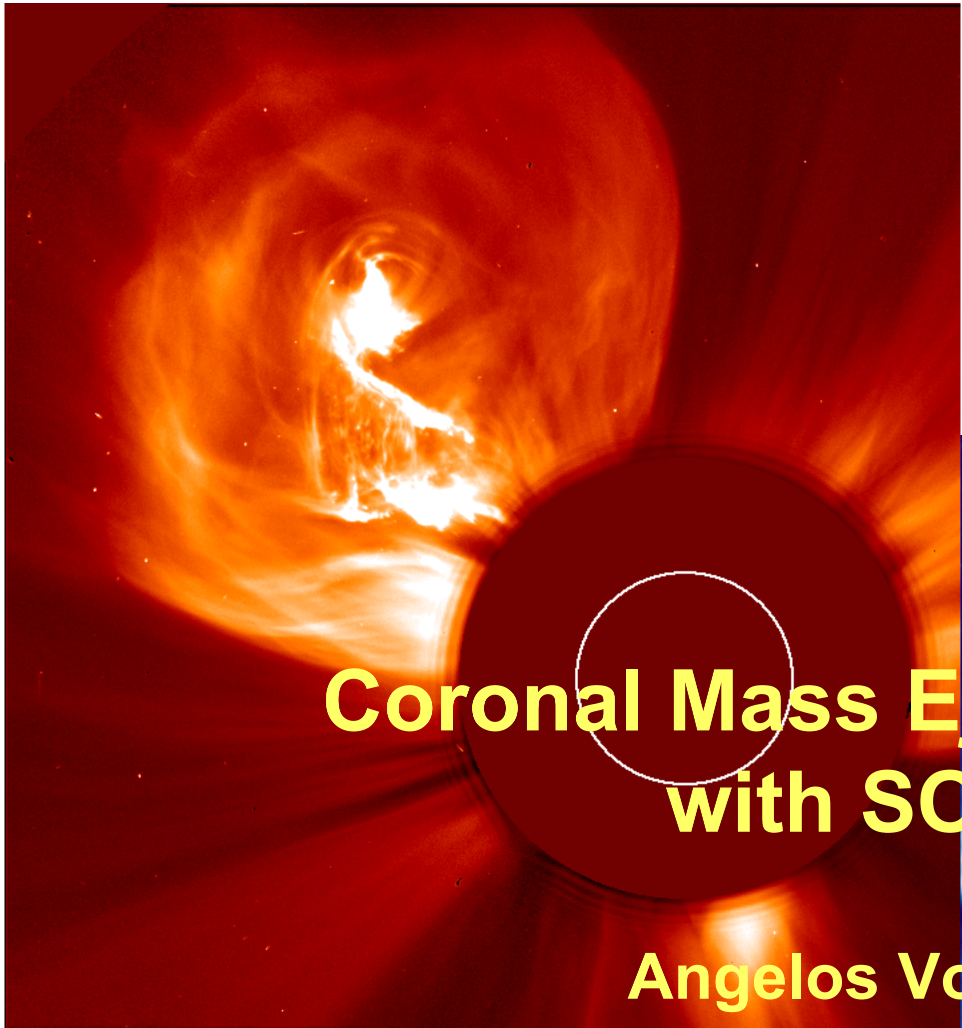


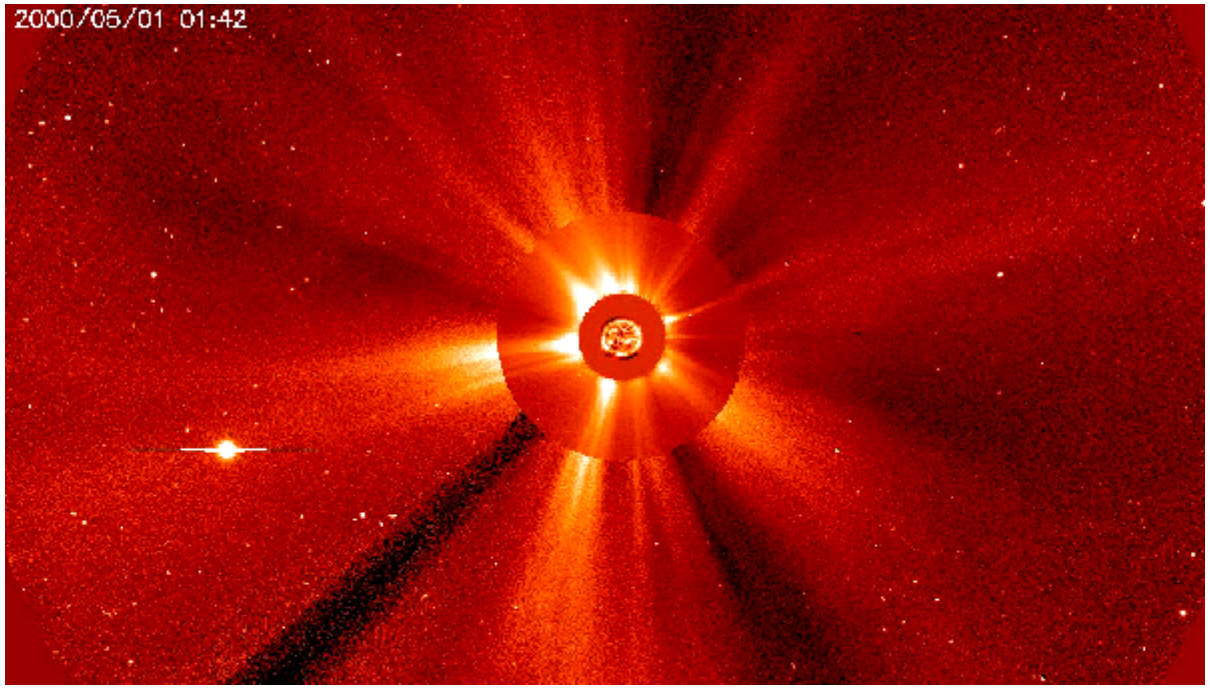
Coronal Mass Ejection Studies with SOLAR-C

Angelos Vourlidas, *NRL*

Why do we care about CMEs?

CMEs:

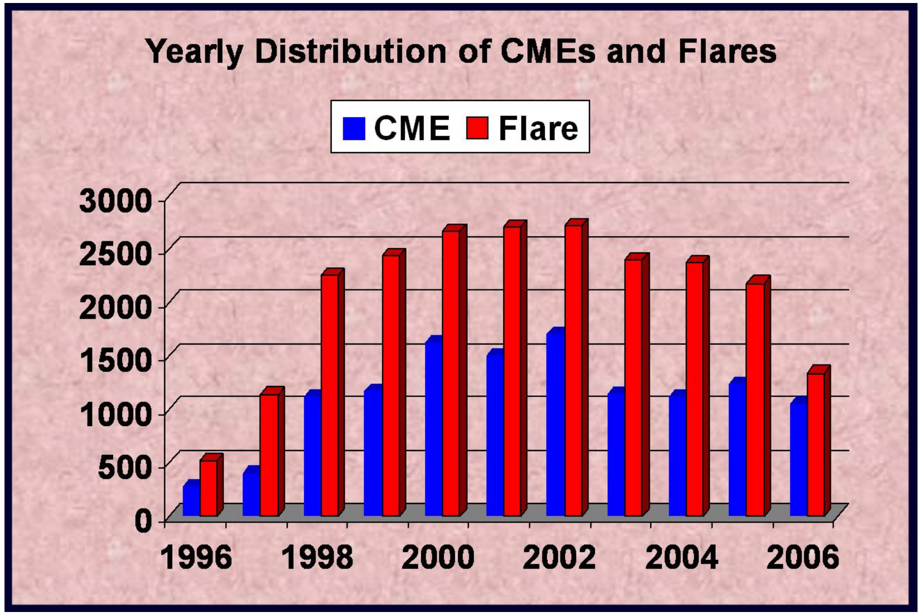
- **Are the major explosive energy release phenomenon in the solar system**
- **Are the main driver of space weather for Earth (+other planets)**
- **Provide access to many interesting physics: e.g., modulate Galactic Cosmic Rays, accelerate particles, etc**

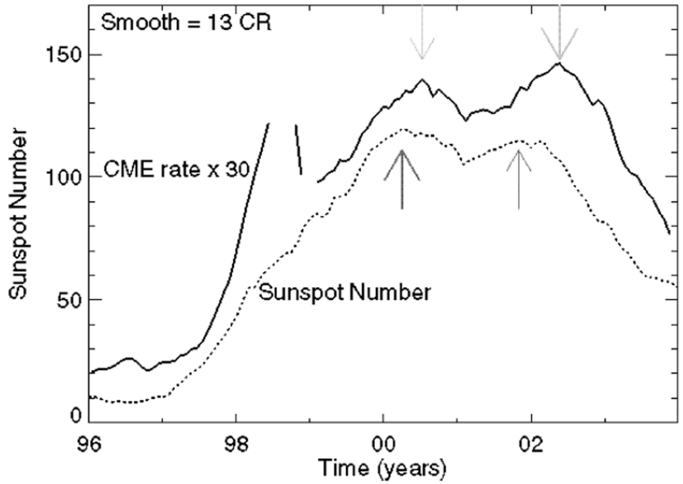


CMEs in the LASCO Era (1)

