Exploring the Solar Corona with Solar Orbiter: Insights from Metis-Led observations' campaigns

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Outline

- Metis Instrument
- Observations
- Science objectives – SOOPs (Solar Orbiter Observing Plans)
- Science highlights and work in progress
- What’s next

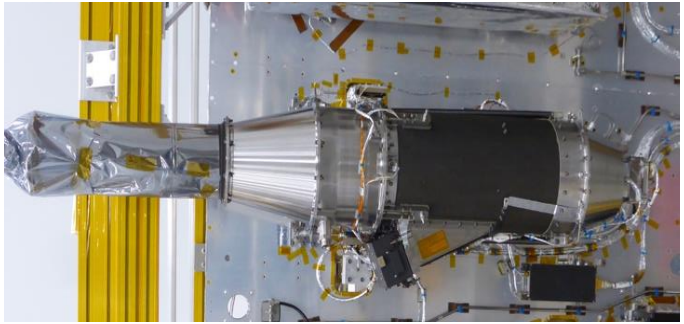
Metis: the Solar Orbiter coronagraph

Metis is an externally-occulted coronagraph designed to provide full imaging of the extended corona in:

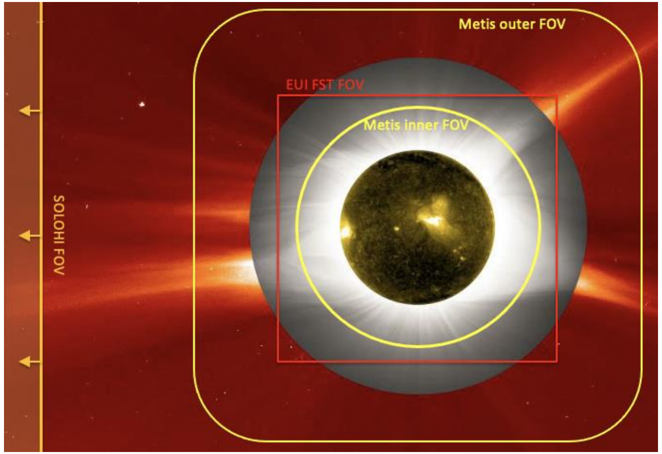
- **total and polarised visible-light brightness** (580-640 nm)
- **UV H I Lyman-α line** (121.6 ± 10 nm)

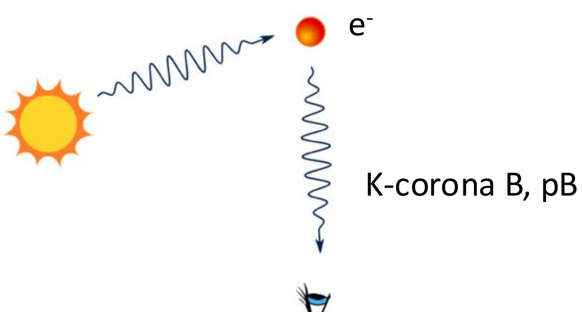
Metis observations allow the investigation of the:

- **density distribution of coronal e^- and H I atoms** (protons)
- **2D solar-wind outflow** (H I/proton component)
- **large-scale dynamics of e^- and H I in CMEs** and other solar transients

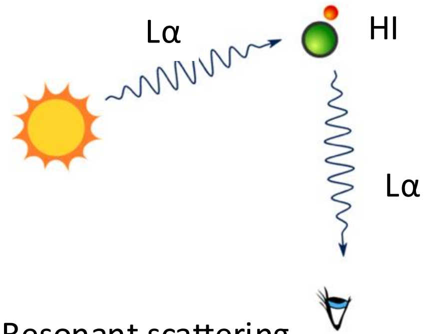


FOV: (1.6° x 2.9° annular, 1.7 – 3.0 $R_\odot$ @ 0.28 AU)





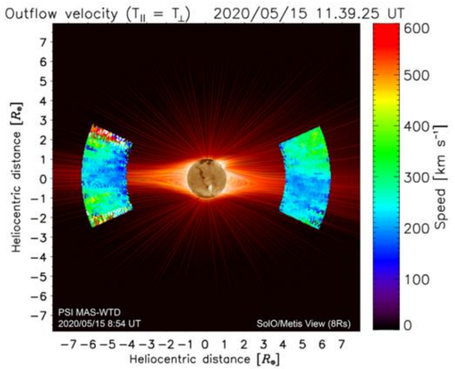
Thomson scattering



Resonant scattering

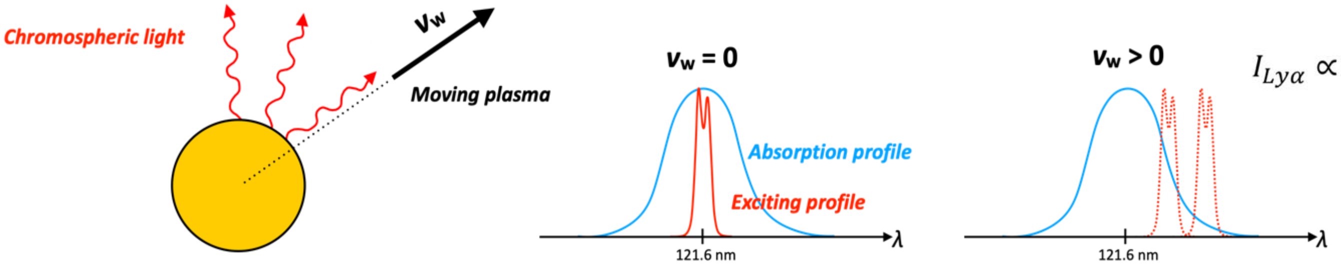
Metis measurements: Solar wind outflow

- Metis maps the regions where **the solar wind undergoes acceleration** from $\sim$ 100 km/s to near its asymptotic value
- **Doppler dimming analysis** (Withbroe+ 1982; Noci+ 1987):
  - The outflow speed, v_w, can be derived from the comparison of coronal UV H I Ly-α emission (dimmed due to coronal expansion by a factor ϕ) with Ly-α emission for a static corona (no dimming) expected based on the electron density from pB maps of the coronal plasma (Dolei+ 2018; Dolei+ 2019)
  - It depends upon several physical and geometrical parameters: electron density n_e; hydrogen ionization ratio, R, which in turn depends on the electron temperature, T_e; Doppler dimming factor, ϕ, due to the presence of outflow speed, v_w, H I kinetic temperature, T_k; and the exciting chromospheric radiation, $I_\odot$.



Romoli+, 2021

$$pB \propto \int_{LoS} n_e(x)dx$$



$$I_{Ly\alpha} \propto \int_{LoS} R(T_e)n_e(x)\,\Phi(v_w, T_k, I_\odot)\,dx$$

Metis spatial & temporal resolution

- **Spatial resolution:** checked in-flight with Star observations → VL< 2px , UV between 4-7 pixels
- **Temporal resolution:**
  UV: > 1s limited by countrate
  VL: 60s in pB, 20s in tB, >1s in fixed polarization

Metis acquisition schemes:

VL channel	VL-pB	Polarised brightness acquisition
	VL-tB	Total brightness acquisition
	VL-FP	Fixed polarisation acquisition
	VL-TN	Temporal noise acquisition
UV channel	UV-Analogue	Analogue mode acquisition
	UV-PC	Photon counting acquisition [a]
	UV-PC-Offset	Photon counting offset mode
	UV-TN	Temporal noise acquisition

VL-pB: (DIT > 15 s x 4 polarizations) > 60 s

VL-tB: DIT > 20 s

VL-FP, UV-Analogue: DIT > 1 s

DIT = Detector Integration Time

Antonucci et al. A&A, A10 (2020)

Metis observations

Observations limited by telemetry and by the off-pointing from other RS instruments

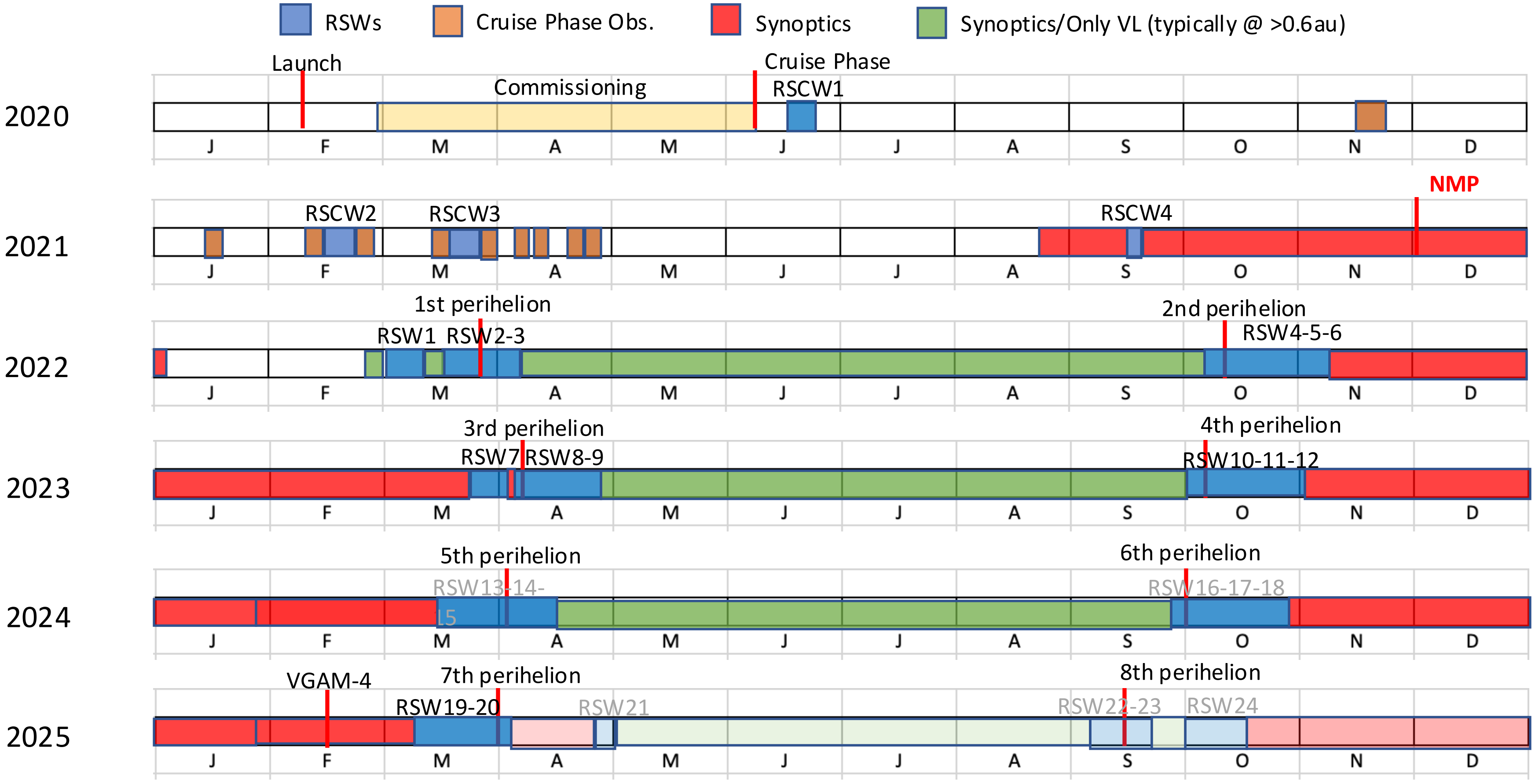
Metis observations performed:

- During **Remote Sensing Windows (RSWs)** with payload shared objectives (30 days/orbit)

- Along the rest of orbit as **synoptics (at reduced cadence and/or resolution)**

- During **Target of Opportunities** (UV star observations and joint observations with other assets)

Metis observations are listed in the Metis webpage: http://metis.oato.inaf.it/obs_summary_new.html#



Interruptions in the flow of observations due to: **S/C off-pointing or unexpected Metis and/or S/C switch off**

Metis: Science Objectives

Key scientific questions of the Solar Orbiter mission addressed by Metis.

Solar Orbiter top-level questions	Metis contribution
What drives the solar wind and where does the coronal magnetic field originate?	Investigation of the region where the solar wind is accelerated to near its asymptotic value.
How do solar transients drive heliospheric variability?	Investigation of the region where the first, most dramatic phase of the propagation of CMEs occurs.
How do solar eruptions produce the energetic particle radiation that fills the heliosphere?	Identification of the path of shock fronts accelerating particles in the solar corona.
How does the solar dynamo work and drive connections between the Sun and the heliosphere?	Study of the overall magnetic configuration by identifying the closed and open magnetic field regions in the corona.

Antonucci et al. A&A, A10 (2020)

Scientific objectives definition per orbit SAP – Science Activity Plan (Zouganelis, 2020)

During the RSW, Solar Orbiter observations are organized into **Solar Orbiter Observing Plans (SOOPs)**, where a SOOP is a set of common operations from multiple instruments addressing several mission sub-objectives.

L_FULL_LRES_MCAD_Probe-Quadrature – Objective 1 (solar wind)
L_FULL_HRES_HCAD_Coronal-Dynamics – Objective 1, 2 (transients), 4 (Sun-Heliosphere)
L_FULL_HRES_HCAD_Eruption-Watch – Objective 2, 3 (particles)
R_FULL_HRES_HCAD_Density-Fluctuations – Objective 1
L_BOTH_HRES_LCAD_CH-Boundary-Expansion – Objective 1

L_BOTH_LRES_MCAD_Pole-to-Pole – Objective 1, 4
L_FULL_HRES_MCAD_Coronal-He-Abundance – Objective 1
R_BOTH_HRES_LCAD_Dark-Halos – Objective 1

Probe-Quadrature (A. Zhukov, D. Telloni)

This SOOP is designed to observe the corona while Parker Solar Probe (PSP) is in quadrature with Solar Orbiter during a PSP perihelion passage, when PSP passes above a limb observed by Solar Orbiter. Off-pointing to a limb allows SPICE and EUI to acquire high-cadence observations of the solar wind source region, which can provide data on plasma densities, temperatures, composition, Doppler shifts, and small-scale coronal dynamics.

The goal of the SOOP is to acquire above-the-limb observations of the source region of the solar wind plasma that will be later sampled in situ by Parker Solar Probe. This goal is closely linked to the main science objective of Solar Orbiter: connecting solar and heliospheric phenomena.

Metis: high spatial and temporal cadence (cadence 20/30 min + 1h/day, VL cadence 1-20 s)
Metis and SolO-HI are leading this SOOP & Synoptic support from other full disk RS instruments

Boundary-Expansion (R. Susino)

This SOOP is specifically targeted at overexpanded CH boundaries as slow wind sources, requiring a different PHI mode and SPICE observations. It was explicitly created to address the science objective "**Does slow wind originate from the over-expanded edges of coronal holes**?"

Metis: high spatial and temporal cadence (cadence 5 min + 1h/day, VL cadence 10 s)
Pointing requirements: Off-pointing (for SPICE), combined with disk-centre. During perihelion

Coronal-Dynamics (V. Andretta)

This SOOP is aimed at observing structures in the outer corona and linking them to the heliosphere observed in-situ.

At larger latitude: this SOOP could be used for scanning the outer corona and for characterizing features such as pseudo-streamers and equatorial CH, more frequent in an active phase of the cycle. During perihelia, there is a reduction of the dependence on the solar rotation, allowing the study of the temporal evolution of the coronal structures.

Metis: high spatial and temporal cadence (cadence 20/30 min + 1h/day, VL cadence 1-20 s)
At high latitude: METIS standard modes to observe large scale coronal structures - CME Watch On

Density-Fluctuations (V. Andretta)

Study of **density fluctuations in the extended corona** as a function of the outflow velocity of the solar wind while evolving in the heliosphere.

Metis: FP: 1 s cad/2 min, TB: 20-60 s cad, PB: 60 s cad. - UV: same cad./dur as VL observations
Distance: near perihelia (< 0.35 au)
SolO-HI, EUI/FSI, SPICE needed
Synoptic support from other full disk RS instruments

Eruption-Watch (C. Sasso)

The Eruption Watch SOOP is a full-disk, high resolution plan, designed to catch eruptive events.

Science objectives:

- 3D morphology, physical plasma properties, and evolution of the CMEs (and shocks) in synergy with observatories on the ecliptic plane.

- Characterize the interaction with ambient corona for high solar wind streams.

- Study of Prominence Eruptions/CME (and shocks) at high temporal resolution.

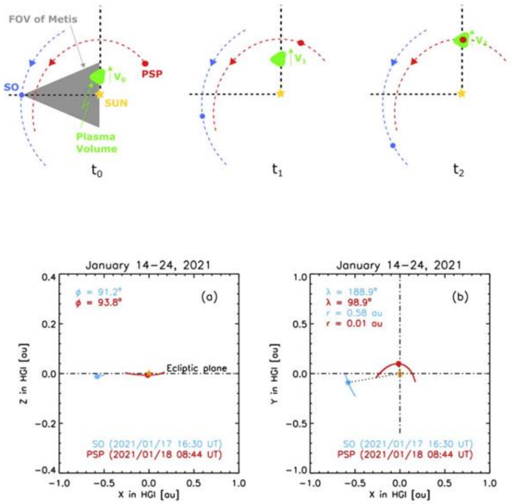
Metis: 10 min. cadence with VL bin. 4x4, VL masking, and UV bin. 2x2 + 2 h at 1 min. cadence
All remote sensing instruments are involved while in-situ payload provides continuous observations.

Metis science highlights
Solar-wind diagnostics with in-situ & coronal data

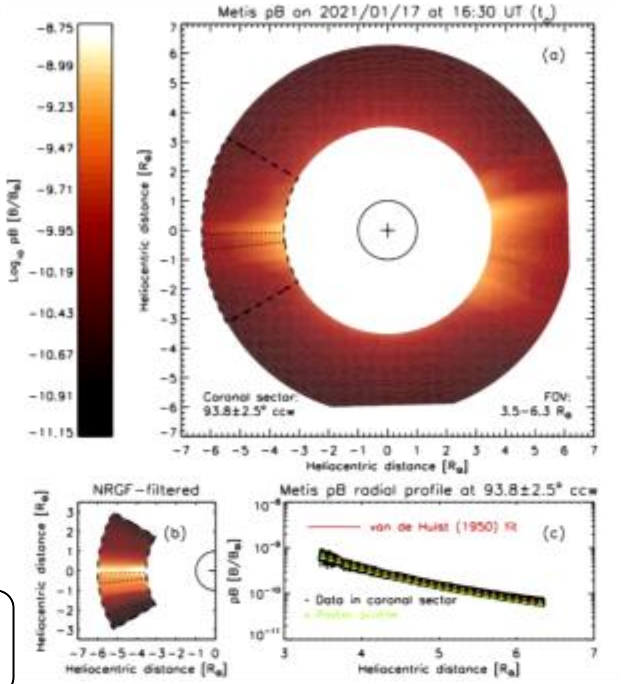
Exploring the evolution of solar wind from its source on the extended corona to the inner heliosphere

Remote sensing and in-situ coordinated measurements, like during **quadratures between Solar Orbiter and PSP**, but not only, provide a valuable tool to probe the physical parameters of the solar wind throughout the solar corona and the heliosphere.

The **flow-aligned magnetic field** and the **bulk kinetic energy flux density** can be inferred along the coronal current sheet, allowing in particular **estimation of the Alfvén radius at 8.7 solar radii** during the time of this event. This is the very first study of the same solar wind plasma as it expands from the sub-Alfvénic solar corona to just above the Alfvén surface.



