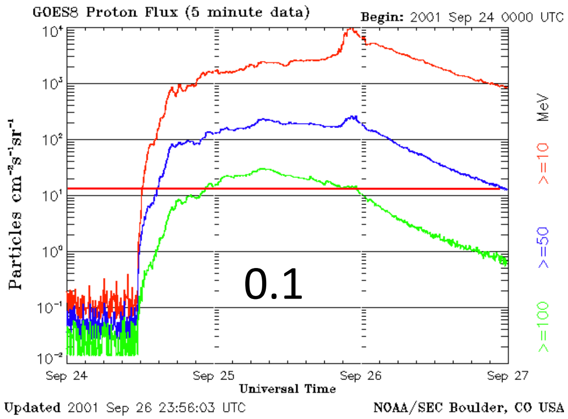
Reconnection forms the flare arcade and the flux rope, which is the fundamental magnetic structure of a CME. The magnetic flux in the flare ribbons (ϕ_r) and the poloidal flux of the flux rope (ϕ_p) must be the same. ϕ_p can be measured when the flux rope reaches earth. Observations support this flare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

CME-Flare Relationship

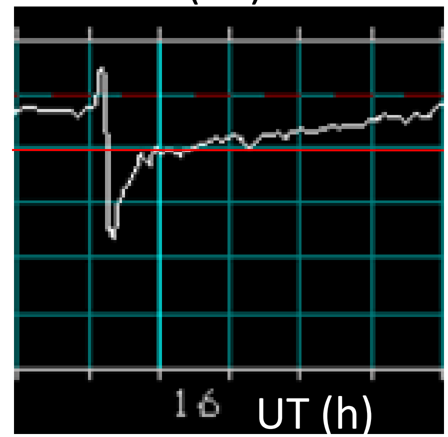
- Part of the same process: CSHKP model
- Flares (even X-class) without CMEs, but no CME without flare (if one counts weak arcades)
- Eruptive & non-eruptive flares (Munro et al. 1979): good classification
- Prominence eruptions vs. flares: not a good classification

CMEs & Space Weather

10,000



Dst (nT)



0
- 100
- 200
- 300
- 400
- 500

CMEs

On the way and upon arrival

SEPs

Magnetic storms

Upon arrival at Earth

Shock-driving Capability is Crucial

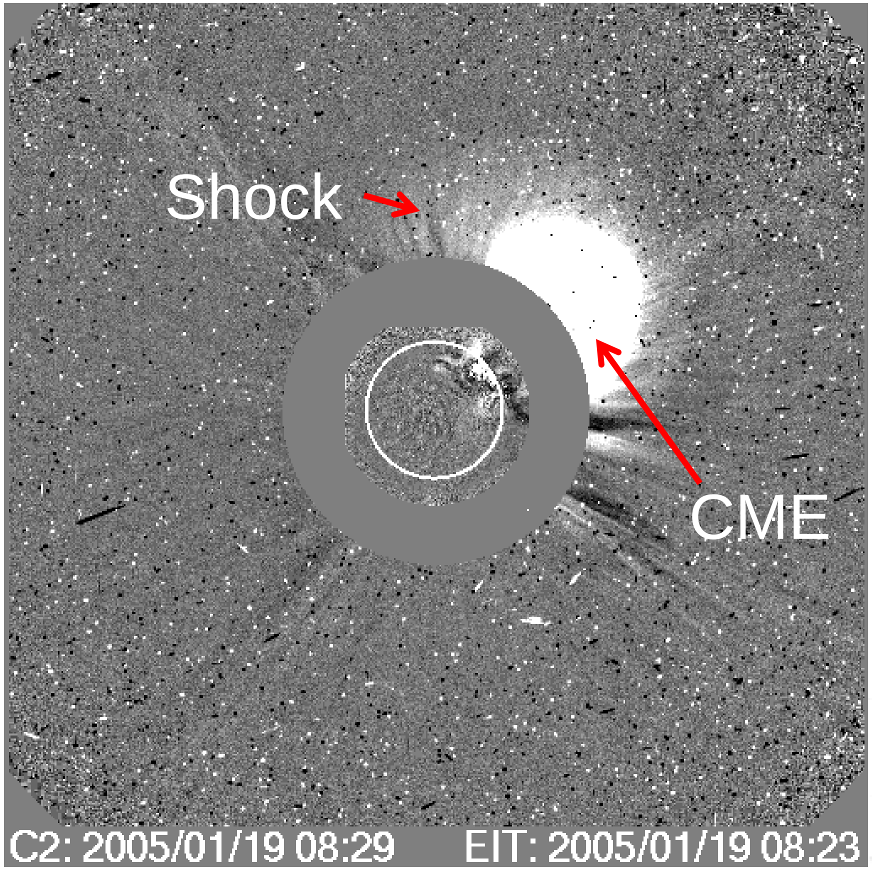
$V_{CME} - V_{SW} > V_{MS}$

Space systems
Airplanes
atmosphere

Space systems
Magnetosphere
Ionosphere
Atmosphere
Ground

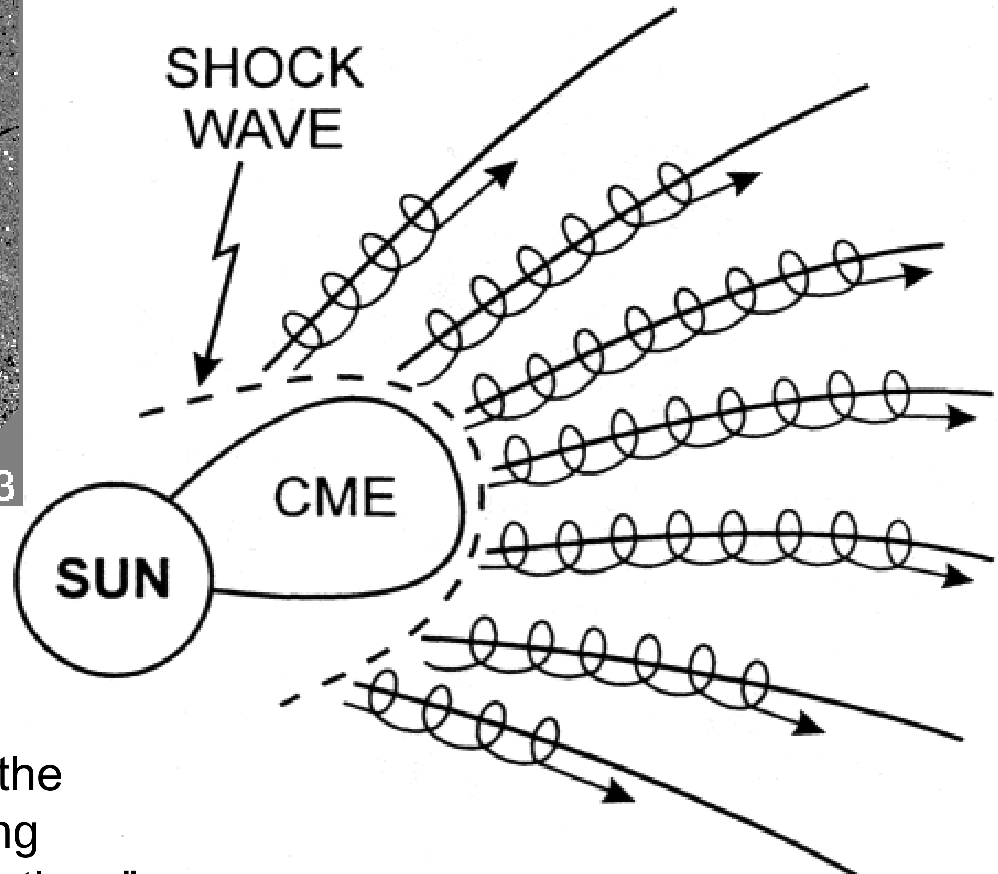
CME's Magnetic Structure Is Crucial (Bz <0)

CMEs and SEPs



A fast CME driving a shock
(cdaw.gsfc.nasa.gov)

