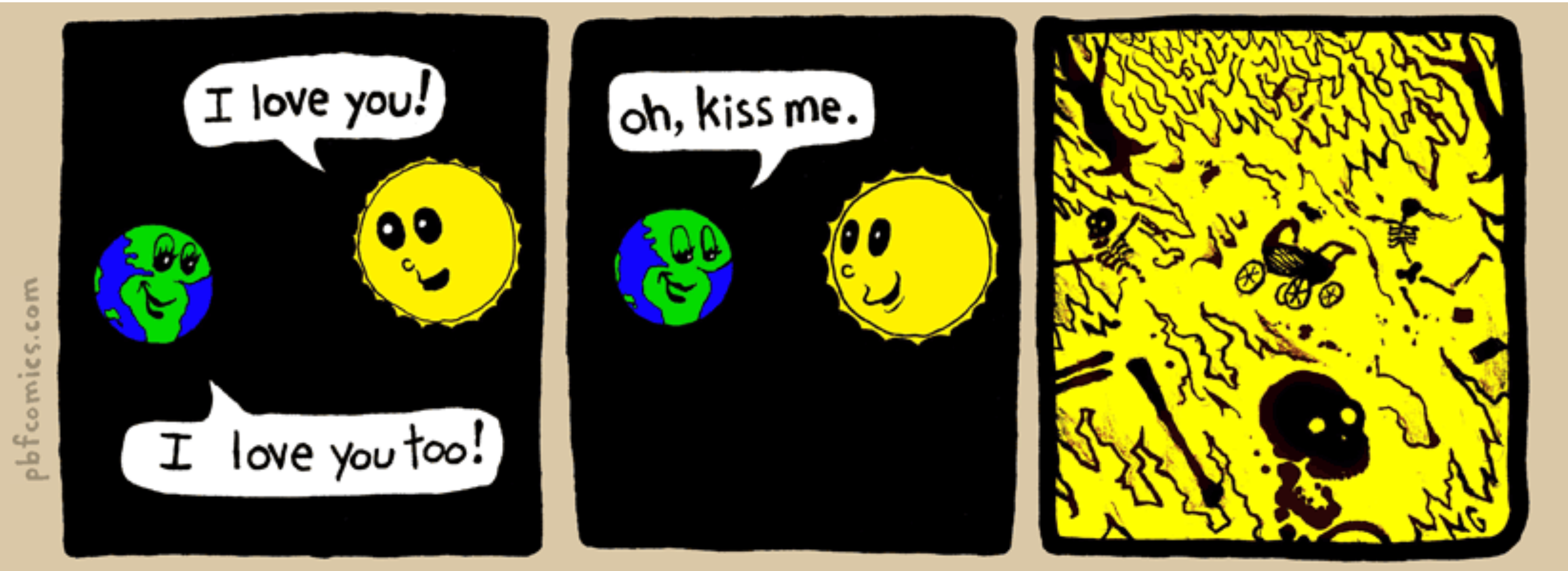
Ήλιος και Γη: μια σχέση έρωτα και καταστροφής



Ηλιακές εκρήξεις:
εκλάμψεις και εκτινάξεις μάζας

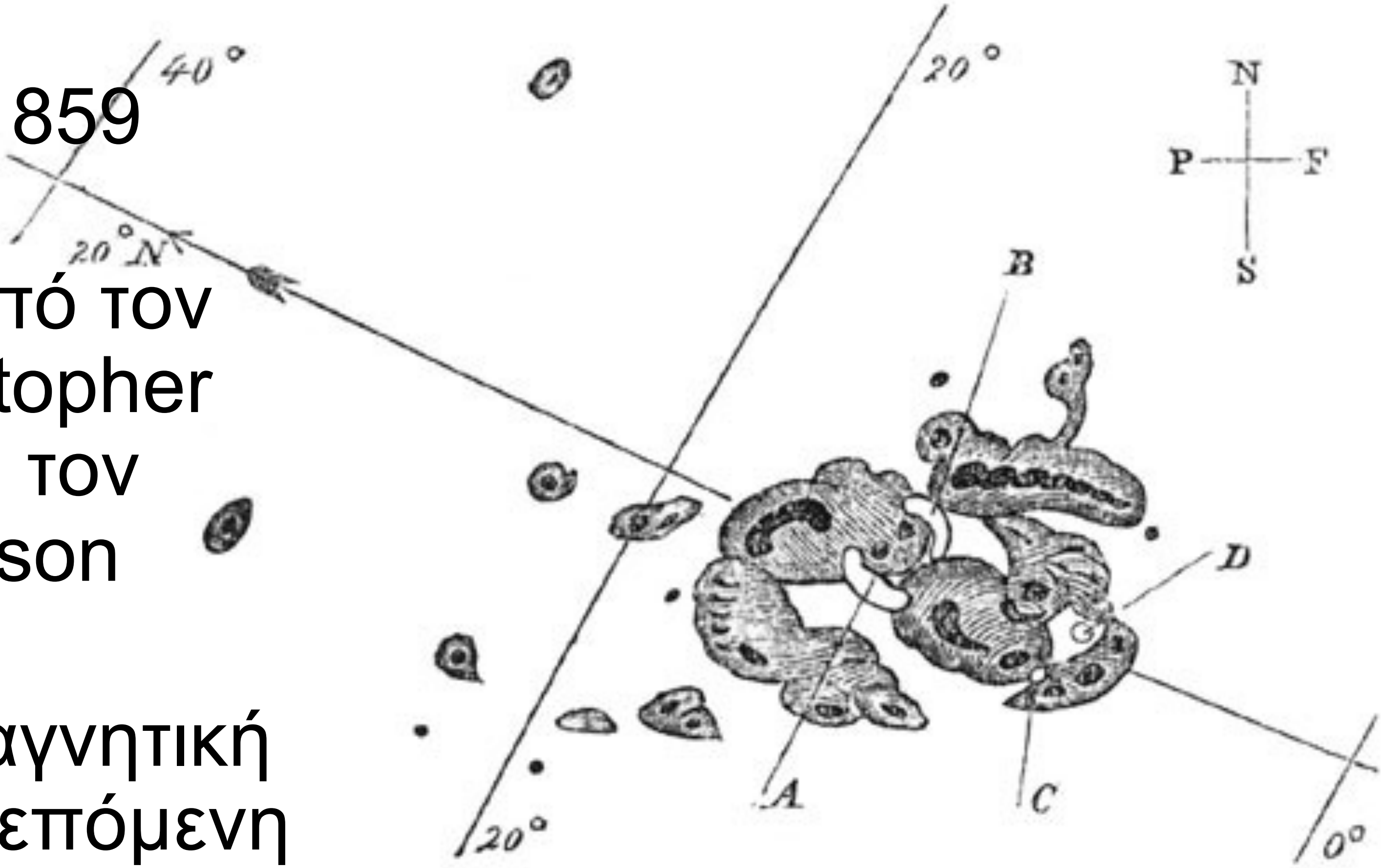
Solar flares
Coronal Mass Ejections

The mother of all flares

1 Σεπτεμβρίου 1859

- Παράλληλα από τον Richard Christopher Carrington και τον Richard Hodgson

- Ισχυρότατη μαγνητική καταιγίδα την επόμενη μέρα



Drawing by Carrington


Septem
Fri
day's
Septem
Μικροζυθοποιία
Fri
day's
Pale Ale
Beer

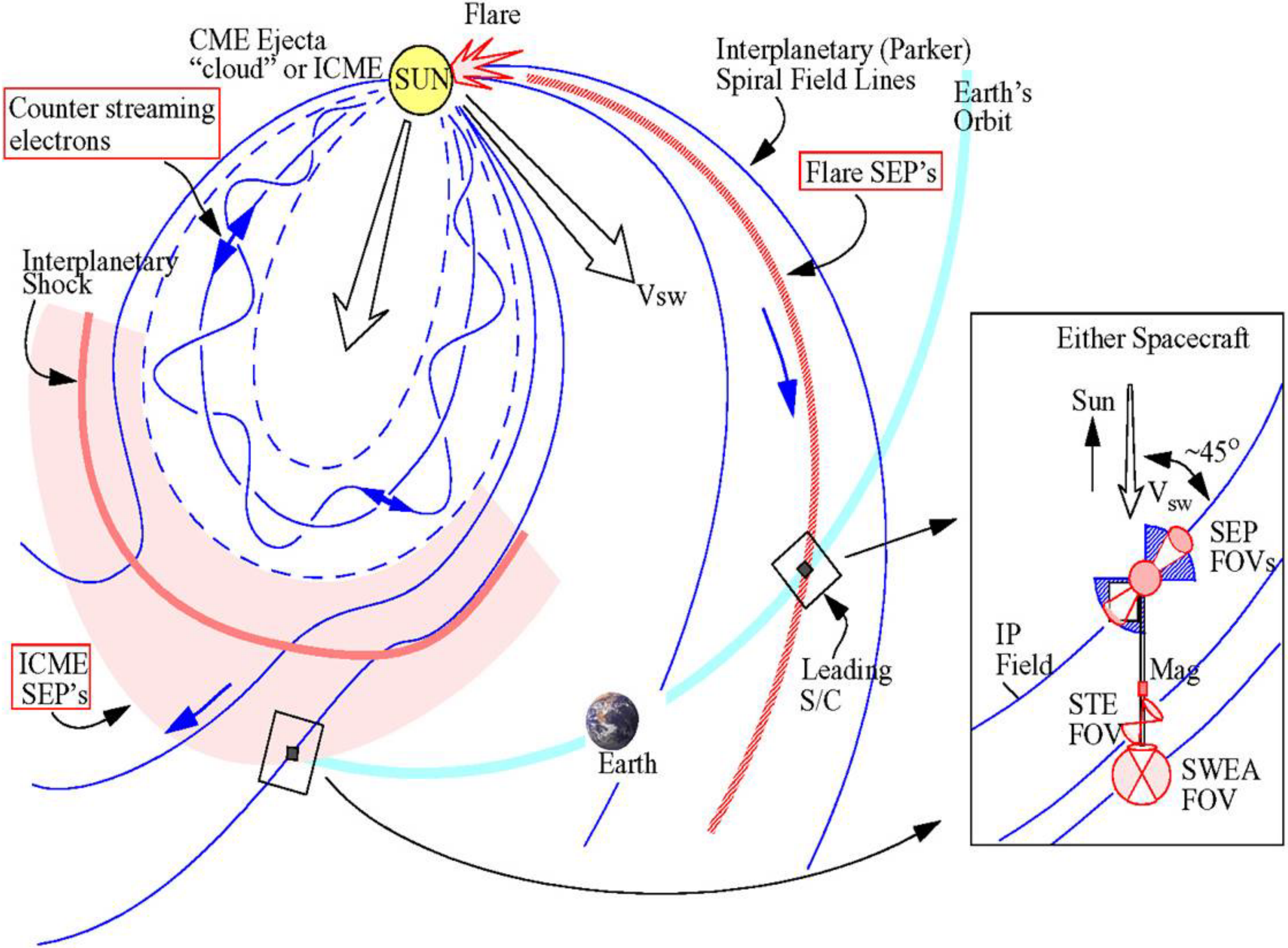
Εκλάμψεις
και
στεμματικές εκτινάξεις μάζας

Οι δύο τύποι
ηλιακών “εκρήξεων”
(solar eruptions)

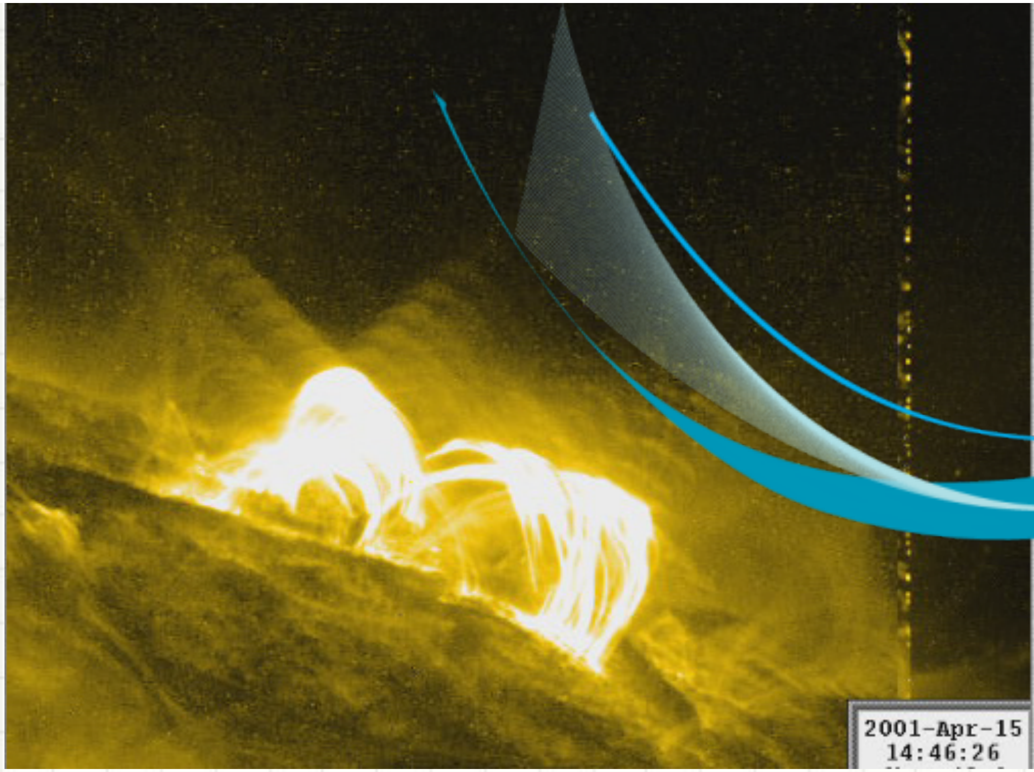
Εκλάμψεις
και
στεμματικές εκτινάξεις μάζας

Οι δύο τύποι
ηλιακών “εκρήξεων”
(solar eruptions)

που είναι τρεις

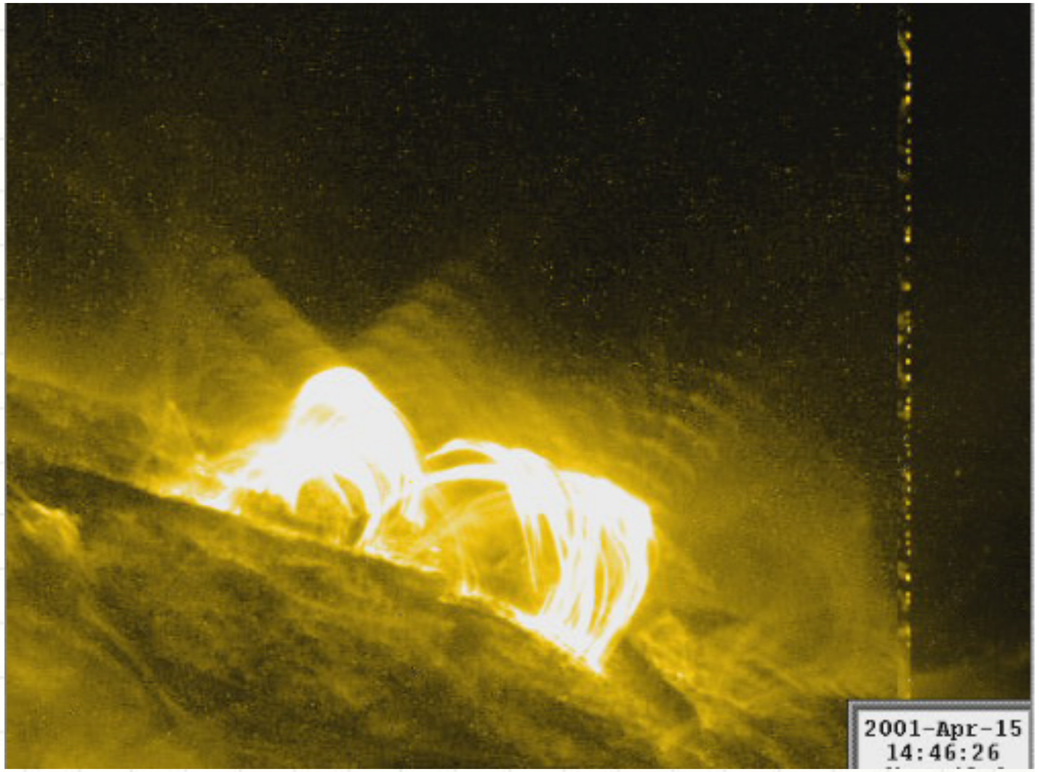

Flare
CME Ejecta
"cloud" or ICME
SUN
Counter streaming
electrons
Interplanetary (Parker)
Spiral Field Lines
Earth's
Orbit
Flare SEP's
Interplanetary
Shock
Vsw
Either Spacecraft
Sun
~45°
V_{sw}
SEP
FOVs
IP
Field
Mag
STE
FOV
SWEA
FOV
Leading
S/C
ICME
SEP's
Earth

Ηλιακή έκλαμψη



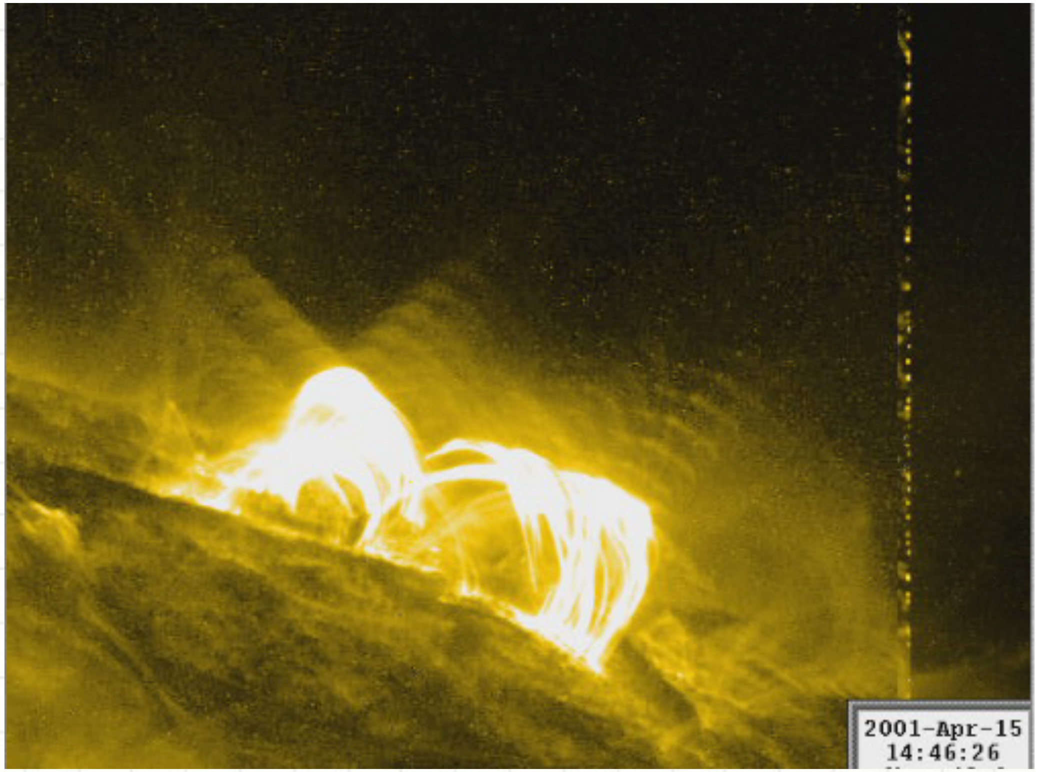
Αιφνίδια, ταχεία και έντονη
αύξηση της λαμπρότητας (έντασης)
ηλεκτρομαγνητικής ακτινοβολίας
σε πολλά διαφορετικά μήκη κύματος
(μεγάλο δυναμικό εύρος)

Ηλιακή
έκλαμψη



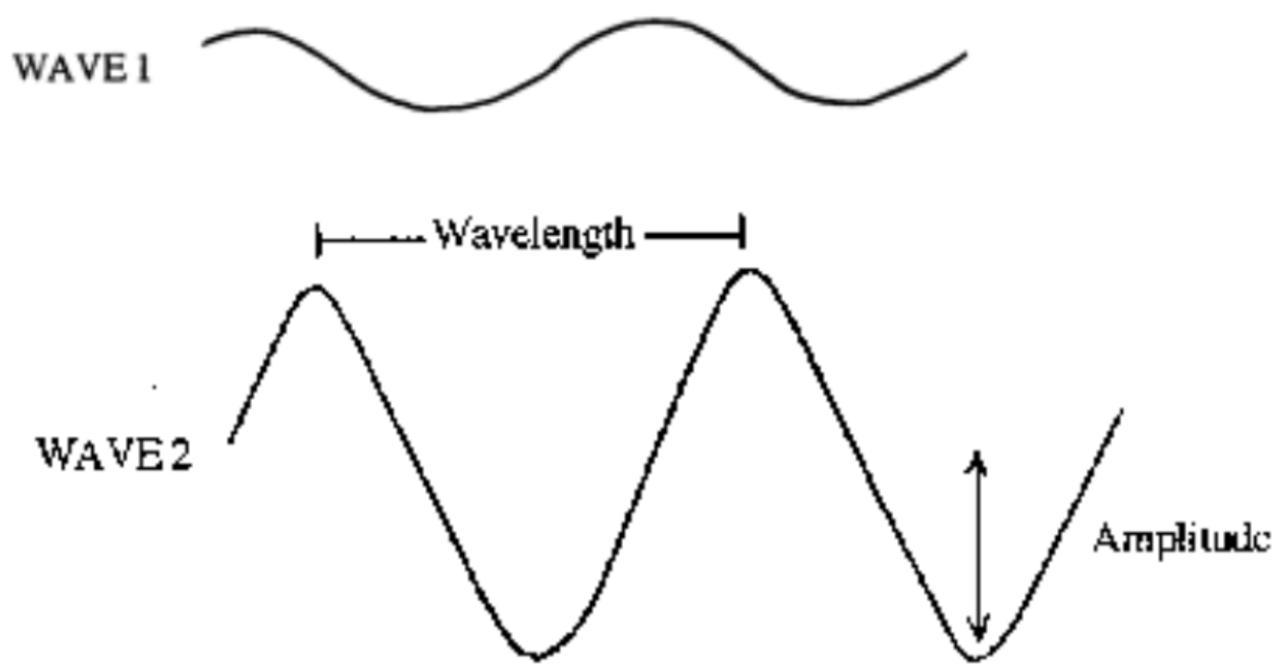
καθώς και
αιφνίδια, ταχεία και έντονη
έκλυση σωματιδίων πολύ
μεγάλης ενέργειας

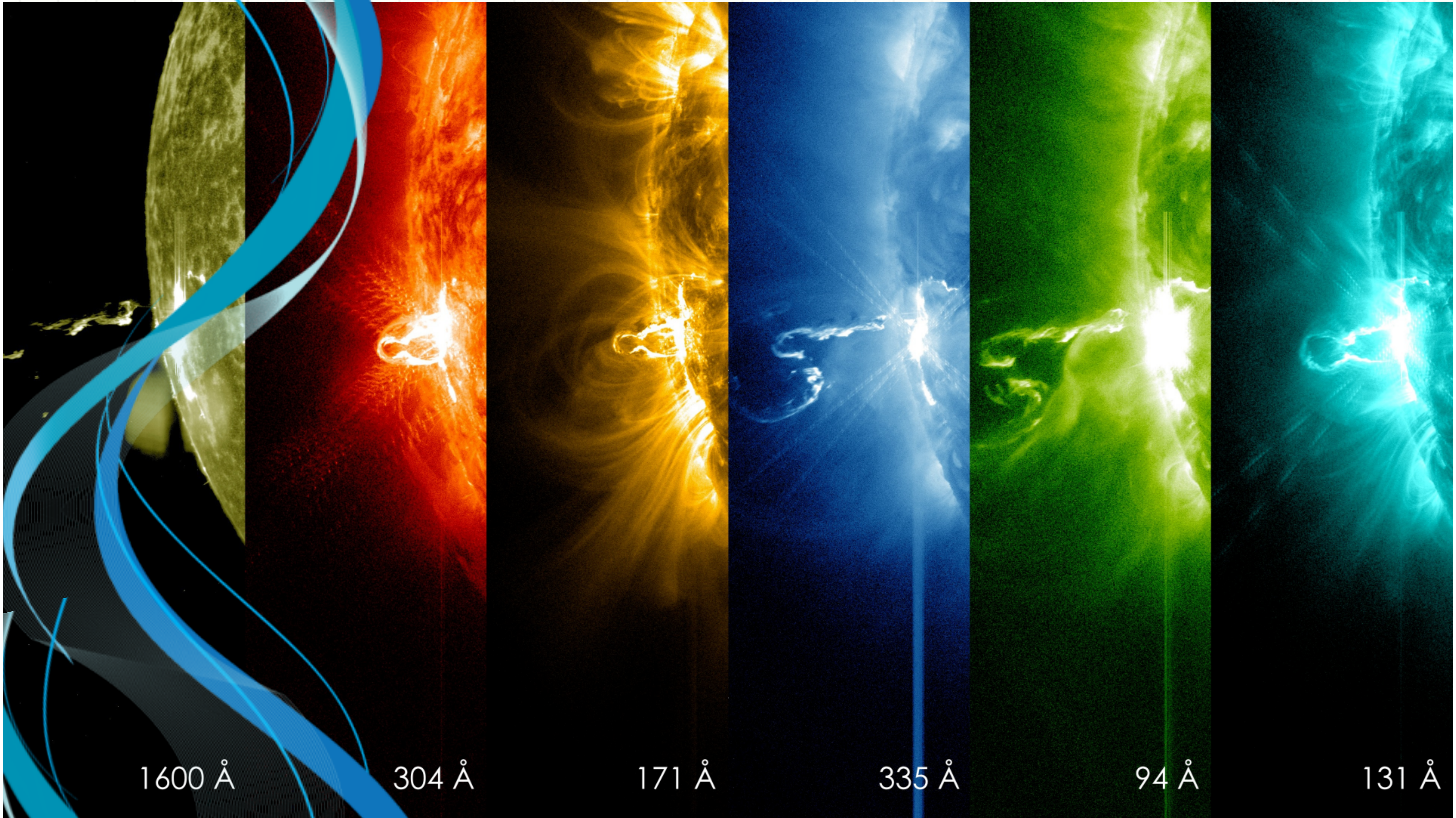
Ηλιακή έκλαμψη



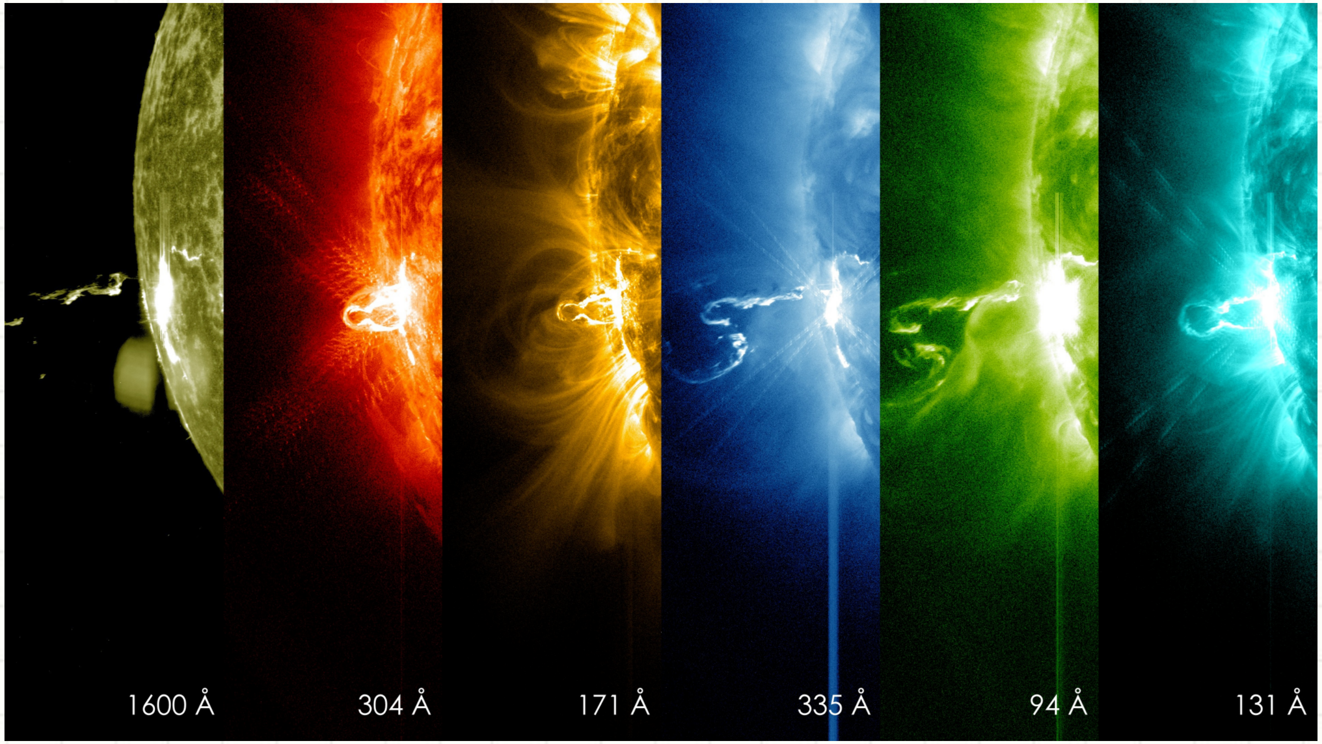
Αυτό σημαίνει:
Ισχυρή και απότομη έκλυση ενέργειας στην ατμόσφαιρα του Ήλιου: 10^{22} – 10^{25} Joules