First Solar Orbiter – PSP quadrature, January 18th, 2021

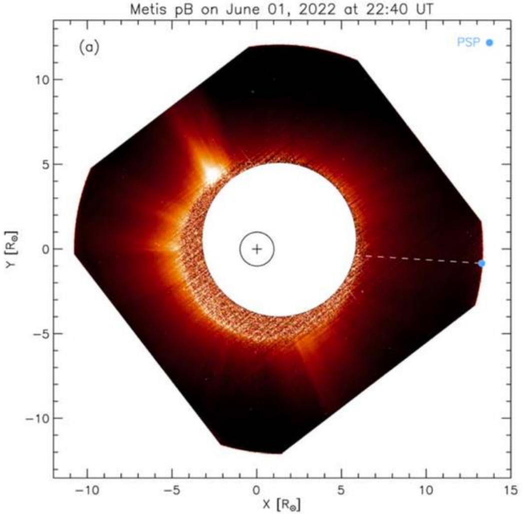


Telloni+ 2021
Biondo+ 2022
Telloni+ 2022
Niembro+ 2023
Telloni+ 2023a
Telloni+ 2023b

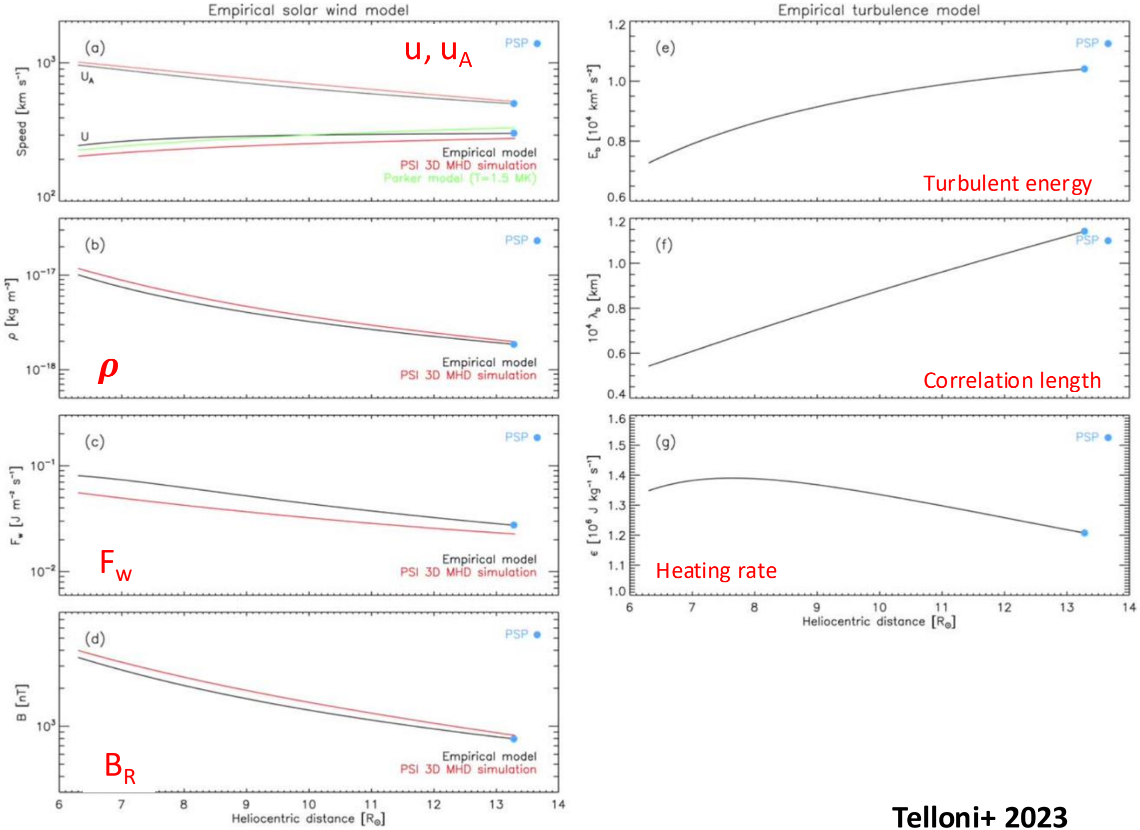
Solar-wind diagnostics with in-situ & coronal data

Coronal heating rate in the slow solar wind

- *Estimate of coronal parameters from 6.3 to 13.3 $R_\odot$ using 1D model conservation of mass and magnetic flux and PSP constraints (left)*
- *Heating rate can be empirically estimated solving the propagation equation of Alfven with a dissipation and turbulence term using WKB approximation*



2022 June 1,
Solar Orbiter @0.936 au
PSP @ *13.3* $R_\odot$



Telloni+ 2023

Metis high-cadence observations

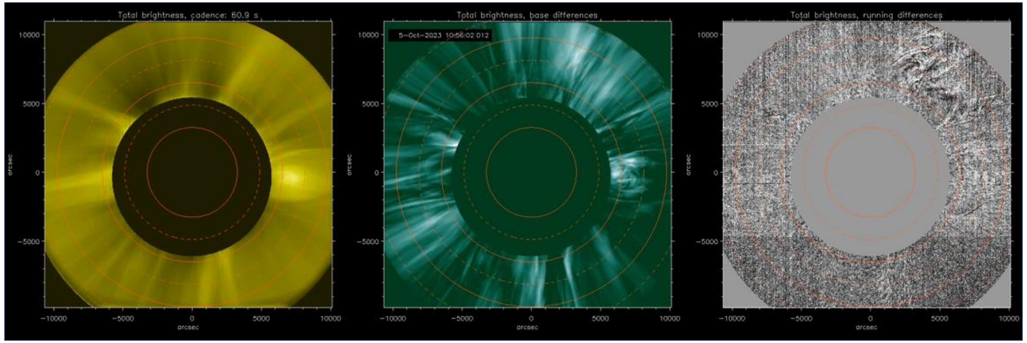
Key points about Metis high-cadence observations:

- **[Temporal resolution]** Metis cadences can be at least a factor 5 or even an order of magnitude higher than existing coronagraphs operating continuously in space.
- **[Spatial resolution]** While observing around Solar Orbiter perihelia (d ~ 0.3 au), the plate scale of the VL channel can be as low as 2000 km/pixel, better than most coronagraphs in operation.
- **[SNR]** Thanks to its innovative externally occulted design, the typical signal-to-noise ratio of Metis observations in the VL channel can easily exceed the value of 200 (indeed, saturation of the brightest features can be a problem sometimes, even at short exposure times).
- **[Duration]** The length of the observations is mainly limited by the mission telemetry constraints. But 24-hours long observation are becoming feasible.
- **[UV Ly-α]** It is possible to observe simultaneously with matching cadences in the UV (Ly-α) channel.

Brightness normalized to mean radial profile

Normalized base difference

Normalized running difference



Dates run: 2023-10-05T08:00:00 – 2023-10-06T08:00:00
(total: 24 hrs):

1) Total brightness, **cadence: 20 s**, duration: 2h8m (2023-10-05T08:30:30 – 2023-10-05T10:38:42)
2) Total brightness, **cadence: 60 s**, duration: 11h27m (2023-10-05T10:55:00 – 2023-10-05T22:22:28)
3) Polarised brightness, **cadence: 120 s**, duration: 6h45m (2023-10-05T22:45:01 - 2023-10-06T05:30:04)

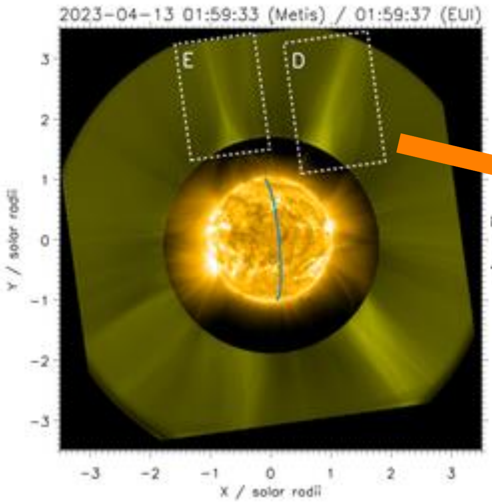
Waves in the middle corona (> 1.5 R_{Sun})

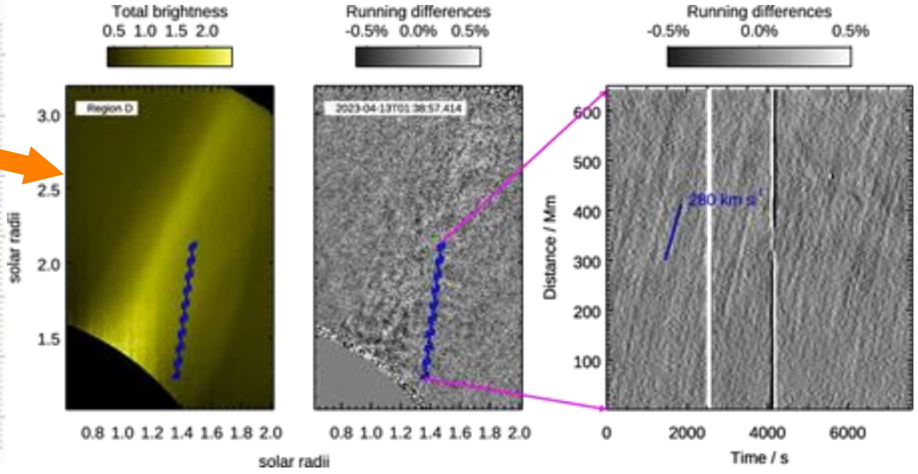
An example while close to the 3st Solar Orbiter perihelion

Leakage of p-modes into the corona?