- **CME observations over a FULL solar cycle**

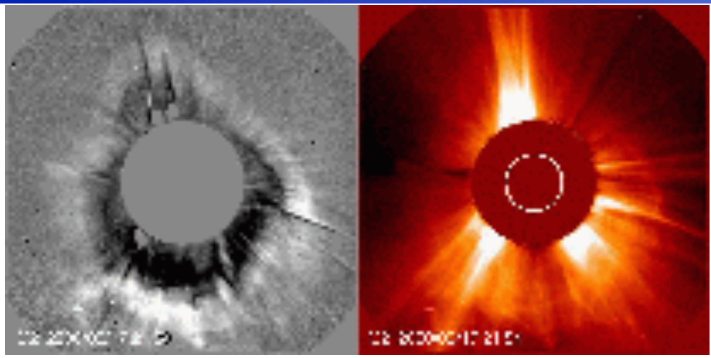
CME/day: 0.5 – 4.5
Flare/day: 1.5 – 7.5



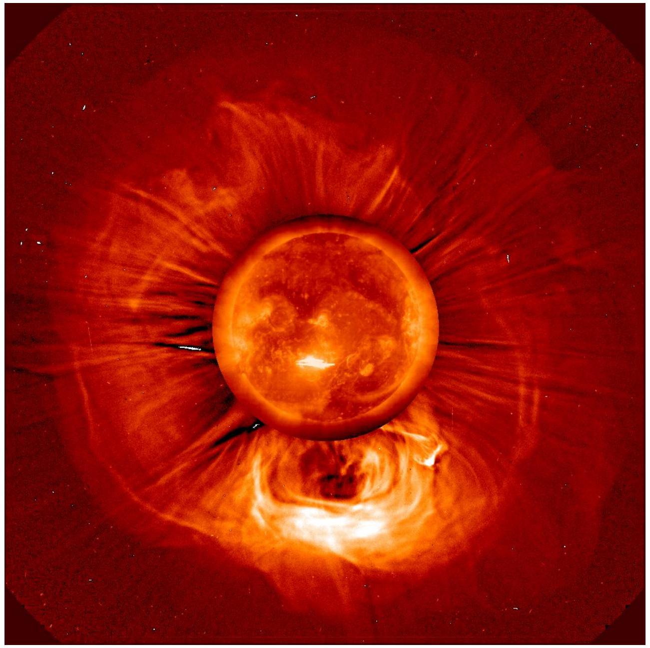


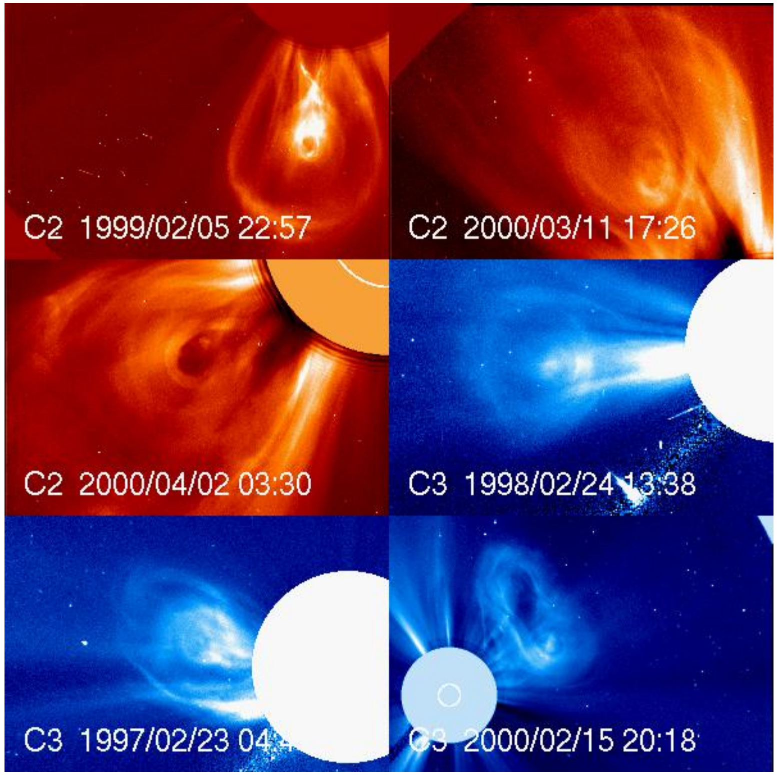
CME rates peak ~6 months AFTER Sunspot rates

CME in the LASCO Era (2)



Verification of the Halo-CME type

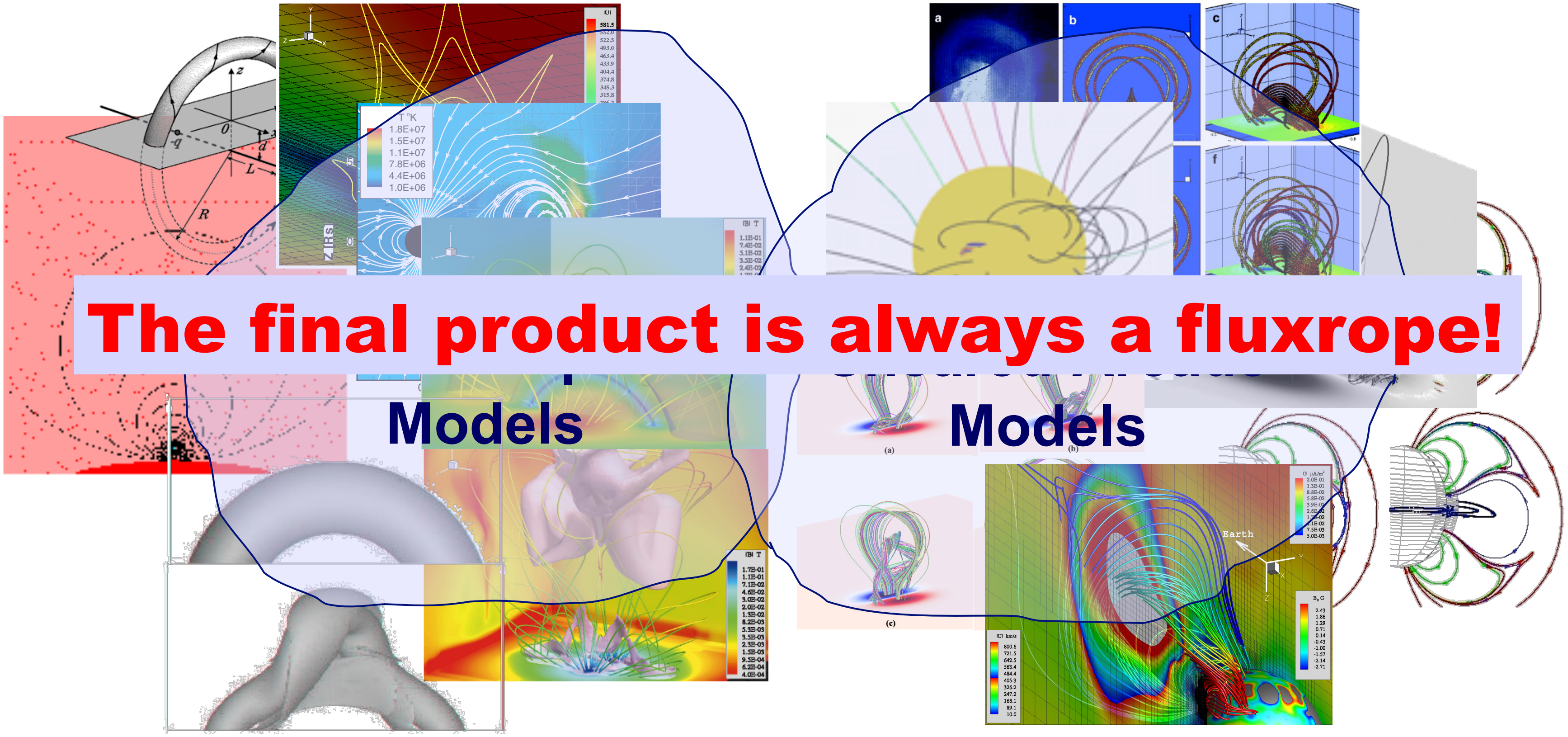




Most CME have fluxrope structures

CME Initiation Models (quite a few but…)

(from I. Roussev's ESPM 2008 presentation)

