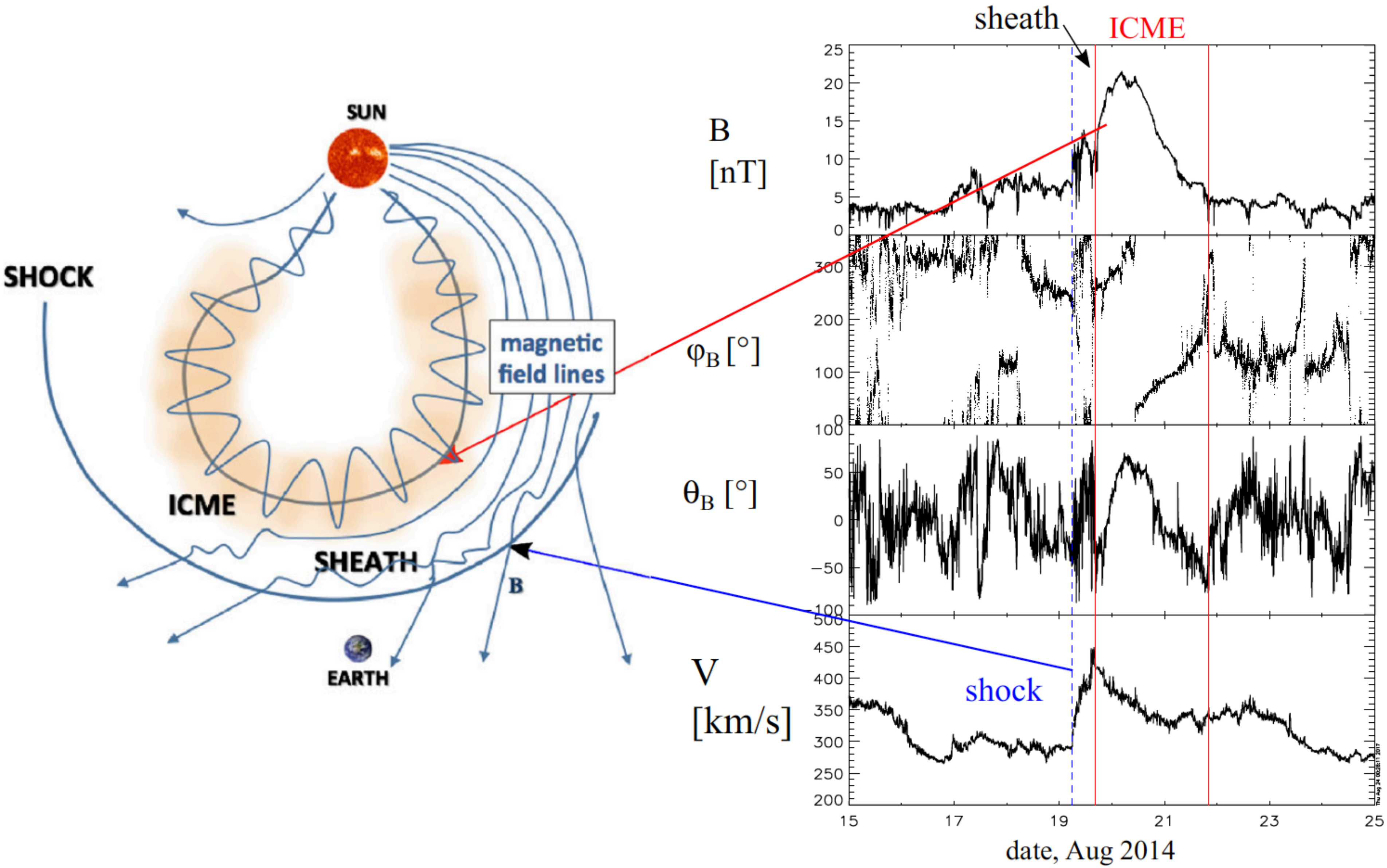
(Solar) Eruption


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

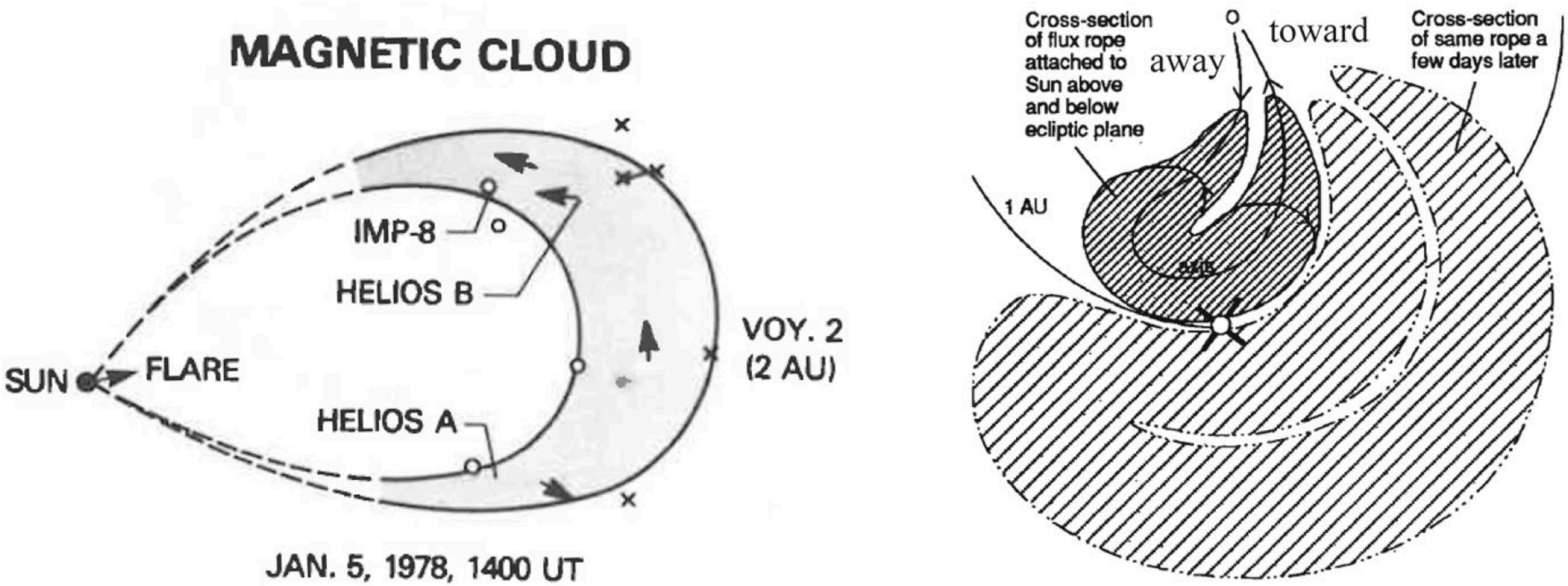
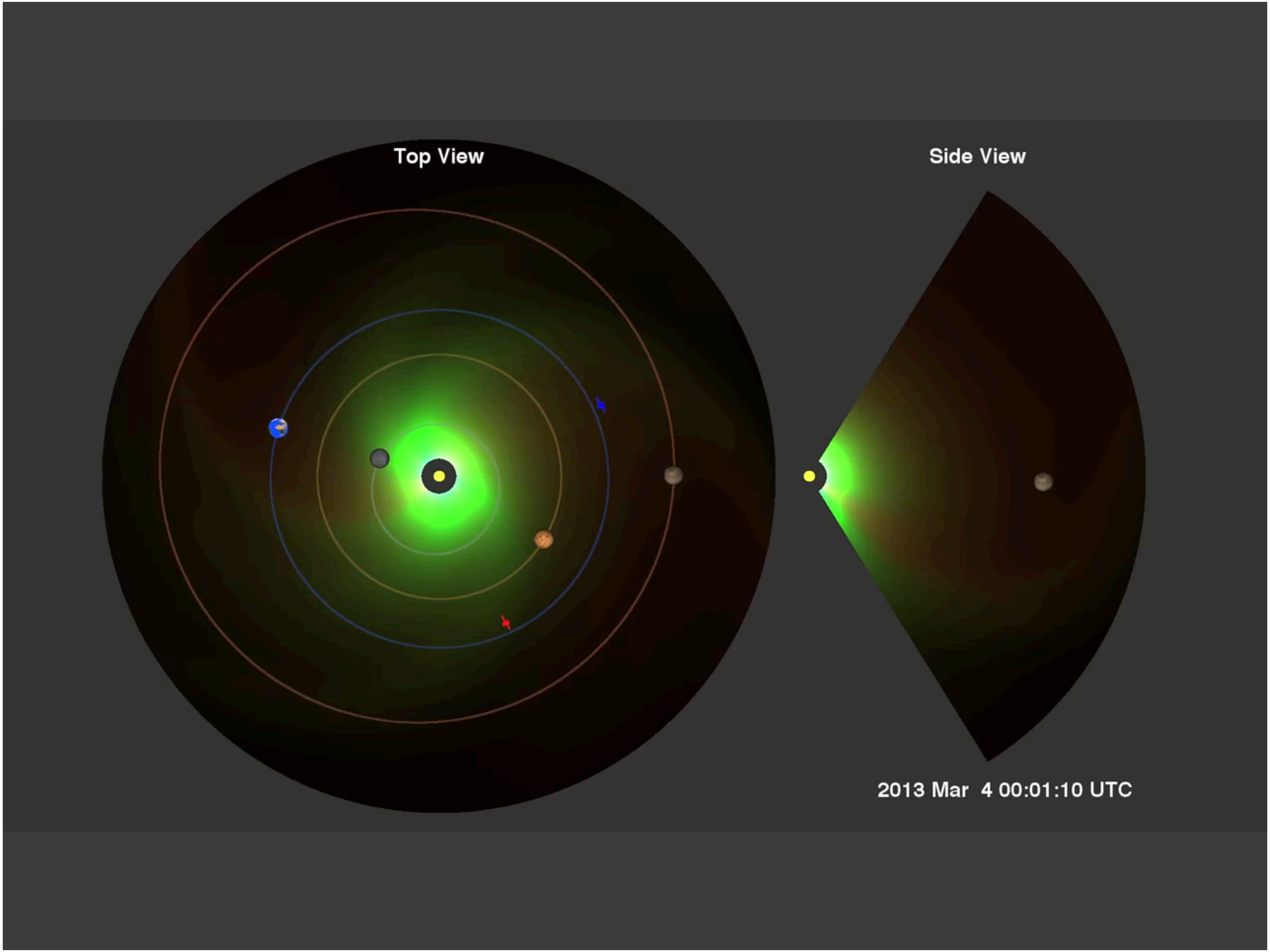
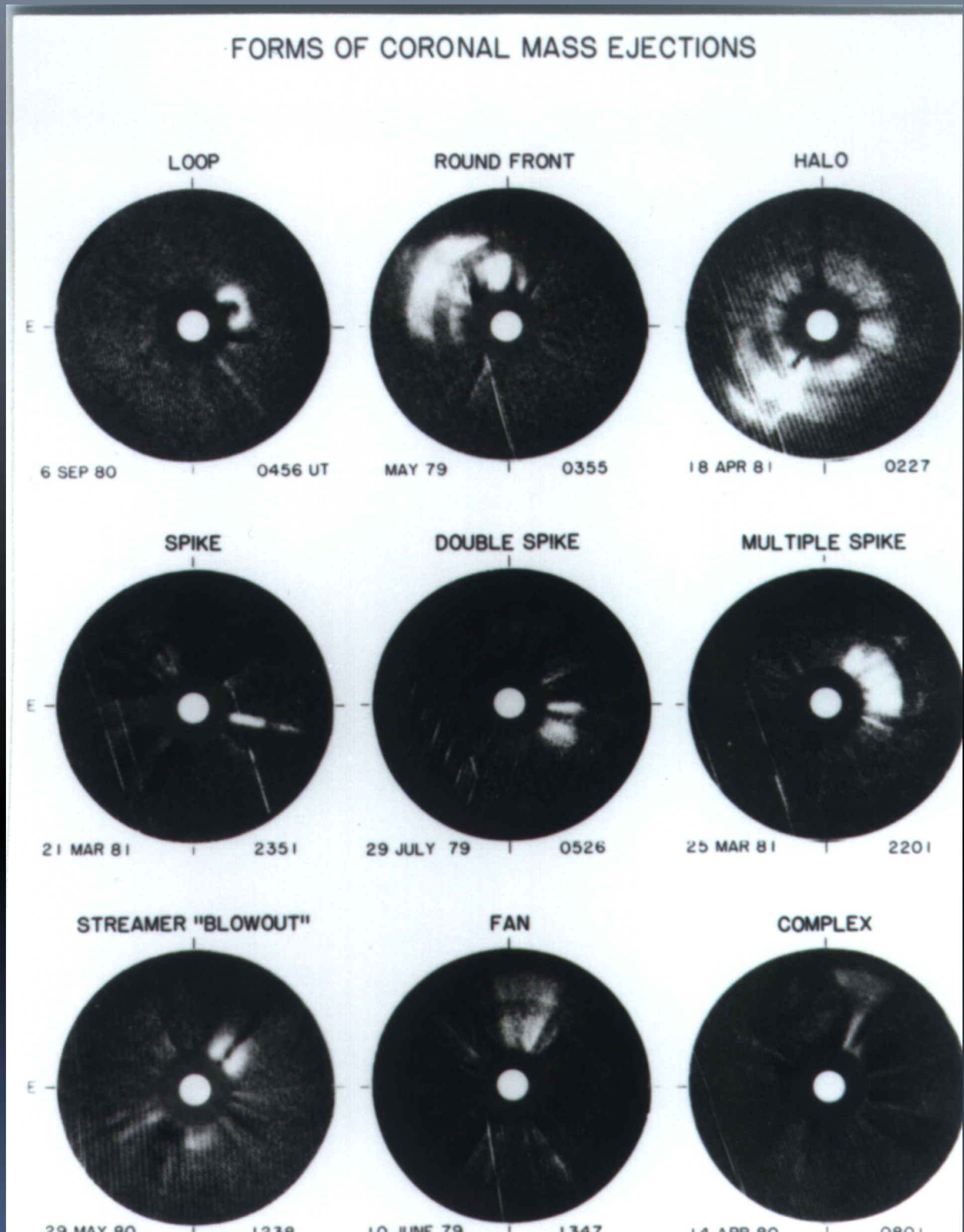


Fig. 8 (Left) The global flux rope axis configuration as deduced from multi-spacecraft observations for a magnetic cloud observed on January 6–8, 1978. All these spacecraft were located close to the ecliptic plane at radial distances between 1–2 AU. (Right) Schematic of a flux rope loop that is distorted along the Parker spiral and carries a sector boundary crossing. Images reproduced by permission from [left] Burlaga et al. (1990); [right] from Crooker et al. (1998), copyright by AGU


Top View
Side View
2013 Mar 4 00:01:10 UTC

1979-1985:Solwind Observations

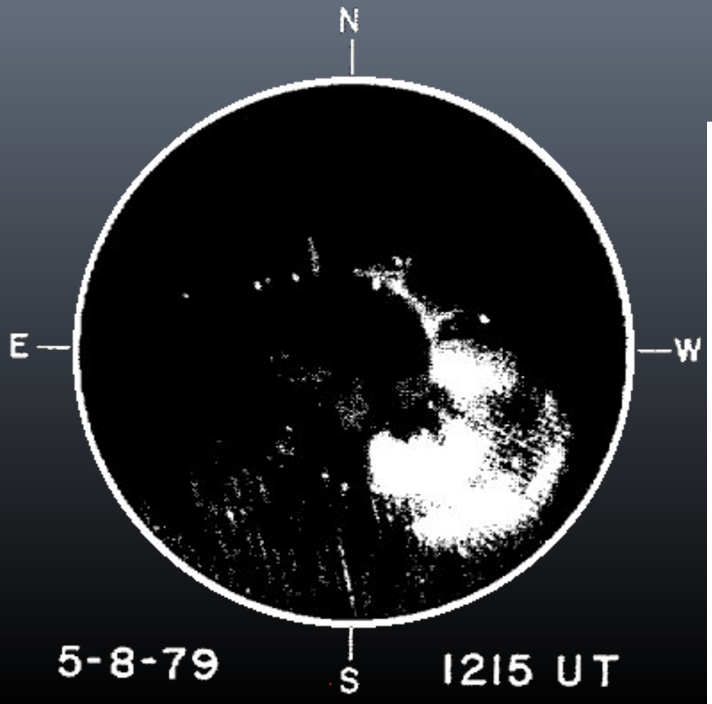


Howard et al. 1984

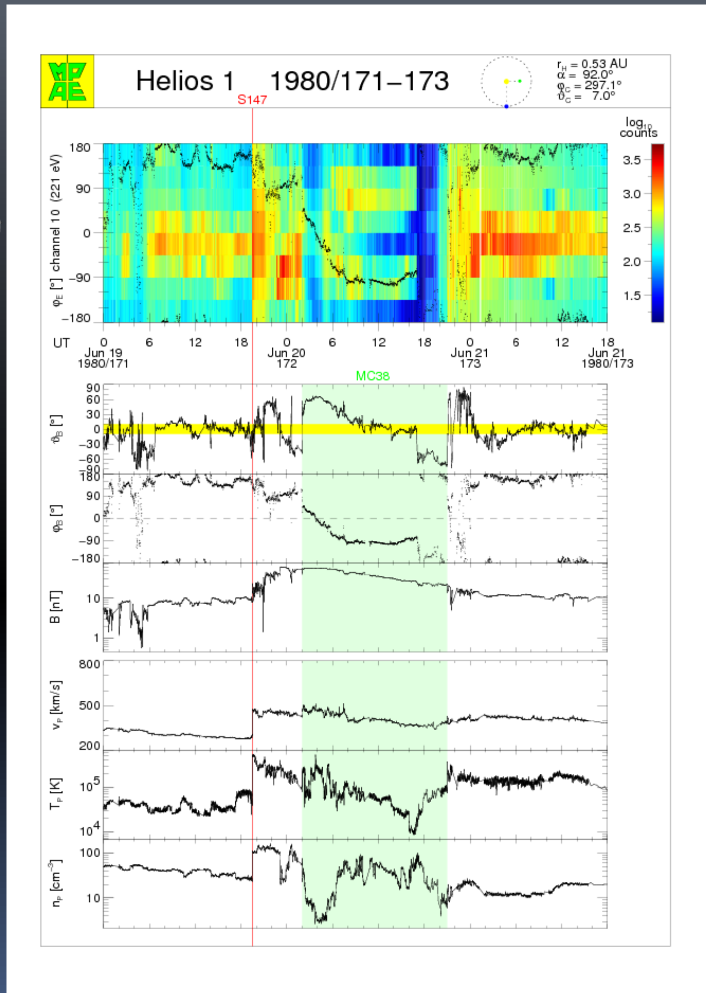
USAF P78-1 (Solwind 1979-1985)

Same characteristics as OSO-7

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

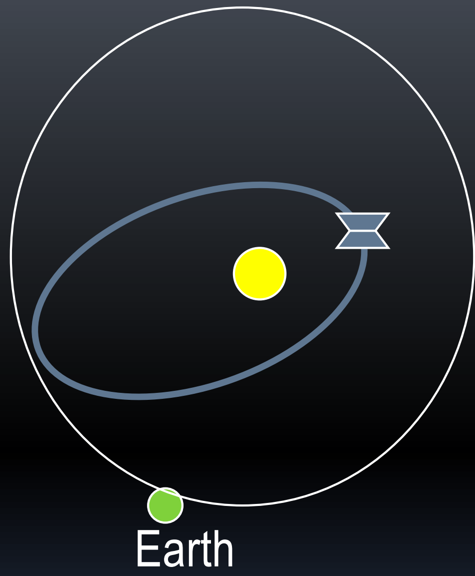


Solwind Coronagraph on board
P78-1 (1979-1985)