Main properties:

- Periods: of the order of 4 - 5 min (3 - 4 mHz)
- Amplitudes: ~10^{-3} of background.
- Propagation speed: of the order of 200 – 400 km s^{-1}
- Coherent: at least for the duration of the observations (up to 2 h). No sign of damping. over large volumes (several tens or even hundreds of Mm).
- Ubiquitous in bright, near-stationary structures, but detectable also at their edges.
- Persistent: Observed in the same structure for many days, for the duration of the high cadence program.
- No obvious dependence on magnetic topology: Detectable both in streamers and pseudo-streamers.





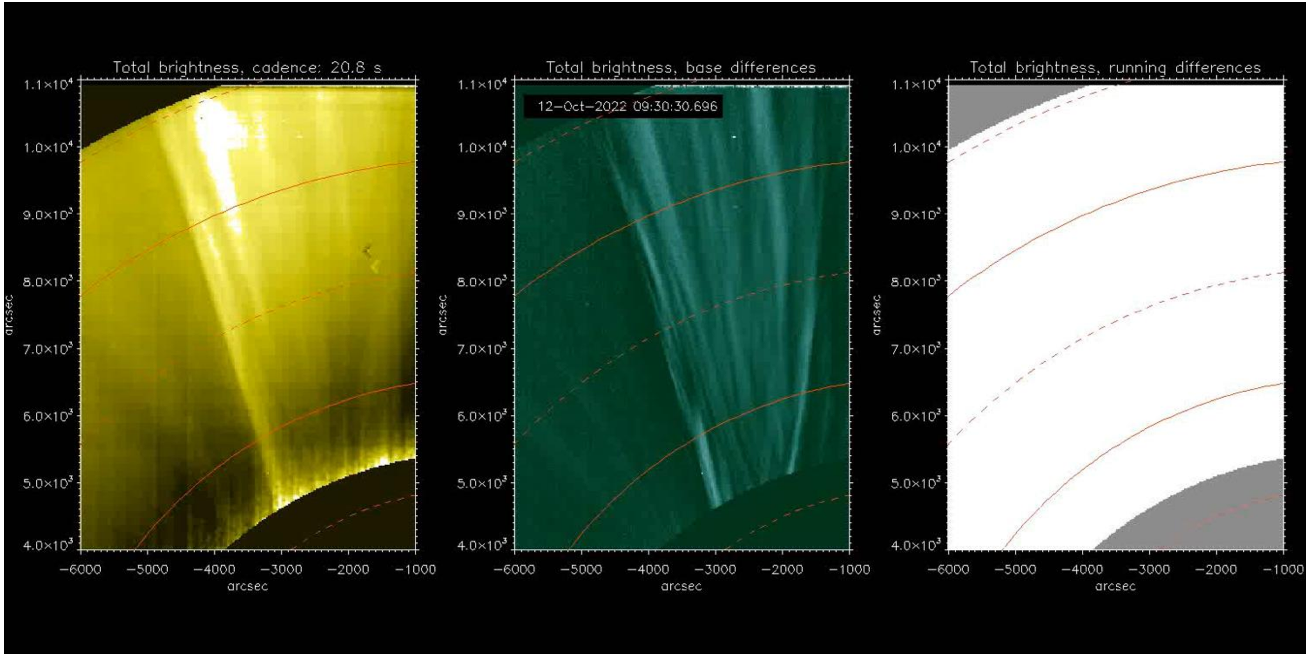
Andretta et al., submitted

Alfvènic outflows driven by Interchange Reconnection in a Pseudo-streamer

Observations of a large pseudostreamer eruption and the post-eruption relaxation phase: outward propagation of helical structures, extending up to 3 solar radii that appears to correspond to the stalk of the pseudostreamer.

The helical structures persisted for more than 3 hr following a jet-like coronal mass ejection associated with a polar crown prominence eruption.

Event observed on 2023 Oct. 12, following an on-disk flare at perihelion



Romano et al., ApJ, 2025

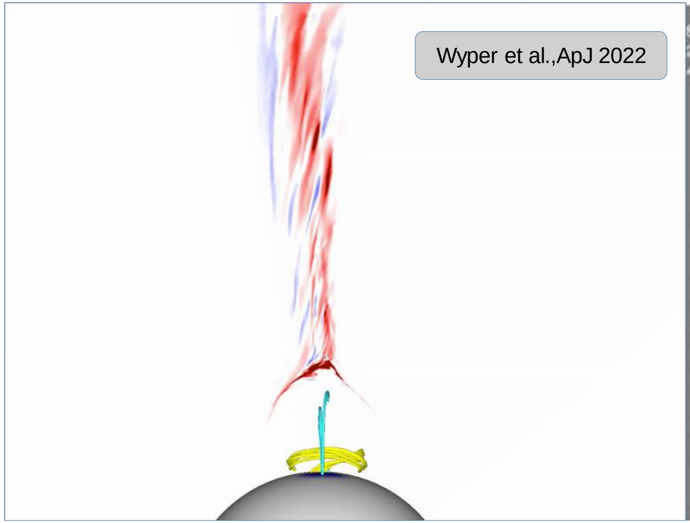
Alfvènic outflows driven by Interchange Reconnection in a Pseudo-streamer

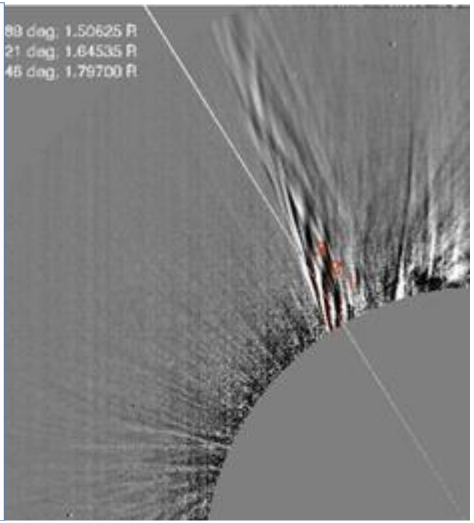
The features seen by Metis exhibited a notable trend: their inclination decreased as their polar angle and height increased.

A comparative analysis with a high-resolution magnetohydrodynamic simulation of bursty interchange reconnection, shows strong similarities in the evolution of the observed and simulated structures.
The Metis helical structure may be interpreted as a consequence of twist (nonlinear torsional Alfvén waves) and plasma liberated by interchange reconnection.
These observations and simulations suggest that sustained bursty interchange reconnection occurred following the eruption.

Additionally, they conjecture that these observations may represent the upper ends of the spatial and energy scales of the interchange reconnection process that has been proposed recently as the origin of the Alfvénic solar wind.

Event observed on 2023 Oct. 12, following an on-disk flare at perihelion





Romano et al., ApJ, 2025

CH boundaries as slow wind sources

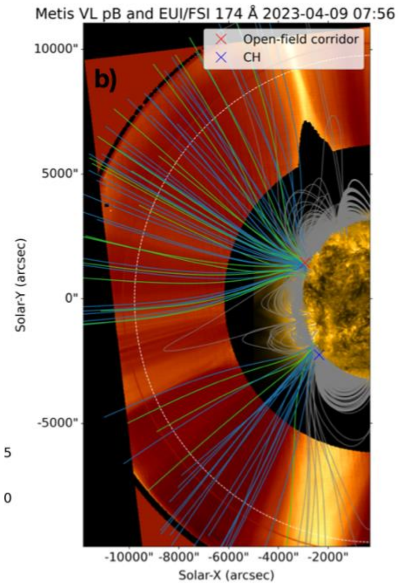
Investigating Solar Wind Outflows from Open-Closed Magnetic Field Structures Using Coordinated Solar Orbiter and Hinode Observations

Analysis of solar wind outflows from two locations: a narrow open-field corridor and a small, mid-latitude coronal hole, observed off-limb by the Metis and on-disk by the EIS on Hinode.

Magnetic field extrapolations suggest that the upflow regions seen in EIS were the sources of the outflowing solar wind observed with Metis.

Plasma in the narrow **open-field corridor has higher electron densities and lower outflow velocities** compared to the coronal hole plasma in the middle corona, even though the plasma properties of the two source regions in the low corona are found to be relatively similar.

The **speed of solar wind from the open-field corridor shows no correlation with the magnetic field expansion factor** (geometry of flux tubes), unlike the coronal hole. These pronounced differences at higher altitudes may arise from the dynamic nature of the low-middle corona, in which reconnection can readily occur and may play an important role in driving solar wind variability.



The magnetic field extrapolations derived from the PSI-MAS MHD simulation during Carrington rotation 2269.

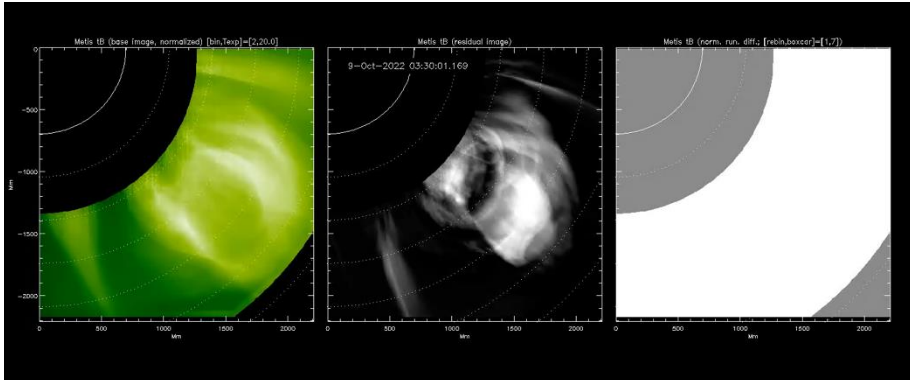
Ngampoopun et al., Sol. Phys., in press

Solar transients

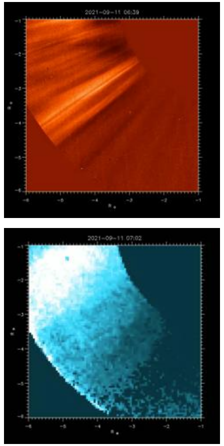
- Metis observations of CMEs and related phenomena are crucial to
  - **identify of the mechanism/s driving the eruptions;**
  - ascertain whether **the main source of the flux injection** into the heliosphere **resides in the corona;**
  - Study **the restructuring of the global solar atmosphere** following a CME.
- The unique combination of VL and UV images allows for the first time the investigation of the thermodynamic evolution of CME plasma
  - UV Lα and VL probe different quantities during the CME transient, thus allowing for the **derivation of the several physical parameters** of the event.
- **Synergies** with EUI/FSI, SoloHI (eruption watch campaigns during RSWs), STEREO, and LASCO, for 3D and geometry reconstruction, and more.