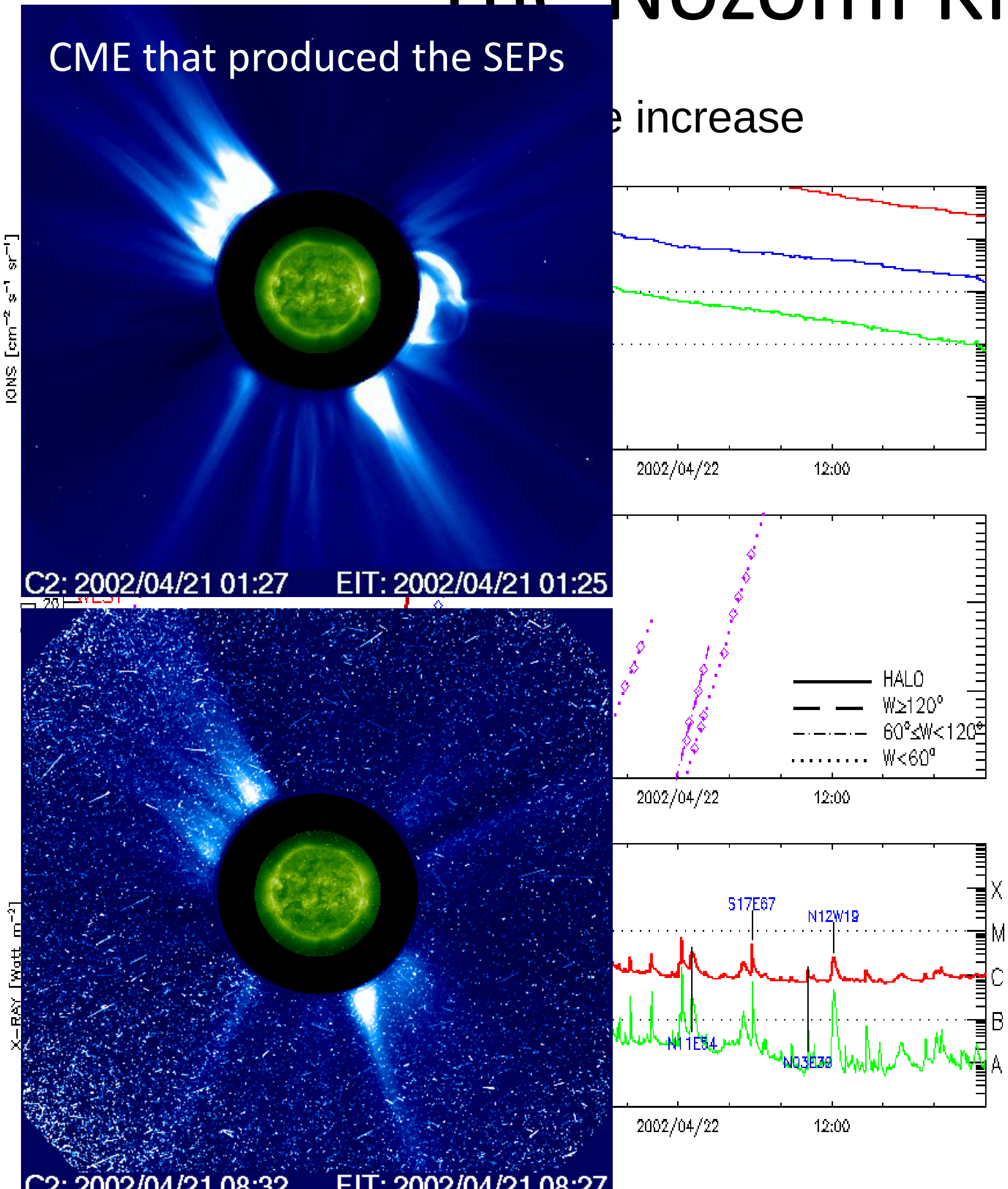
Solar Energetic Particles (SEPs) propagate along magnetic field lines in helical paths



"energetic protons are accelerated in the shock front just ahead of the expanding loop structures observed as mass ejections"
Kahler, Hildner, & Van Hollebeke (1978)

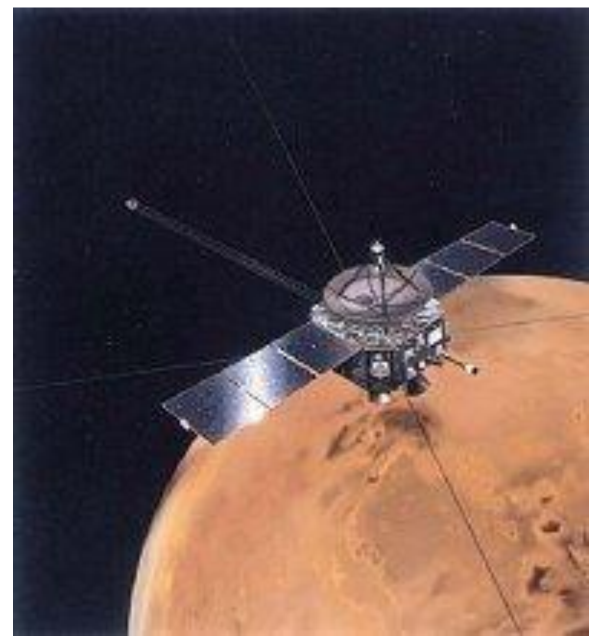
The Nozomi Killer?

e increase



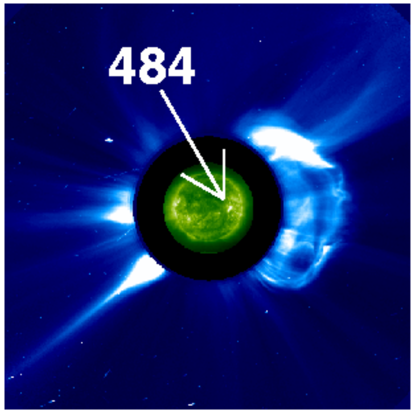
Japan’s Mars mission, Nozomi ended six months before insertion into Mars orbit due to the April 21 2002 particle storm

Onboard communications and power systems were damaged

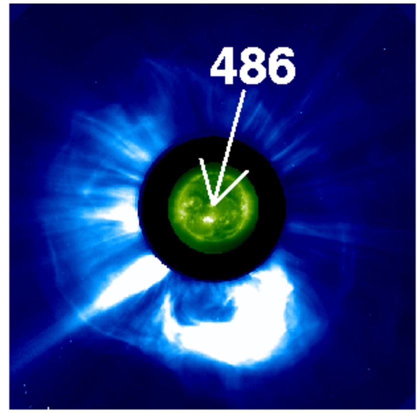


Nozomi = Hope

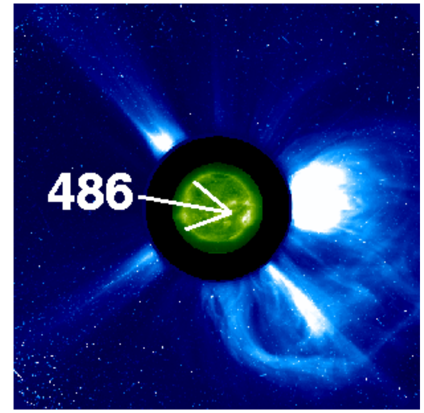
Violent Particle Radiation in 2003 from sunspot regions numbered 484 & 486 along with SOHO CMEs



