Mapping Solar Wind Speed with Metis/SO observations

Silvio M. Giordano[1],

Daniele Spadaro[2], Roberto Susino[1], Rita Ventura[2], Marco Romoli[3,4],
Silvano Fineschi[1], Luca Zangrilli[1], Daniele Telloni[1] and Metis team

[1] INAF - Astrophysical Observatory of Torino, Italy,
[2] INAF - Astrophysical Observatory of Catania, Italy,
[3] Dept. of Physics and Astronomy, University of Florence, Italy
[4] INAF - Astrophysical Observatory of Arcetri, Florence, Italy

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Solar wind speed maps from Metis coronagraph observations

Summary

The measurement of the solar wind speed is crucial
- for studying the mechanisms of wind acceleration and
- for defining the environment in which CMEs expand
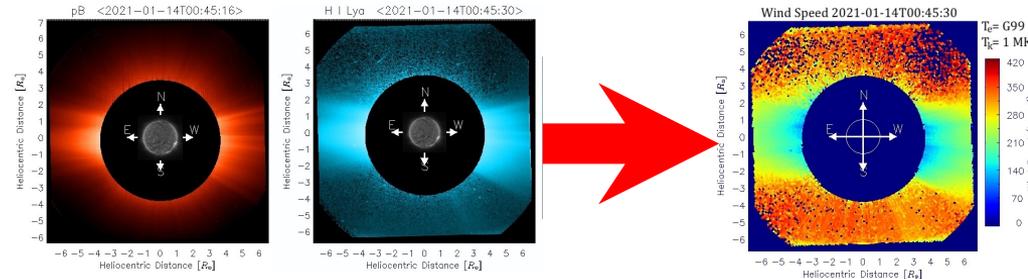- are also important for validating MHD simulations
- …

➤ Metis for the first time can provide maps of solar wind speed in the corona from ≈ 1.7 to 10 Rsun
   from indirect measurements exploiting the Doppler Dimming effect

➤ Since the diagnostics require the use of an empirical model of a solar corona
   We have developed a tool that allows is to see how the parameters affect the of the wind speed determination

➤ Here we present
   - the diagnostics technique
   - maps of the wind speed at solar minimum
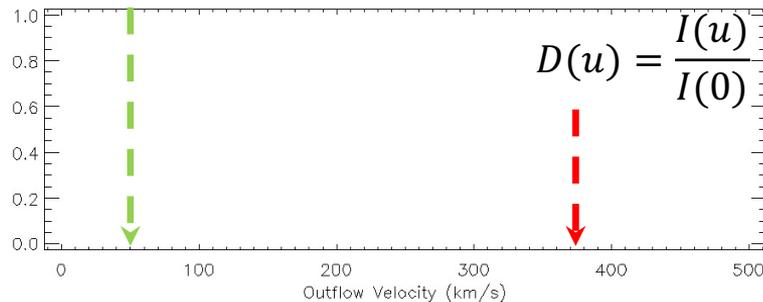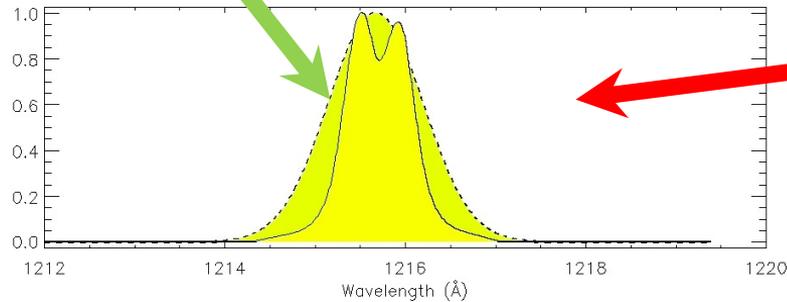
H I Lyα Radiative Component
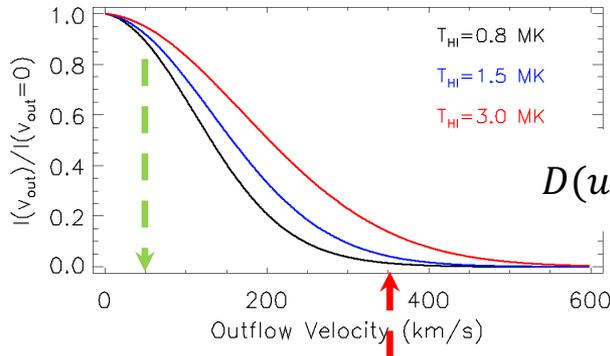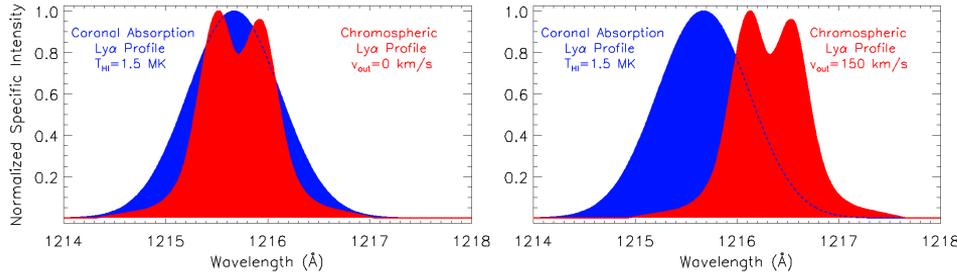
$$I_{obs} \simeq I_r = \frac{b\, B_{12}\, h\, \lambda_0}{4\pi} \int_{l.o.s} n_{HI}\, dl \int_{\Omega} p(\mathbf{n} \cdot \mathbf{n}')\, d\Omega \int_0^{+\infty} I_{ex}\left(\lambda - \frac{\lambda_0}{c}\,\mathbf{u} \cdot \mathbf{n}'\right) \Phi(\lambda, T_{\mathbf{n}'})\, d\lambda$$

$$n_{HI} = \frac{1}{1 + 2A_{He}}\, n_e\, R_{HI}(T_e)$$ Neutral Hydrogen density

$\Phi(\lambda, T_{\mathbf{n}'})$ Absorption Profile

$$\boxed{I = \mathcal{F}(I_{ex}(\lambda), A_{He}, n_e, T_e, T_k, K_i, \mathbf{u})}$$

H I Lyα Intensity is a function of

$I_{ex}(\lambda)$	Specific Intensity of Chromospheric radiation
A_{He}	Helium Abundance
n_e	Coronal Electron Density
T_e	Coronal Electron Temperature
T_p	Coronal Kinetic Temperature (neutral hydrogen)
$K_i = \dfrac{T_\perp}{T_\parallel}$	Anisotropy factor
$\mathbf{u}$	**Outflow Speed**

$$D(u) = \frac{I(u)}{I(0)}$$

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$$I = \mathcal{F}(I_{ex}(\lambda), A_{He}, n_e, T_e, T_k, K_i, \boldsymbol{u})$$

uncertainty

I_{obs} Observed H I Lyα Intensity   Metis UV images   statistical and instrumental

n_e Computed Electron Density   Metis pB images   statistical and instrumental

$\int I_{ex} d\lambda$ Disk intensity   LASP Interactive Solar Irradiance Datacenter   daily variation 5% solar min, 20% solar max,
https://lasp.colorado.edu/lisird/   not uniform: negligible at r > 3.5 Rs (Dolei+ 2018)

$I_{ex}(\lambda)$ Disk profile   Analytical (Auchère 2005), empirical (Lemaire+ 2002)   negligible (Capuano+ 2021)

T_e Electron Temperature   Models, Literature, constant value

T_k Kinetic Temperature   UVCS Temperature images of H I Lyα line Width

K_i Anisotropy factor   values: 1 (isotropy), 2 (maximum anisotropy)

A_{He} He Abundance   values: 10% (typical), 2.5% (Moses+ 2019)

Empirical Coronal Model

H I Lyα Radiative Component

$$I_R(\mathbf{n}) = \frac{1}{\sum_{i=1}^{n} a_i} \frac{hB_{12}}{2\sqrt{\pi}\lambda_0} n_{pe} I_{disk}$$

$$\times \int_{-\infty}^{+\infty} n_e R_{H_i} dx$$

$$\times \int_{0}^{\alpha_2} \left[\frac{1}{12} \left(11 + 3 \left(cos^2(\phi) \cos^2(\theta) + \frac{1}{2} \sin^2(\phi) \sin^2(\theta) \right) \right) \right]$$

$$\times \sum_{i=1}^{n} \frac{a_i}{\sqrt{w^2 + \sigma_i^2}} \exp\left[-\frac{\left(\delta\lambda_i - \frac{\lambda_0}{c} v_w \cos\theta \right)^2}{w^2 + \sigma_i^2} \right] \sin\theta \, d\theta$$

$$n_{pe} = \frac{1}{1 + 2\,A_{He}}$$

$$\rho = \sqrt{r_{pos}^2 + d_{pos}^2}$$

$$\alpha = \arcsin\left(\frac{1}{\rho}\right)$$

$$\phi = \frac{\pi}{2} - \arctan\left(\frac{d_{pos}}{r_{pos}}\right)$$

$$w = \frac{\lambda_0}{c} \sqrt{\frac{2K_B T_k}{m_p}} \sqrt{\frac{cos^2(\theta)}{k_i} + sin^2(\theta)}$$