Ετήσια παγκόσμια κατανάλωση ενέργειας: 10^{25} Joules


WAVE 1
Wavelength
WAVE 2
Amplitude



Flare at various wavelengths



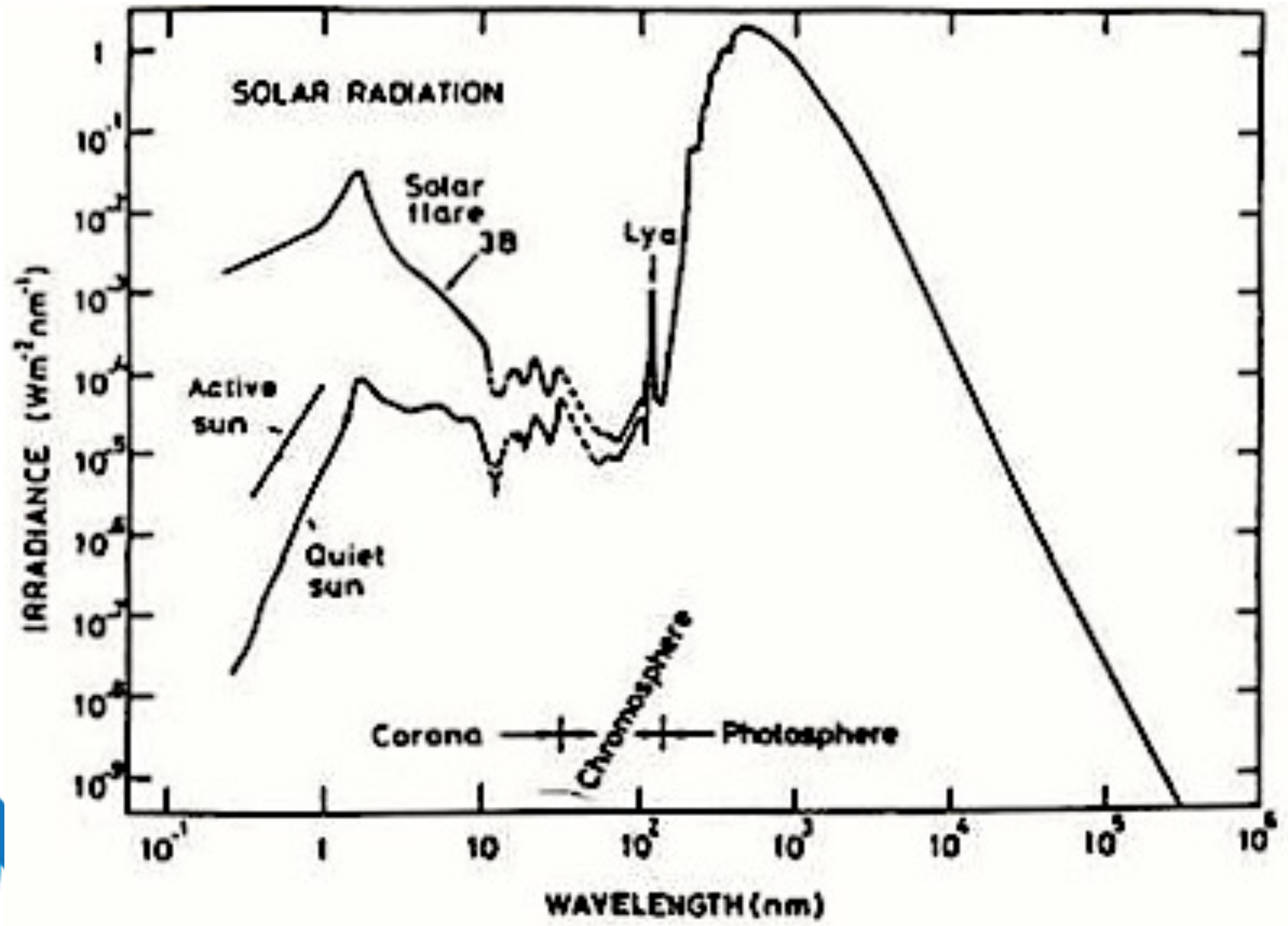
Αυξημένη λαμπρότητα σε:

Μαλακές ακτίνες Χ – πάντα

Σκληρές ακτίνες Χ – σχεδόν πάντα

Ραδιοκύματα – σπάνια

Ακτίνες γάμμα – σπάνια


SOLAR RADIATION
Solar flare 3B
Lyα
Active sun
Quiet sun
Corona
Chromosphere
Photosphere
IRRADIANCE (Wm⁻²nm⁻¹)
WAVELENGTH (nm)

Ταξινόμηση εκλάμψεων

Ροή ακτινοβολίας μαλακών ακτίνων X (0.1-0.8 nm) στη γεωστατική τροχιά (GOES):

A1 = 10^{-8} W m^{-2}

B1 = 10^{-7} W m^{-2}

C1 = 10^{-6} W m^{-2}

M1 = 10^{-5} W m^{-2}

X1 = 10^{-4} W m^{-2}

Z1 = 10^{-3} W m^{-2}

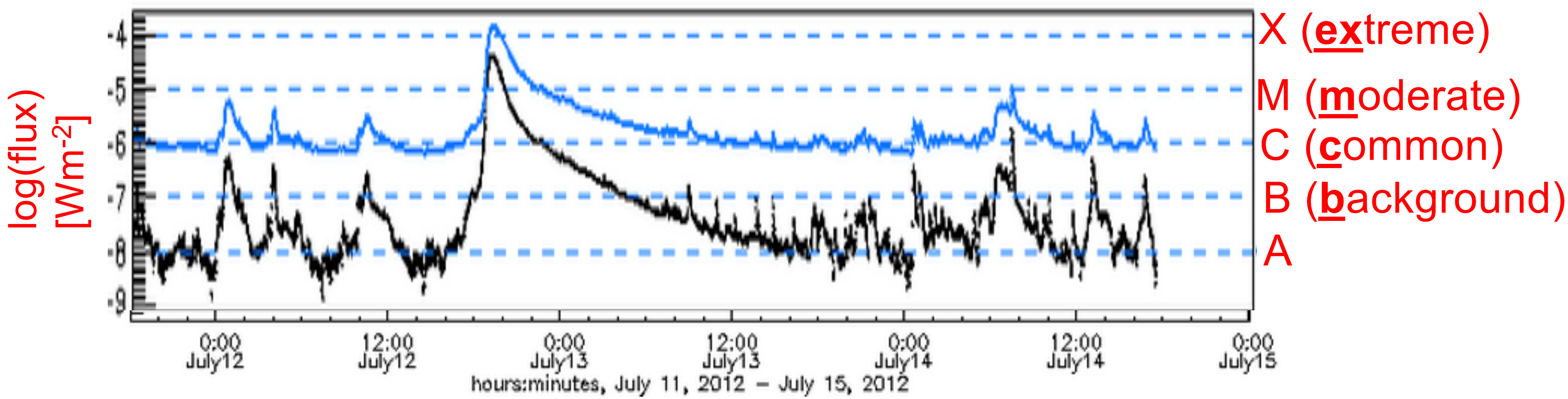
Για σύγκριση, η ολική ροή είναι 1.366 W m^{-2}

Solar Flare Class

12 July 2012: X1.4 class flare

0.1-0.8 nm

0.05-0.4 nm



X1.4 class: flux(0.1-0.8nm) = 1.4×10^{-4} W/m^2

$B5 = 5 \times 10^{-7}\ W\ m^{-2}$

$B5 = 5 \times 10^{-7}$ W m^{-2}

$M8 = 8 \times 10^{-5}$ W m^{-2}

$B5 = 5 \times 10^{-7}\ W\ m^{-2}$

$M8 = 8 \times 10^{-5}\ W\ m^{-2}$

$X7 = 7 \times 10^{-4}\ W\ m^{-2}$

$B5 = 5 \times 10^{-7}$ W m^{-2}

$M8 = 8 \times 10^{-5}$ W m^{-2}

$X7 = 7 \times 10^{-4}$ W m^{-2}

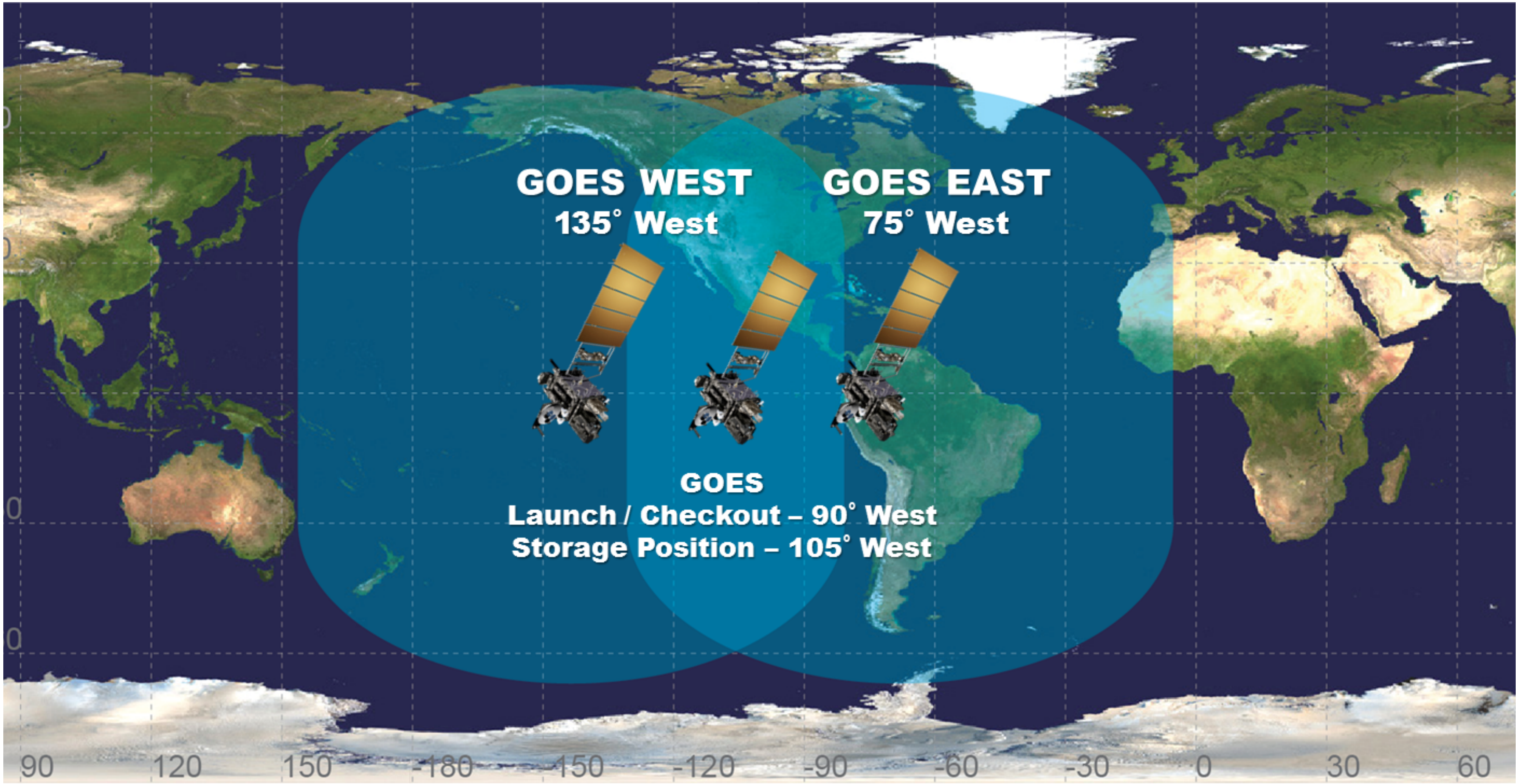
Big daddy:
4 Nov 2003, 19:29-20:06 X17.4
Διαδοχικές εκτιμήσεις:
X28+, X37, X45 ή X40

Έκλαμψη του 1859: ίσως X40

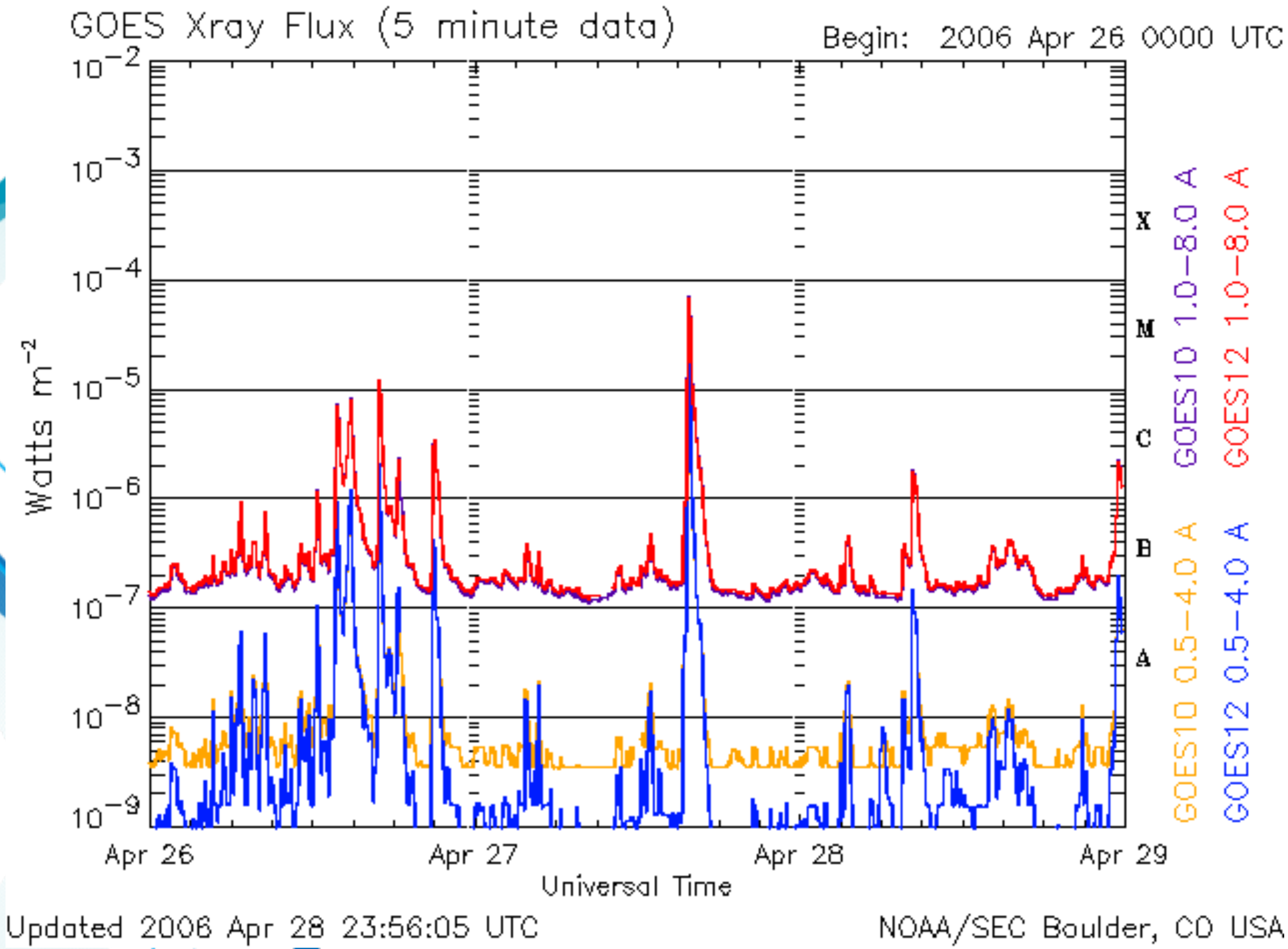
Από πού προέρχονται οι μετρήσεις (και γιατί)

GOES

Geostationary Operational Environmental Satellites

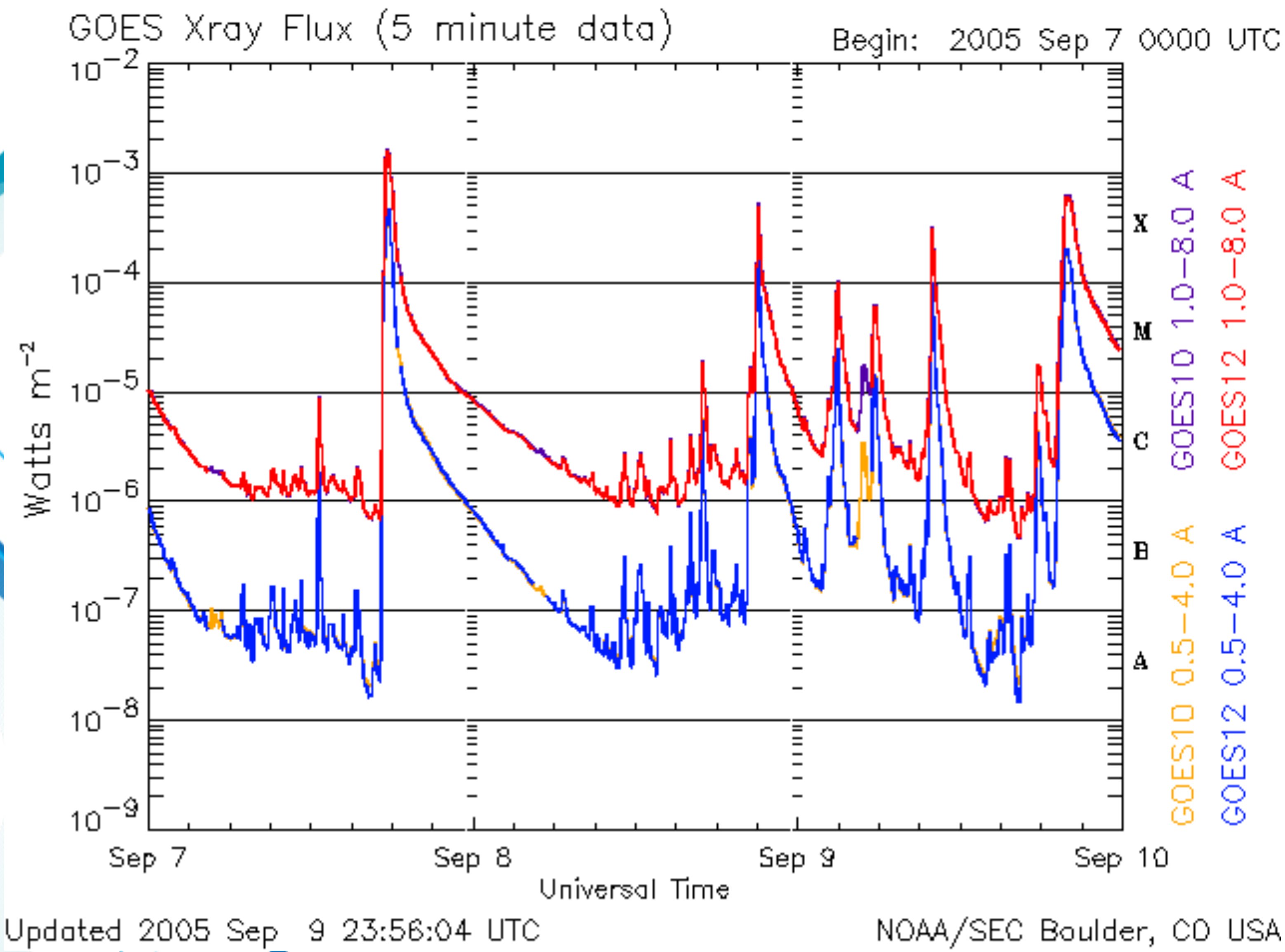


Soft X-Ray Light Curves from GOES (Geostationary Operational Environmental Satellites)

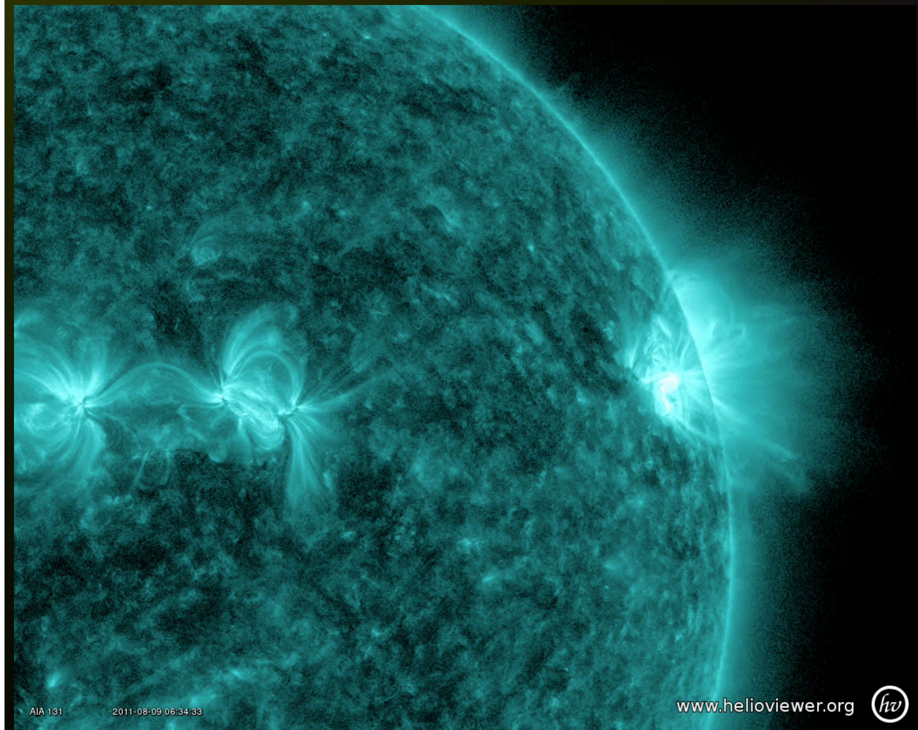


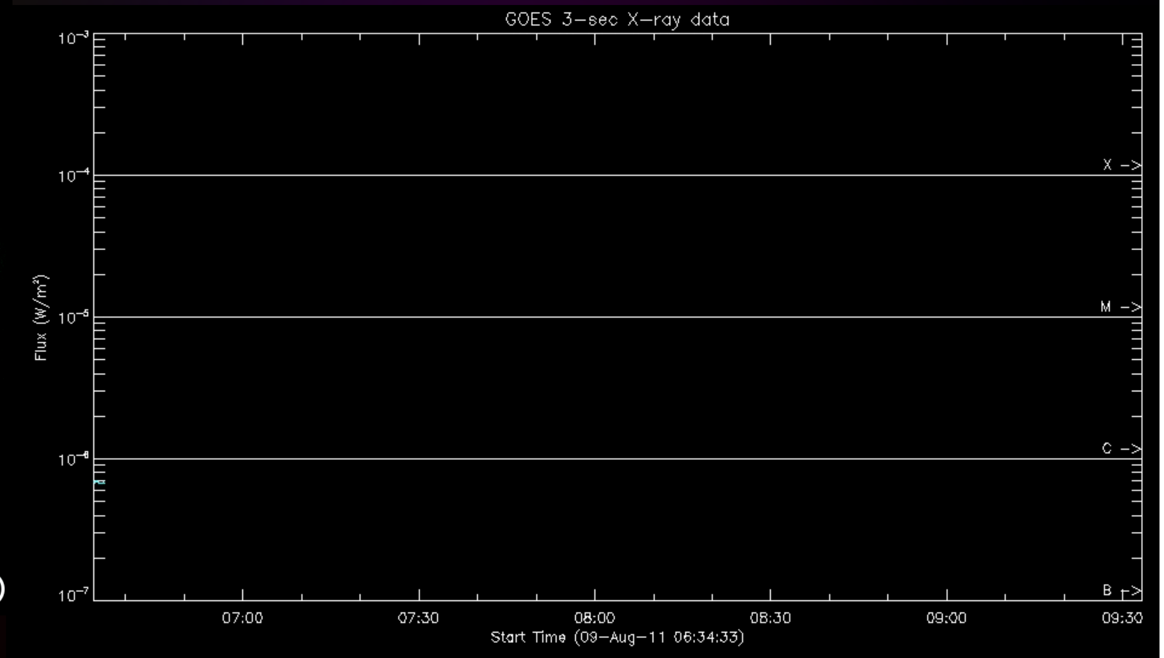
M7 Flare

Soft X-Ray Light Curves from GOES (Geostationary Operational Environmental Satellites)

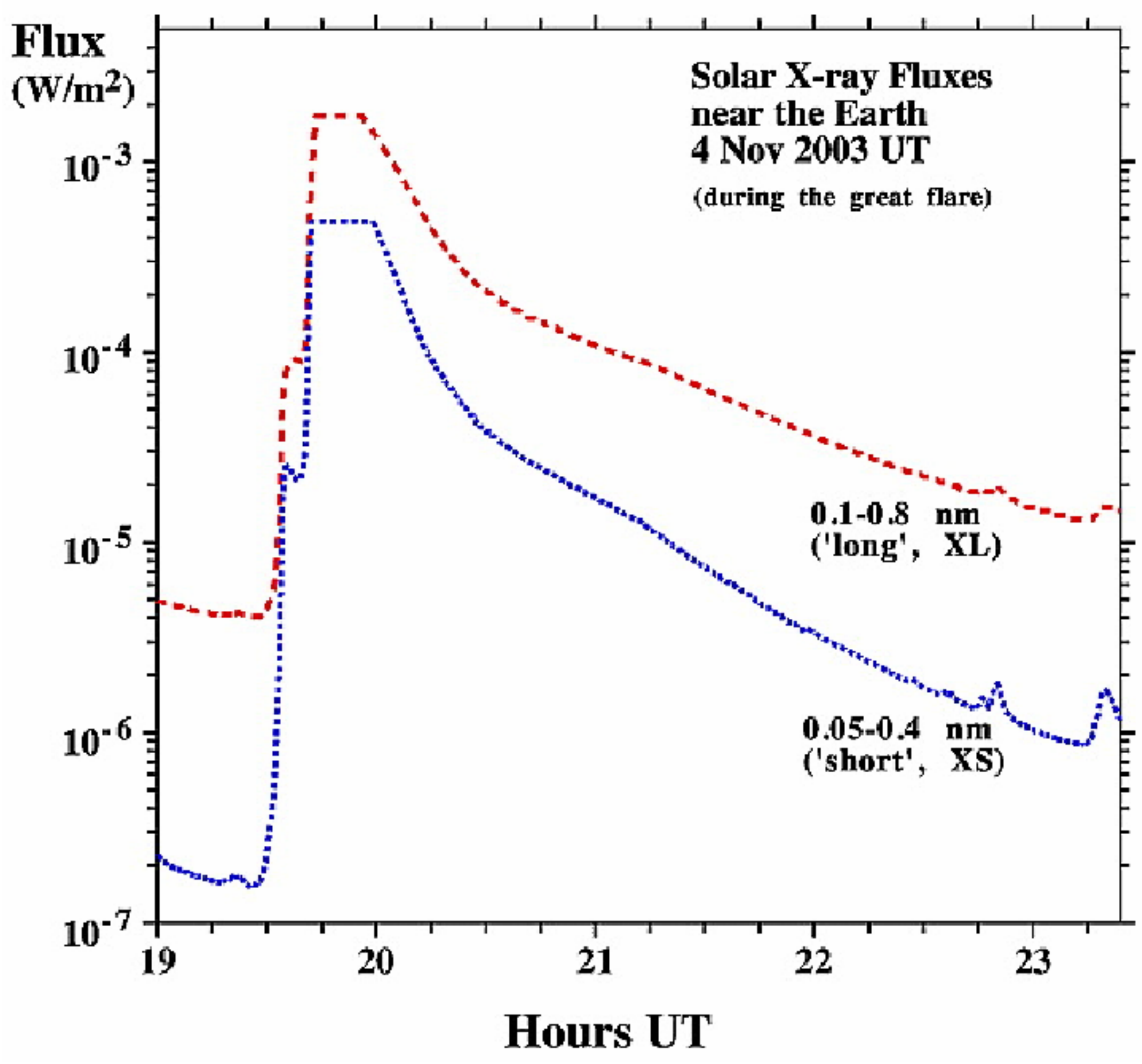


X17 Flare


AIA 131
2011-08-09 06:34:33
www.helioviewer.org

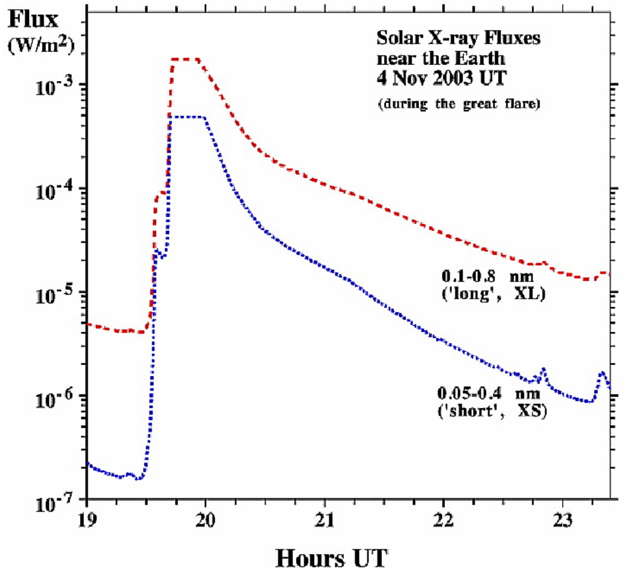

GOES 3-sec X-ray data
Flux (W/m²)
X ->
M ->
C ->
B ->
07:00
07:30
08:00
08:30
09:00
09:30
Start Time (09-Aug-11 06:34:33)

4 Nov 2003: X17.4 Flare



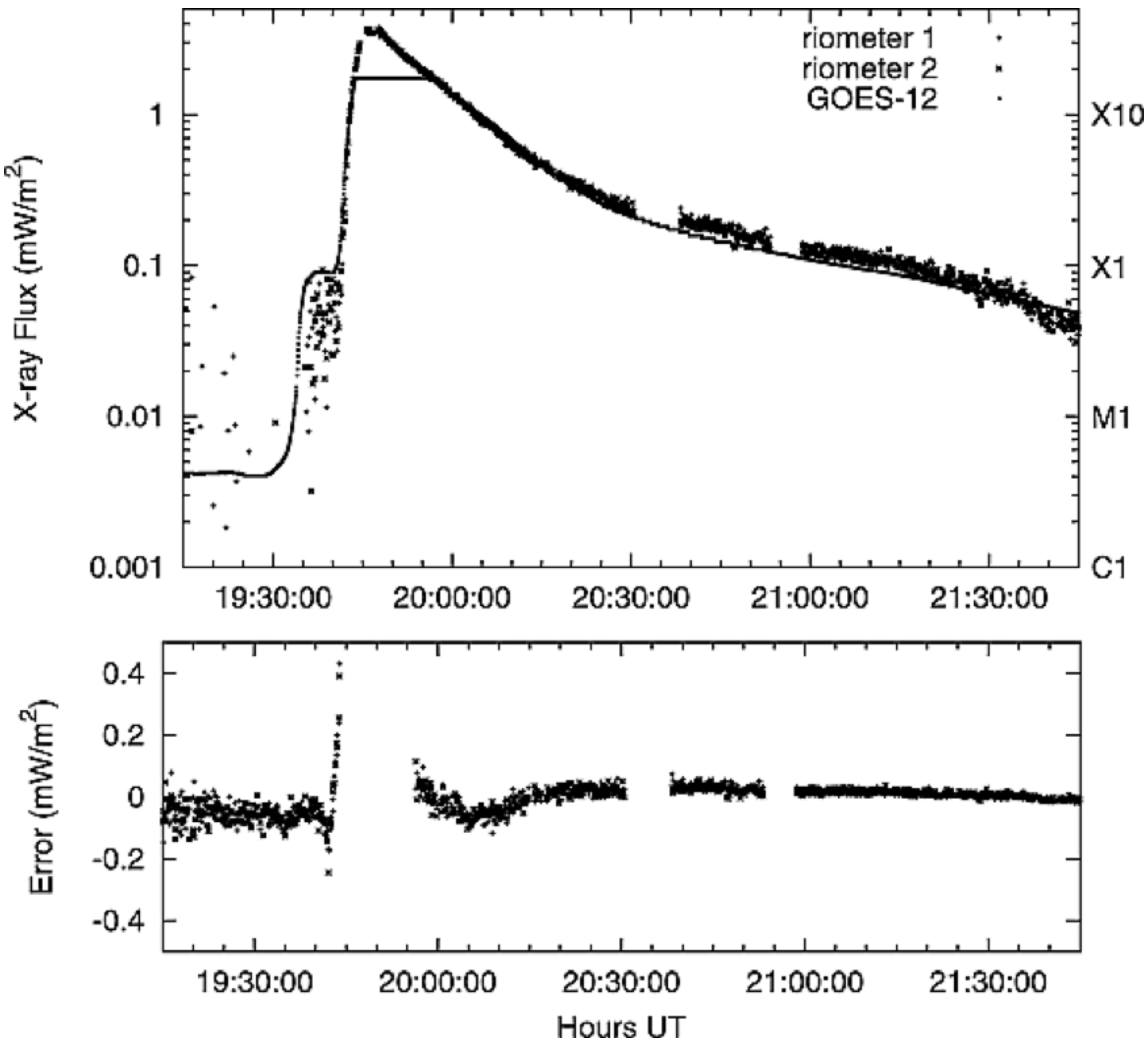
[2] The largest solar X-ray flare ever recorded occurred on 4 November 2003 (2003/11/04). The X-ray flux of this event was so high that the X-Ray Sensor (XRS) payloads on the NOAA GOES satellites, the de facto standard for quantifying flares since 1974, were saturated for 12 min. The saturation level of the 0.1–0.8 nm X-ray detector on the GOES-12 satellite is 1.74 mW/m^2 (X17.4).