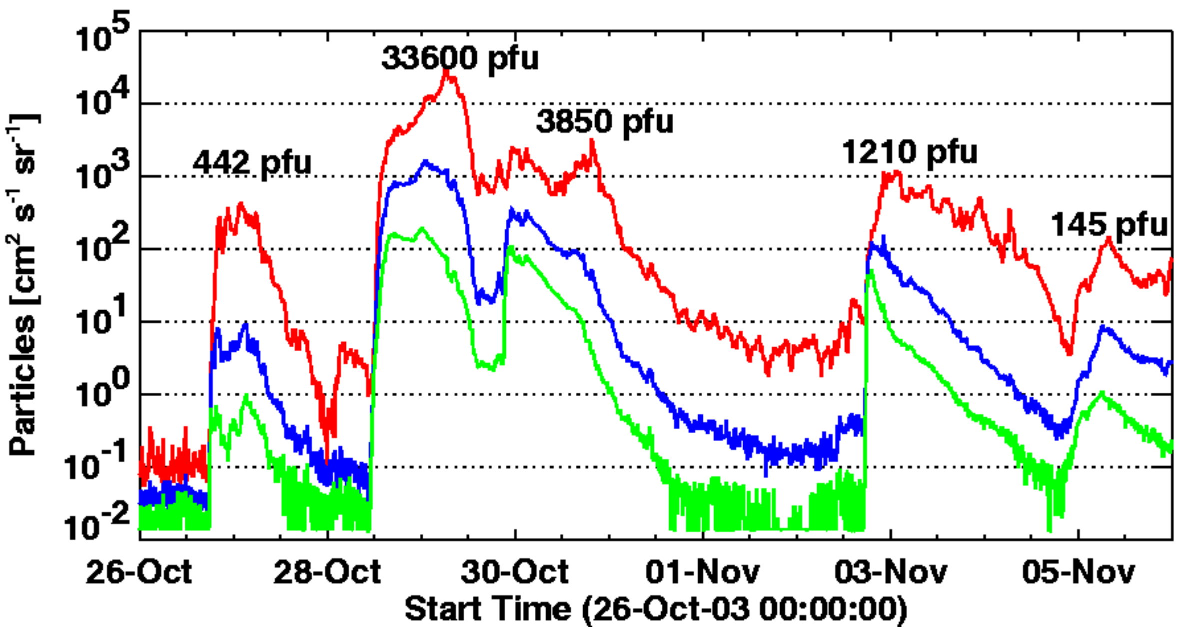
2003/10/26 18:06



2003/10/28 11:30

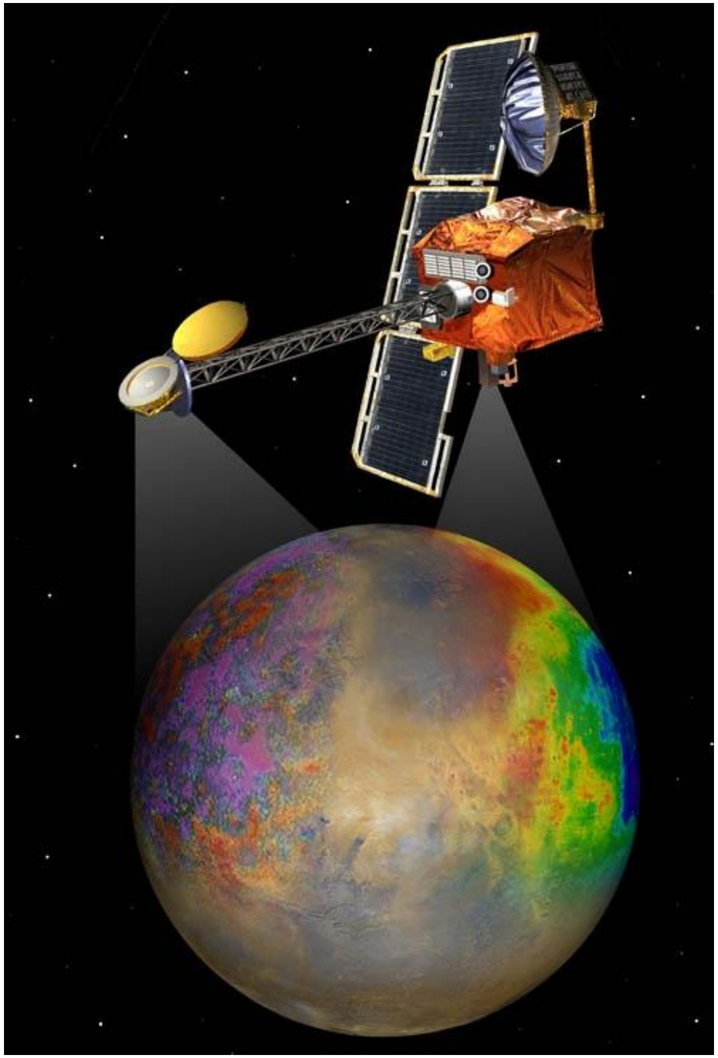


2003/11/02 17:54



Earth immersed in particle radiation for nearly 2 weeks

MARIE: The Martian Radiation Environment Experiment



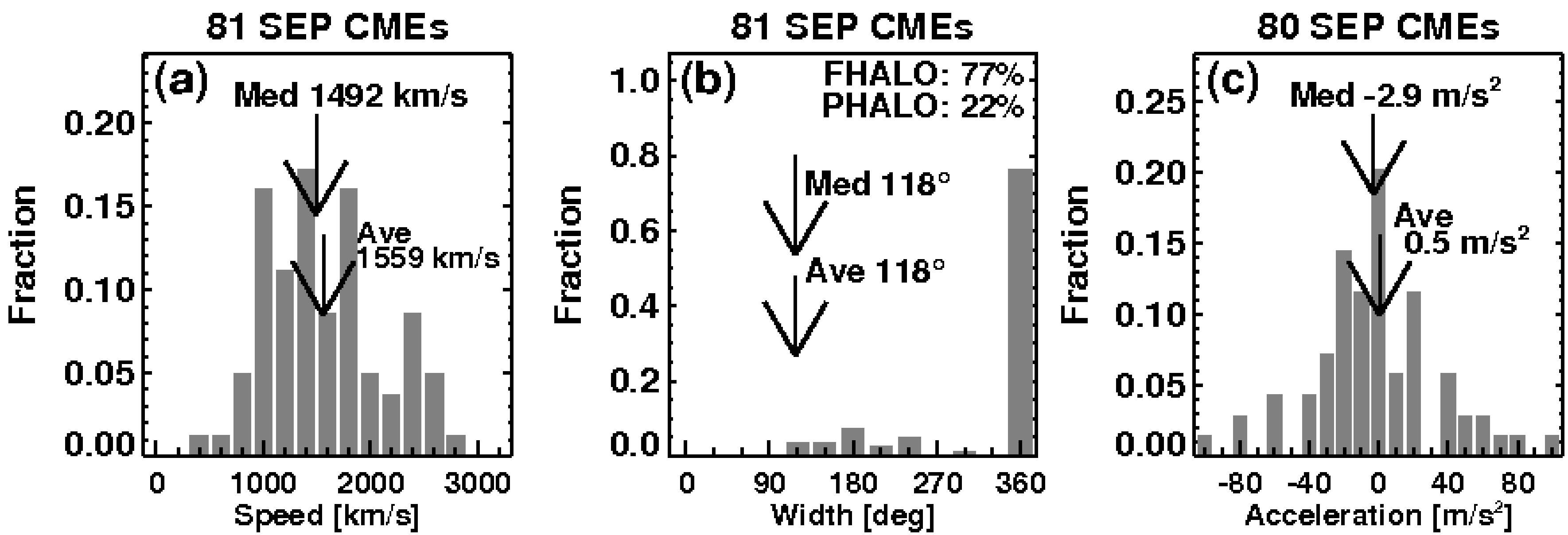
Mars Odyssey

The MARIE instrument on the Mars Odyssey gave us a first look at the radiation levels faced by a possible future astronaut crew.

The experiment took data on the way to Mars and in orbit, so that future mission designers will know better how to outfit human explorers for their journey to Mars.

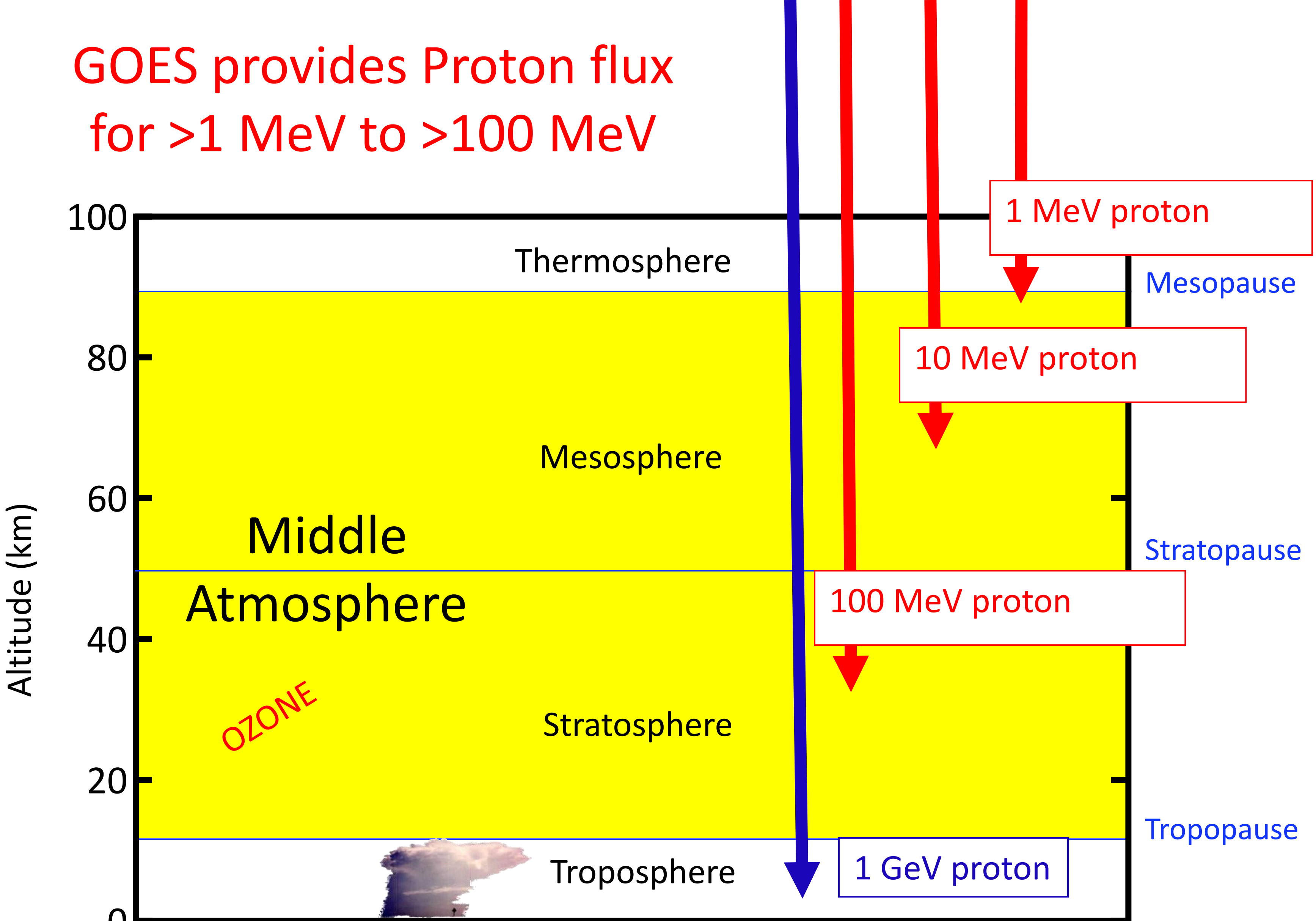
Another SEP event in October 2003 rendered MARIE inoperative. It is ironic, as MARIE was designed to measure the radiation environment at Mars.