Auchère 2005
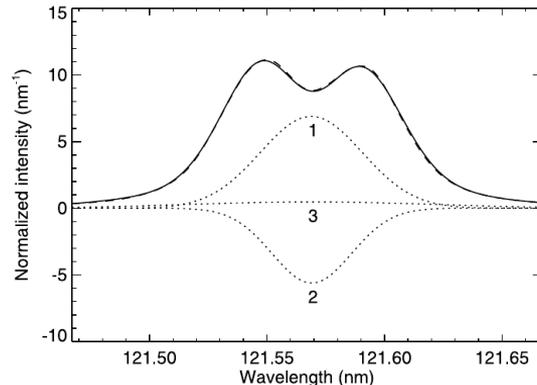
Component	a_i	$\delta\lambda_i$ (nm)	σ_i (nm)
1	1.878	0.001859	0.03075
2	-1.188	0.002087	0.02390
3	0.3075	0.002159	0.07353

pB_{obs}

pB <2021-01-14T00:45:16>

n_e

Electron Density <2021-01-14T00:45:16>

$I_{ex}(\lambda)$

T_e
T_k
K_i
A_{He}
$\boldsymbol{u}$ Wind speed free parameter
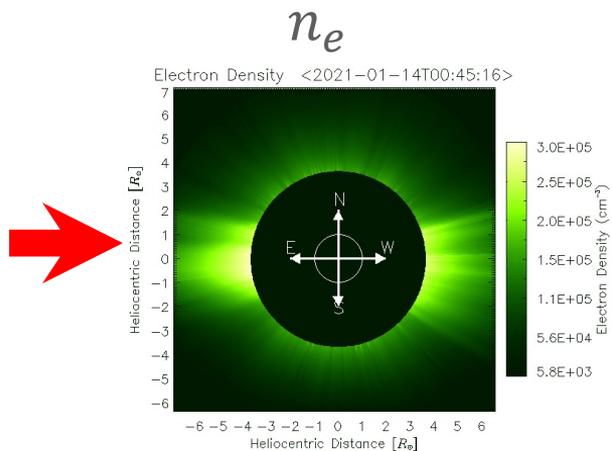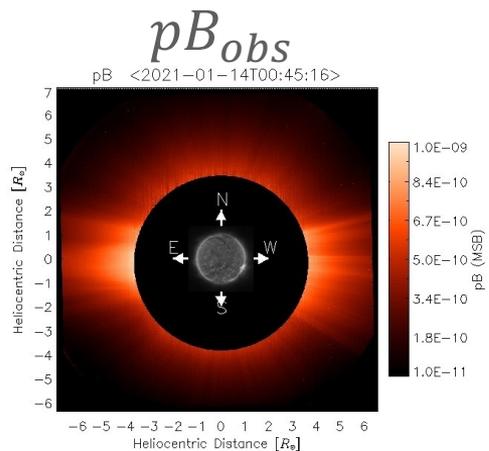
I_{syn}

Doppler Dimming Tool

I_{obs}

H I Lya <2021-01-14T00:45:30>
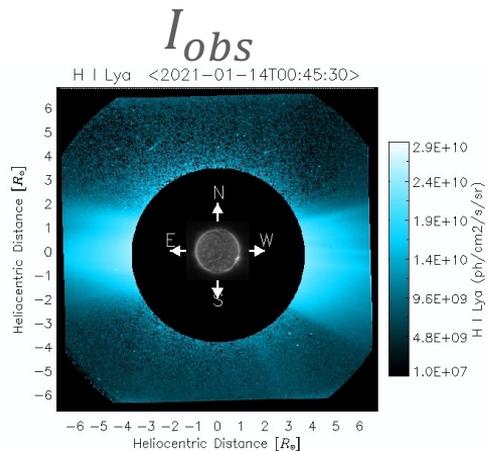
Iterative Method
Loop over each spatial element of the map
Set wind speed $\boldsymbol{u}$ = 0 km/s
→ Compute Synthetic Intensity, I_{syn}
→ Compare with Observed Intensity, I_{obs}
if | I_{syn} - I_{obs} |< ε → get u
else Set a new $\boldsymbol{u}$
→ Save Wind Speed map

Wind Speed 2021-01-14T00:45:30

T_e= G99
T_k= 1 MK
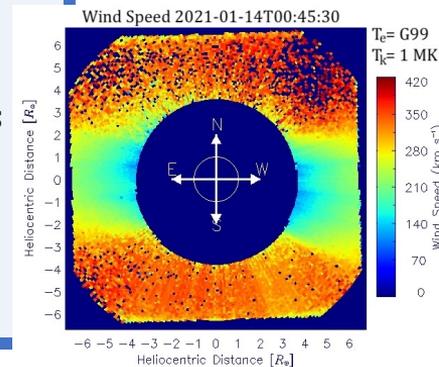
Compute $n_e(r, \vartheta, z)$, T_e and **u** <mark>3D distribution in cylindrical symmetry</mark>

Extrapolation along the LoS at larger than observed height is necessary

<mark>2nd Loop: **u** profile along the LoS as radial profile inferred by 1st loop, u(r, ϑ, z)</mark>

<mark>Doppler Dimming Tool</mark>

Electron Density <2021-01-14T00:45:16>

H I Lya <2021-01-14T00:45:30>
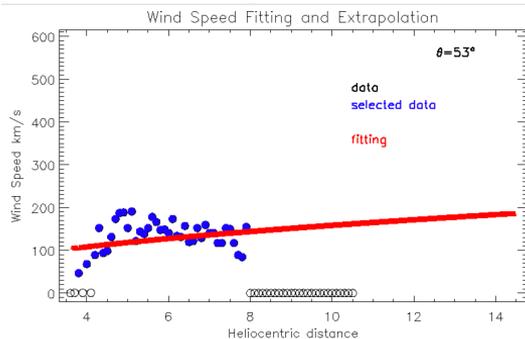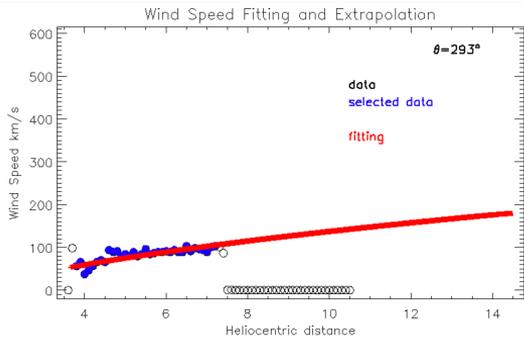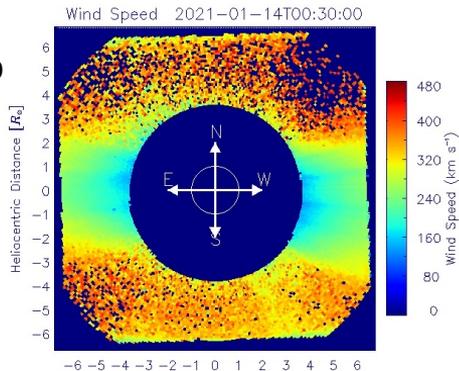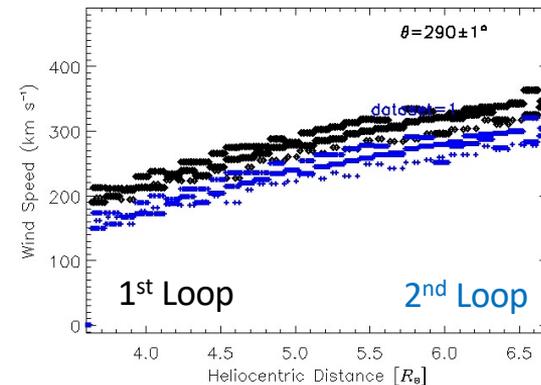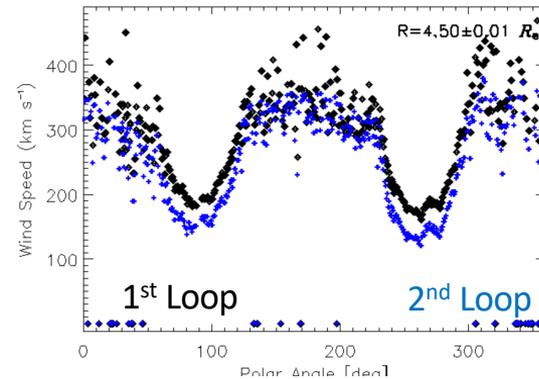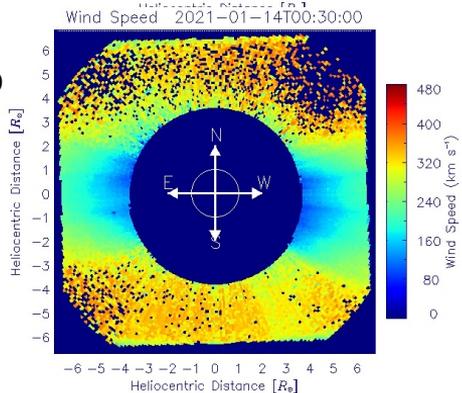
Wind Speed map
2021 Jan 14