[3] The peak magnitude of the flare could only be estimated from the GOES data by using extrapolation techniques. An initial estimate of the 0.1–0.8 nm flux placed the flare at 2.8 mW/m^2 (X28) peaking at 1950 UT [*NOAA* , 2003]. Another estimate of the flare peak has been made by *Woods et al.* [2004] using measurements from the XUV Photometer System (XPS) payload on the NASA SORCE satellite. This sensor measured the solar irradiance over the 0.1–7 nm band during the flare with a time cadence of 5–6 min. They estimate that the 0.1–0.8 nm flux of the flare peaked at 3.4 ± 0.6 mW/m^2 (X34 ± 6) at 1947 UT ± 3 min.



Flux
(W/m2)
Solar X-ray Fluxes
near the Earth
4 Nov 2003 UT
(during the great flare)
0.1-0.8 nm
('long', XL)
0.05-0.4 nm
('short', XS)
Hours UT

X40 !!



riometer 1
riometer 2
GOES-12
X-ray Flux (mW/m2)
X10
X1
M1
C1
19:30:00
20:00:00
20:30:00
21:00:00
21:30:00
Error (mW/m2)
Hours UT

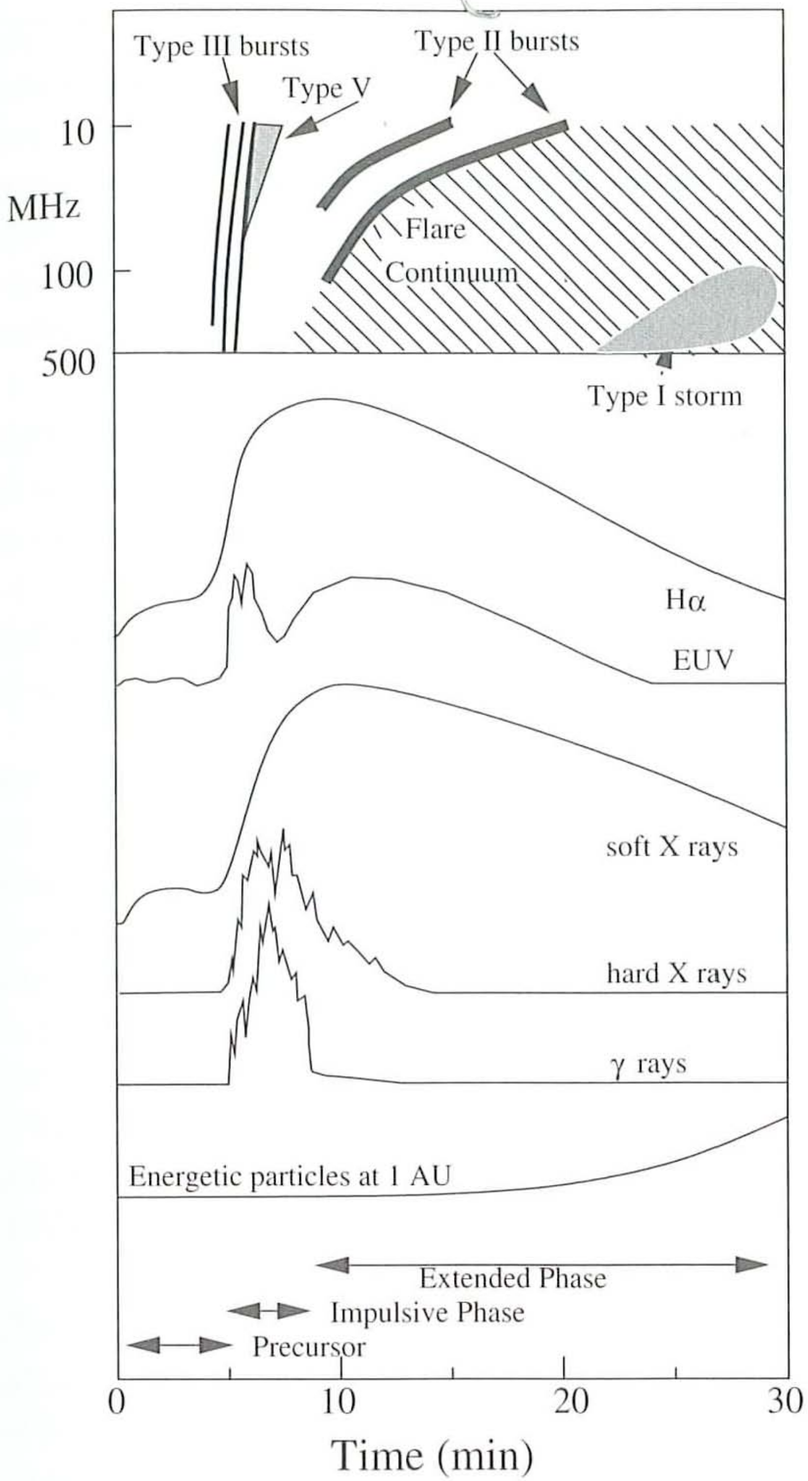
Four main types of meter-wave radio emissions are produced by flares. They typically occur in the following order:

Type III bursts emit in the frequency range from ~10 kHz to ~100 MHz **during the first few minutes** of a flare event. Electron streams from the active region induce plasma oscillations in the coronal layers they travel through, with decreasing frequency as the plasma density drops off.

Type IV bursts are generated **within plasma clouds** moving outwards from the flare site, as electrons trapped in the plasma magnetic fields emit gyrosynchrotron radiation at frequencies around 10 to 100 MHz and sometimes over a larger frequency range. The plasma clouds originate as coronal transients.

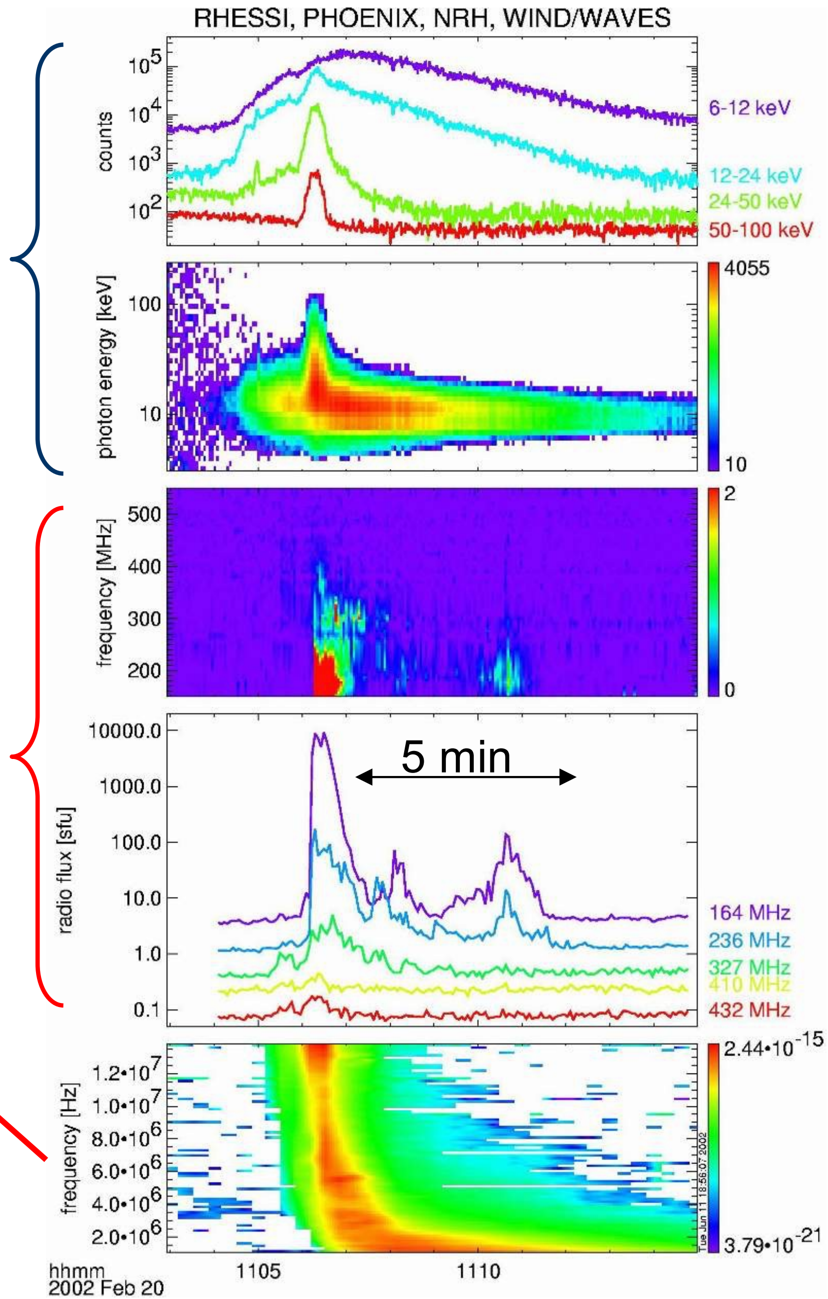
Type II bursts are intense but limited to frequencies below 100 MHz. Two frequency bands, a fundamental and a harmonic, drift downward in frequency as the disturbance that excites the plasma oscillations moves outwards through lower and lower densities in the corona. Type II are caused by **shock waves**.

Type I bursts can hardly be considered ‘bursts,’ since they last as long as a few days. Energetic electrons are thought to fuel plasma oscillations, resulting in the high brightness temperatures and strong polarizations that are observed. Continuum radiation from 50 to 400 MHz is emitted from the relevant active region



Type III bursts
Type V
Type II bursts
10
MHz
100
500
Flare
Continuum
Type I storm
Hα
EUV
soft X rays
hard X rays
γ rays
Energetic particles at 1 AU
Extended Phase
Impulsive Phase
Precursor
0
10
20
30
Time (min)

- A set of complementary observations of EM emissions from flare-accelerated electrons :
  - Hard X-rays ($h\nu$ > 20 keV): energy spectra and imaging
  - Radio emission: spectra and imaging from ground (400 GHz > ν > 20 MHz)
  - Radio emission: spectra from space (ν < 14 MHz)



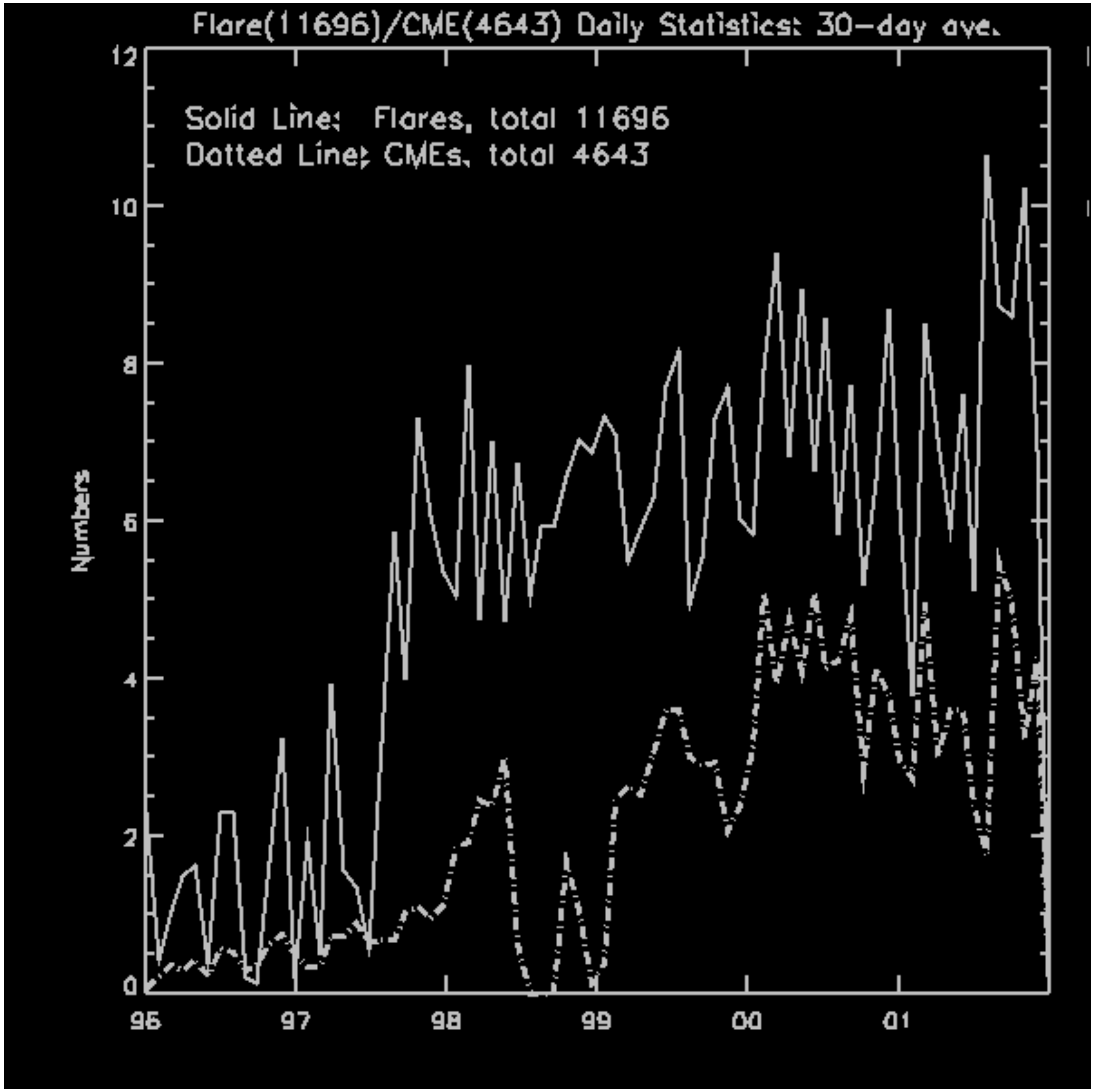
Vilmer et al. 2002 Solar Phys 210, 261

Συχνότητα εμφάνισης

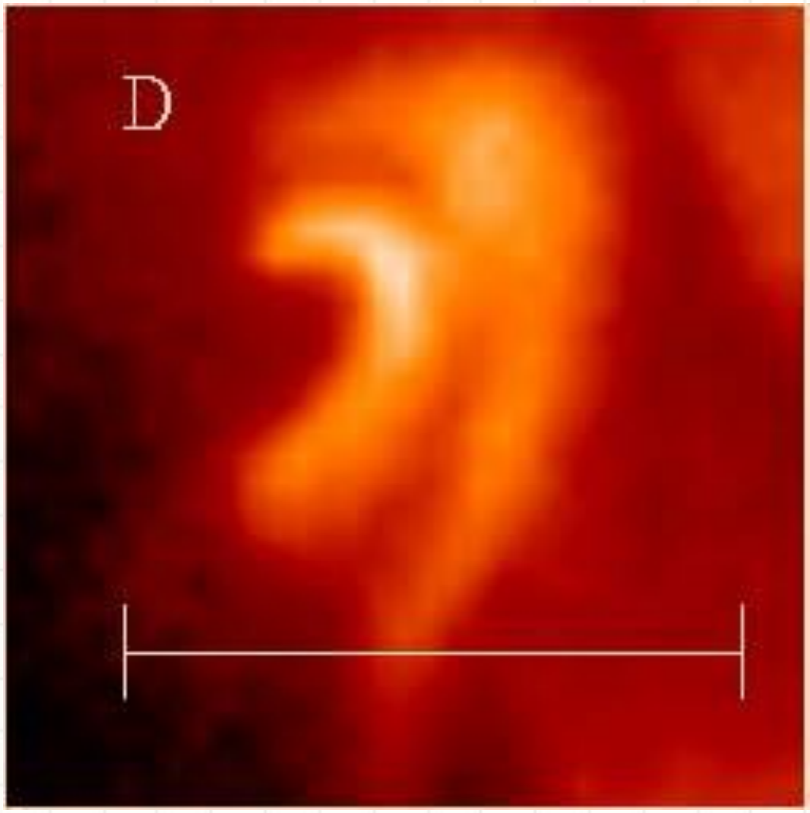
Στο ηλιακό ελάχιστο:
1 / μέρα

Στο ηλιακό μέγιστο:
10 / μέρα

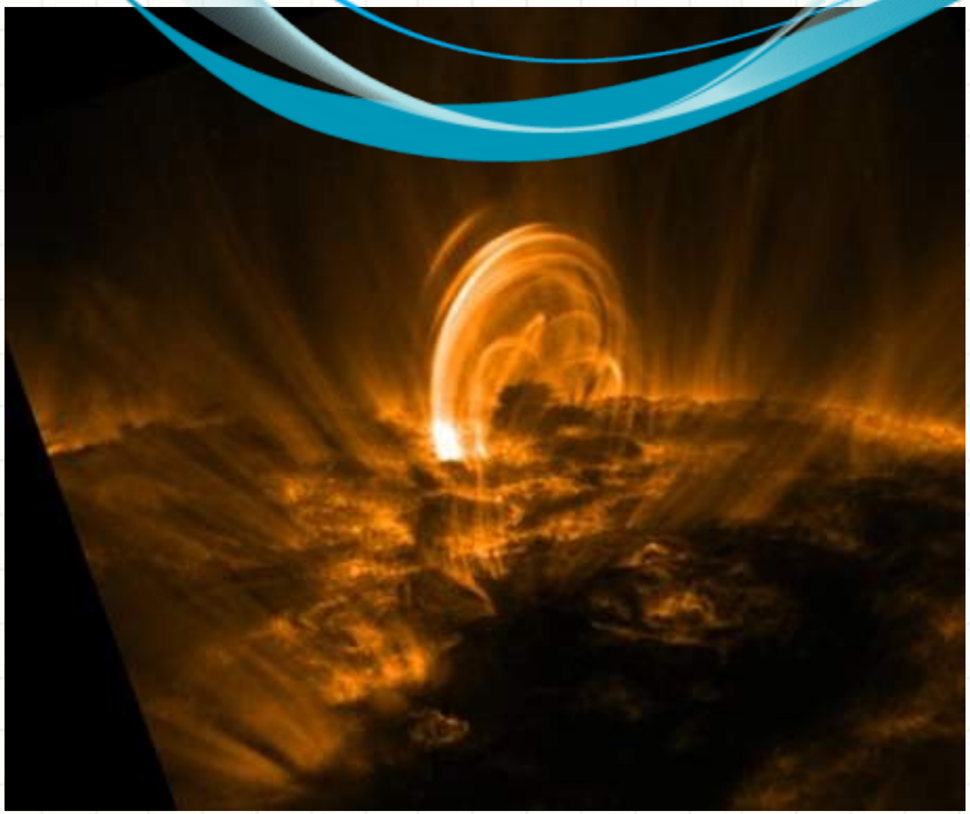
GOES X-rays:
11696 εκλάμψεις
Από Ιανουάριο 1996
ως Δεκέμβριο 2001



EXPLOSIVE X-CLASS FLARES



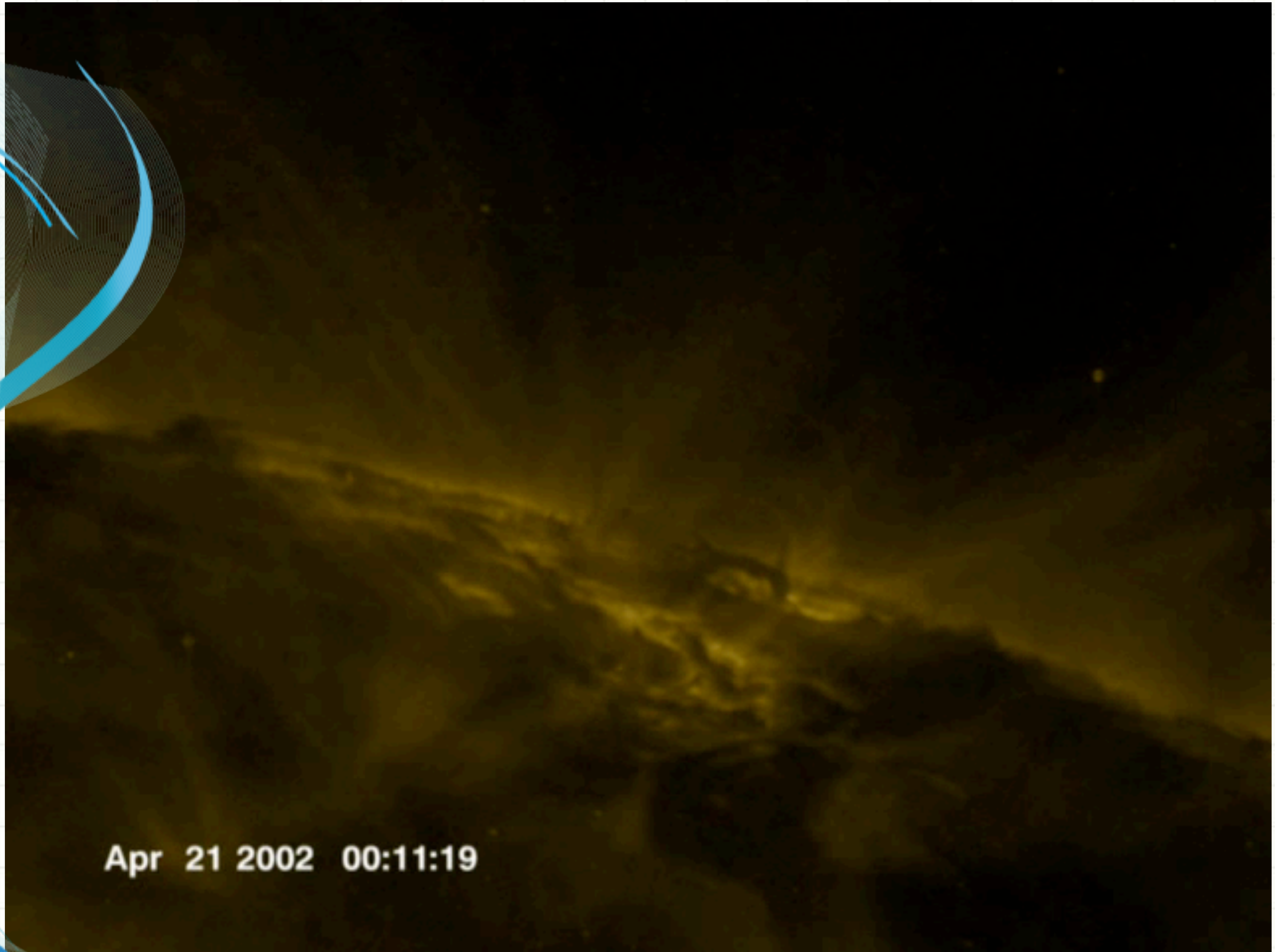
“Simple” flare loop
Yohkoh Soft X-ray Telescope



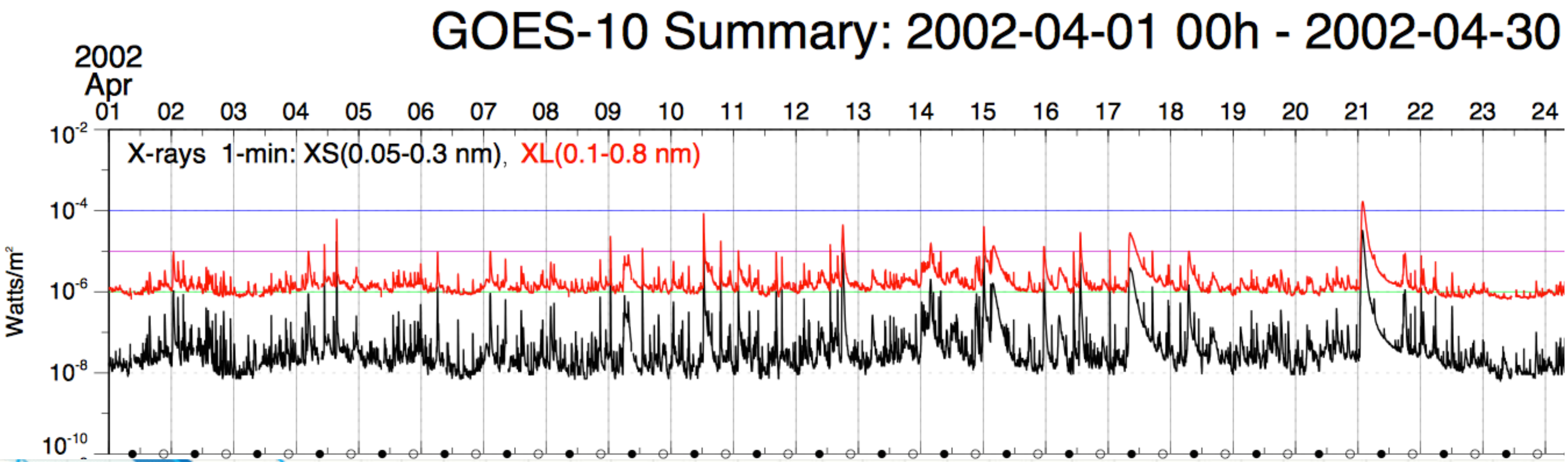
19 April 2001 post-flare loops
TRACE 171 Å band (UV)