SEP Producing CMEs



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

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

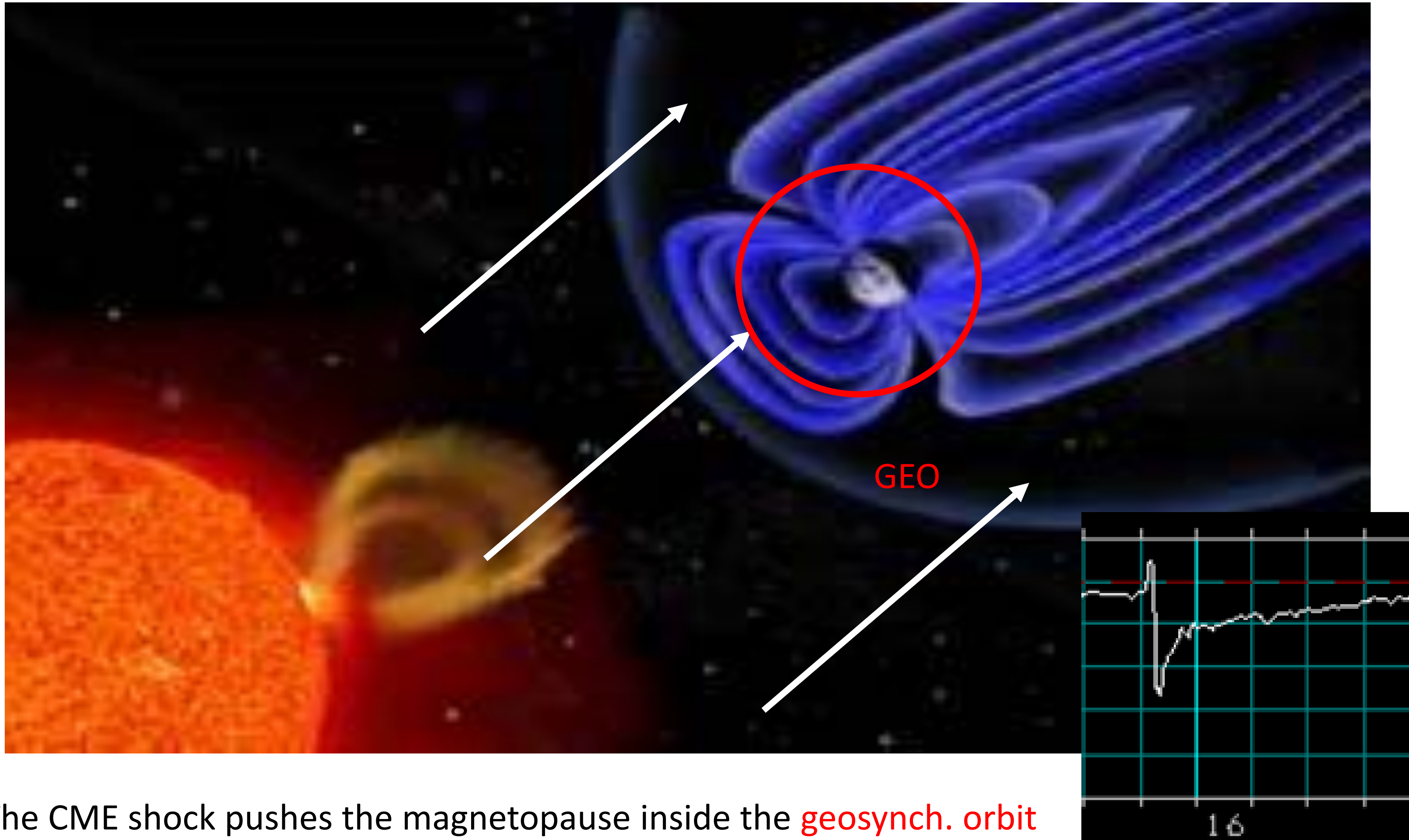


Particle radiation from the Sun can destroy ozone: 100 MeV protons penetrate to the stratosphere where ozone resides. These particles create HOx an NOx that interacts with ozone, thus reducing its concentration

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 geosynchronous satellites to the interplanetary space

Satellites Exposed to Interplanetary Space during Geomagnetic Storms

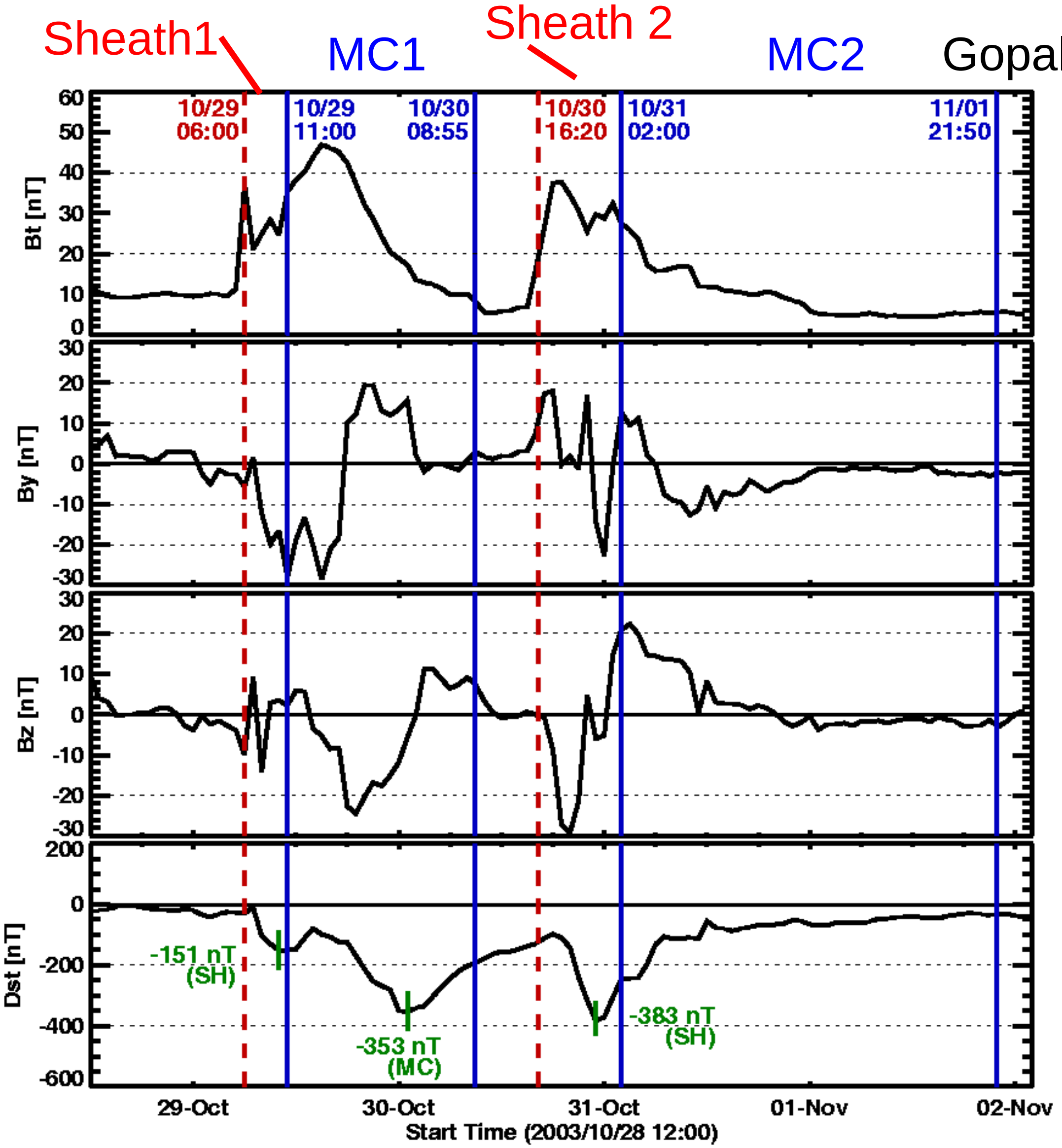


The CME shock pushes the magnetopause inside the geosynch. orbit

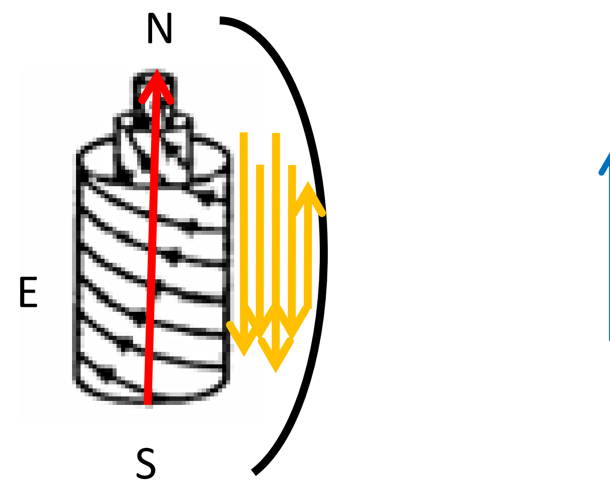
Out of the Ecliptic B from CMEs

- 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

Gopalswamy et al., 2008



Sheath Superstorm

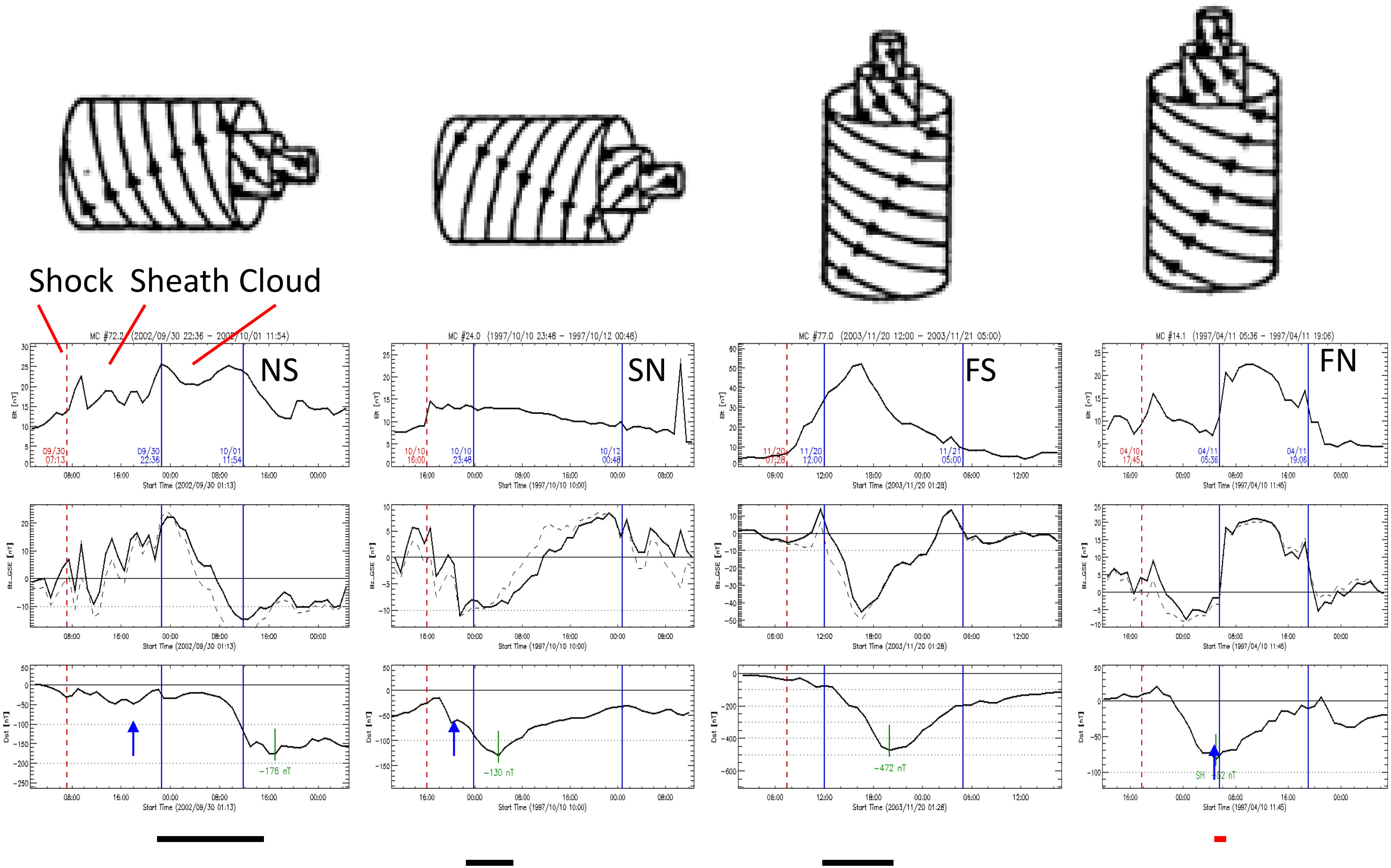


ENW (FN)