Wind Speed 2021-01-14T00:45:30

T_e= G99
T_k= 1 MK

Giordano et al. 2025
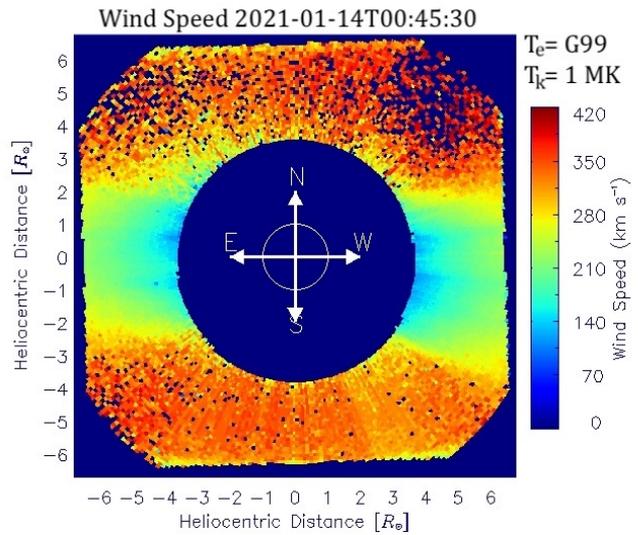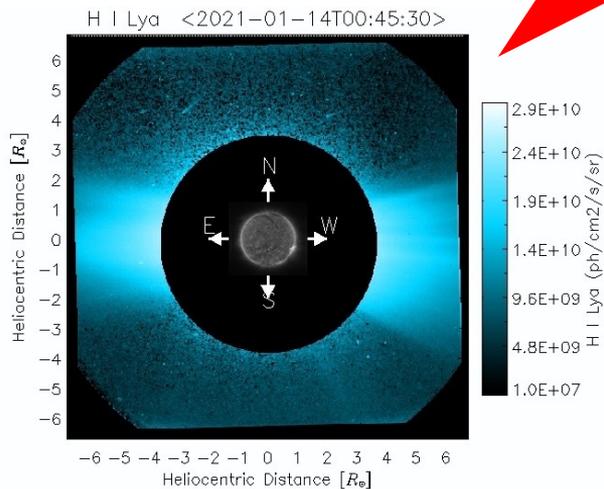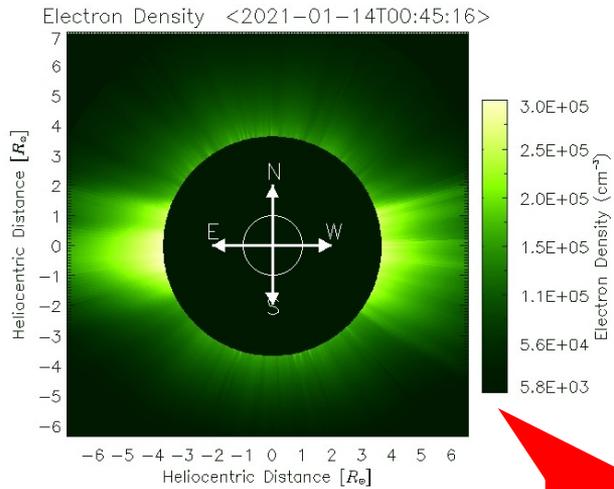
Wind Speed Uncertainty
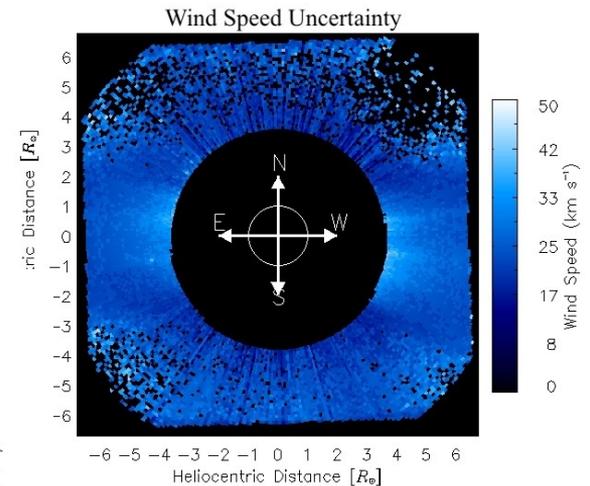
Speed uncertainty
from observations
± 25 km/s

$4R_\odot$
$6R_\odot$
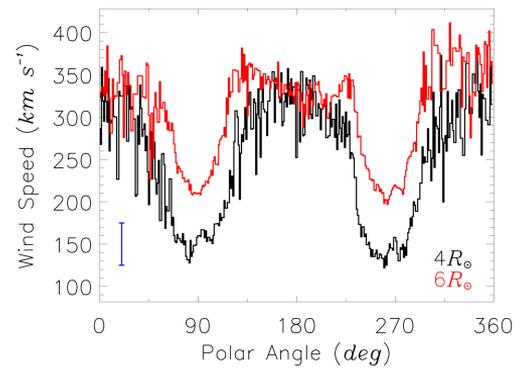
We carried out an exploration of the parameter space of the coronal model
and
developed a tool that allows for the interactive generation of solar wind velocity maps
with different input parameter settings.

T_e — Electron Temperature = [0.4, ... 1.2]MK and →

T_k — Kinetic Temperature = [1.0, ... 3.0] MK

K_i — Anisotropy factor = [1, 2]

A_{He} — He Abundance = [2.5, 10]%

Gibson 1999
Vasquez 2002 Streamer
Vasquez 2003 CH
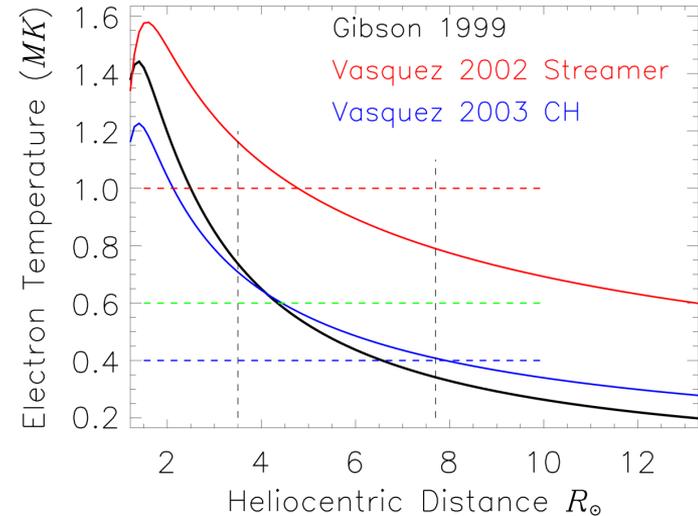
Wind Speed Uncertainty from Temperatures

Electron Temperatures

Wind Speed at 5.00$R_\odot$

T_e = G99   0.4MK   0.6MK   1.0MK

Wind Speed ($km\ s^{-1}$)

T_p = 1.0MK
K_i = 1
A_{He} = 10%

Polar Angle (deg)

T_e range*
CH
from 0.4 MK
to   0.6 MK
Streamer
from 0.5 MK
to   0.9 MK
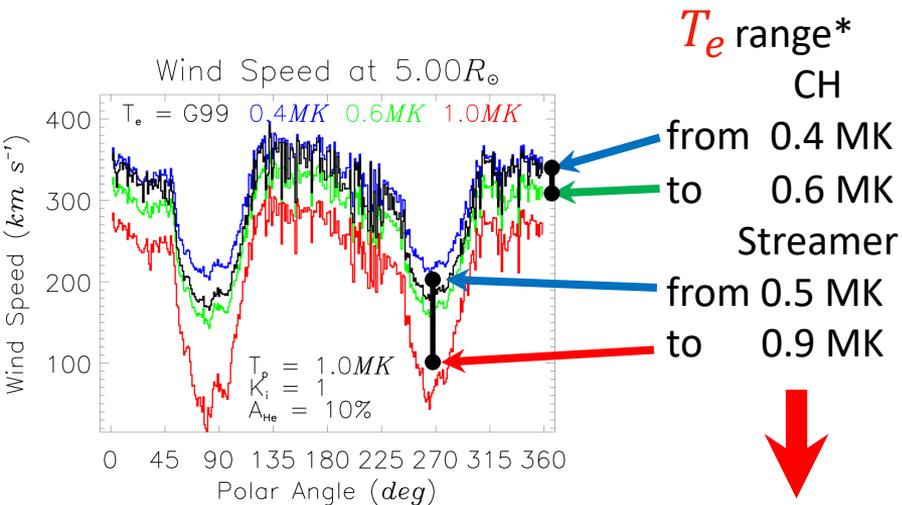
Speed uncertainty
CH: ± 20 km/s
Streamer ± 50 km/s

* From UVCS
Gibson+ 1999
Vasquez+ 2003

Kinetic (proton) Temperatures

Wind Speed at 5.00$R_\odot$

T_k = 1.0MK   1.5MK   2.0MK   2.5MK   3.0MK

Wind Speed ($km\ s^{-1}$)