Burlaga: Magnetic Clouds

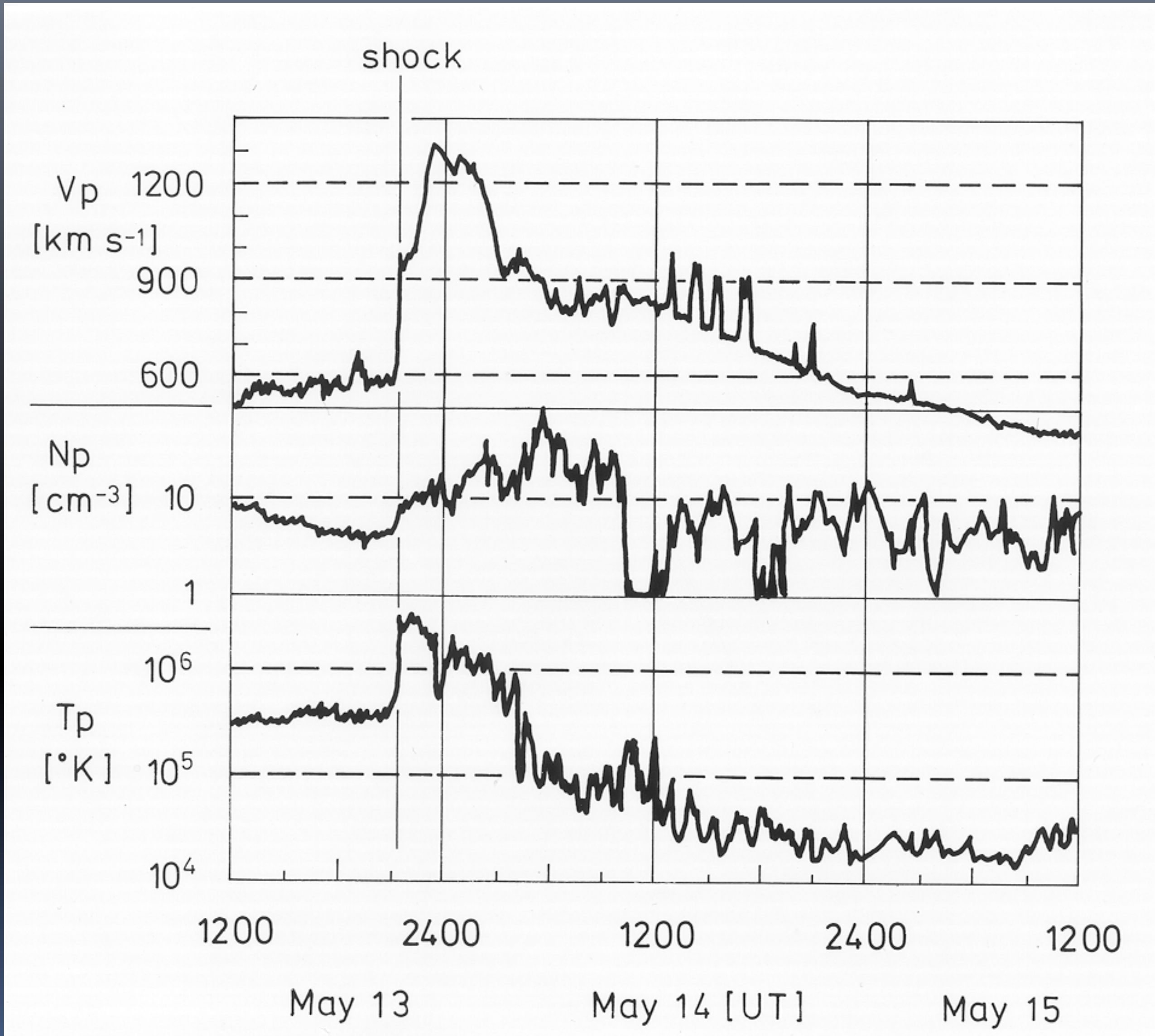
Helios-Orbit: 0.29 – 1 AU



The Helios 1 & 2 Spacecraft

(1974-1986)

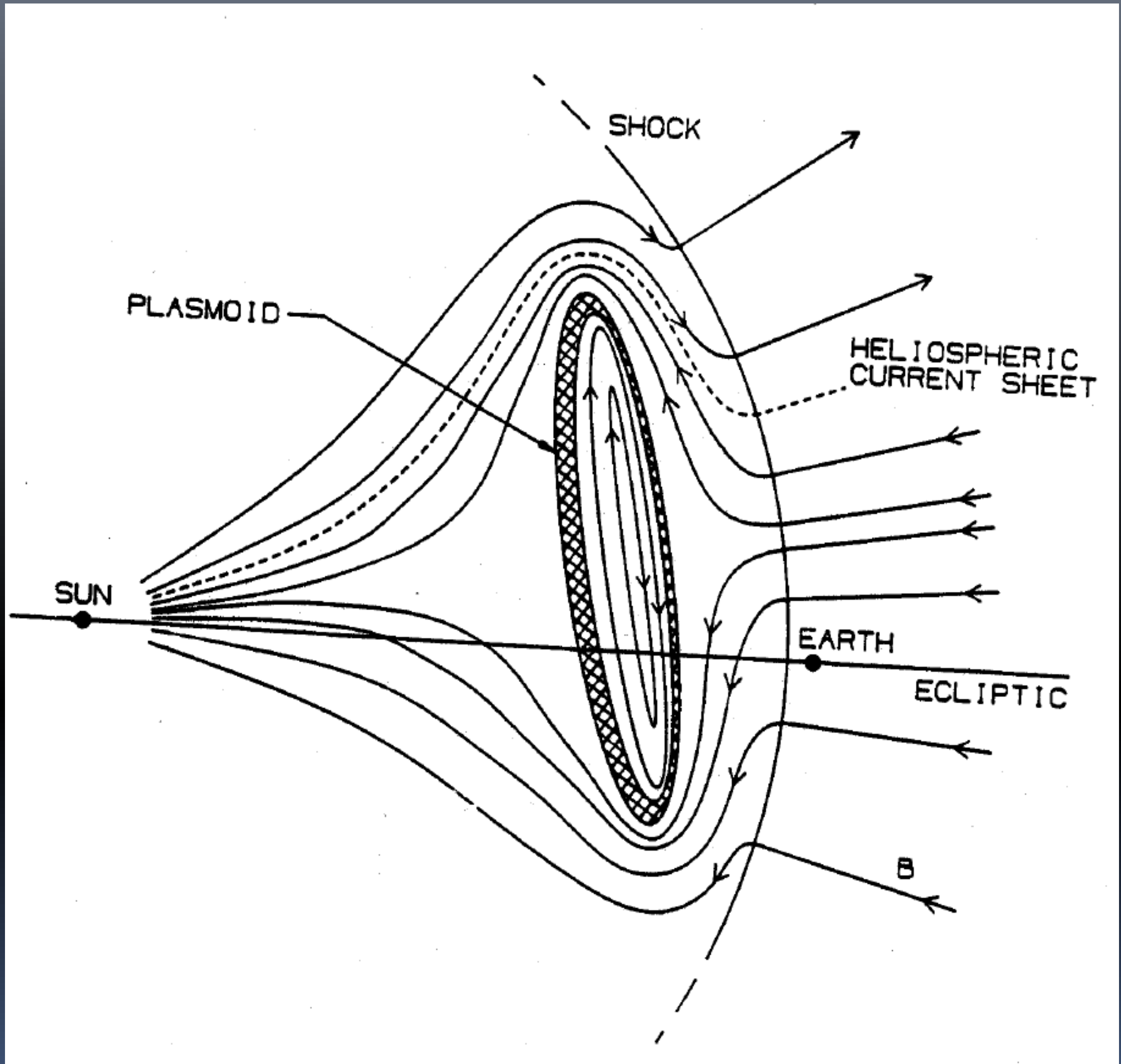
Fast Interplanetary Shock detected by Helios 1 in 1978



<u>All Helios 1 directed CMEs</u> with v>400 km/s in the FOV of the Solwind Coronagraph caused a Shock at Helios 1

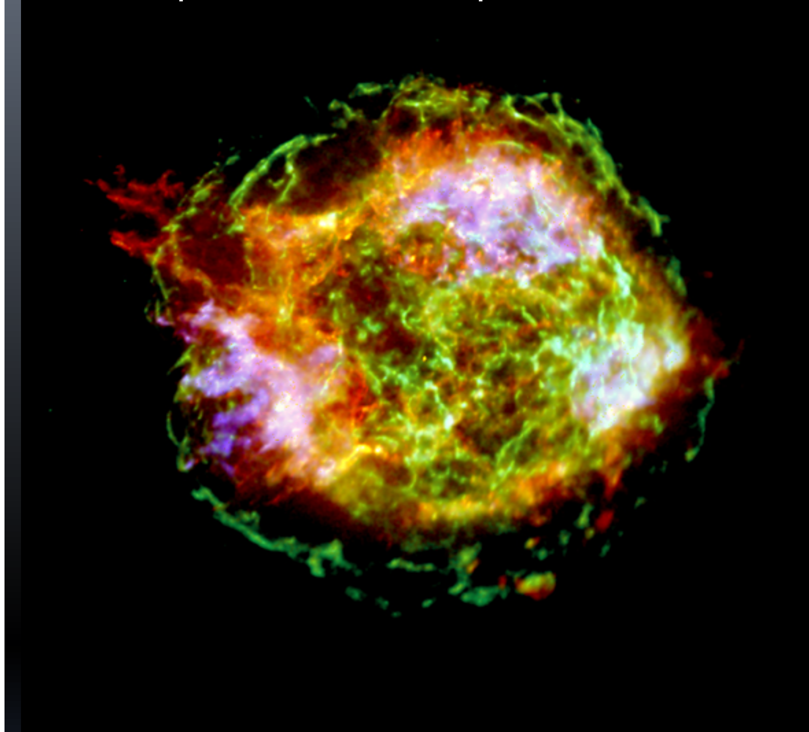
72% of shocks assoc. with Solwind CMEs

Fast Coronal Mass Ejections Drive Shock Waves



Gosling, 1993

Supernovae Cassiopeia A



Chandra Observations: The bright outer ring green) ten light years in diameter marks the location of a shock wave generated by the supernova explosion. The colors represent different ranges of X-rays.

CME Properties

- Mass: ~$10^{12\text{-}14}$ kg
- Speed: few hundred - 3000km/s

..or

- Mass: ~1 million Nimitz-class aircraft carriers
- Speed: 1.5 -10 million km/hour

Earth?

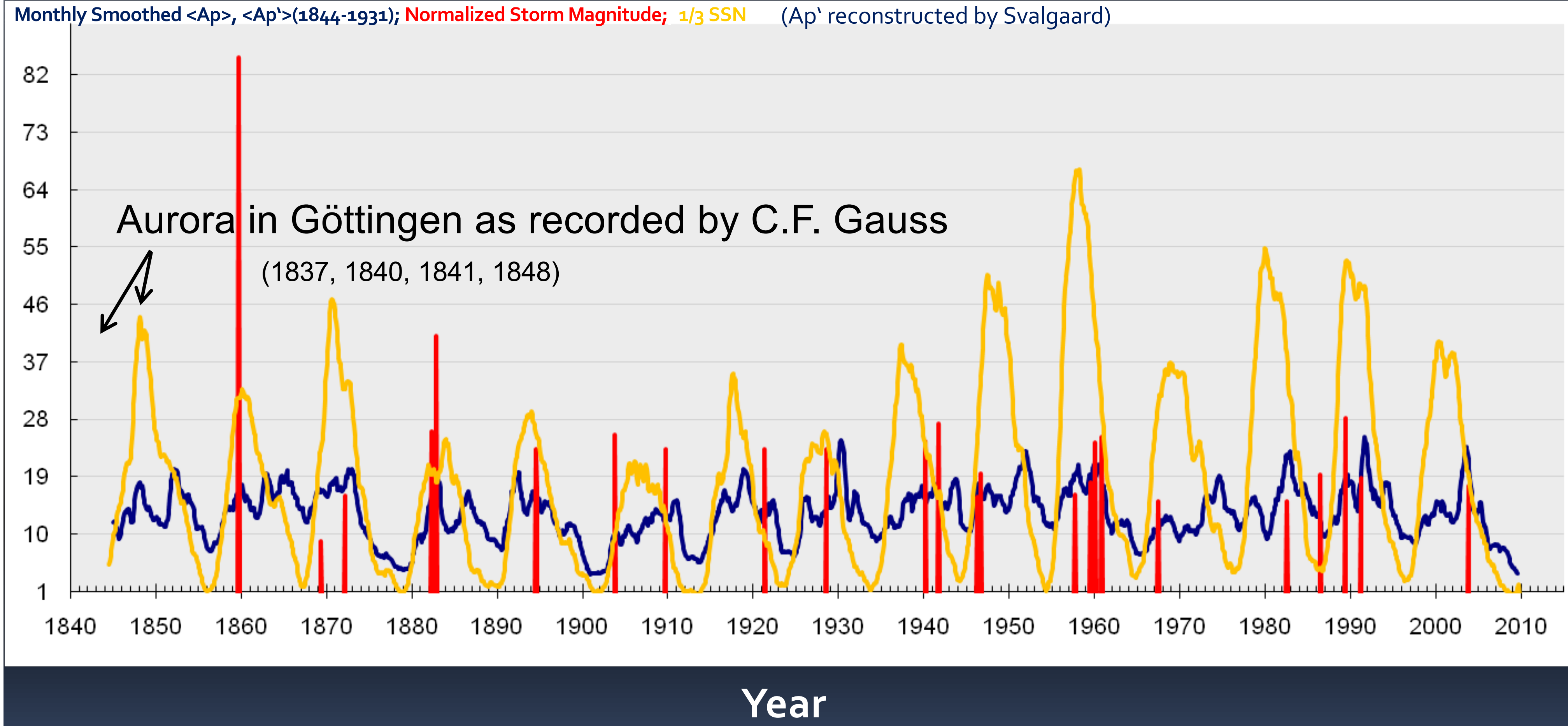
- Arrives to Earth in 1-4 days

SWx impacts of CME

- Contribute to SEP (particle radiation): 20-30 minutes from the occurrence of the CME/flare
- Result in a geomagnetic storm: after 1-4 days
- Result in electron radiation enhancement in the near-Earth space: takes 2-5 days

Affecting spacecraft electronics (surface charging/internal charging), radio communication, navigation, power grids, pipelines, etc

Magnetic Activity, Superstorms (∑ap>1500) and Sunspots 1844-2010



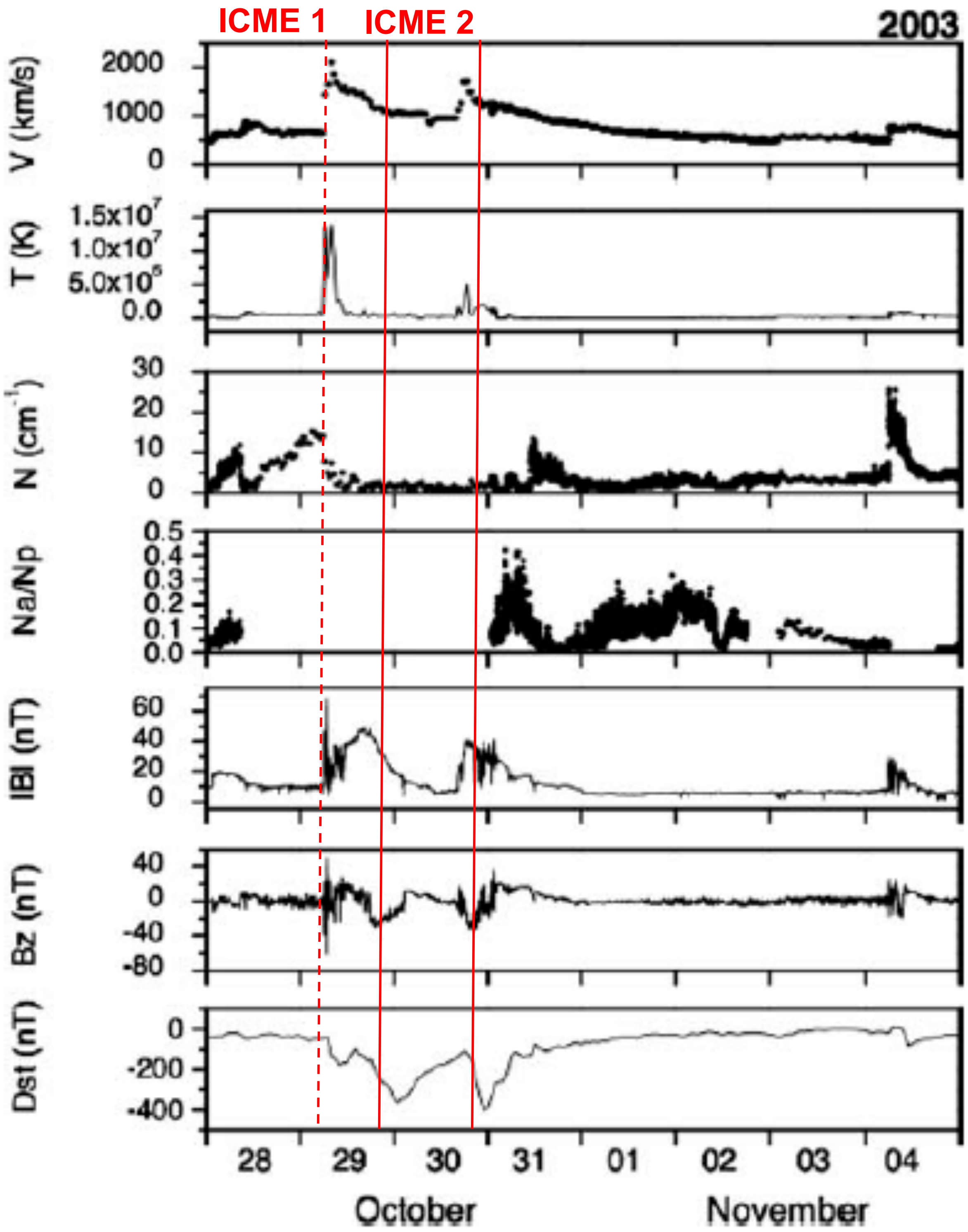
Analysis of more than 30 years of solar wind data reveals that storms with Kp ≥ 8- are almost solely caused by CMEs, i.e. - aurora at lower latitudes is caused by CMEs (Bothmer and Schwenn, 1995)

Geoeffective CMEs

The case of consecutive CMEs

Bothmer and Schwenn (1995):

The strongest geospace magnetic storms are caused by multiple ICMEs



The October 2003 CMEs

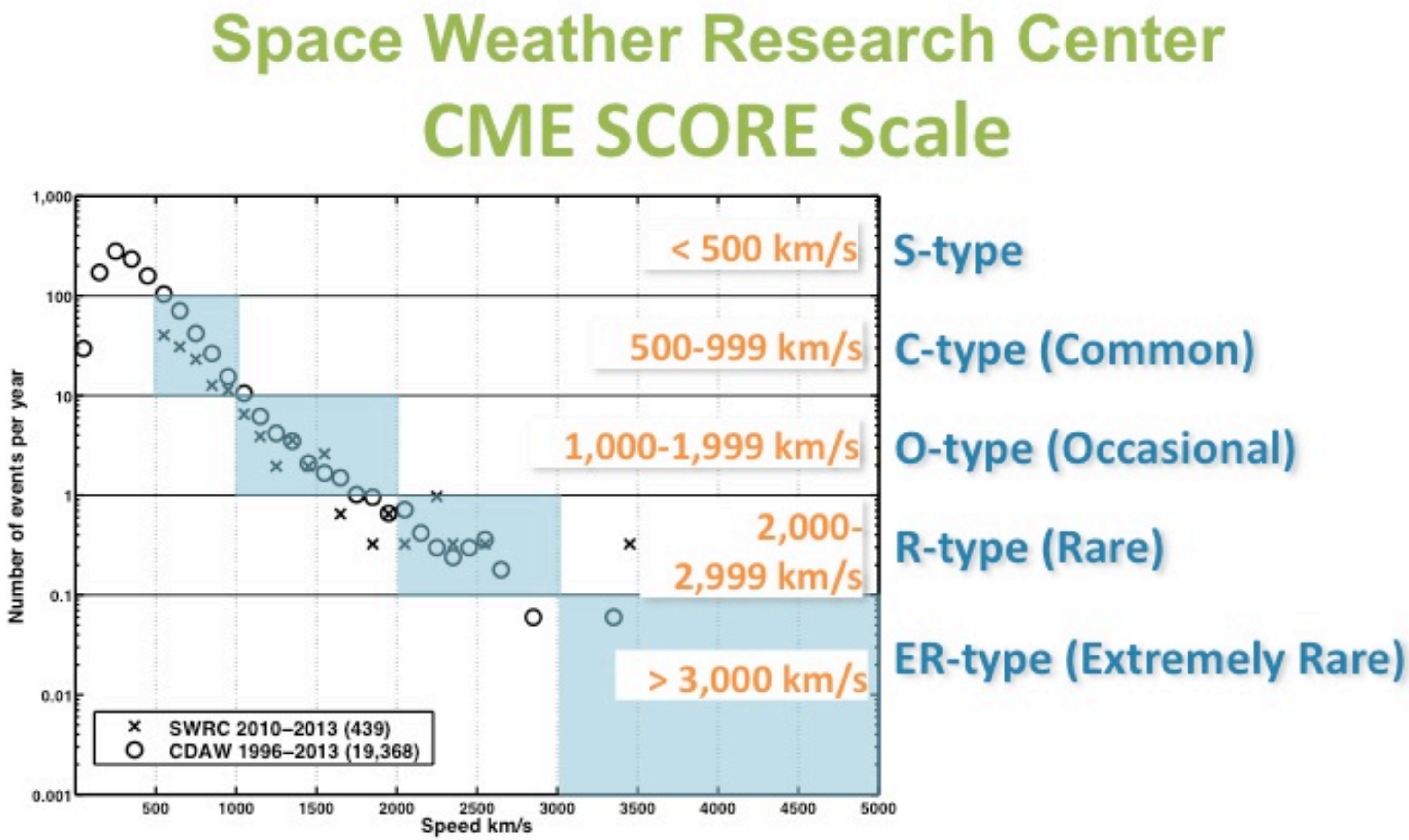
Three important phases:

1. Strong shock driven by ICME 1
2. –Bz in trailing portion of ICME 1
3. -Bz in compressed leading edge of ICME 2

Bothmer and Schwenn (1995): The strongest storms are caused by multiple ICMEs

CME SCORE

- A simple new category system for CMEs based on frequency of detection and **speed**
- Complements Flare Classes
- Applicable in space weather operations and research



Characteristics of CMEs in the Solar Wind

Signature	Sample References
Helium Enrichment	*Hirshberg et al., 1970*
Unusual Ion and Electron Temperature	*Gosling et al., 1973; Klein & Burlaga, 1982*
Unusual Ionisation States (e.g., He^{+}, Fe^{16+})	*Schwenn et al., 1980*
High Magnetic Field Strength	*Hirshberg & Colburn, 1969; Klein & Burlaga, 1982*
Low Magnetic Field Variance	*Pudovkin et al., 1979*
Smooth Rotation of the Magnetic Field Vector (Magnetic Cloud)	*Klein & Burlaga, 1982; Bothmer & Rust, 1997; Bothmer & Schwenn, 1998*
Bi-directional Suprathermal Electron Fluxes (E > 40 eV)	*Gosling, 1990; 1993*
Bi-directional Ion Fluxes	*Marsden et al., 1981*

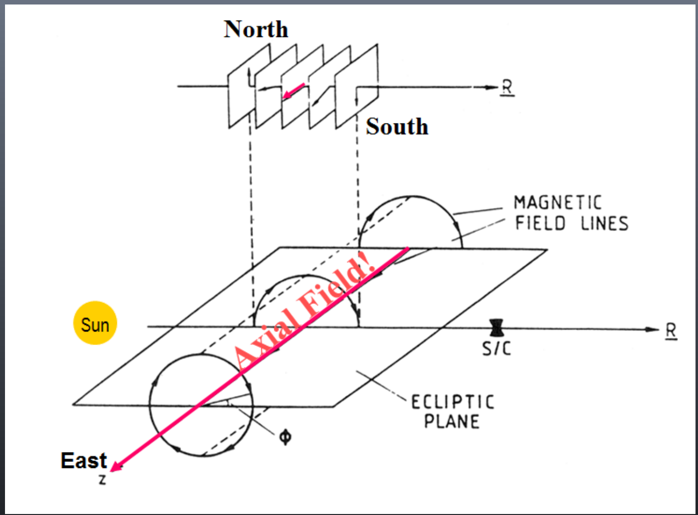
Basic Characteristics

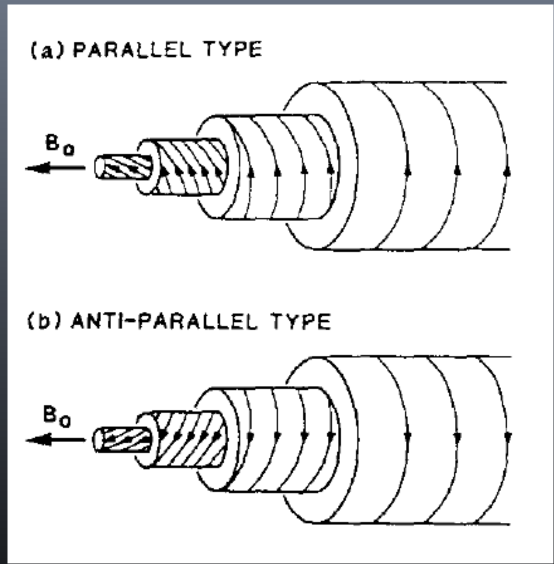
Table 3.4. Basic characteristics of CMEs.

Speed	<300–>3000 km/s
Mass	5×10^{12}–5×10^{13} kg
Kinetic energy	10^{23}–10^{24} J
Angular width	$\sim 24°$–$72°$
Occurrence frequency	~ 1–~ 4 (sol. min.–sol. max.)

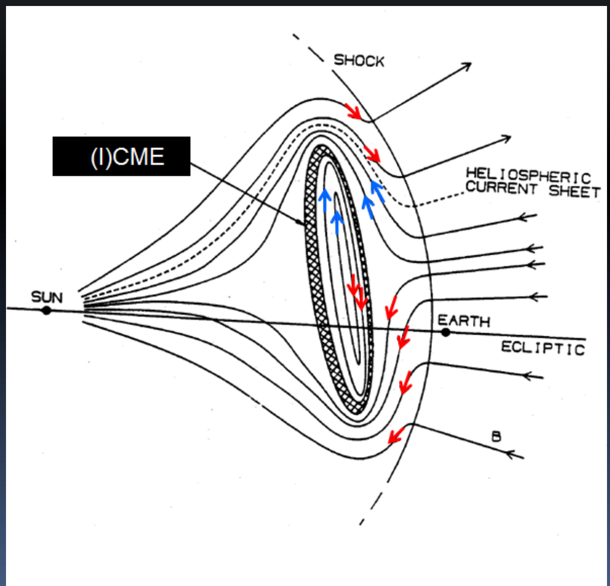
From Bothmer (2006).

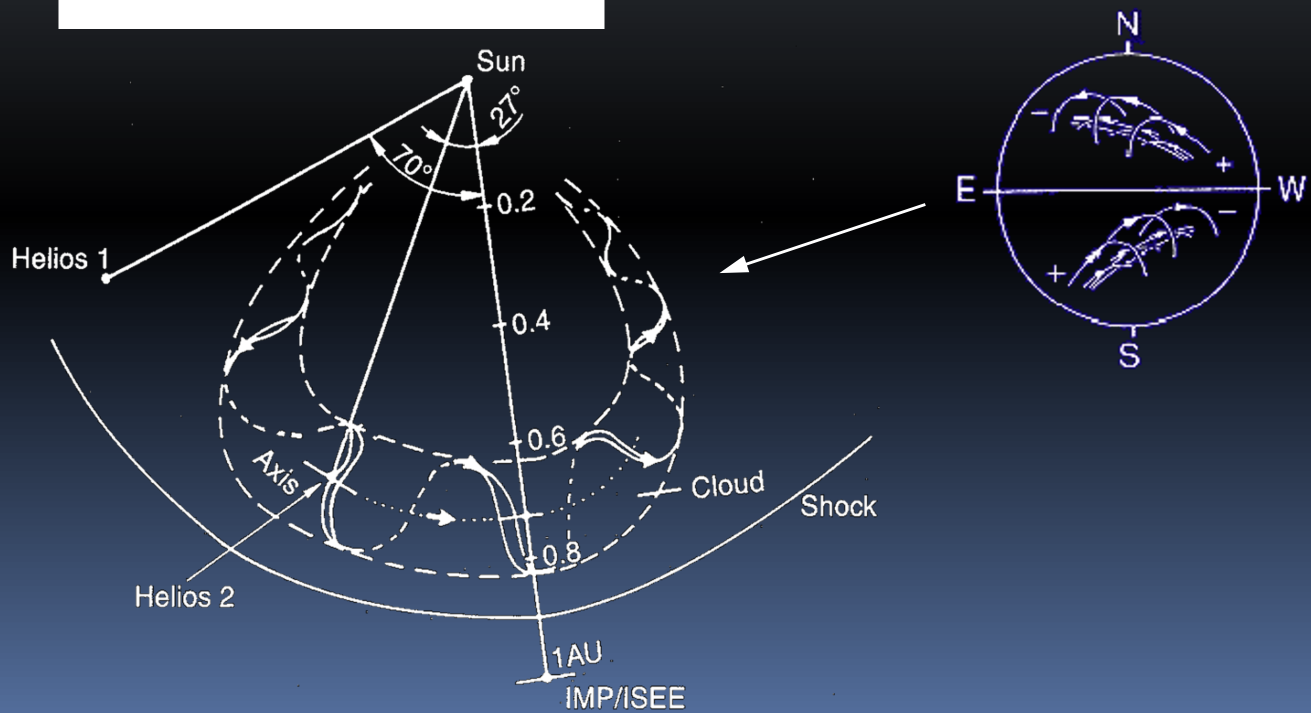
1983: ερμηνεία των CMEs ως σωλήνων μαγνητικής ροής ή μαγνητικών σχοινιών (Magnetic Flux Ropes)





Goldstein, Marubashi, Bothmer & Schwenn, Lepping: Cylindrical Flux Ropes





Gosling, AGU Geophys. Monogr. 1990

Σωλήνας μαγνητικής ροής:

κυλινδρική δομή που αποτελείται

από μαγνητικό πεδίο

που συνήθως είναι **συνεστραμμένο**

γύρω από τον άξονα του κυλίνδρου,

σαν ένα καραβόσχοινο.

Σωλήνας μαγνητικής ροής:

κυλινδρική δομή που αποτελείται

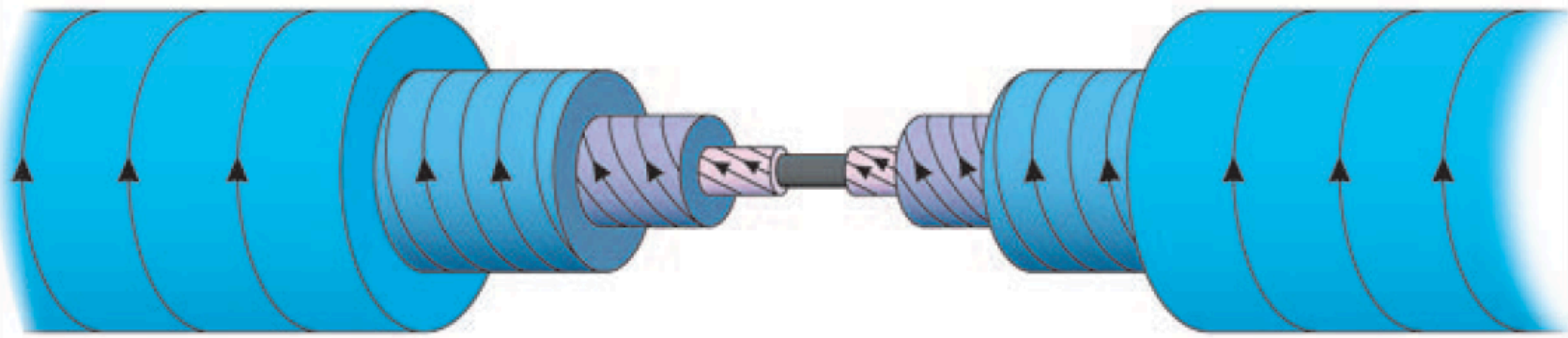
από μαγνητικό πεδίο

που συνήθως είναι **συνεστραμμένο**

γύρω από τον άξονα του κυλίνδρου,

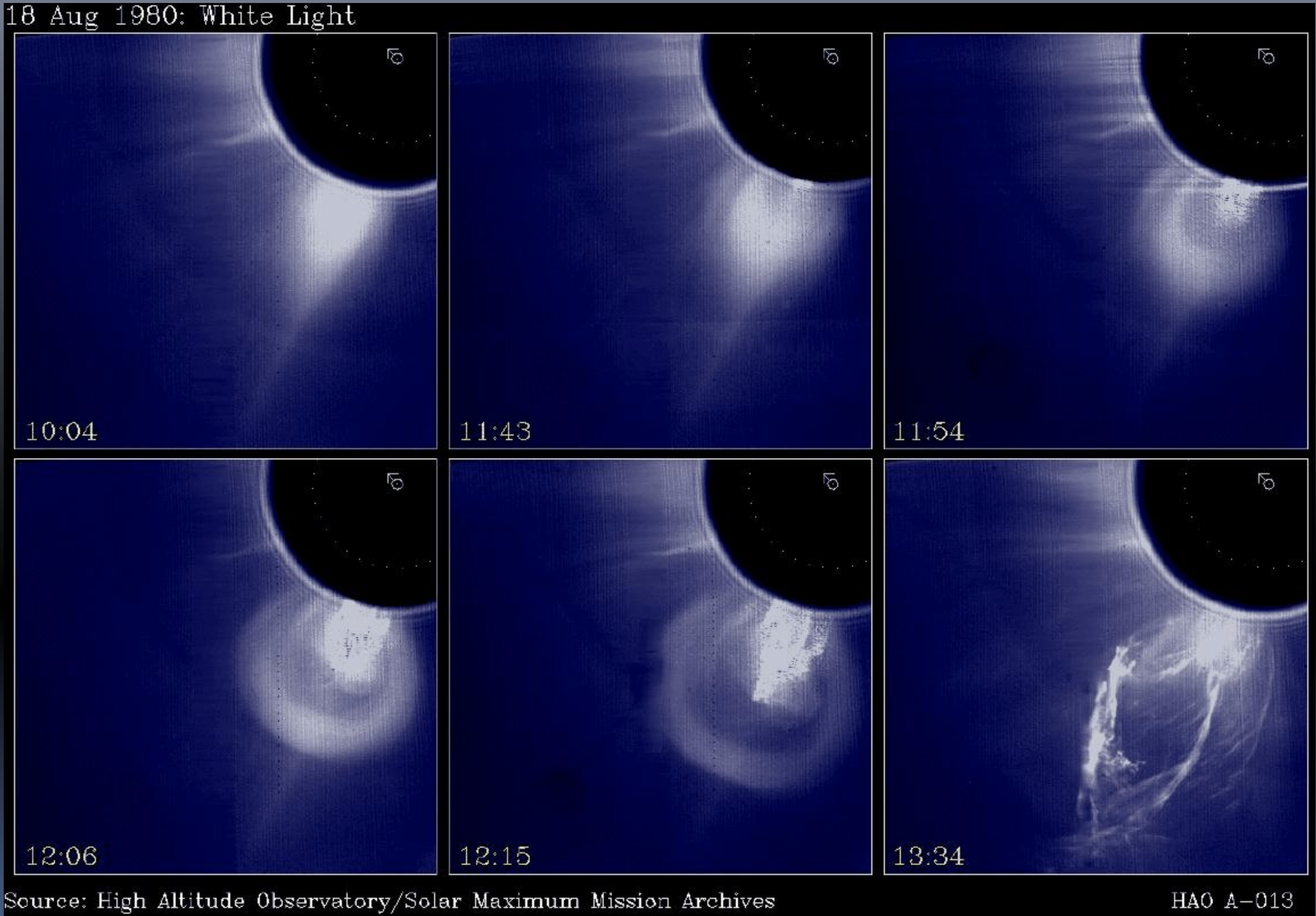
σαν ένα καραβόσχοινο.

Σωλήνας μαγνητικής ροής:
κυλινδρική δομή που αποτελείται
από μαγνητικό πεδίο
που συνήθως είναι **<u>συνεστραμμένο</u>**
γύρω από τον άξονα του κυλίνδρου,
<u>σαν ένα σχοινί πλοίου</u>.



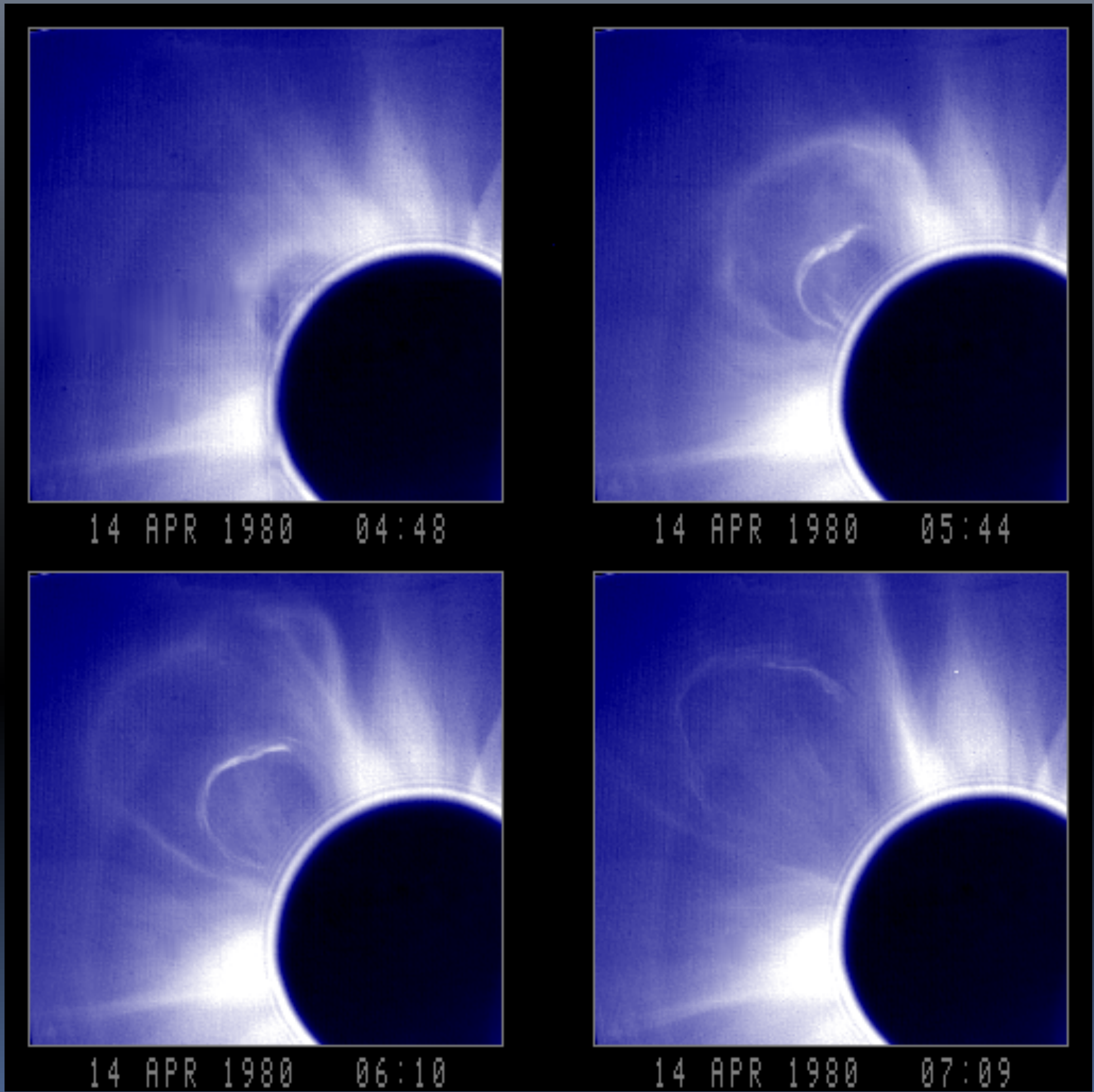
Interior Structure of Flux Rope

1980, 1984-1989: SMM Observations



Hundhausen, 1980

SMM Observations of Three Part Structured CMEs



Hundhausen, 1980

NASA Solar Maximum Mission (SMM) (1980, 1984-1989)

1.6 - 6 solar radii

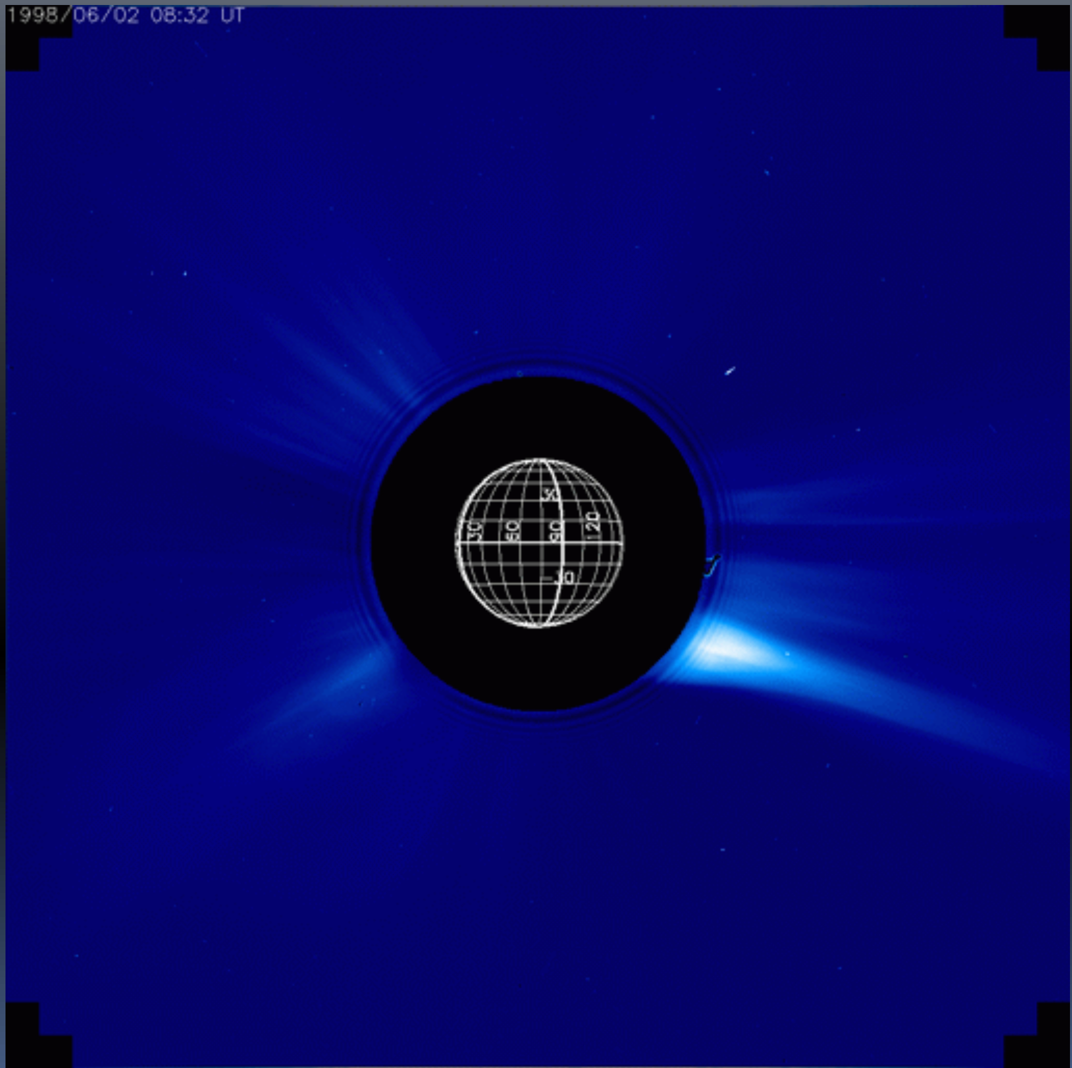
5 cm SEC Vidicon detector, (30 arc second resolution)