Yohkoh, 1991-2005

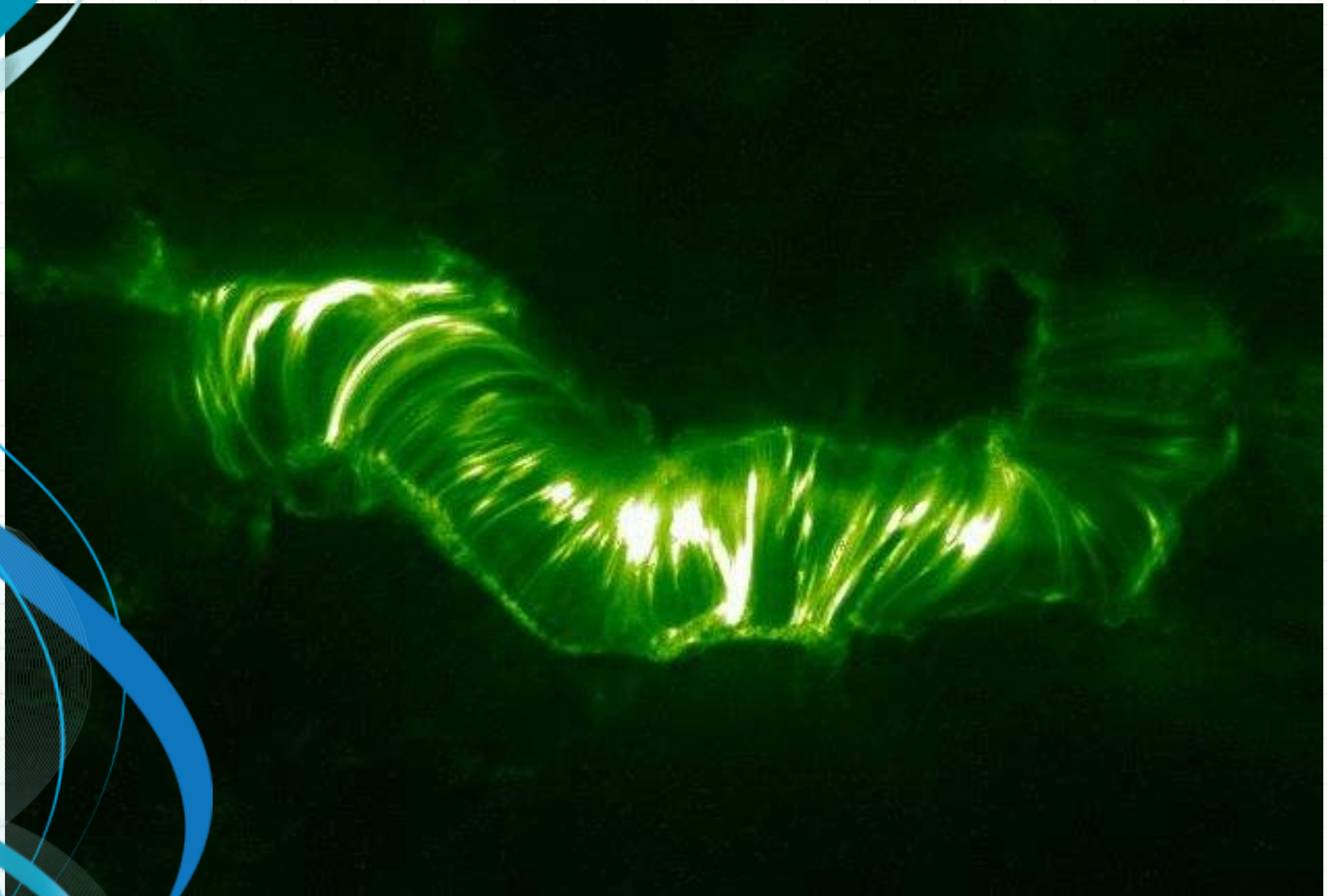
TRACE, 1998-2010



TRACE, 1998-2010

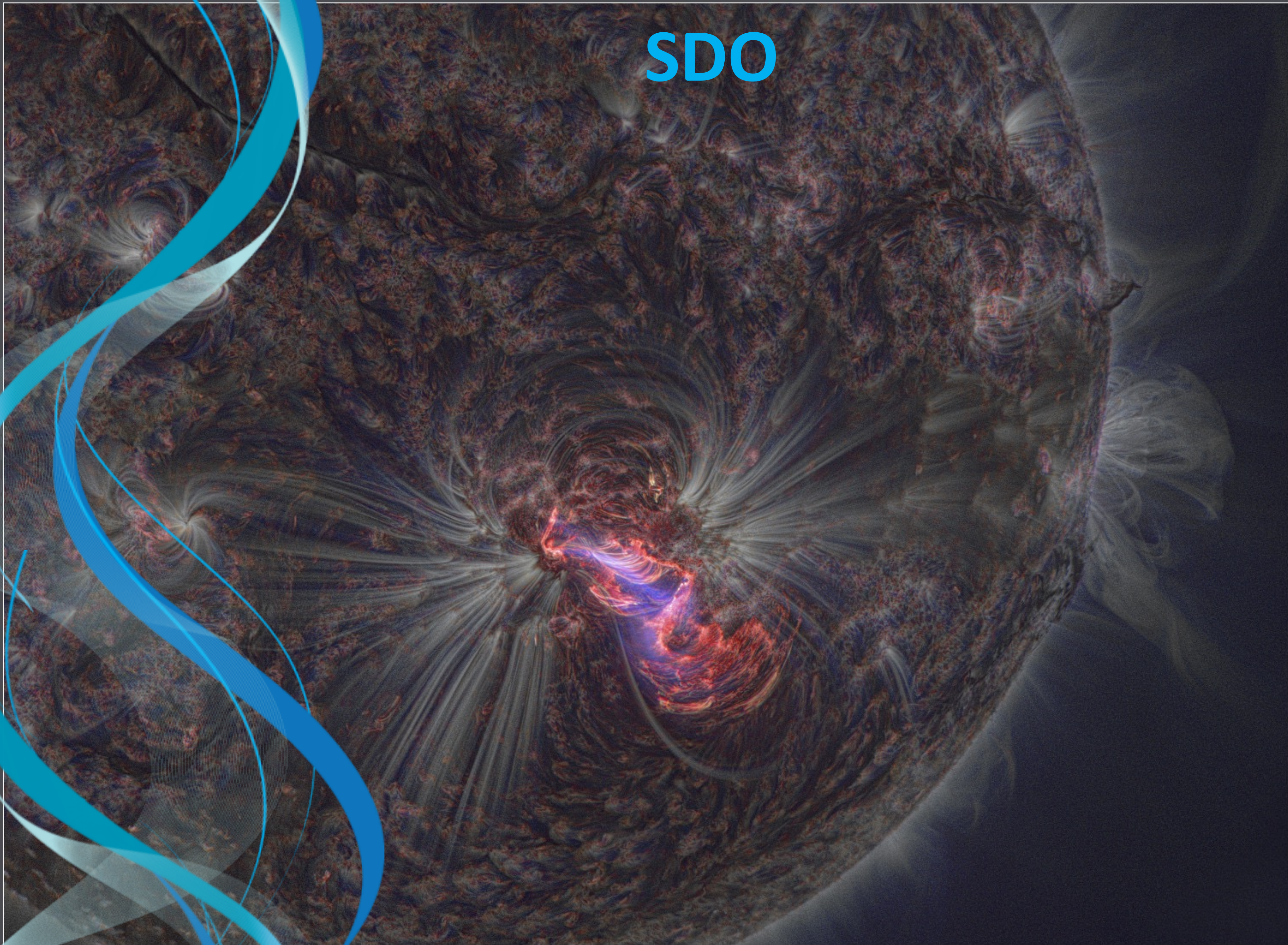

GOES-10 Summary: 2002-04-01 00h - 2002-04-30
2002
Apr
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
X-rays 1-min: XS(0.05-0.3 nm), XL(0.1-0.8 nm)
Watts/m²
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰

Arcade of Loops in the 14 July 2000 "Bastille Day" Flare



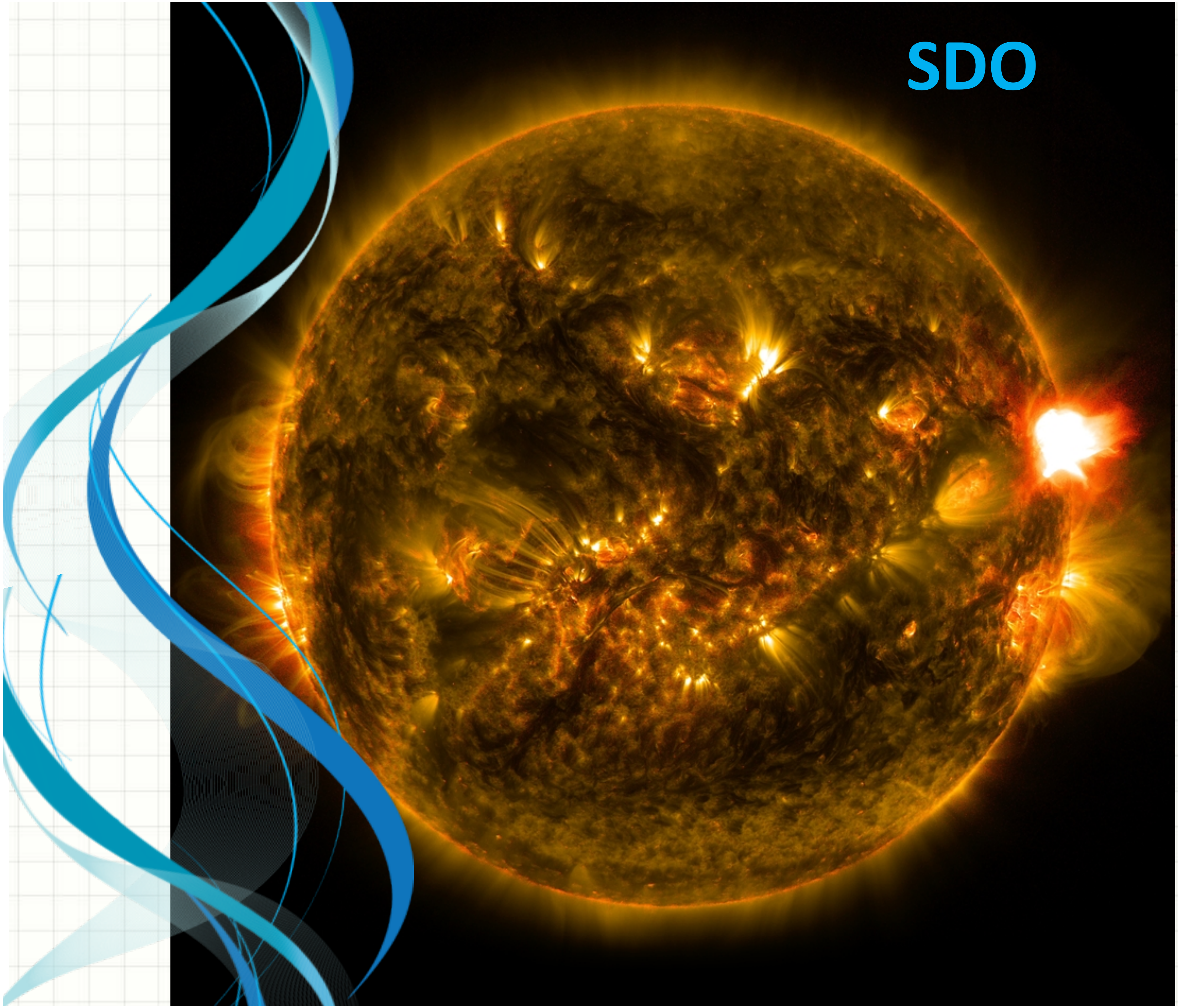
TRACE

SDO

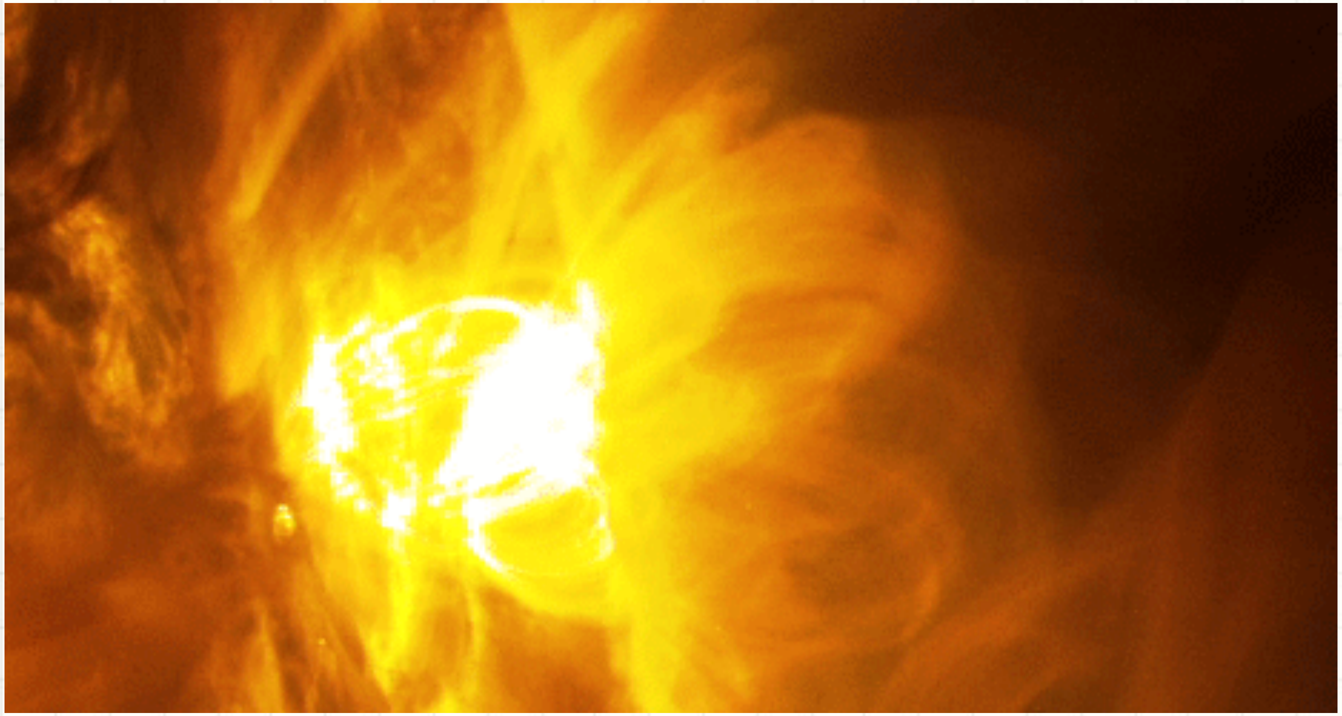


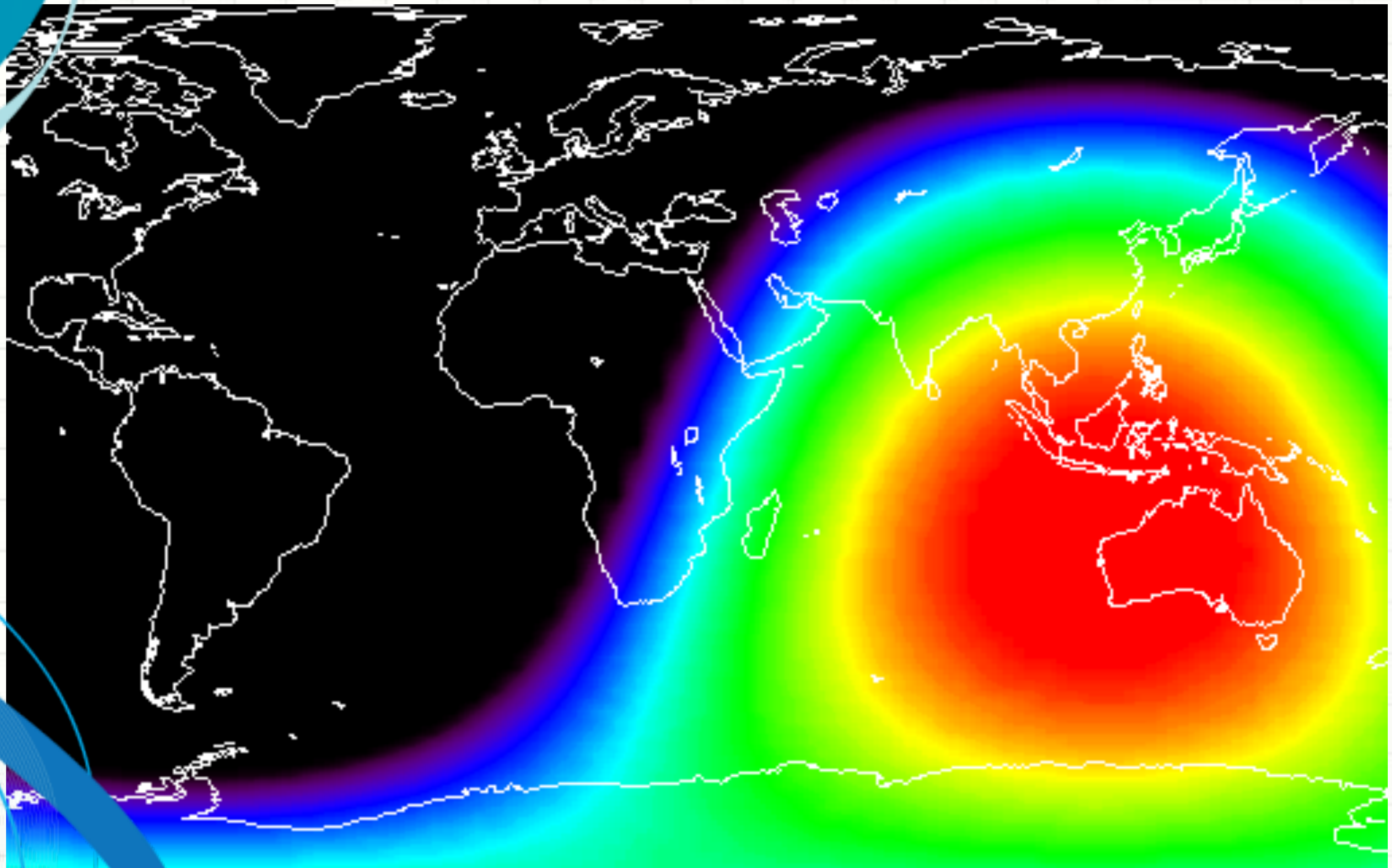
X 3.1 flare in sunspot 2192, 24. 10. 2014, 21:42 UT

SDO AIA 193, 171, 304, NAFE processing Miloslav Druckmüller

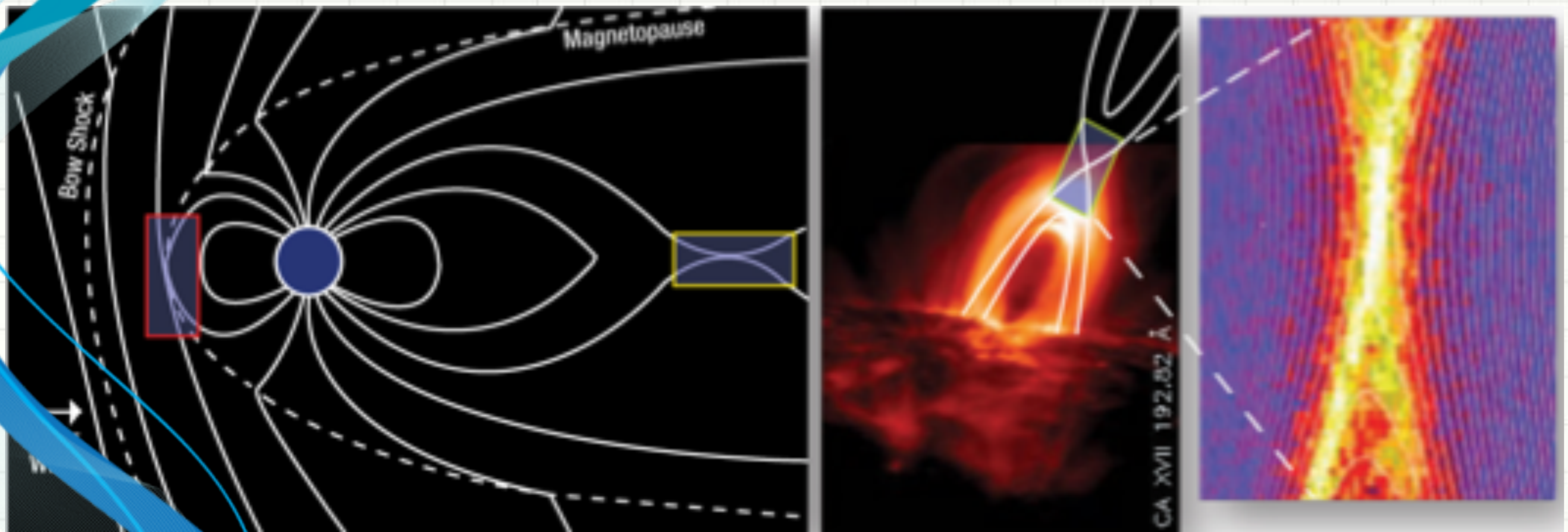

SDO

SDO

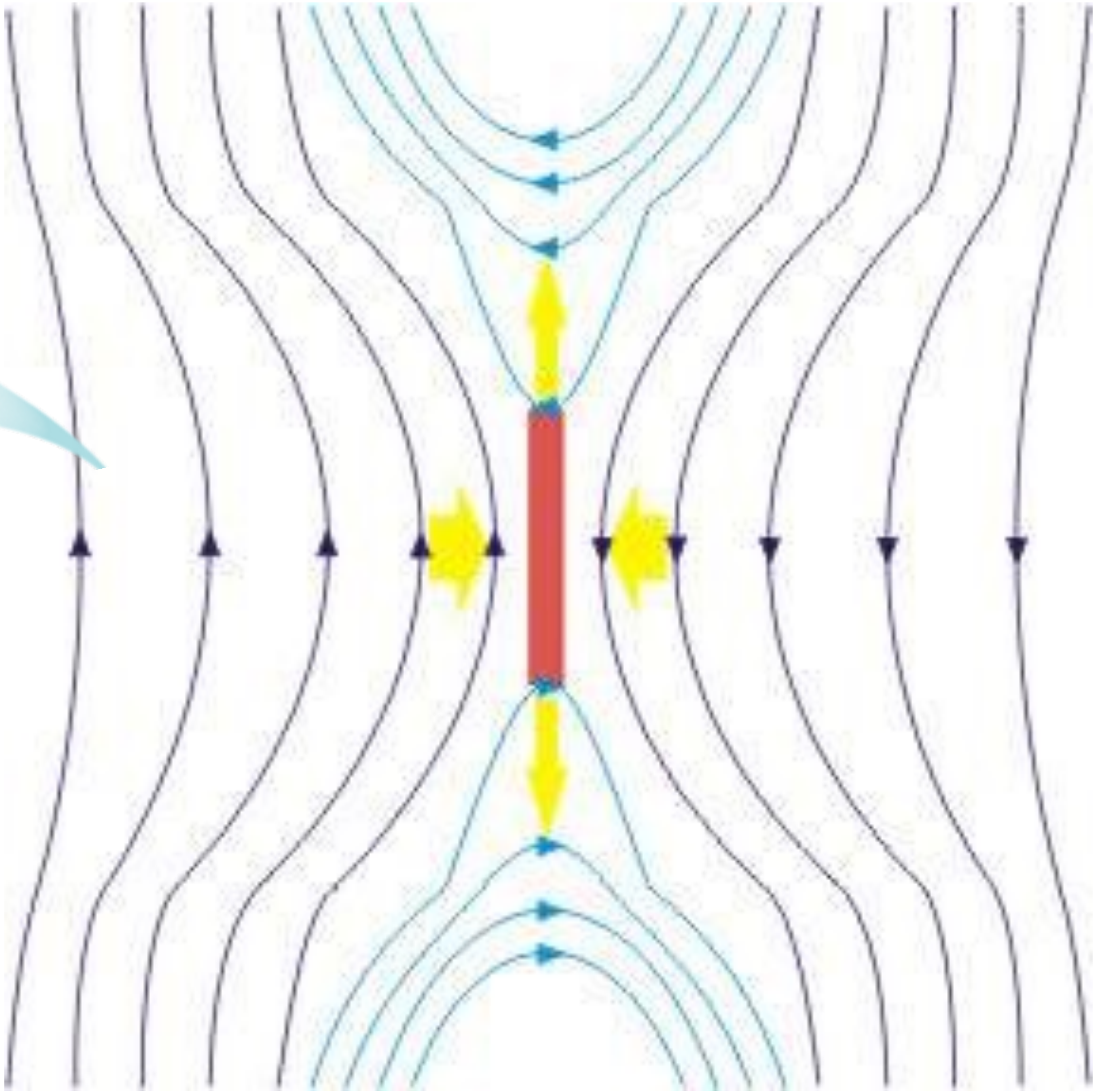


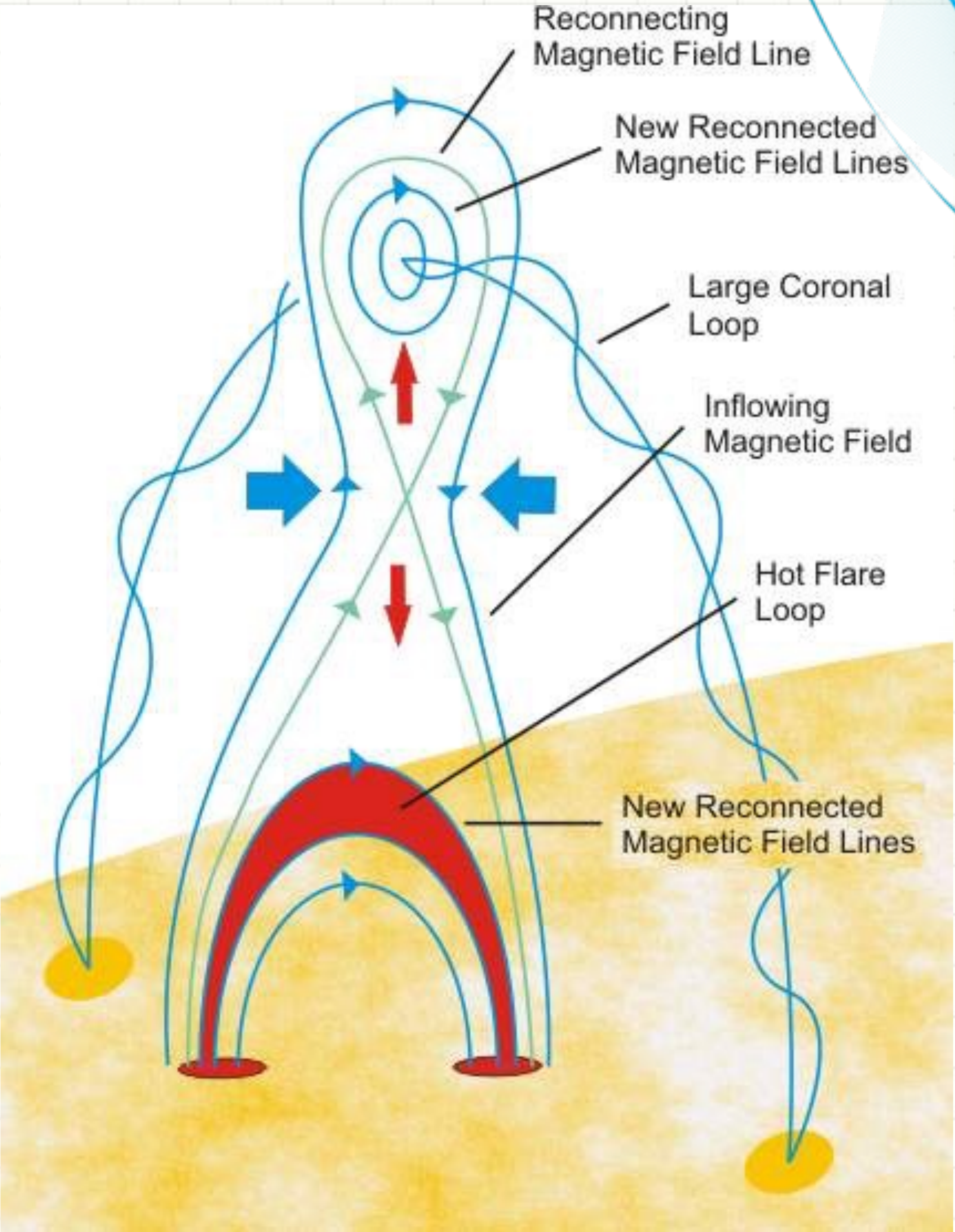


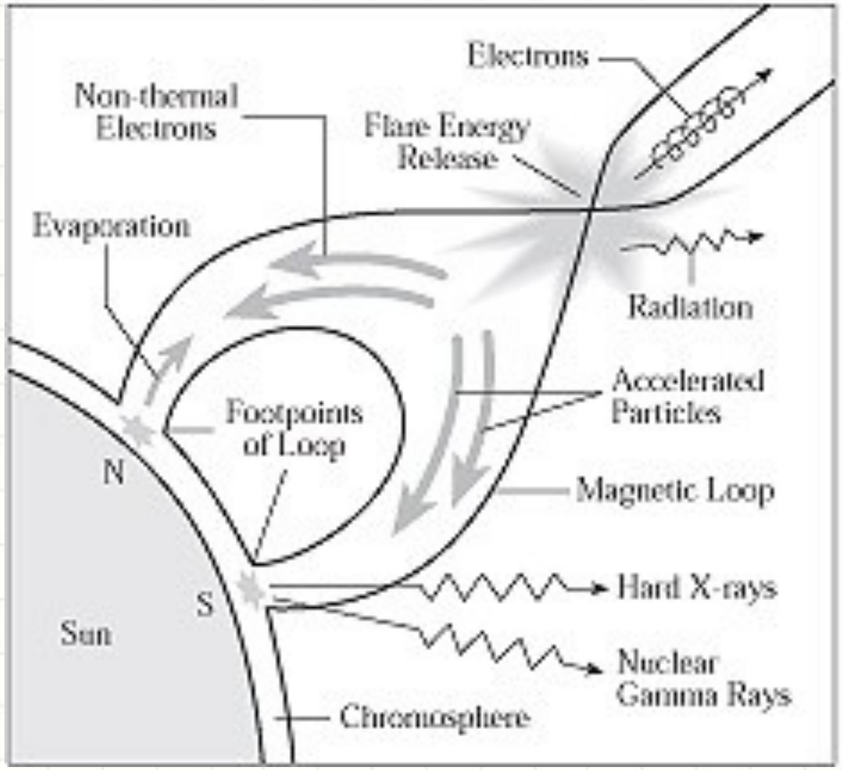
Flare: rapid energy release triggered by an instability in the magnetic configuration. Results in acceleration of non-thermal particles and heating of chromospheric/coronal plasma, emitting radiation in almost all wavelengths