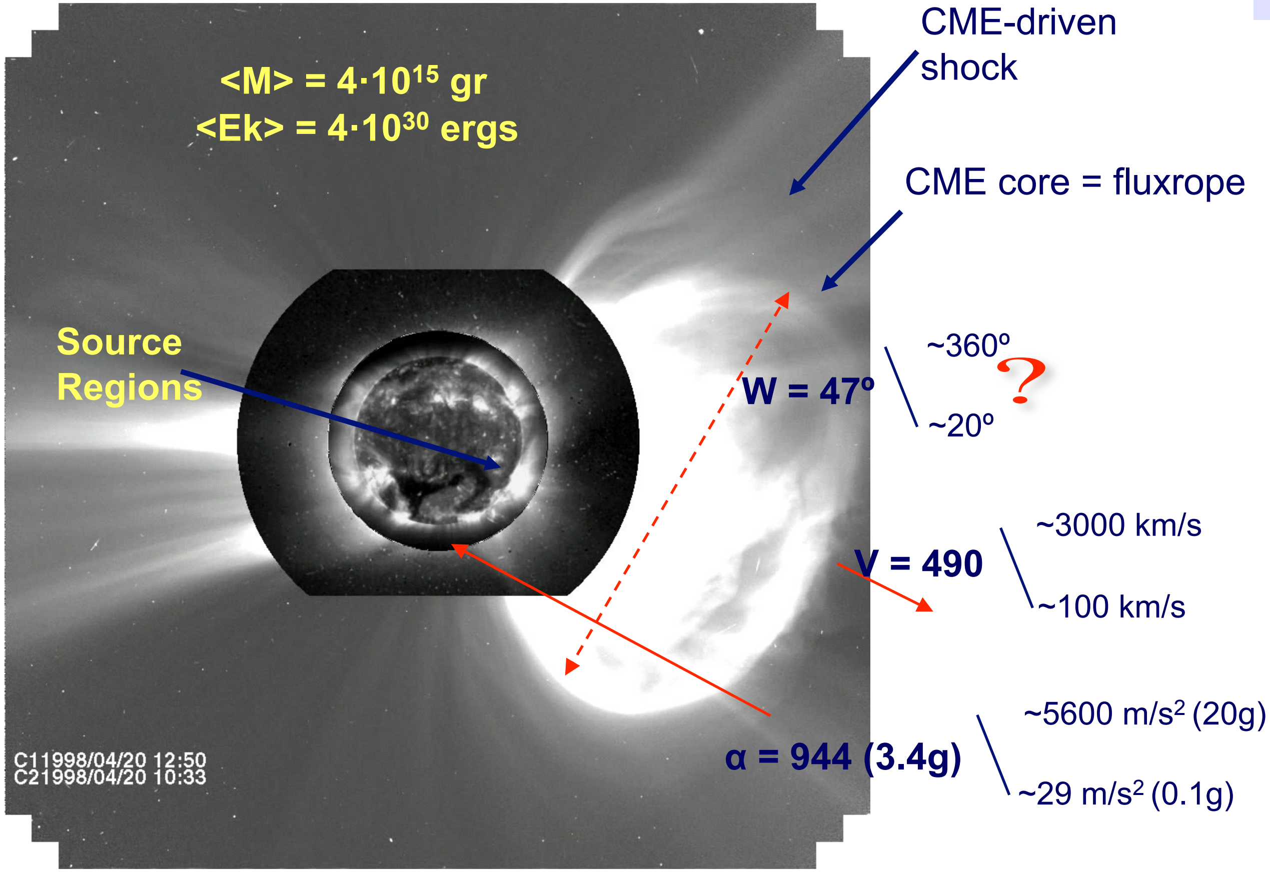


Amari *et al.* (2000, 2003, 2007); Antiochos *et al.* (1999); Forbes & Isenberg (1991); Gibson & Low (1998); Kliem *et al.* (2004); Lin *et al.* (2001); Linker *et al.* (2001); Lynch *et al.* (2005); Manchester *et al.* (2003, 2004); Moore *et al.* (2001); Sturrock *et al.* (2001); Titov & Démoulin (1999); Tokman & Bellan (2002); and Roussev *et al.* (2003, 2004, 2007).

CMEs in the LASCO Era (3)

- **With >15,000 Events recorded, the basic CME properties are well-known**

Tendency for
Slow CMEs to Accelerate
and
Fast CMEs to Decelerate



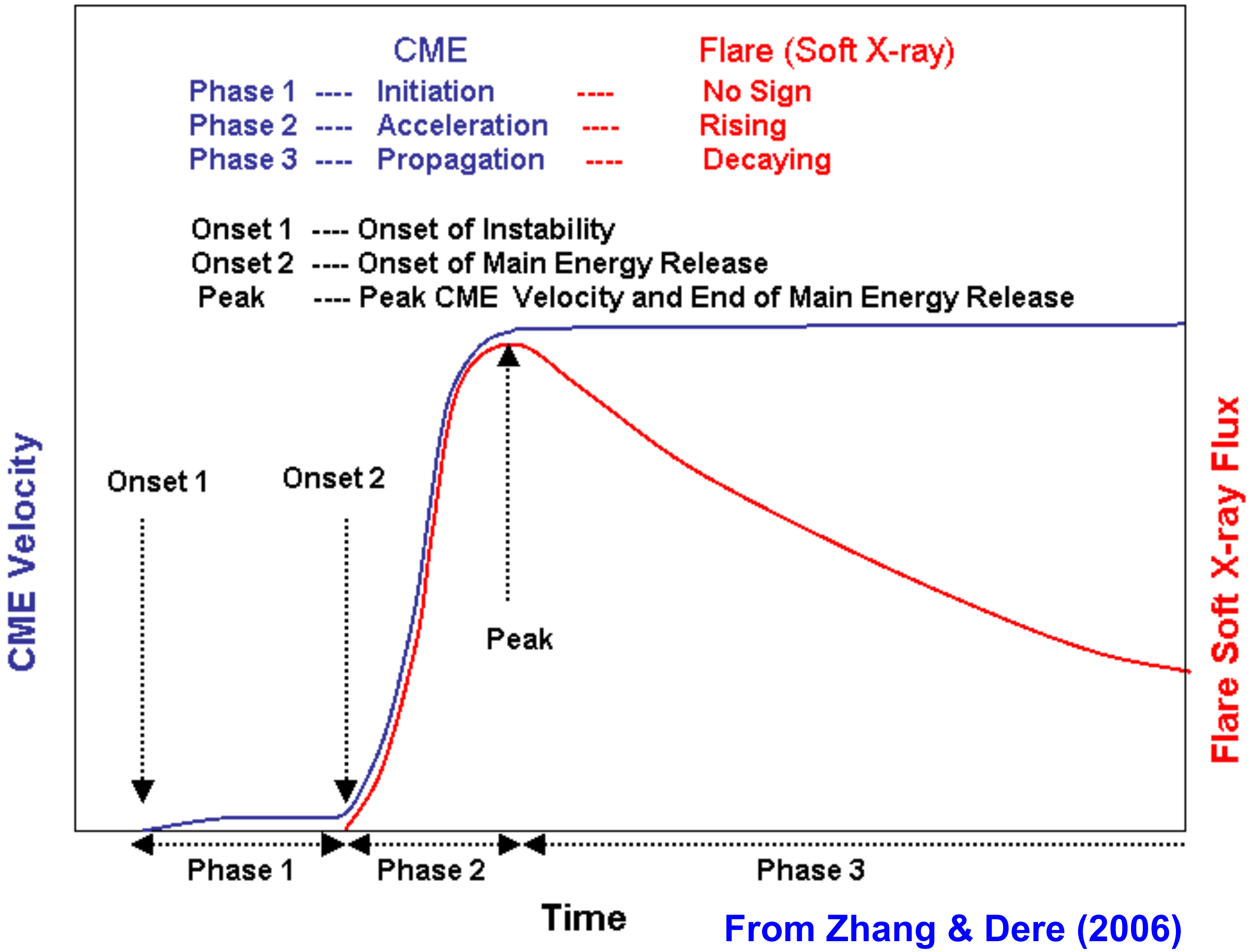
CME Kinematics – Flare Association

(from J. Zhang's SHINE 2007 presentation)

Three phases:
P1: Initiation
P2: Acceleration
P3: Propagation

CME main acceleration coincides with flare energy release phase (e.g.,Zhang et al. ApJ 2001)

CME Kinematic Evolution and Timing with Associated Flare



From Zhang & Dere (2006)

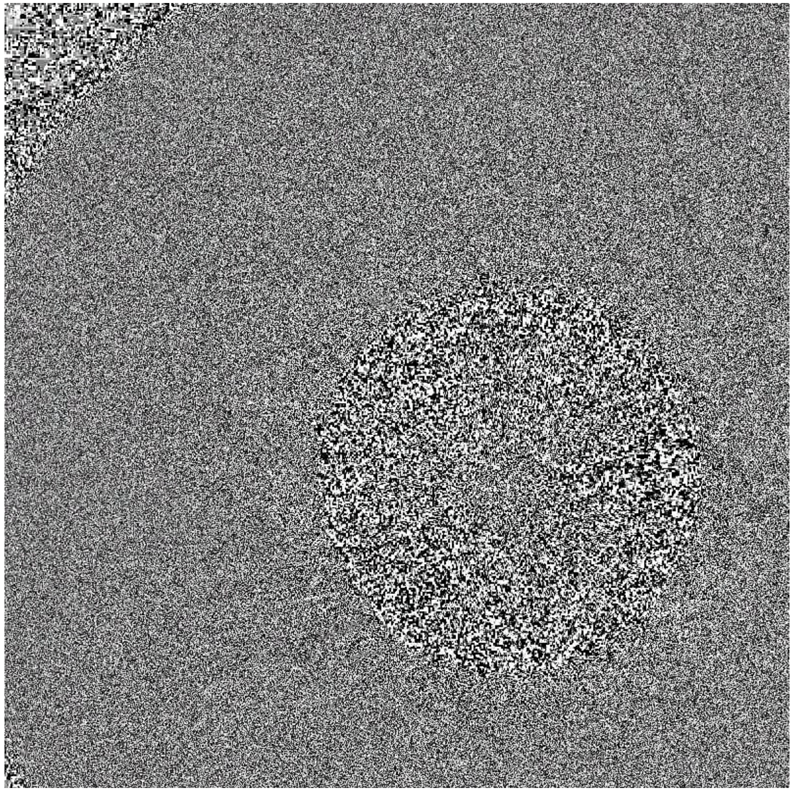
Cycle 23: Review of LASCO Era

- Knowledge of CME Properties over a full solar cycle and 1000's of events
- Establishment of relation to coronal phenomena (flares, filament eruptions)
- Discovery of CME counterparts in low corona (EUV-waves, dimmings, plasmoids)
- CME role in Sun-Earth Connection is established, extensively analyzed.
- Theory converges towards fluxrope as the ejected structure
  - 3D MHD modeling captures the main CME features (shock, core, speed, width)
- Clear understanding of CME images (shock, core, front, streamers)