Russano+, in prep.
Bemporad+, in press
Russano+ 2024
Frassati+ 2023
Heinzel+ 2023
Niembro+ 2023
Zimbardo+ 2023
Mierla+ 2023
Rodriguez+ 2023
Bemporad+ 2022
Andretta+ 2021

RUSSANO+: High spatial - temporal resolution CME observed in VL and UV

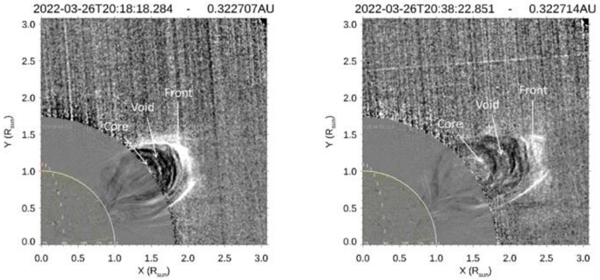


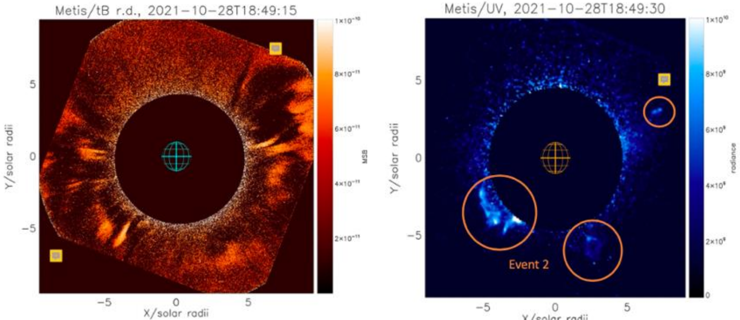
RUSSANO+: Eruptive events with exceptionally bright Ly-α emission



Quiescent filament (NW CME) and active filament (SE/SW fast halo CME)

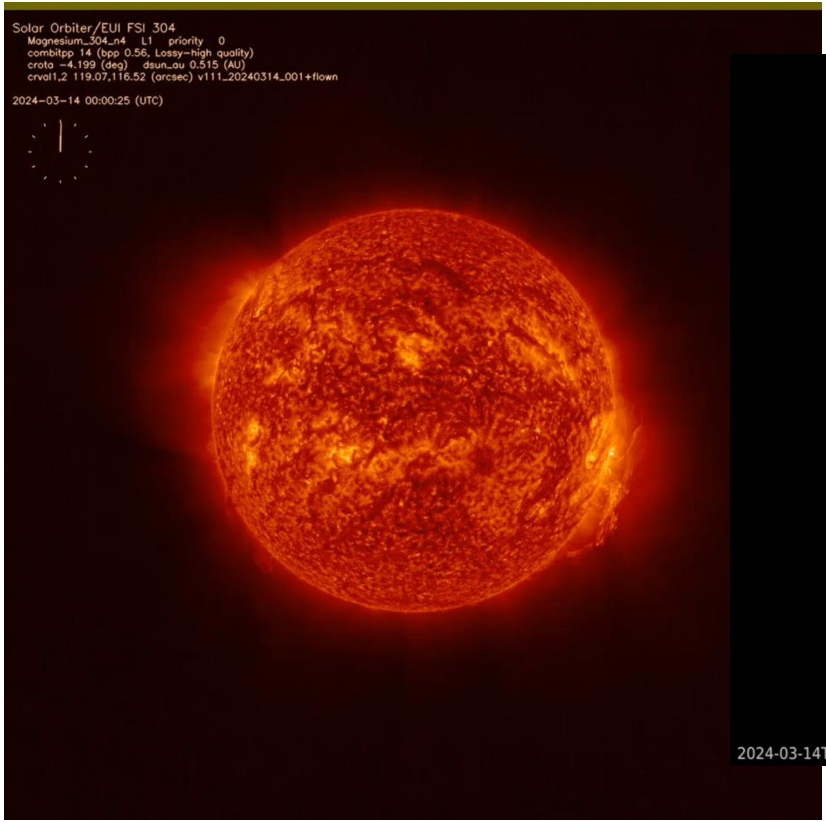
BEMPORAD+: Small-scale flows in the void of a CME

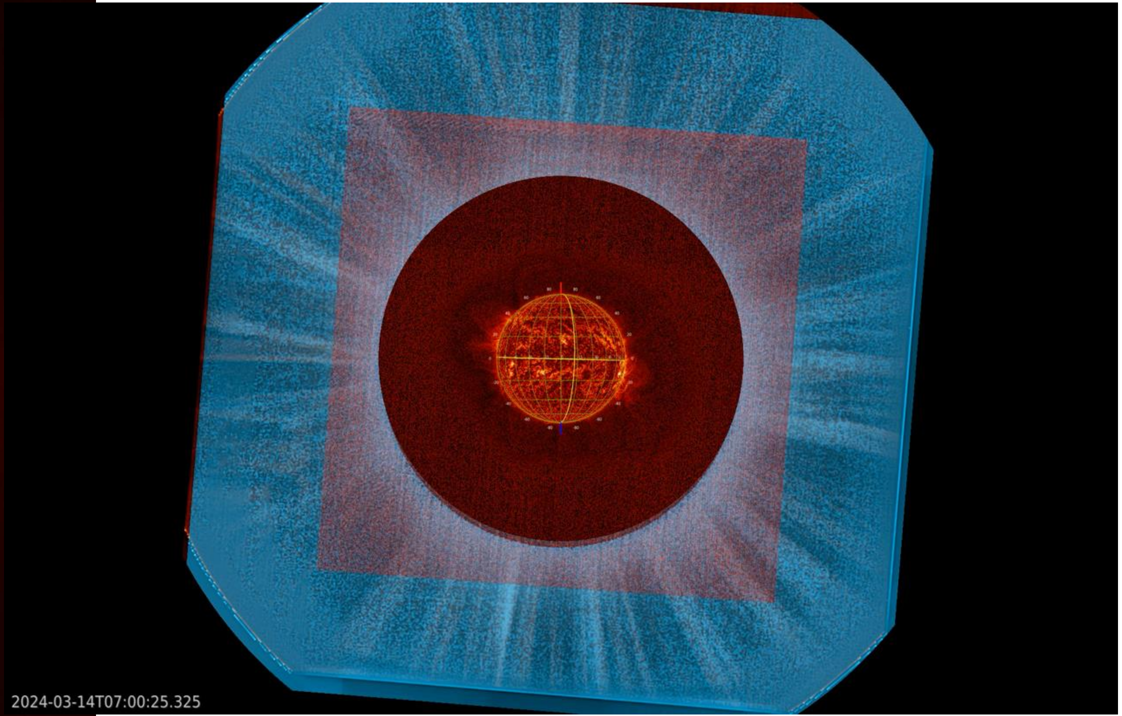




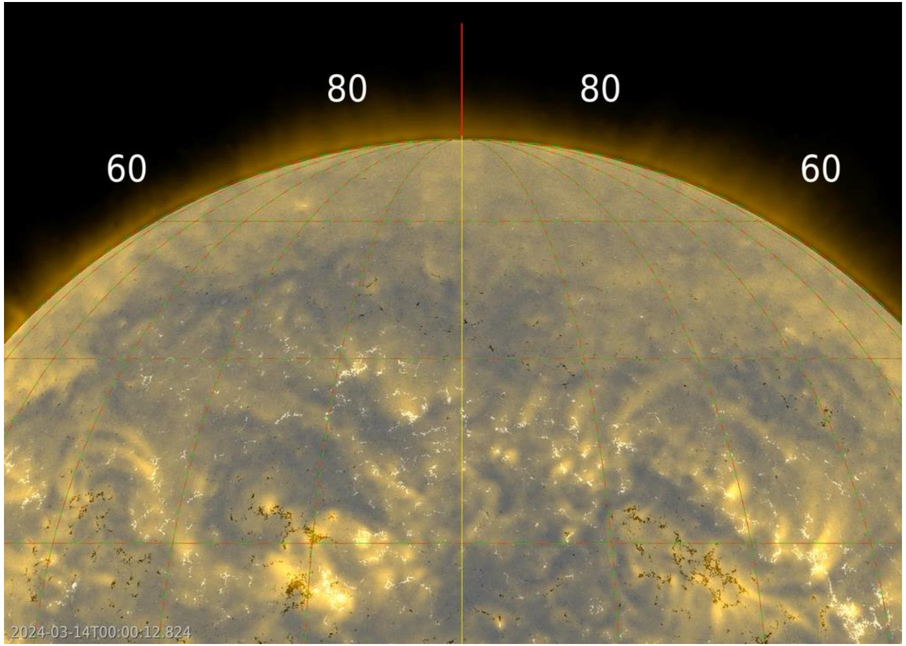
DE LEO+: Two distinct eruptive events observed by Metis on October 28, 2021