T_e = G99
K_i = 1
A_{He} = 10%

Polar Angle (deg)

T_k range**
CH
from 3.0 MK
to   2.0 MK
Streamer
from 2.5 MK
to   1.5 MK
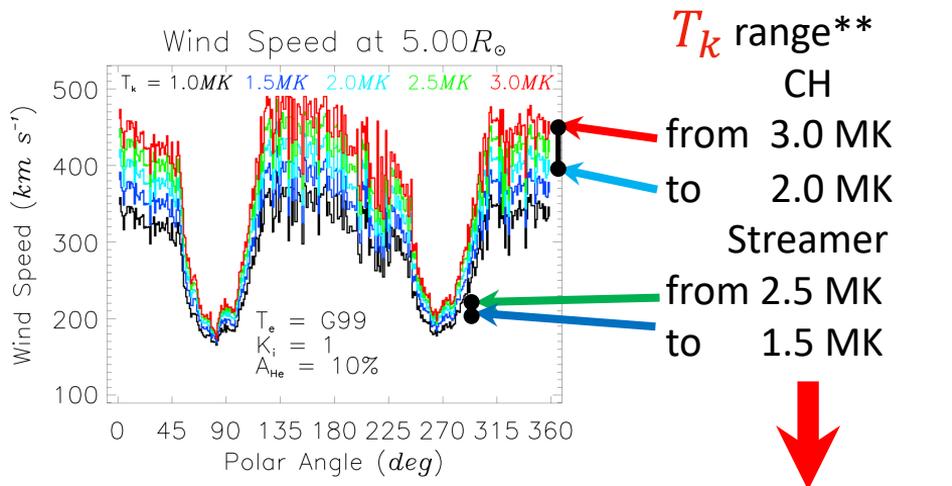
Speed uncertainty
CH: ± 25 km/s
Streamer ± 5 km/s

** From UVCS
Cranmer+ 1999
Dolei+ 2016

Wind Speed at $5.00 R_\odot$
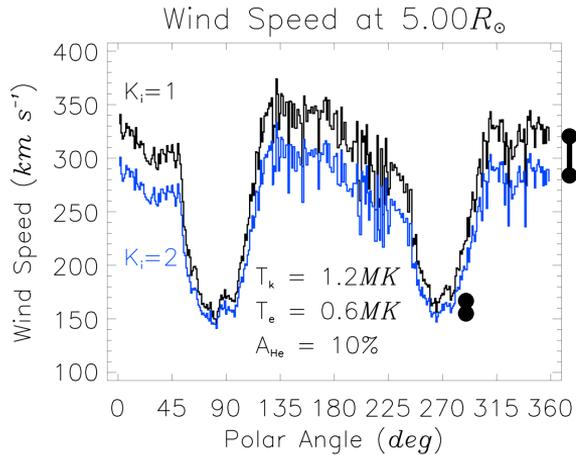
$K_i = 1$

$K_i = 2$

$T_k = 1.2 MK$
$T_e = 0.6 MK$
$A_{He} = 10\%$

Wind Speed ($km\ s^{-1}$)

Polar Angle (deg)

K_i

Speed uncertainty
CH: ± 20 km/s
Streamer ± 5 km/s

A_{He} < 5 km/s (negligible)

Wind Speed Overall Uncertainty

Taking into account the <u>measurement</u> uncertainty,
as well as the uncertainty related to <u>temperatures</u> (and anisotropy),
the overall uncertainty at solar minimum can be estimated:

≈ 40 km/s in coronal holes (fast wind)
≈ 50 km/s in streamers (slow wind)

Table 3: **Computation parameters and effect on wind speed determination**

Computation Input Parameters	Source	Adopted values	Effect on wind speed determination
Lya disk Irradiance	**Machol et al. (2019) (LASP)**	**7 days averaged**	**< 5%**
Lya disk profile	**Auchère (2005) (SUMER)**	**analytical**	**<10%** **Capuano et al. (2021)**
Electron Temperature	**Gibson et al. (1999)** **Vásquez et al. (2003)** **see Fig. 7**	**G99 profile** **V03 profiles** **[0.4, ...1.6] MK**	**~40% (slow wind)** **~20% (fast wind)** **see Fig. 10, 11**
Kinetic Temperature	**Cranmer et al. (1999)** **Antonucci et al. (2000)** **Dolei et al. (2016)** **(UVCS)**	**[1.0, ..., 3.0] MK**	**~10% (slow wind)** **~18% (fast wind)[1]** **see Fig. 12**
Anisotropy	**Susino et al. (2008)** **Cranmer (2020)** **(UVCS)**	**[1,2]**	**~5% (slow wind)** **~15% (fast wind)** **see Fig. 13**
He Abundance	**Moses et al. (2020) (SCORE)**	**[2.5,10] %**	**<5%**

[1] **The kinetic temperature is varied between 1 and 3 MK in the parameter grids, resulting in an overall wind speed uncertainty of approximately 30%. However, kinetic temperatures exceeding 2 MK are not physically expected in coronal holes. By restricting the kinetic temperature range to 1–2 MK, the wind speed uncertainty is reduced to about 18%.**

Wind Speed maps at Solar minimum

2020-06-21

2021-01-14

2021-02-12

2020-02-17

T_e = G99
T_k = 1 MK

Wind Speed 2020-06-21

Giordano et al. 2025

Metis & UVCS outflow velocity results at the North pole
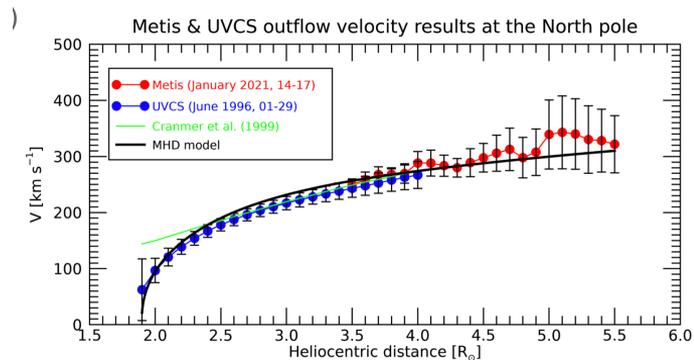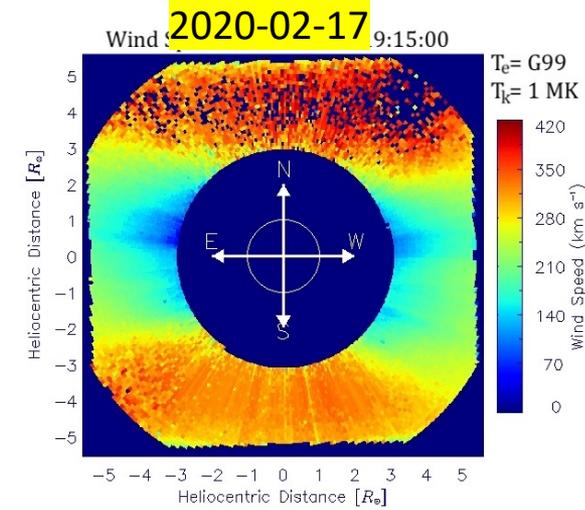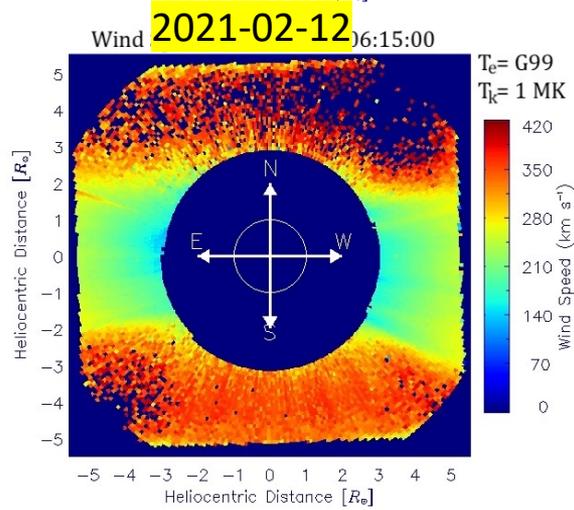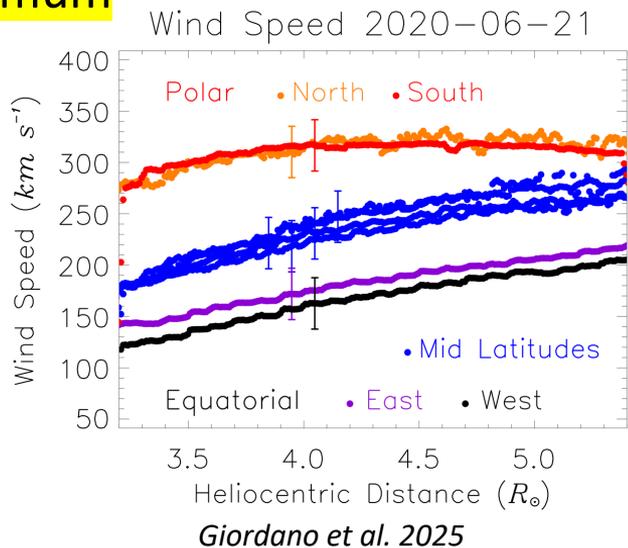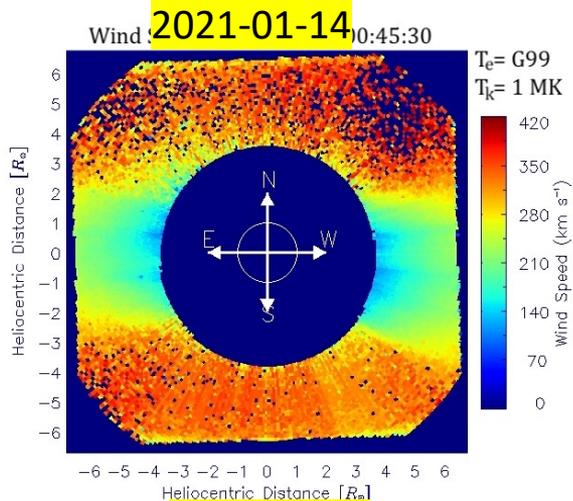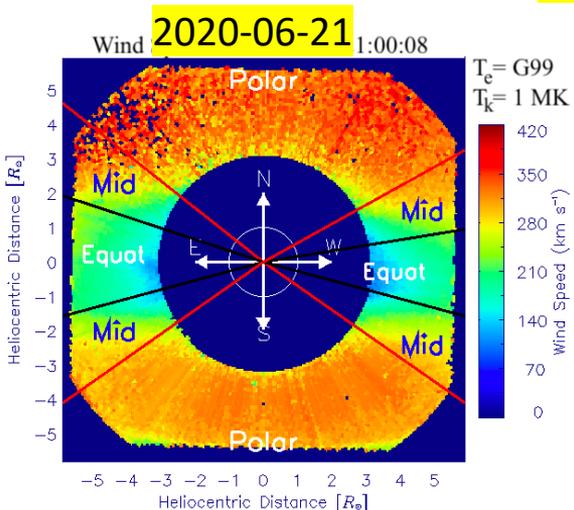
Telloni et al. 2023

