Probing the origin of the slow solar wind, CMEs and SEPs using combined imagery, in-situ data and numerical modeling

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Many thanks to: Neil R Sheeley[3], Jackie Davies[4], Allan Tylka[5] D. Odstrcil[4], A. Vourlidas[4], Chee Ng[3], Benoit Lavraud[1,2], Yi-Ming Wang[3], Valbona Kunkel[3], Vincent Génot[1,2] CDPP team and many many others…

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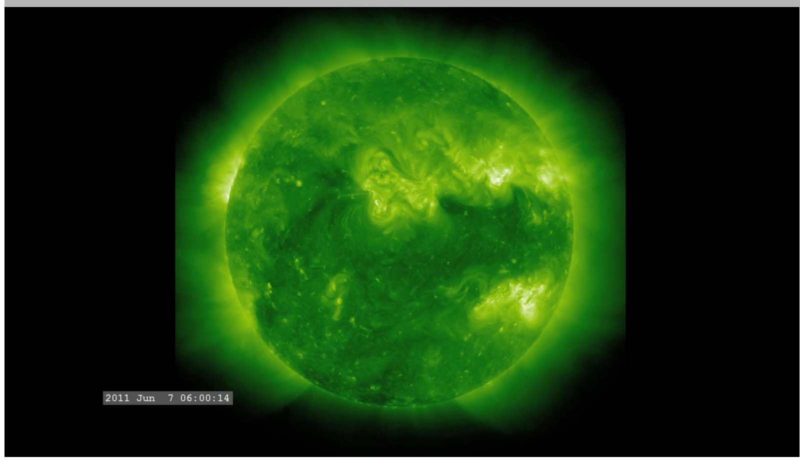

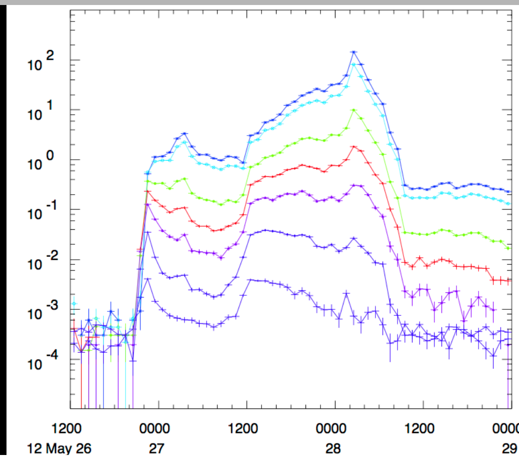

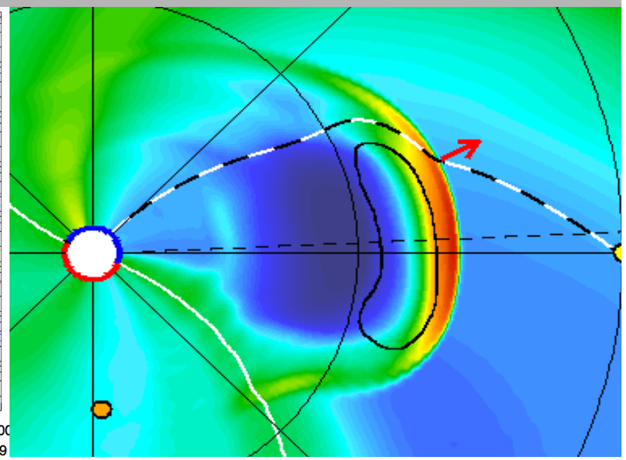

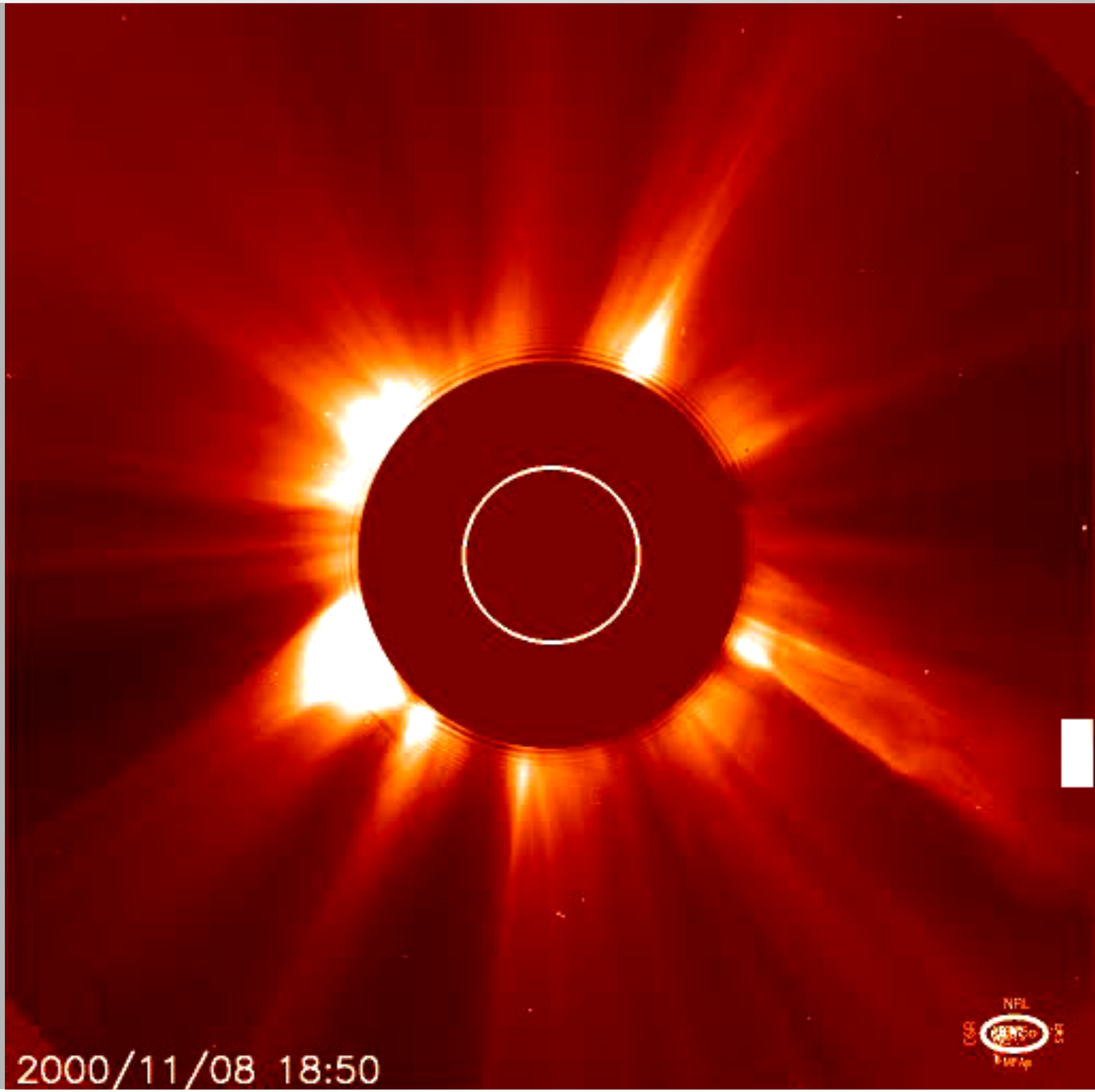
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Plan of lecture:

To review recent (mainly STEREO) observational results on:

- **the slow solar wind**
  >> solar/coronal origin, origin of variability

- **the properties of CMEs**
  >> solar/coronal origin, topology, energy budget, propagation

- **the acceleration of SEPs**
  >> solar/coronal origin, spatial spread and content, GLEs

For each topic I will highlight the importance of the Solar Probe + and of the Solar Orbiter missions in solving key science questions.

The coronal magnetic field is continually driven out of its equilibrium state,

>> Transient activity is a signature of the magnetically-dominated corona's constant struggle to retrieve a lower energy state.

Effects on the interplanetary medium

- → Changes the electromagnetic output of the Sun
- → Can define the source region location of the fast solar wind
- → Generates a fraction (all?!) of the slow solar wind
- → Releases strong magnetic field regions in the interplanetary medium
- → Fast ejection generates converging flows and pressure gradients
- → Changes the flux and spectra of particules (thermal, suprathermal, high-energy)

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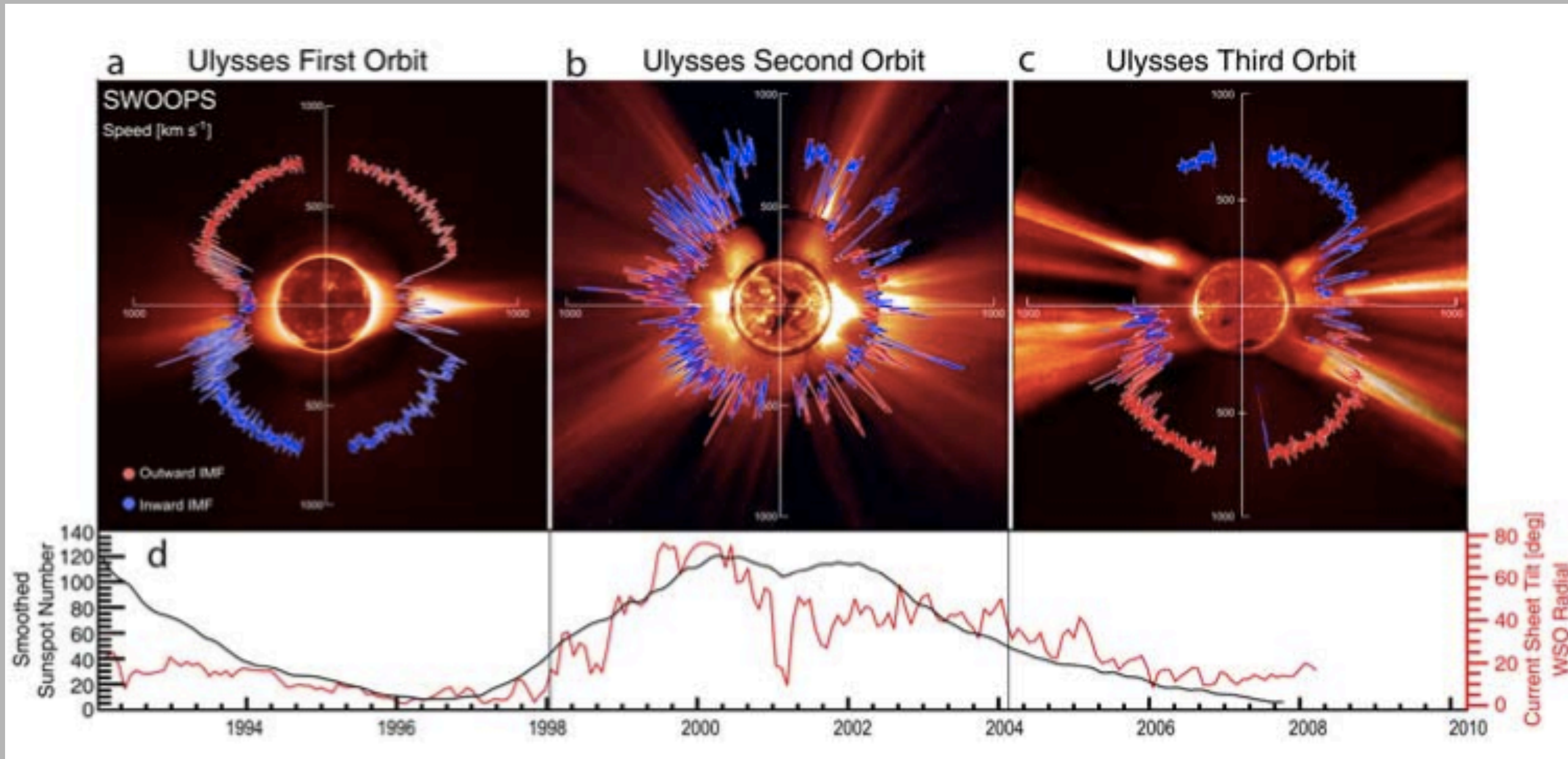
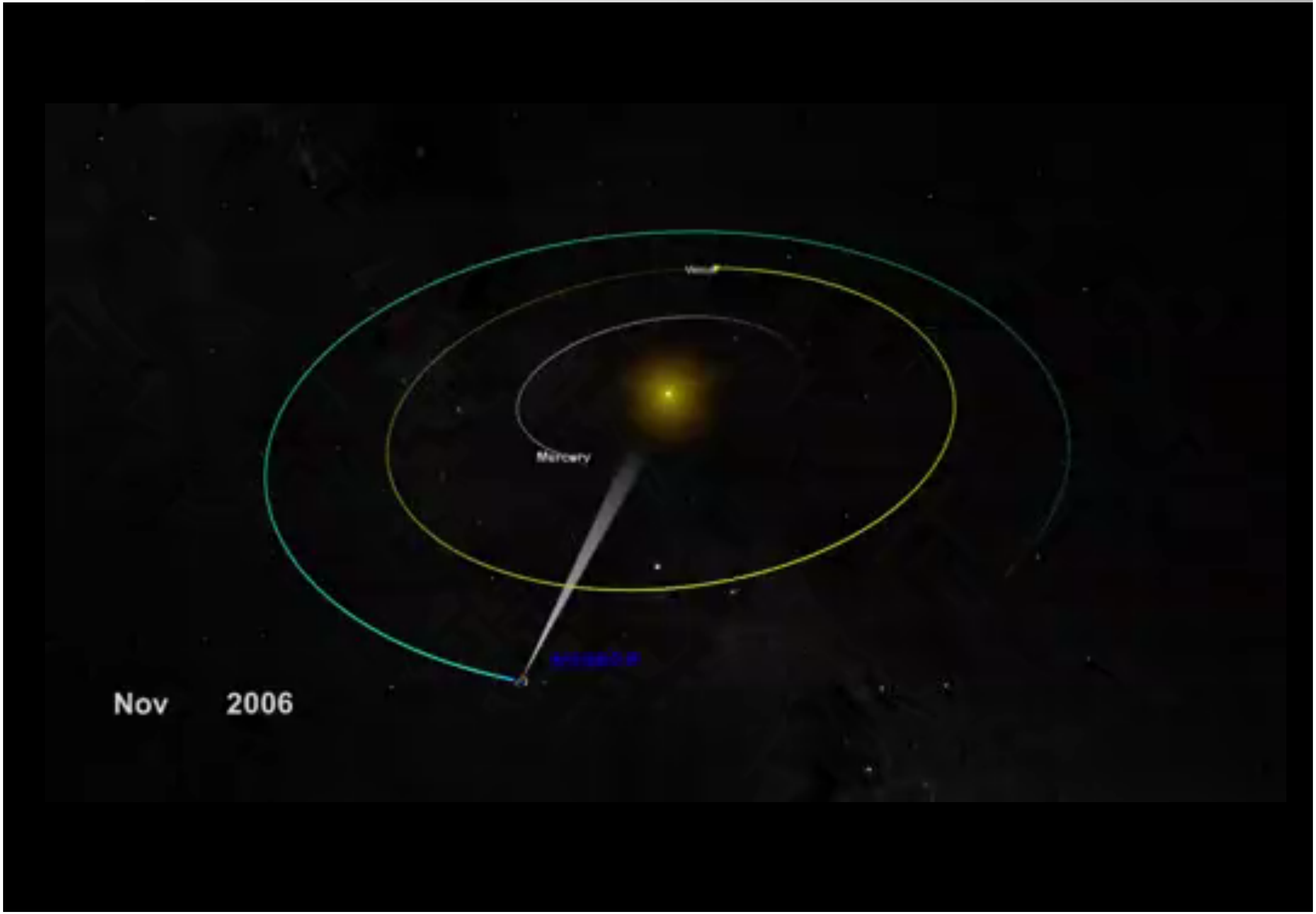
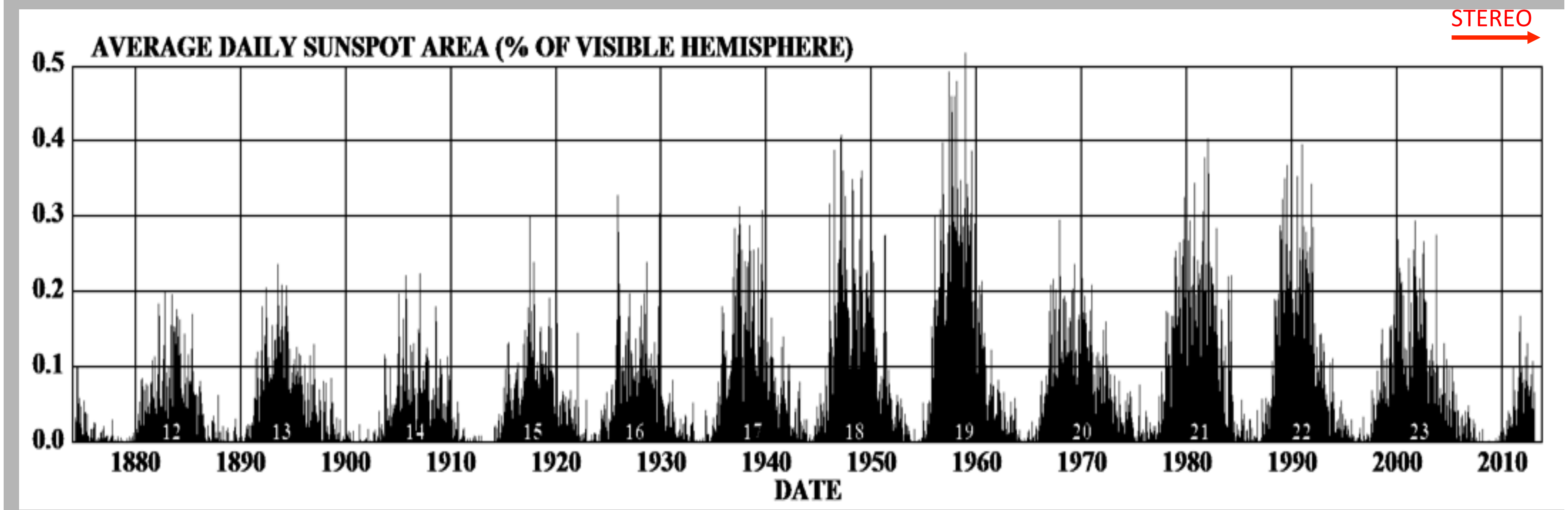