Magnetopause
Bow Shock
CA XVII 192.82 Å

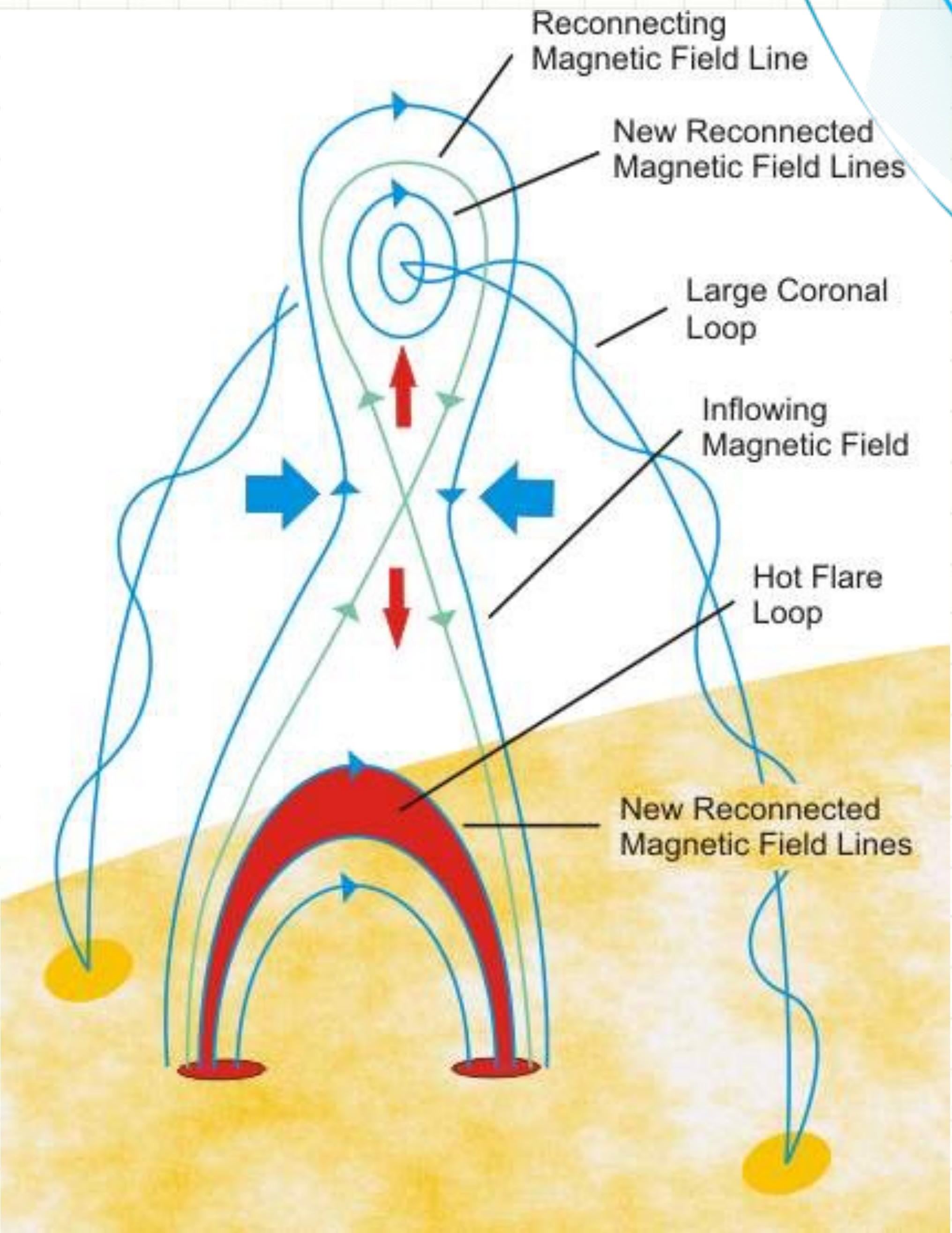
Magnetic Reconnection

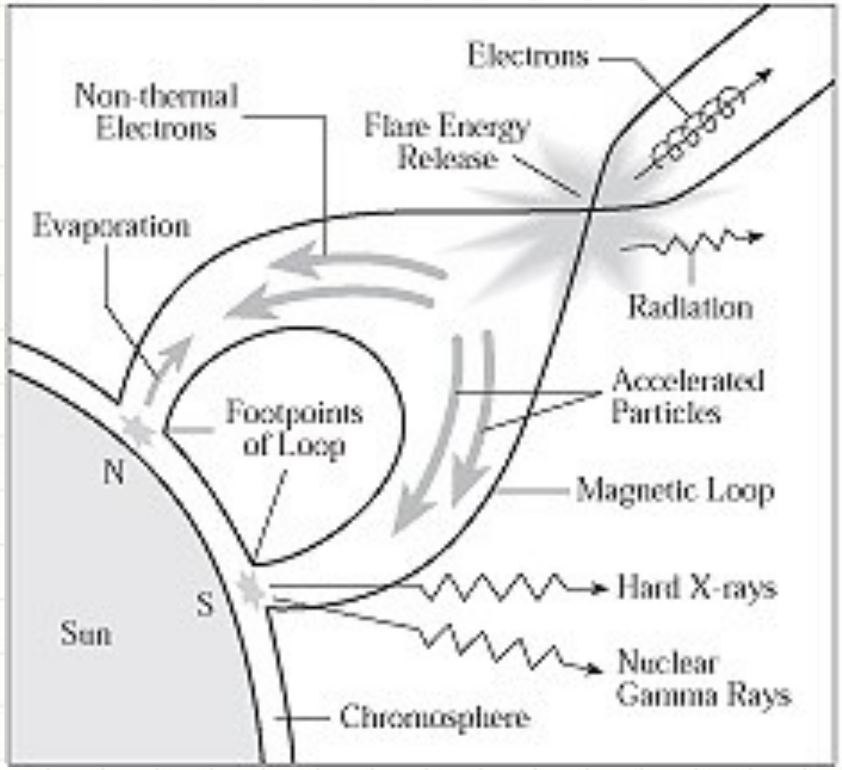



Reconnecting
Magnetic Field Line
New Reconnected
Magnetic Field Lines
Large Coronal
Loop
Inflowing
Magnetic Field
Hot Flare
Loop
New Reconnected
Magnetic Field Lines


Electrons
Non-thermal
Electrons
Flare Energy
Release
Evaporation
Radiation
Accelerated
Particles
Footpoints
of Loop
N
Magnetic Loop
S
Hard X-rays
Sun
Nuclear
Gamma Rays
Chromosphere

The hard X-ray, EUV, and microwave emissions from a flare come from an entirely different source than the soft X-rays that are observed. The soft X-rays (and also Ha) are seen emanating from closed loops or arcades, which contain the flaring plasma. The 'spike' wavelengths, on the other hand, seem to result from the impact of accelerated electrons into plasma **at the footpoints** of these loops, or in high lying, extended cusp-shaped regions above the soft x-ray loops.


Reconnecting
Magnetic Field Line
New Reconnected
Magnetic Field Lines
Large Coronal
Loop
Inflowing
Magnetic Field
Hot Flare
Loop
New Reconnected
Magnetic Field Lines

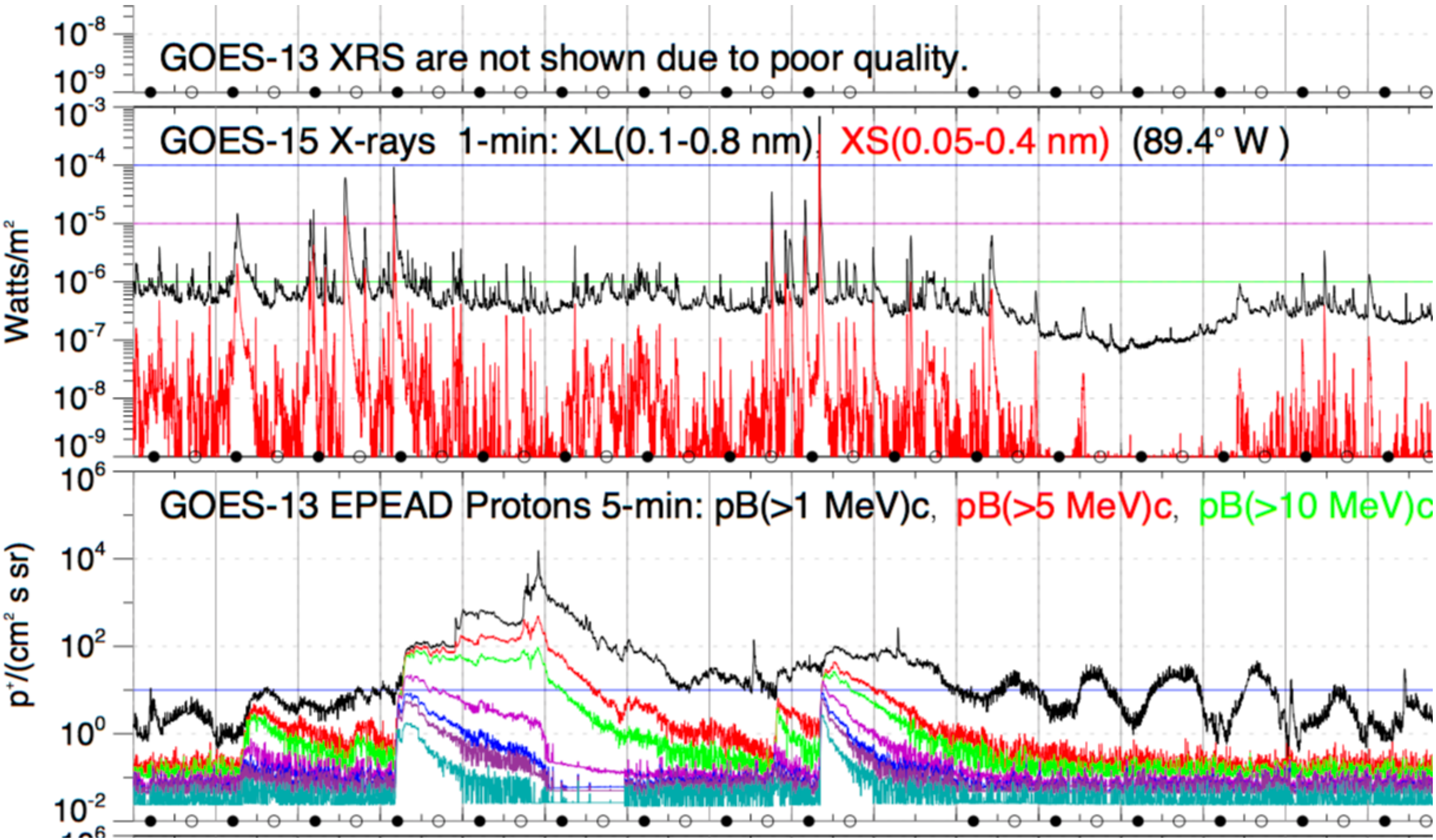

Electrons
Non-thermal
Electrons
Flare Energy
Release
Evaporation
Radiation
Accelerated
Particles
Footpoints
of Loop
N
Magnetic Loop
S
Hard X-rays
Sun
Nuclear
Gamma Rays
Chromosphere

Grand Daddy

November 4th, 2003

During Solar Cycle 23, Sunspot 486 produces the strongest Solar Flare in recorded history.

Estimated as X28+



GOES-13 XRS are not shown due to poor quality.
GOES-15 X-rays 1-min: XL(0.1-0.8 nm), XS(0.05-0.4 nm) (89.4° W)
Watts/m²
GOES-13 EPEAD Protons 5-min: pB(>1 MeV)c, pB(>5 MeV)c, pB(>10 MeV)c
p⁺/(cm² s sr)

Ηλιακή Φυσική

Στεμματικές εκτινάξεις μάζας

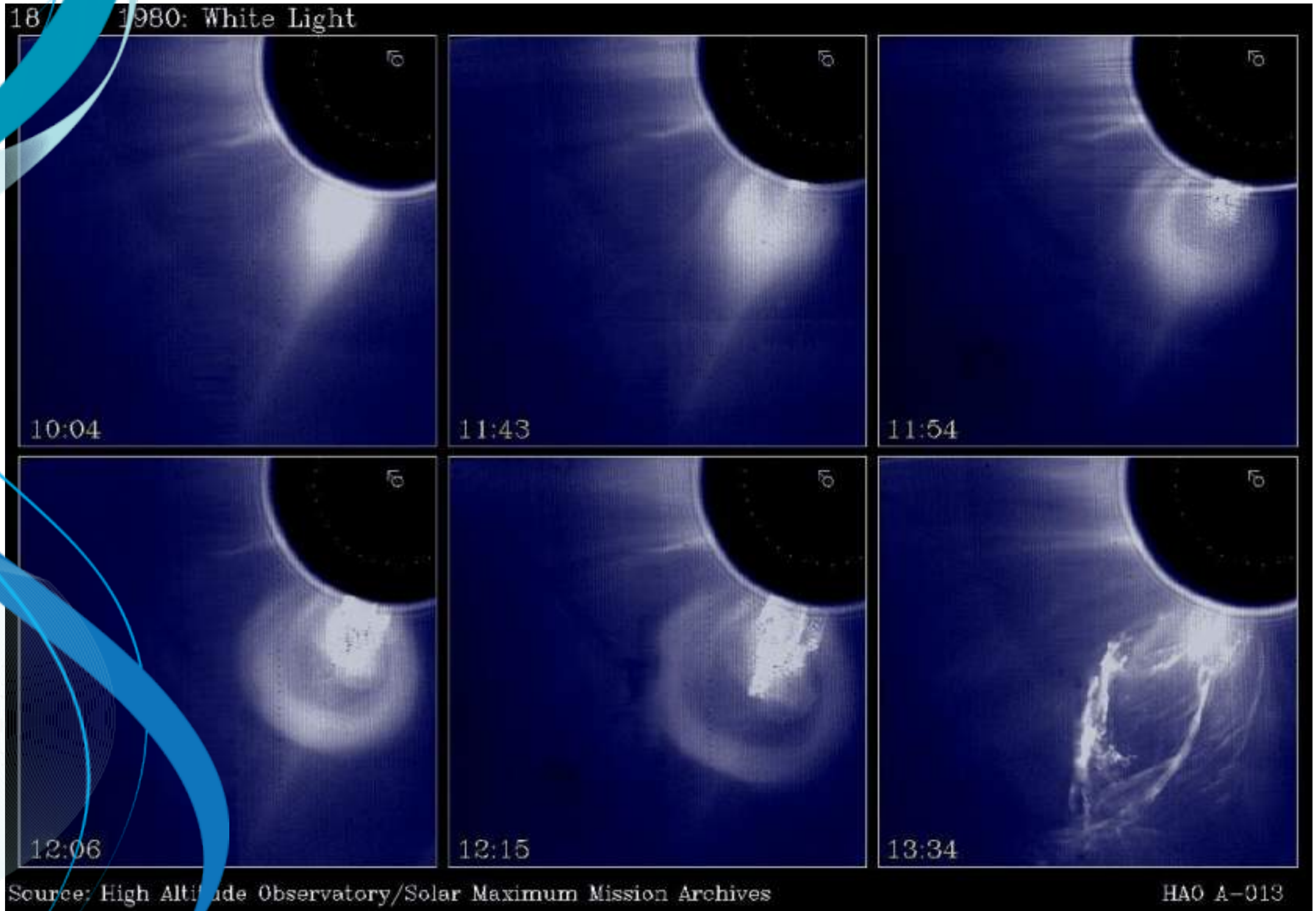
"The answer is blowing in the (solar) wind"

Bob Dylan

Εκλάμψεις
και
στεμματικές εκτινάξεις μάζας

Οι δύο συνιστώσες
των ηλιακών εκρήξεων
(solar eruptions)

Coronal Mass Ejection

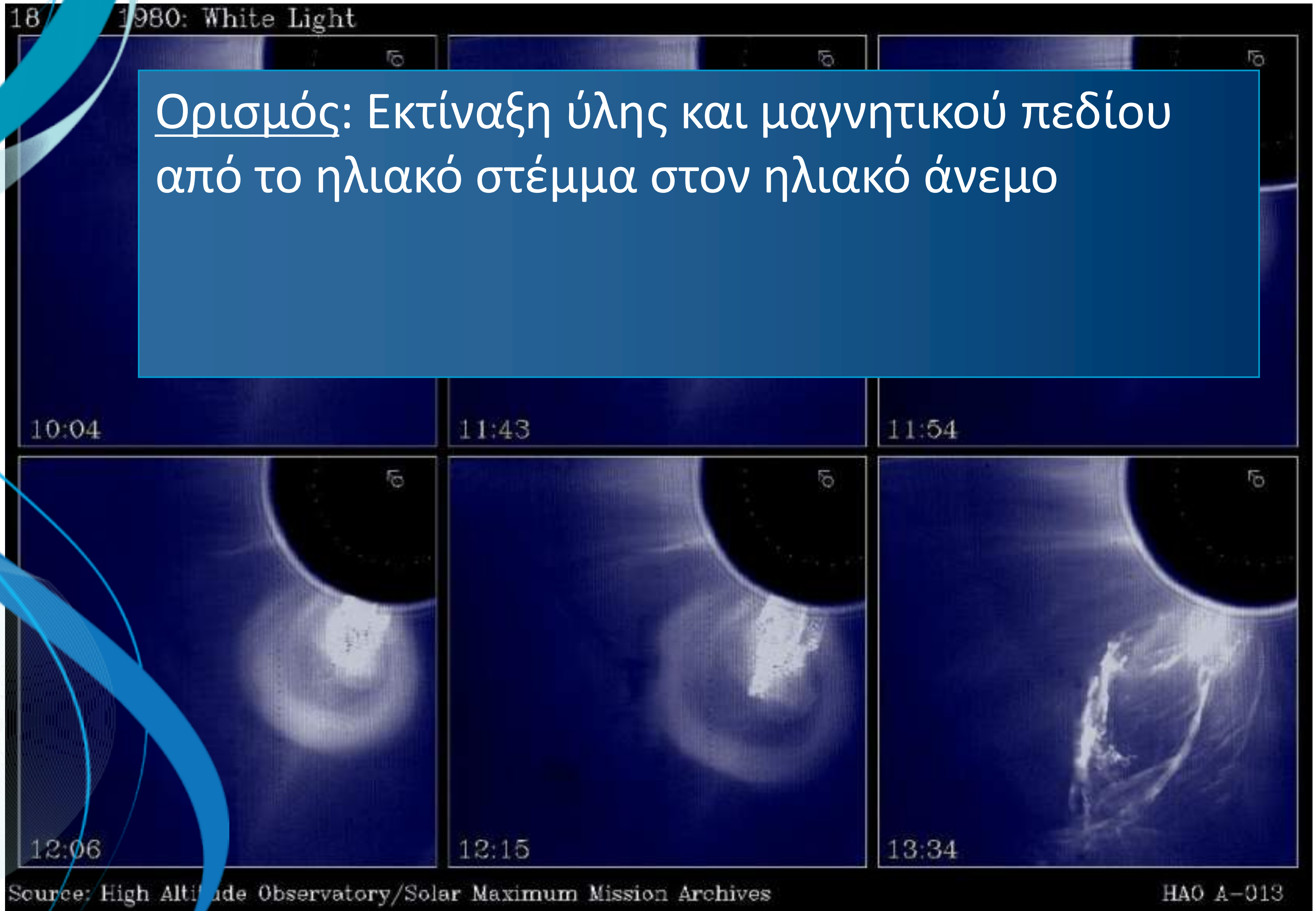


Coronal Mass Ejection

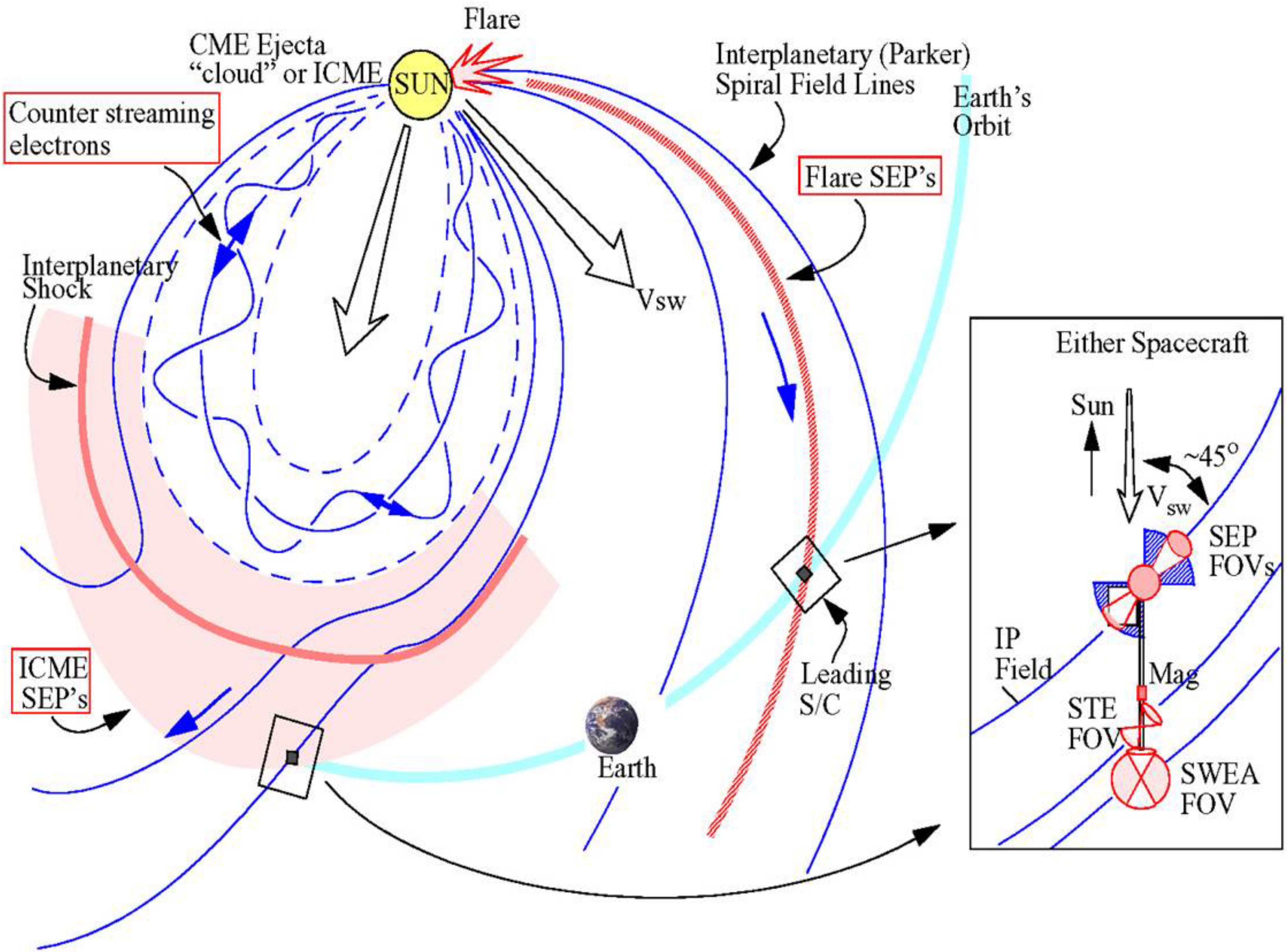
Ορισμός: Ένας νέος, διακριτός, λαμπρός σχηματισμός που εμφανίζεται στο οπτικό πεδίο ενός στεμματογράφου και απομακρύνεται από τον Ήλιο σε χρονικό διάστημα λεπτών έως ωρών

Coronal Mass Ejection

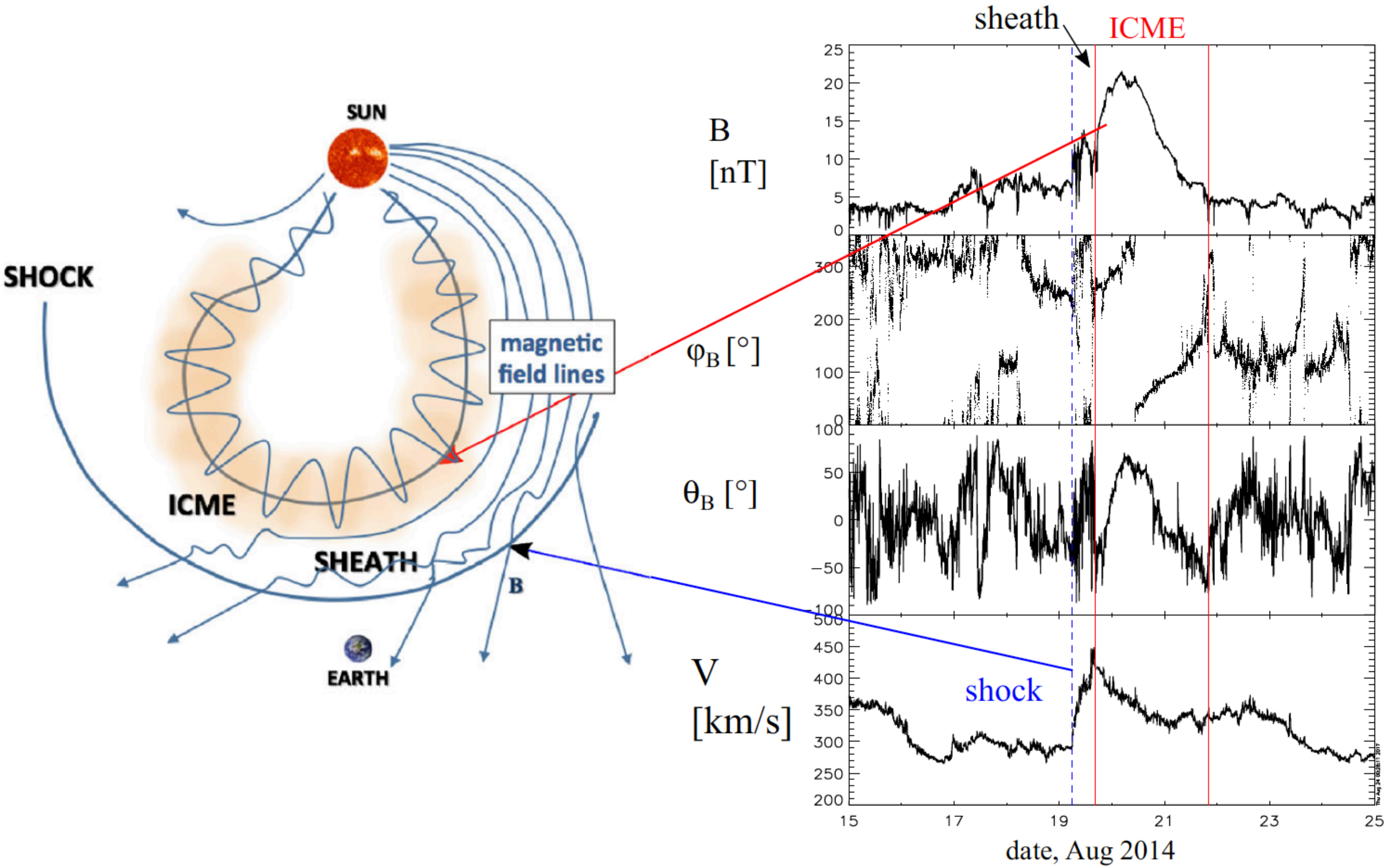
<u>Ορισμός</u>: Εκτίναξη ύλης και μαγνητικού πεδίου από το ηλιακό στέμμα στον ηλιακό άνεμο



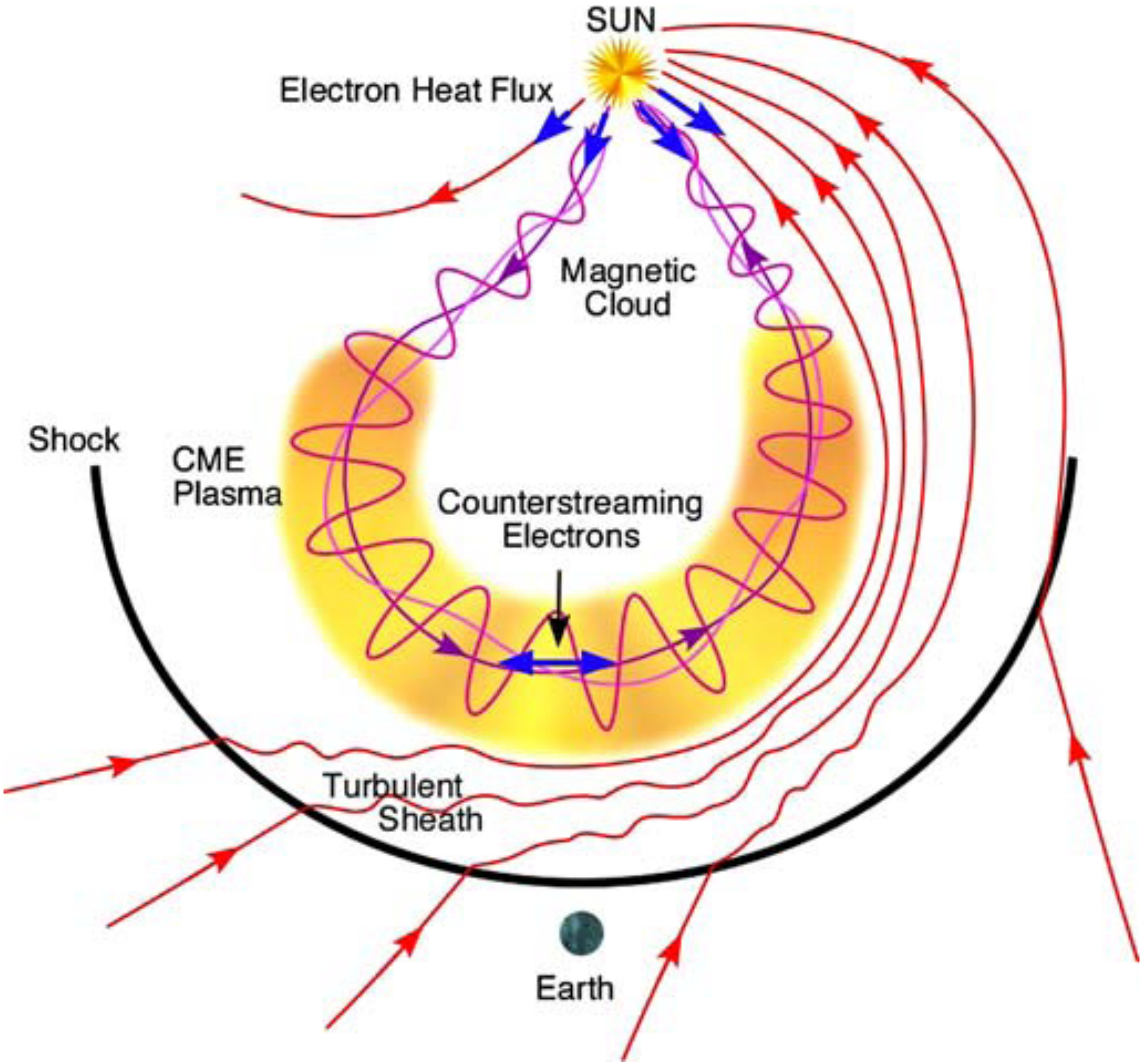
Source: High Altitude Observatory/Solar Maximum Mission Archives