Solar Wind Speed Maps

- Metis/SO observation: January 14-17, 2021

Polarized Brightness
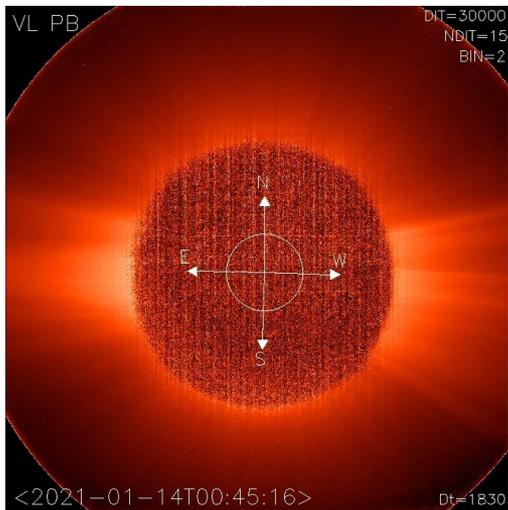
H I Ly-alpha Intensity
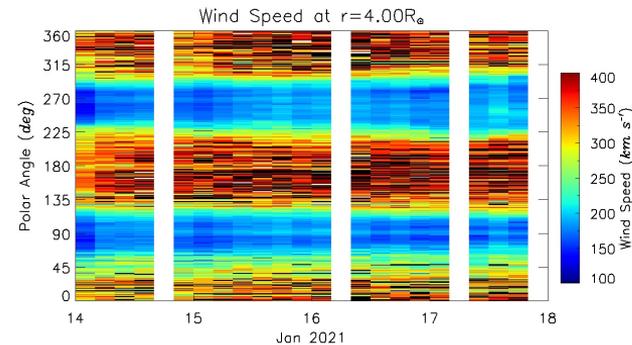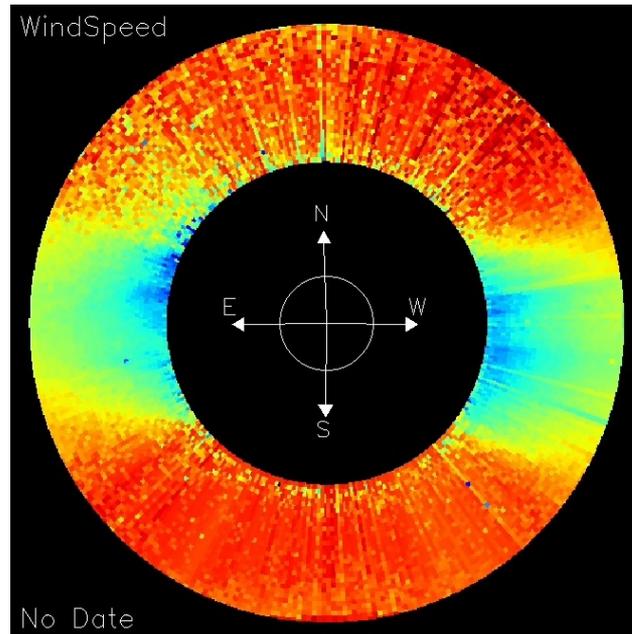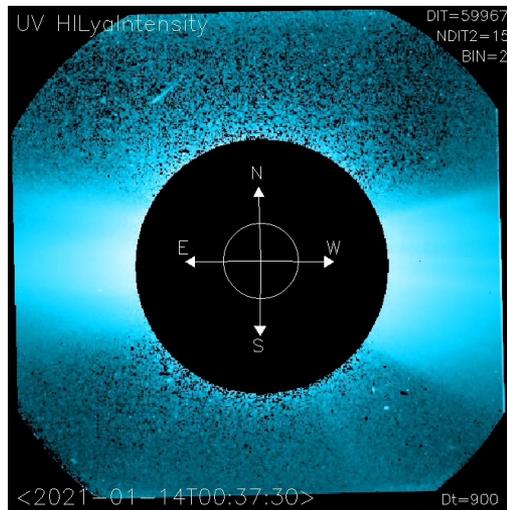
DDT Graphical User Interface v2.20 - IDL

☑ *customizable*
☑ *documented*
☑ *friendly*

- **Download**
https://drive.google.com/drive/folders/1RW7HE0txAjlqylsfozIxaQUhPzDbCvCn?usp=drive_link