McComas et al. 2008


Mercury
Nov 2006


STEREO
AVERAGE DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)
0.5
0.4
0.3
0.2
0.1
0.0
12
13
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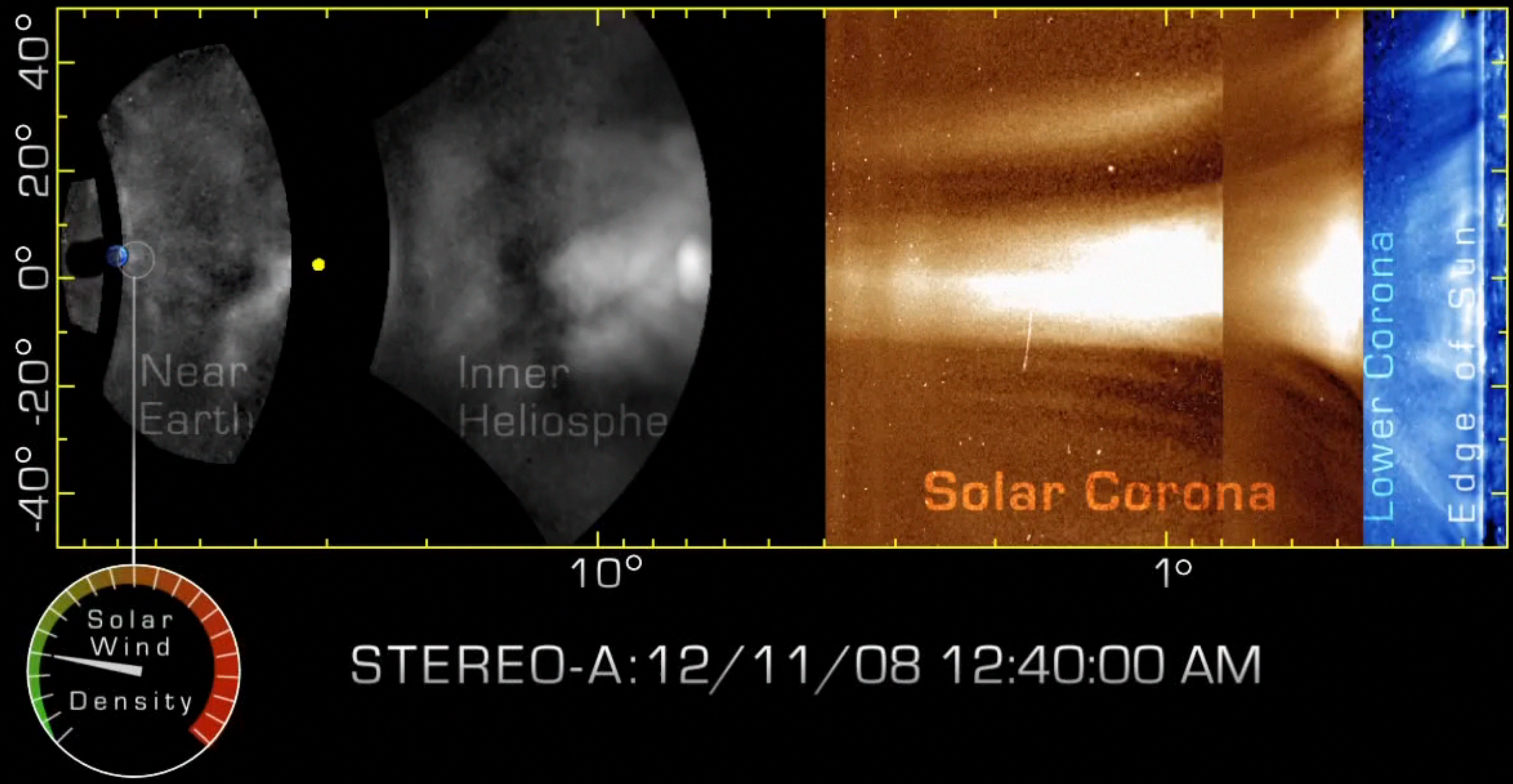
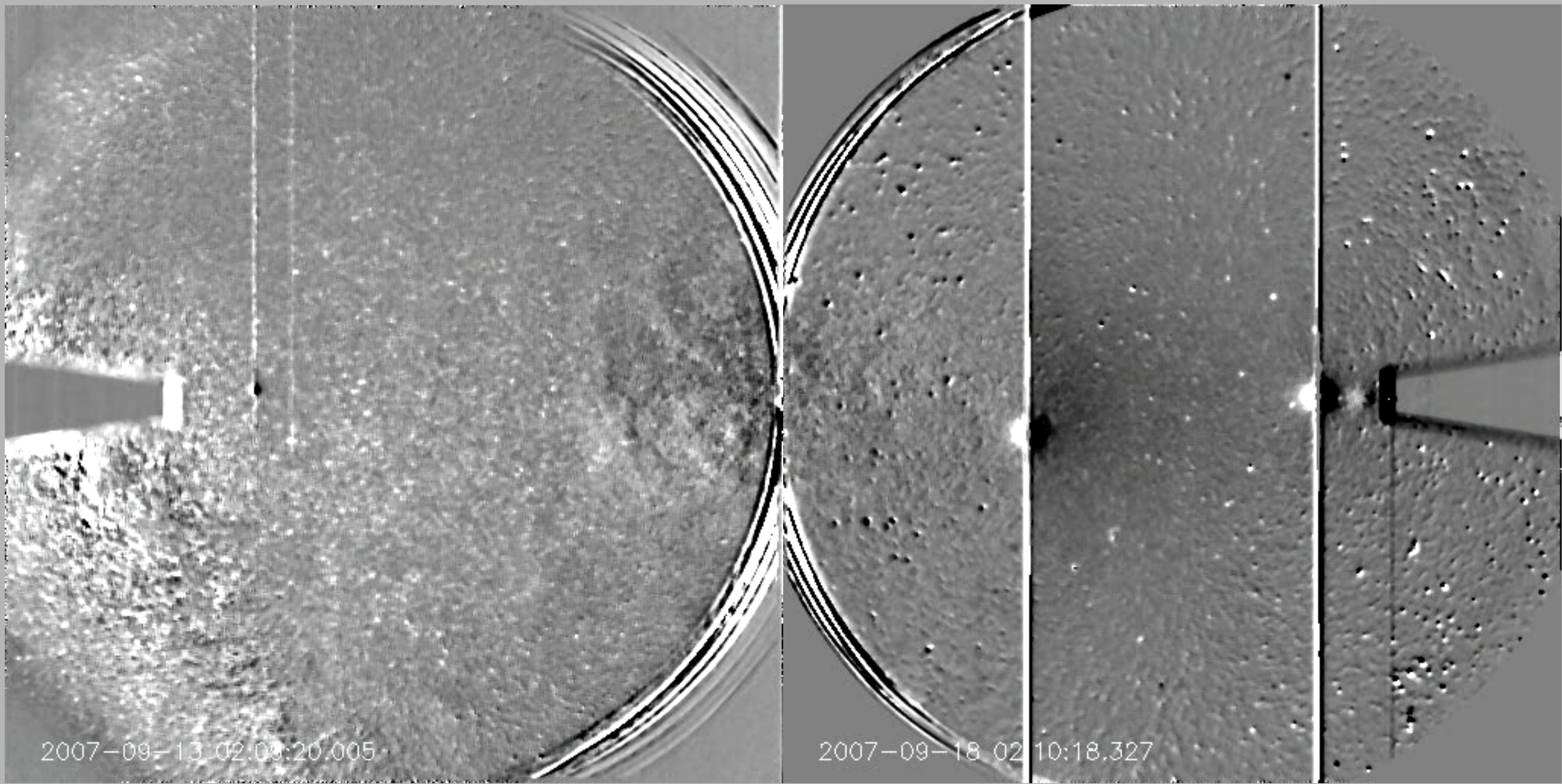
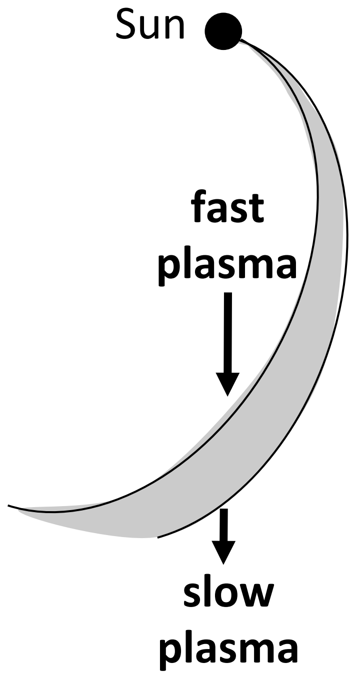


DeForest et al. 2013



HI-2A

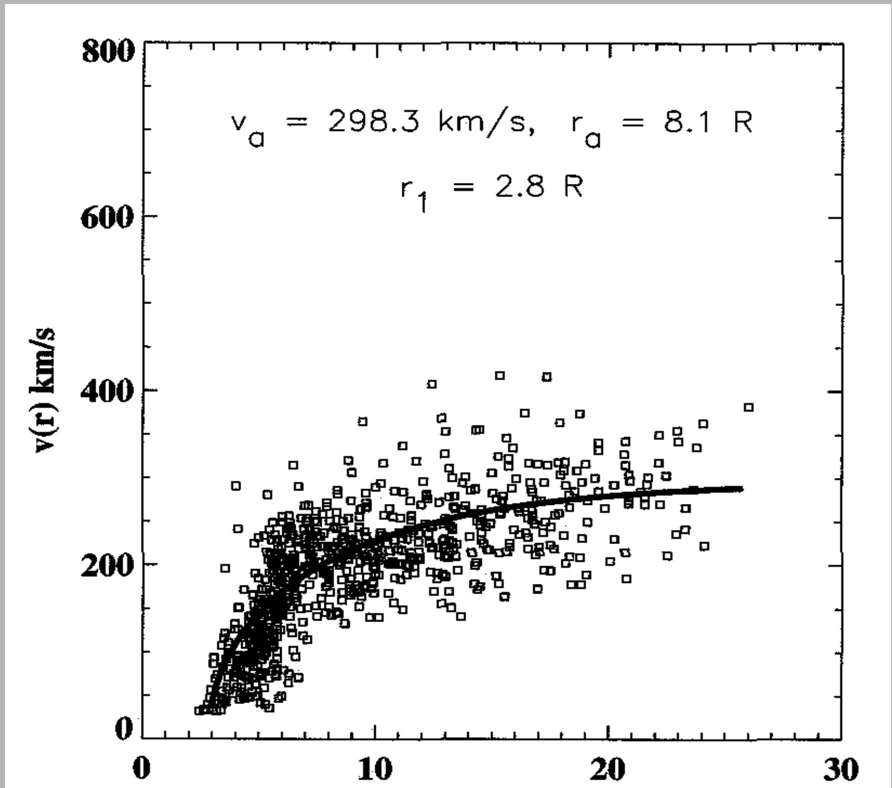
HI-2B

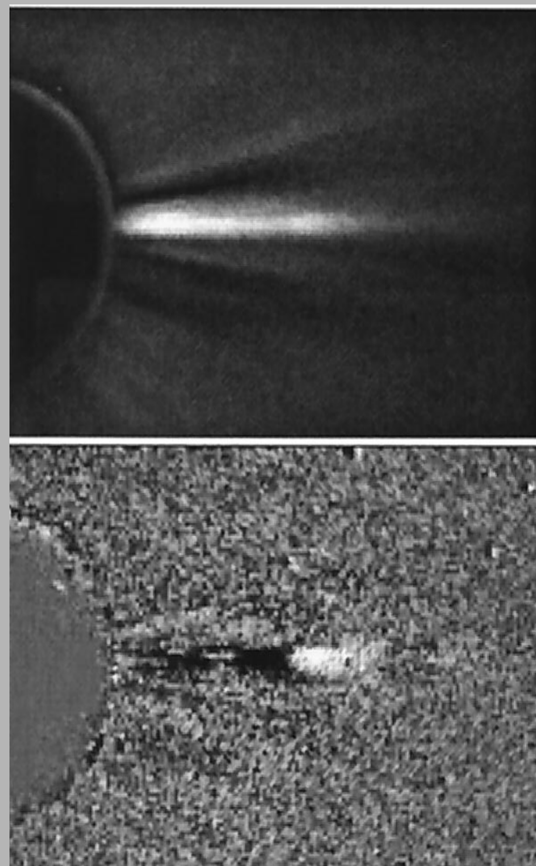

Sun
fast
plasma
slow
plasma

The variability of the slow solar wind can be generated either through:

- the formation mechanism of the wind

- or is added to the wind in a separate transitive process.

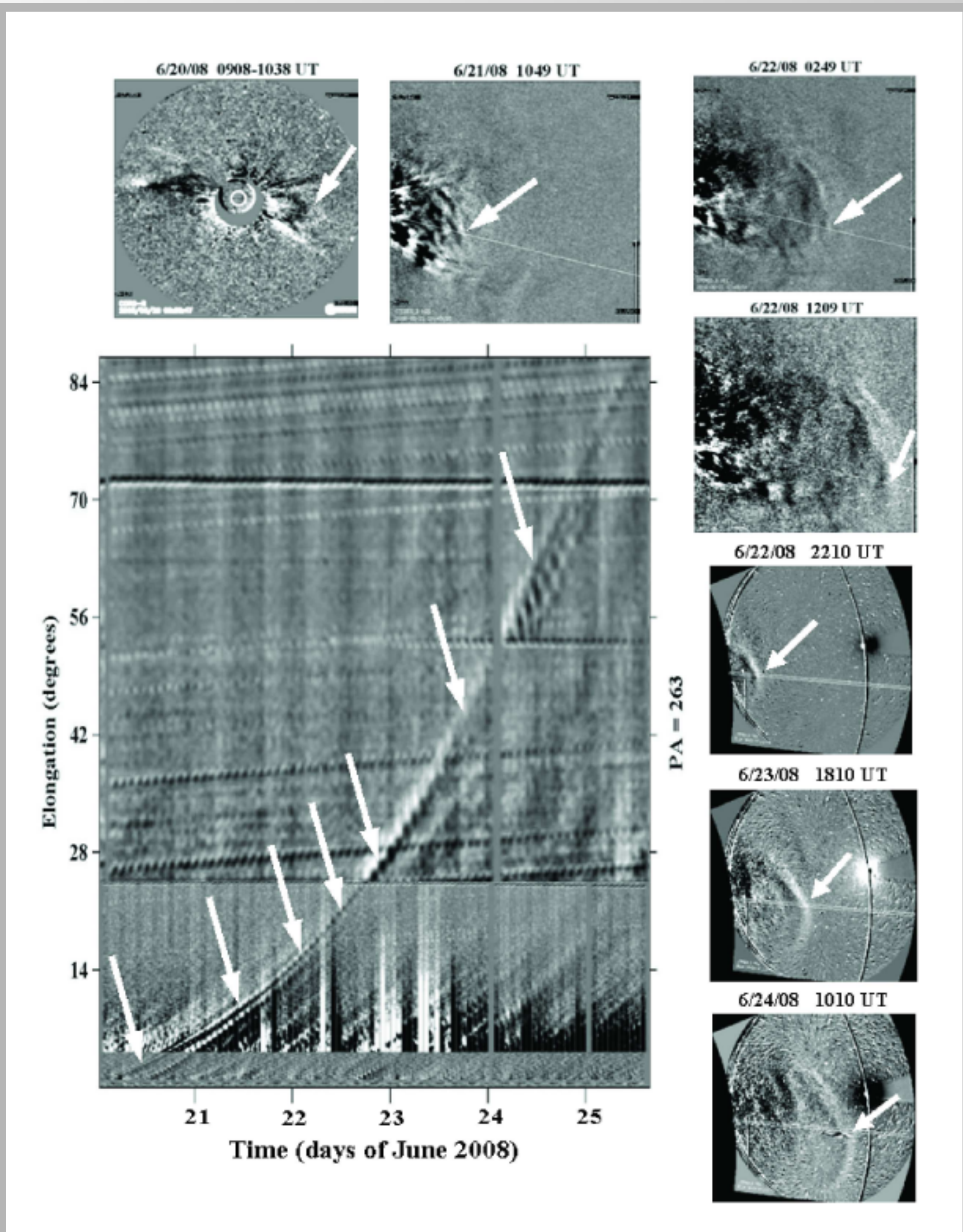




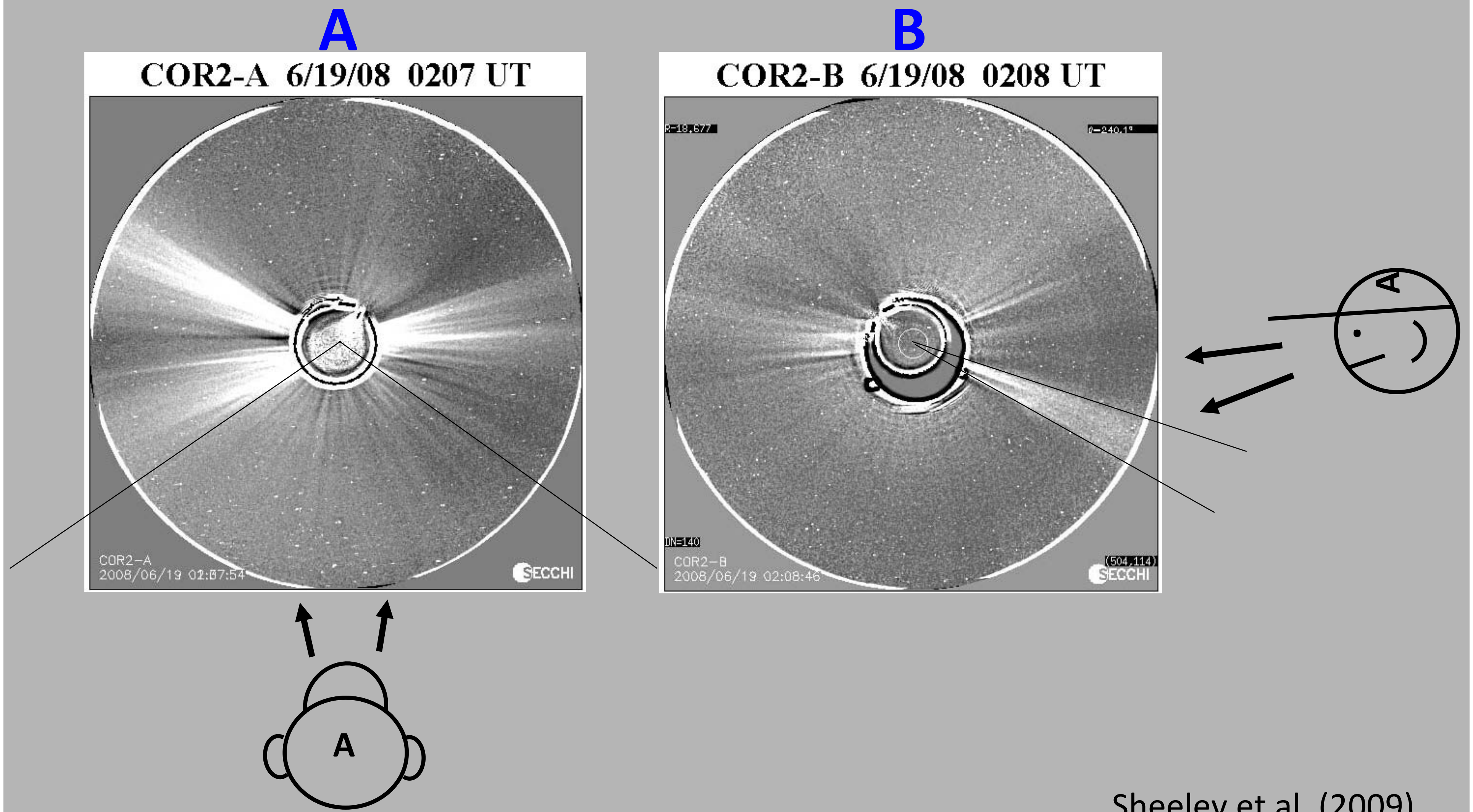
4-6 edge-on blobs per day (1996-1998)
Sheeley et al. (1999)

Wang et al. (2008)

These blobs provide a subset of the density variability of the slow solar wind.