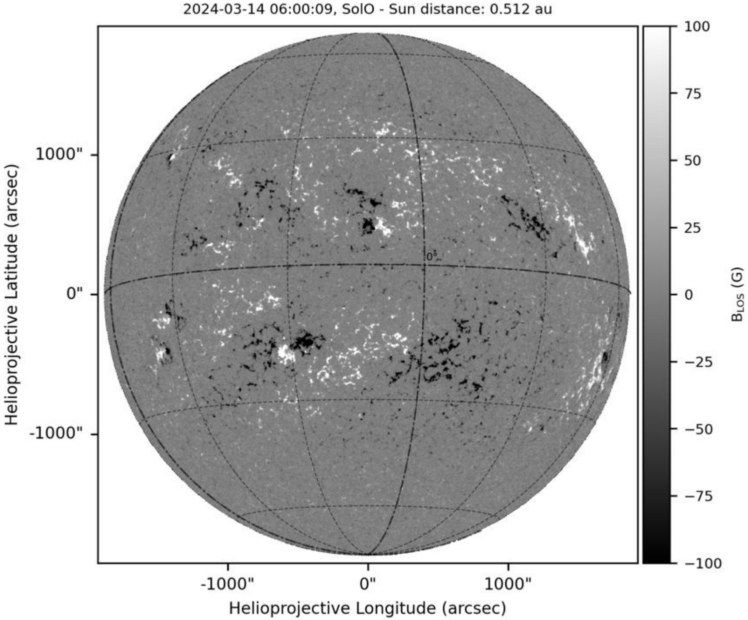
Eruption Watch Campaign March 2024
14 March 2024





HMI (SDO)+SWAP174 (PROBA2)/PHI (SolO)

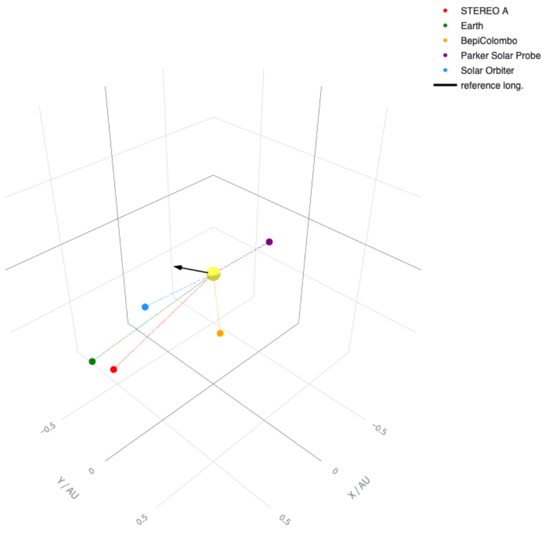


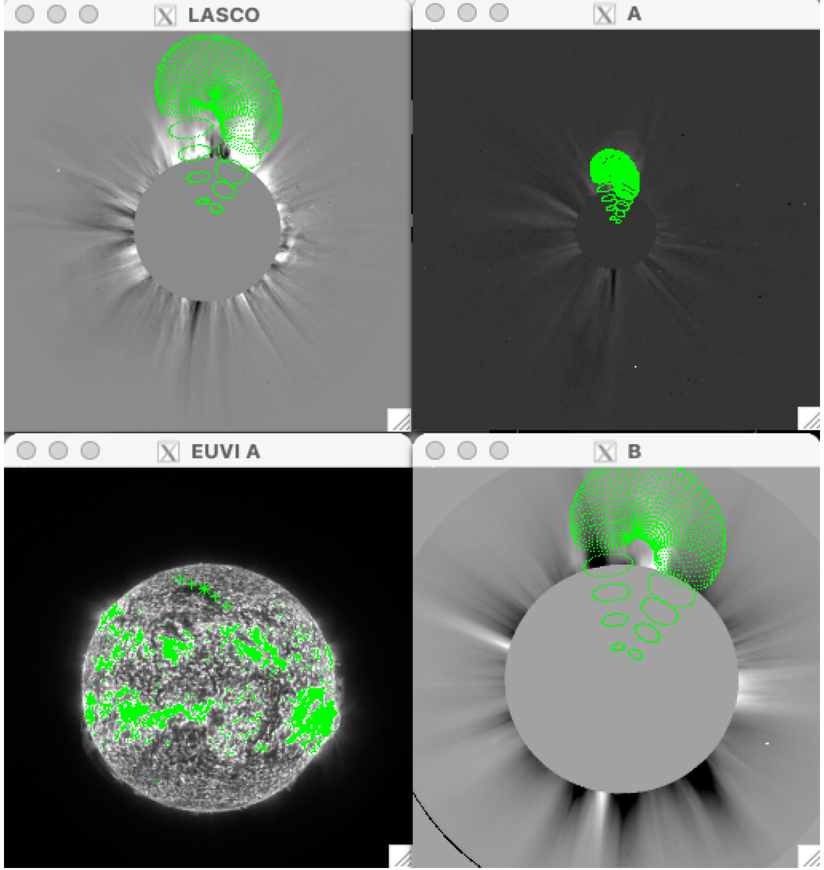


CME front
Triangulation and GCS reconstruction

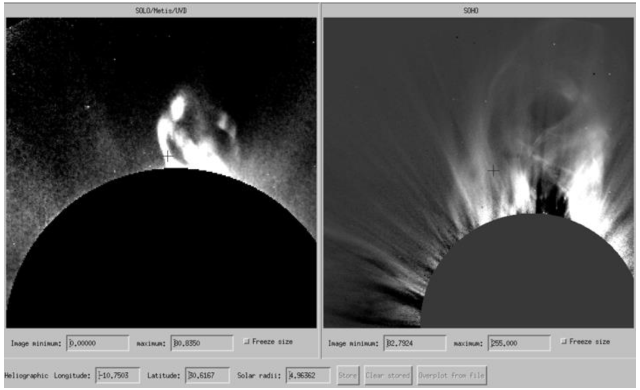
Velocity
387 +/- 30 km/s
De-projected: 637 km/s

Cactus V = 481 km/s.