- **Install**
`tar -zxvf ddt_v2.20.tar.gz`

- **Run**
```
cd v2.20/wcode
sswidl
@ddtc
ddt_run,/GUI
```

- **Display**
```
iCID
pyCID
```
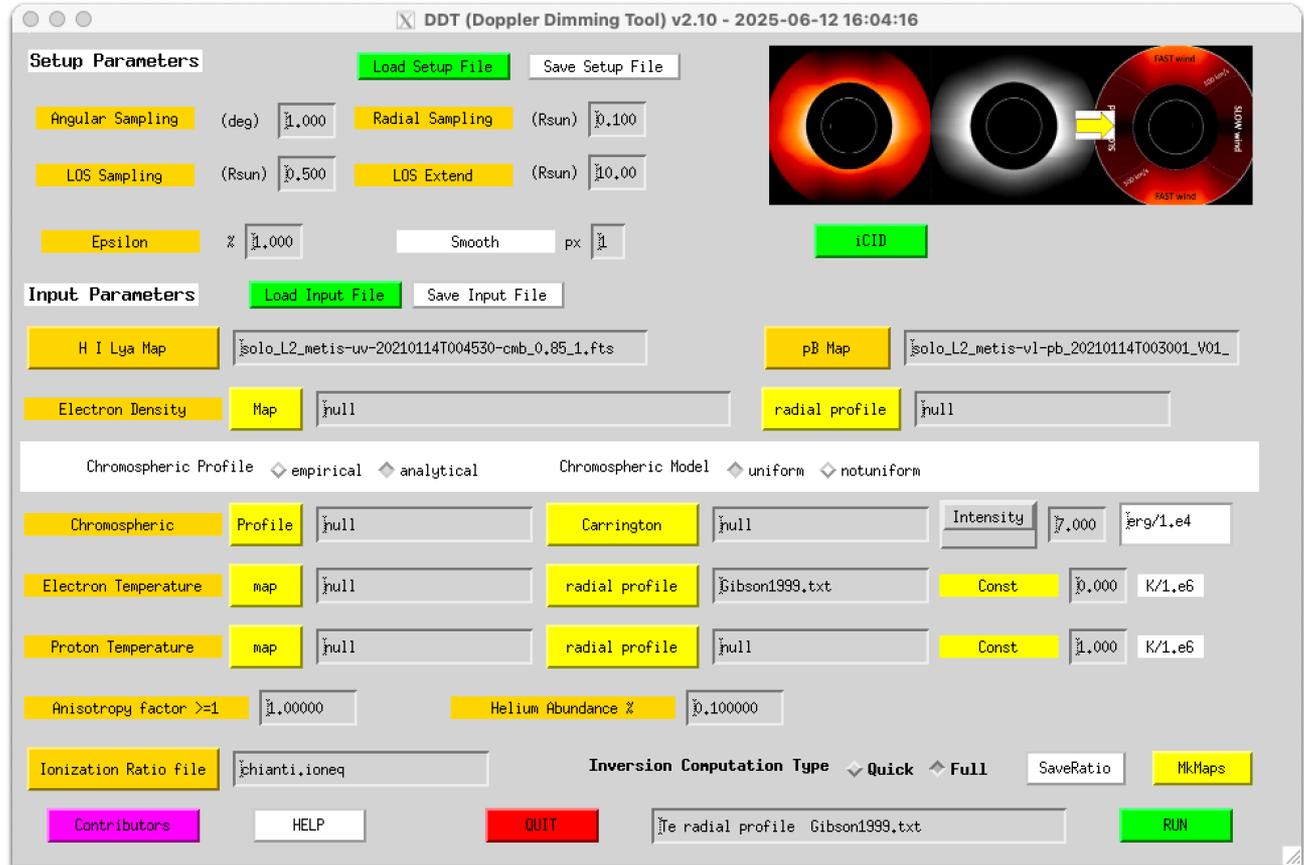

DDT = Doppler Dimming Tool

DDT Graphical User Interface

The code can be run without the GUI,
by editing the "Setup File" and "Input File"
then executing the command: `ddt_run,/NOGUI`

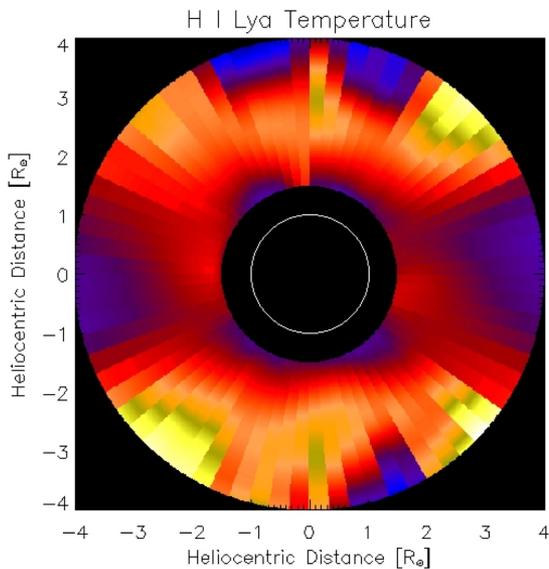# DDT Graphical User Interface
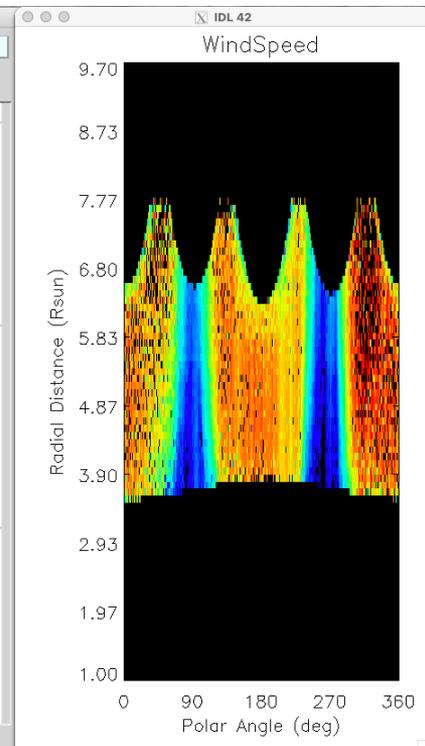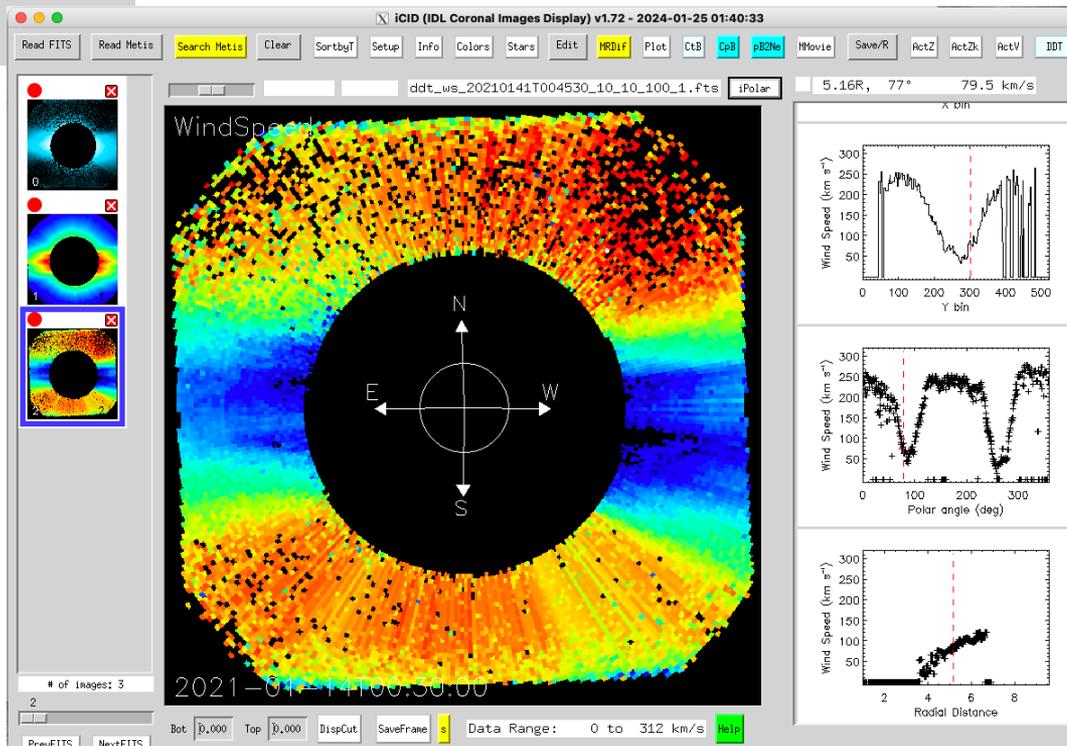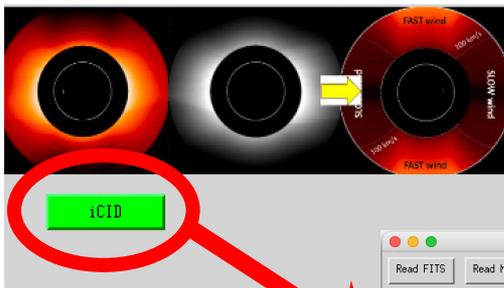
Maps are saved as
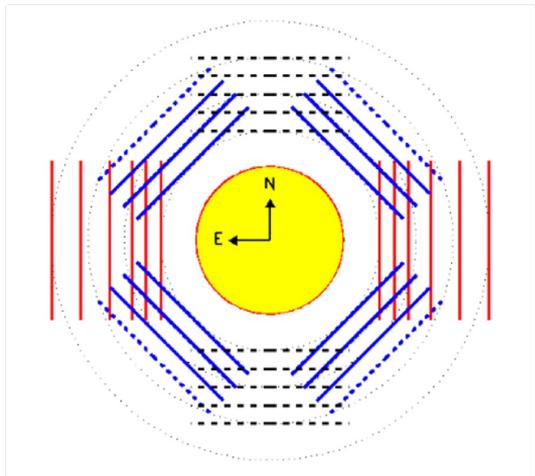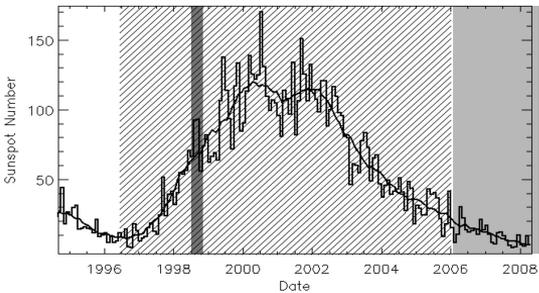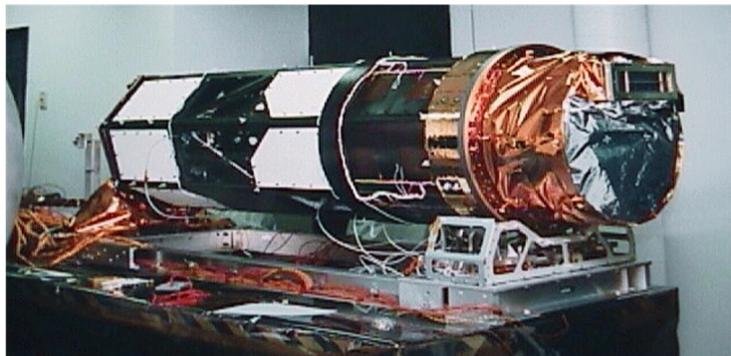a) FITS files
b) IDL-save files