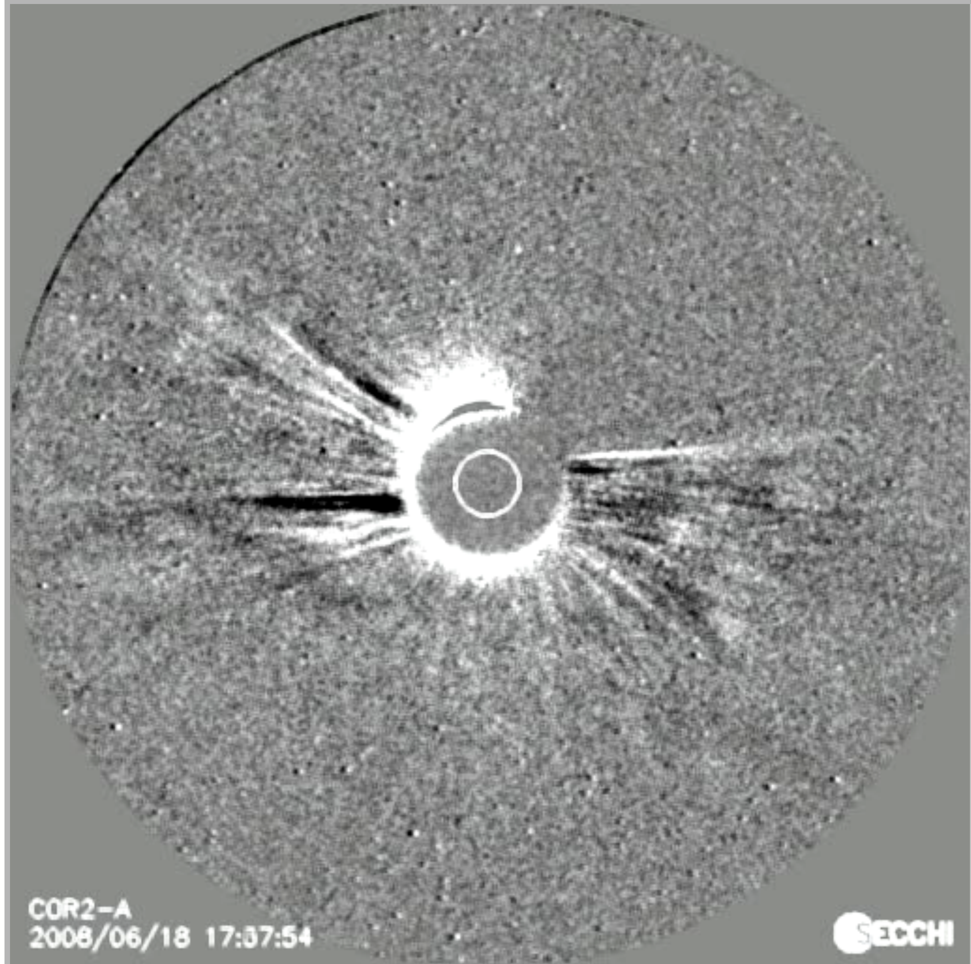


Sheeley and Rouillard (2010)
Rouillard et al. (2011)



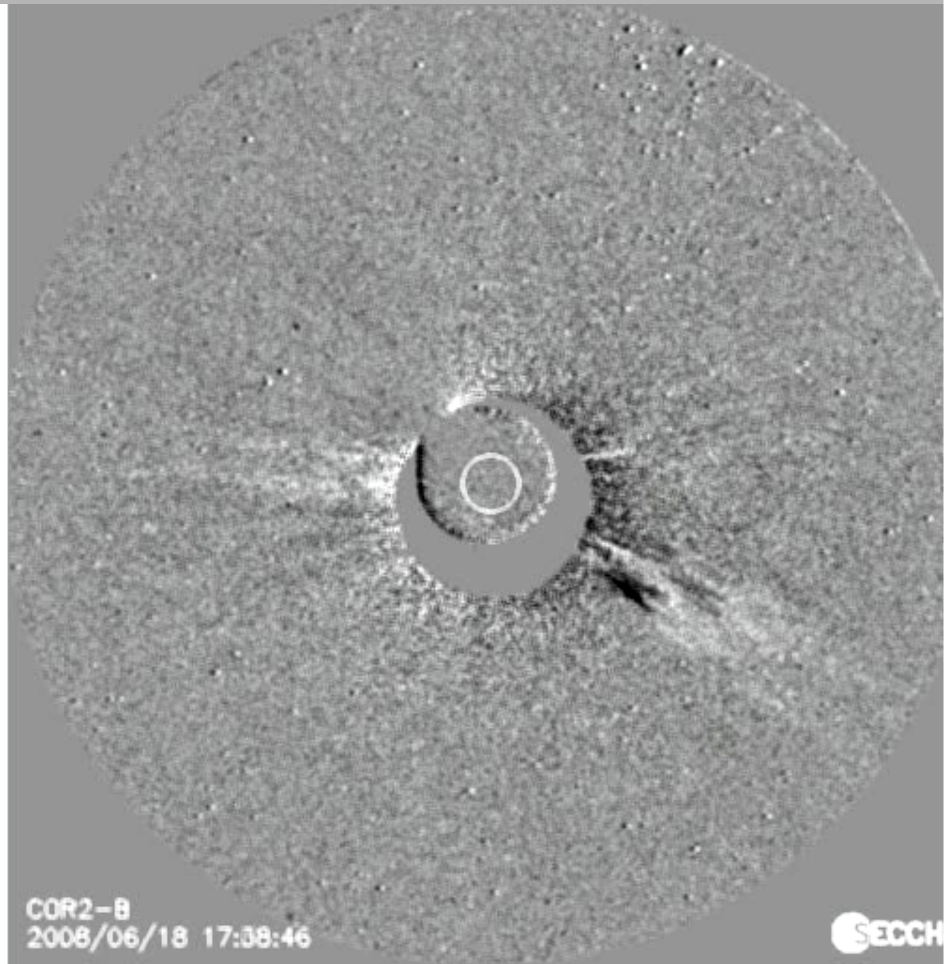
Sheeley et al. (2009)

COR-2A



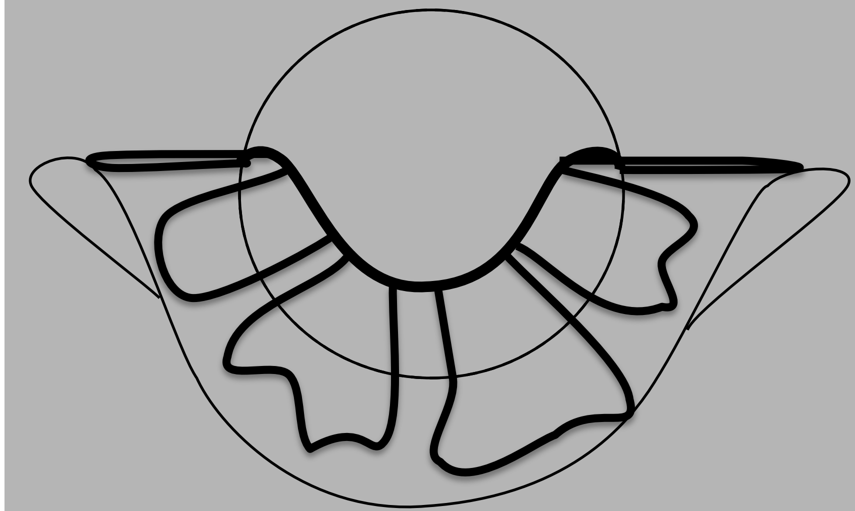
Arc-like structures emitted over 20-40 degrees PA range

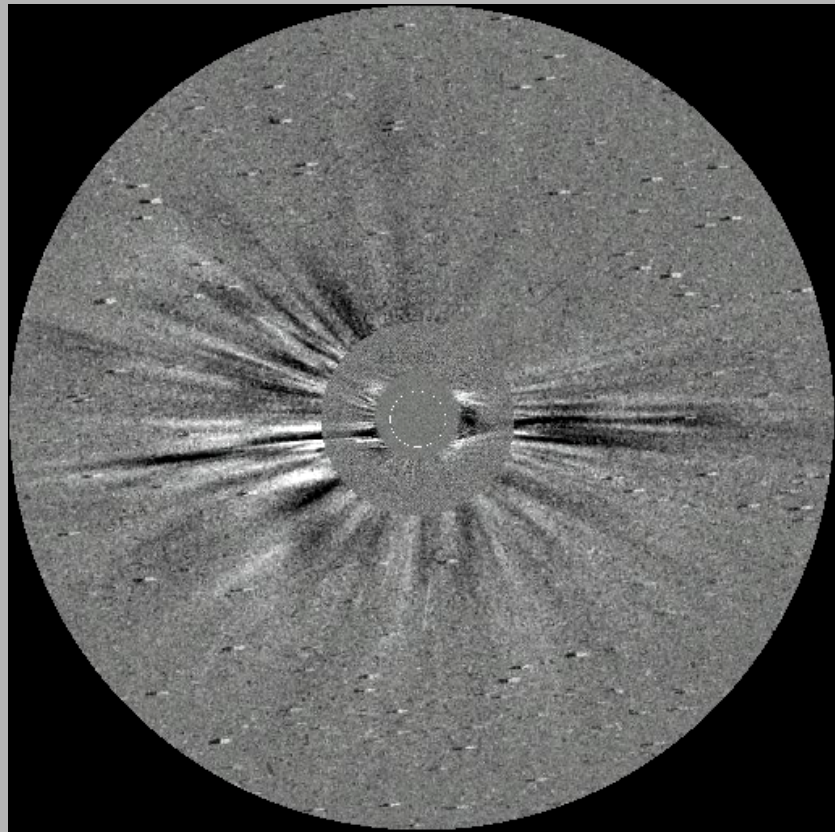
COR-2B



2-3 edge-on blobs per day

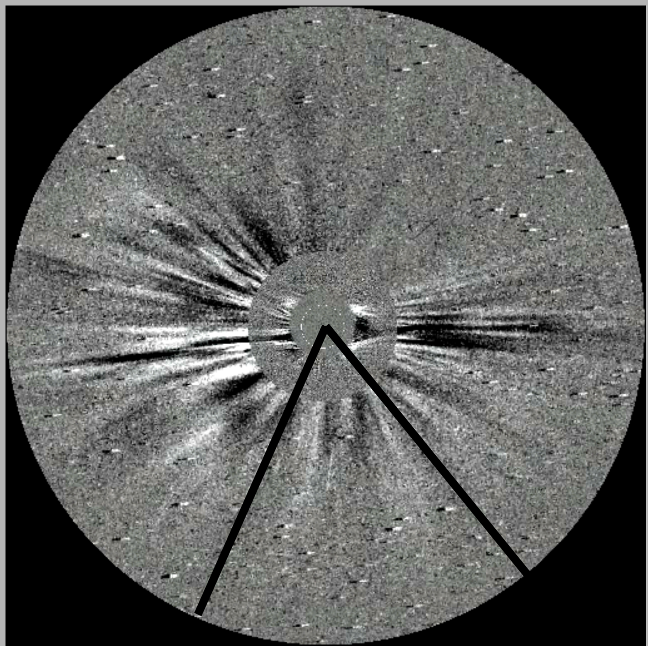
Blobs observed face-on at high latitudes tend to be faint so we average and subtract a combination of16 running COR-1 frames and 6 running COR-2 frames: many more arc-shaped structures appear!

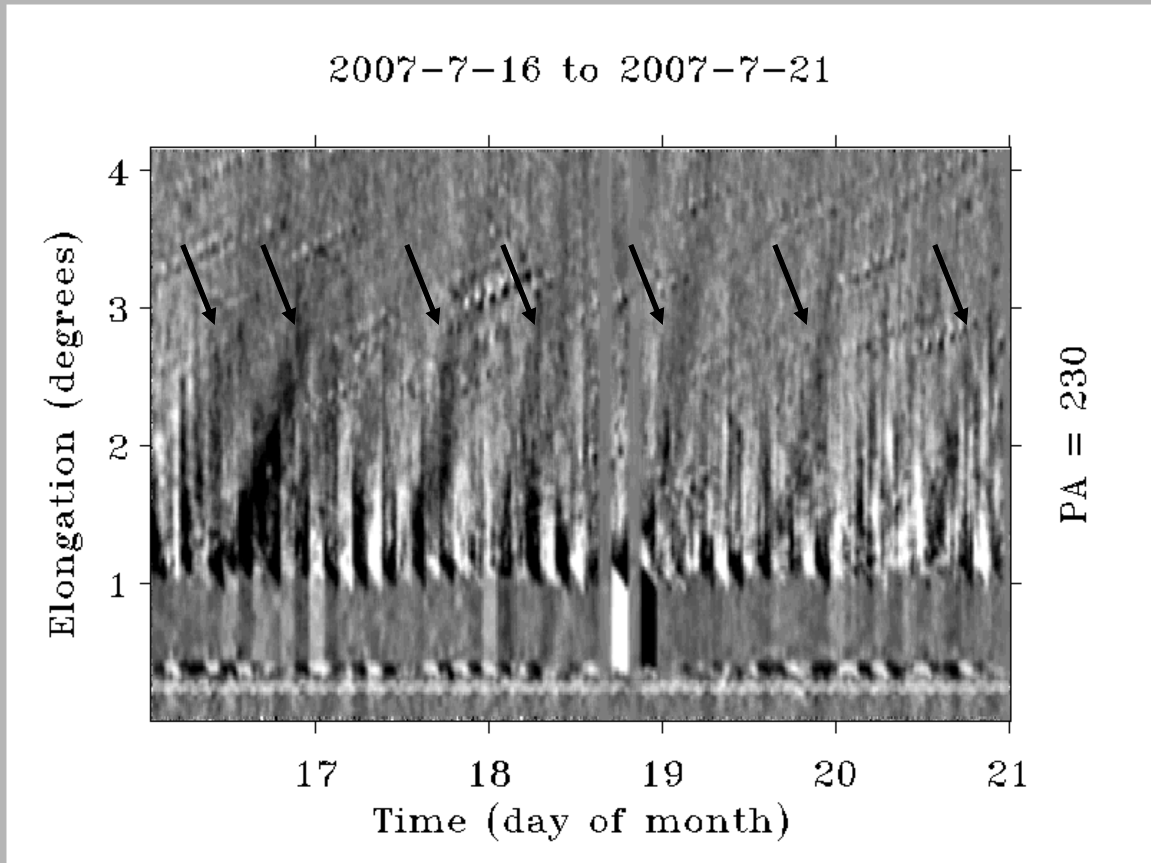




COR-1B and COR-2B: June 2008

Blobs observed face-on at high latitudes tend to be faint so we average and subtract a combination of16 running COR-1 frames and 6 running COR-2 frames: many more loop structures appear to emerge.

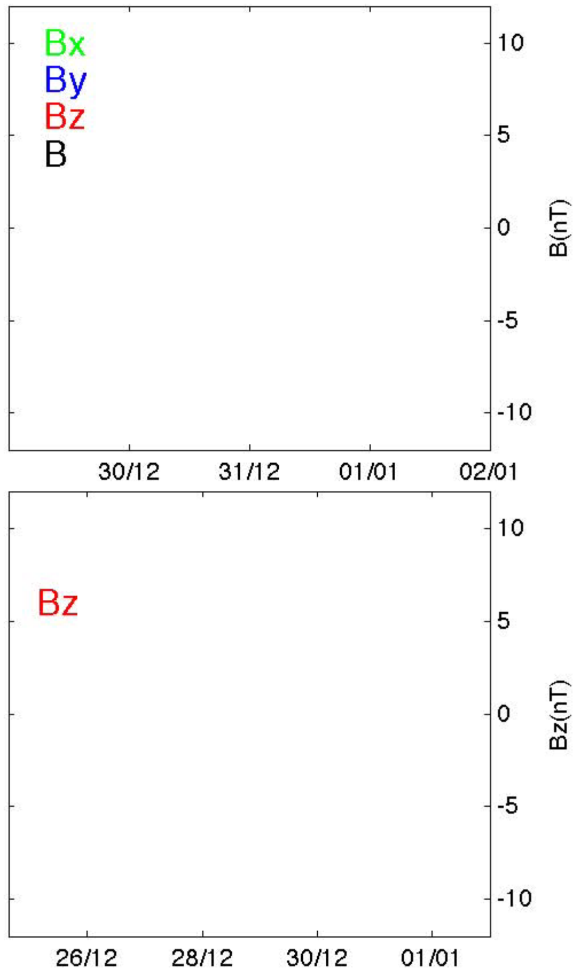




2-3 face-on blobs per day along one position angle.

30-40 degrees PA range

- The easiest transients to detect in-situ are magnetic flux ropes (often magnetically dominated regions of the solar wind with changes in magnetic field orientation and strength).



- The easiest transients to detect in-situ are magnetic flux ropes (often magnetically dominated regions of the solar wind with changes in magnetic field orientation and strength).

- Cartwright and Moldwin found evidence that the distribution of FRs is double-peaked.

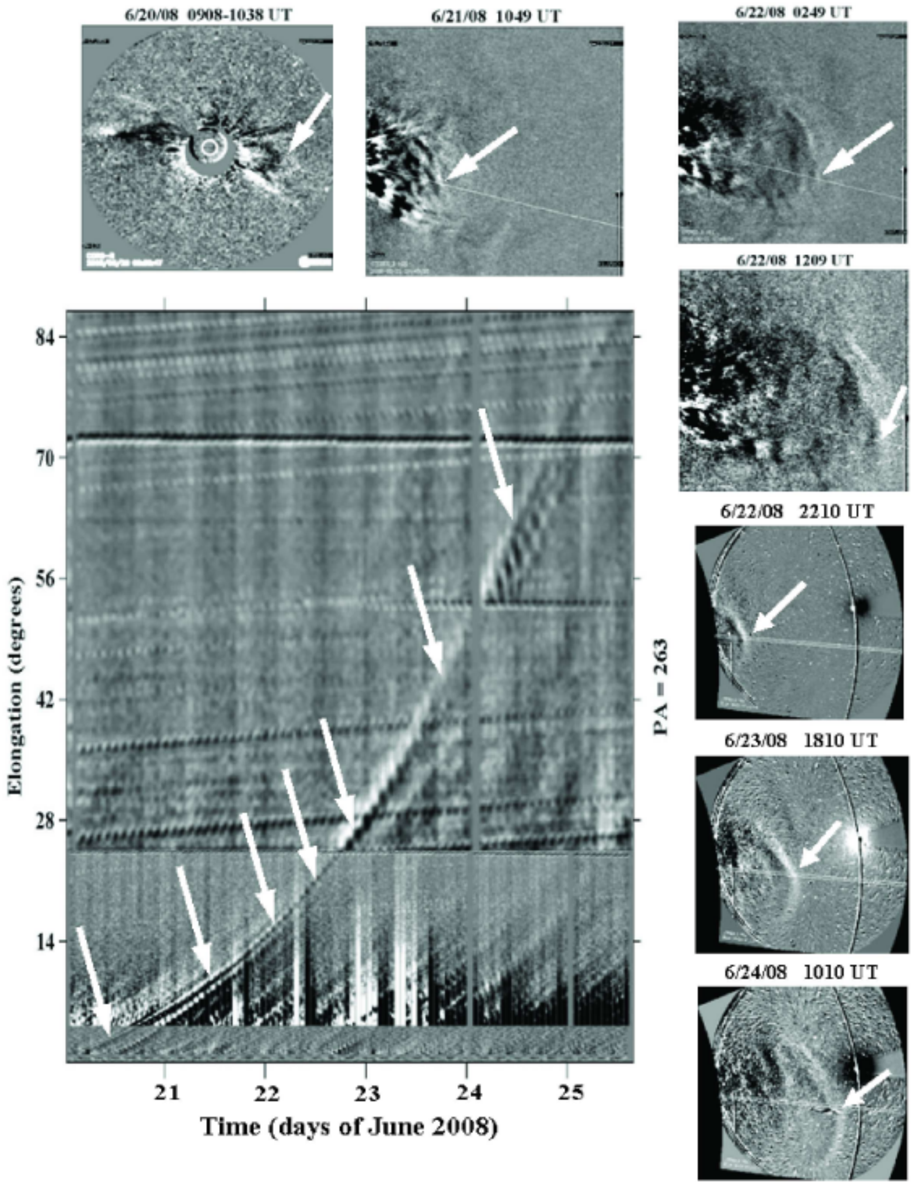
- Small-scale flux ropes are much more abundant than larger flux ropes (Feng et al. 2007)

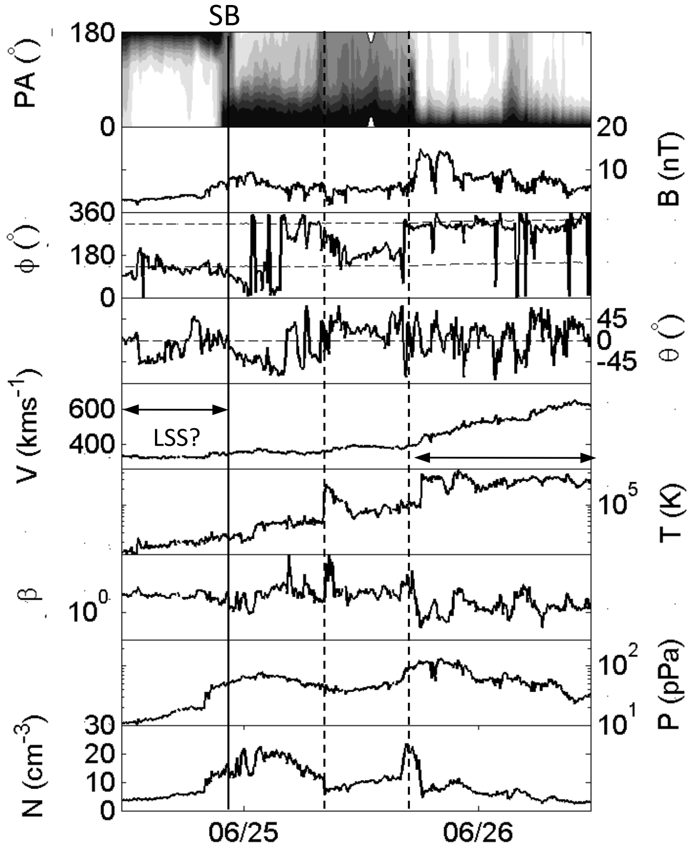
- Small scale flux ropes are ten times too adundant to corresond to CMEs as defined by LASCO CME list (Janvier et al. 2014)

- Small magnetic flux ropes with R < 0.1 AU have a steep power-law in contrast to the larger flux ropes (Magnetic Clouds) that have a Gaussian-like distribution (Janvier et al. 2014).