When MCs have high inclination the rotation is in the Y direction. In the Z-direction, the field will be always to the north or south. In this example, Bz is always north pointing so no storm. But there was a big storm due to the sheath consisting of intense south pointing Bz

Gosling and McComas1987; Tsurutani et al 1988

Summary of MC Structure



Cloud & Sheath Storms

Cloud storms are caused by southward IMF in the cloud portion

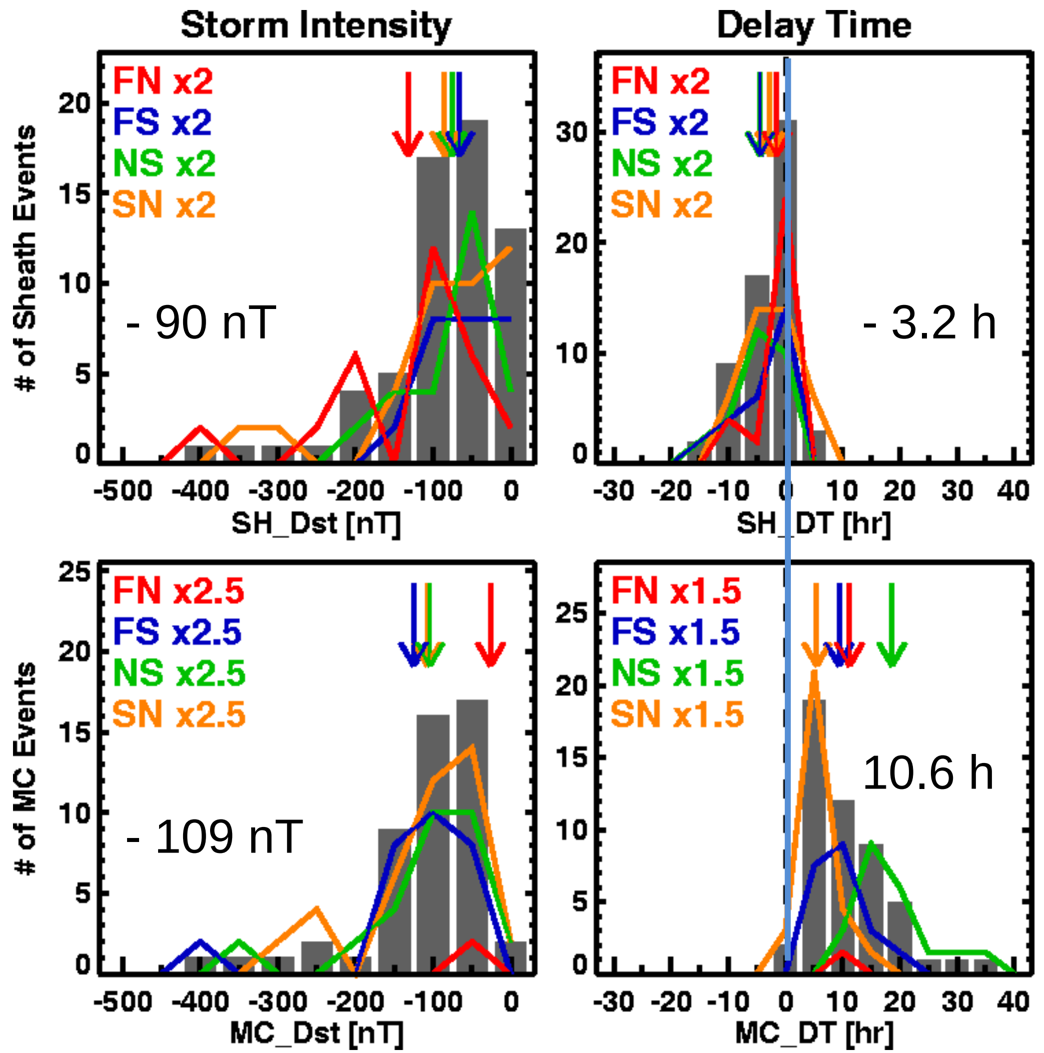
Sheath storm is due to southward IMF in the sheath portion

The average storm intensity is similar for sheath and clod storms

Delay time from ICME arrival to storm peak (Maximum Dst)

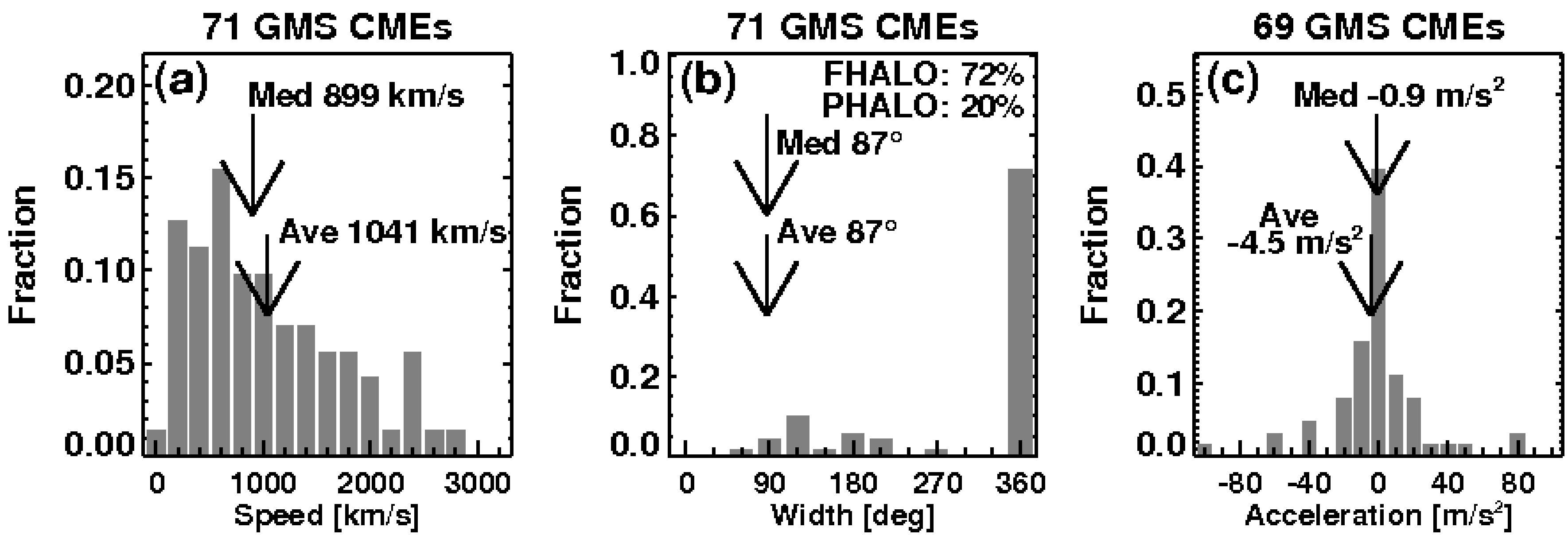
Delay time is negative for sheath storms because sheath arrives at Earth before the ICME does