UVCS/SOHO

Kohl+ 1995
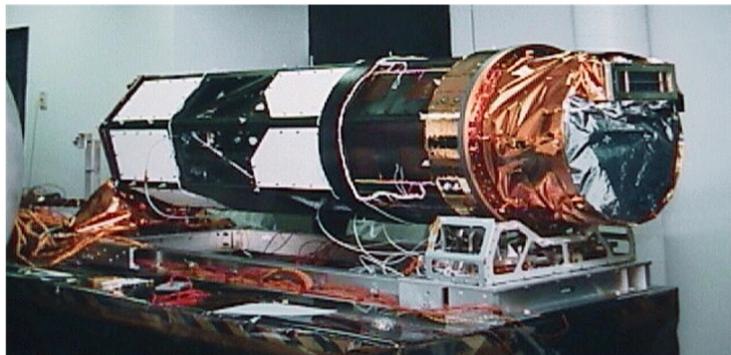
UltraViolet Coronagraph Spectrometer
almost daily full corona observation
from 1996 to 2006, operational until 2012

UVCS Detectors

Spatial dir. 350 px

Spectral dir. 1024 px

LYA channel

Fe XII 1242   HI Lya 1216   S X 1196

OVI channel

Si XII 520
O VI 1037
O VI 1032
H I Lyb 1025

Si XII 499

Redundant path

I Lya

1998/01/02
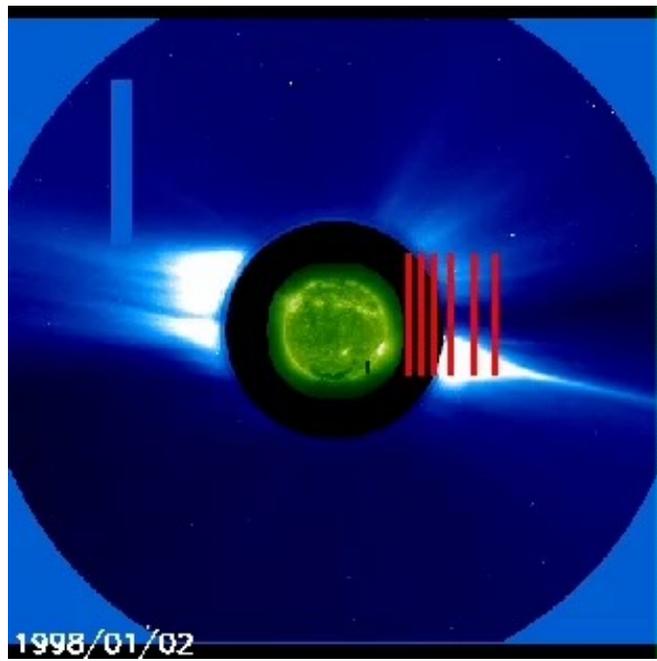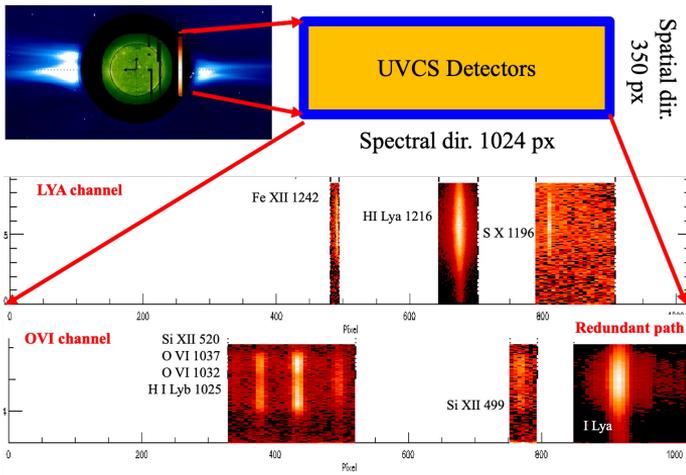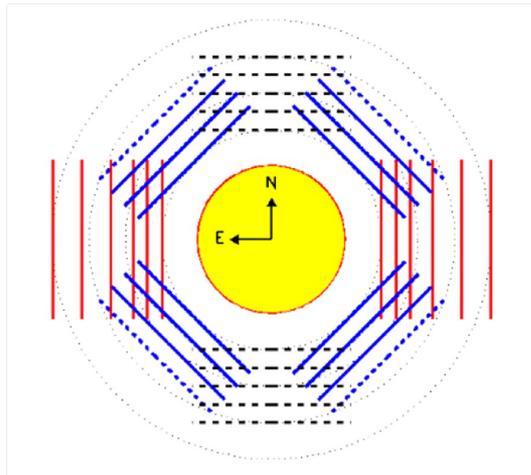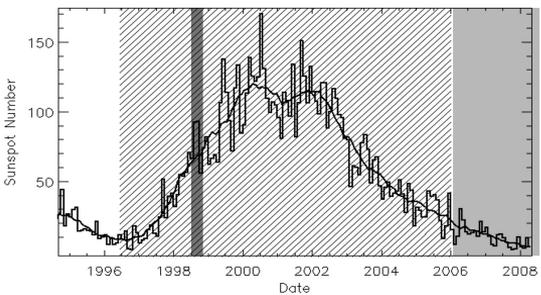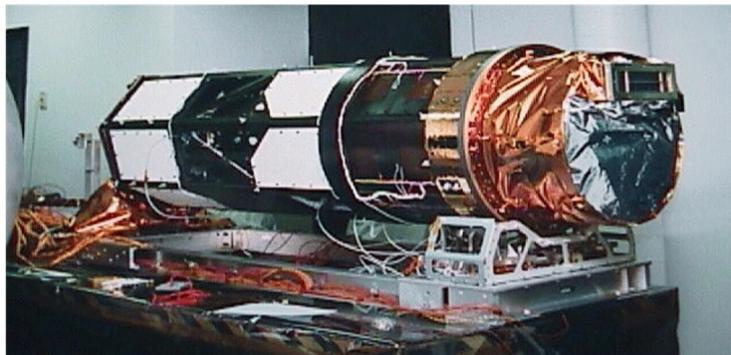
UVCS/SOHO Kohl+ 1995

UltraViolet Coronagraph Spectrometer
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UVCS/SOHO   Kohl+ 1995
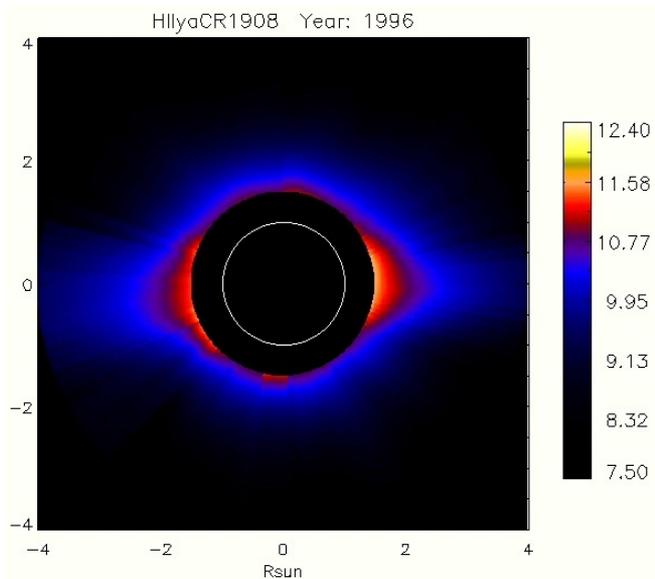
UltraViolet Coronagraph Spectrometer
almost daily full corona observation
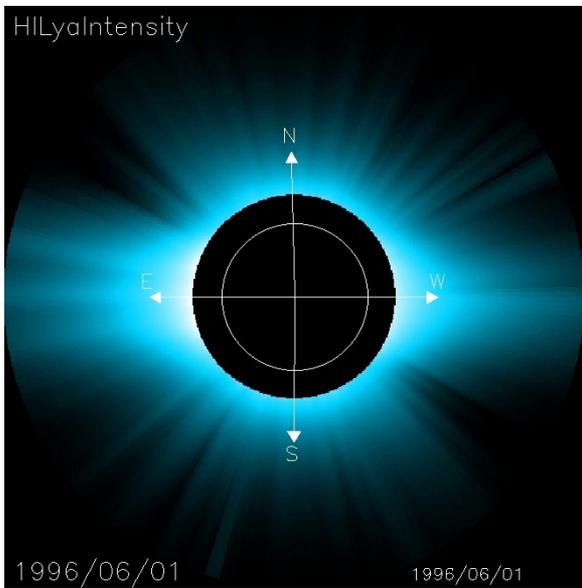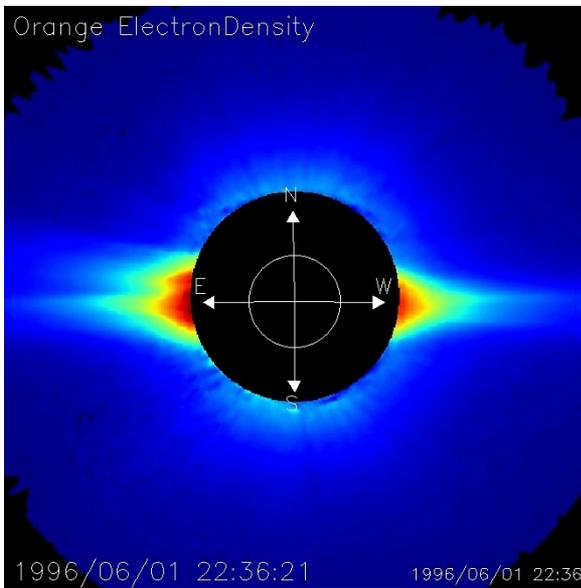from 1996 to 2006, operational until 2012