- Electron signatures of closed loops in slow solar wind (Kilpua et al. 2009) and refolded magnetic field lines (Crooker et al. 2003).

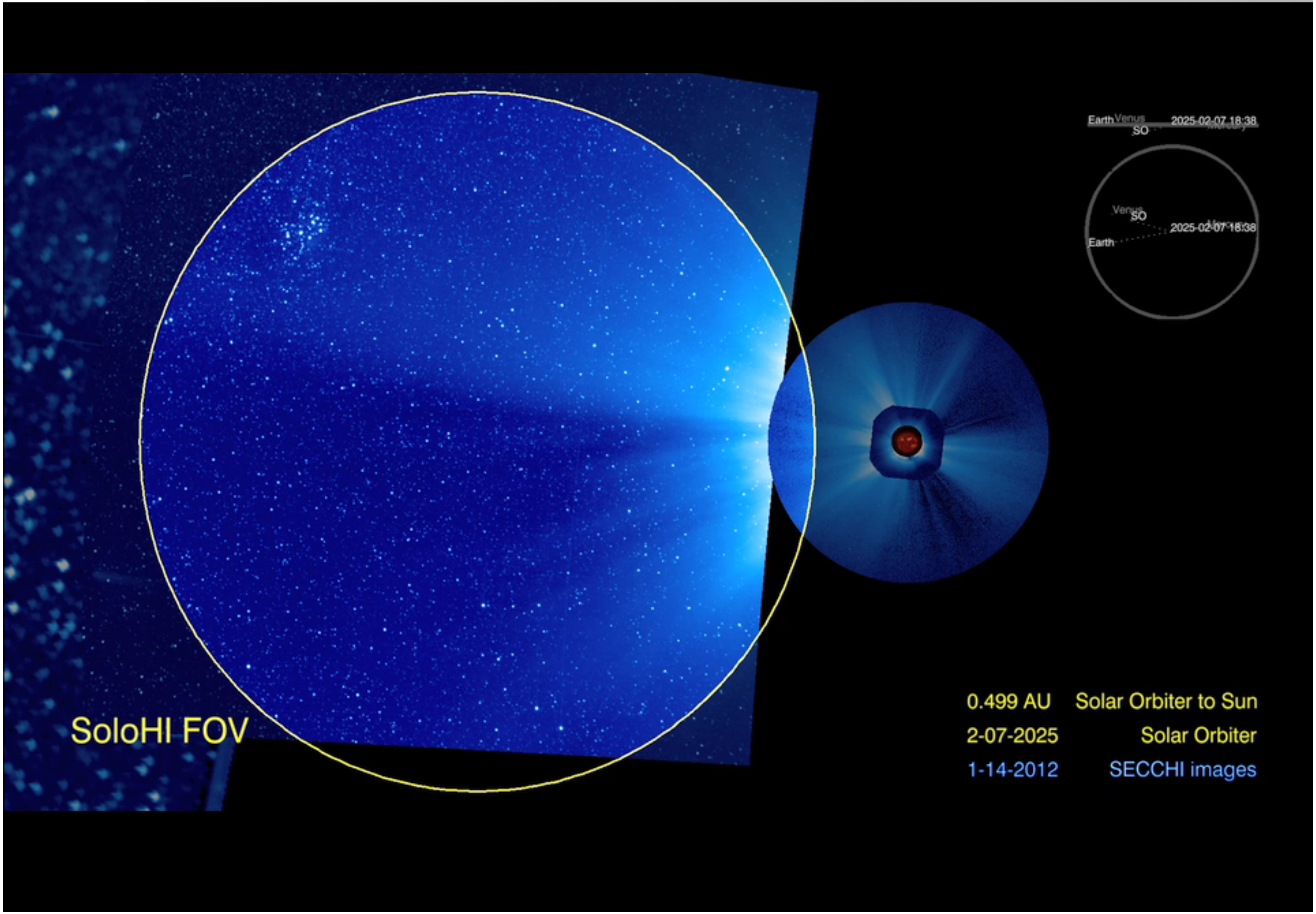
- For the connection to be made between small magnetic flux ropes and their coronal sources their radial size must exceed 0.02AU (Rouillard et al. 2011) and to be entrained in CIRs.

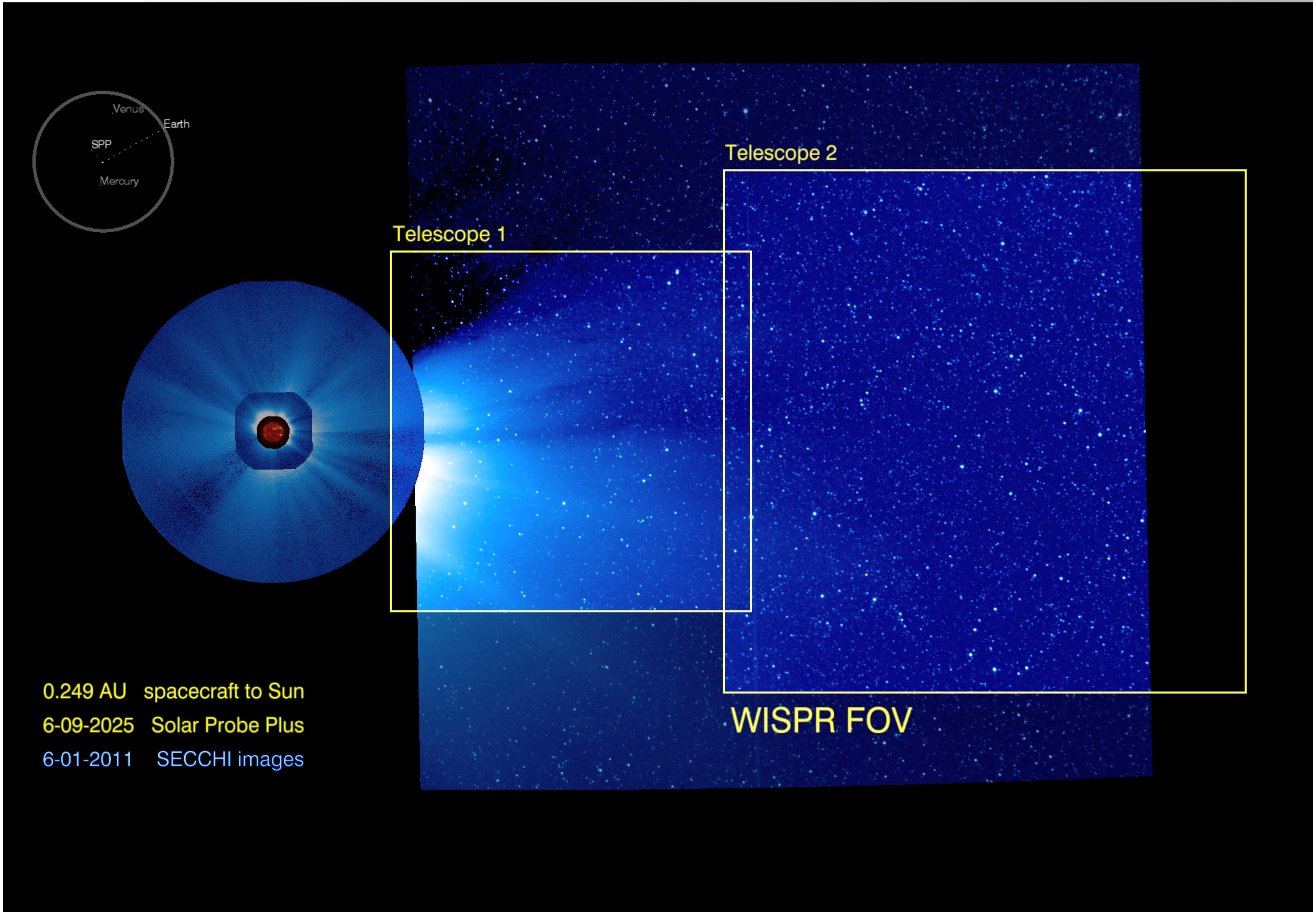




Sheeley and Rouillard (2010)

Rouillard et al. (2011)


SoloHI FOV
Earth Venus SO 2025-02-07 18:38
Venus SO 2025-02-07 18:38
Earth
0.499 AU Solar Orbiter to Sun
2-07-2025 Solar Orbiter
1-14-2012 SECCHI images


Venus
Earth
SPP
Mercury
Telescope 2
Telescope 1
WISPR FOV
0.249 AU spacecraft to Sun
6-09-2025 Solar Probe Plus
6-01-2011 SECCHI images

What observations do we need from Solar Orbiter and Solar Probe?

- In-situ measurements in regions above the the tip of streamers,

- Plasma measurements of the expansion speed of the rope: competition between plasma pressure and poloidal/toroidal forces.

- Composition measurements to identify the source regions, combined with spectral measurements of coronal loops,

- High-resolution images of small-scale transients (MAJOR IMPROVEMENT TO CURRENT 1AU OBSERVATIONS): currently it is impossible to identify the source of flux rope with sizes <0.05AU measured at 1AU.

to name a few…

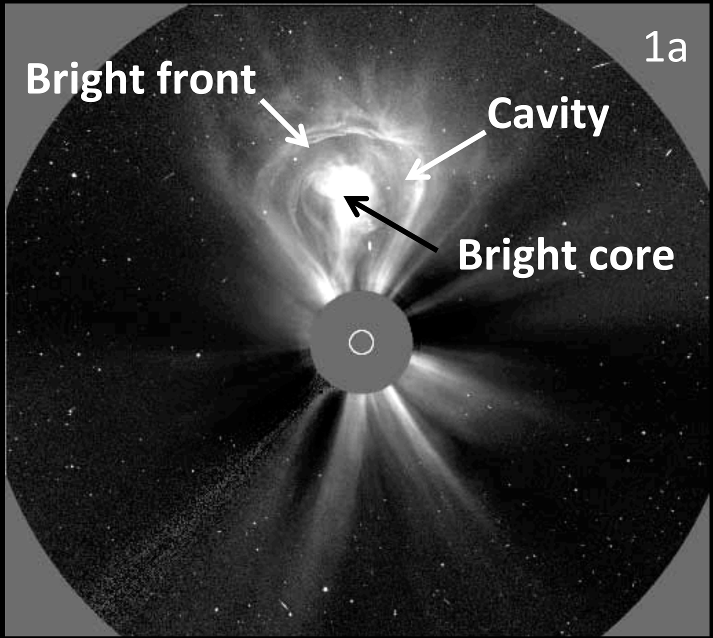
Plan of lecture:

To review recent (mainly STEREO) observational results on:

- **the properties of CMEs**

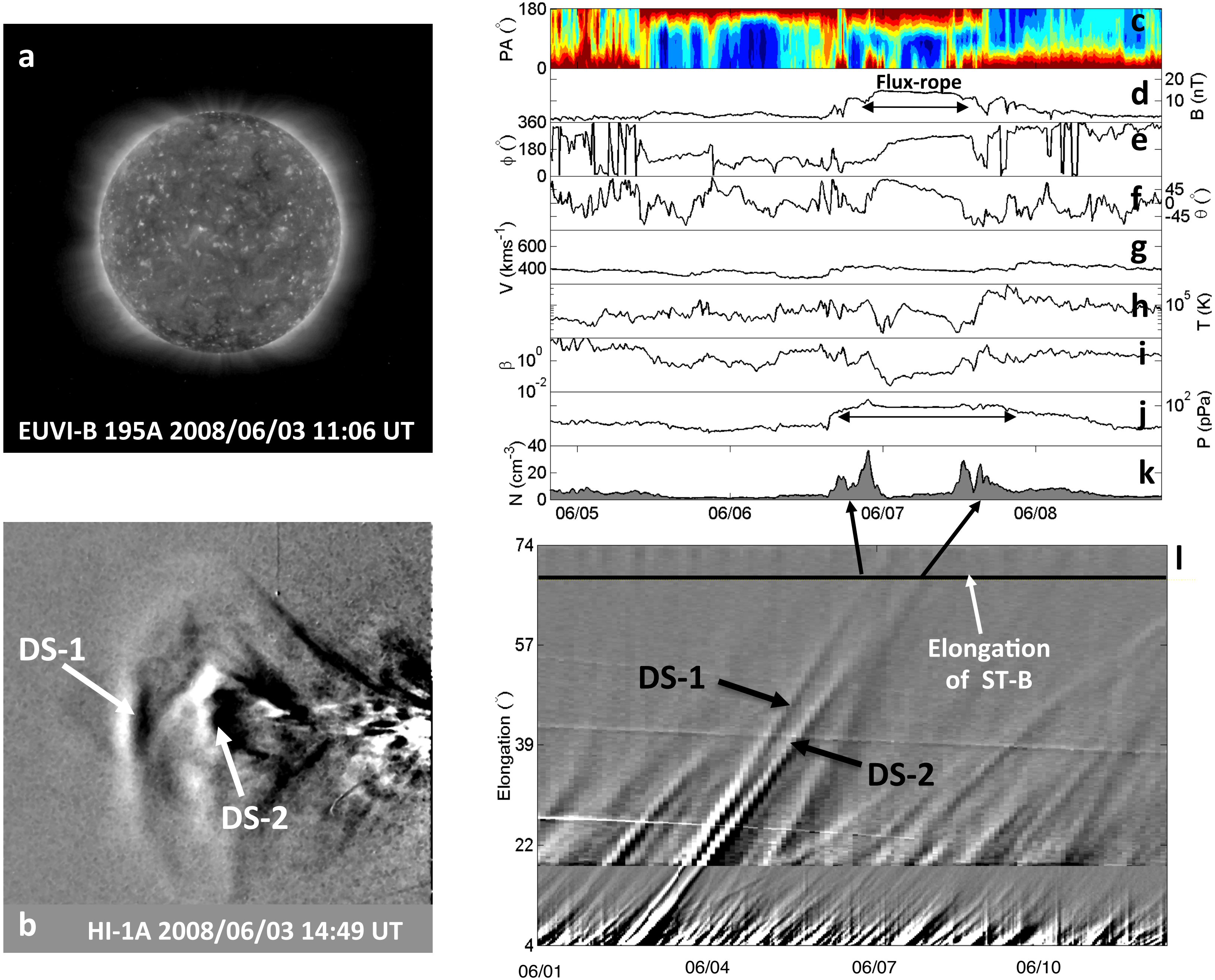
  >> solar/coronal origin, topology, energy budget, propagation

So-called 3-part structure: bright front, cavity and a core (e.g.: Illing and Hundhausen, 1986):

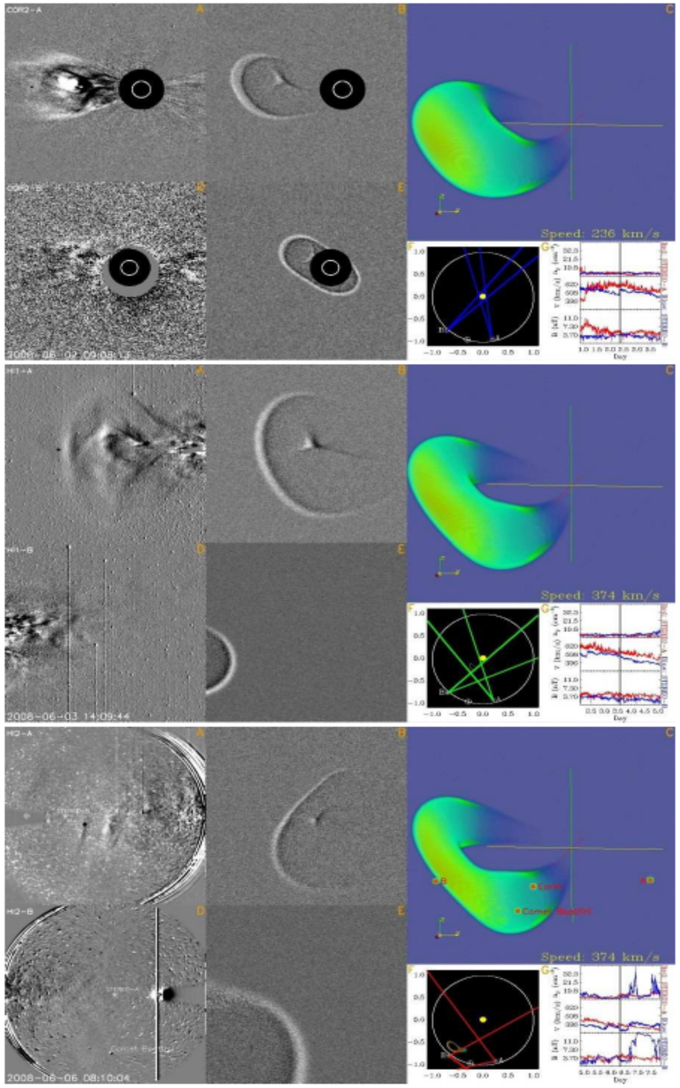


2000/02/27 07:42UT - LASCO C3

The Halpha 656.3nm line of neutral hydrogen is the principal prominence spectral line observed in the SECCHI white light instruments (spectral band-passes are for COR1: 543-786nm; COR-2: 650-750nm; HI-1: 630-730nm; HI-2: 400-1000nm).



Mostl et al. (2009), Wood et al. (2010) Rouillard et al. (Review paper: 2010d)



Wood et al. (2010)

Wood et al. (2010) and Moestl et al. (2009) and Rouillard et al. (2009) find same orientations of flux ropes in white-light and in situ.