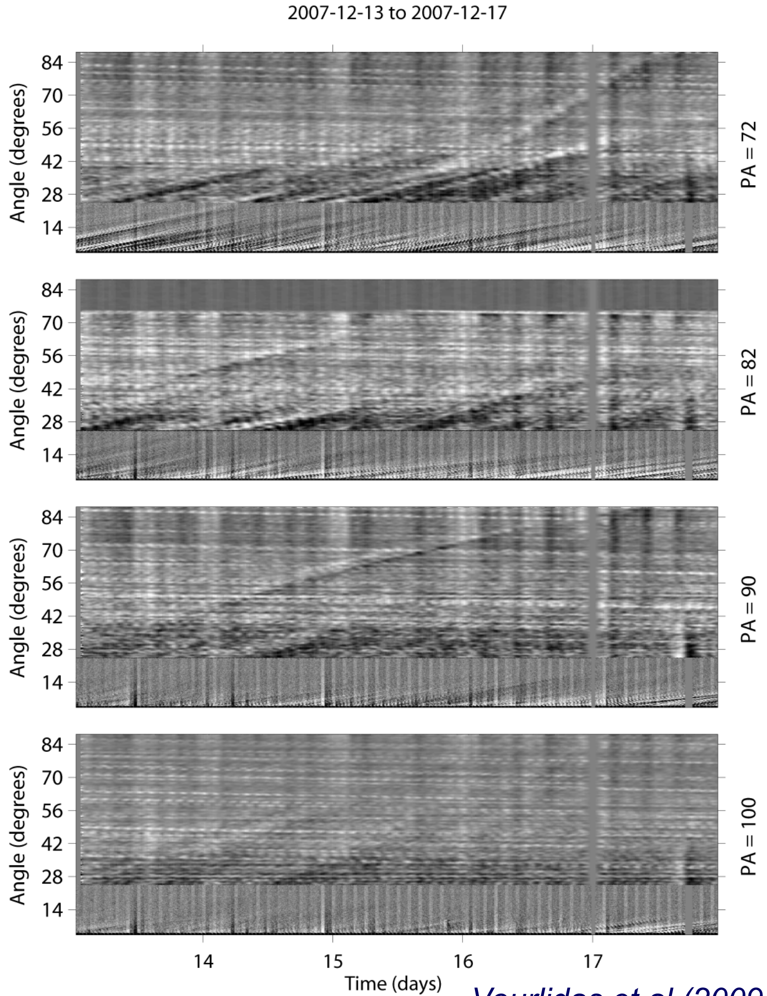
- But we don't know
  - true size, direction, entrained magnetic field, initiation mechanism, energy partition, relation to extended corona, propagation in heliosphere, geoeffectiveness, SEP accelerations, etc…..

Cycle 24: The SECCHI Era

- **Complete coverage of the Sun-Earth Heliosphere**
- **Simultaneous observations from 2 viewpoints**



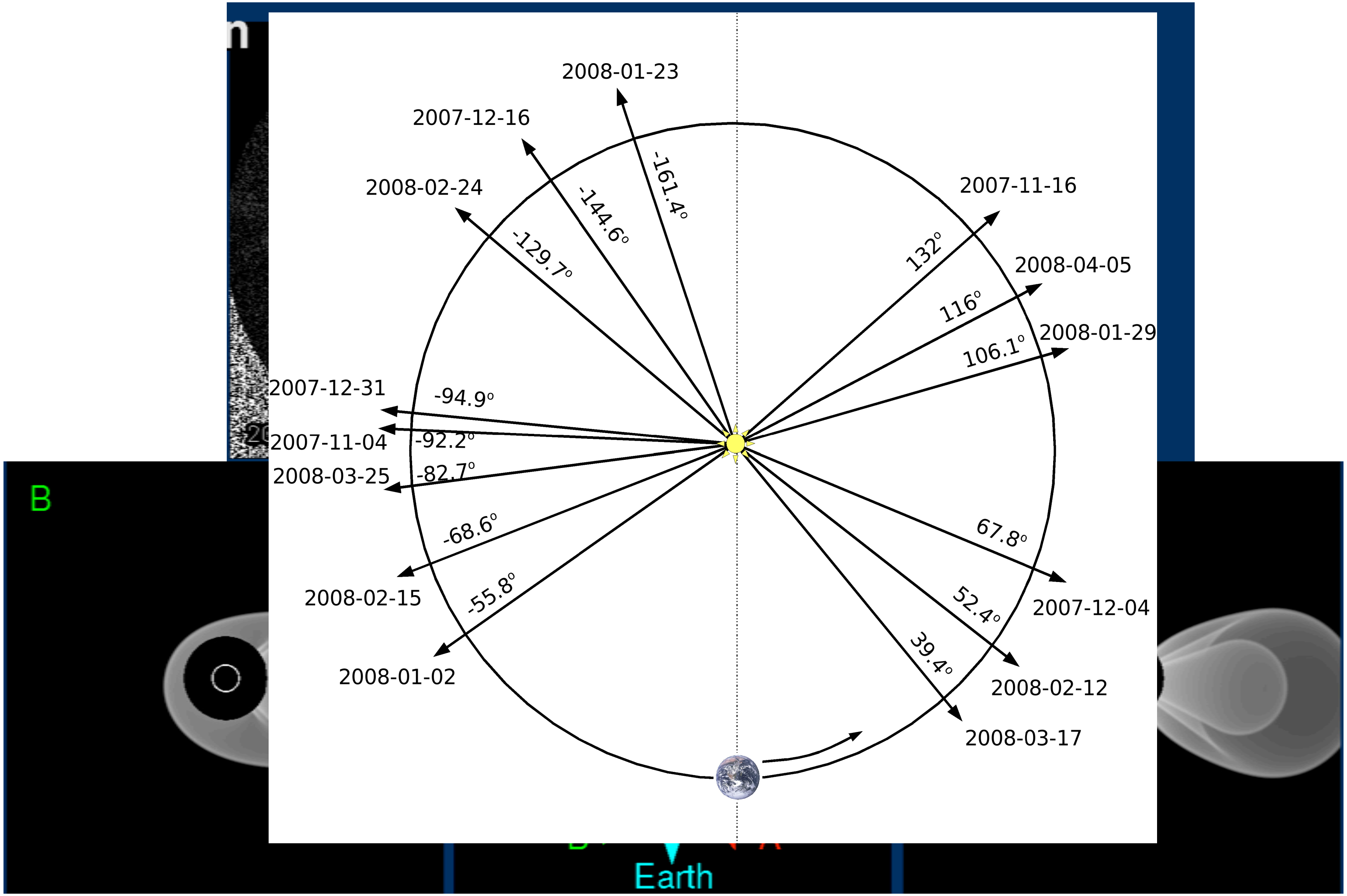
Woods et al (2009)



Vourlidas et al (2009)

SECCHI Era: Size & Direction of CME

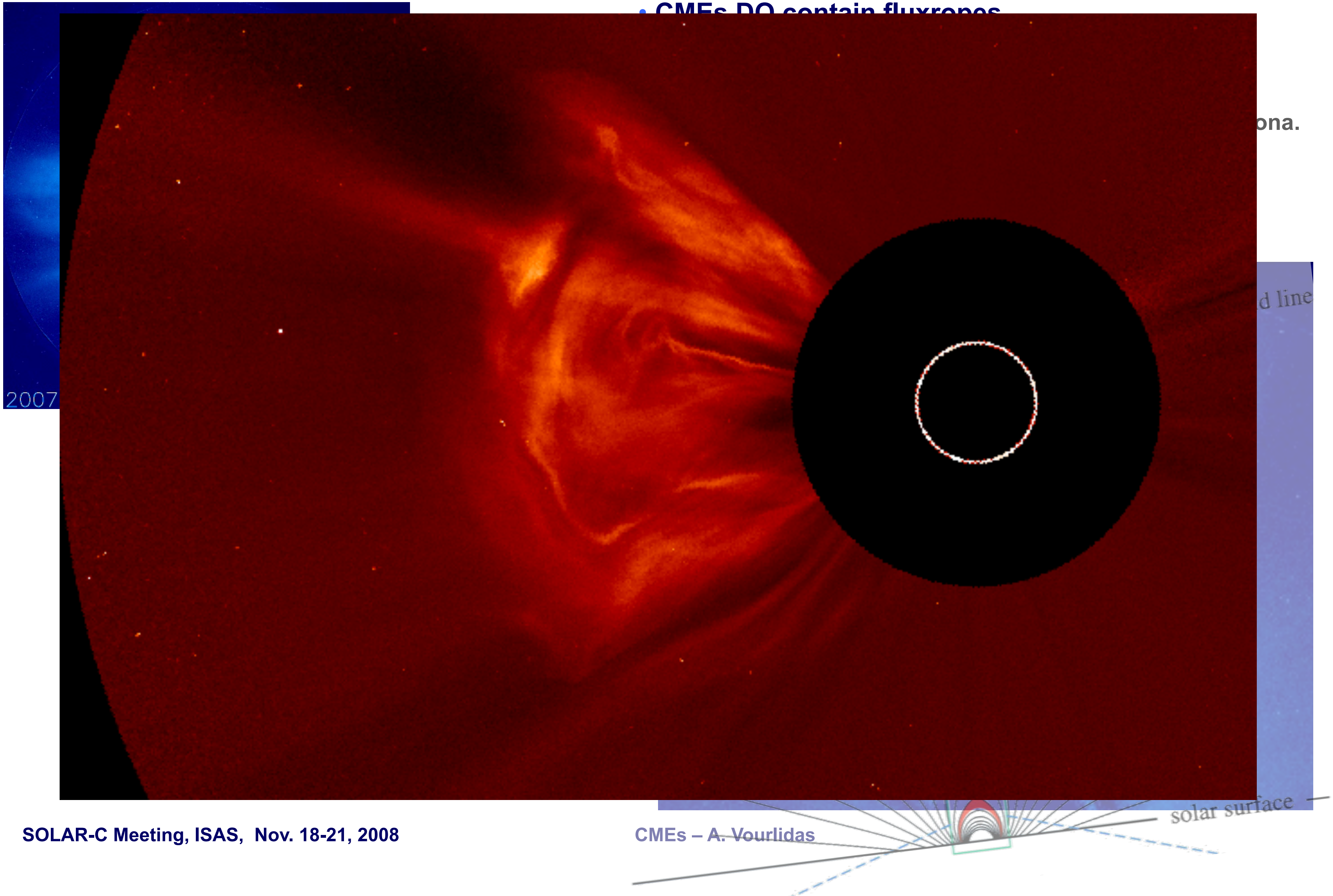
From Thernisien et al 2009



CME Current Sheets & Internal Structure

• CMEs DO contain fluxropes

ona.