The delay is longest for SN-type ICMEs because BzS is at the tail end



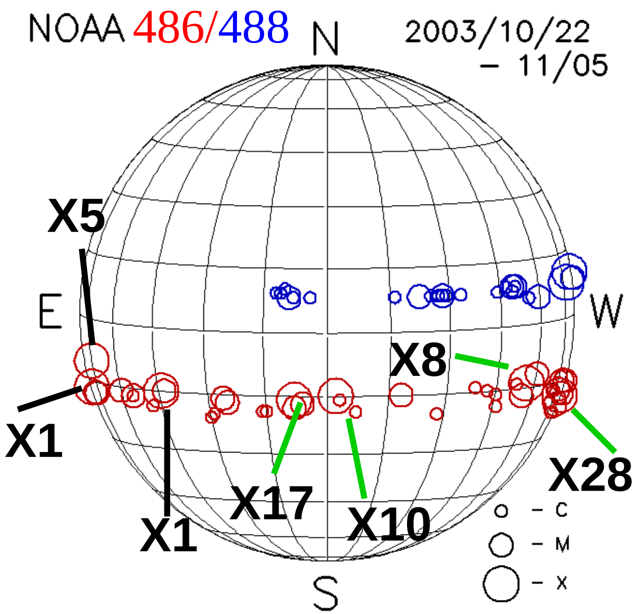
CMEs Producing Geomagnetic Storms

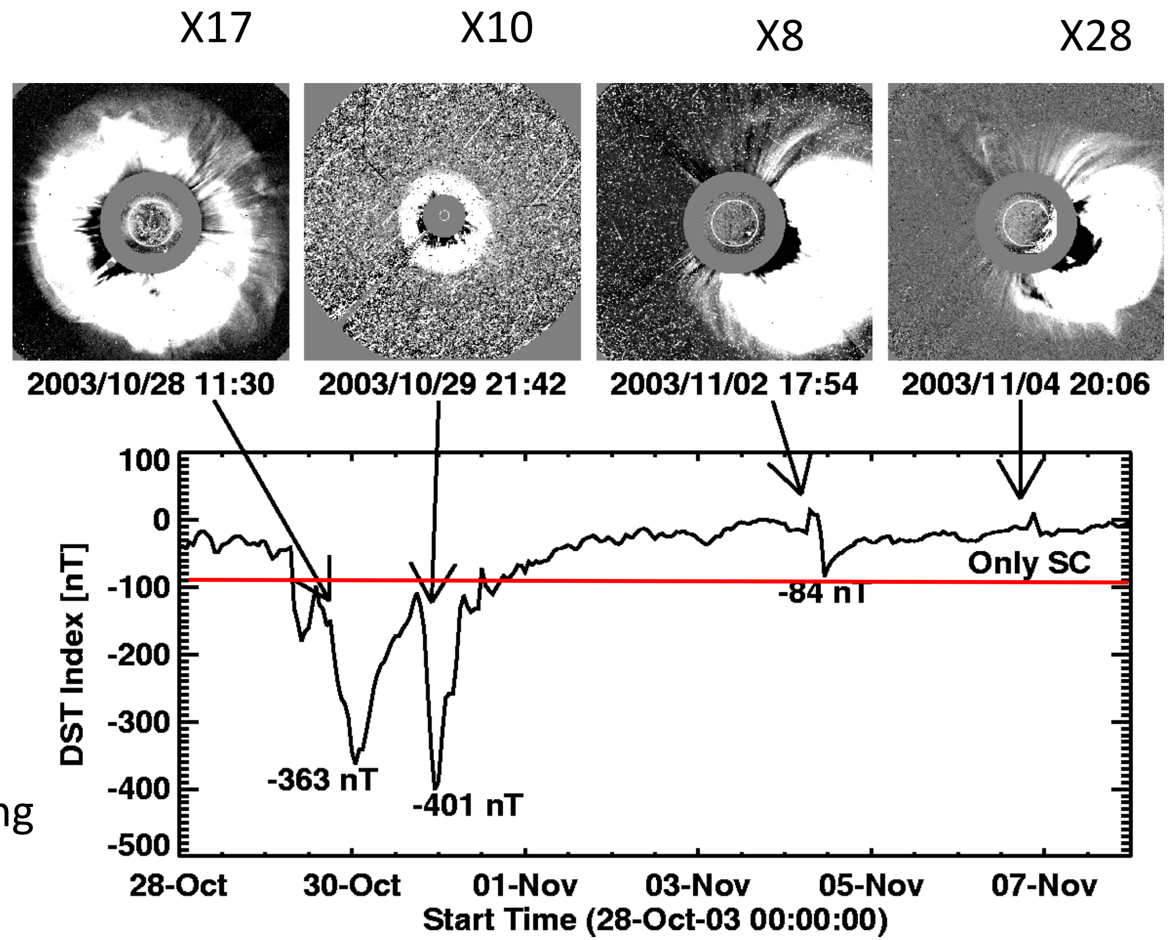
Large Dst (≤ -100 nT) events from cycle 23 and the associated LASCO CMEs considered



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

Solar Source location important for Earth Impact





Heliographic coordinates of the CME source location. CMEs occurring near the disk center head directly toward Earth causing storms (e.g. CMEs associated with the X17 and X10 flares)

Dst index measures an average horizontal field of the Sun
Storm conditions when Dst< -30 nT
Major storms when Dst < -100 nT