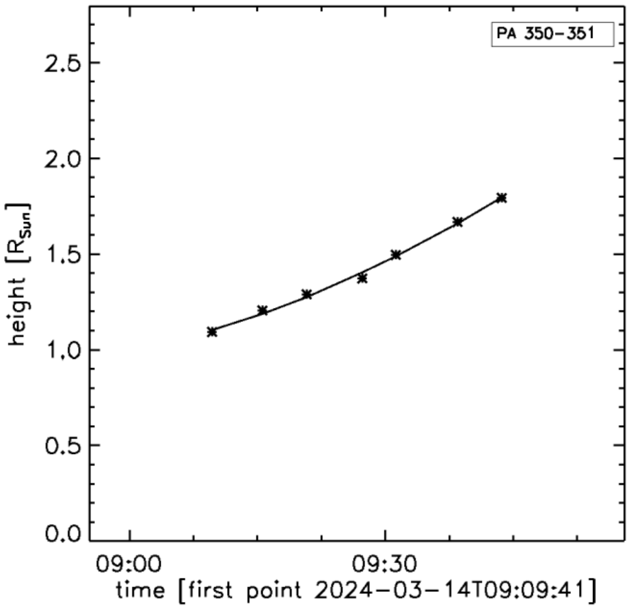


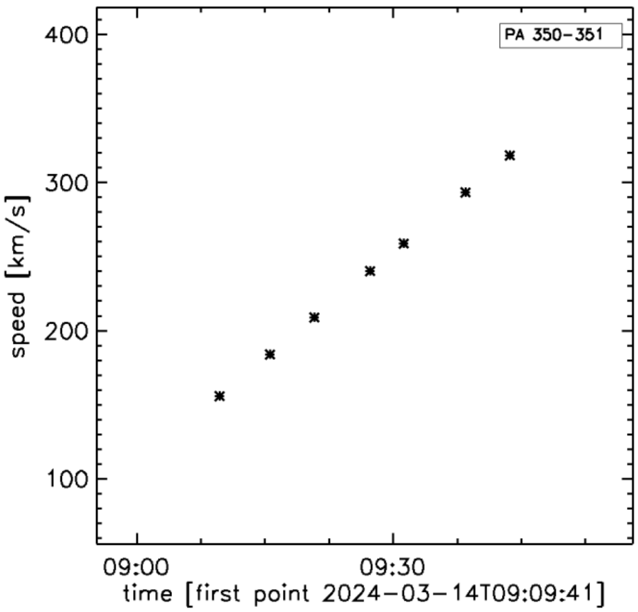


Heliocentric distance	0.52 AU
Longitud. Separation to Earth lon.	-12.7°



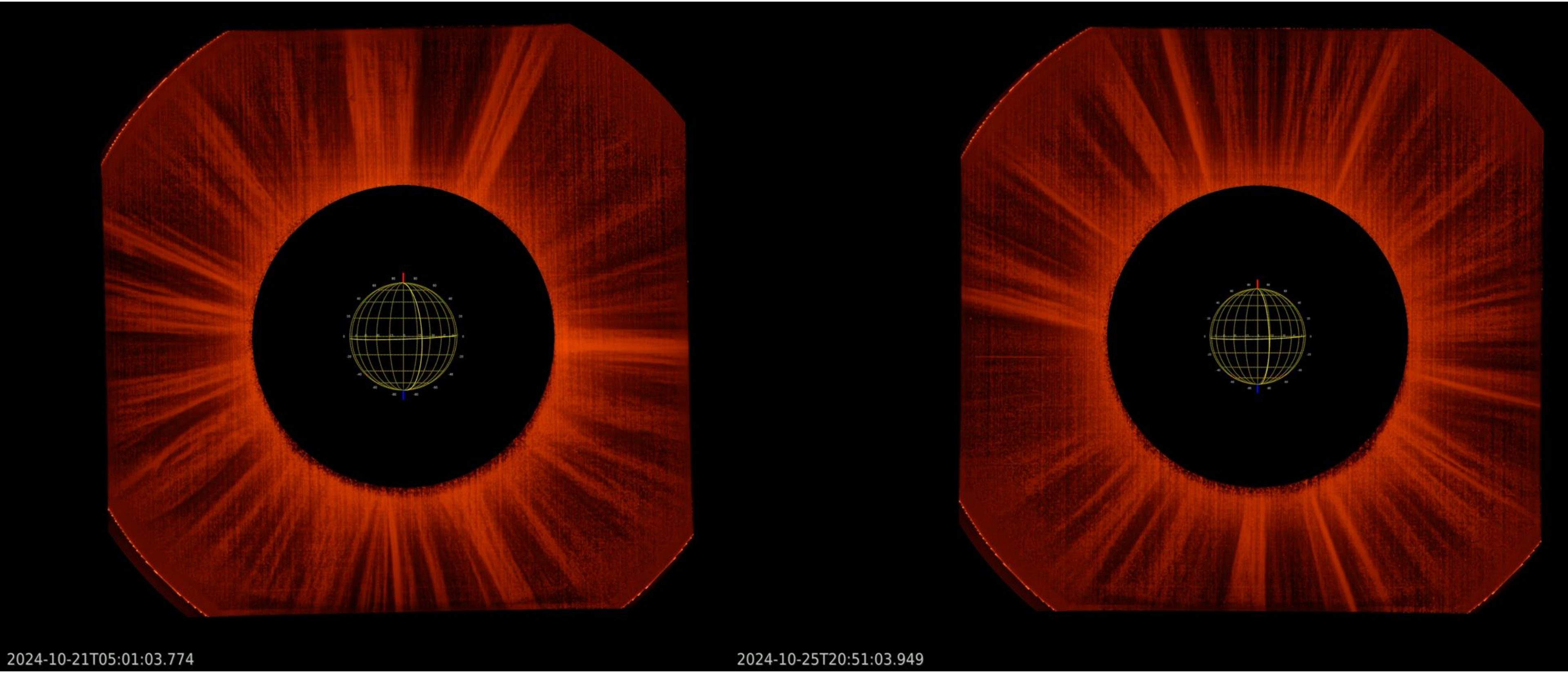
- We see the filament up to the edge of the FOV at 3.7 Rs in EUI
- There is no obvious deflection
- It is accelerating reaching around 320 km/s at the edge of the FOV.





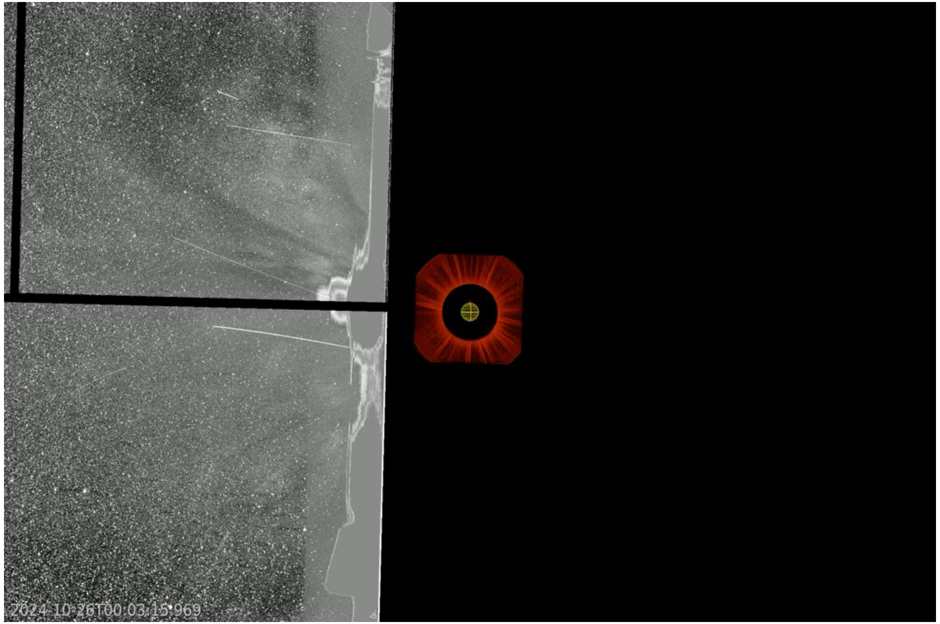
This fit with the scenario of the prominence still accelerating between EUI and coronagraphs --> Metis analysis

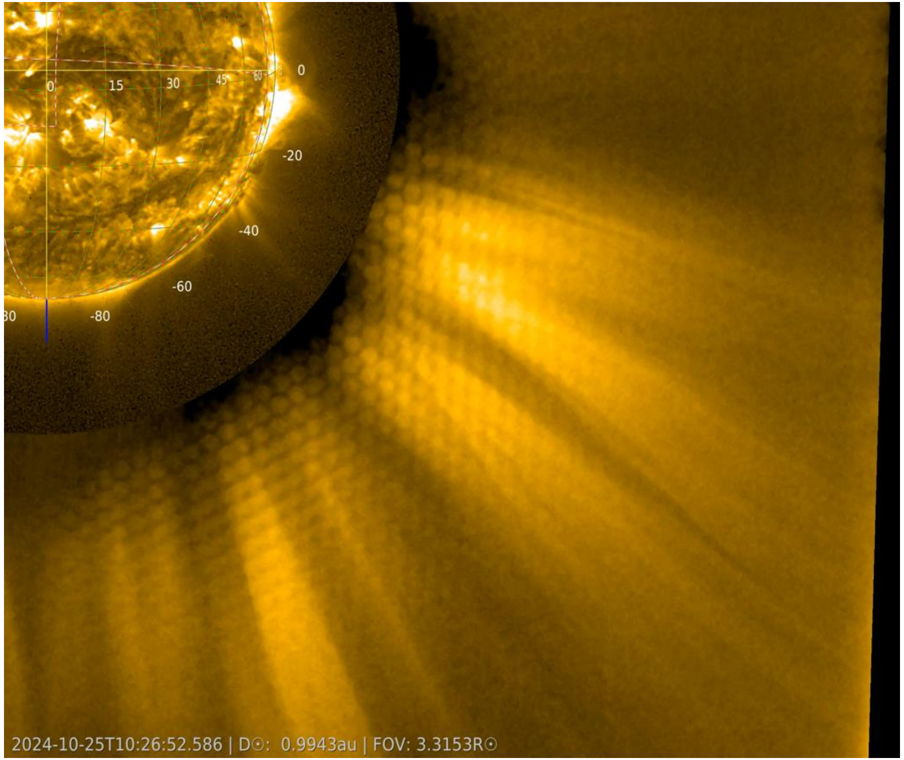
Eruption Watch Campaign October 2024
21-27 October 2024

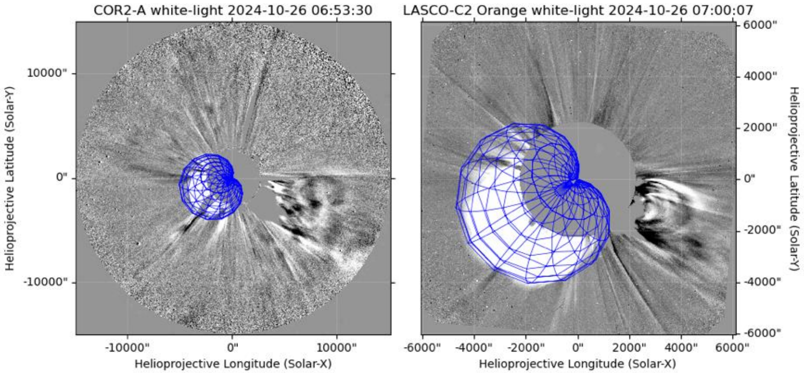


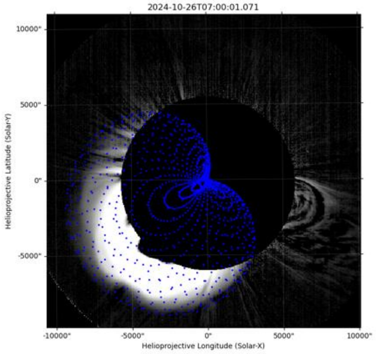
Metis: GLOBAL (cadence 10 min) + CMEOBS (cadence 1 min)