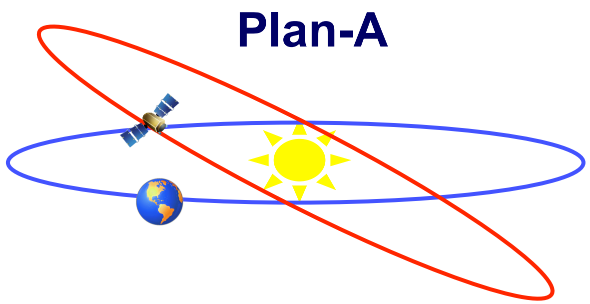
Cycle 24: SECCHI Era *(Anticipated Contributions)*

- 3D measurements
  - true size, velocity, propagation direction, relation to AR
- Detail analysis of the acceleration phase
  - energy partition between CME and flare, initiation mechanism(?)
- Propagation in the heliosphere
  - Interaction with other CMEs & fast/slow solar wind, internal structure
- CME formation in the low corona
  - nature of waves/shocks, interaction w/ background fields
- Clearer understanding of CMEs geoeffectiveness
  - SEP acceleration, interaction with geospace

- But we may not know
  - entrained magnetic field, initiation mechanism, effects on/from global corona, geoeffectiveness, role in SEP acceleration, …

Cycle 25: SOLAR-C Era

- **Mission Considerations**
  - Max Inclination of 45º
  - 2016 launch (cycle 24 ~min)
  - High inclinations in 4-5 yrs (cycle 25 ~max)
  - Optional co-rotation with Earth (TBD)
  - Elliptical or circular (1 AU) orbits (TBD)



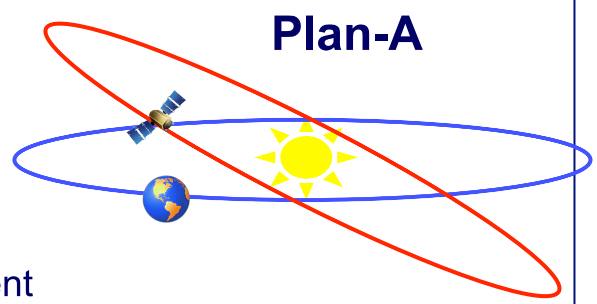
- **Synergies in 2016 – 2020**
  - SDO operational
    - EUV coverage of inner corona (<1.5 Rs)
  - STEREO operational(?)
    - Full coverage of inner heliosphere (+/- 45º from solar limbs)
  - Solar Probe /Orbiter(?)
    - In-situ coverage of corona/heliosphere

→ **Good EUV coverage in the Ecliptic plane**

→ **But coronagraphic coverage is uncertain**

CME Science Objectives for Plan-A

- **Orbit Advantages**
  - Viewpoint away from symmetry plane
    - Varying line-of-sight through dust (F-corona)
  - Simultaneous imaging of far-side and earth-facing solar hemispheres

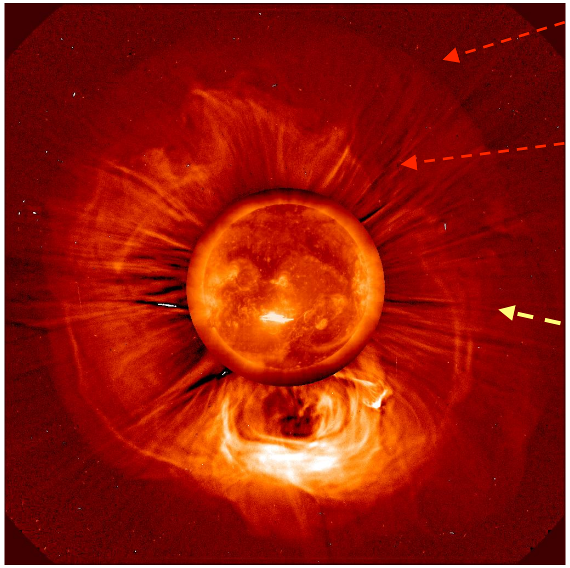


- **Science Objectives:**
  - **How CMEs affect the large scale corona?**
  - **What is the 3D morphology of CMEs/CIRs/Plumes?**
    - Validate STEREO results offering a truly independent measurement
    - Obtain direction with a single observation
    - Stronger constraints on IPS and Faraday rotation analysis
  - **How does the solar wind structures propagate & interact w/ each other?**
    - Observed the formation of solar wind and the birth of CIRs.
  - **Space weather on Earth and inner planets (w/ Heliospheric Imager)**
    - Which CMEs are headed towards Earth, Solar Orbiter/Probe, etc?

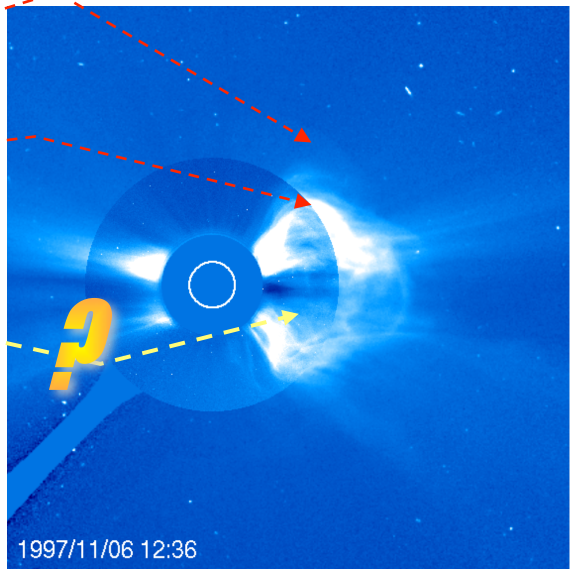
Why we need out-of-ecliptic CME Observations?

- **The effects of CMEs on the global corona are unknown**
  - How does the shock propagate around the Sun?
  - Are there sympathetic CMEs?
  - How do streamers reform?
  - What is the interplay between CMEs, shock waves and Coronal Holes?
  - Where does the solar wind originate?