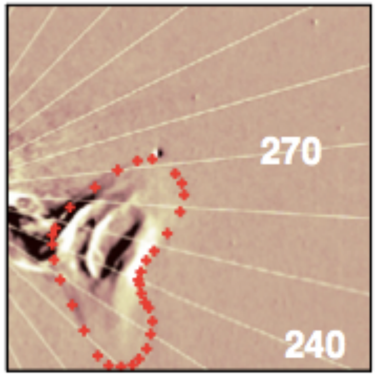
The STEREO mission has:

- revealed the 3-D geometry of magnetic flux ropes transported in Coronal Mass Ejections

- Shown that magnetic flux ropes retain their circular cross-section during their propagation to 1AU (Wood et al. 2009; 2010; Moestl et al. 2009; Rouillard et al. 2009) unless:

    - they compress very slow solar wind ahead (Savani et al. 2009)

    - they are compressed by high-speed solar wind (e.g; Rouillard et al. 2010)



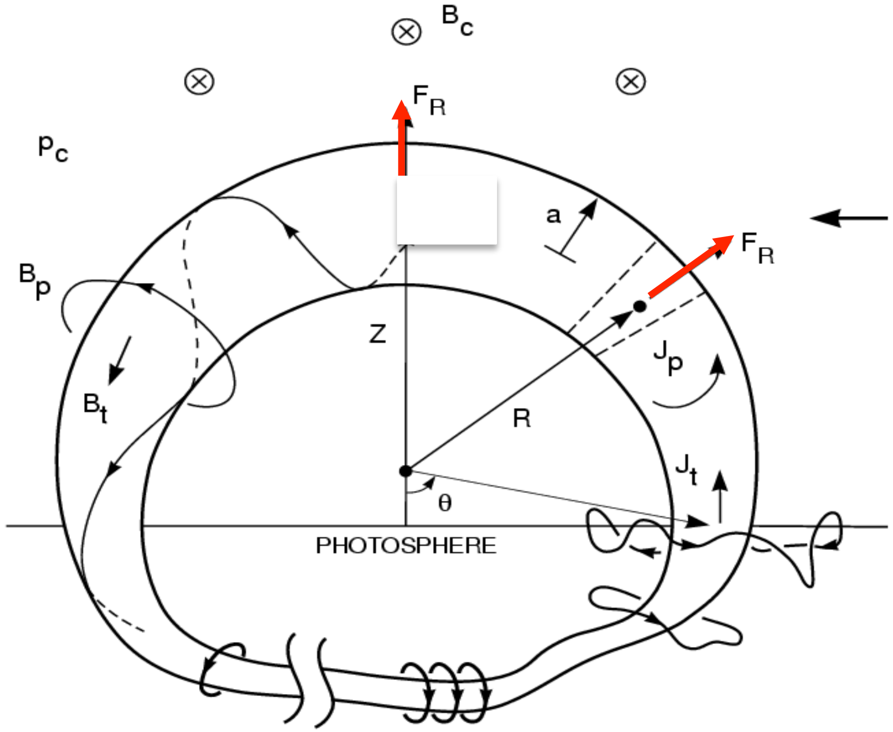
Savani et al. 2009

- Magnetic flux ropes can be deflected towards the ecliptic plane, this happens inside 30Rs (Makela et al. 2013, Isvanin et al. 2014)

- Magnetic flux ropes may rotate during their propagation to 1AU (Vourlidas et al. 2011; Isvanin et al. 2013), seen in simulations of eruptions: Lynch et al. 2009

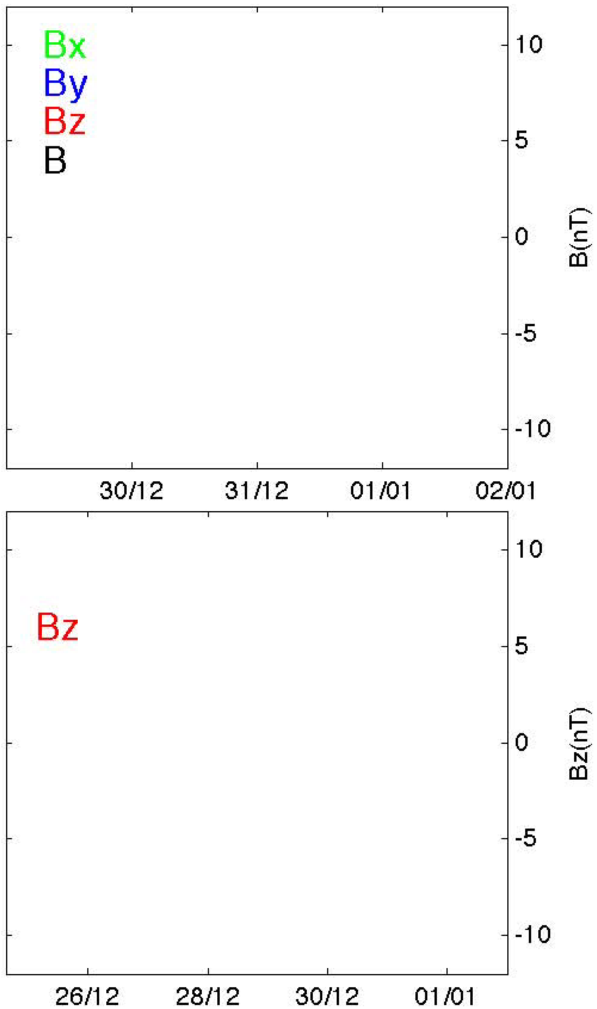
- Magnetic Flux ropes may reconnect with the coronal/solar wind magnetic field during propagation to 1AU (Ruffenach et al. 2012; 2014).

The accumulation of poloidal magnetic flux in larger transients, via some yet debated mechanism, generates a range of radial forces and instabilities (e.g. kink, torus) that lead to violent eruptions.



In the eruptive flux rope model of Chen (1989), the Lorentz (hoop) force (Bateman 1978) is enhanced by an increasing poloidal field >> leading to rapid acceleration.

>>> Very good match between simulated and observed kinematic (Kunkel and Chen 2010).



Kunkel and Rouillard (2014)

What observations do we need from Solar Orbiter and Solar Probe?

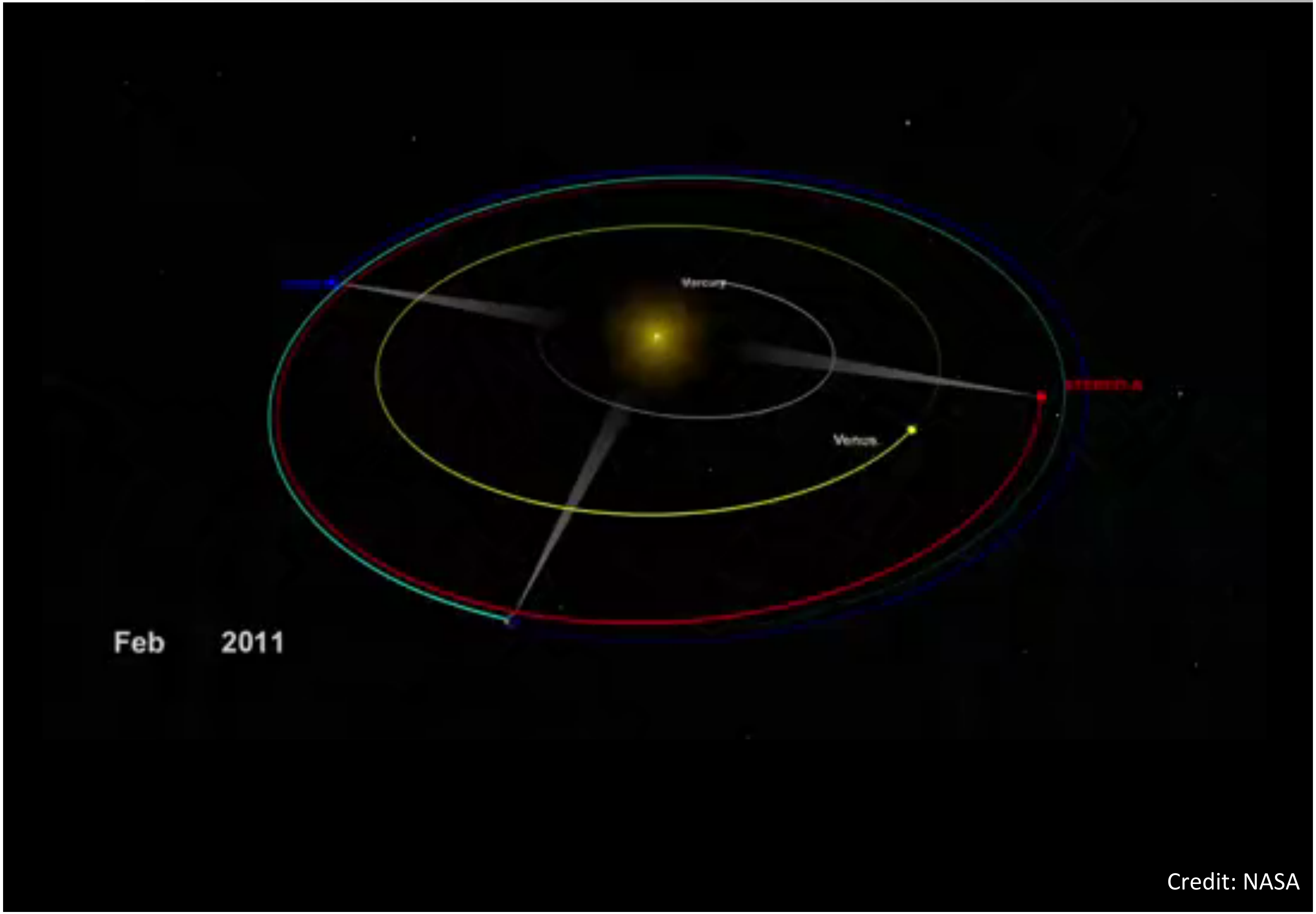
- B-field measurements in regions where the magnetic forces have a significant role in the motion of the CME.

- Plasma measurements of the expansion speed of the rope: competition between plasma pressure and poloidal/toroidal forces.

- Composition measurements to assess the rate of drainage of the prominence material.

- High-resolution images of CMEs to obtain a global geometry of CMEs during the initial phase (assessing expansion/contraction of cross-sections).

to name a few…



Credit: NASA

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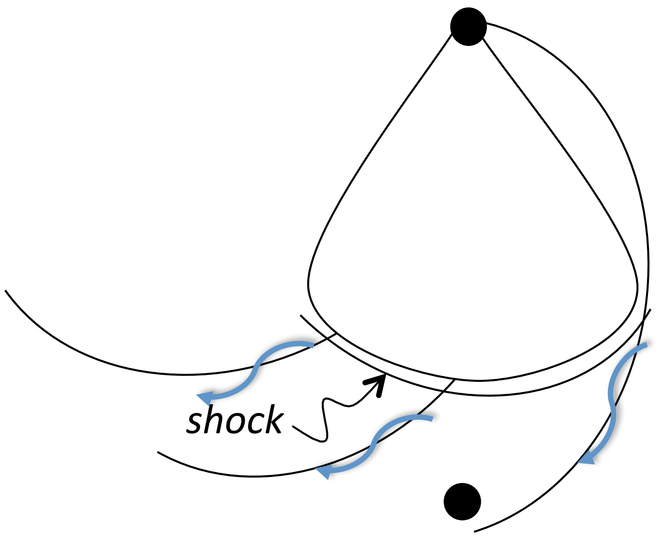
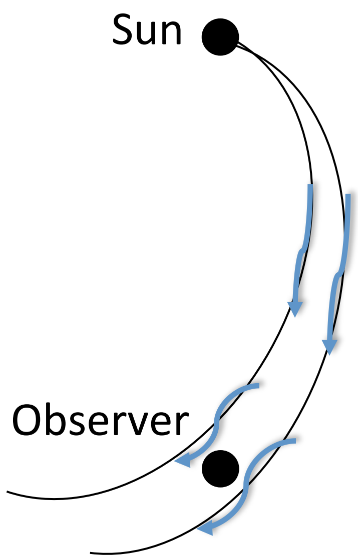
To review recent (mainly STEREO) observational results on:

- **the acceleration of SEPs**

  >> solar/coronal origin, spatial spread and content, GLEs





- Proton rich.
- High fluxes sustained for long time intervals
- Occur during major CME events.
- Associated with Type IIs

- Electron rich.
- Short duration
- $^3He/^4He$ enhanced by large factors (x10^4
- Enhanced Ne-Si and Fe over CNO as compared to gradual SEP events
- Enhancement of 'ultra heavy' ions (Z ≥ 3)
- electron rich
- small intensities and short duration (flares and SEPs)

Reames (1999)

- Over the course of cycle 23, a tenth of large SEP events were found to have Fe/O ratios (at energies 12-60 MeV/nuc) higher than the mean gradual SEP event ratio of 0.134 (Reames, 1999) by more than a factor of 4 (Cohen et al. 2008).

- Many of these gradual events also exhibited abundance ratios of $^{3}He/^{4}He$ that far exceeded that found in the solar wind (e.g., Cohen et al. 1999, Mason et al. 1999, Wiedenbeck et al. 2000, Cane et al. 2003, Tylka et al. 2005), also unexpected for gradual SEP events. These abundance ratios measurements show that a single SEP event may have both characteristics of impulsive and gradual events.

- Energetic electrons and type-III radio bursts, which are often associated with 3He-rich SEPs, were not visible for some events above instrument backgrounds in this recent minimum, nor were X-ray flares, jets, or a clear CME (Mason et al. 2008).

- Recently, Cane et al. (2010) presented a study of 280 protons events detected between 1997 and 2006 and find a continuum of event properties and argued that, 'a priori', the simplest `two-class' picture of SEP events is not supported.

For a planar shock, the downstream spectrum depends on the compression ratio. A ratio $2 < r < 4$ will give a differential intensity with a power law dist. and an index in the range $1 < q < 2$.

The maximum energy attainable over any given interval depends on

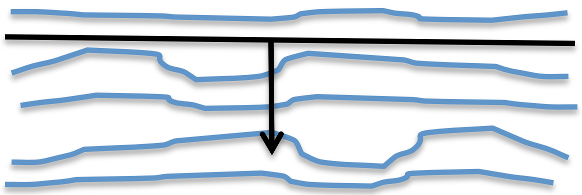
> the shock speed,
> the perp and parallel diffusion coefficients
> the angle between the mean magnetic field and the shock normal.

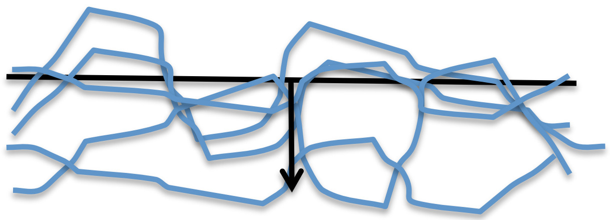
Since these quantities vary from one event to the next, this could explain the large variety of spectra observed in SEPs.

Because $k_{//}$ is much larger than k_{perp}, quasi-perp shock accelerate particles faster than quasi-parallel shocks and should produce the highest energy particles. HOWEVER for simple unbraided magnetic fields the number of shock crossings is limited for particles with low energies.

The injection problem for quasi-perp shock can be solved for in two scenarios:

- flare remnants producing a sea of weakly energised seed particles (e.g. Tylka and Lee 2005)
- field-line meandering increasing particle motion across the shock (Giacalone 2003)



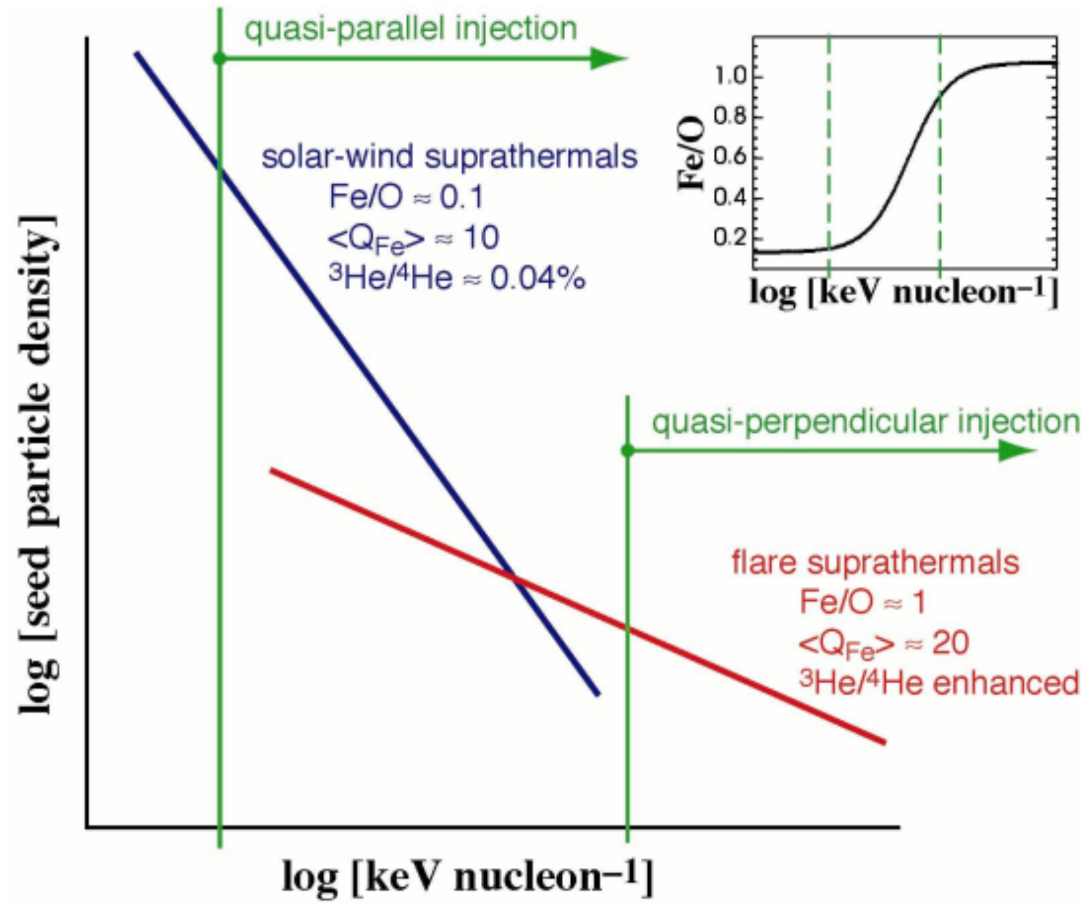


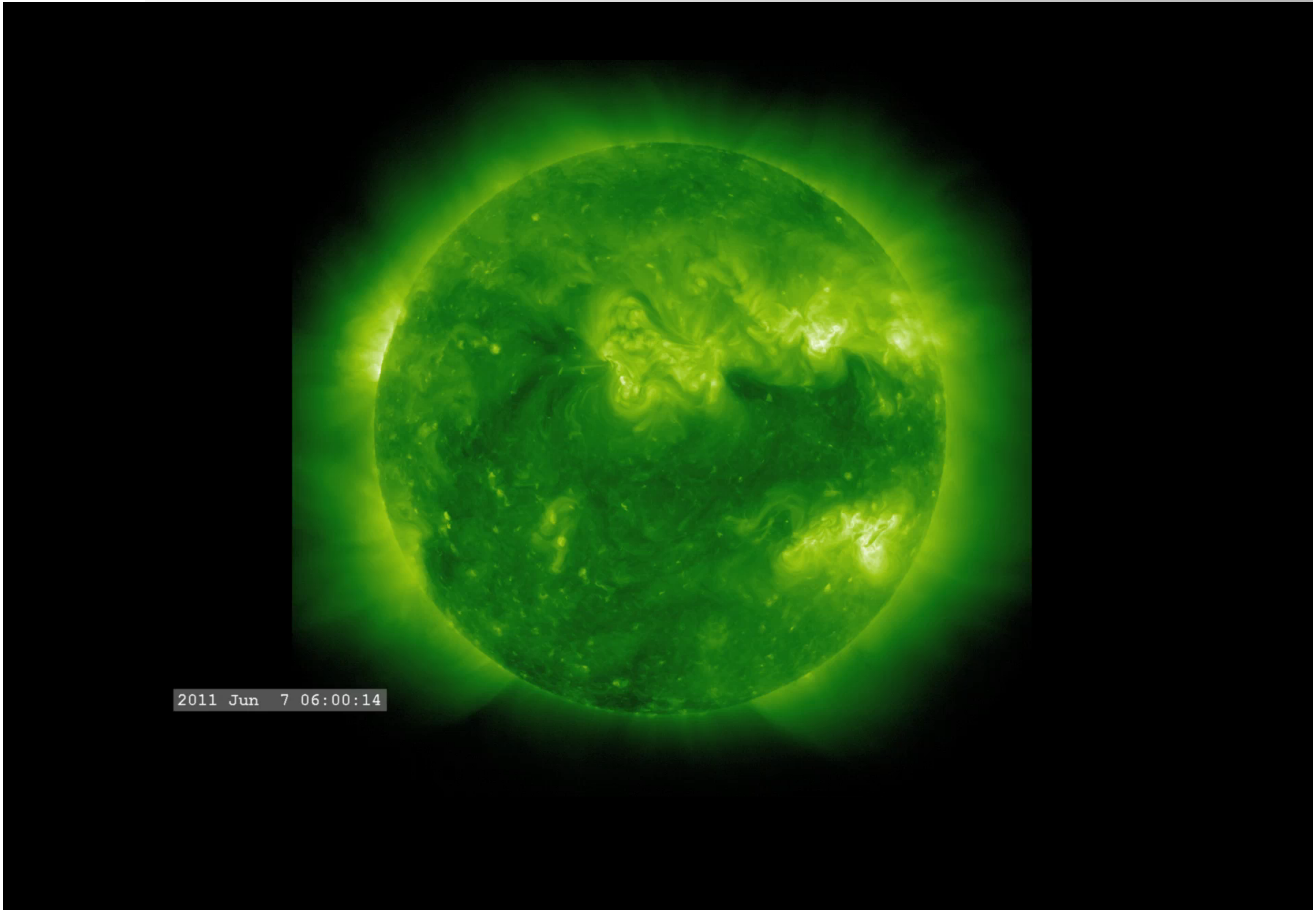
- Can shock acceleration explain the observations of Fe-enriched (energy dependent composition)?