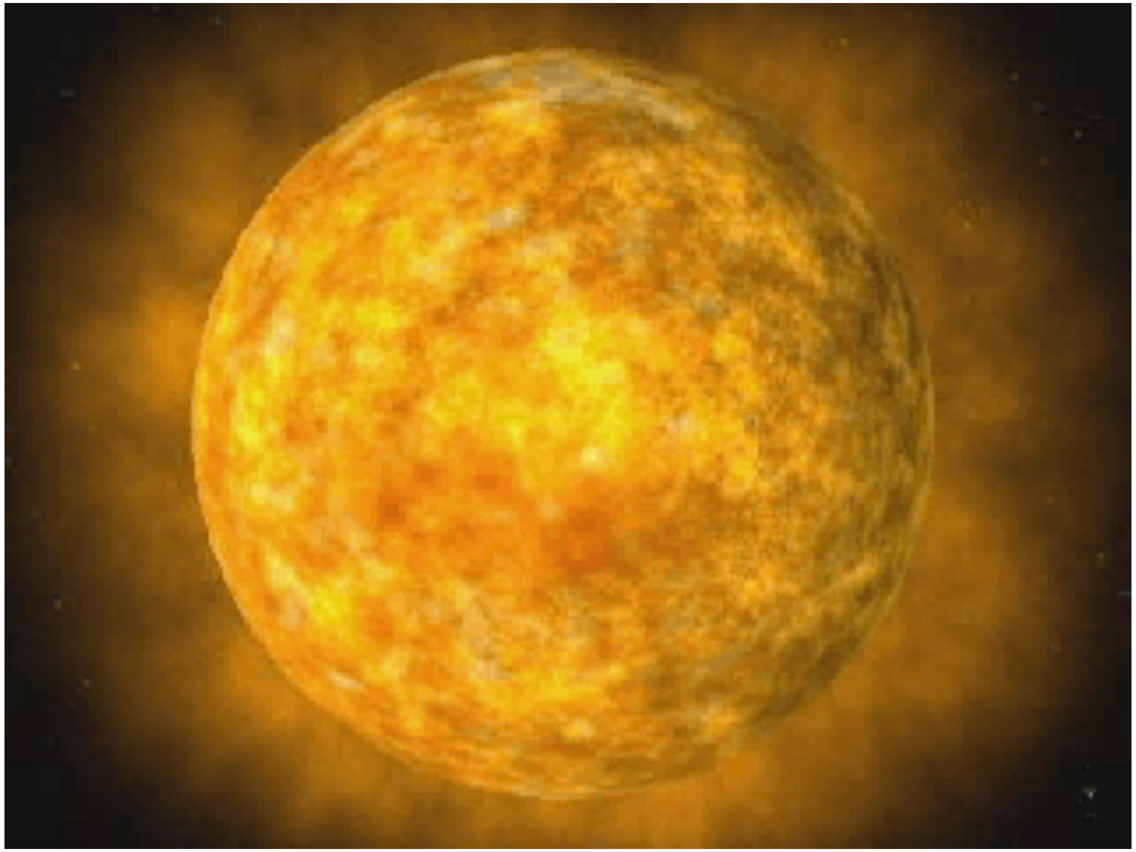


Flare
CME Ejecta
"cloud" or ICME
SUN
Interplanetary (Parker)
Spiral Field Lines
Earth's
Orbit
Counter streaming
electrons
Flare SEP's
Interplanetary
Shock
Vsw
Either Spacecraft
Sun
~45°
V_{sw}
SEP
FOVs
IP
Field
Mag
STE
FOV
SWEA
FOV
ICME
SEP's
Leading
S/C
Earth



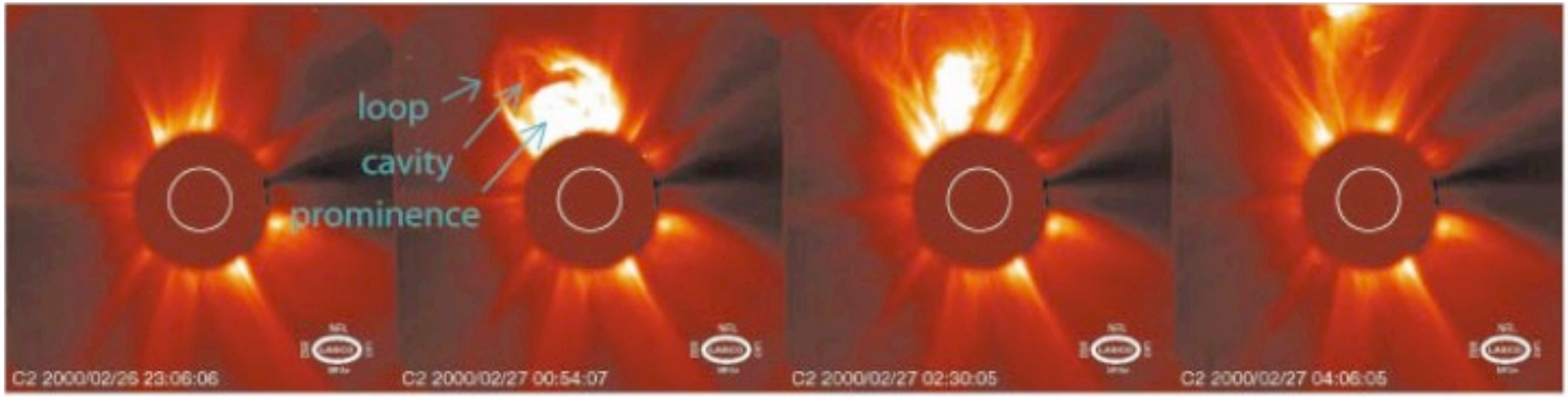
SUN
SHOCK
magnetic field lines
ICME
SHEATH
B
EARTH
sheath
ICME
B [nT]
φB [°]
θB [°]
V [km/s]
shock
date, Aug 2014


SUN
Electron Heat Flux
Magnetic
Cloud
Shock
CME
Plasma
Counterstreaming
Electrons
Turbulent
Sheath
Earth



Morphology of Coronal Mass Ejections

Three-part structure:

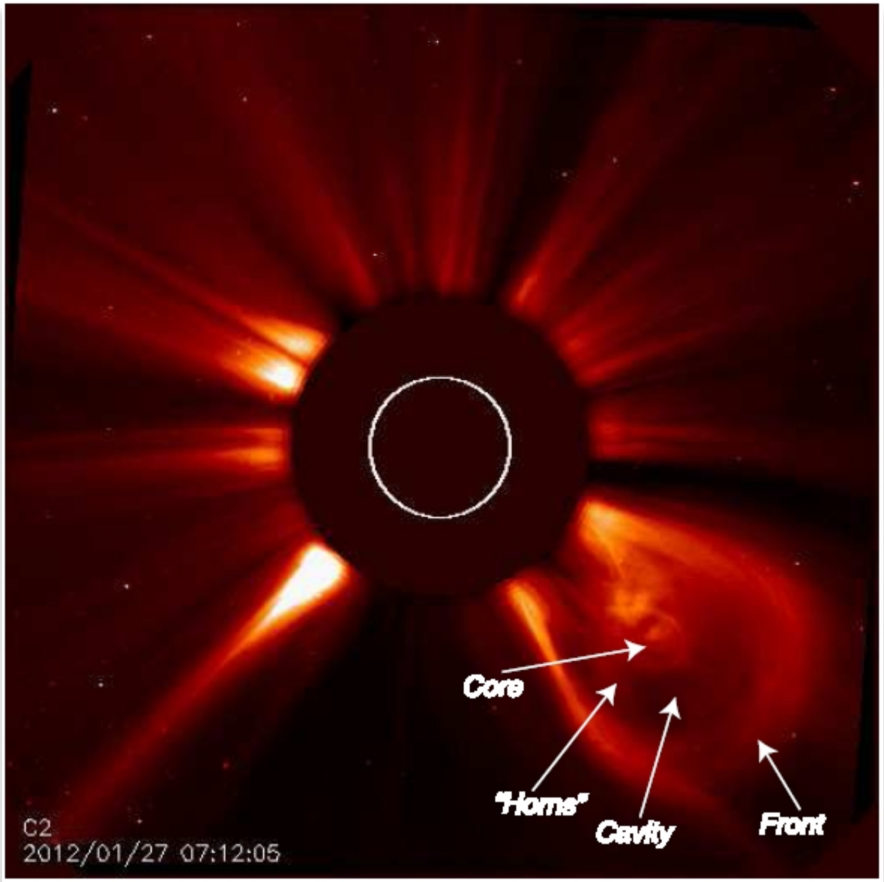


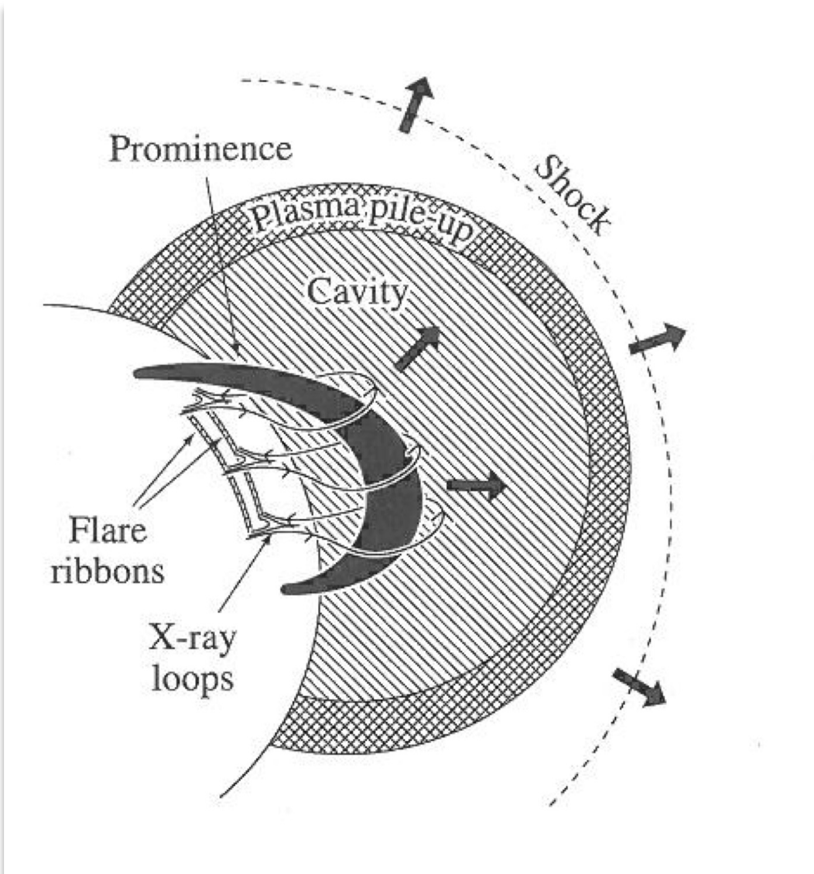
– Bright outer rim
– Dark cavity behind rim
– Bright inner core of erupted prominence material

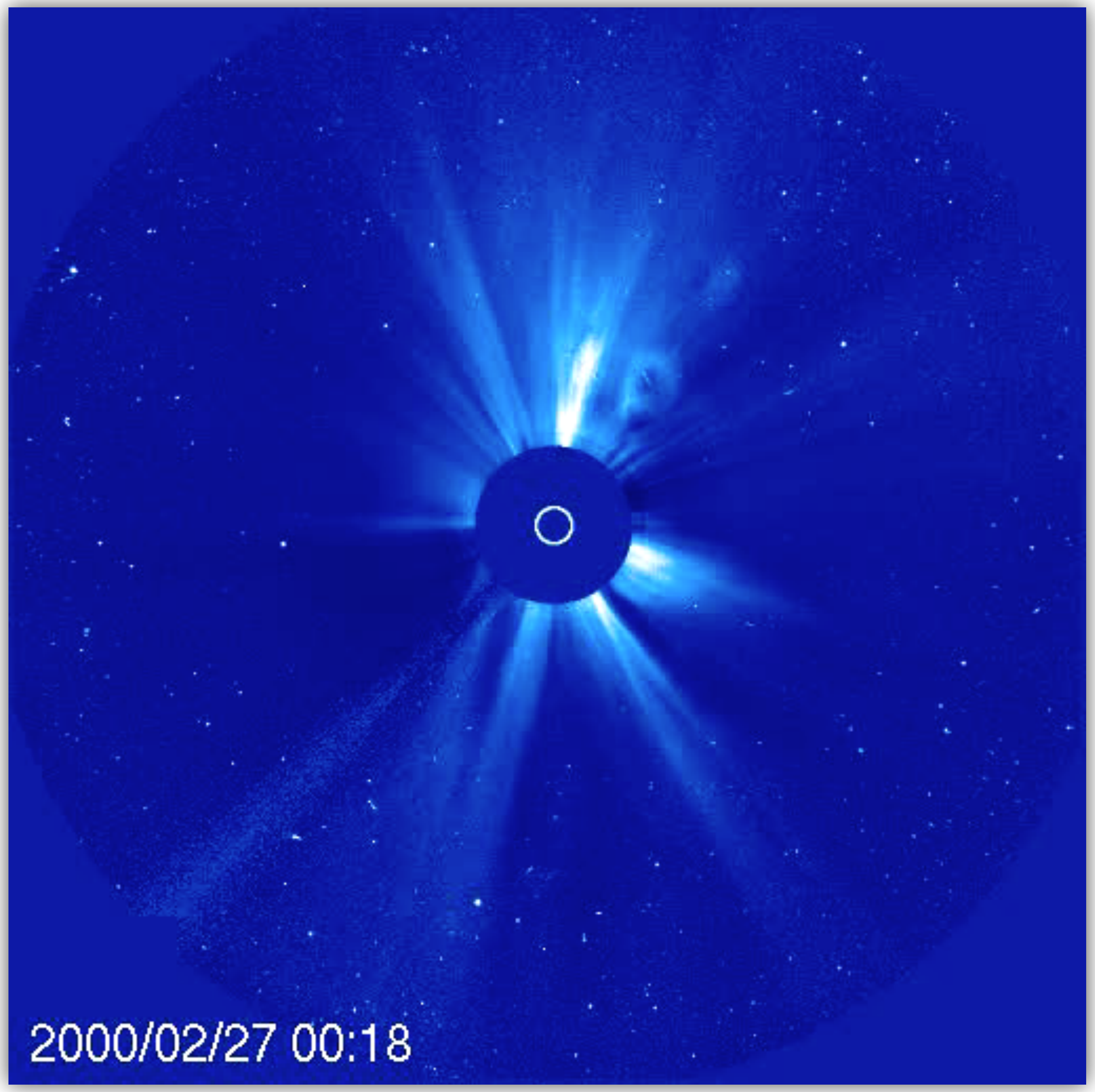
Eruptions: CME structure

Most CMEs have the three part structure, consisted of:

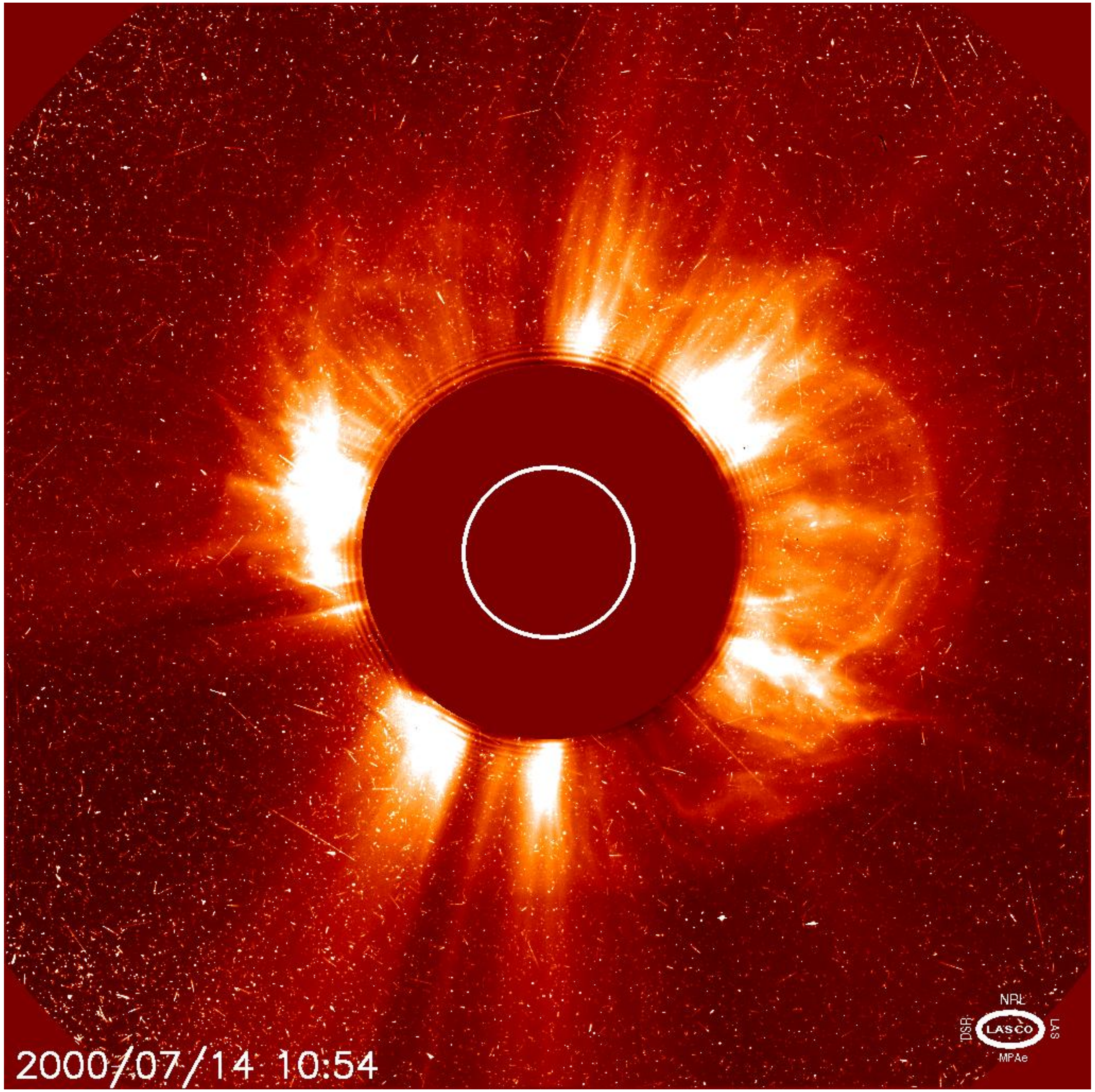
- Leading edge (compression)
- Cavity (low density material)
- Hot core (flux rope/prominence)



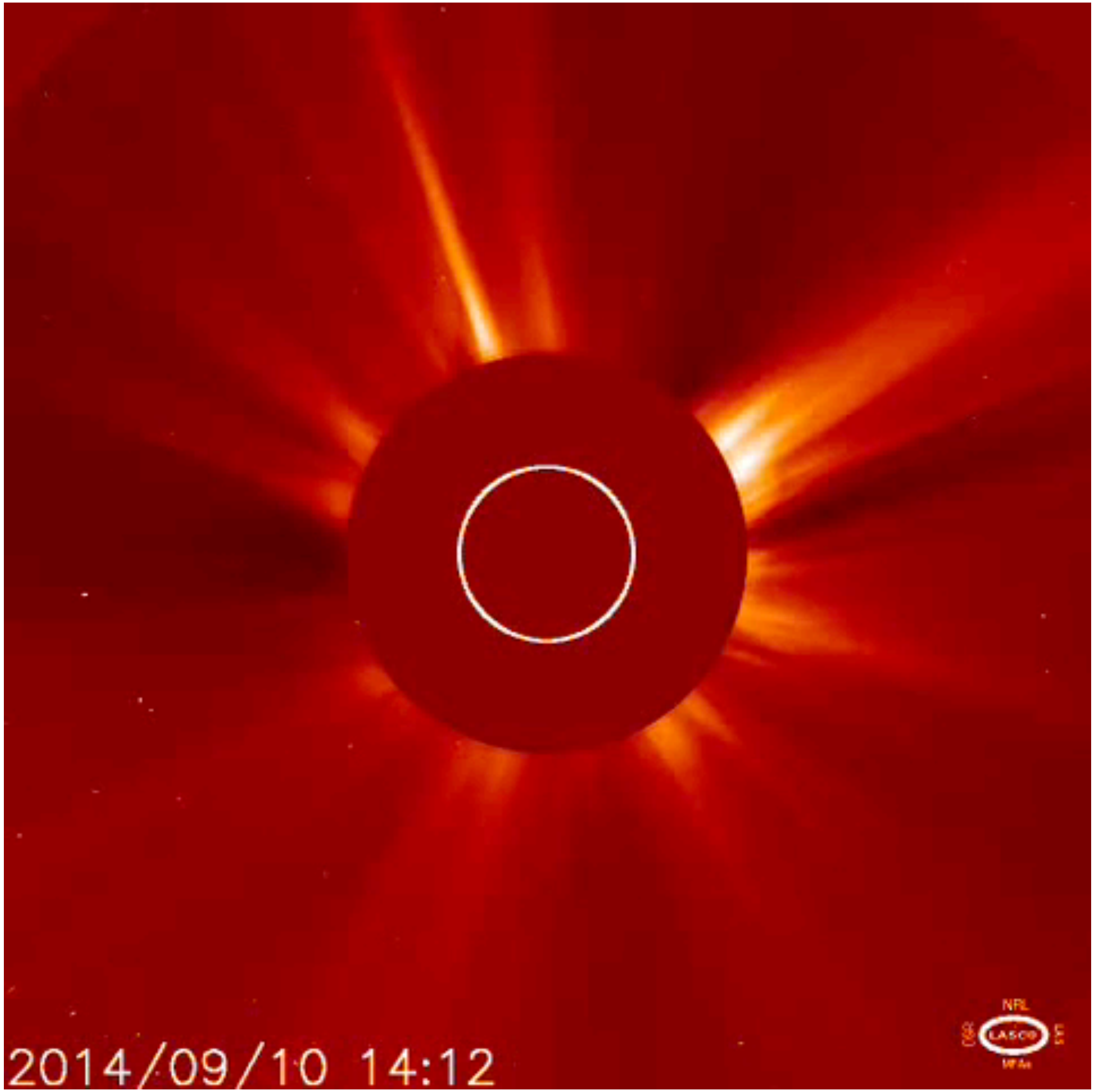



2000/02/27 00:18

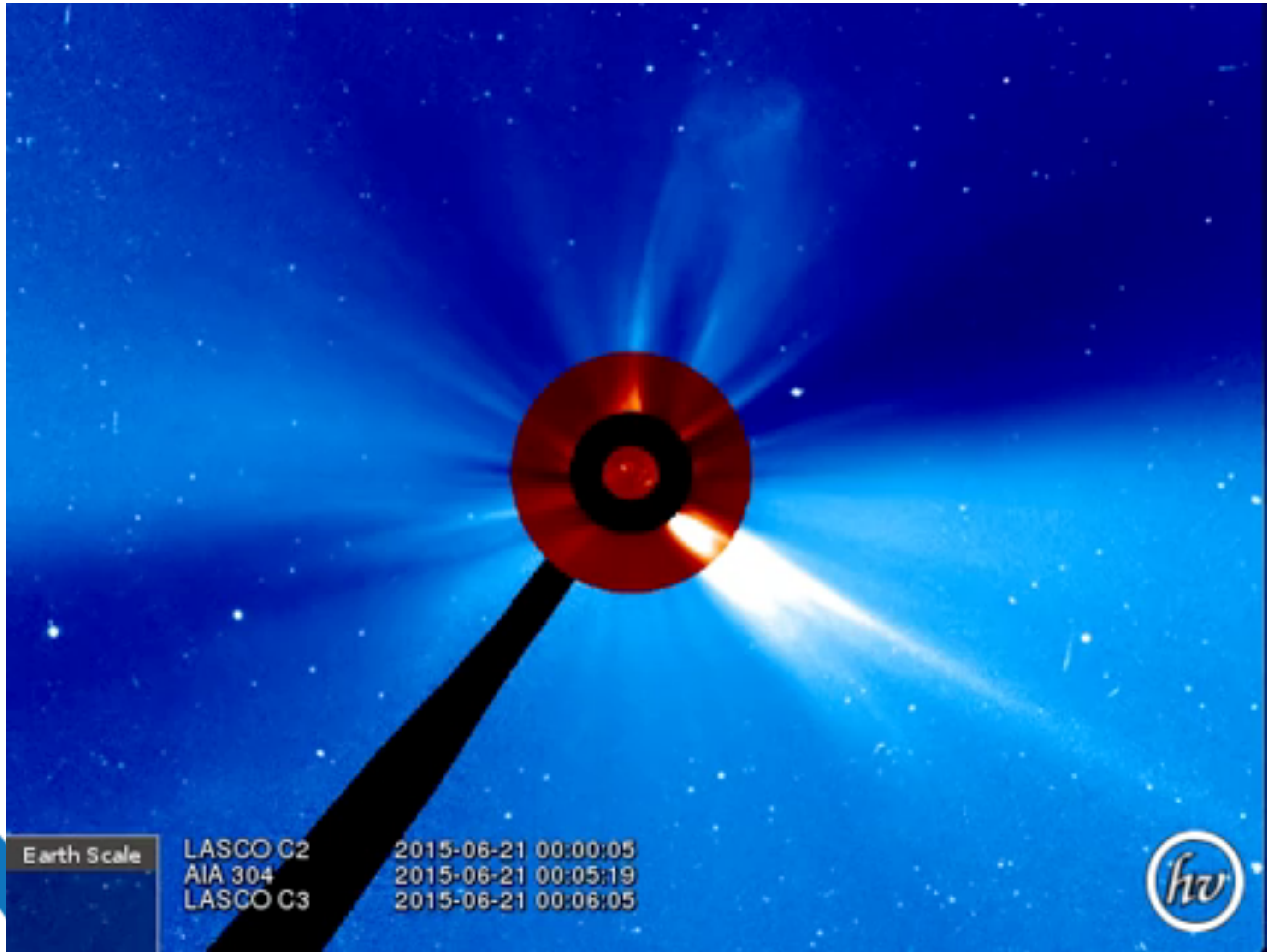
Halo CME



Halo CME



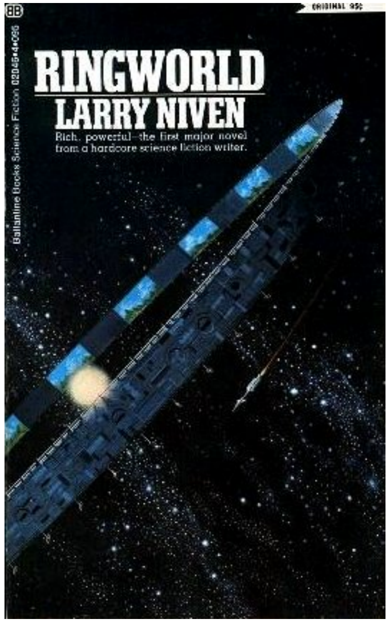
Halo CME

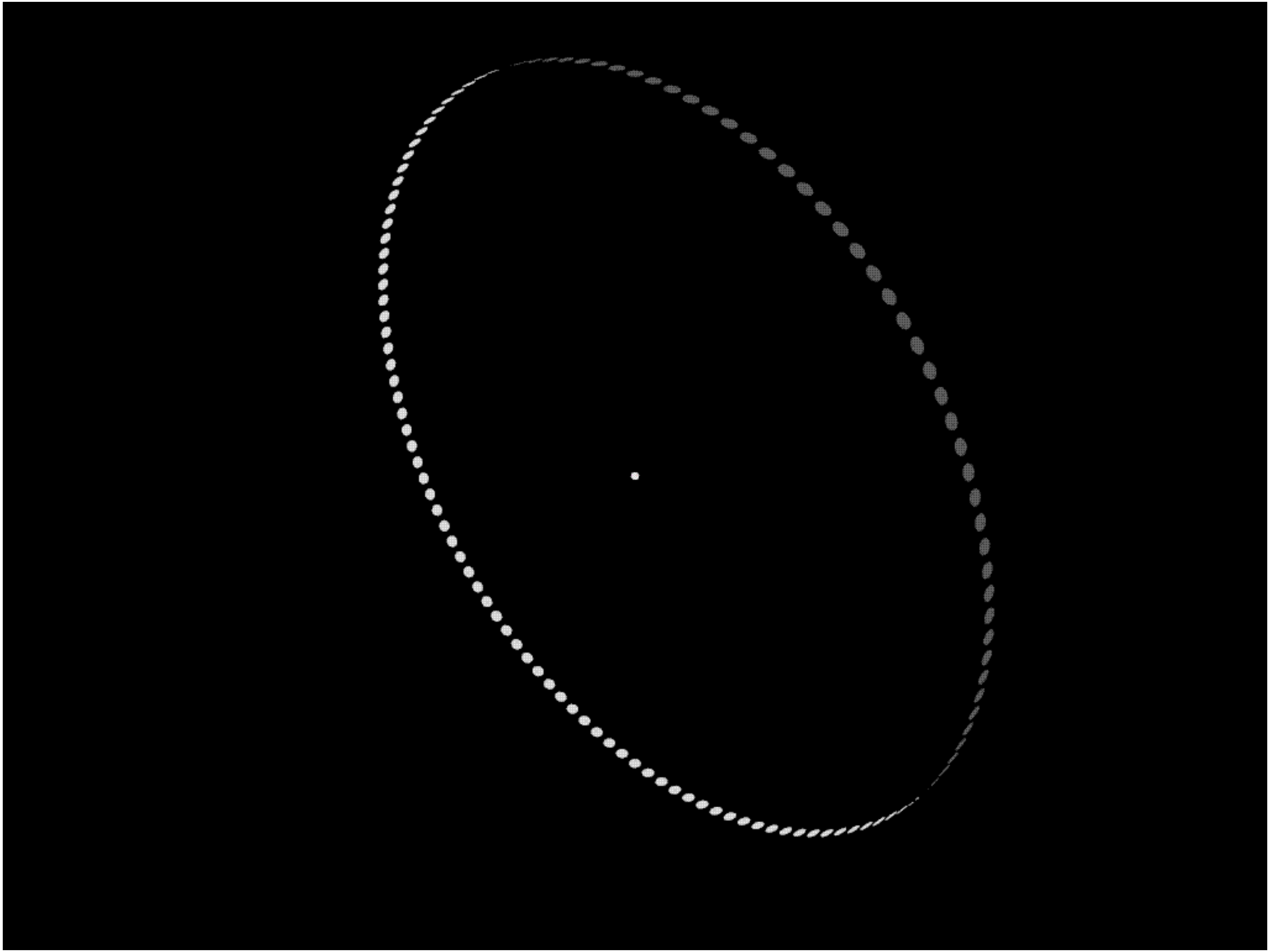

Earth Scale
LASCO C2
AIA 304
LASCO C3
2015-06-21 00:00:05
2015-06-21 00:05:19
2015-06-21 00:06:05