CME statistics, 3-part structure to CMEs

Weakness: quadrant field of view, cadence

(Howard, 2006)

Since 1996: SOHO/LASCO Observations of CME Internal Structure



ESA Solar and Heliospheric Observatory - SOHO (1995-)

EIT /LASCO provide wide field of view &dynamic range:

EIT: UV Disk Imager, (2.5 arc sec pixels)

C1: 1.1-3 solar radii (5.6 arc sec pixels)

C2: 2.-7 solar radii (12 arc sec pixels)

C3: 4-32 solar radii (60 arc sec pixels)

CCD Imagers (1024 x 1024)

Initiation of CME, Helical flux rope model, shocks and CMEs, geomagnetic effects

Weakness: Cadence, single viewpoint

(Howard, 2006)

Near-Sun Evolution of a CME

SOHO/LASCO C2

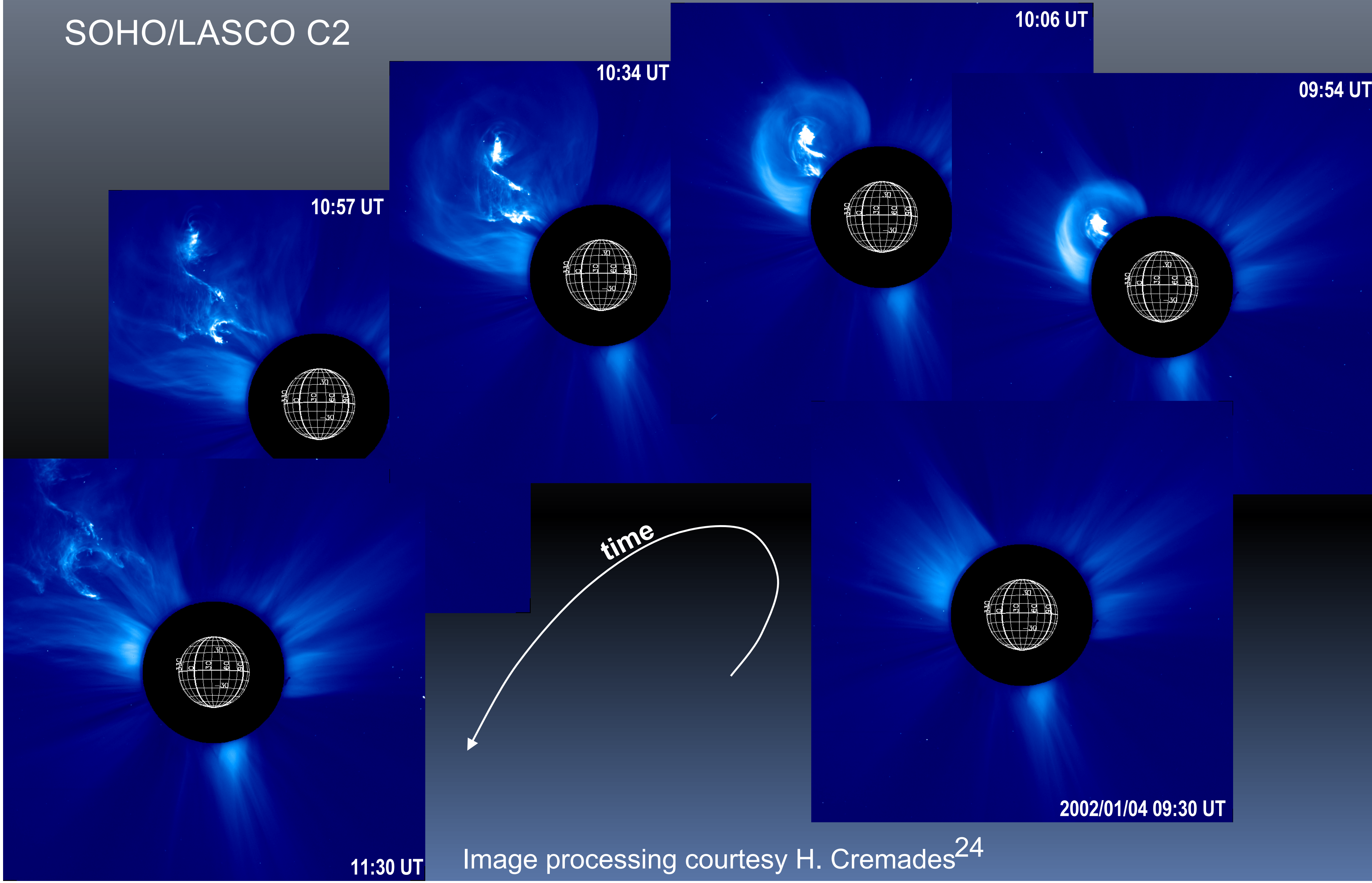
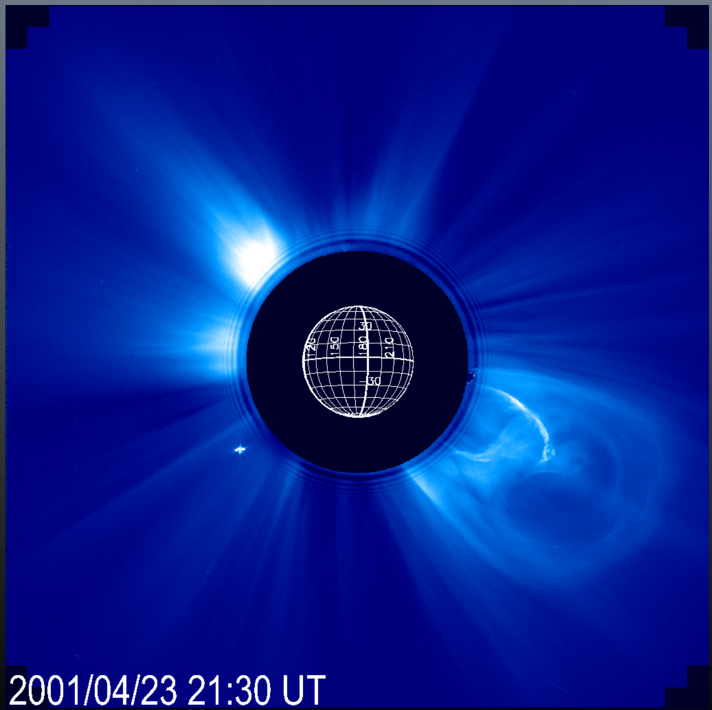
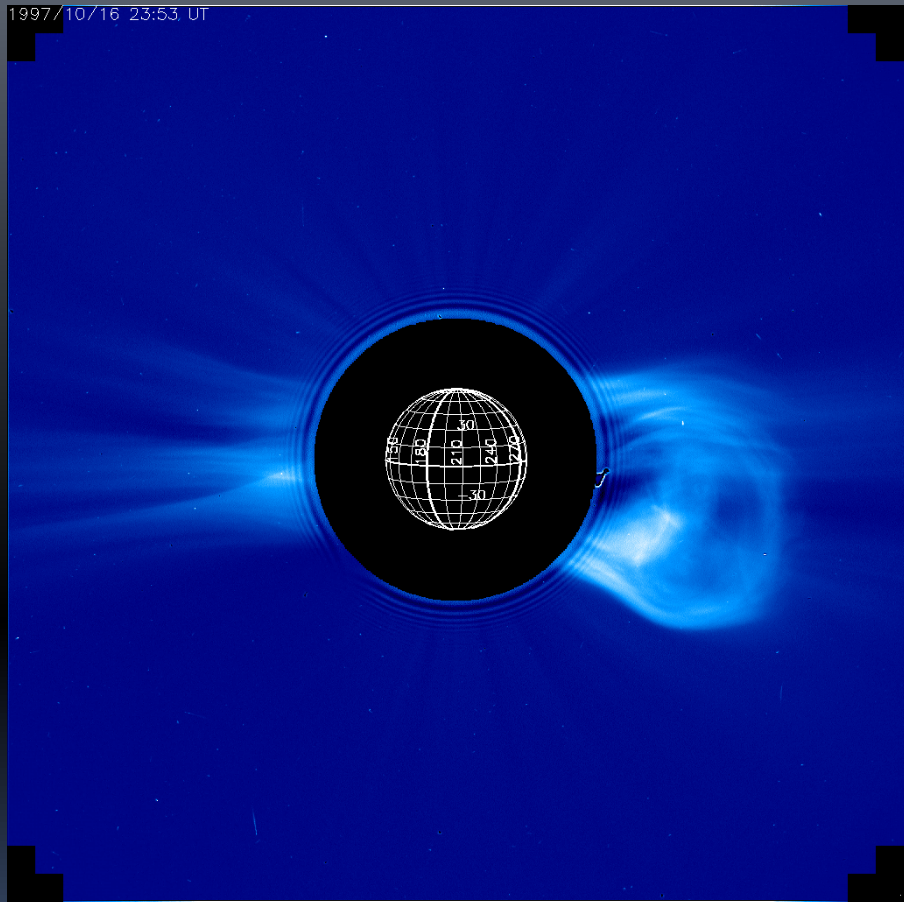
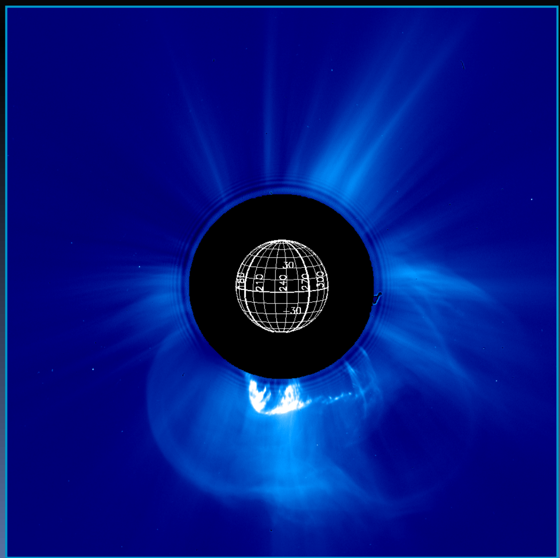


Image processing courtesy H. Cremades

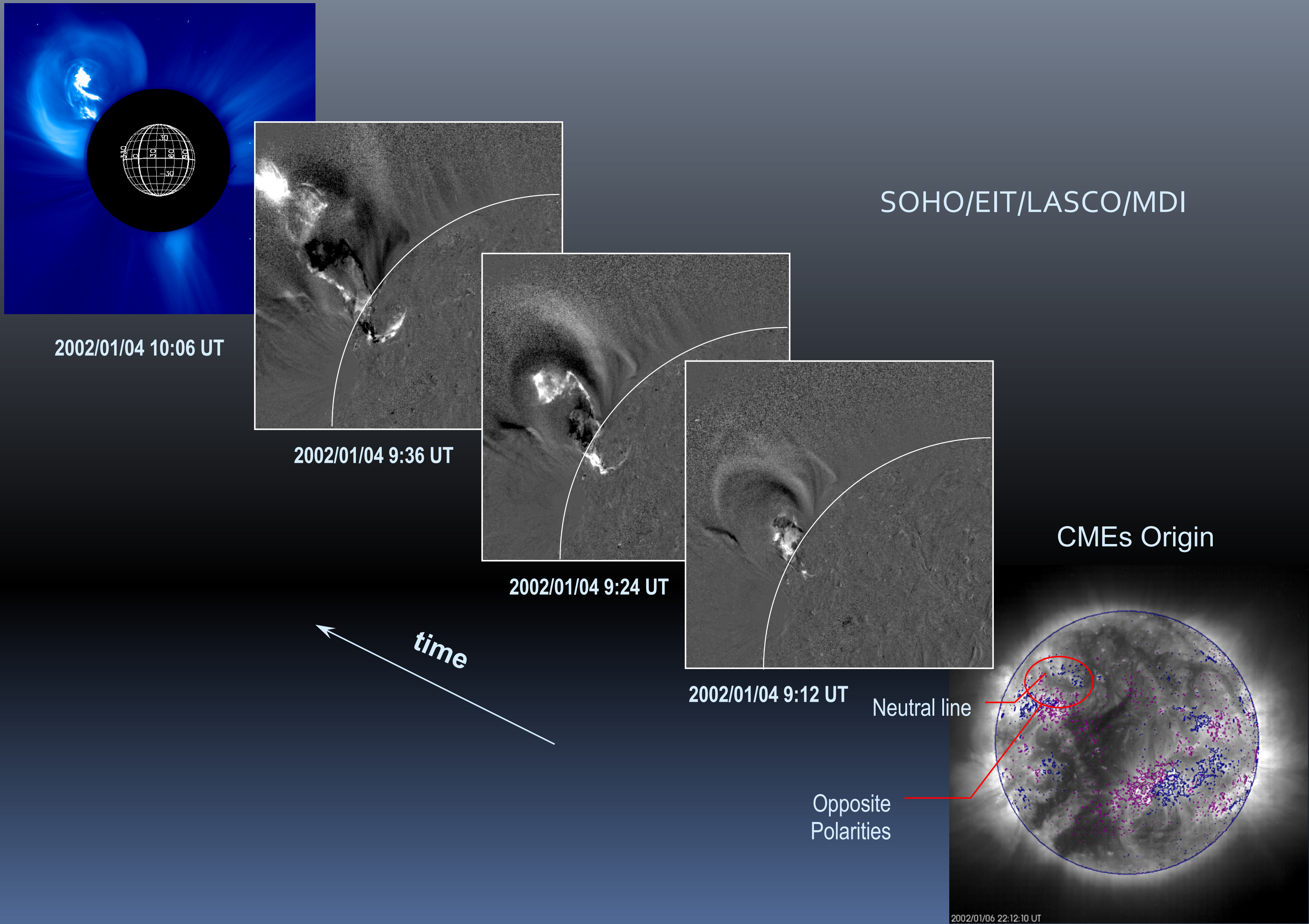
SOHO/LASCO Reveals Flux Rope Structure of CMEs



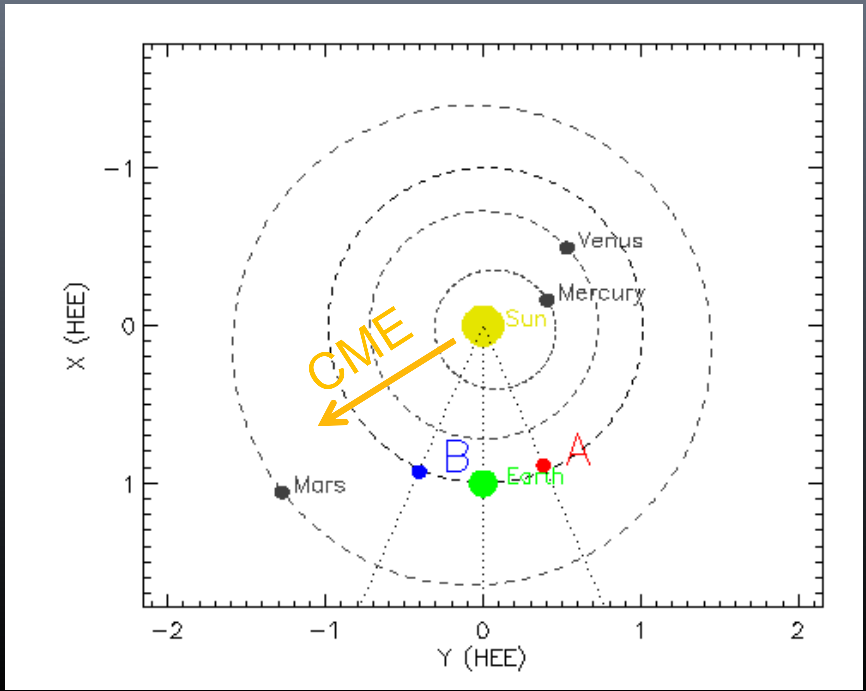




CMEs ξεκινούν από εντοπισμένες διπολικές περιοχές στη φωτόσφαιρα και παρατηρούνται καλύτερα στο χείλος



CME Observation with STEREO B and A - EUVI 171 Å - 47° Angular Separation, 25th March 2008, Δt=75s



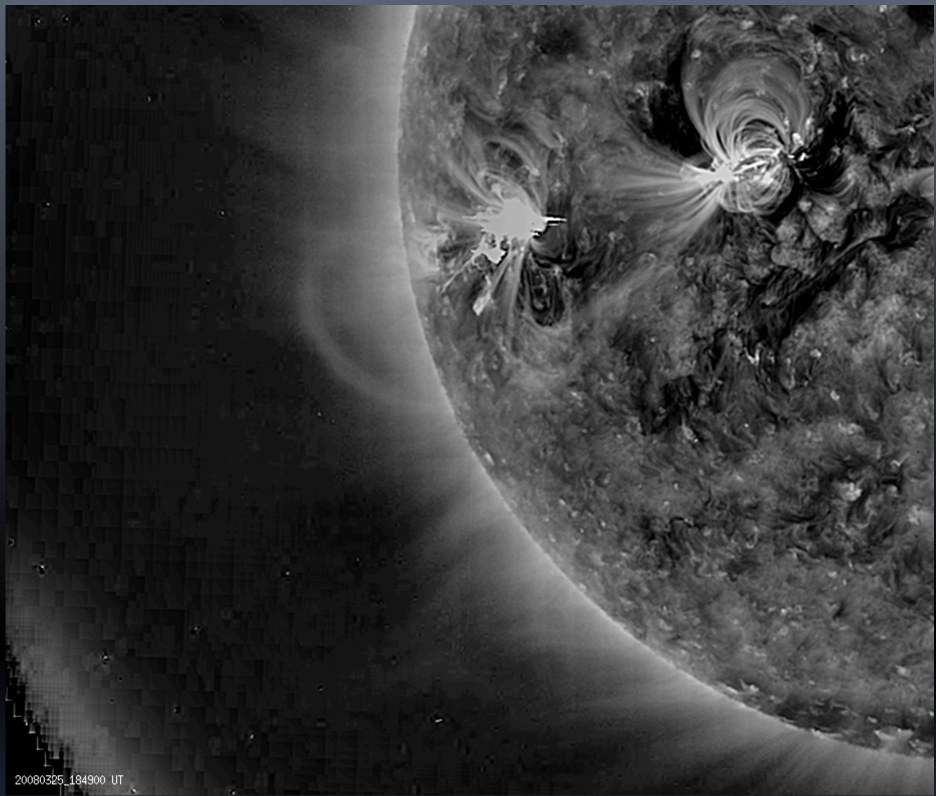
Evolution of CME in less than < 7 min.