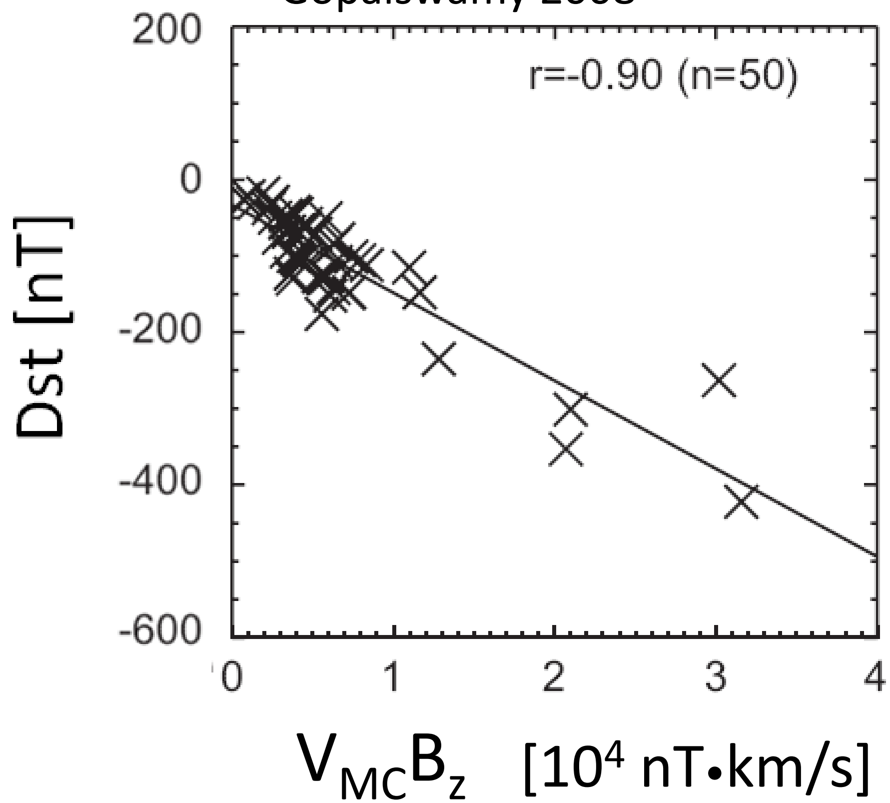
Geomagnetic Storm and CME parameters

$Dst = -0.01VB_z - 32$ 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

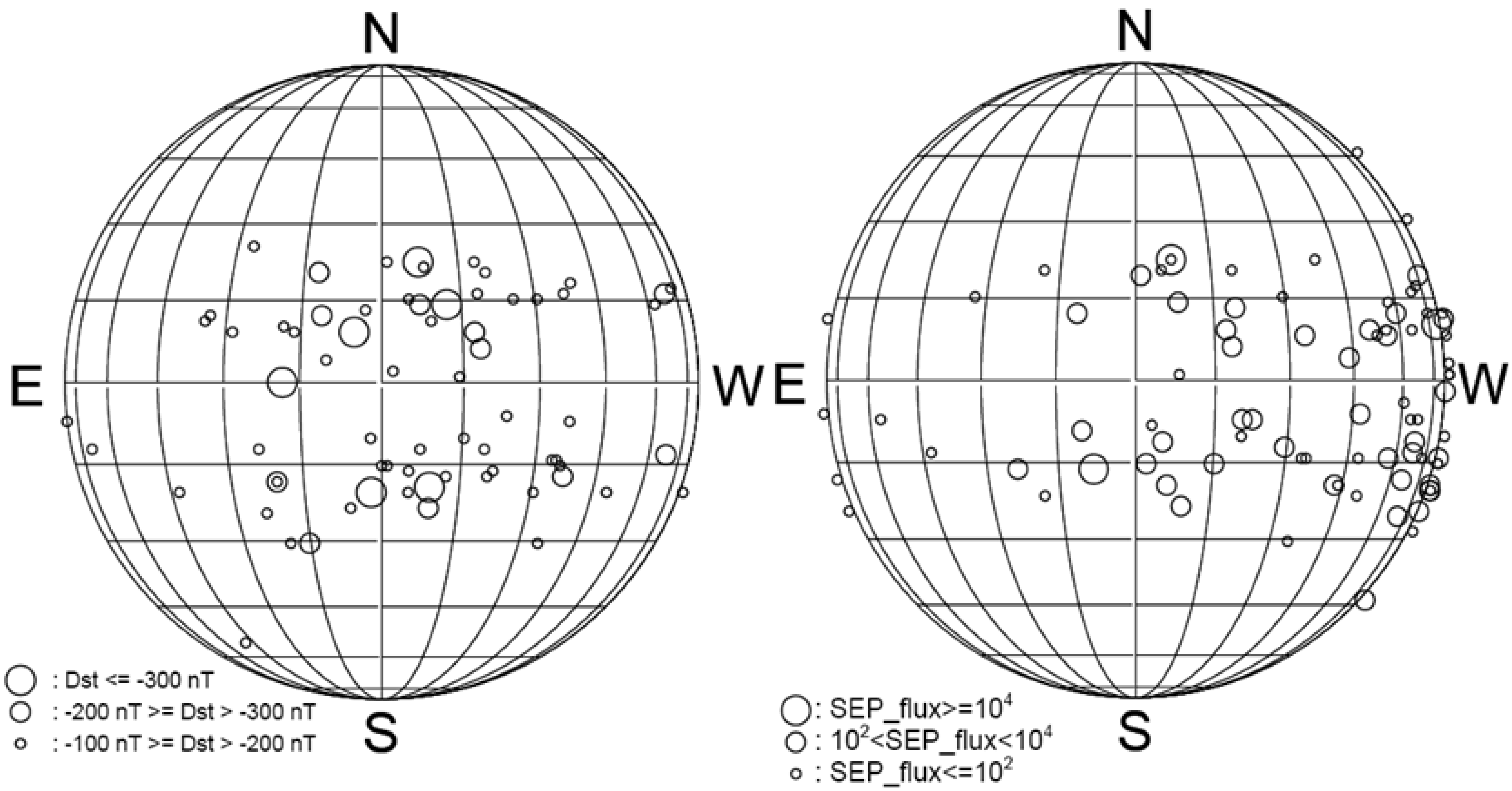
Active Region
Free energy

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

Heliospheric
Mag Field

Active Region
Mag Field

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

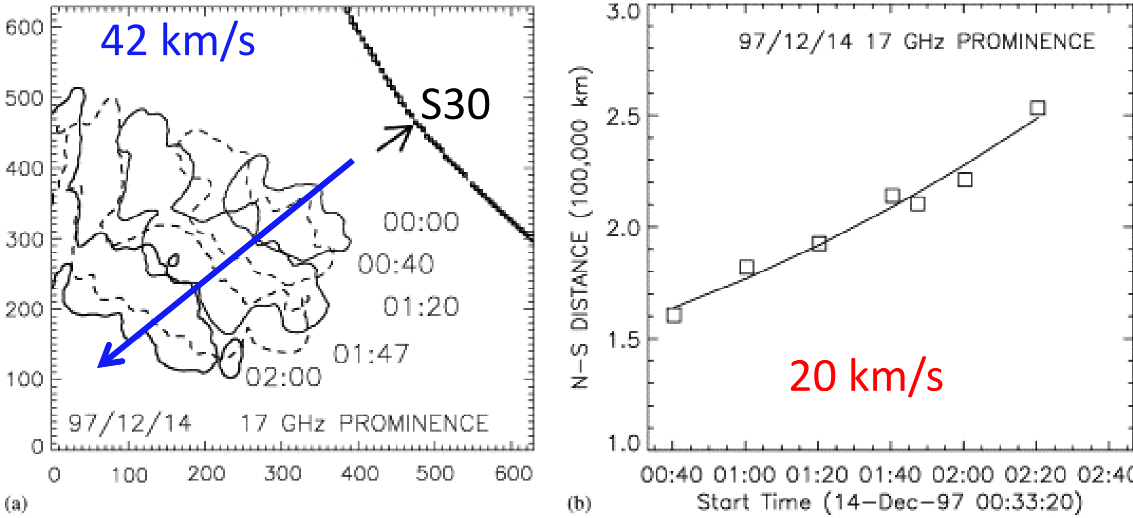
Many double-whammy events

CME Interactions

- Non-radial motion of CMEs during the minimum phase
- CME – CME interactions during solar maximum
- CME – Coronal hole interaction during the declining phase
- CMEs tend to align with the heliospheric current sheet: CME rotation

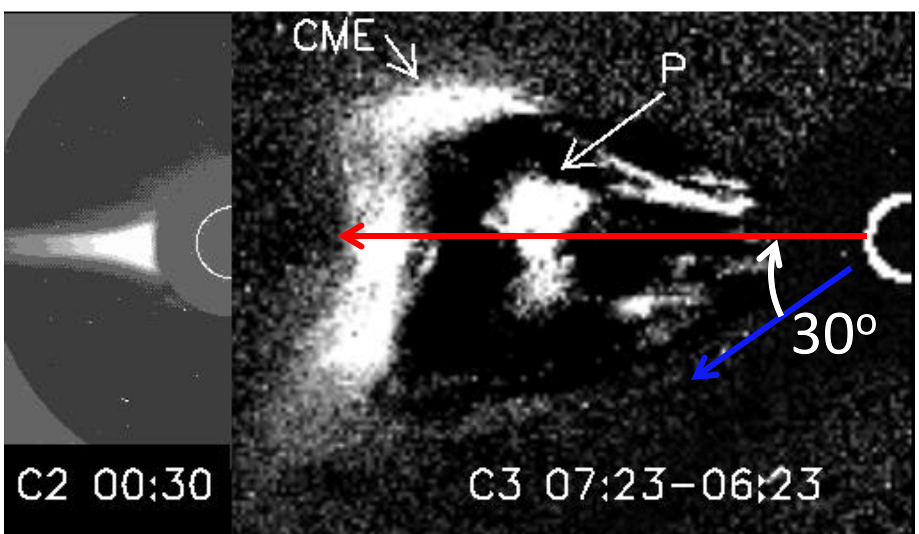
Non-radial Motion: Toward Equator

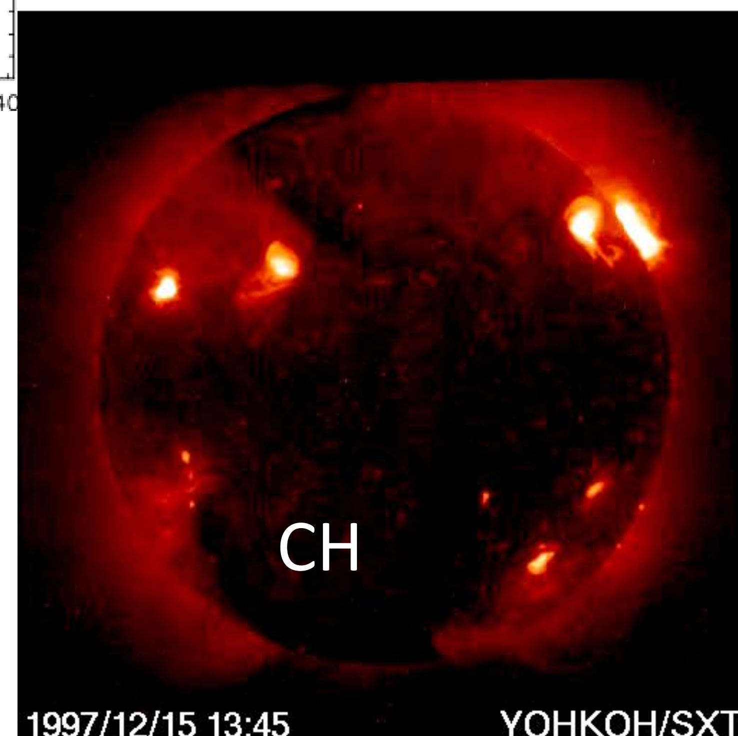
NoRH PE: Gopalswamy and Thompson, 2000 JASTP



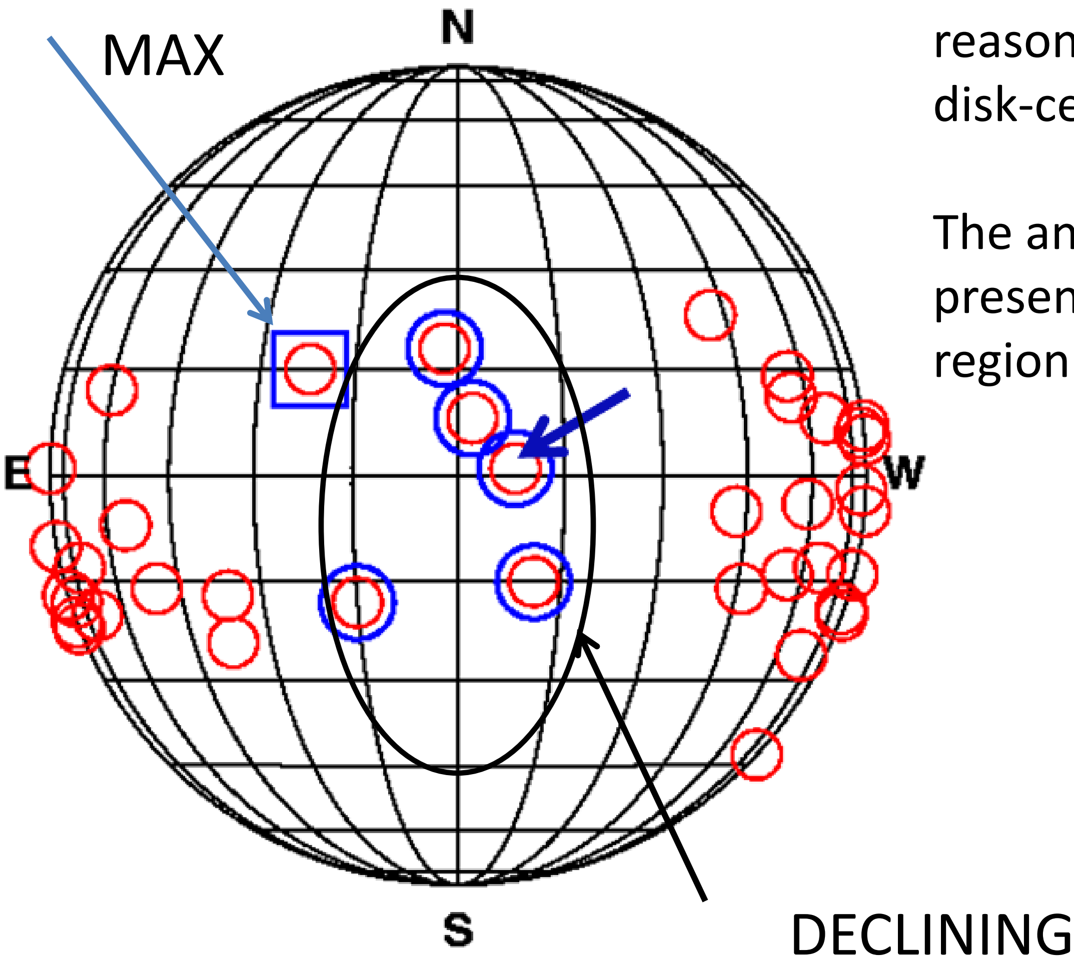
Hildner, 1977
MacQueen et al. 1986
Gopalswamy et al. 2000
Plunkett et al. 2001
Cremades et al. 2004
Gopalswamy et al. 2003,2009
Panasenco et al. 2010
Byrne et al. 2010
Lugaz et al. 2009

Deflection by 30°





Why driverless shocks from disk center?