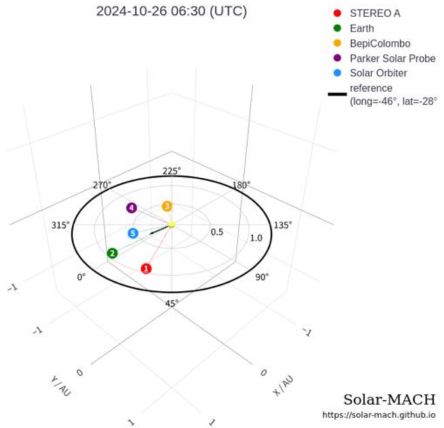
SoloHI & EUI: FSI coronagraphic mode





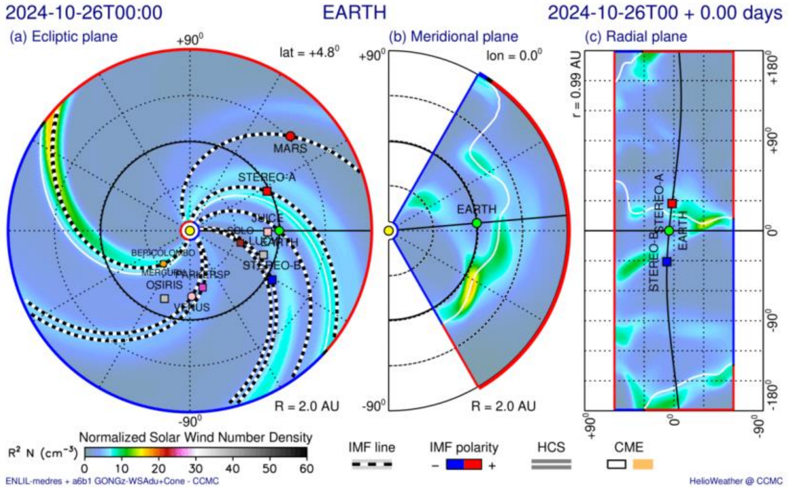


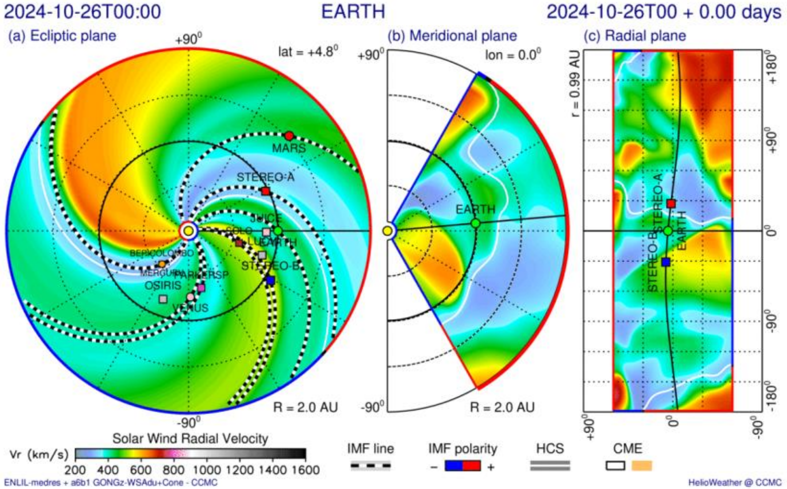




WSA-Enlil

V estimation 1800 km/s



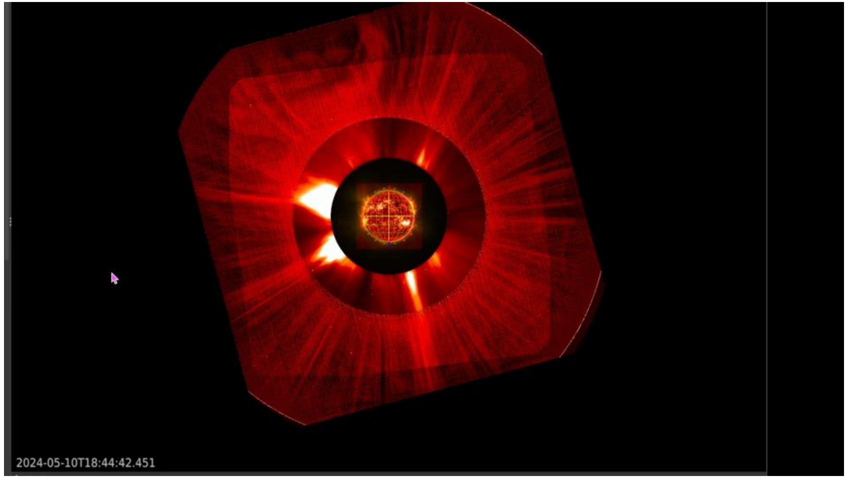


P. S. Sahani

Observations of Solar Activity from Solar Orbiter Before, During, and After the May 2024 Geospatial Superstorm

R_FULL_LRES_LCAD_RS-Synoptics-Low
16.04.2024 - 01.07.2024

Metis: VL synoptics (cad 2 h)
EUI: FSI 17.4 & 30.4 nm synoptics (cad 10 min)
PHI: Synoptics full disk (cad 6 h)
SPICE: Regular synoptics at disk center
STIX: Disk center observations
SolOHI: Synoptics

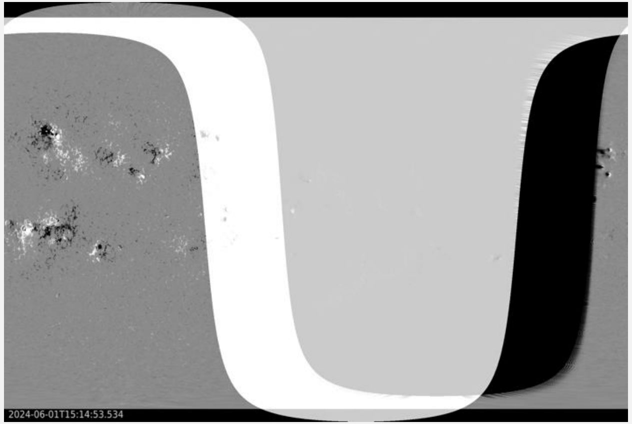


IS data

Heliocentric distance	0.67 AU
Longitud. Separation to Earth lon.	-193.5°

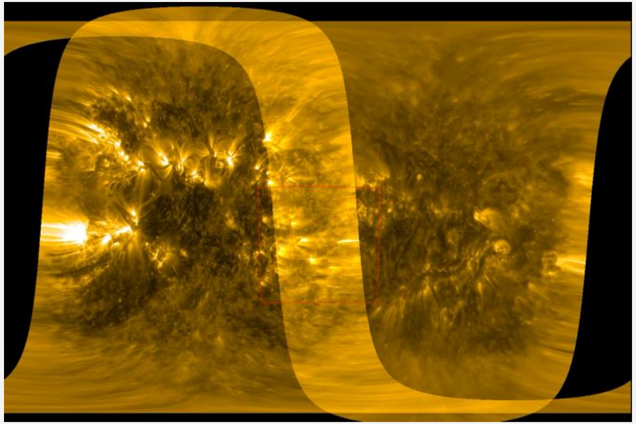
PHI + HMI / EUI + AIA
16/04 – 03/06/2024

What Solar Orbiter can provide:



PHI → formation of the AR 3664 and analysis of the parameters before the X16 flare of the 20th of May

Metis → GCS reconstruction (Sasso, Lario, 2025)
LL: Every day: 1x4 VL images, 4 UV images,
Synoptics: higher cadence: 12 min to 30 min



Future: importance of multi-spacecraft view

Conclusions and future perspectives

- Metis data contribute to the knowledge of middle corona dynamic morphology, solar wind and transients acceleration.
- Coordinated campaigns with other instruments are performed to enhance the science return.

Flying out of the ecliptic:

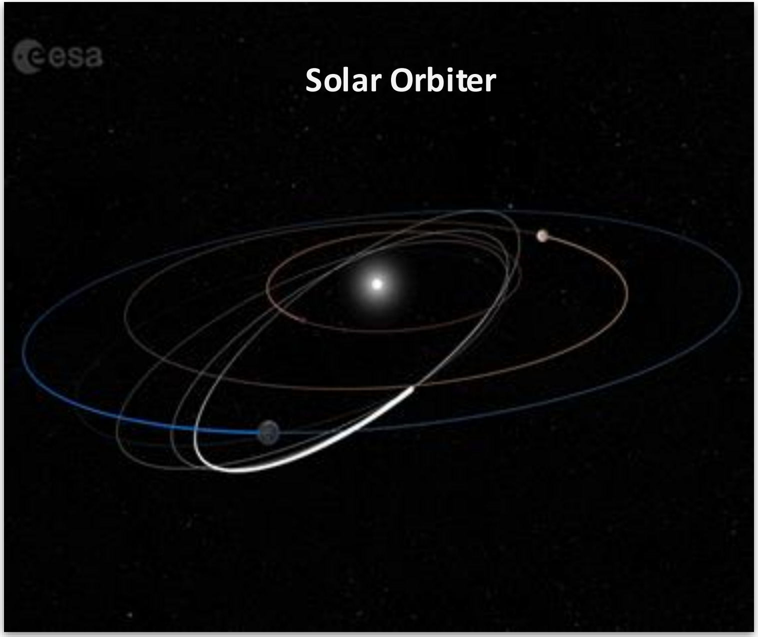
SolO orbital inclination wrt ecliptic will progressively increase after a series of VGAMs:
Feb 25 -> 17^o, Dec 26 -> 24^o, Mar 28 -> 30^o, Jun 29 -> 33^o
The out-of-ecliptic vantage point offers the opportunity to coronagraphs to observe for the first time the corona from mid-latitudes and to investigate:

- **The longitudinal structure and distribution of the propagating CME plasma** and their geoeffectiveness
- **The longitudinal extent of coronal features and solar wind**, exploring possible longitudinal patterns related to the magnetic field polarity

L_BOTH_LRES_MCAD_ Pole-to-Pole (A. Burtovoi)

This SOOP is designed to be used as a whole- or half-orbit synoptic campaign that scans the Sun from one high latitude to the other (to be used at min inclination of 15º).

- Longitudinal distribution of coronal plasma at different heliolatitudes
- Probing the latitudinal distribution of the interplanetary dust cloud (F-corona)
- Study of Galactic and Solar Cosmic Ray modulation at different heliolatitudes



Metis website:
www.metis.oato.inaf.it
metis@inaf.it

Instrument Team Science Data Publications Meetings Solar Orbiter News Links Gallery

July 14, 2022

The first Metis Data Release is now available

Metis: the multi-wavelength coronagraph for the Solar Orbiter mission

Metis is the coronagraph of the scientific payload of Solar Orbiter, the first mission of the European Space Agency (ESA) program Cosmic Vision 2015-2025. Solar Orbiter has been conceived to explore for the first time the poles of the Sun and the circumsolar region.

The Metis experiment is an international collaboration led by the Italian National Institute for Astrophysics (INAF) and supported by the Italian Space Agency (ASI), involving several Universities in Italy and research institutes in the world.

The innovative instrument design has been conceived for simultaneously imaging the visible and ultraviolet emission of the Sun's corona. Observations obtained with Metis will enable us to diagnose, with unprecedented temporal coverage and spatial resolution, the structures and dynamics of the full corona.

Find out more »

Metis science objectives