Importance of vantage point

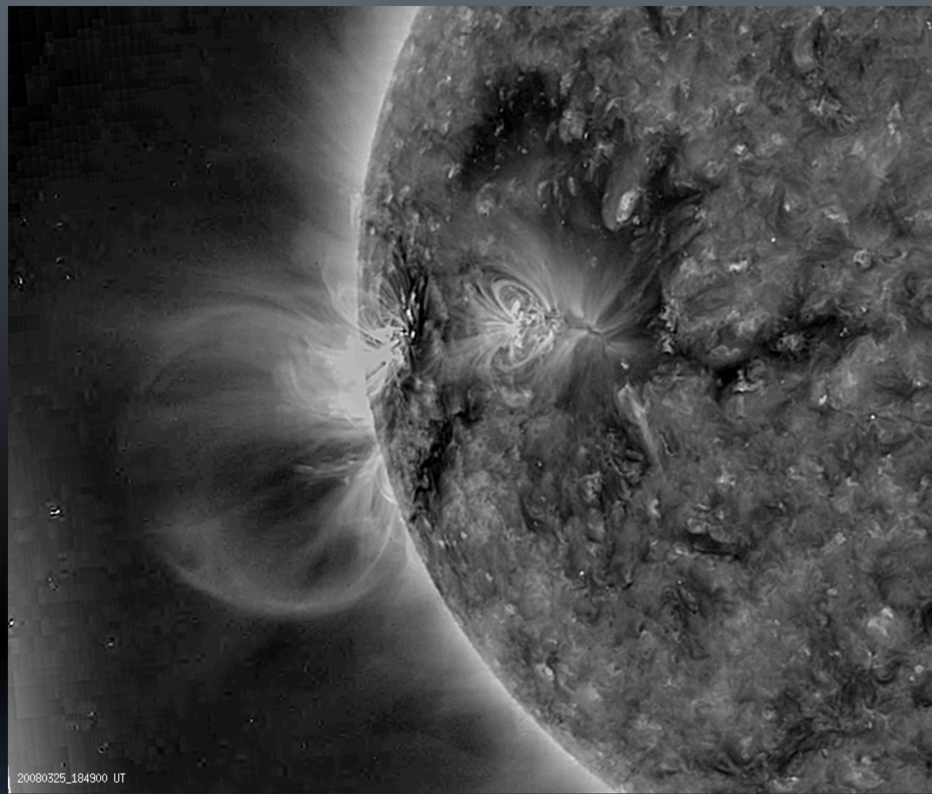
Wavelet Processing:
G. Stenborg, A. Vourlidas, NRL

Simultaneous SECCHI/EUVI A and B Observations, 171 Å, 18:49 UT

B

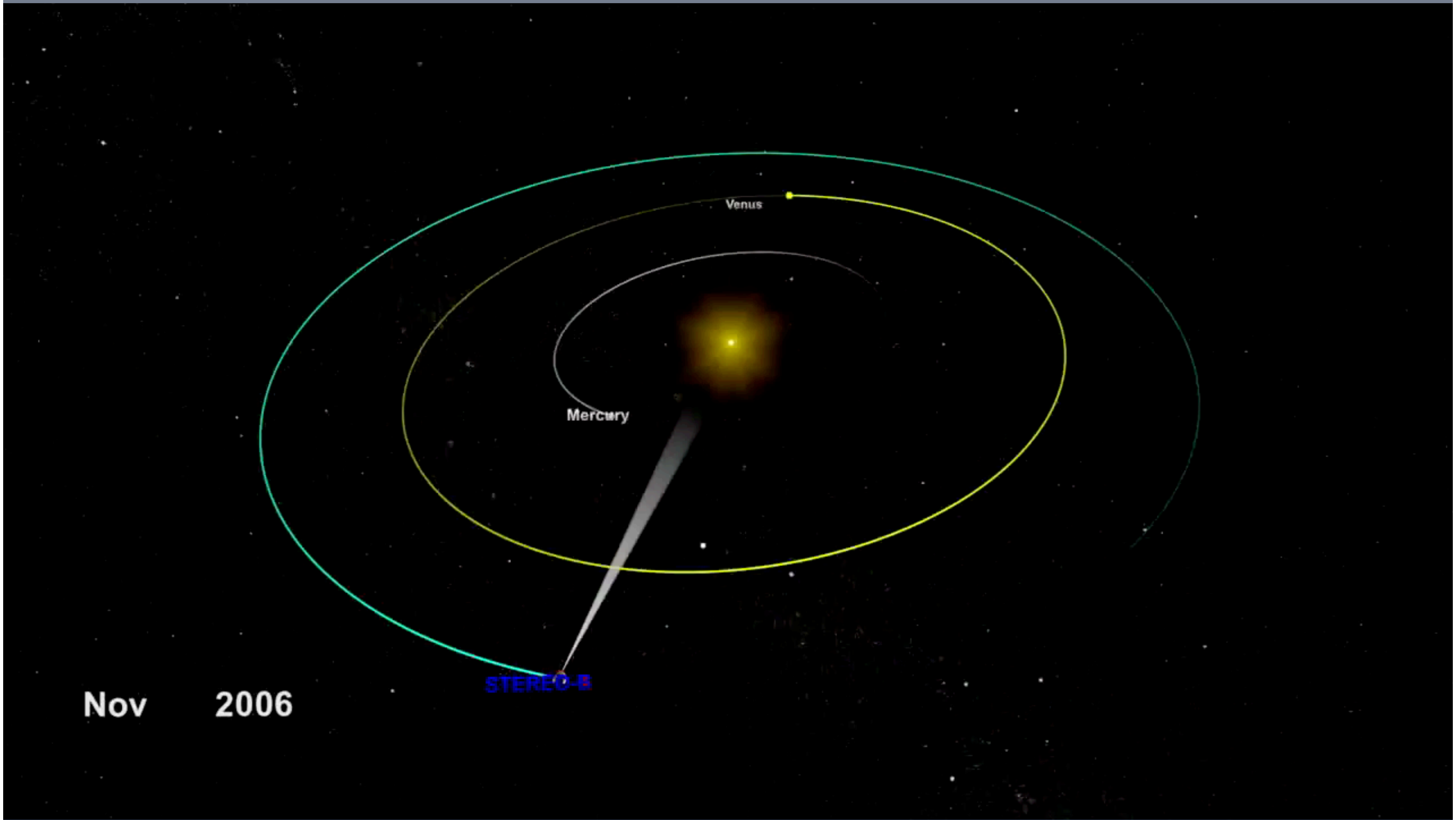


A



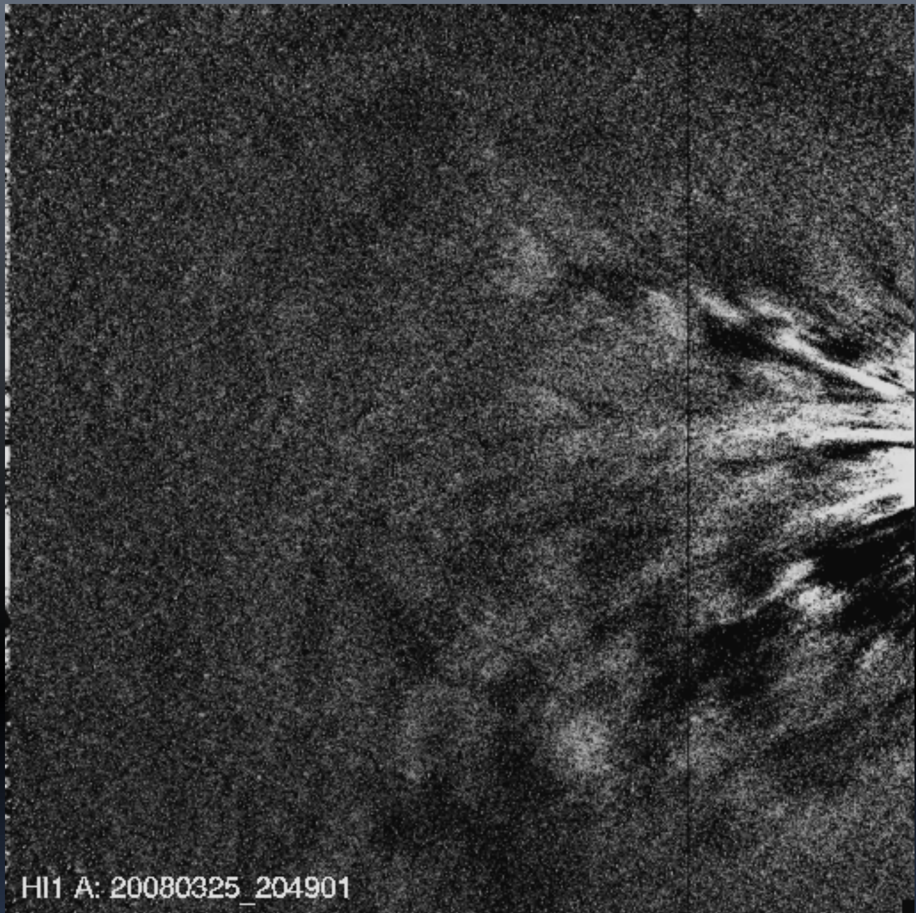
Only STEREO A reveals the CME's Flux Rope Structure

Wavelet Processing: G. Stenborg, A. Vourlidas, NRL

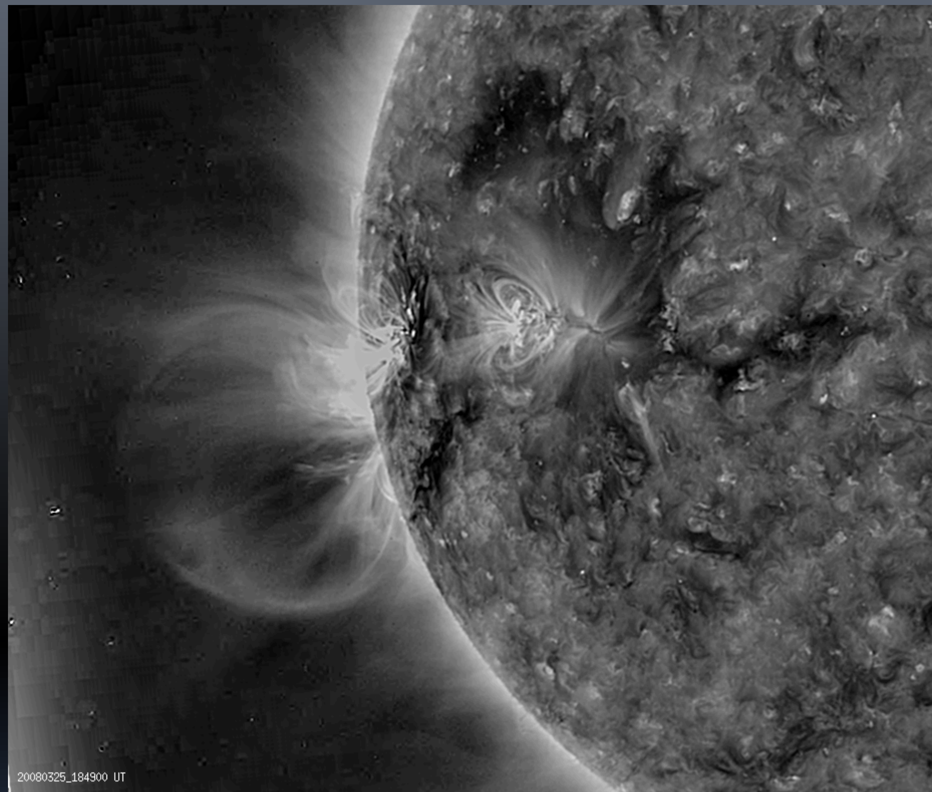

Venus
Mercury
STEREO-B
Nov 2006

Observations of "Selfsimilar Expansion" into the Inner Heliosphere – EUVI A, HI 1 A

HI 1 A



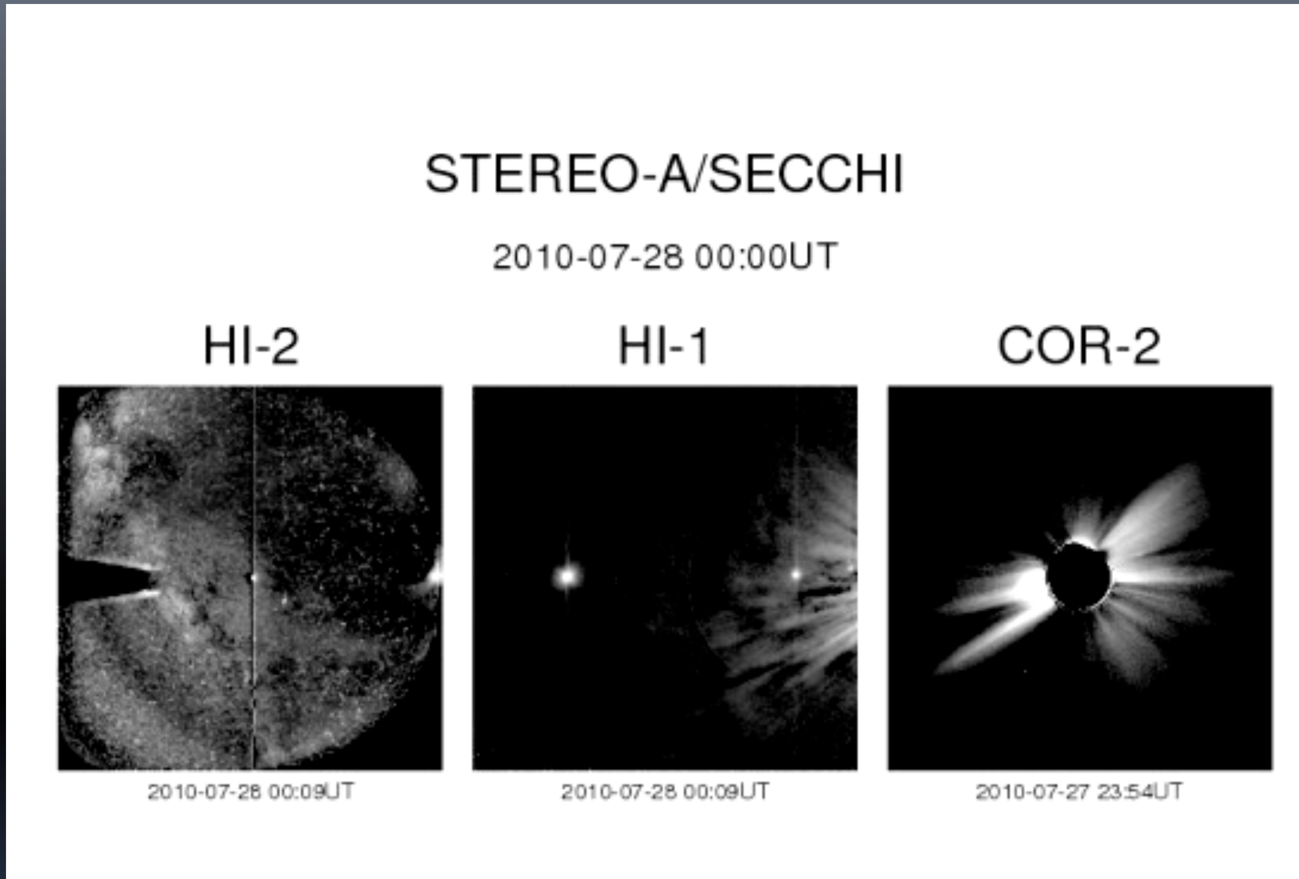
EUVI A



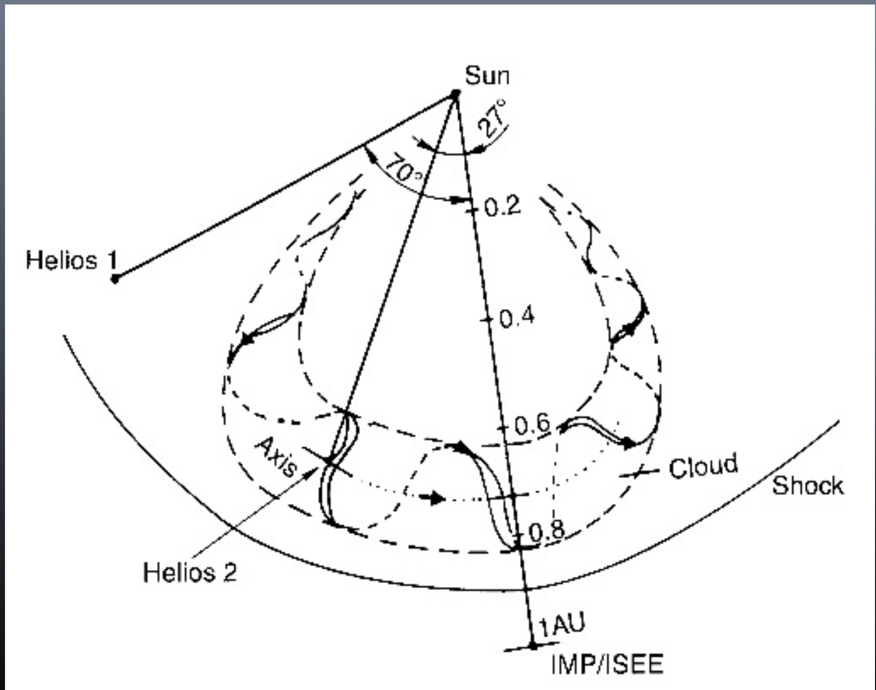
Flux rope structure visible to about 0.8 AU (HI 2 A) !

V_{CME}≈1200 km/s at Sun but only ~600 km/s in HI 1 A -

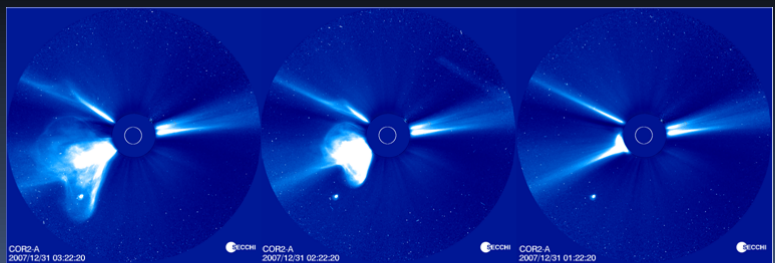
Considerable Deceleration !

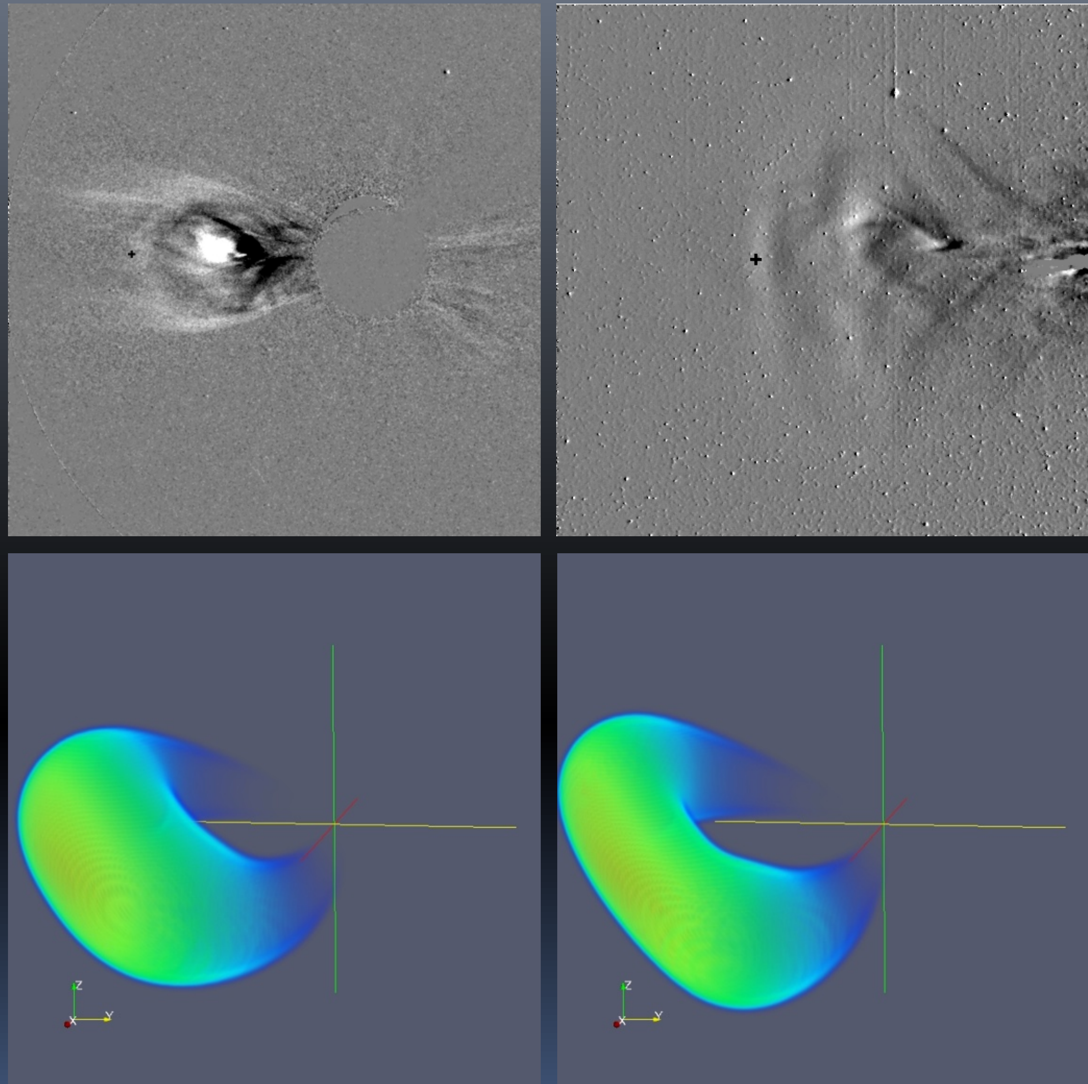

STEREO-A/SECCHI
2010-07-28 00:00UT
HI-2
HI-1
COR-2
2010-07-28 00:09UT
2010-07-28 00:09UT
2010-07-27 23:54UT

Flux Rope Modelling (Wood et al. 2010)