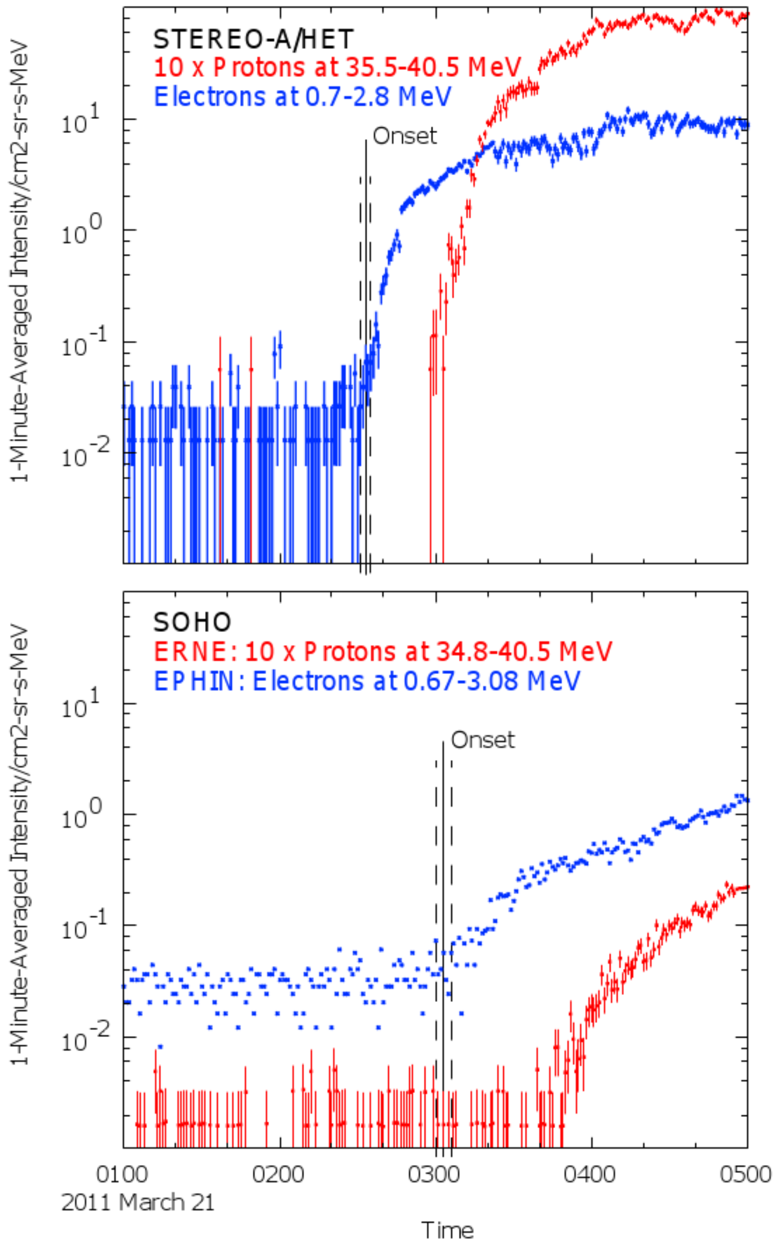
- Tylka and Lee (2005) proposed an analytical model based on the two assumptions:

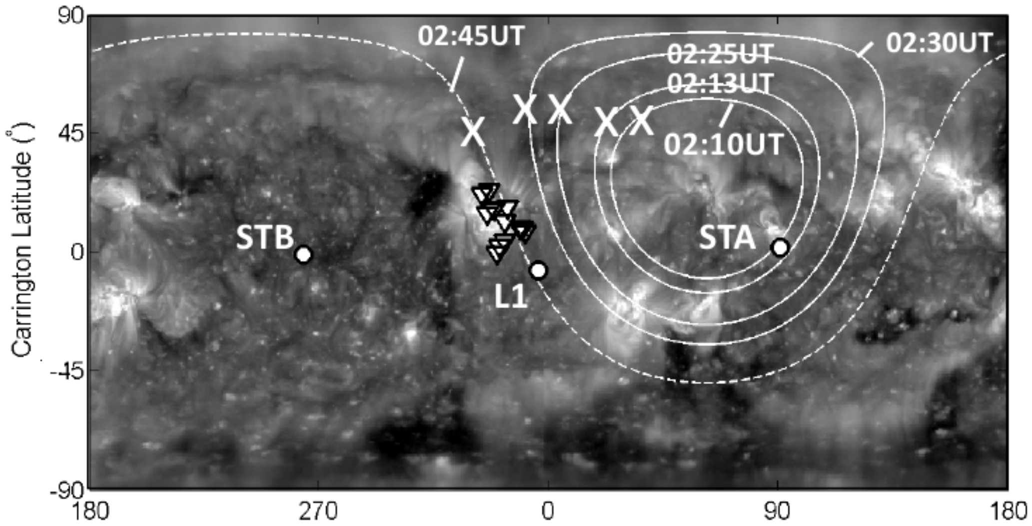
  (1) seed population is energy dependent

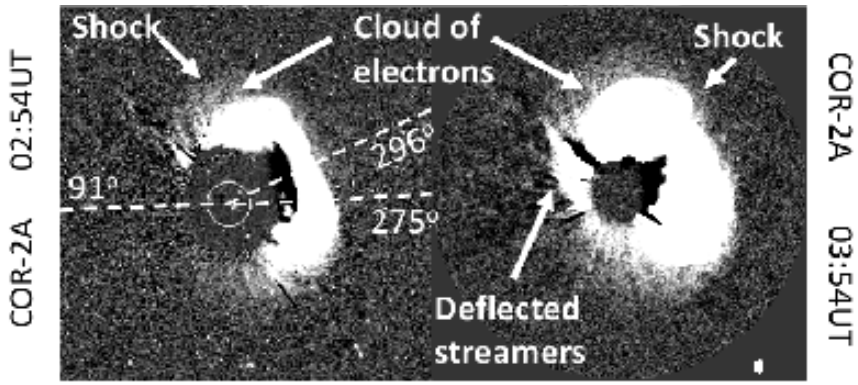
  (2) injection energy is higher for Q-perp



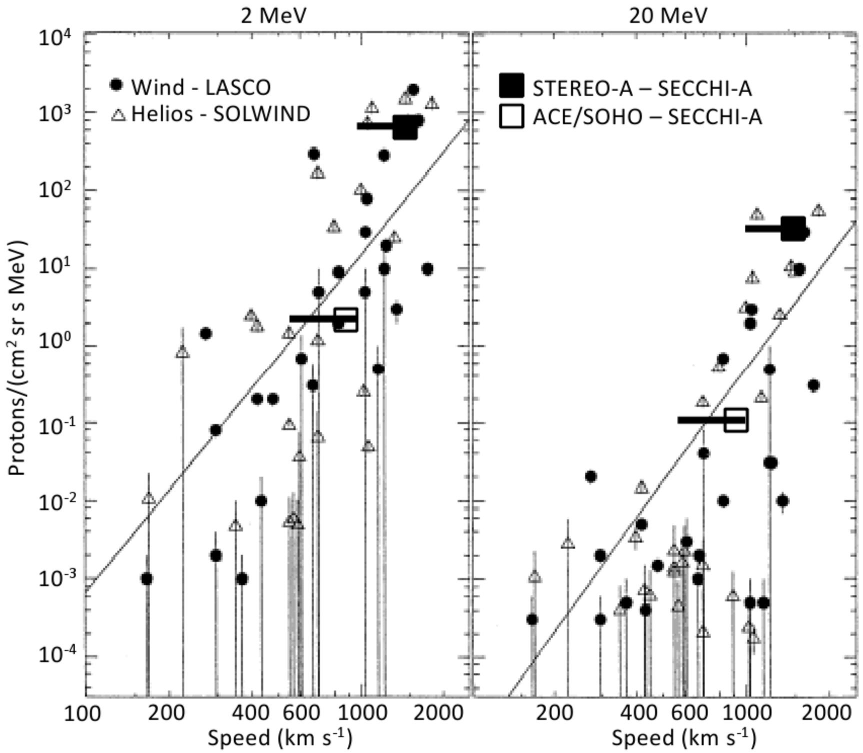

2011 Jun 7 06:00:14

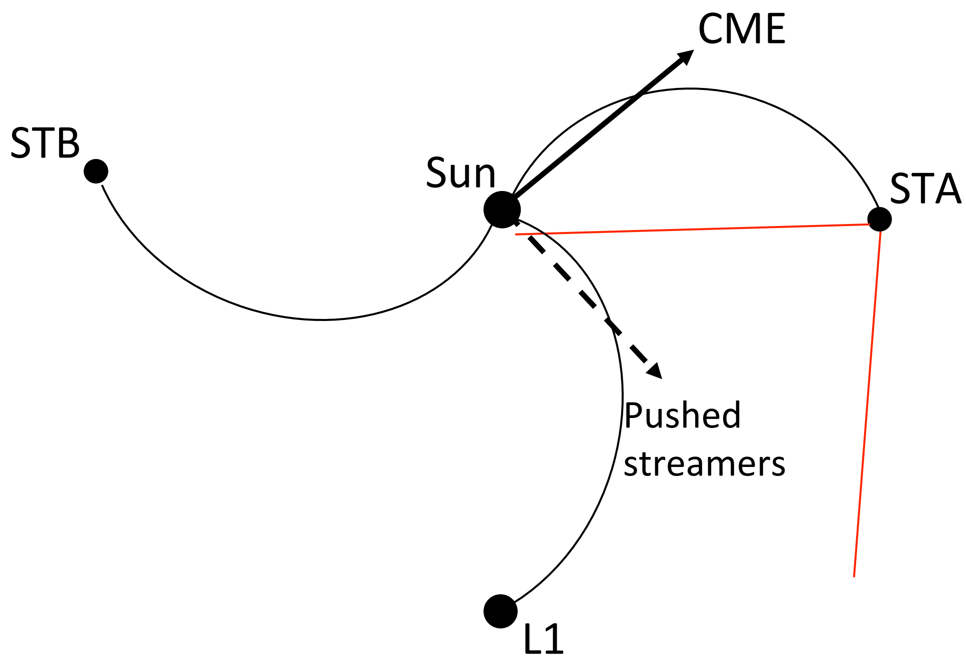






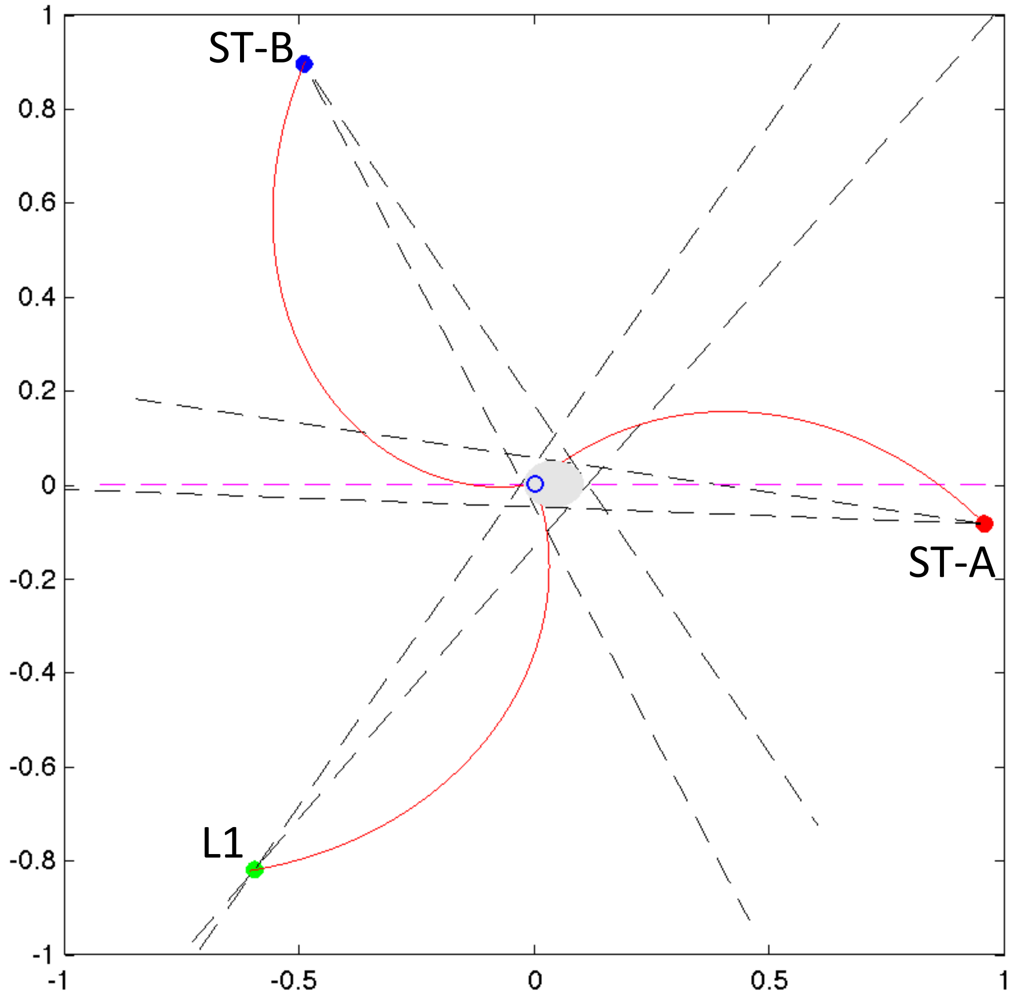
Rouillard et al., Ap. J. 2012



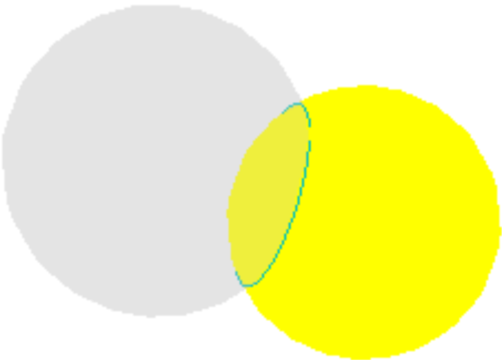


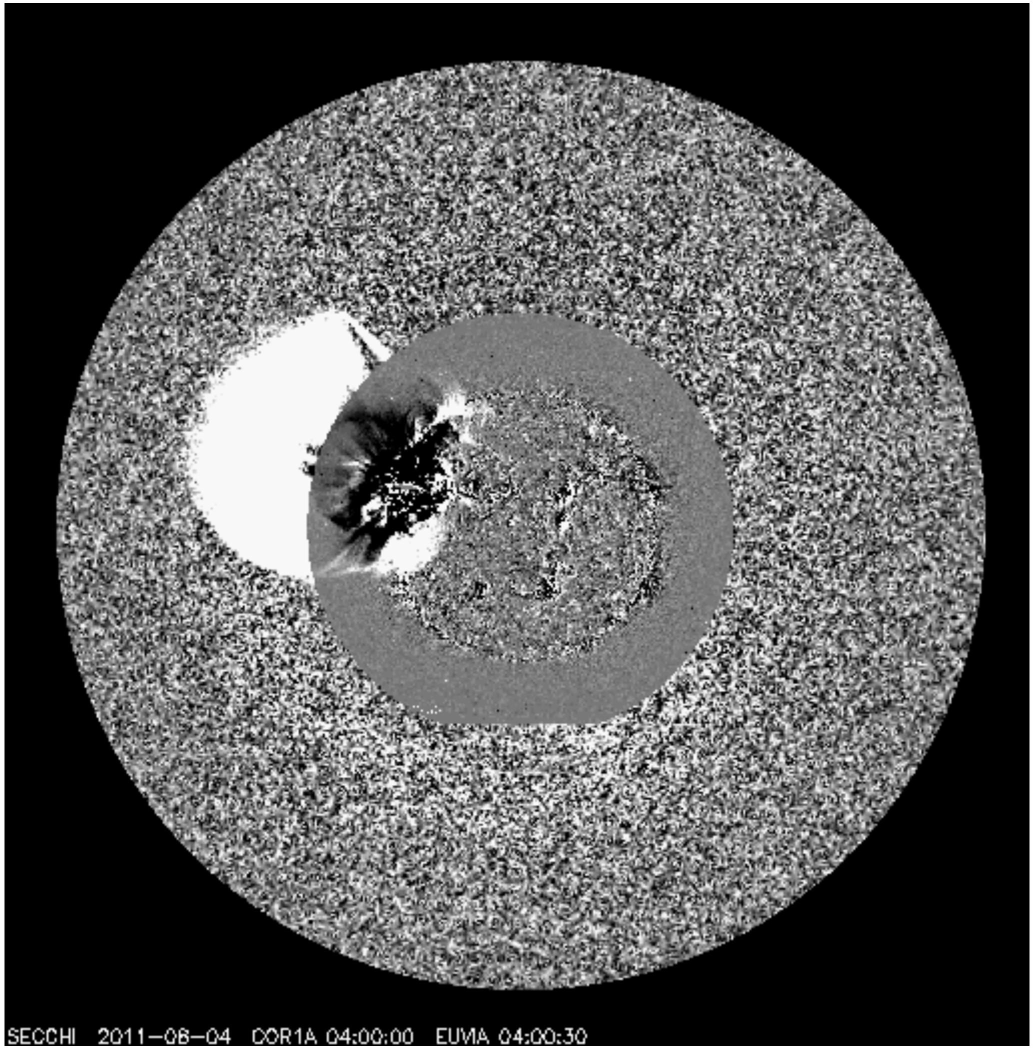
Maximum SEP flux versus shock speed could be compared along two different set of field lines for a SINGLE CME event. These direct measurements could be plotted on the Kahler et al. (2001) scatter plot.