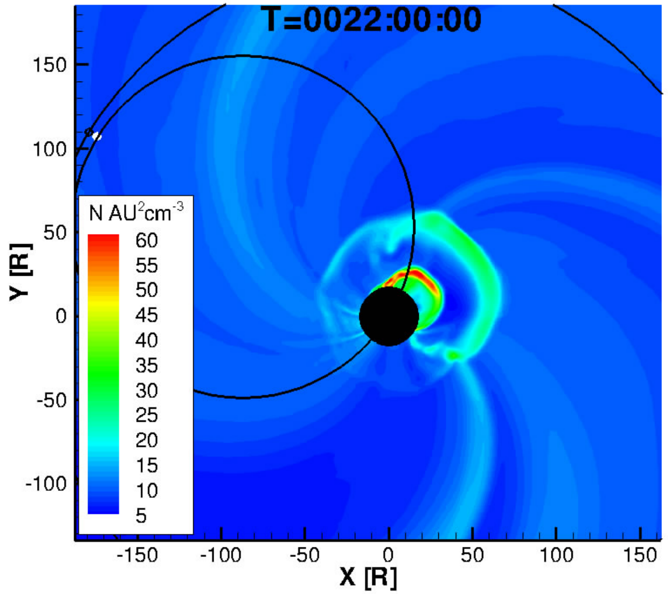
X-plane



Y-plane



Z-plane



SECCHI

MHD Simulation by Lugaz

What to Expect from a 45º Viewing Angle

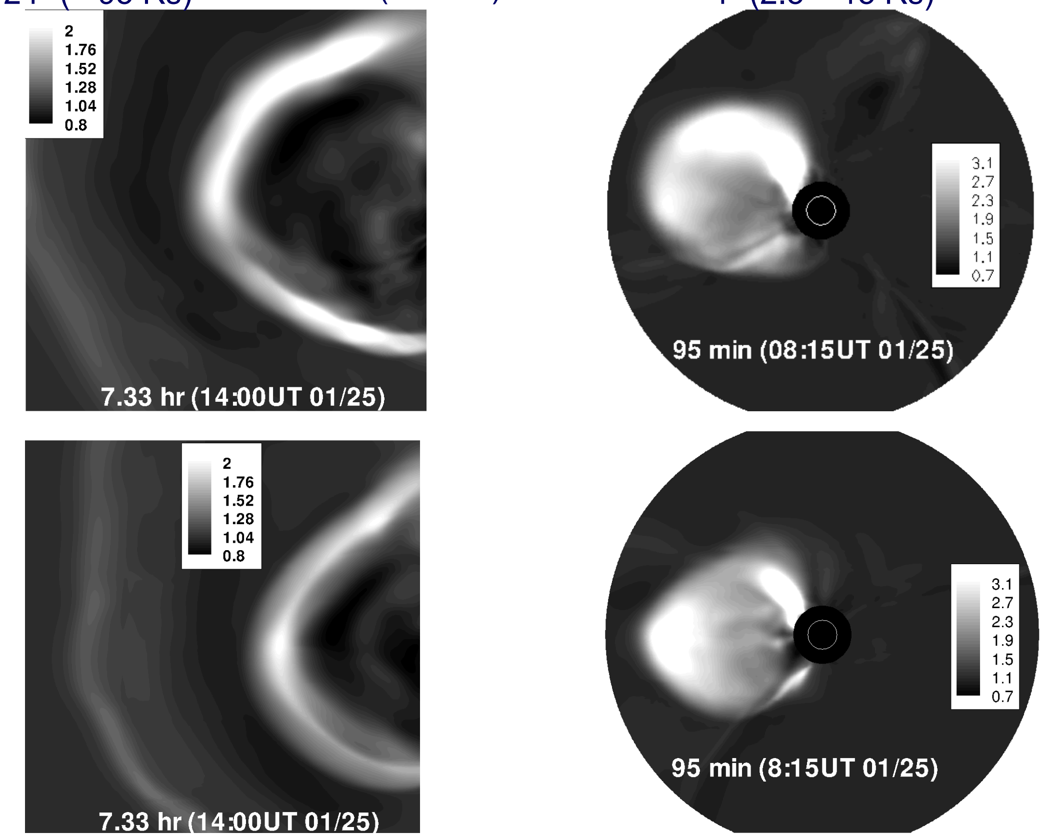
MHD Simulation provided by N. Lugaz

- **Decouple shock from streamer bending**
- **Better measurement of CME ecliptic extent**
- **Better estimate of CME mass/density distribution**

24º (~ 95 Rs) 4º (~15 Rs) 4º (2.5 – 15 Rs)

SOLAR-C

STEREO



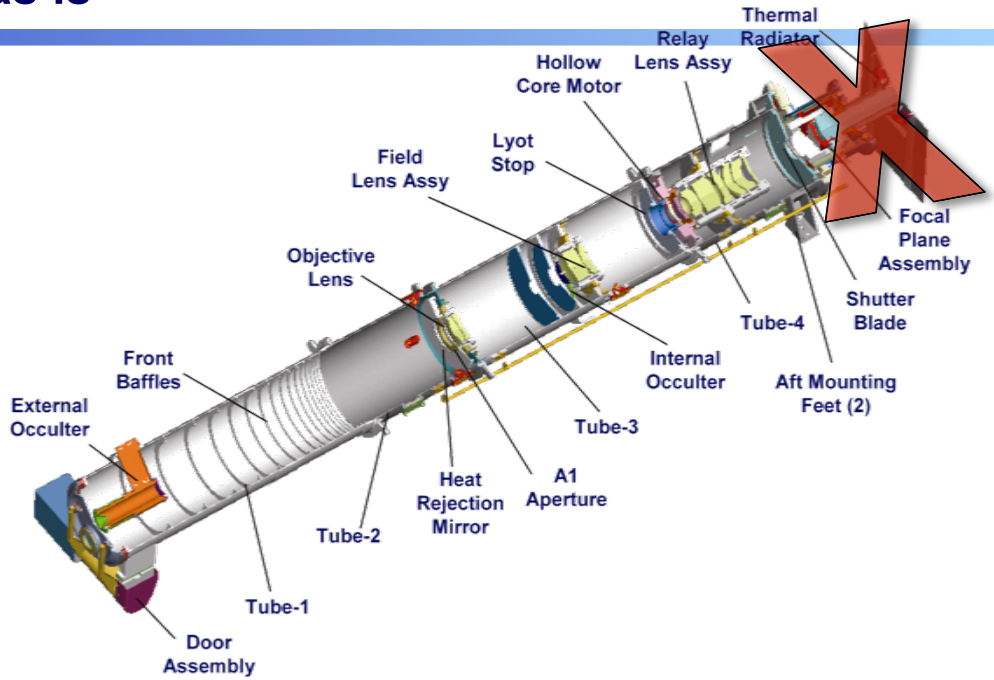
SOLAR-C

STEREO

Instrument Concepts for Plan-A

Option 1: Use SECCHI/COR2 (almost) as is

	COR2	Modified
FOV (Rs)	2.5 -15	**1.5 - 15**
Spatial Res. (")	30	30
Exposure (sec)	2	2
Bandpass (nm)	650-750	650-750
Polarization	Yes	Yes
Detector	2kx2k CCD	**2kx2k APS**
Mass (Kg)	10	**5.5**
Volume (m)	$120x14^2$	**$120x10^2$**
Power (W)	10	**8**
TRL	9	**5**



Why?

- High TRL design, meets science objectives
- APS implementation lowers mass/power/volume

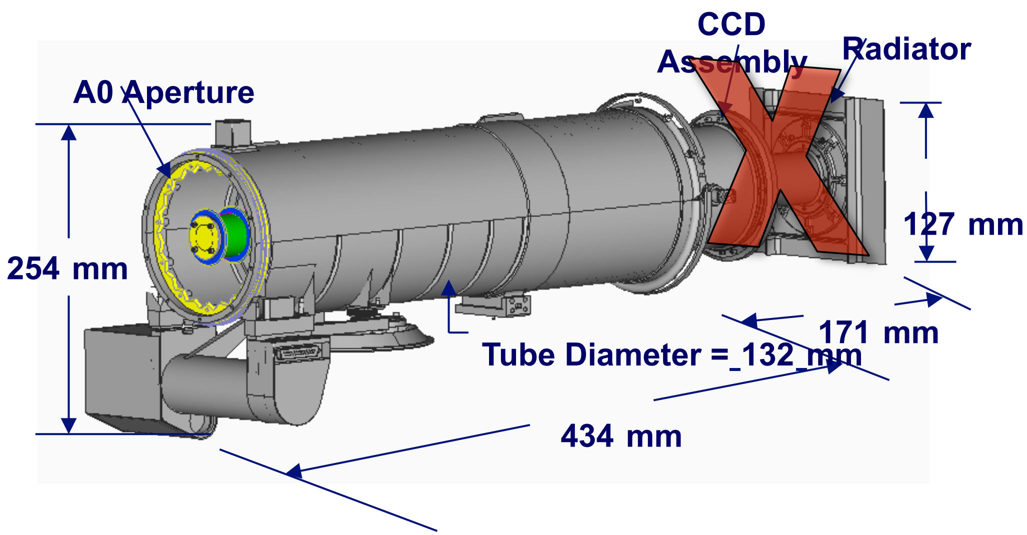
Changes from COR2

- CCD →APS
- Occulter position mechanism (as in LASCO)

Instrument Concepts for Plan-A

Option 2: Compact Coronagraph (CCOR)

	COR2	CCOR
FOV (Rs)	2.5 -15	**1.5 - 15**
Spatial Res. (“)	30	30
Exposure (sec)	2	~5
Bandpass (nm)	650-750	650-750
Polarization	Yes	Yes
Detector	2kx2k CCD	2kx2k APS
Mass (Kg)	10	**<4**
Volume (m)	$120x14^2$	**$45x13^2$**
Power (W)	~10	**~3**
TRL	9	**4**



Why?

- Very compact design, meets science objectives
- APS implementation lowers mass/power/volume

Changes from COR2

- CCD →APS (exists)
- Occulter position mechanism (ala LASCO)
- Lower TRL (design studies for 3 missions)

Augmentation Options for Plan-A

- **Heliospheric Imager (details)**
  - Extend FOV to ~90 Rs (24º) along Sun-Earth line
  - Solar wind, dust, Space Weather studies
  - Moderate to small resource requirements (<4kg, <3W)
  - Low risk.
- Compact Spectrograph (details)
  - Coronal spectroscopy capability with modest resources
  - Solar wind & CME velocities, thermal broadening, heating profiles
  - Composition of plasma in CMEs, plumes, solar wind.