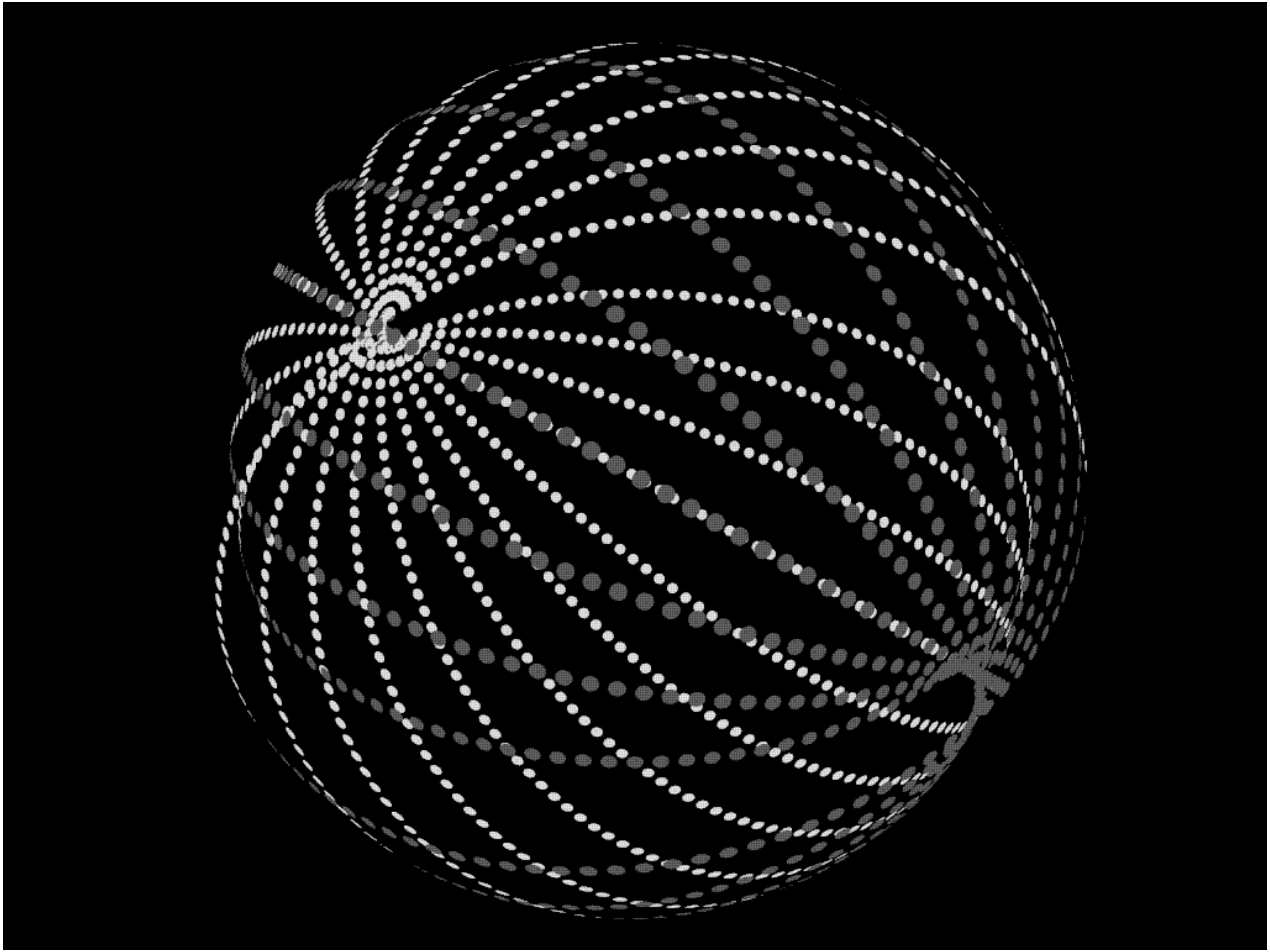
Halo

Halo

Halo


RINGWORLD
LARRY NIVEN
Rich, powerful—the first major novel from a hardcore science fiction writer.
Ballantine Books Science Fiction





CME / flare

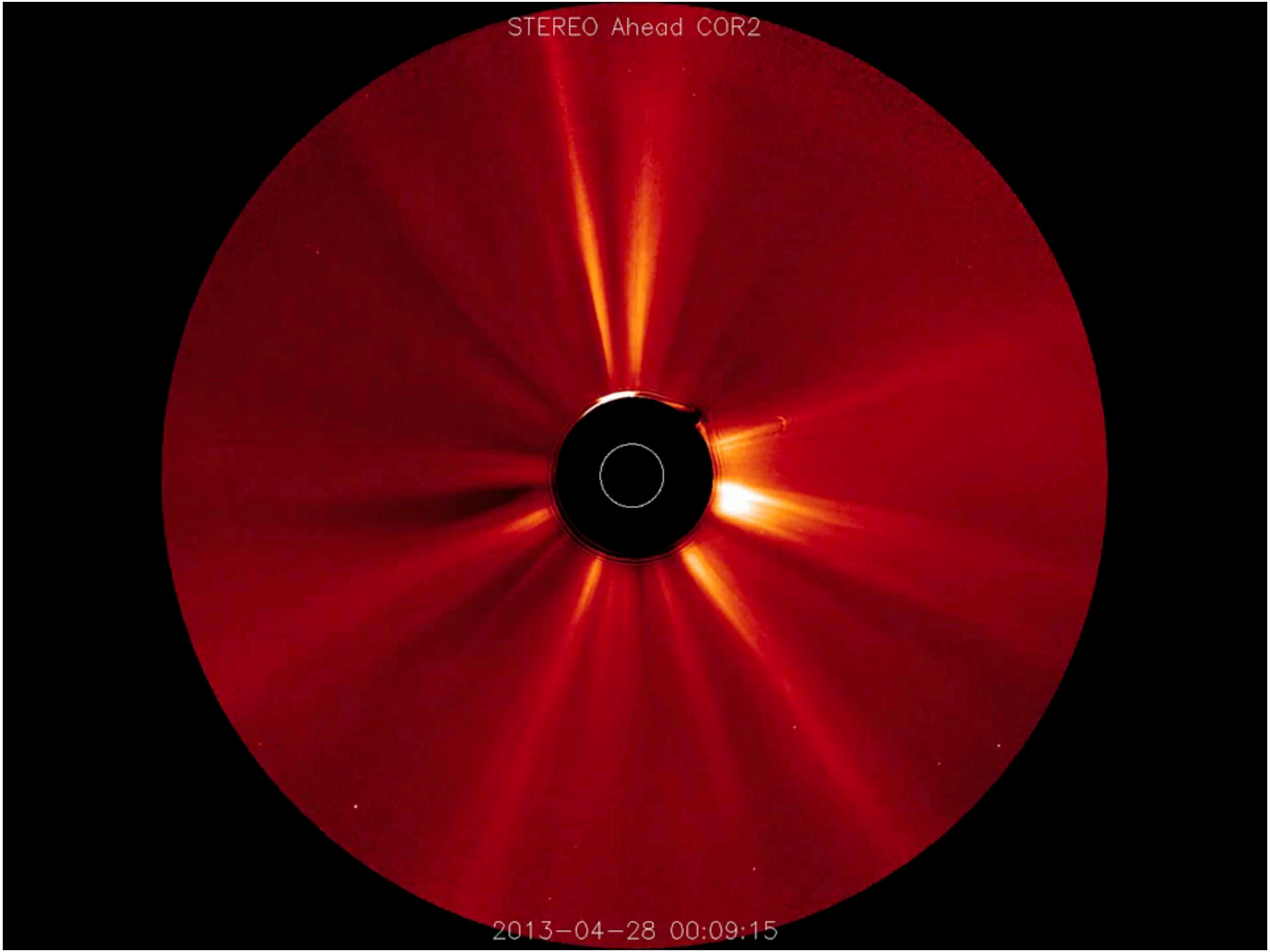
The most energetic CMEs occur in close association with powerful flares.

Nevertheless large-scale CMEs **do occur** in the absence of major flares even though these tend to be slower and less energetic.

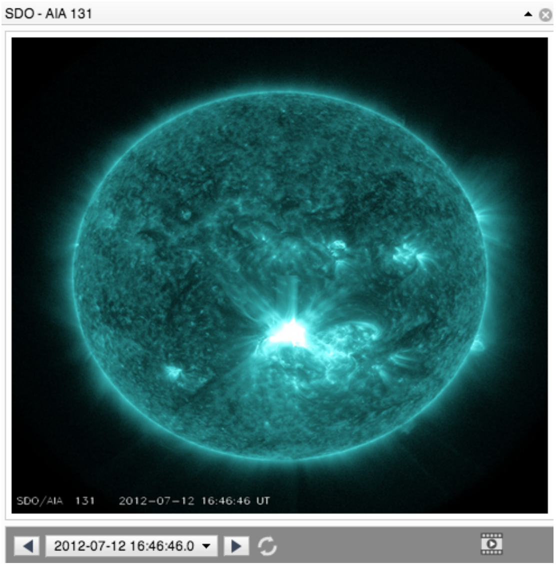
[redacted]

[redacted]

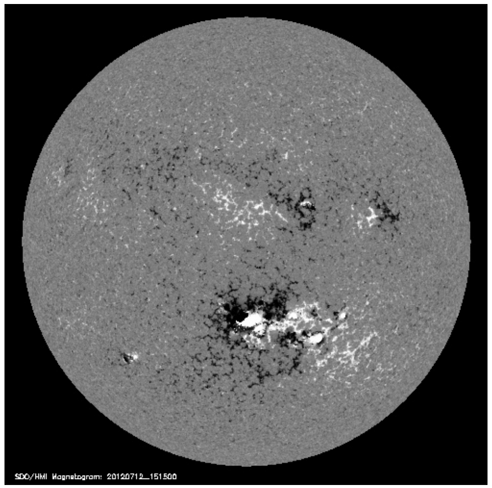
Το εξαήμερο των εκτινάξεων

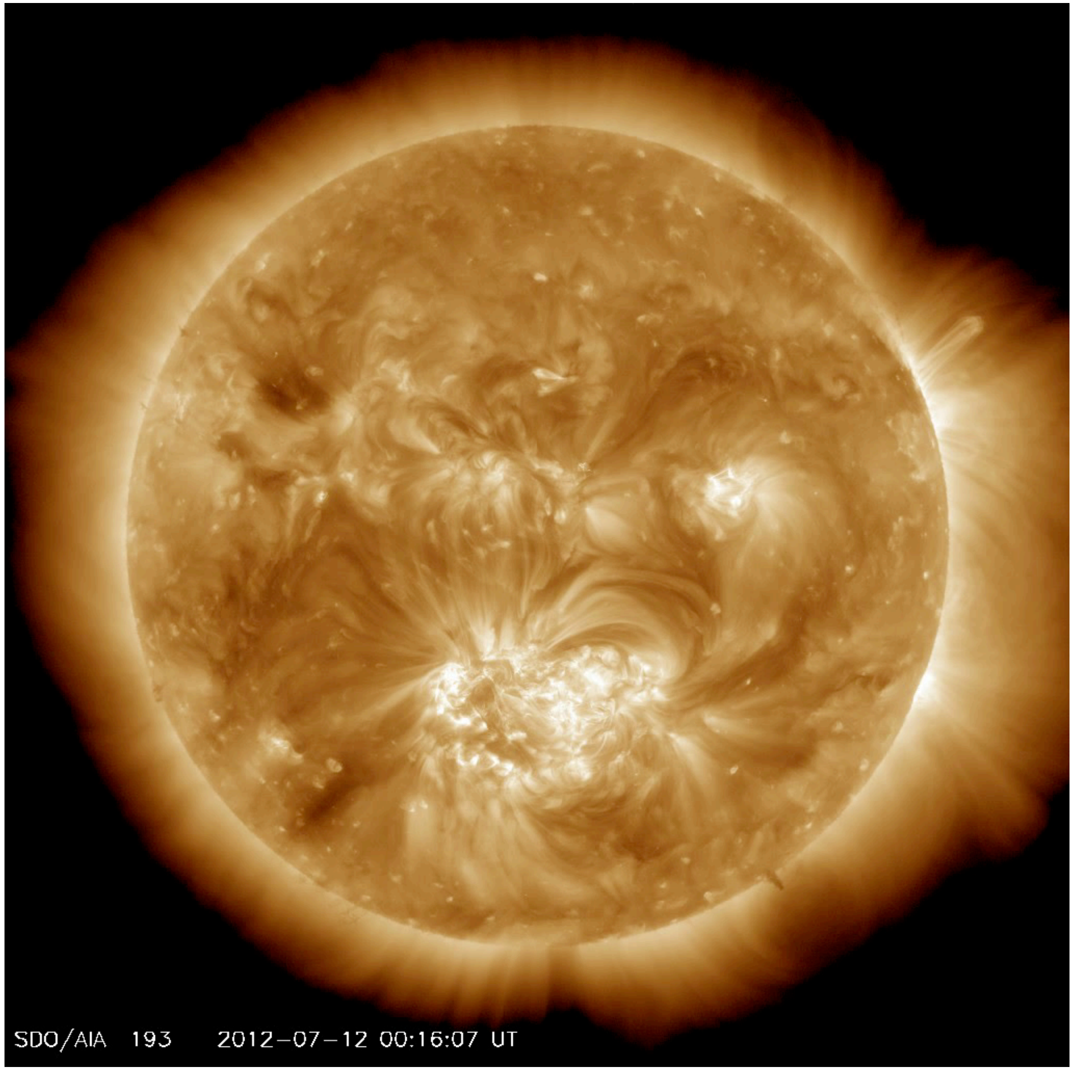

STEREO Ahead COR2
2013-04-28 00:09:15

Most CMEs Originate From Active Regions



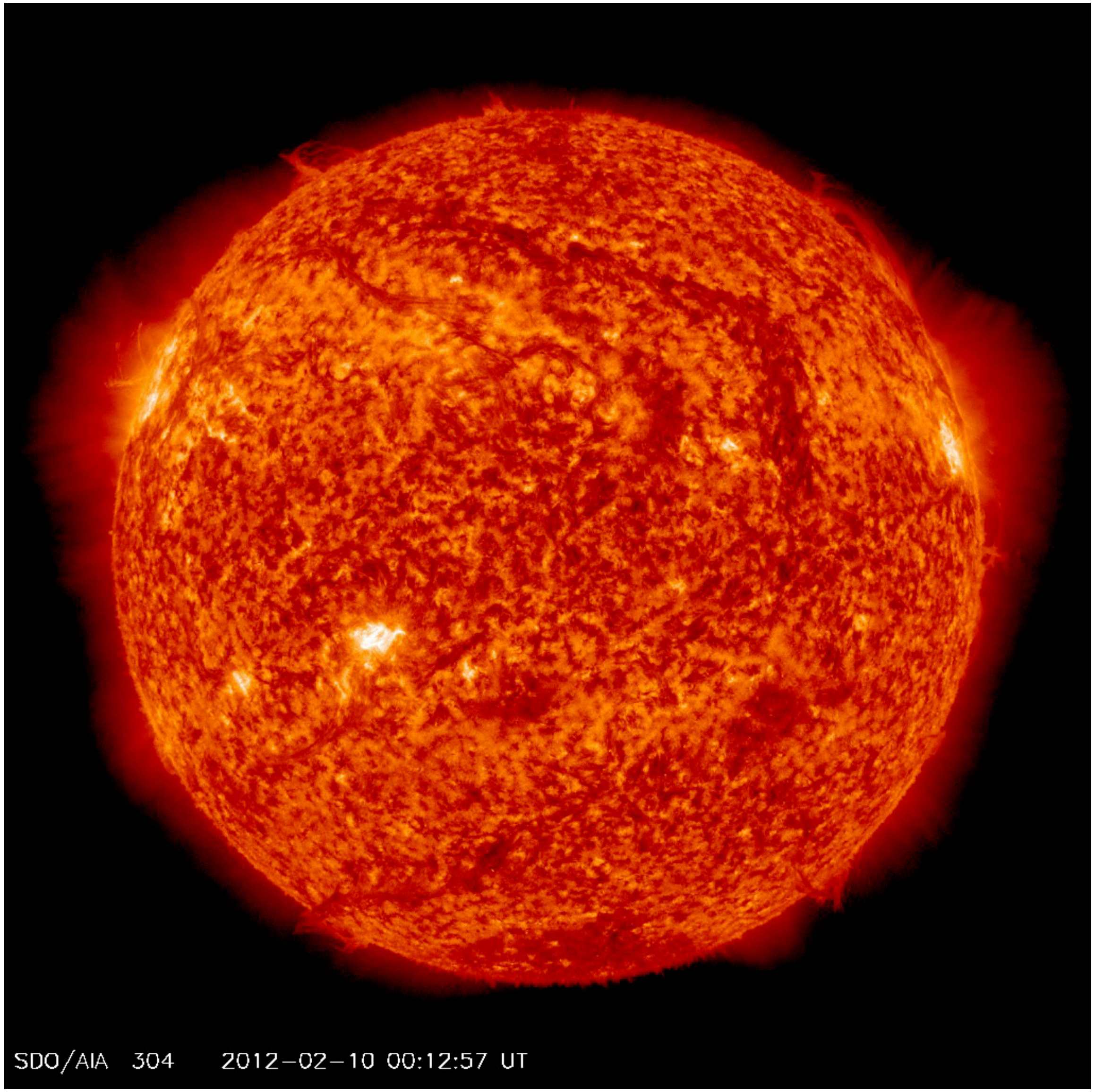
2012 July 12 X1.4 class flare and a following CME

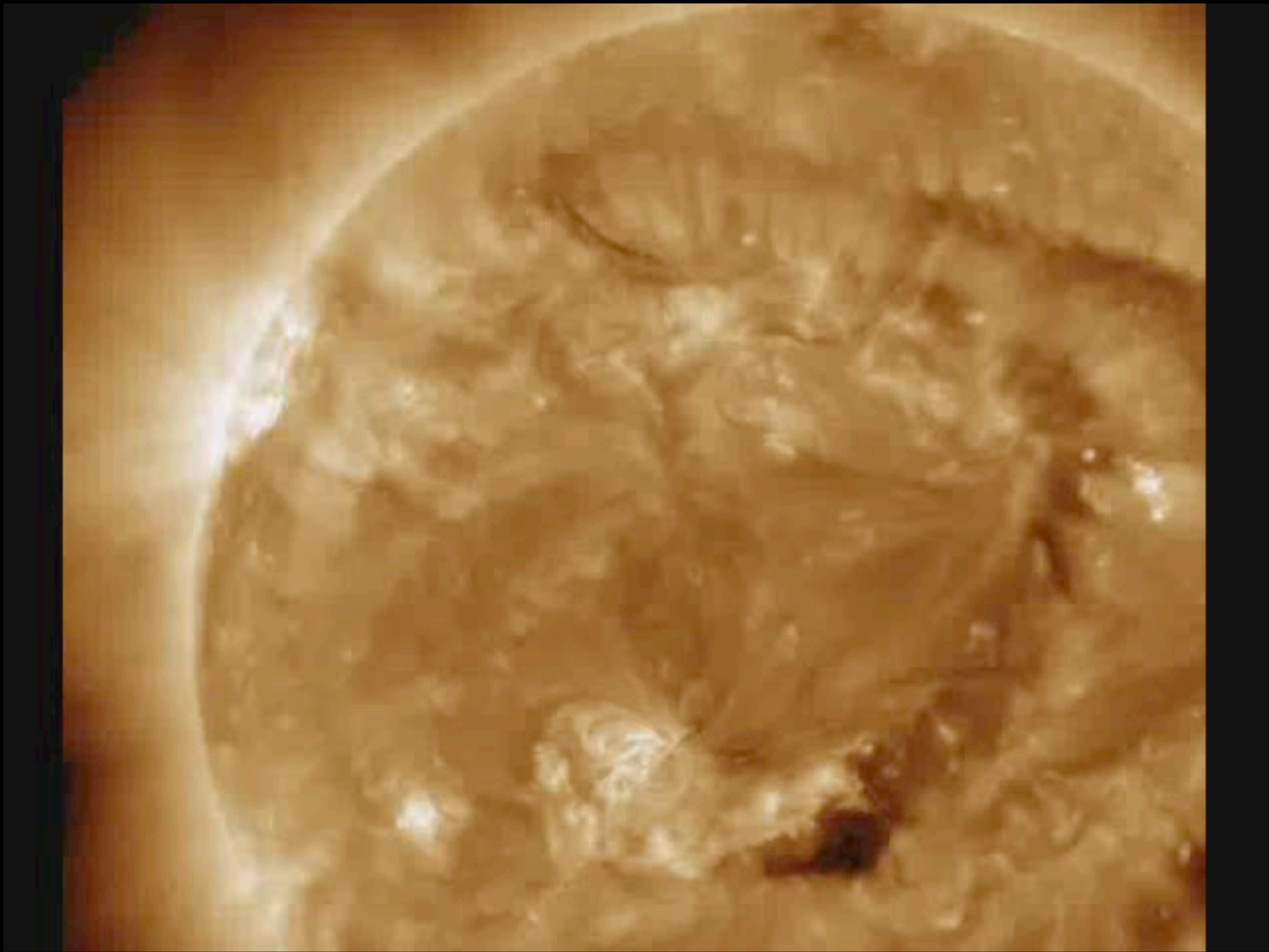


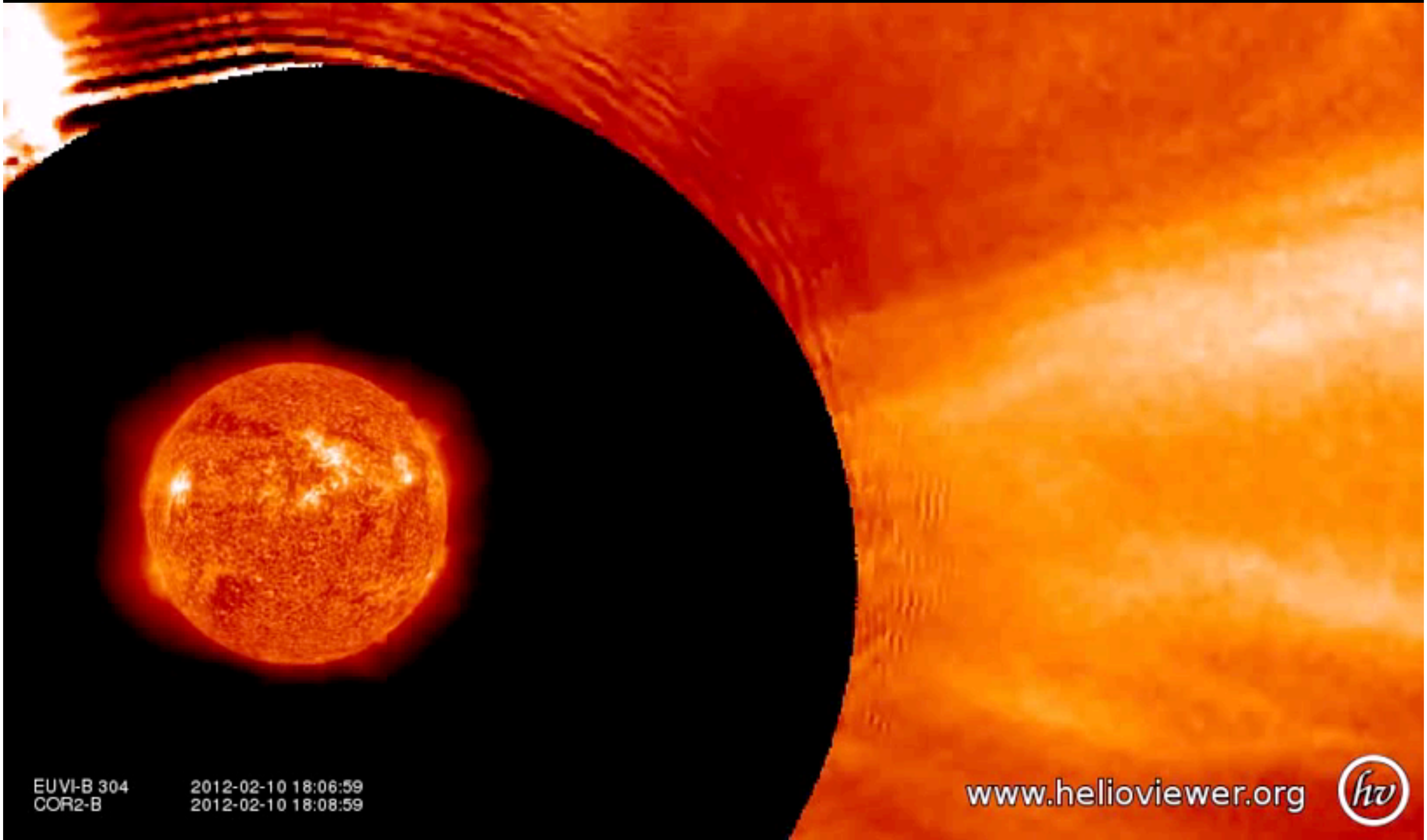


CME από έκρηξη νήματος (filament eruption)

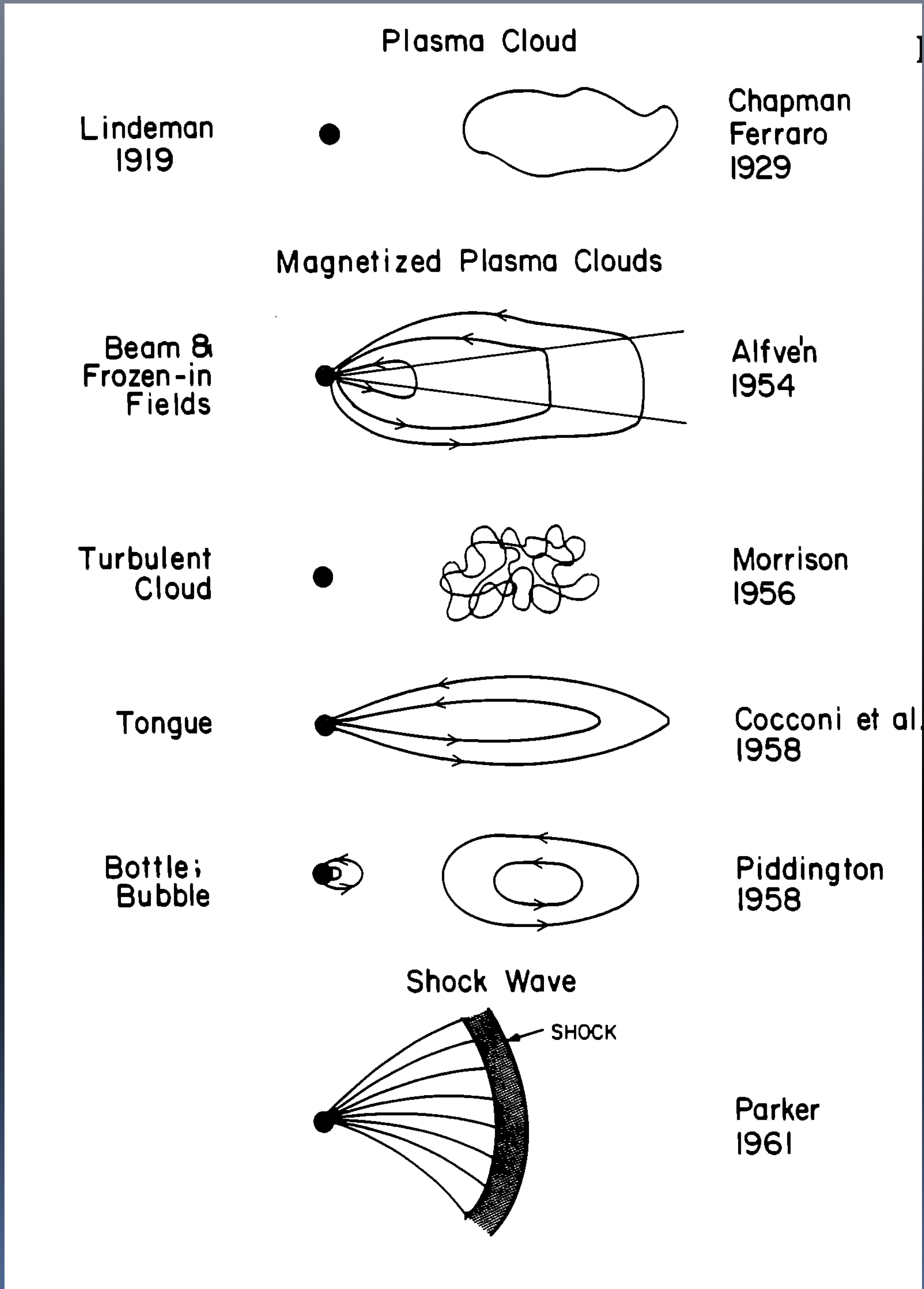
Northeast (upper left) quadrant, starting around 19:00 UT on Feb 10, 2012






EUVI-B 304
COR2-B
2012-02-10 18:06:59
2012-02-10 18:08:59
www.helioviewer.org

Early Ideas of CMEs



George Francis Fitzgerald (1892) proposed that "a sunspot is a source from which some emanation like a comet's tail is projected from the Sun…"and asked "is it possible then that matter starting from the Sun with the explosive velocities we know possible there, and subject to an acceleration of several times solar gravitation, could reach the Earth in a couple of days?".

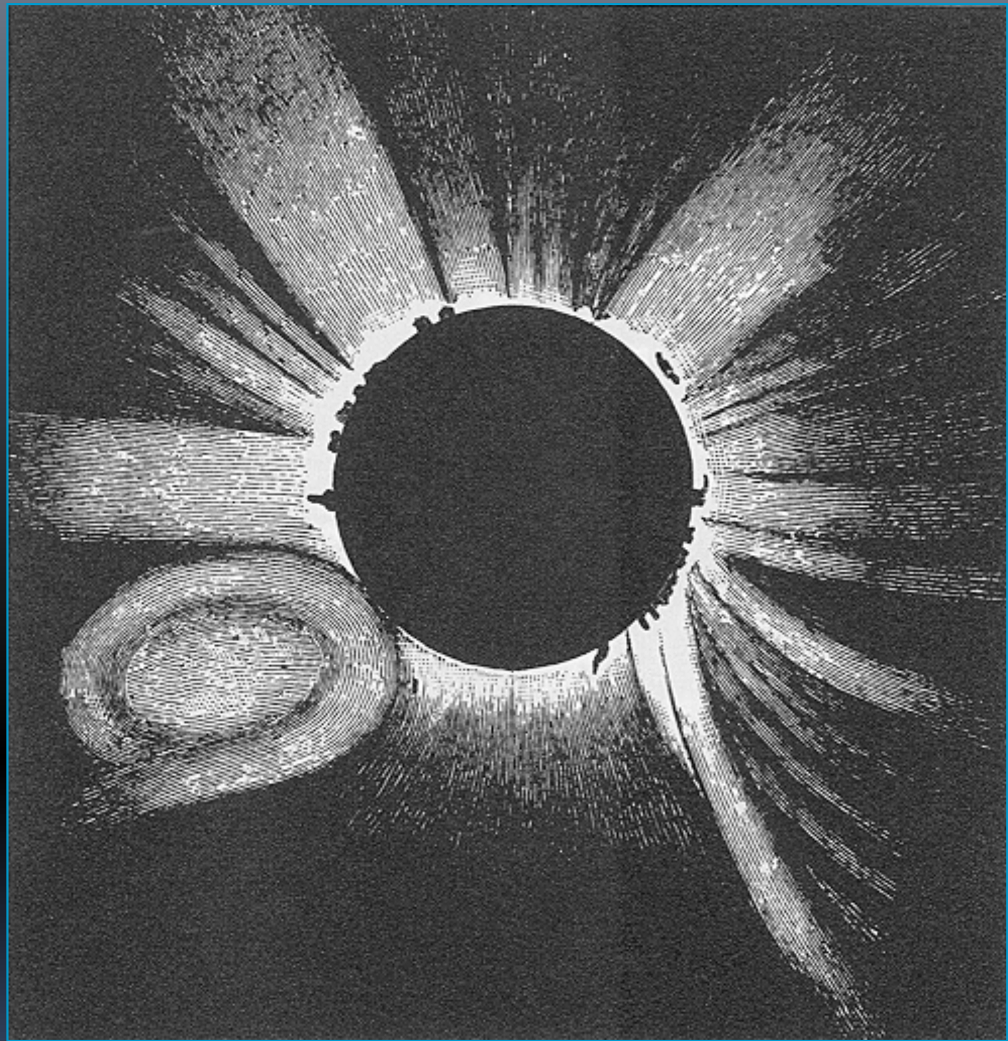
Oliver Lodge (1900) suggested that magnetic storms are caused by " . . . a torrent or flying cloud of charged atoms or ions".