2012 July 23 CME event:

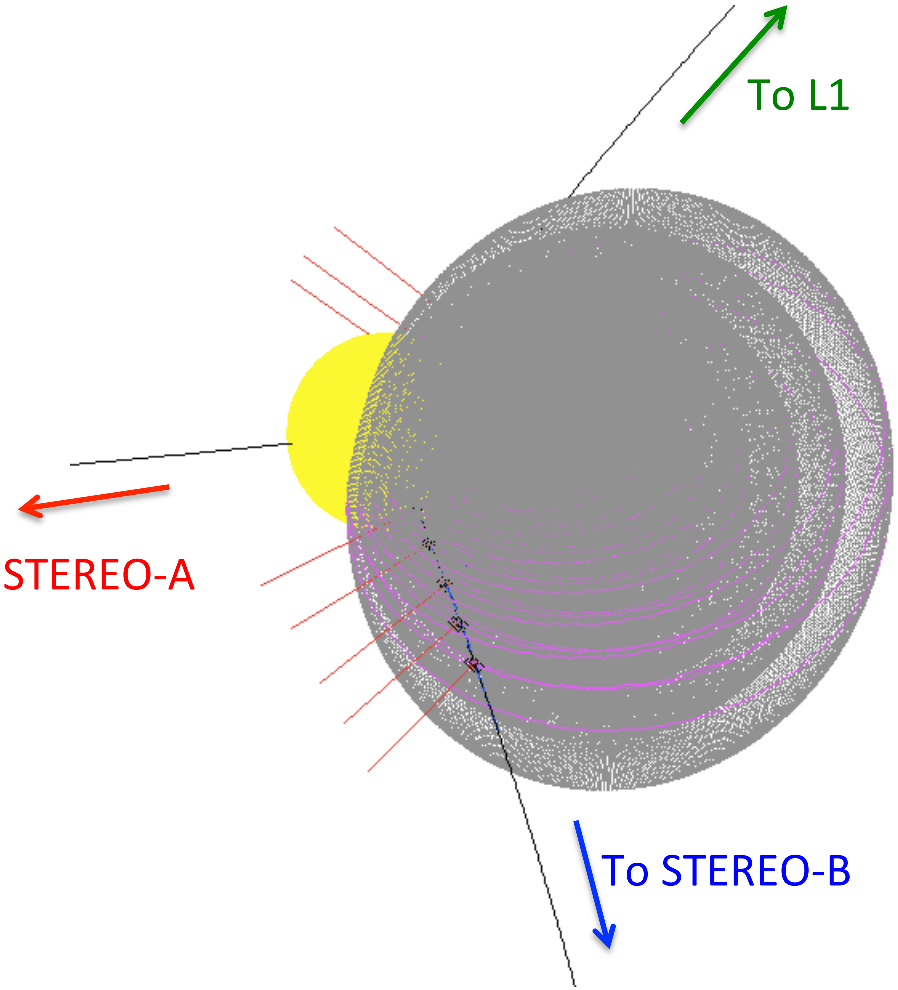


Rouillard et al. In preparation (2014)




SECCHI 2011-06-04 COR1A 04:00:00 EUVA 04:00:30

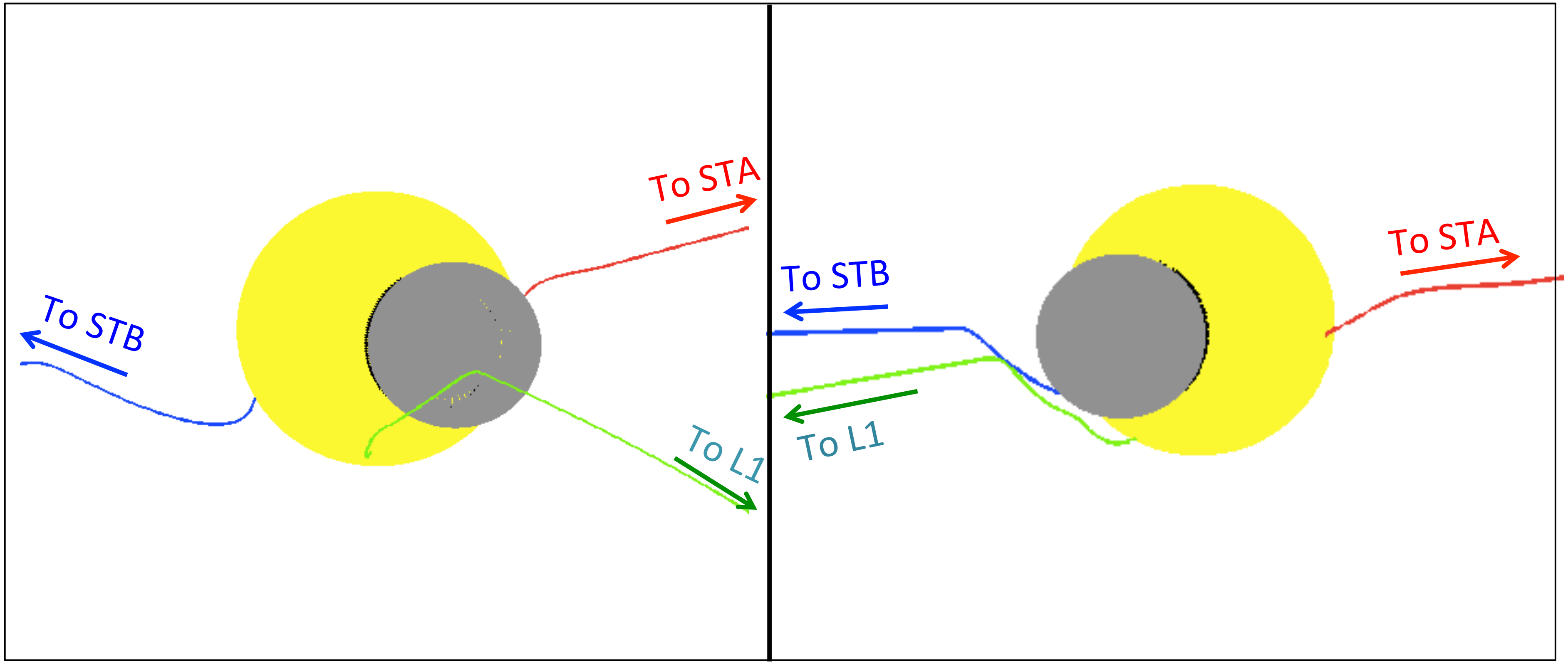
2013 04 11 event



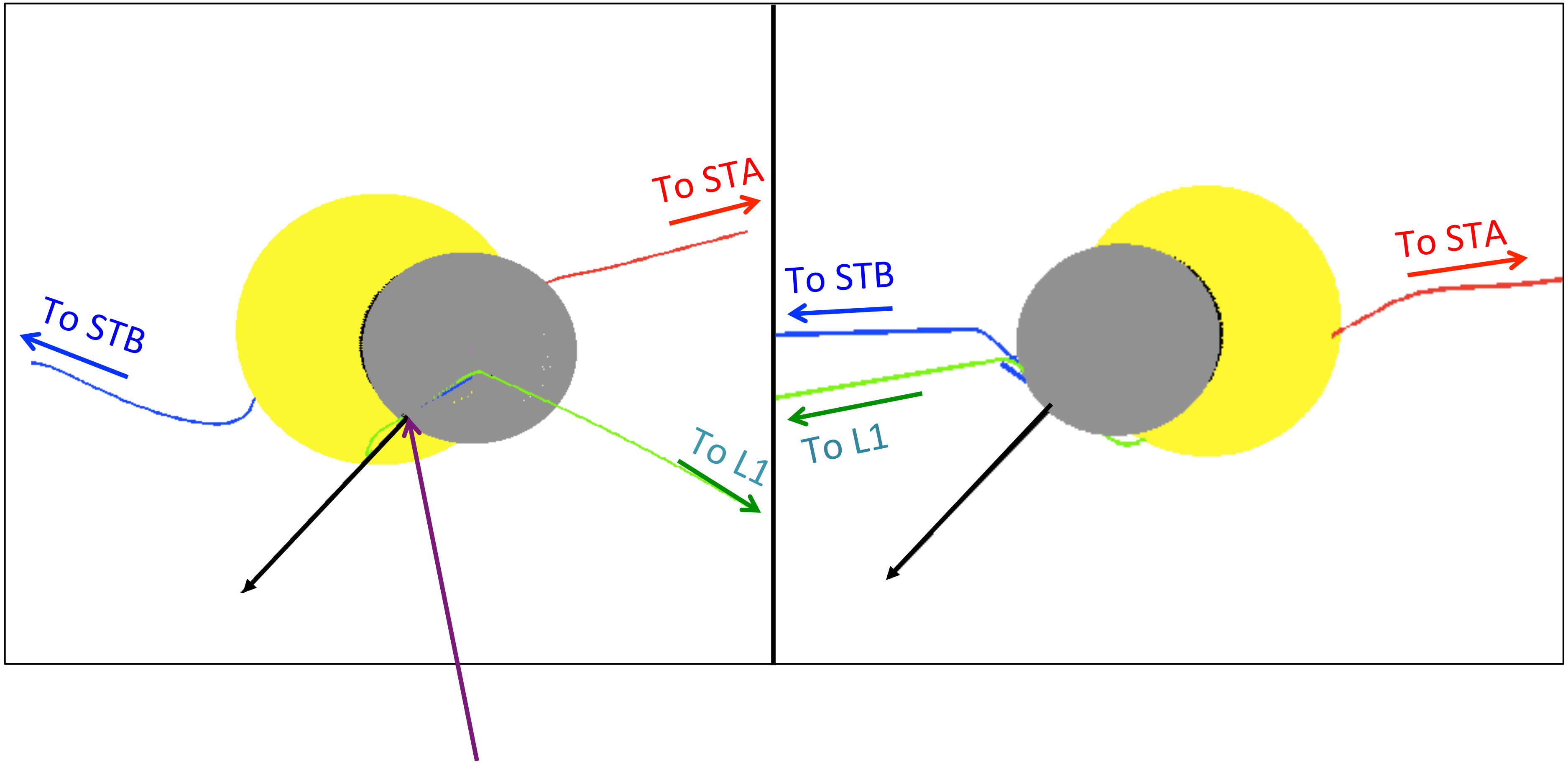
Once each ellipsoid is computed, we trace the 3-D location of the magnetic field lines connected to the point of in-situ measurements that are considered to be Parker (Archimedean-like) spirals. The 3-D location of the spiral depends on the measurements of the solar wind speed at the particle onset time. We then determine the intersection of this spiral with the ellipsoid at each timestep. At this intersection point, we then compute at each time step:

- the 3-D normal vector to the surface (shock normal) and the shock geometry,
- the 3-D shock velocity

GLE event of 2012 March 17:

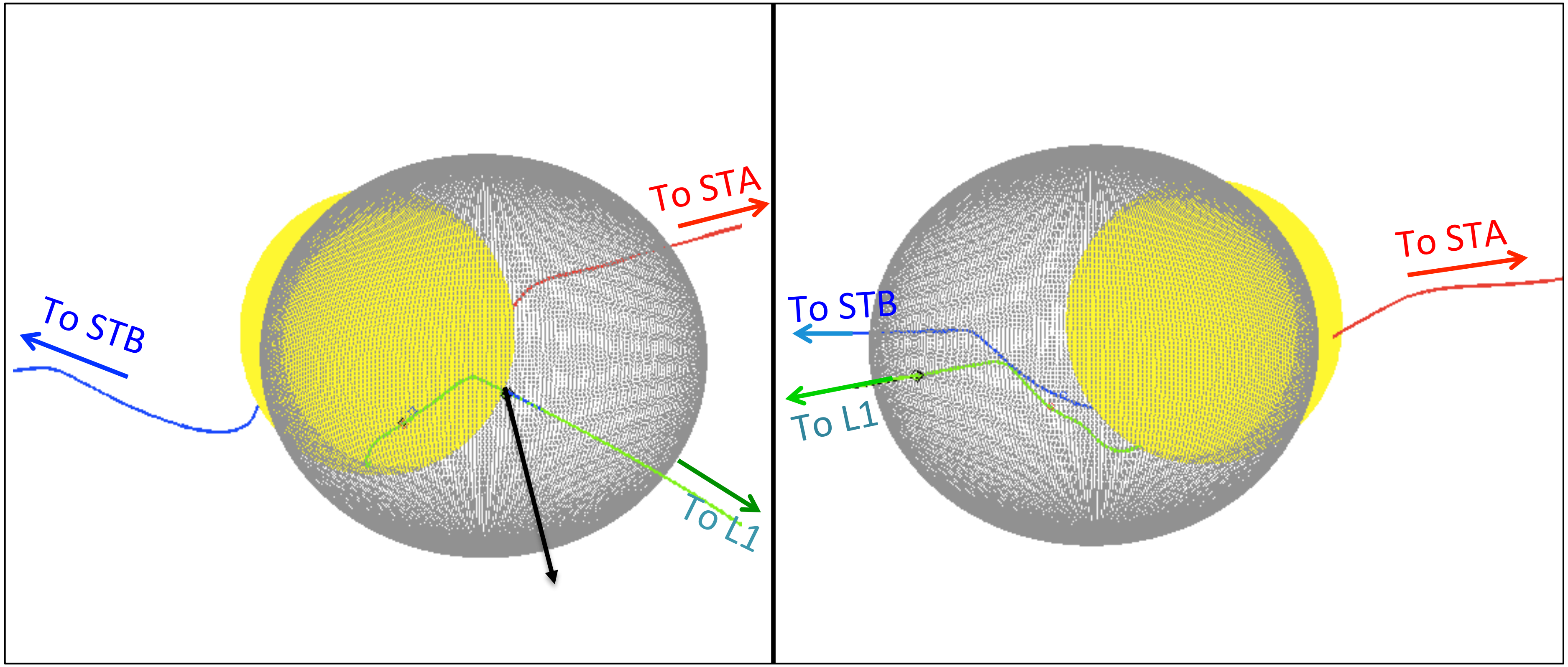


GLE event of 2012 March 17:

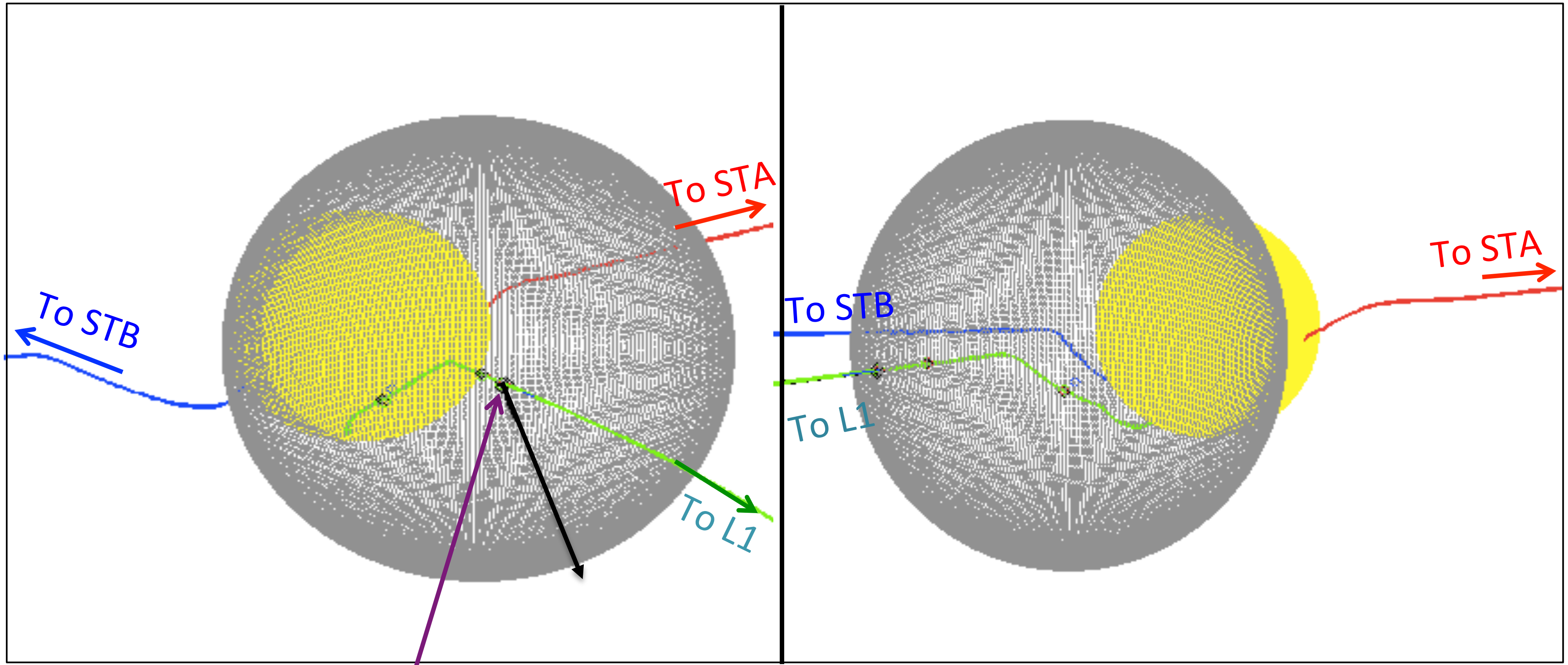


Quasi-perp geometry lasting at
most 10 minutes on very long field line

GLE event of 2012 March 17:

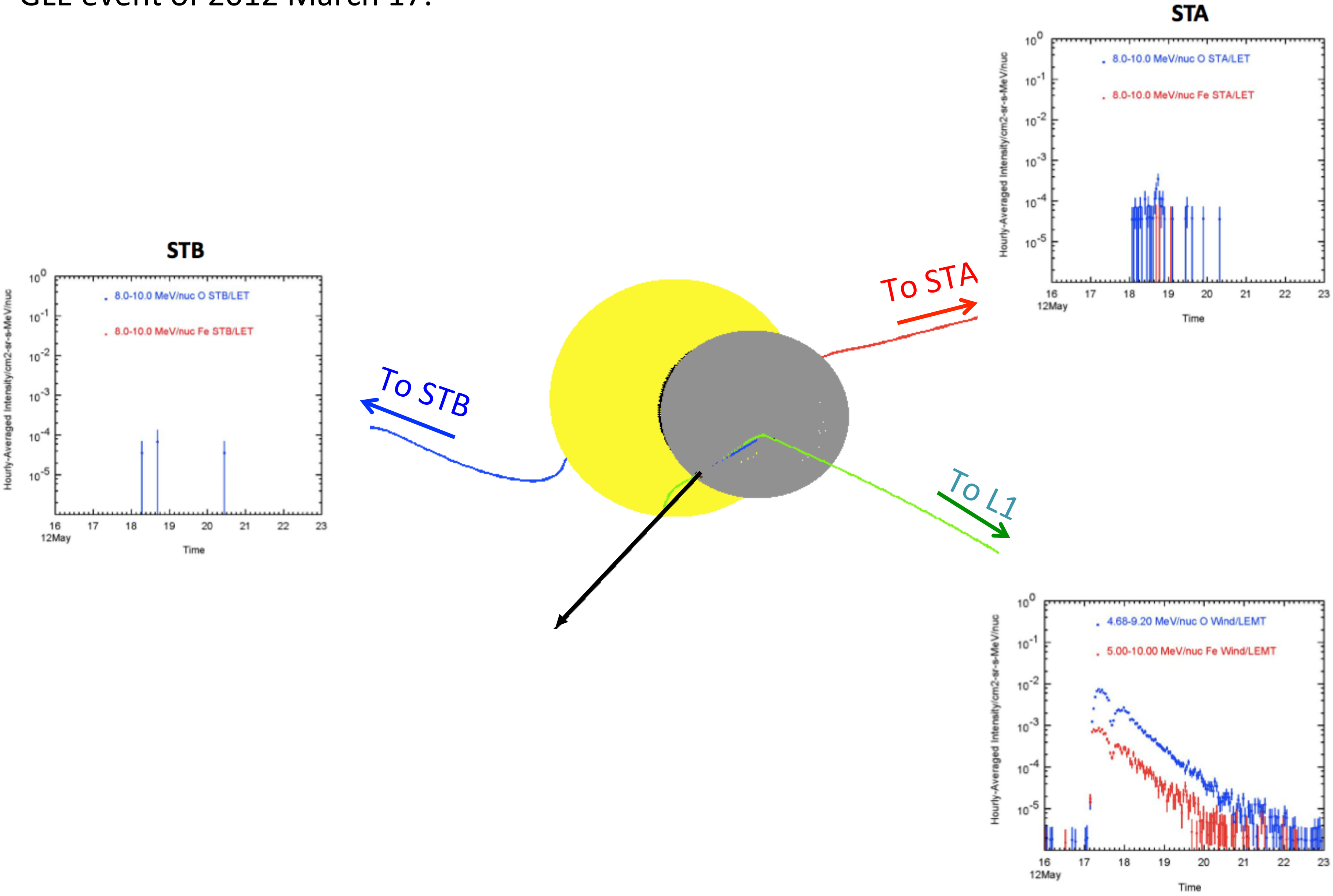


GLE event of 2012 March 17:

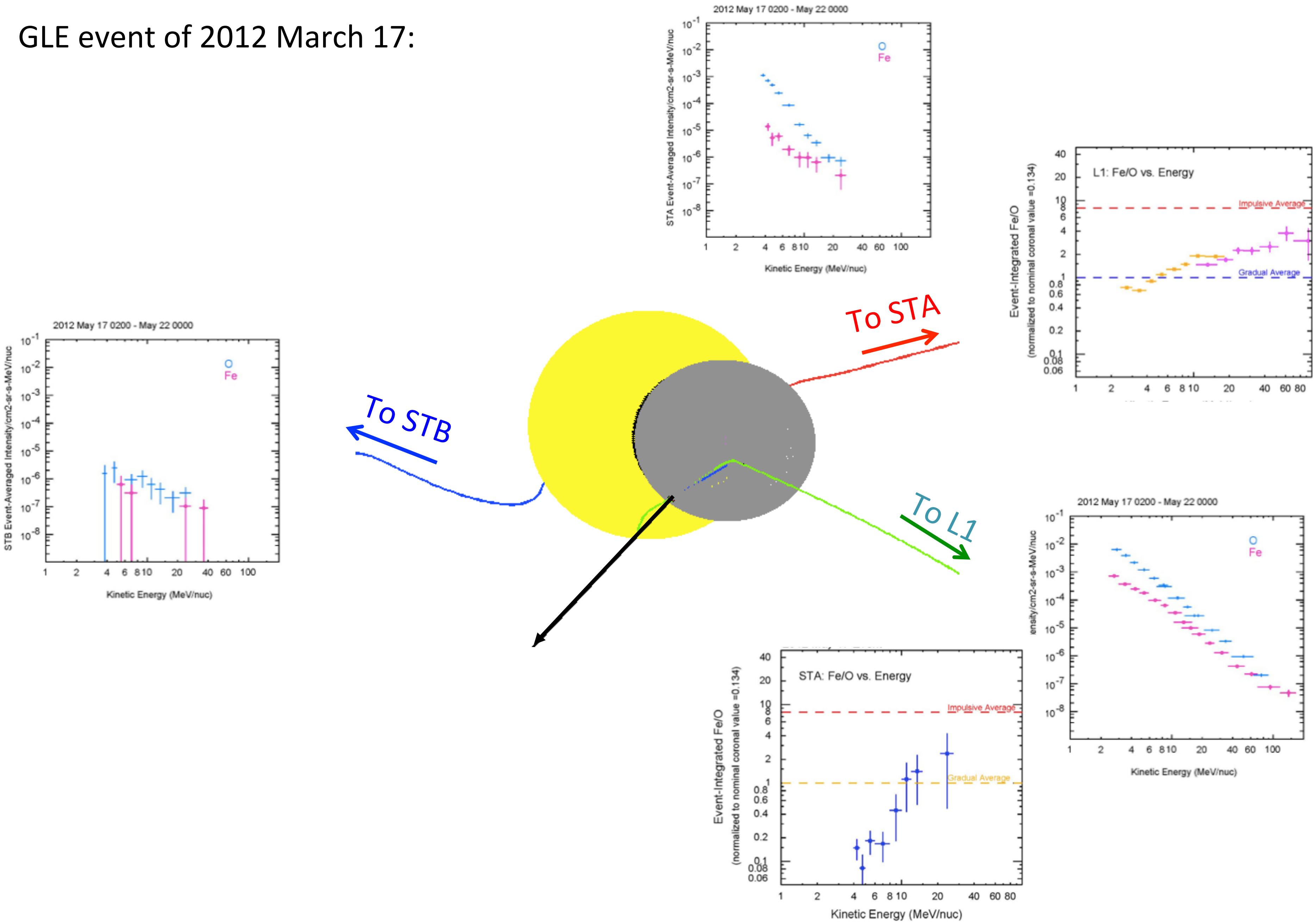


Quasi-parallel geometry lasting at most 10 minutes on very long field line

GLE event of 2012 March 17:



GLE event of 2012 March 17:



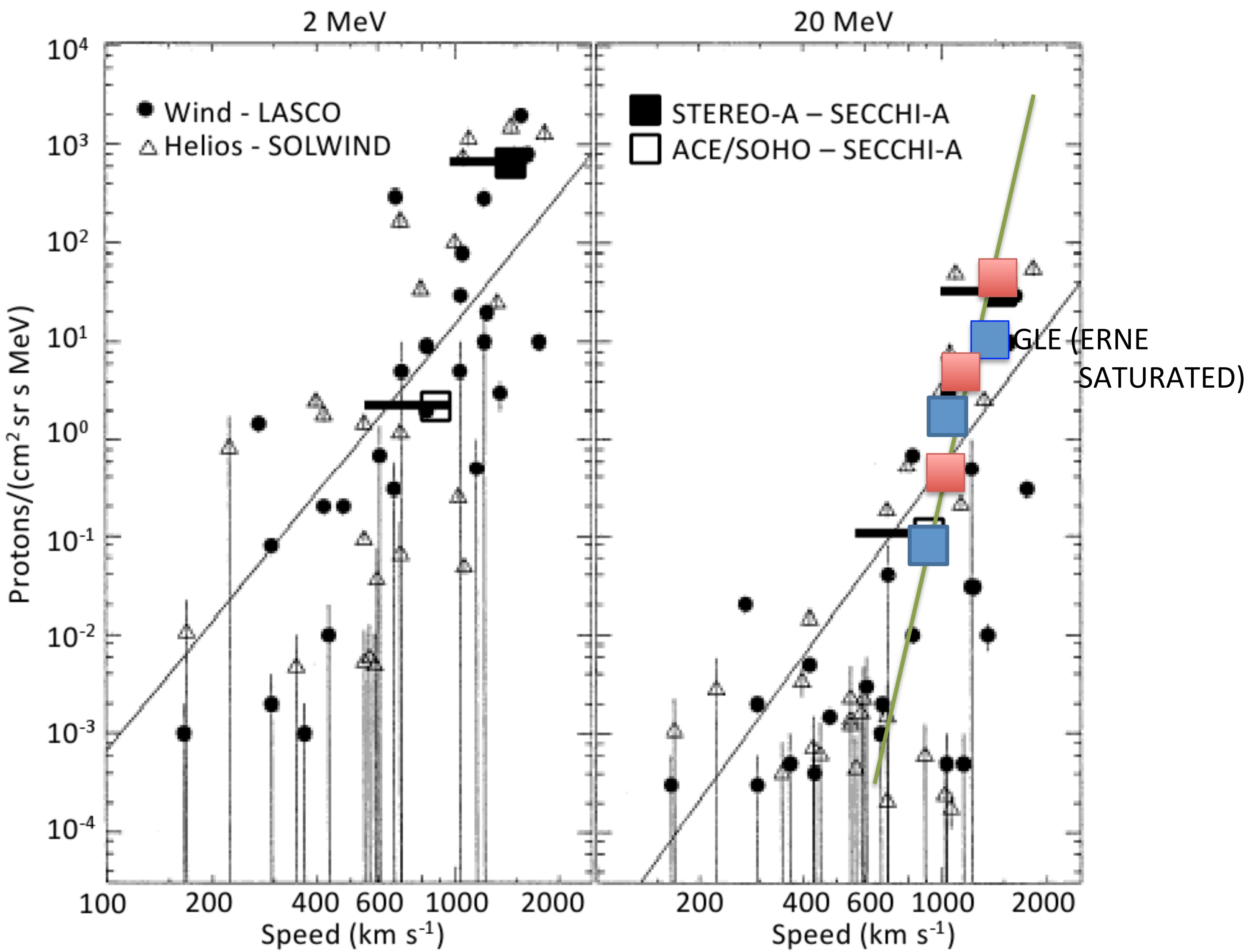
- The expansion of CMEs is associated with an initial strong lateral and radial expansion (30-40 minutes).

- During this phase magnetic connexion to the shock occurs in a region of the corona where characteristic speeds are very high and shock formation may not occur.

- Deriving the local shock geometry requires a magnetic model. Lateral expansion is not necessarily associated with a quasi-perp shock.

- Some coronal magnetic configurations can lead to quasi-perp shock extending over long distances (>1Rs).

- The only GLE event was likely associated with a quasi-perp shock and very high shock speeds derived on the magnetic field line connected to L1.


2 MeV
20 MeV
Wind - LASCO
Helios - SOLWIND
STEREO-A – SECCHI-A
ACE/SOHO – SECCHI-A
GLE (ERNE
SATURATED)
Protons/(cm² sr s MeV)
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
100
200
400
600
1000
2000
Speed (km s⁻¹)

What observations do we need from Solar Orbiter and Solar Probe?

- In-situ measurements of shock properties near the Sun

- In-situ measurements of suprathermal particles (injection problem),

- SEP measurements near the Sun without worrying about propagation Issues (diffusion, focusing, adiabatic cooling),

- Composition measurements to assess the flare remnants hypothesis,

- High-resolution images of shocks to determine its local deformations.

to name a few…

Propagation Tool

Welcome to CDPP/Propagation Tool

Tutorials : video (mov files)

- **Introduction to the CDPP Propagation Tool (13M)**
- **Description of the propagation tool main interface (8M)**
- **Case 1: Using the tool in the Jmap Carrington/In situ mode (radial) (37M)**
- **Case 2: Using the tool in the Jmap tool click mode (radial) (39M)**

Tutorials : video (mpeg files)

- **Introduction to the CDPP Propagation Tool (46M)**
- **Description of the propagation tool main interface (47M)**
- **Case 1: Using the tool in the Jmap Carrington/In situ mode (radial) (176M)**
- **Case 2: Using the tool in the Jmap tool click mode (radial) (184M)**

Table of available data

- **Flare Data, Carrington Maps, J-Maps, Solar Wind Speed**

Supported set up

- Check browser/OS support
- Java requirements
- Get java 7.45
- Linux troubleshoot

What's new ?

- New J-maps will be available in February 2014

Launch the Propagation Tool

A new interactive tool accessible to the solar, heliospheric and planetary science communities to track solar storms, streams and energetic particles in the heliosphere

The propagation tool allows users:

- to propagate solar eruptions (CMEs) radially sunward or anti-sunward (**Radial Propagation**),
- to propagate corotating structures (CIRs) in the heliosphere (**Corotation**),
- to propagate solar energetic particles along magnetic fields lines sunward or anti-sunward (**SEP Propagation**),

The START and END points (defined by a right click on the ecliptic plane) can be the Sun, planets or probes situated in the interplanetary medium. The times of propagation between the START and END points are based on simple analytic calculations.

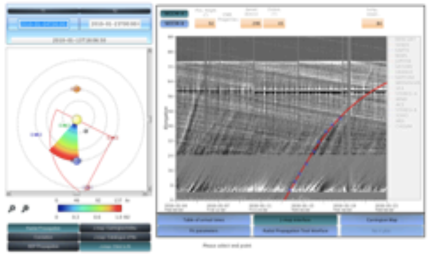
The added values of the tool are an easy access to unique datasets and a fast interoperability :

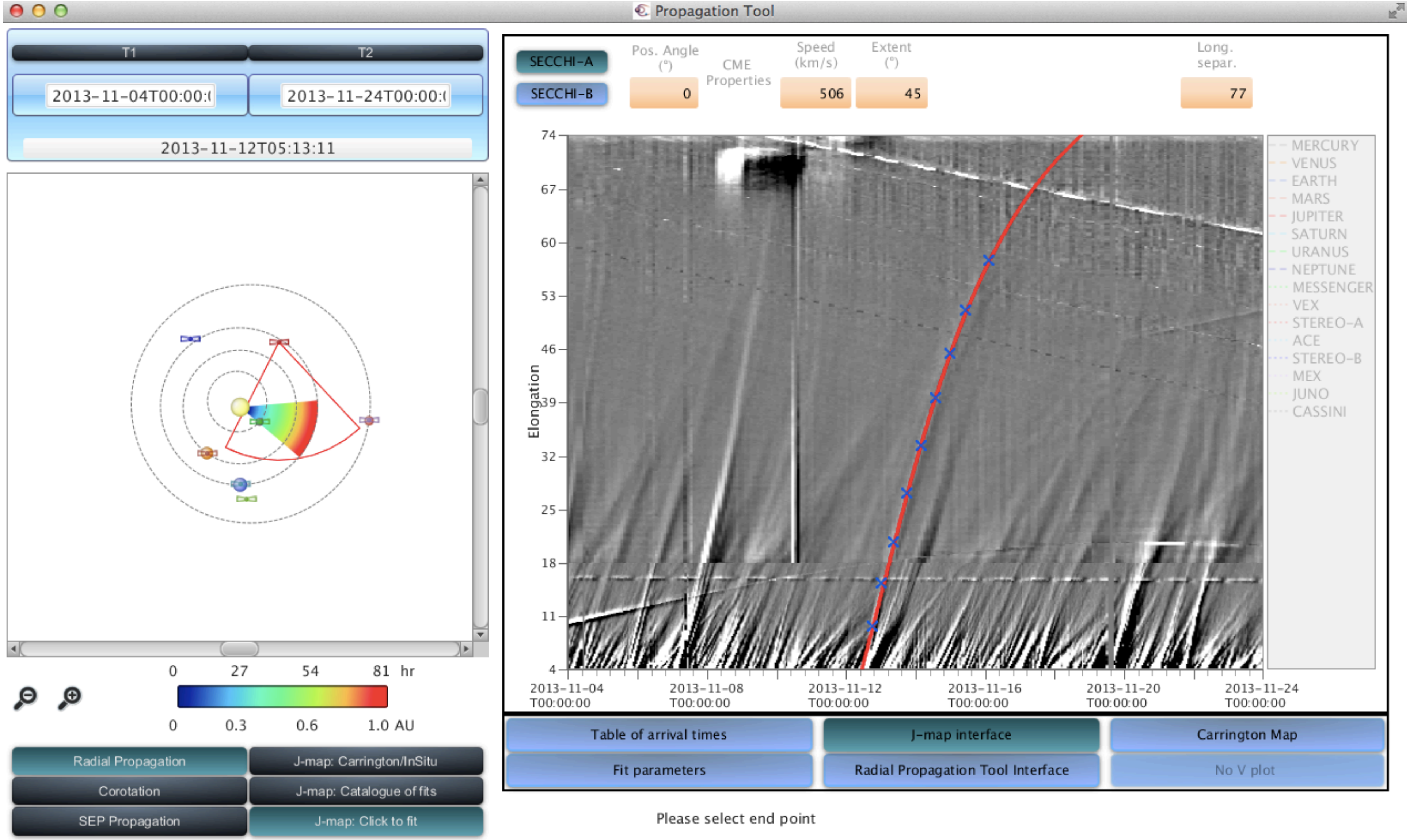
- it integrates the **orbital elements** (using SPICE) of probes and planets. This allows you to determine via simple clicks the position/orientations of imagers that you would like to consider,
- it offers **web-service** access to summary plots of in-situ data stored at the CDPP as well as movies of solar images stored at MEDOC,
- it provides access to a wide range of **Carrington maps** of the solar surface to visualize the location of active regions, coronal holes and solar flares on the Sun

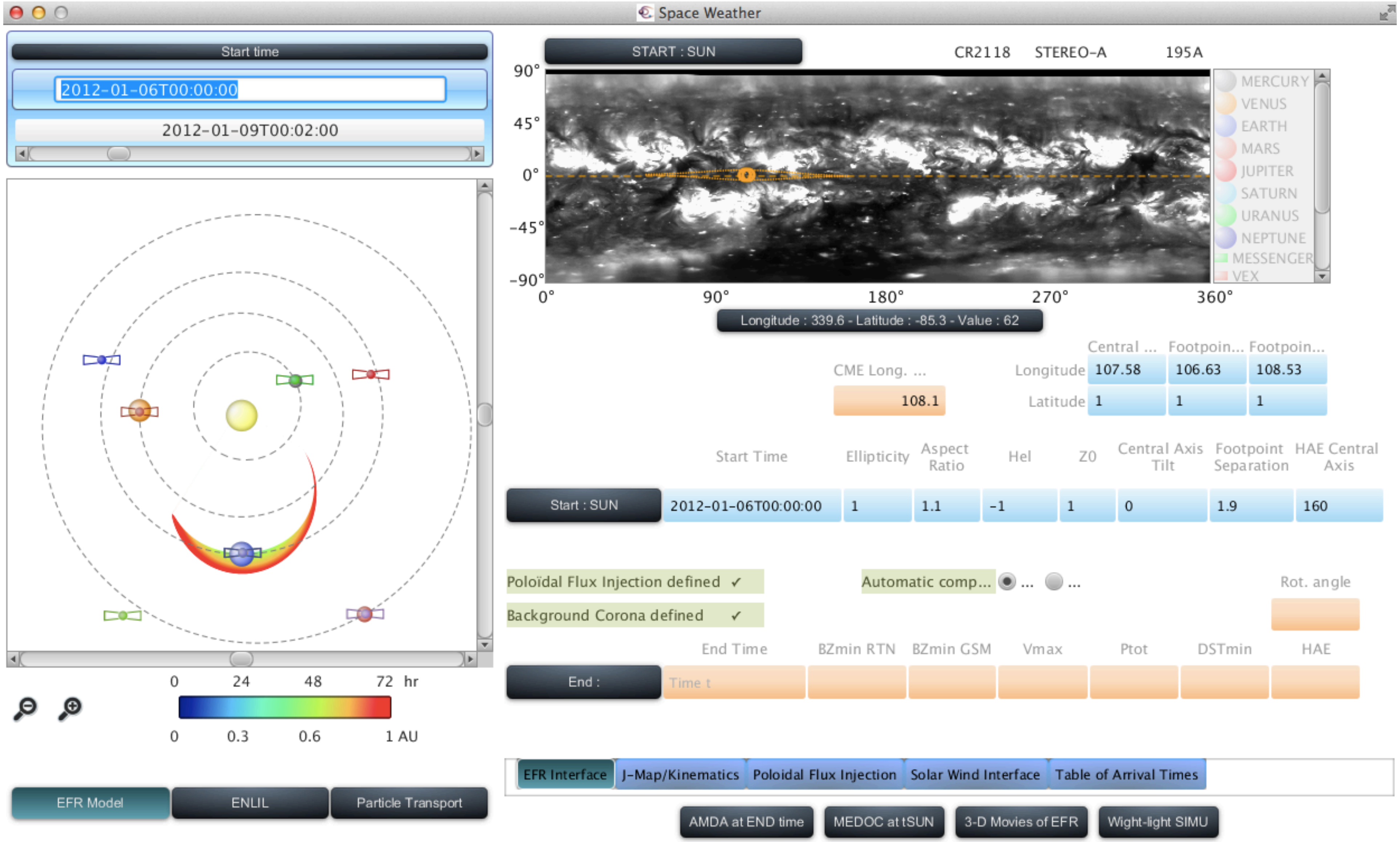
The great novelty of the tool is the immediate visualisation and basic manipulation of maps of solar wind mass flows tracked continuously from the Sun to 1AU. These maps are called J-maps and are generated by extracting bands of pixels in coronal and heliospheric images along the ecliptic planes and stacking them vertically (along the ordinate) with time (along the abscissae). The maps are produced from teraoctets of imagery data that are impossible to manipulate if you are not an expert in the field. The tool was designed to be user friendly and accessible to any scientist interested in locating CMEs/CIRs and particle fluxes in the ecliptic plane.

With the tool you can use these maps to:

- cross check your ballistic calculation of CME/CIR propagations,
- carry out your own calculations of CME/CIR trajectories in the ecliptic plane via a few clicks on the map (simple use),
- use pre-calculated CME trajectories to check if a transient emerged from the Sun and impacted a planet or probe




Propagation Tool
T1
T2
2013-11-04T00:00:(
2013-11-24T00:00:(
2013-11-12T05:13:11
0 27 54 81 hr
0 0.3 0.6 1.0 AU
Radial Propagation
J-map: Carrington/InSitu
Corotation
J-map: Catalogue of fits
SEP Propagation
J-map: Click to fit
SECCHI-A
SECCHI-B
Pos. Angle (°)
0
CME Properties
Speed (km/s)
506
Extent (°)
45
Long. separ.
77
Elongation
74
67
60
53
46
39
32
25
18
11
4
2013-11-04 T00:00:00
2013-11-08 T00:00:00
2013-11-12 T00:00:00
2013-11-16 T00:00:00
2013-11-20 T00:00:00
2013-11-24 T00:00:00
MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
MESSENGER
VEX
STEREO-A
ACE
STEREO-B
MEX
JUNO
CASSINI
Table of arrival times
J-map interface
Carrington Map
Fit parameters
Radial Propagation Tool Interface
No V plot
Please select end point


Space Weather
Start time
2012-01-06T00:00:00
2012-01-09T00:02:00
START : SUN
CR2118 STEREO-A 195A
90° 45° 0° -45° -90°
0° 90° 180° 270° 360°
MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
MESSENGER
VEX
Longitude : 339.6 - Latitude : -85.3 - Value : 62
CME Long. ...
108.1
Central ... Footpoin... Footpoin...
Longitude 107.58 106.63 108.53
Latitude 1 1 1
Start Time Ellipticity Aspect Ratio Hel Z0 Central Axis Tilt Footpoint Separation HAE Central Axis
Start : SUN 2012-01-06T00:00:00 1 1.1 -1 1 0 1.9 160
Poloïdal Flux Injection defined ✓
Background Corona defined ✓
Automatic comp...
Rot. angle
End Time BZmin RTN BZmin GSM Vmax Ptot DSTmin HAE
End :
Time t
0 24 48 72 hr
0 0.3 0.6 1 AU
EFR Model
ENLIL
Particle Transport
EFR Interface
J-Map/Kinematics
Poloidal Flux Injection
Solar Wind Interface
Table of Arrival Times
AMDA at END time
MEDOC at tSUN
3-D Movies of EFR
Wight-light SIMU

THANK YOU!