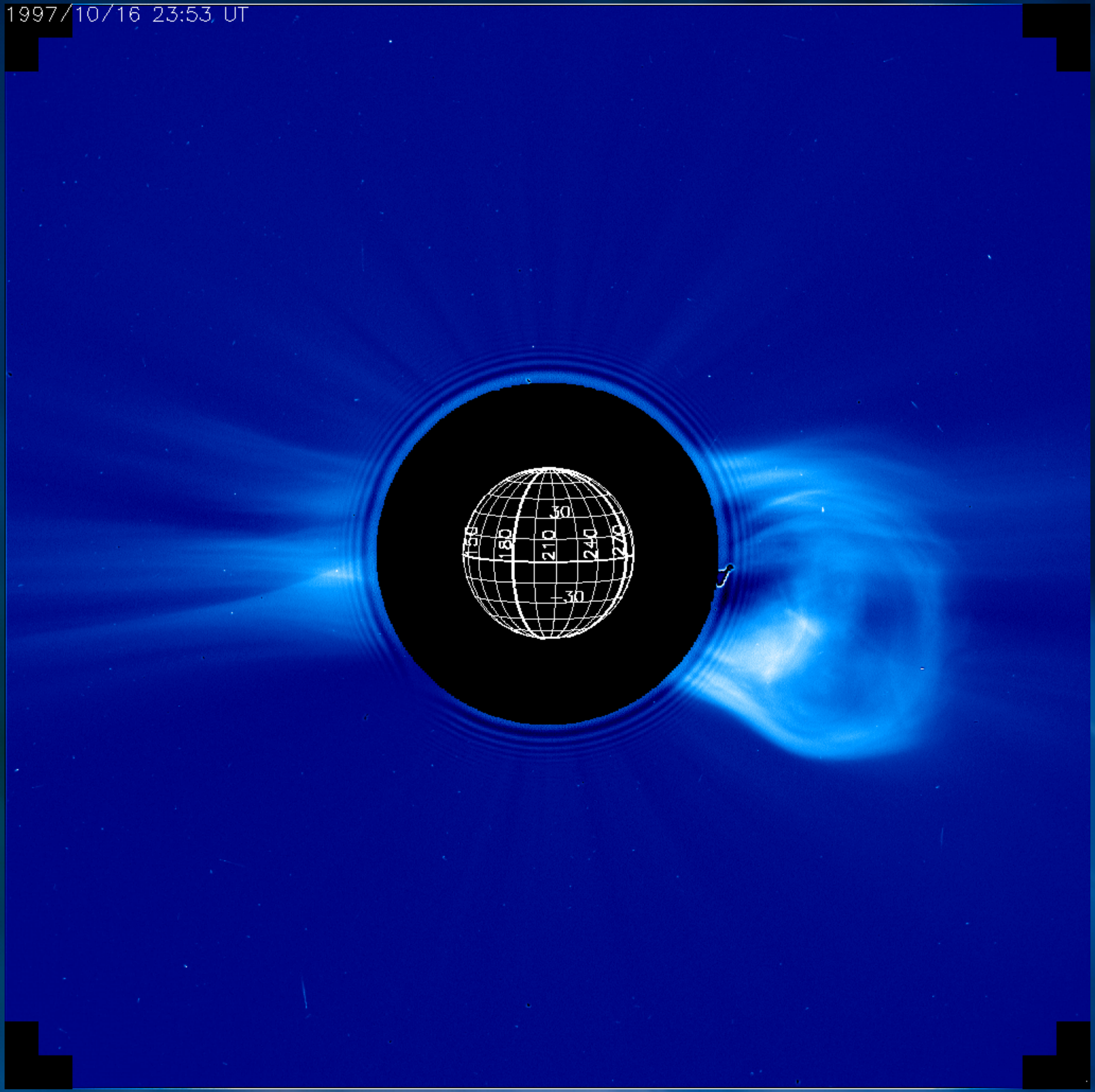
Bothmer und Schwenn, 1998



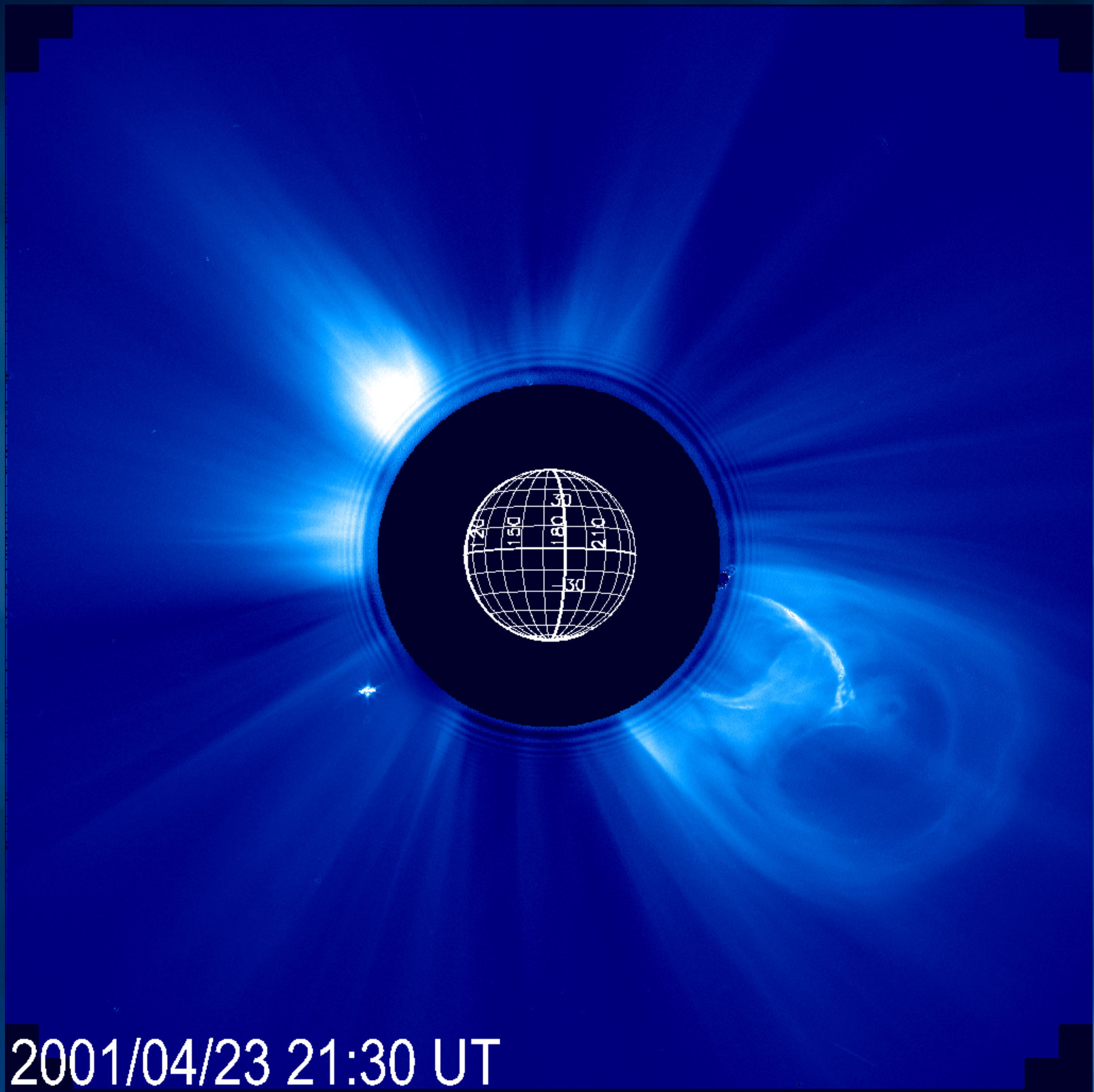


B. Wood, NRL, EGU 2010

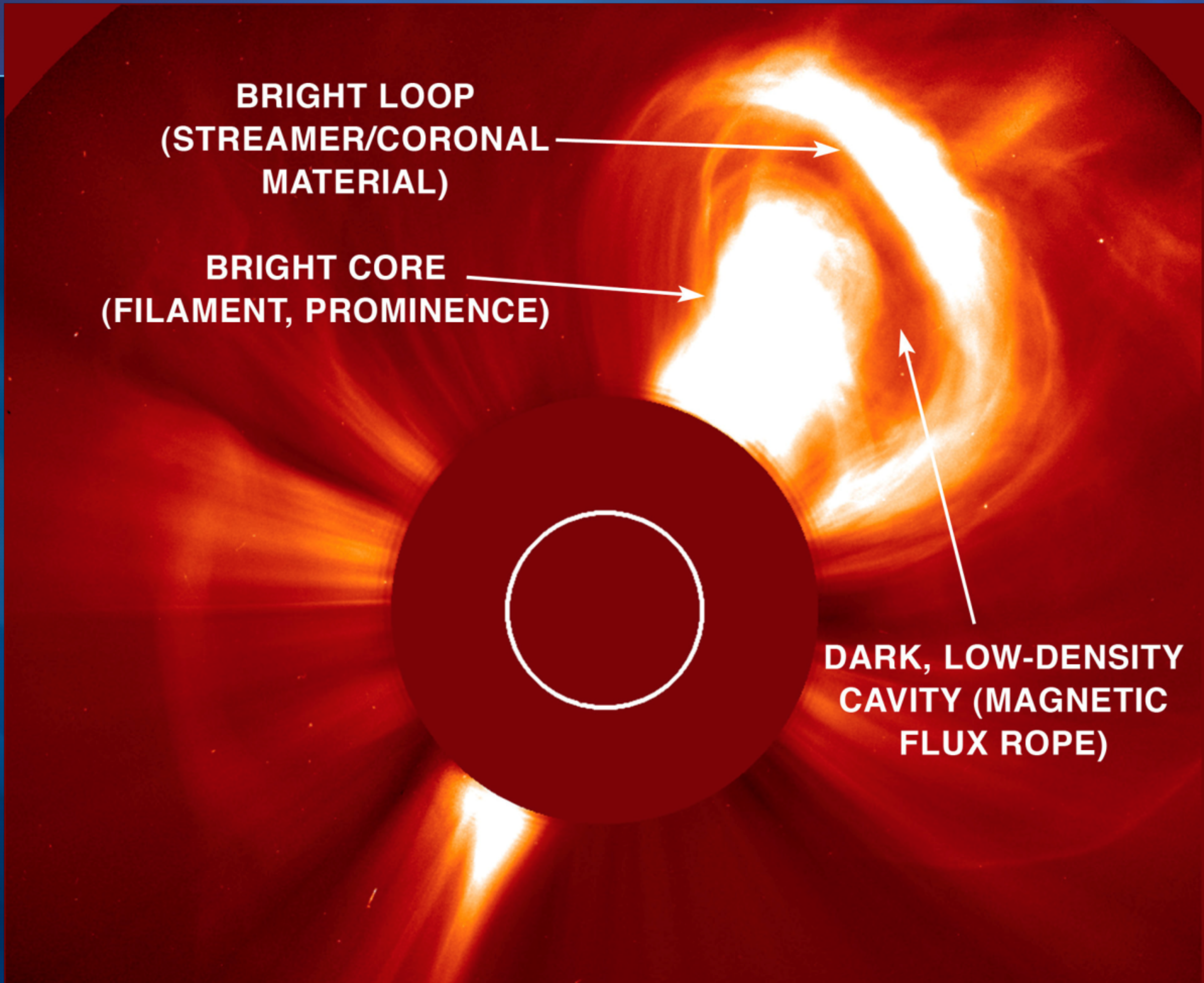
Flux Rope CMEs – Sample 1



Flux Rope CMEs – Sample 2



Cremades & Bothmer, A&A, 2004


BRIGHT LOOP
(STREAMER/CORONAL
MATERIAL)
BRIGHT CORE
(FILAMENT, PROMINENCE)
DARK, LOW-DENSITY
CAVITY (MAGNETIC
FLUX ROPE)

CME eruptions

We studied the pre-eruptive configuration of NOAA 11429 as part of a Sun-to-Earth work (pre-eruptive phase, helicity, eruption, propagation, geomagnetic effects)

THE MAJOR GEOEFFECTIVE SOLAR ERUPTIONS OF 2012 MARCH 7: COMPREHENSIVE SUN-TO-EARTH ANALYSIS

S. Patsourakos[1], M. K. Georgoulis[2], A. Vourlidas[3], A. Nindos[1], T. Sarris[4], G. Anagnostopoulos[4], A. Anastasiadis[5], G. Chintzoglou[6], I. A. Daglis[7], C. Gontikakis[2], N. Hatzigeorgiu[8], A. C. Iliopoulos[4], C. Katsavrias[7], A. Kouloumvakos[1], K. Moraitis[2], T. Nieves-Chinchilla[9], G. Pavlos[4], D. Sarafopoulos[4], P. Syntelis[2,7], C. Tsironis[5,10], K. Tziotziou[2], I. I. Vogiatzis[4], G. Balasis[5], M. Georgiou[7], L. P. Karakatsanis[4], O. E. Malandraki[4,5], C. Papadimitriou[5,7], D. Odstrčil[6], E. G. Pavlos[4], O. Podlachikova[1], I. Sandberg[7], D. L. Turner[11], M. N. Xenakis[4], E. Sarris[4], K. Tsinganos[12,7], and L. Vlahos[10] Hide full author list

Published 2016 January 19 •

The Astrophysical Journal, Volume 817, Number 1

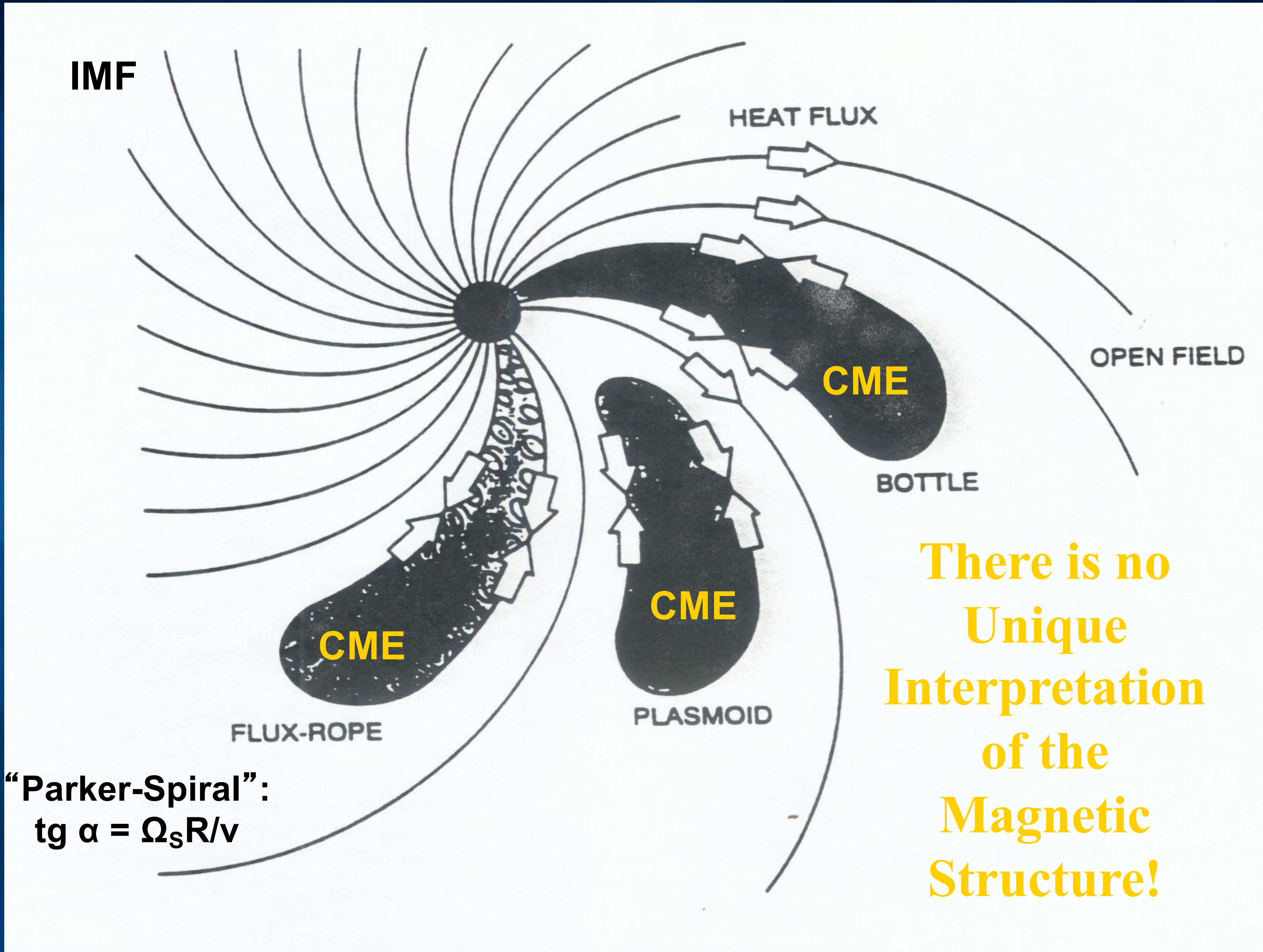
+ Article information

Abstract

During the interval 2012 March 7–11 the geospace experienced a barrage of intense space weather phenomena including the second largest geomagnetic storm of solar cycle 24 so far. Significant ultra-low-frequency wave enhancements and relativistic-electron dropouts in the

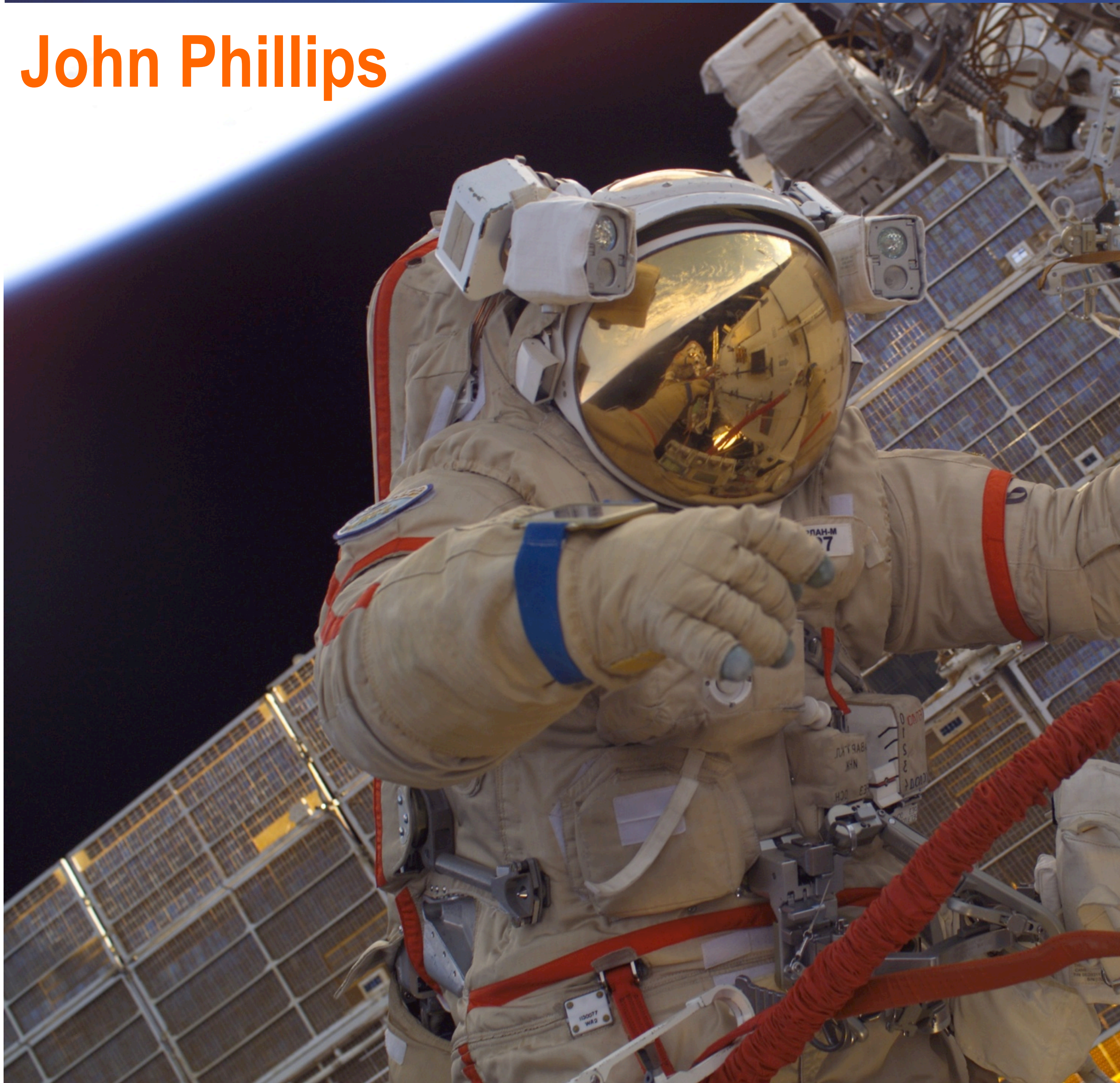
Patsourakos et al. 2016, ApJ 817, 1

Bi-Directional Electron Fluxes as Tracers of the Interplanetary Magnetic Field (IMF) Structure