A magnetized particle cloud was proposed in 1959 by Thomas Gold.

Σωλήνες ροής; (flux rope)

Burlaga, 1991

First depiction of a CME



Eclipse Drawing by the German astronomer
E. Tempel on 18 July 1860

The advent of the space age: In 1962 Mariner 2 recorded shock waves in the solar wind

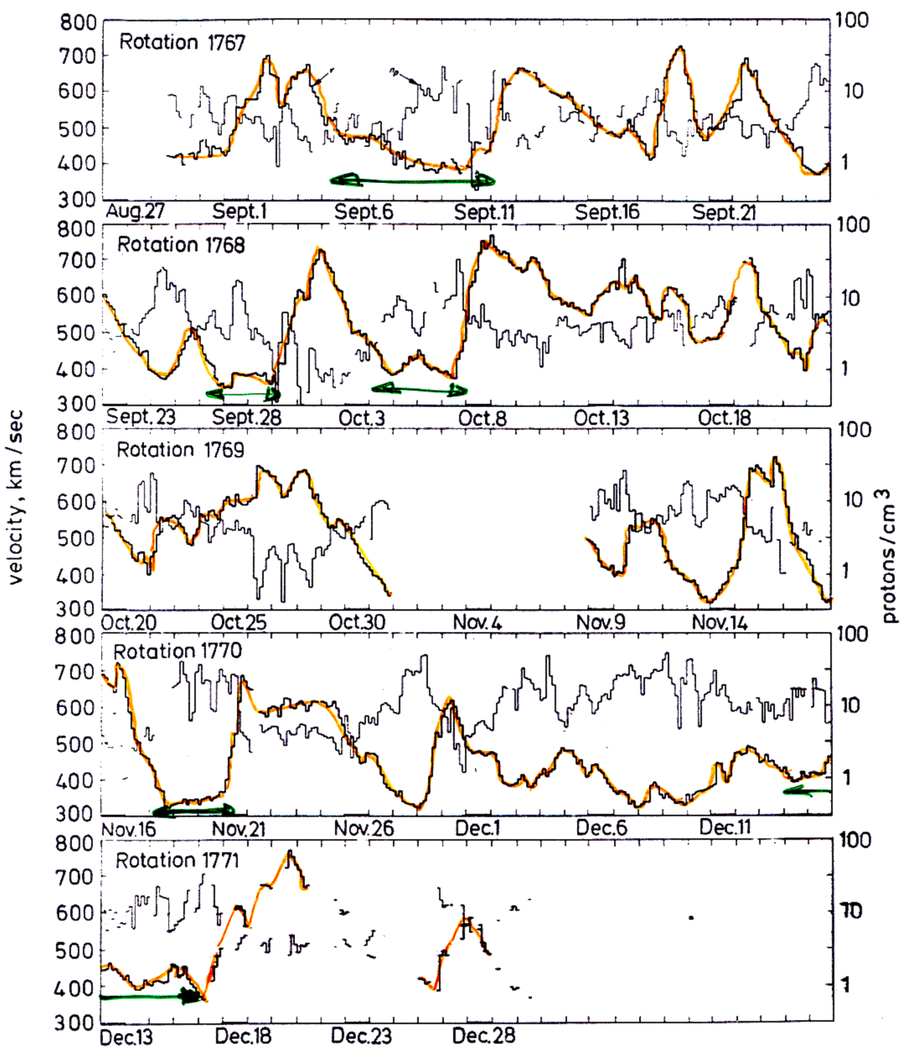
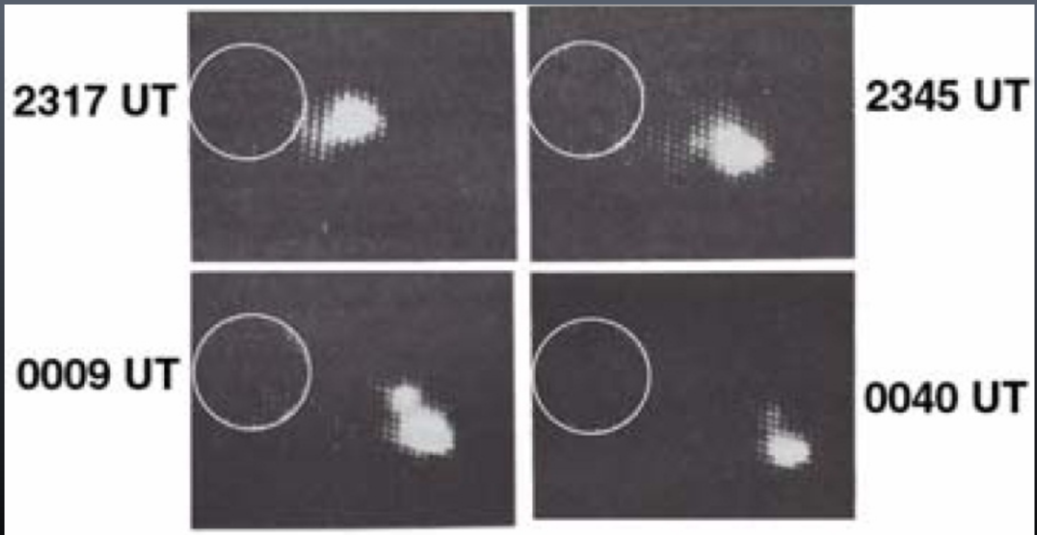


Fig. 1.5 Three-hour averages of the solar wind proton density and flow speed observed by Mariner 2 in 1962 [1.21]. The time coordinate has been broken into 27-day solar rotation periods

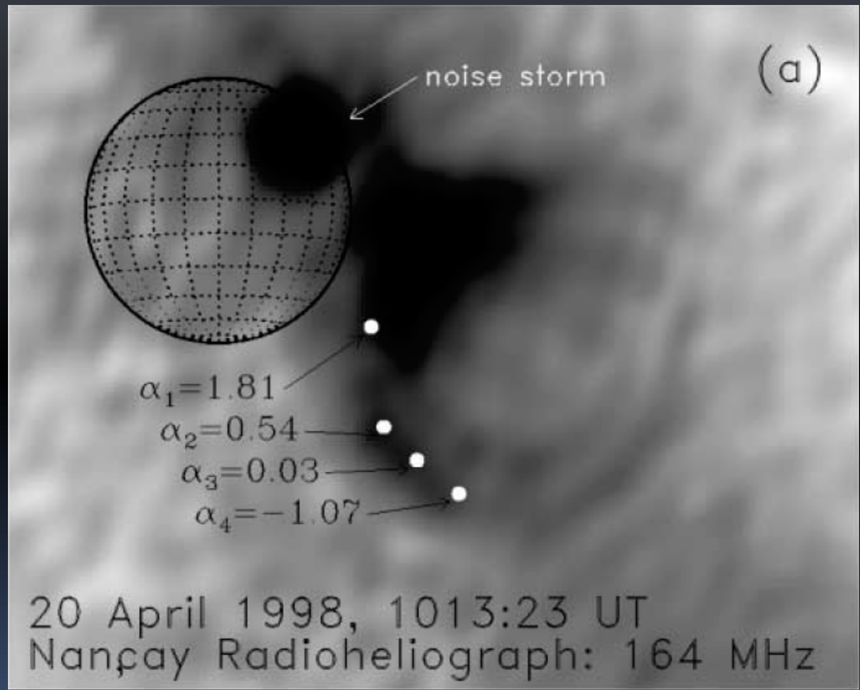
Dylan, 1962

Neugebauer und Snyder (1962)

Οι πρώτες ενδείξεις για εκτόξευση ηλιακής μάζας στο διαπλανητικό διάστημα προήλθαν από μετρήσεις ραδιοκυμάτων το 1970

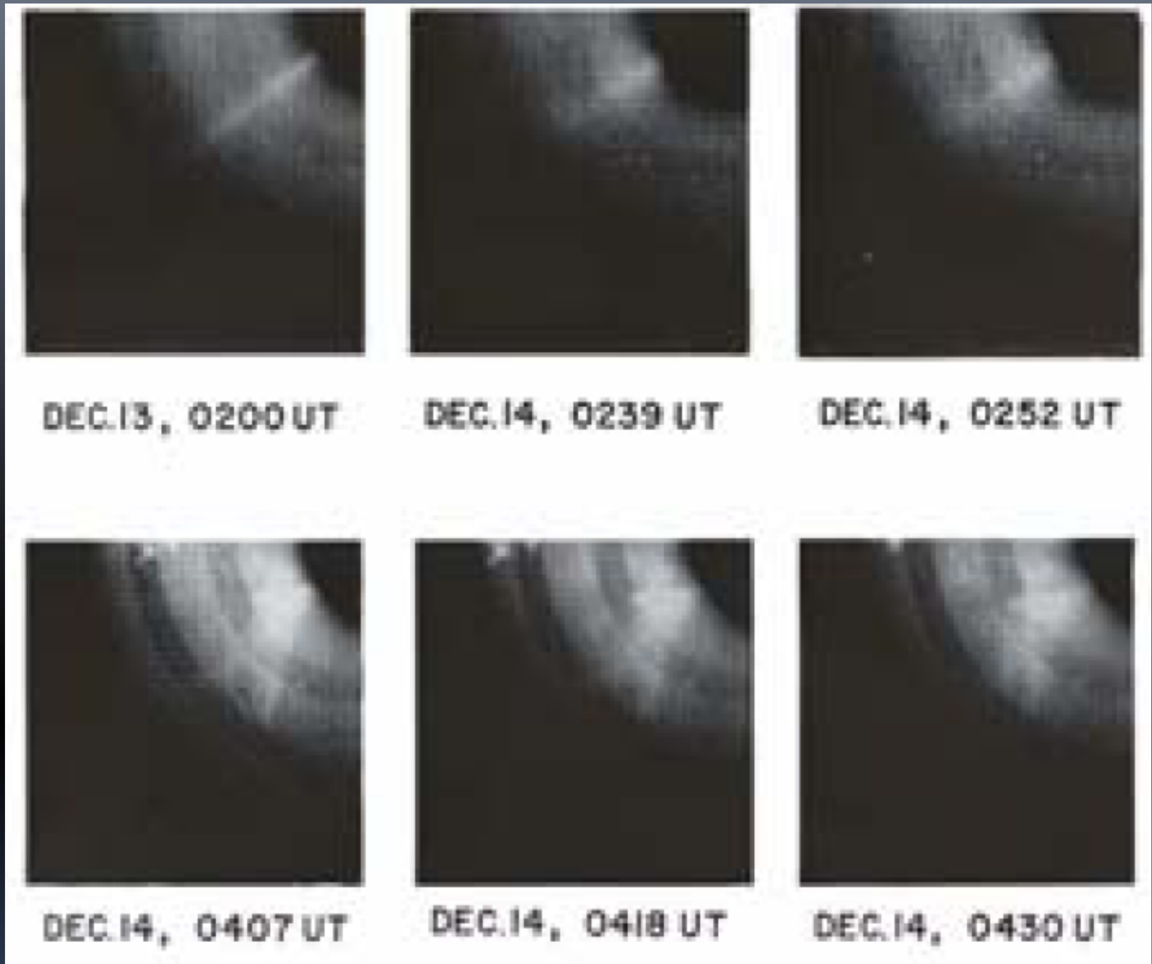


80 MHz Radio Observation of an Expulsion of a Dense Plasma Cloud from the Sun on 1 Mar 1969, made with the Culgoora radioheliograph (Riddle, 1970)



A radio CME observed on 20 April 1998 at 164 MHz. (Bastian *et al.*, 2001)

Η πρώτη αδιαμφισβήτητη παρατήρηση CME: 14 Δεκεμβρίου 1971



On 13-14 Dec 1971, a bright streamer in the southeast participated in the "coronal transient" that traveled outward at over 1000 km/s (Tousey, 1973).

NASA Orbiting Solar Observatory 7

(1971-1973) :

3.0 - 10 Rs; SEC Vidicon detector

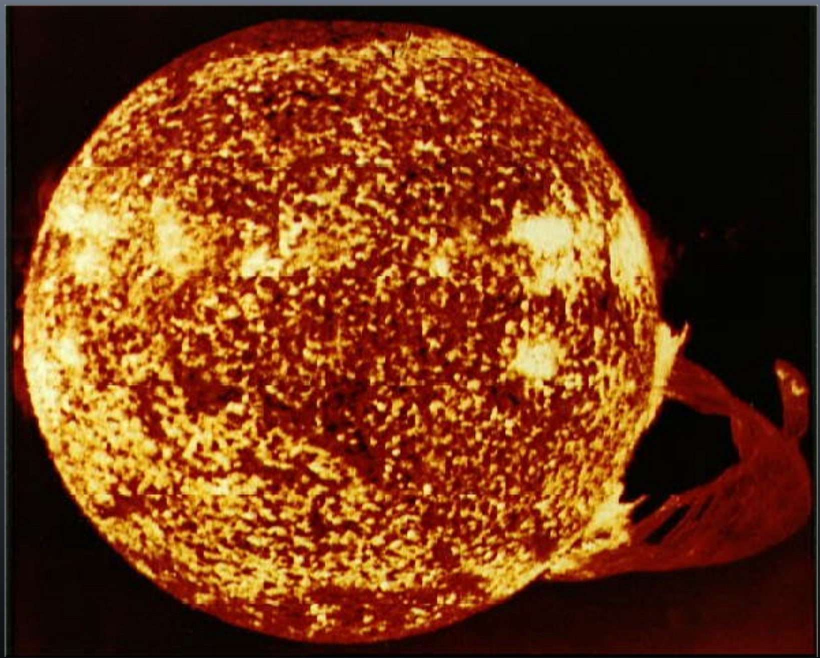
(3 arc min resolution)

Weakness - 4 full images per day

(~30 CMEs observed)

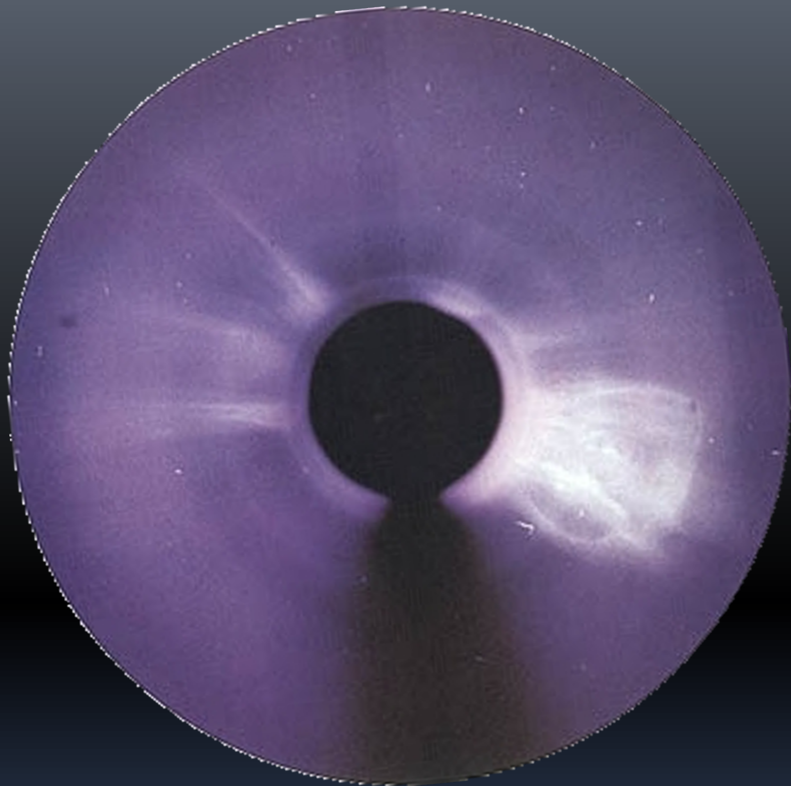
(Howard, 2006)

1973-1974:Skylab



A CME Observed with the Coronagraph

on board Skylab in 1973



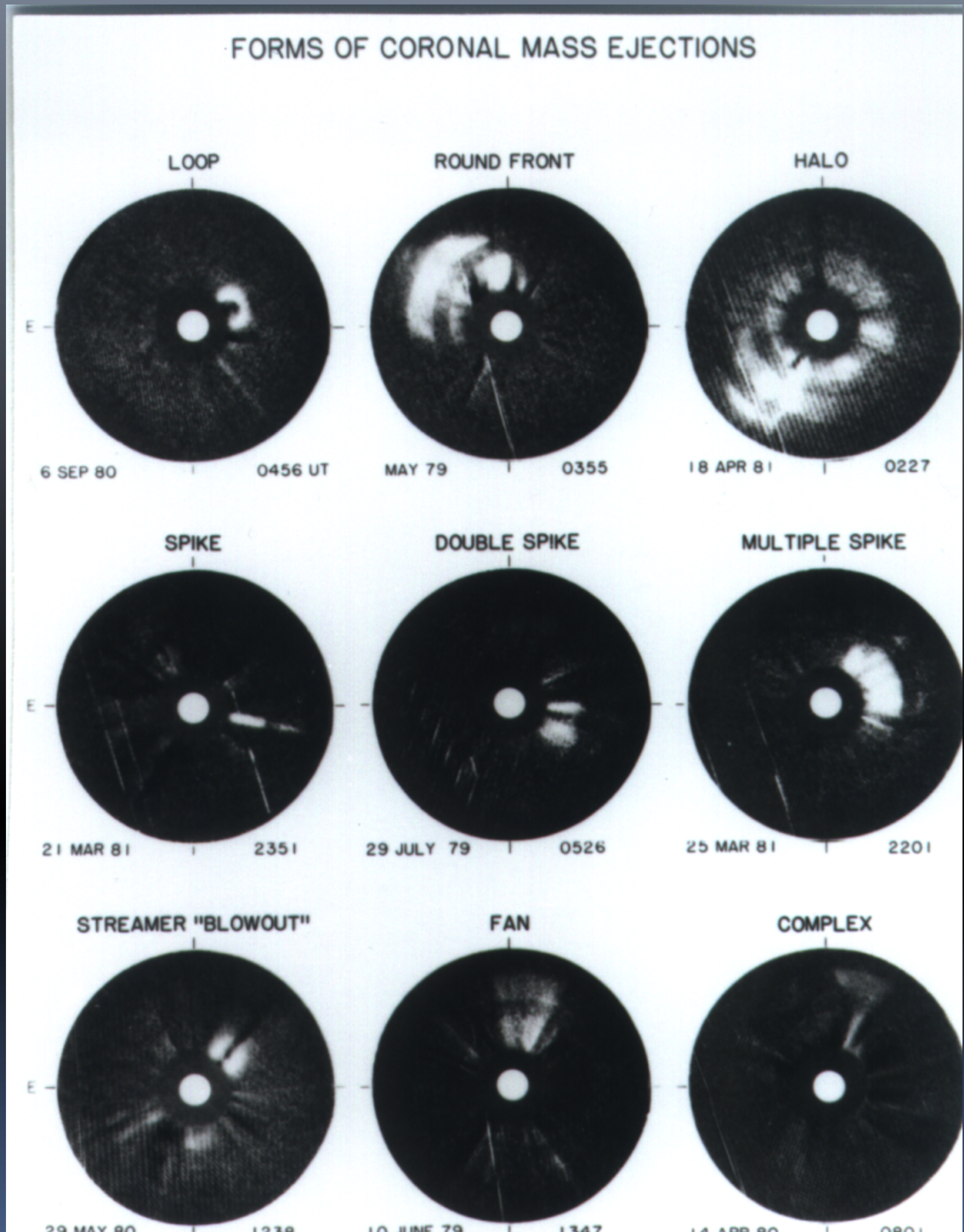
NASA Skylab (1973-1974)

2.0 - 6 solar radii; Film detector (5“ resolution)

~100 CMEs observed, established importance (and beauty); statistics; associations

Weakness: limited film capacity, 3 short duration missions

1979-1985:Solwind Observations

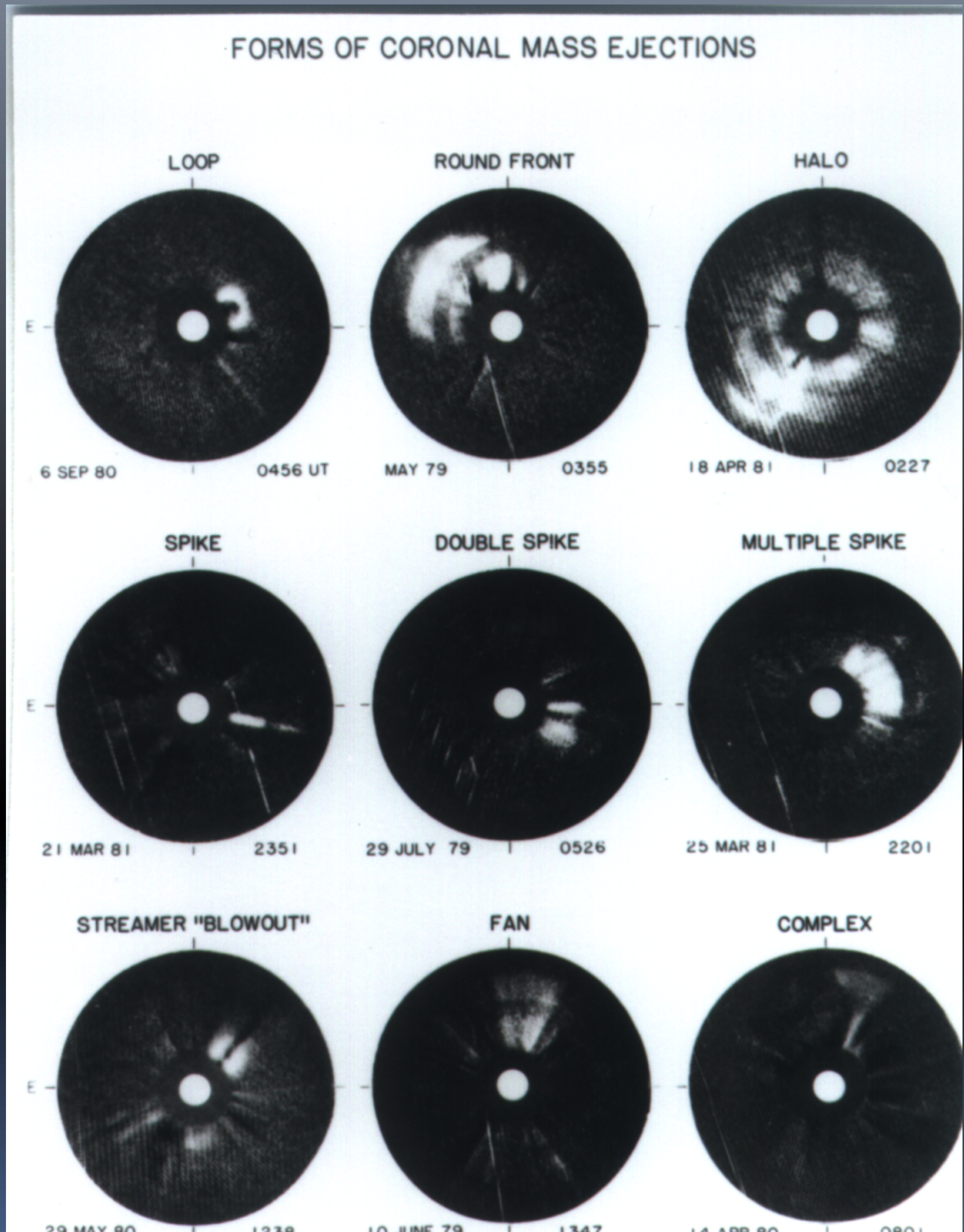


Howard et al. 1984

USAF P78-1 (Solwind 1979-1985)

Same characteristics as OSO-7

1979-1985:Solwind Observations

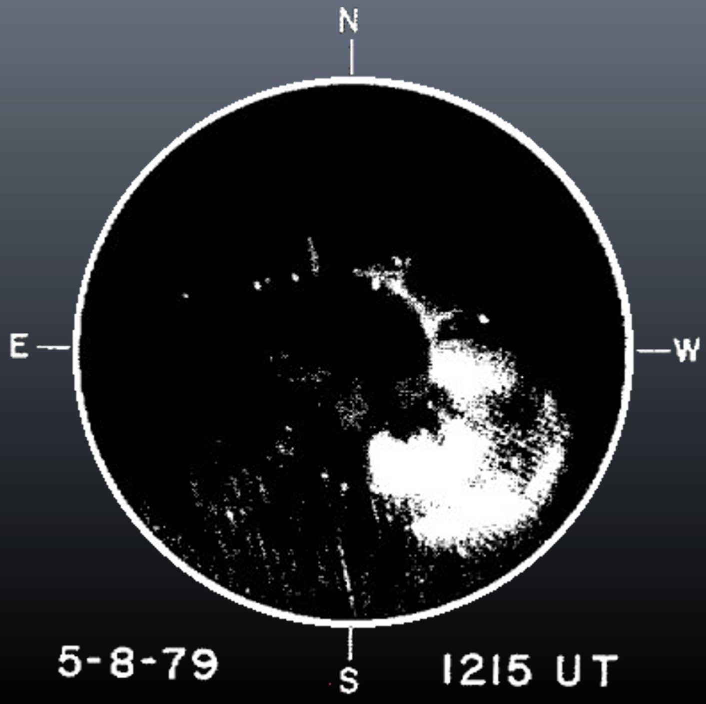


Howard et al. 1984

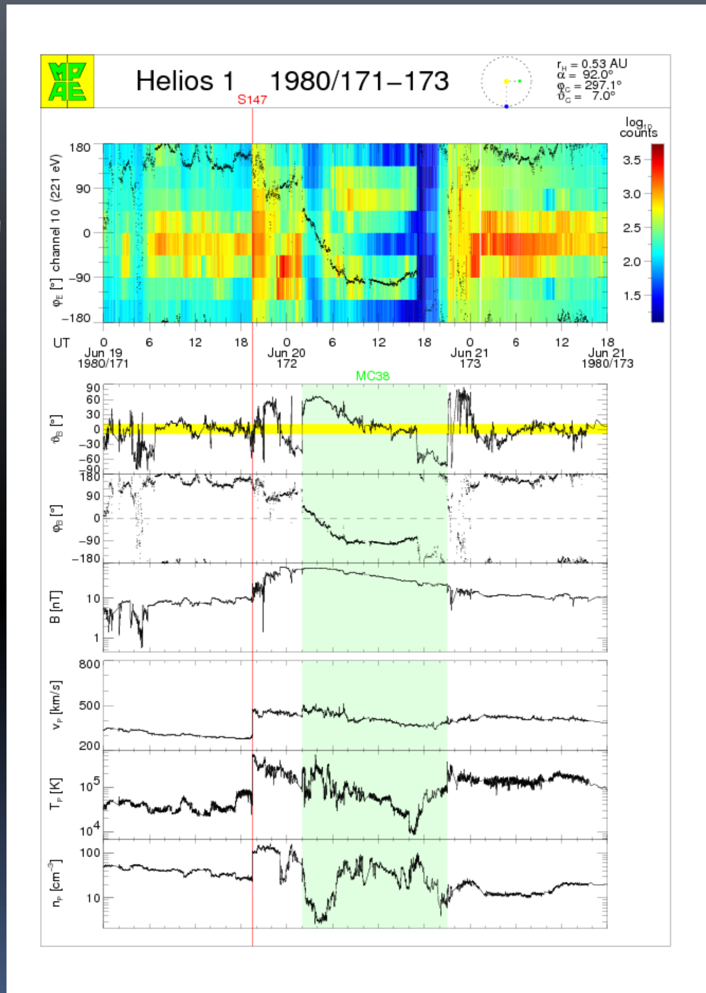
USAF P78-1 (Solwind 1979-1985)

Same characteristics as OSO-7

Correlated Analysis of Remote Sensing and In-Situ Observations with P78-1 and Helios 1 & 2

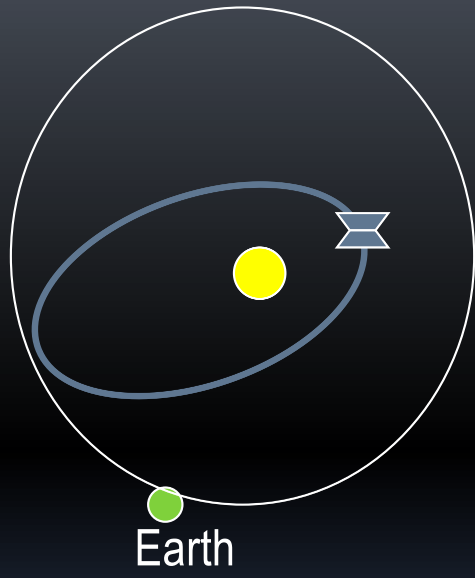


Solwind Coronagraph on board P78-1 (1979-1985)



Burlaga: Magnetic Clouds

Helios-Orbit: 0.29 – 1 AU



The Helios 1 & 2 Spacecraft

(1974-1986)