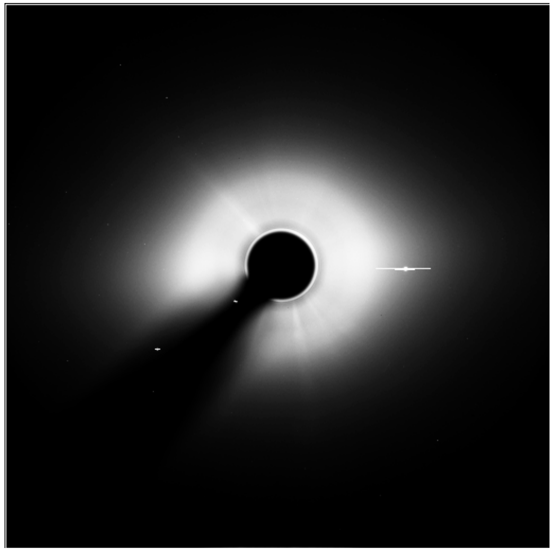
Summary

- **Out-of-ecliptic orbit offers unique advantages for CME & heliospheric studies**
  - The corona has never been imaged before from such a viewpoint
  - Better viewing of global corona, better 3D reconstructions of events, better imaging of solar wind structures, unique dust & IPS measurements.
- **Coronagraph telescope is an important payload complement**
  - Several high TRL options
  - Small mass & power requirements
  - Modest telemetry requirements
  - Large FOV, short exposures, simple electronics
- **Heliospheric Imager is a viable option**
  - It depends on available s/c resources, orbit design
  - High payoff for space weather and solar wind studies

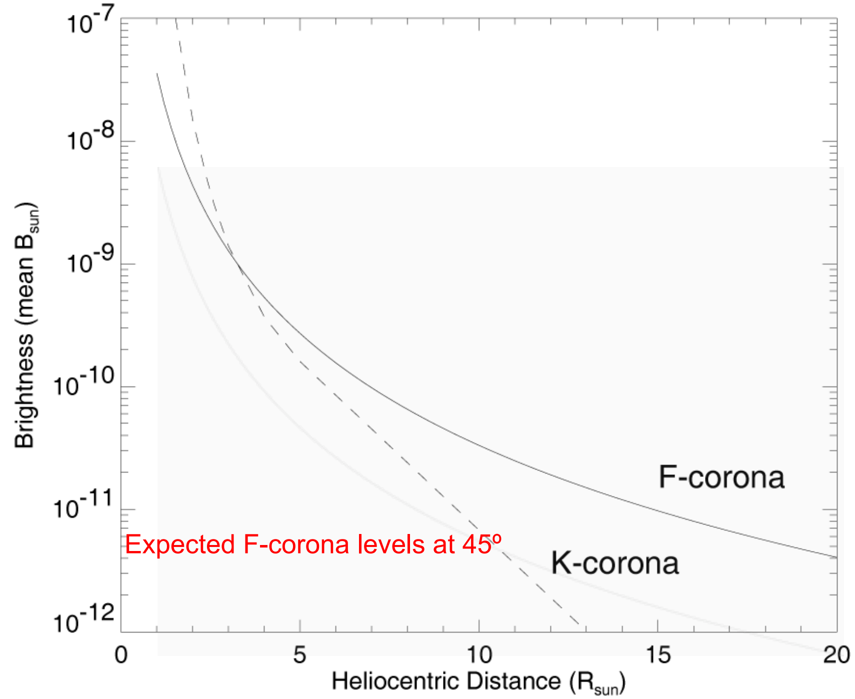
BACKUP SLIDES

Reduction in F-Corona Signal for Plan-A Orbit

- **Reduced F-corona signal improves SNR of white light observations dramatically.**
- **Orbit is ideal for dust studies!**

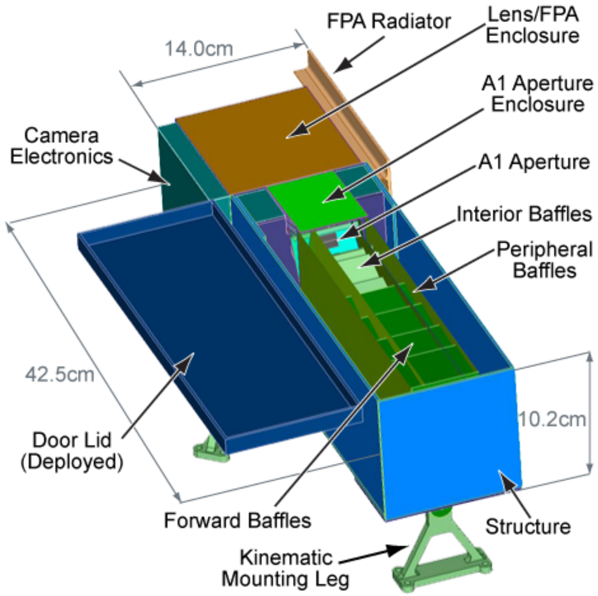


Raw C3 Image



Heliospheric Imager for SOLAR-C (HISOC)

	COR2	HISOC
FOV (Rs)	2.5 -15	**4 - 84**
Spatial Res. (“)	30	36
Exposure (sec)	2	Variable
Bandpass (nm)	650-750	500-700
Polarization	Yes	No
Detector	2kx2k CCD	2kx2k APS
Mass (Kg)	10	**4.5**
Volume (cm)	$120x14^2$	**42x14x18**
Power (W)	~10	**>1**
TRL	9	**4**



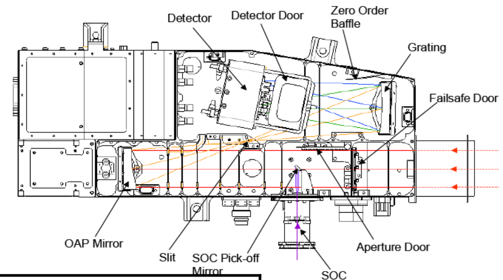
Why?

- Expands mission objectives with minimum resource investment.
- Very compact design
- No mechanisms
- Uses same APS as the coronagraph
- Lower TRL but minimum risk

Coronal Spectrograph Concept

NOTE: This is a strawman concept. Needs further study to adapt it to Solar-C mission requirements.

Based on Alice Spectrograph

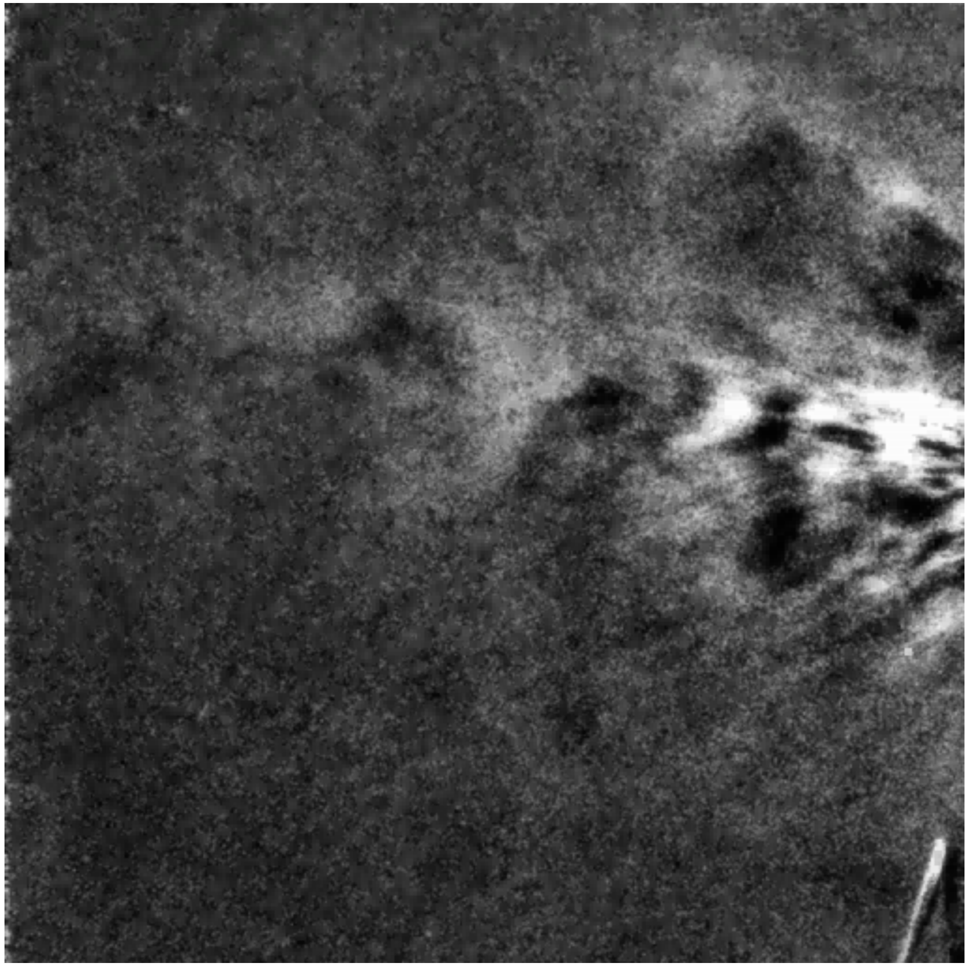


Wavelength range	970-1040 Å
Lines	Lyγ, Fe XVIII, CIII, Ar XII, Fe XII, Lyβ, Fe X, OVI doublet, Si XII (2nd order)
Effective Area	1 cm^2
Mass	<4.4 kg

UV line property	Physical properties measured/ derived	Relevant issues about corona, solar wind and solar transients
Line profile From O VI (O^{+5}, M/Q=3.2), Si XII (Si^{+11}, M/Q=2.5), Lyβ (H^{+0}/proton), C III (C^{+2})	Non-thermal ion velocity in the corona and solar wind Line broadening by CME shocks or expansion Electron temperature	Variations of non-thermal ion velocities with time, heliocentric height, fast/ slow wind regions, and M/Q → Solar wind heating, acceleration and turbulence Ion temperatures associated with heating by CME shocks (mass or M/Q dependency?) → CME/ICME properties and SEP production Electron temperature in the corona and CMEs → coronal and CME temperature structure
OVI λλ1032/1037 intensity ratio	Solar wind ion outflow speed (100-400 km/s), O^{+5} as a proxy	Solar wind ion speed as a function of heliocentric height and within slow/ fast wind regions →Solar wind heating and acceleration, solar wind origin CME propagation speed →CME energetics
Elemental abundance From O VI, Lyβ, Si XII, Fe X and C III line ratios	Si/O, Fe/O, O/H, Si/H, Fe/H in the corona/solar wind and CMEs	FIP effect associated with location of fast /slow solar wind flows and position relative to close/open field regions and heliospheric plasma sheet → solar wind origin Possible mass differentiation along SW flow →dynamics and propagation of solar wind Abundances in CME/ICME →CME initiation
Line intensity From O VI, Lyβ, Si XII, C III and Fe XVIII	Emission line fluxes in the corona/solar wind and CMEs Electron density and temperature	Variations with space and time → solar wind 'blobs' and turbulence Variations with heliocentric height and longitude →coronal and solar wind spatial structure CME density, temperature and composition structures →CME initiation, evolution and energetics, relation to ICME properties CME shock parameters, e,g. compression ratio →SEP production Post-CME current sheet properties →CME initiation and reconnection, SEP production
Doppler shift of lines From O VI, Lyβ, C III	Line-of-sight velocity	3-D CME velocity structures →CME initiation and evolution, CME/ICME structure