Phillips et al., Solar Wind 7, 651-656, 1992

John Phillips



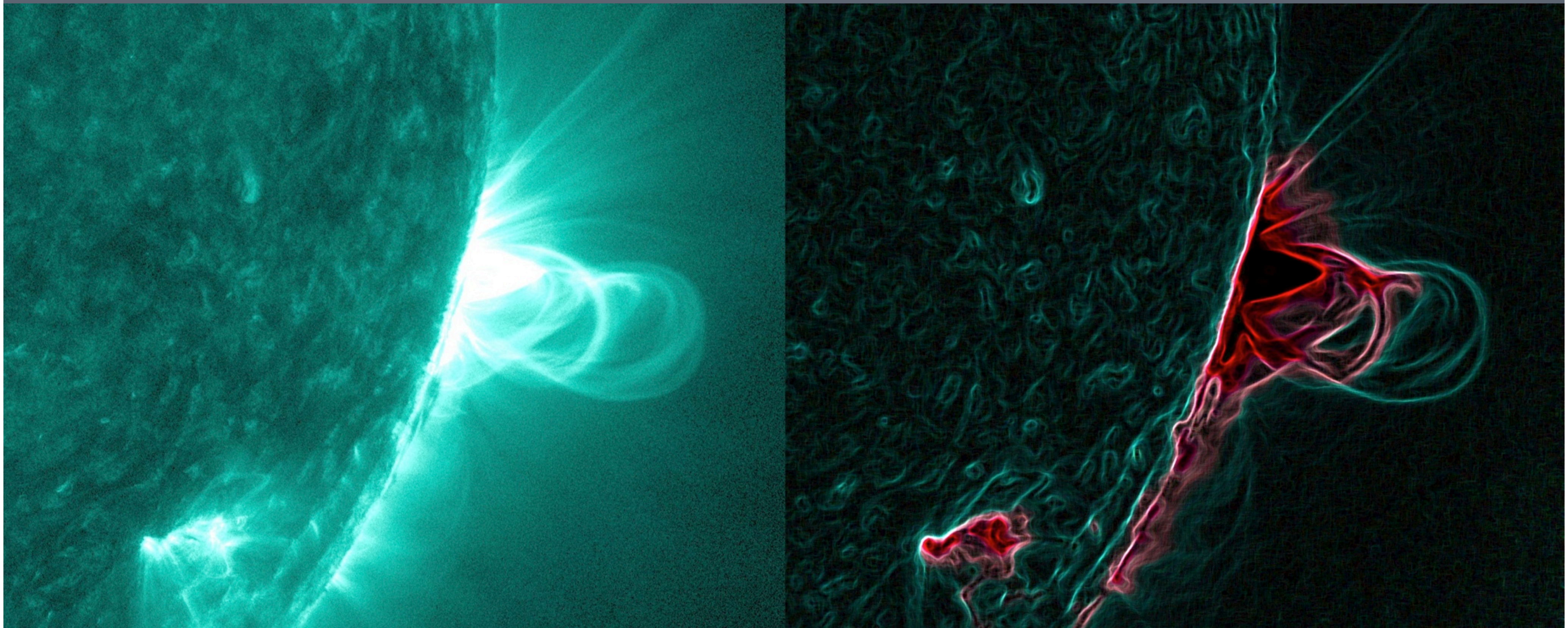
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. A8, PAGES 17,705–17,728, AUGUST 1, 1998

Current understanding of magnetic storms: Storm-substorm relationships

Y. Kamide,[1] W. Baumjohann,[2] I. A. Daglis,[3] W. D. Gonzalez,[1,4] M. Grande,[5] J. A. Joselyn,[6] R. L. McPherron,[7] J. L. Phillips,[8] E. G. D. Reeves,[9] G. Rostoker,[10] A. S. Sharma,[11] H. J. Singer,[6] B. T. Tsurutani,[12] and V. M. Vasyliunas[13]

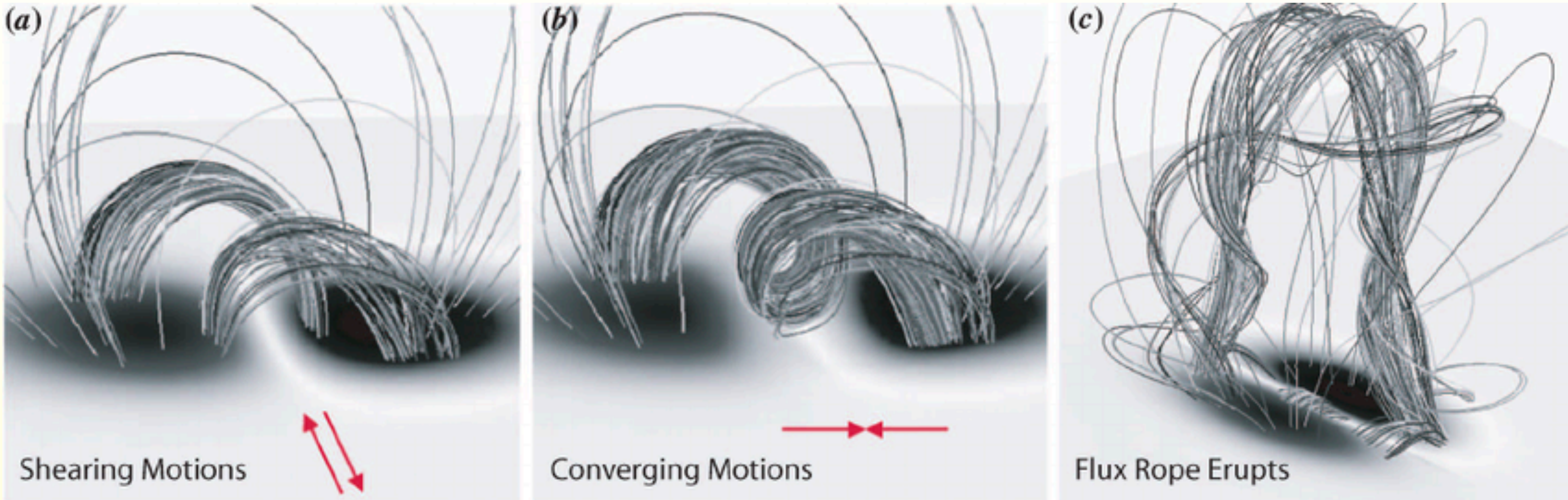
Abstract. This paper attempts to summarize the current understanding of the storm/substorm relationship by clearing up a considerable amount of controversy and by addressing the question of how solar wind energy is deposited into and is dissipated in the constituent elements that are critical to

CME formation by SDO



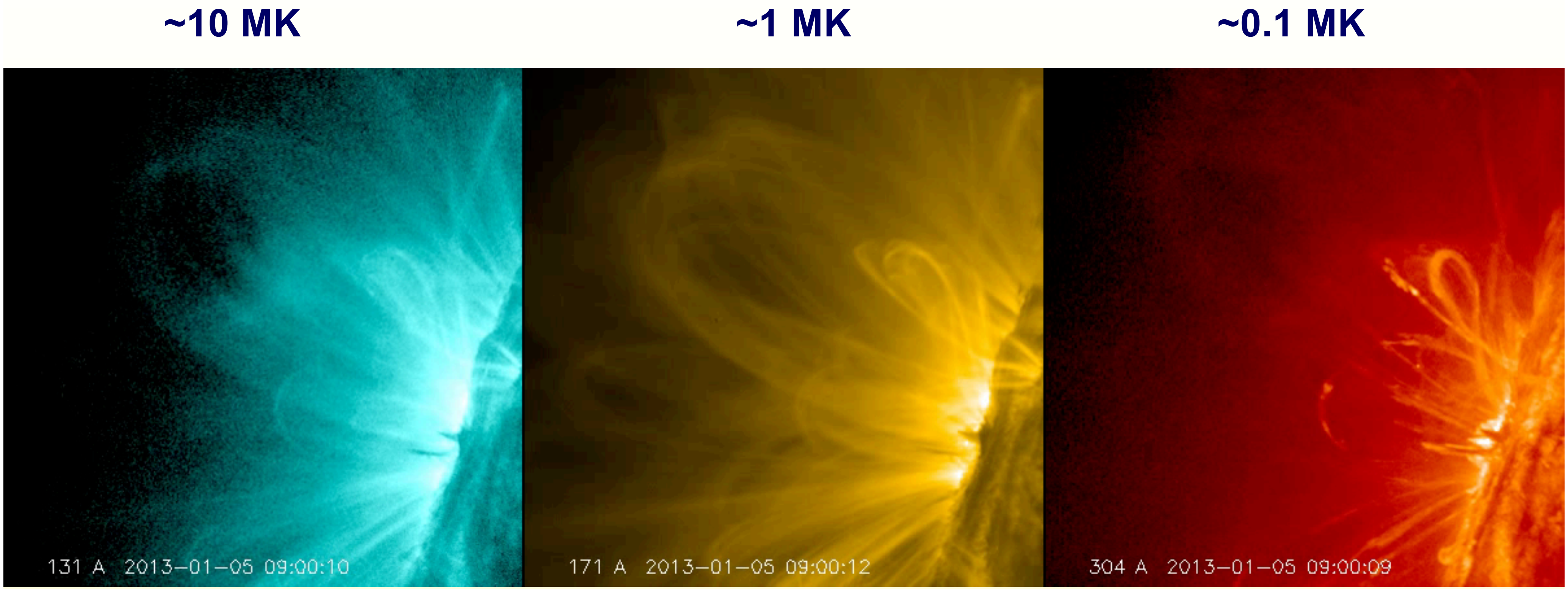
What is a Magnetic flux Rope?

Working Definition: Magnetic field lines wrapping around a common axis



Roussev (2008)

MFR Formation



Nindos et al. (2015)

Solar Energetic Particles: What are they?

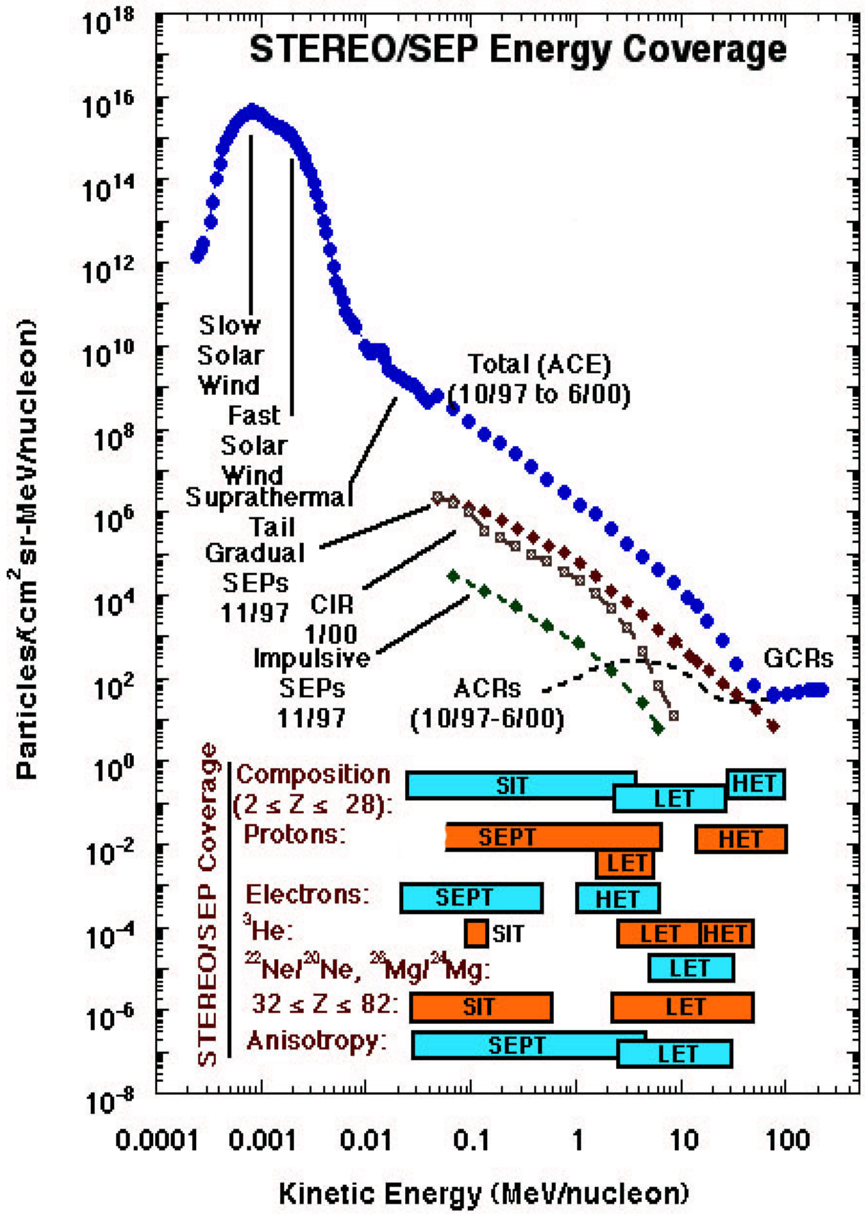
Definition:

Energetic charged particles
(such as electrons and **protons**)
traveling much faster
than ambient particles
in the space plasma

SEPs are ions and electrons of solar or interplanetary origin that occasionally appear **in the energy range between solar wind particles and galactic cosmic rays.**

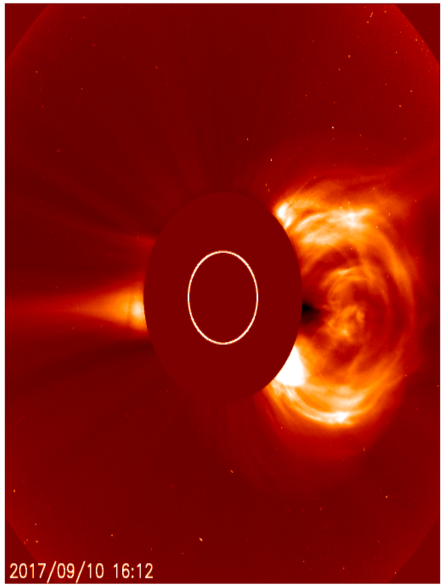
The ions are often of most interest in space weather.

Shown: ACE Ion Spectra and STEREO IMPACT coverage



R. Mewaldt

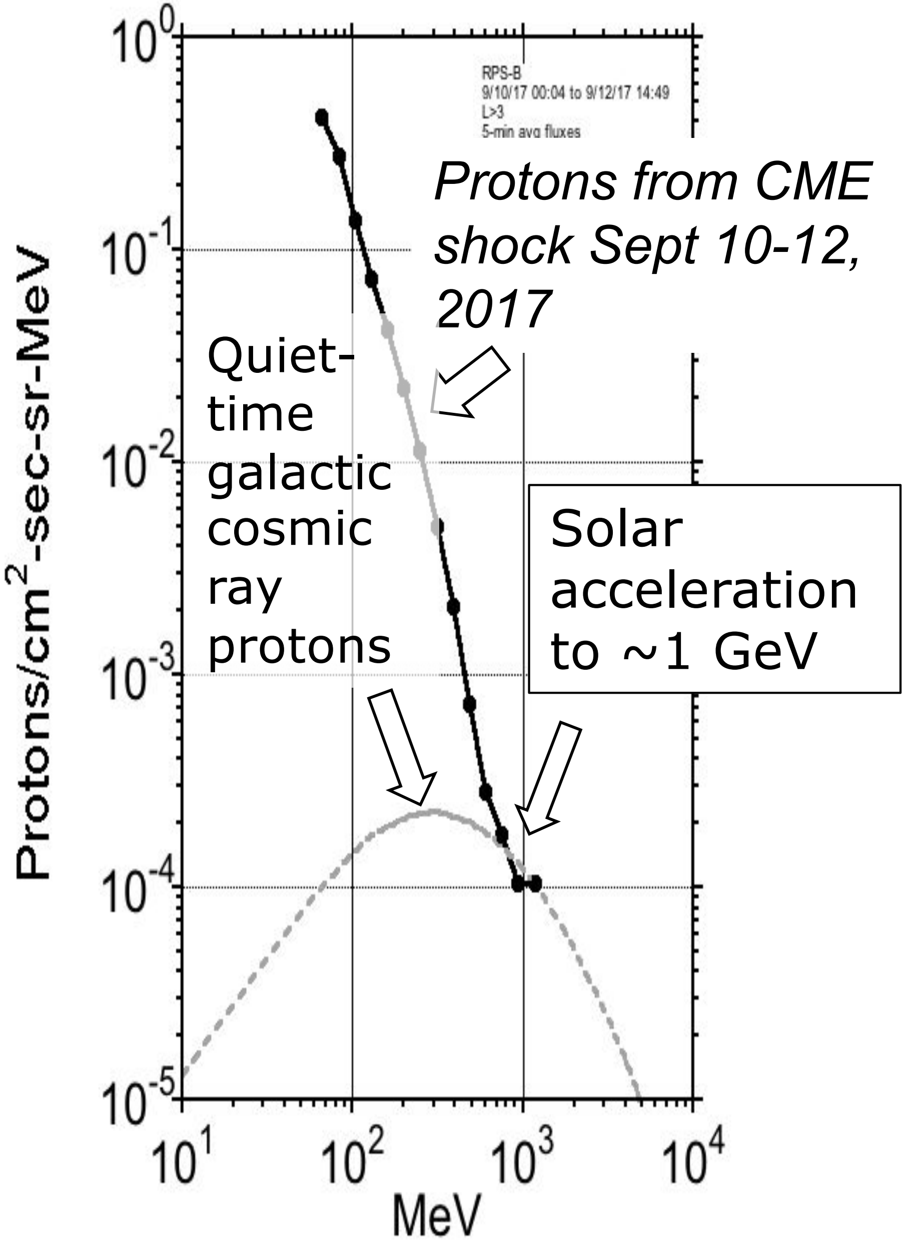
Solar Protons up to 1 GeV in the 10/9/2017 CME Event