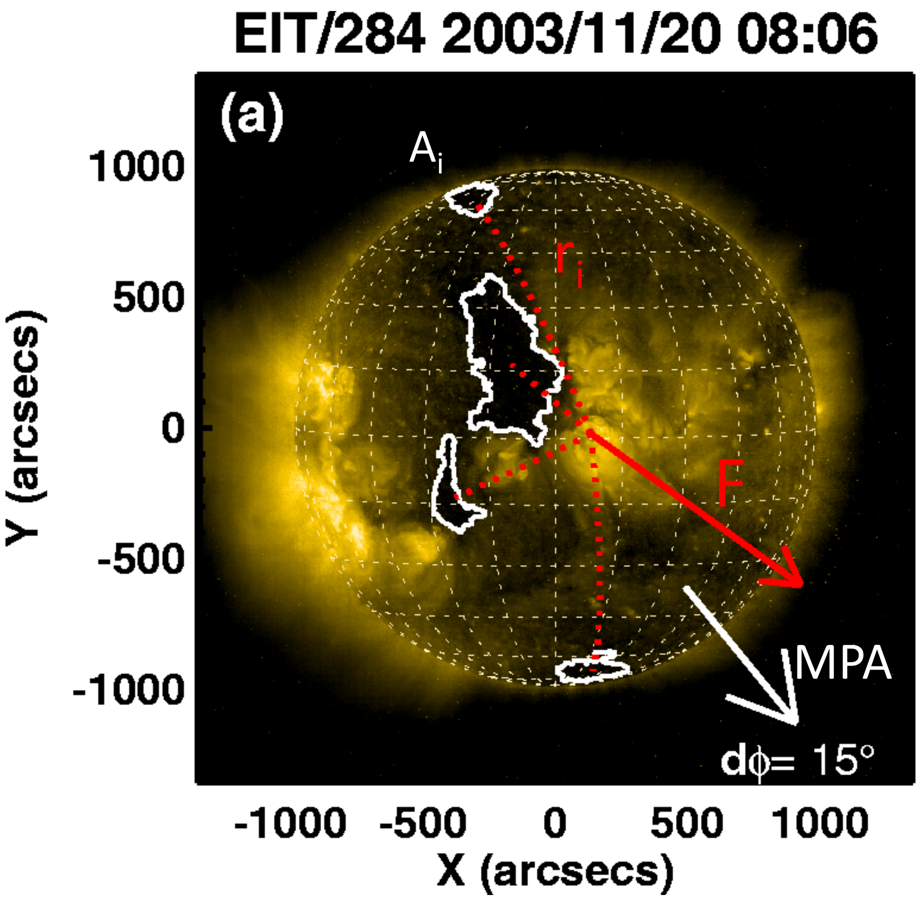


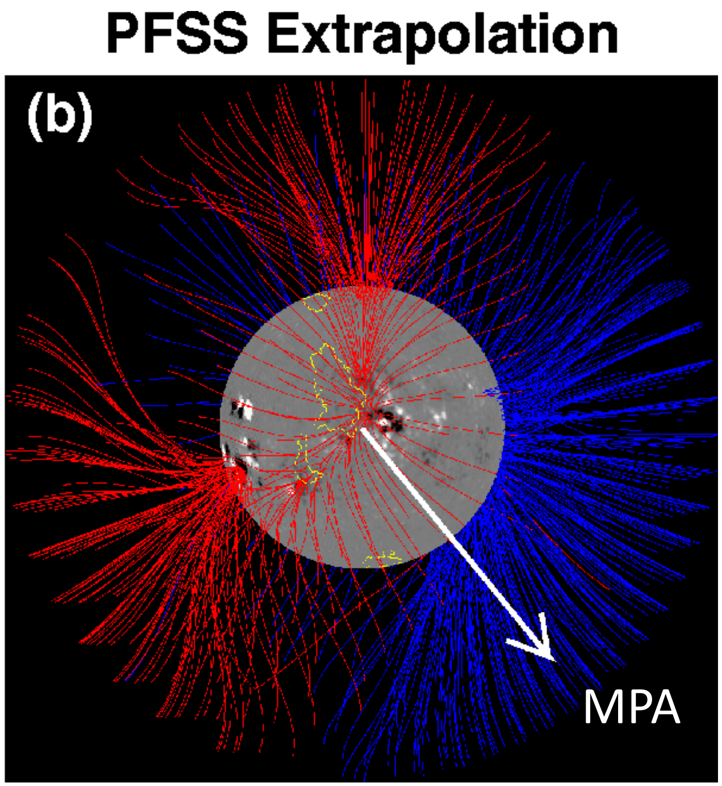
Gopalswamy et al. 2009, JGR

The limb sources are normal (geometrical reason), but the
disk-center sources are anomalous

The anomaly seems to be due to the presence of coronal holes near the source region

Coronal Hole Influence Parameter





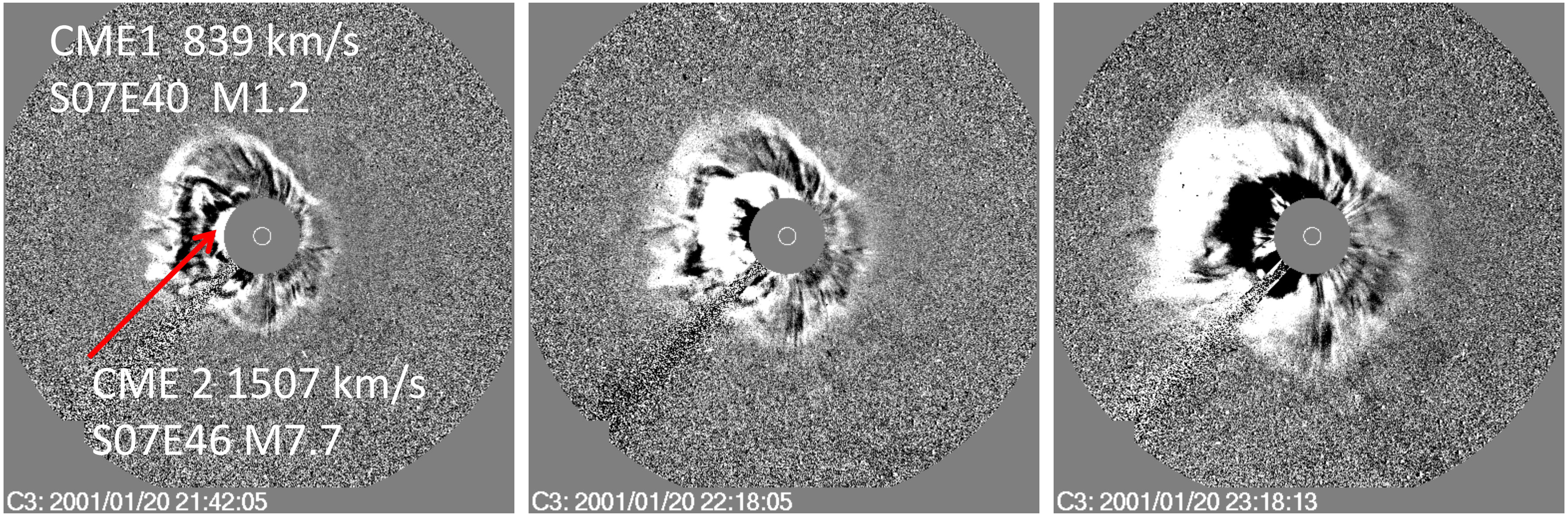
(Open field lines only shown)

$F = \sum f_i \qquad f_i = A_i \langle B_i \rangle / r_i^2$

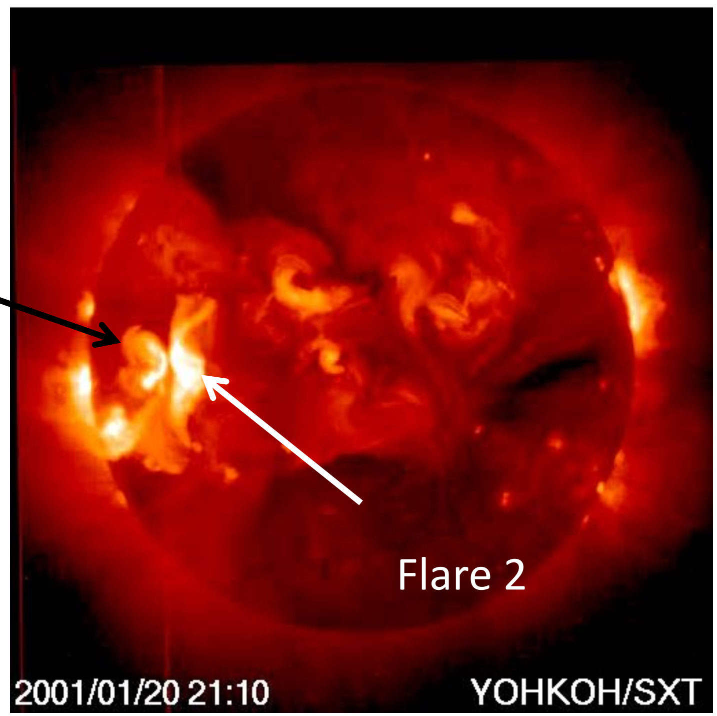
F = 14 G pointed along the PA (FPA) of 234°.

CME position angle (MPA) aligns with the direction of influence FPA

Gopalswamy et al., 2009 JGR

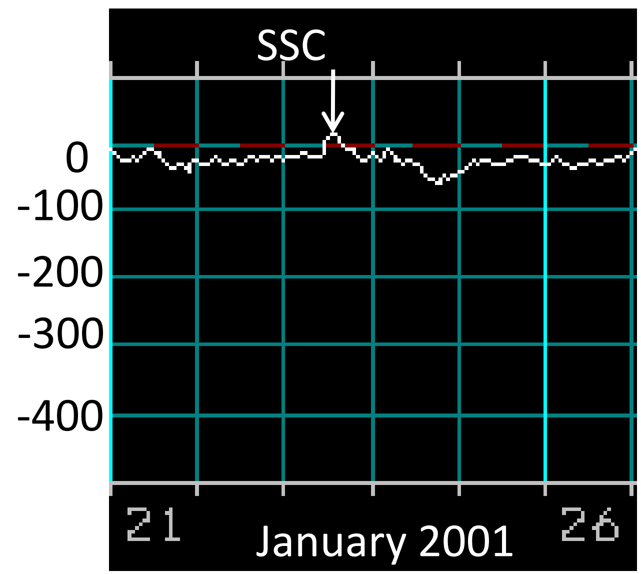


CME Cannibalism



Two CMEs from the same region AR

Dst -61 nT moderate storm



Single shock

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

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