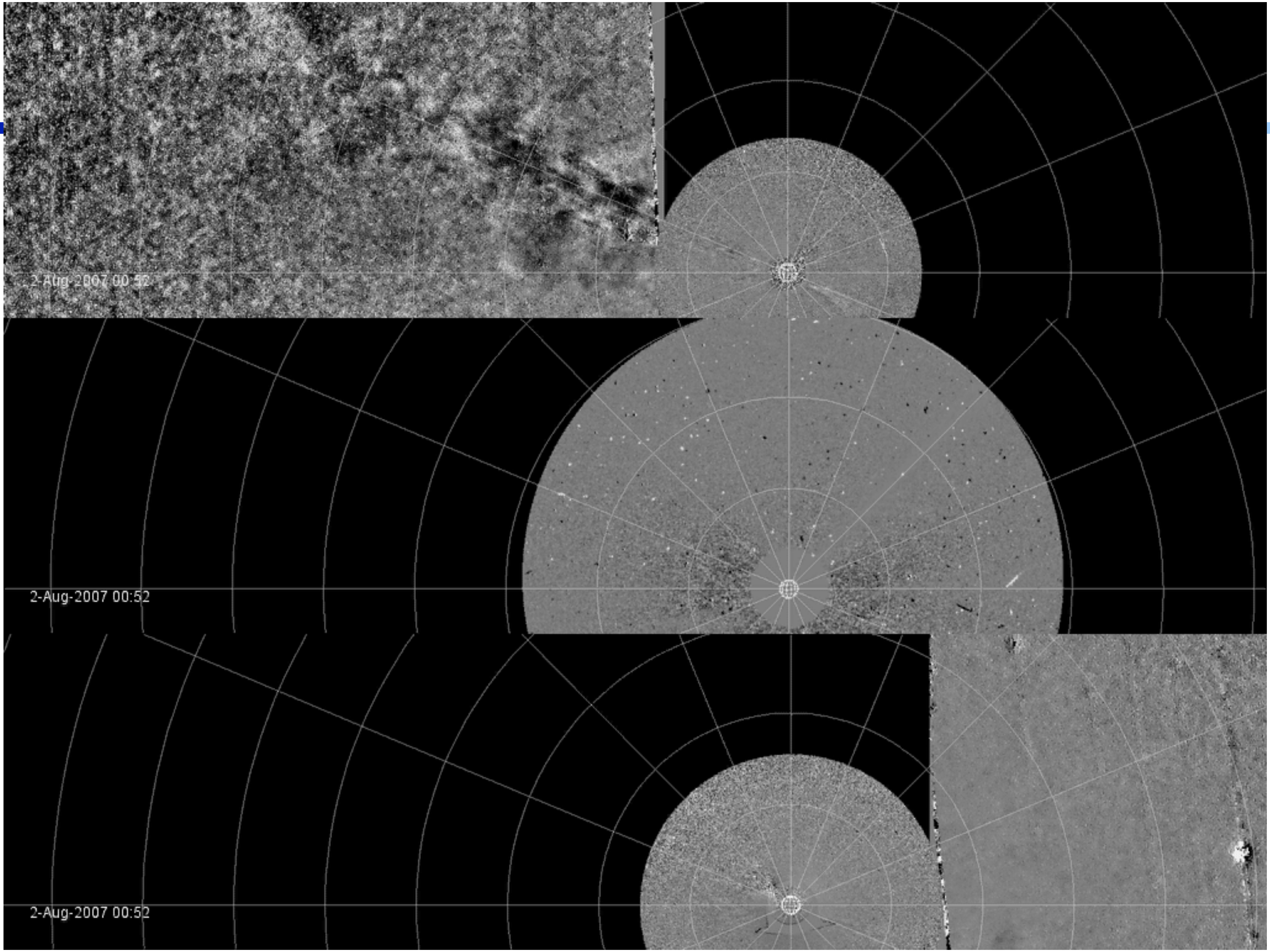
Solar Wind Outflow in HI-1

$\varepsilon = 24°$ $\varepsilon = 4°$

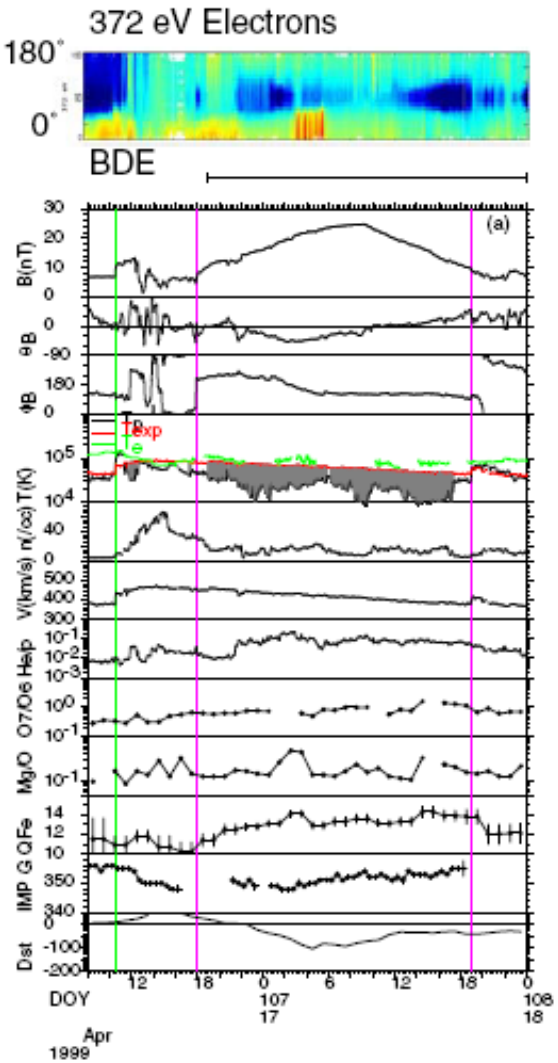


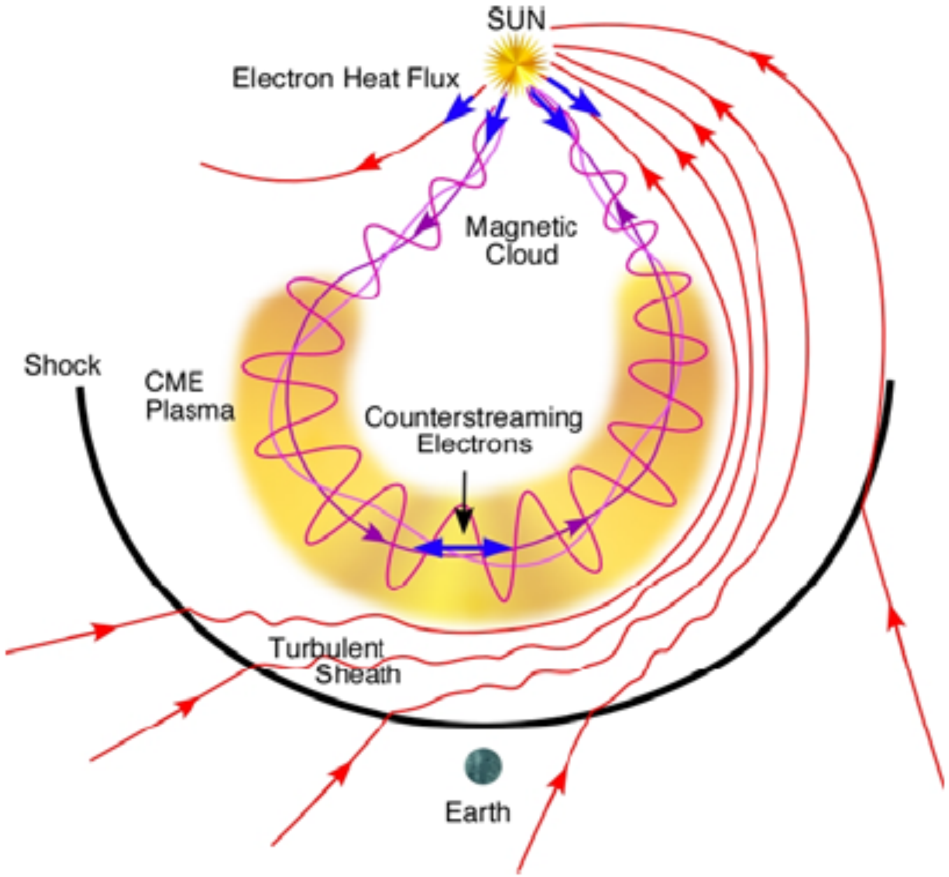
Approximate location of Sun (not to scale!)

HI1-A observations for the month of April, 2007


2-Aug-2007 00:52
2-Aug-2007 00:52
2-Aug-2007 00:52

Current Ideas on Interplanetary CMEs





Corotating Interaction Regions

Pizzo, V. (1978), *J. Geophys. Res.*, 83, 5563