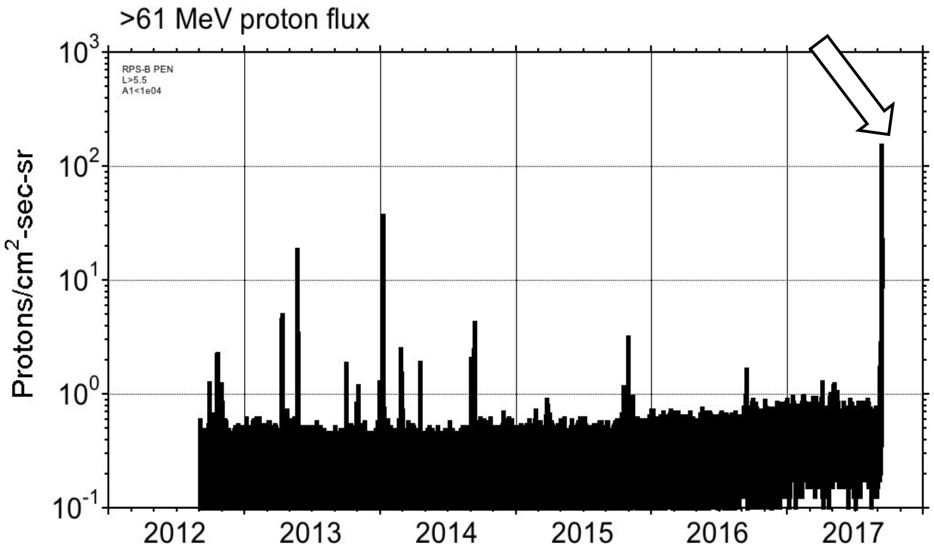


CME liftoff:
10/9/2017 1600UT
Estimated speed:
1081 km/sec

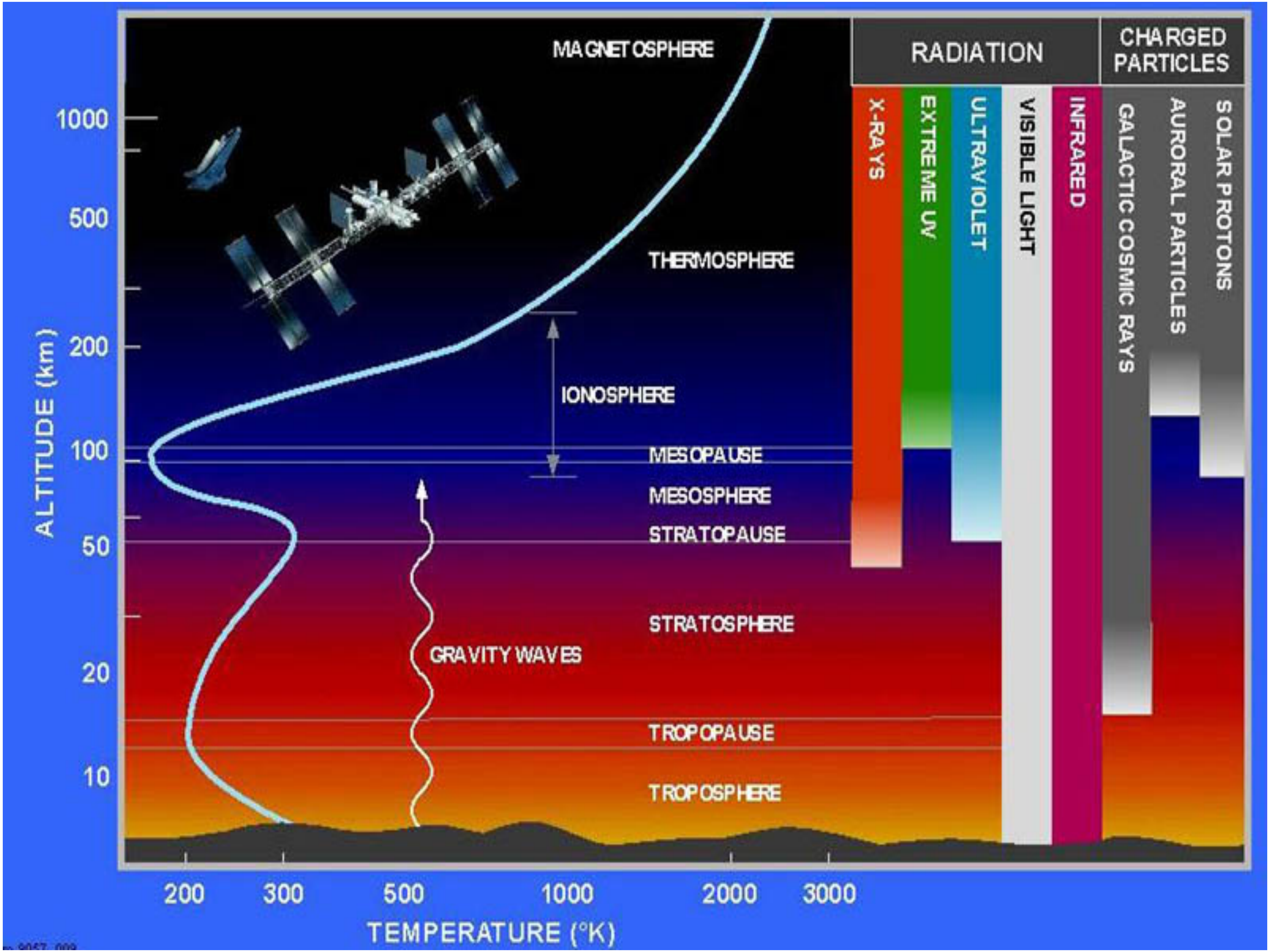
www.spaceweather.gmu/edu

Van Allen Probes/RPS-B Proton Energy Spectrum





Most intense >60 MeV solar proton event seen during the RBSP mission


MAGNETOSPHERE
RADIATION
CHARGED PARTICLES
X-RAYS
EXTREME UV
ULTRAVIOLET
VISIBLE LIGHT
INFRARED
GALACTIC COSMIC RAYS
AURORAL PARTICLES
SOLAR PROTONS
THERMOSPHERE
IONOSPHERE
MESOPAUSE
MESOSPHERE
STRATOPAUSE
STRATOSPHERE
GRAVITY WAVES
TROPOPAUSE
TROPOSPHERE
ALTITUDE (km)
1000
500
200
100
50
20
10
200
300
500
1000
2000
3000
TEMPERATURE (°K)

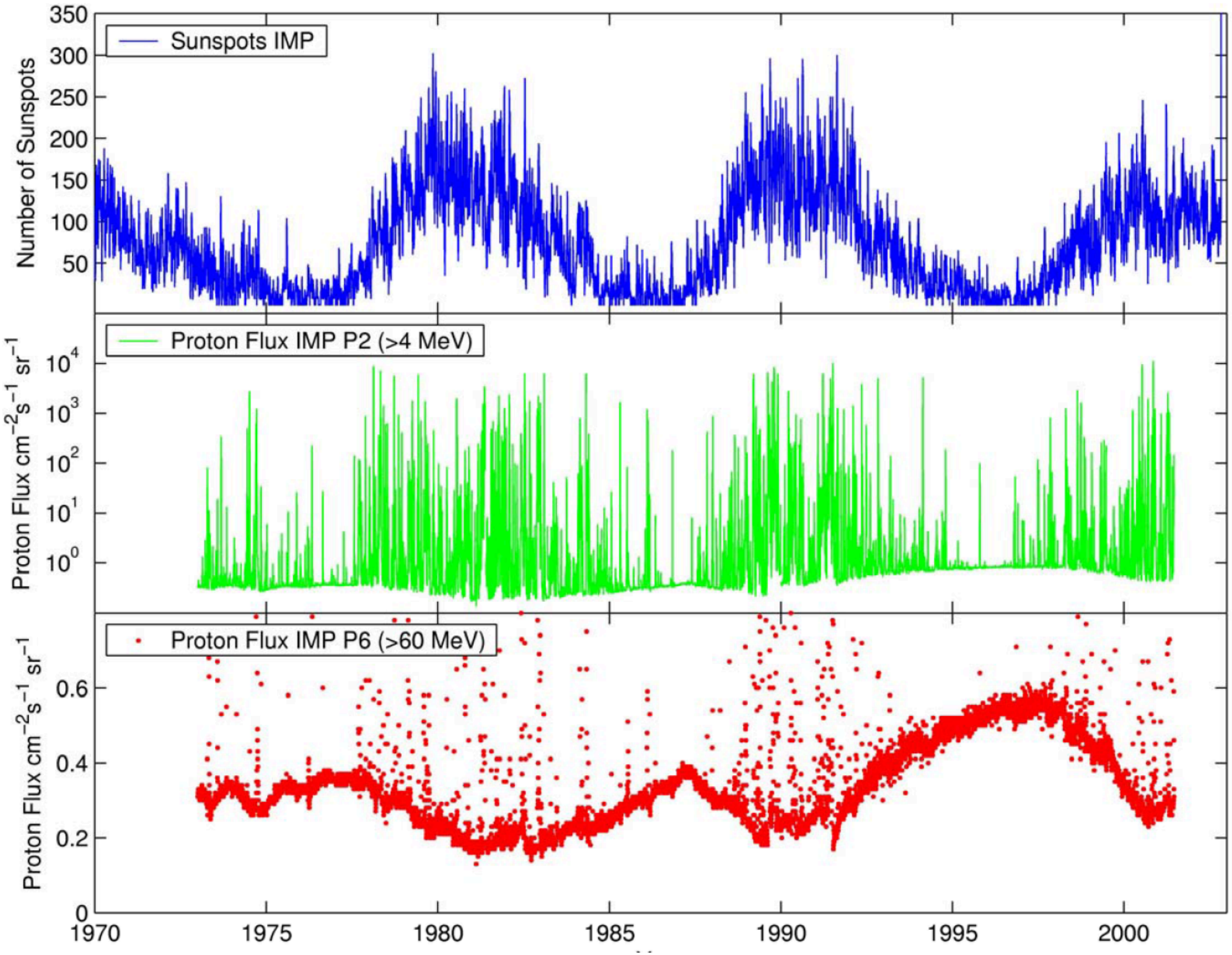
Galactic Cosmic Rays

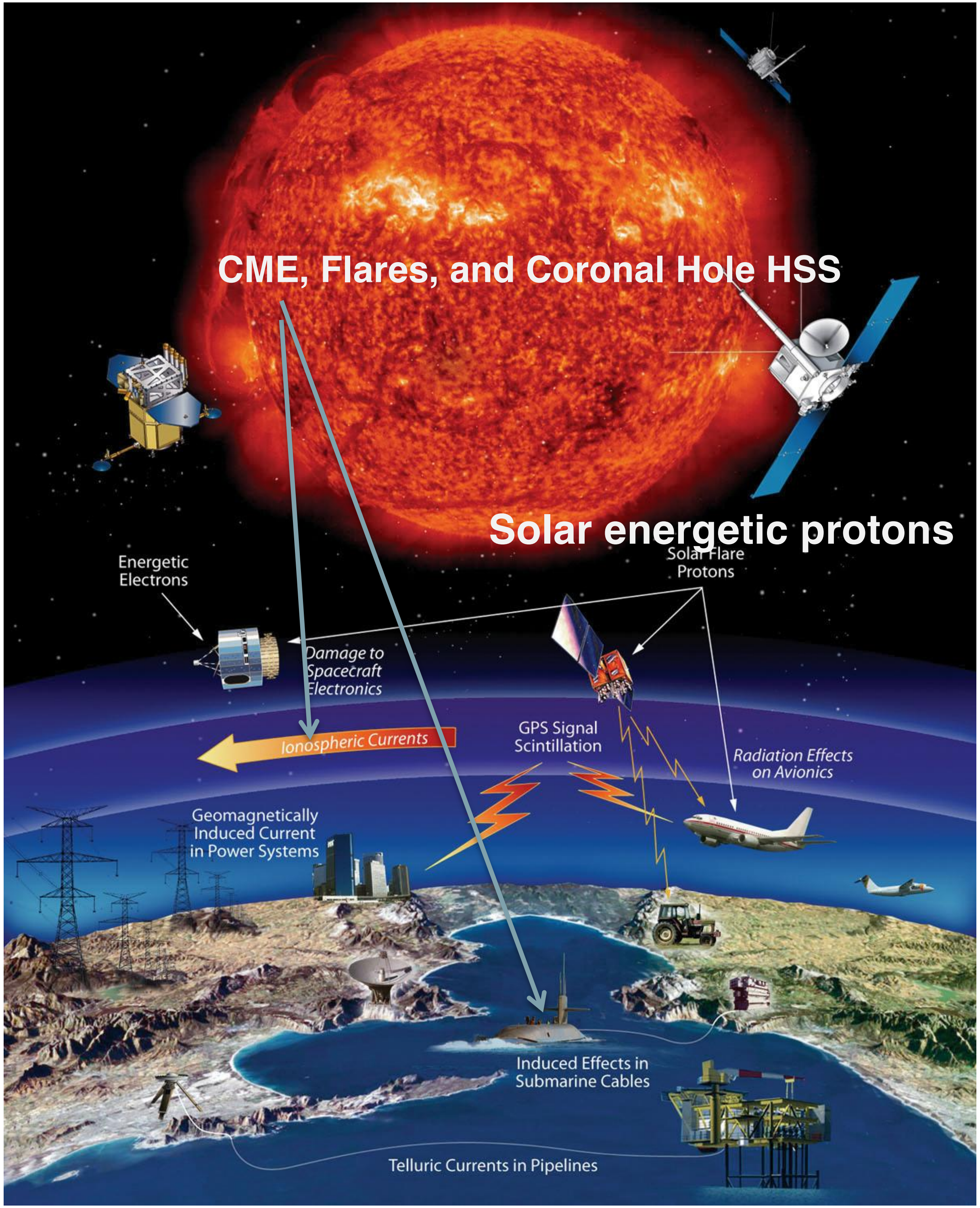
- Galactic cosmic rays (GCR) are high-energy charged particles that originate outside our solar system.
- Supernova explosions are a significant source

Anticorrelation with solar activity
More pronounced/intense during solar minimum

Particles during the solar cycle

- Spikes are solar energetic particles (SEPs): individual events of solar origin (flares, CMEs)
- SEPs are observed during solar minimum although with smaller likelihood
- Background anti-correlated with the solar cycle.





The Sun:
maker of space weather

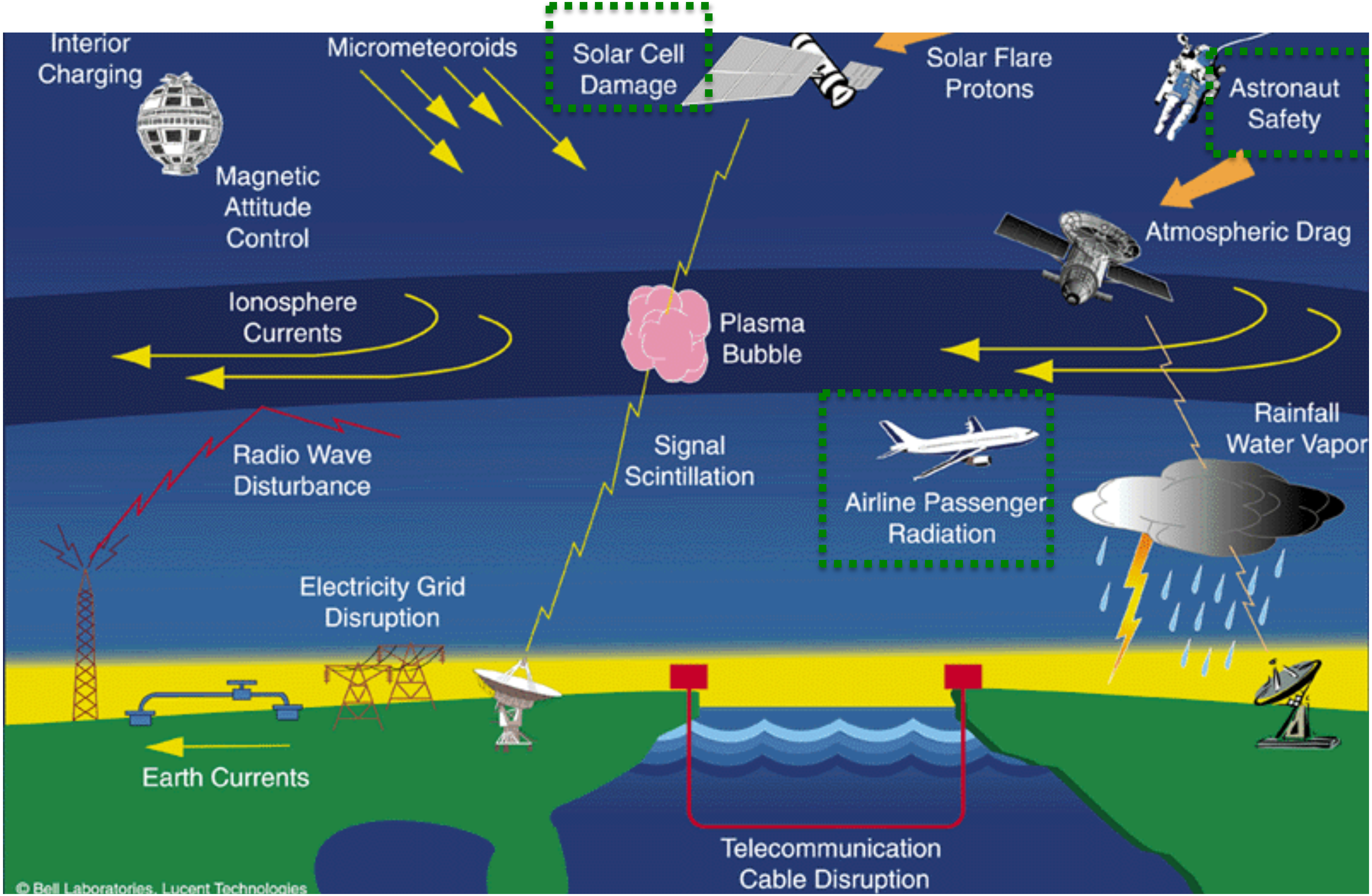
<u>CME, Flares, Coronal Hole HSS:</u>

Three very important solar wind disturbances/structures for space weather

- ✓**Radiation storm**
  - **proton radiation (SEP) <flare/CME>**
  - **electron radiation <CIR HSS/CME>**
- ✓**Radio blackout storm <flare>**
- ✓**Geomagnetic storm**
  - **CME storm (can be severe)**
  - **CIR storm (moderate)**

Why do we care?

Radiation hazards for spacecraft, humans in space and airline passenger safety



Solar Energetic Particles
What are they?

Definition:

Elemental composition

96.4 % protons

3.5% alpha particles

0.1% heavier ions (not to be neglected!)

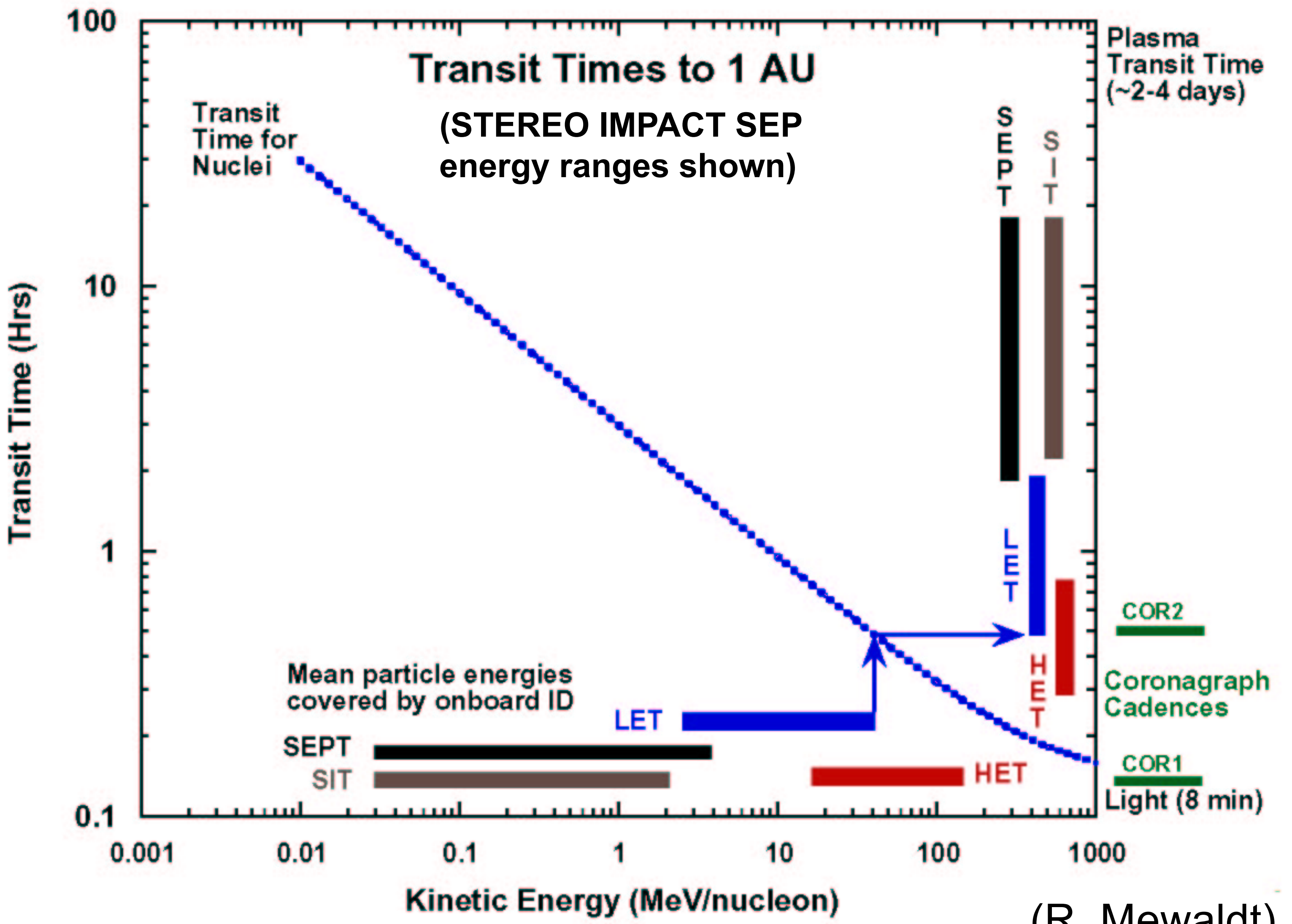
Energies: up to ~ GeV/nucleon

Travel from Sun to Earth **in 1 hour or less.**

The term **SEP usually refers to protons**

(even though "p" is particle)

SEPs provide both a **remote diagnostic** of their source(s) and are themselves a space weather hazard of interest to forecasters.



(R. Mewaldt)

Space Environments and Effects on Spacecraft