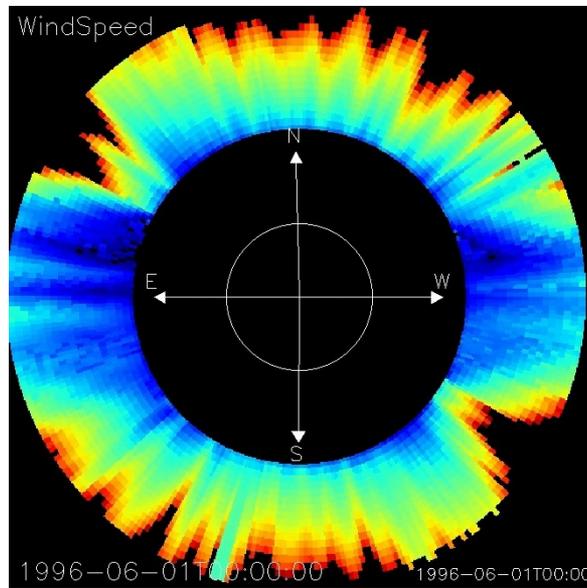**Carrington Rotation 1910 – Jun 1-26, 1996**

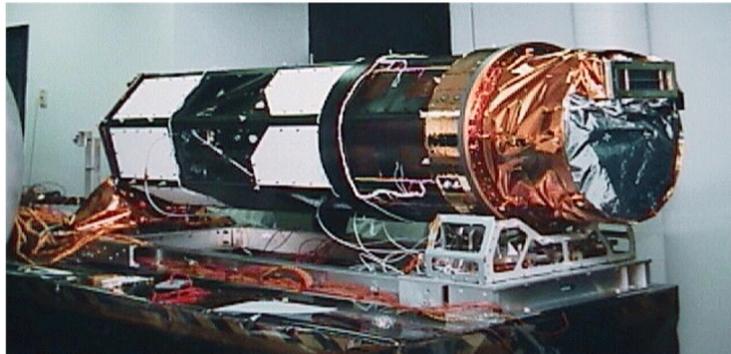**UVCS H I Lya**   **LASCO C2 pB → Electron Density**   **Wind Speed Daily Maps**

UVCS/SOHO

Kohl+ 1995

UltraViolet Coronagraph Spectrometer
almost daily full corona observation
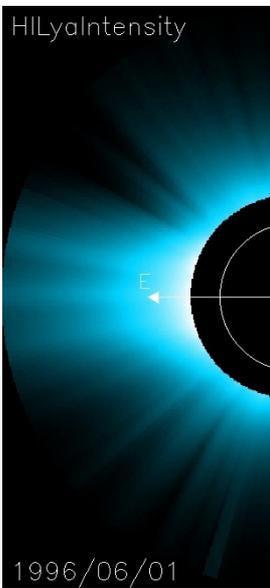from 1996 to 2006, operational until 2012

Carrington Rotation 1910 – Jun 1-26, 1996

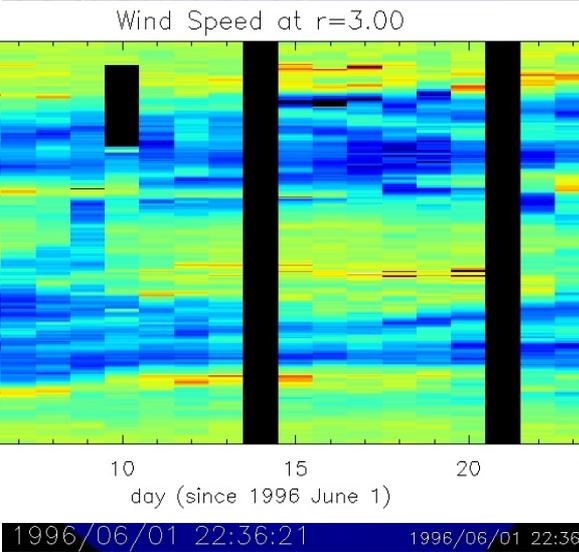**UVCS H I Lya**   **LASCO C2 pB → Electron Density**   **Wind Speed Daily Maps**
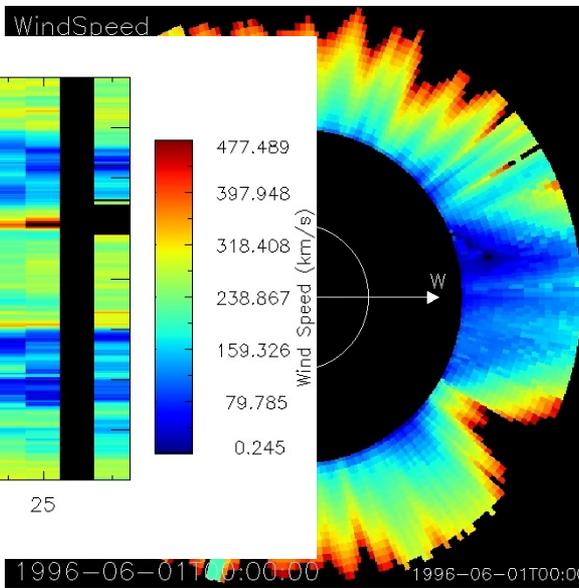
Solar Wind Speed from SOHO UVCS+LASCO/C2 through a full solar cycle
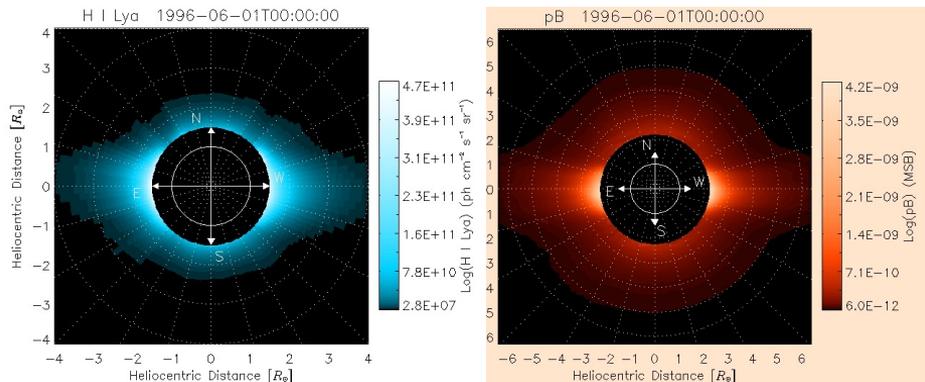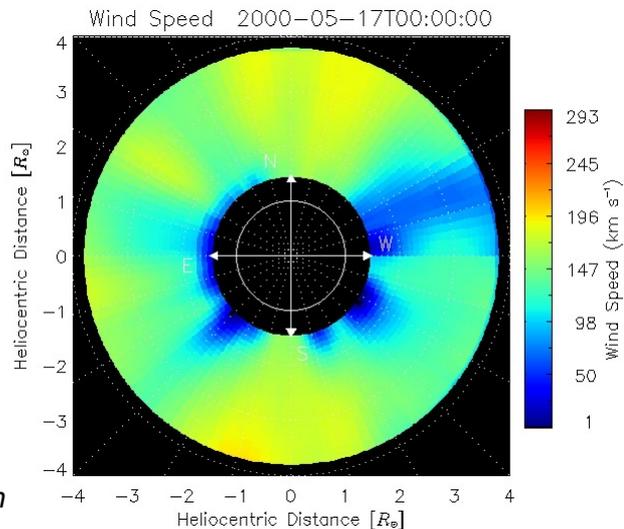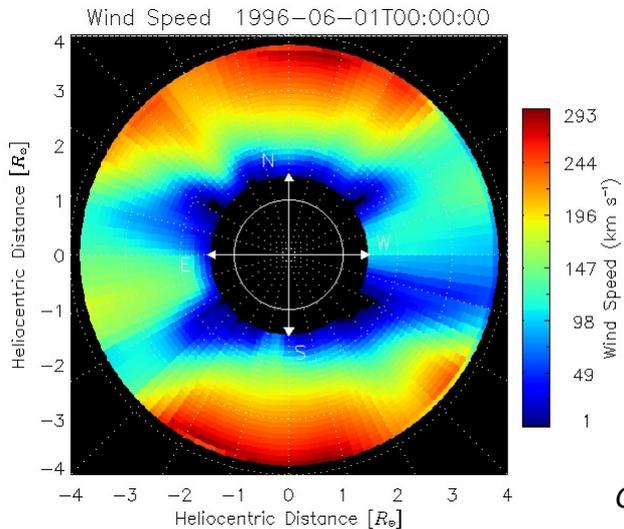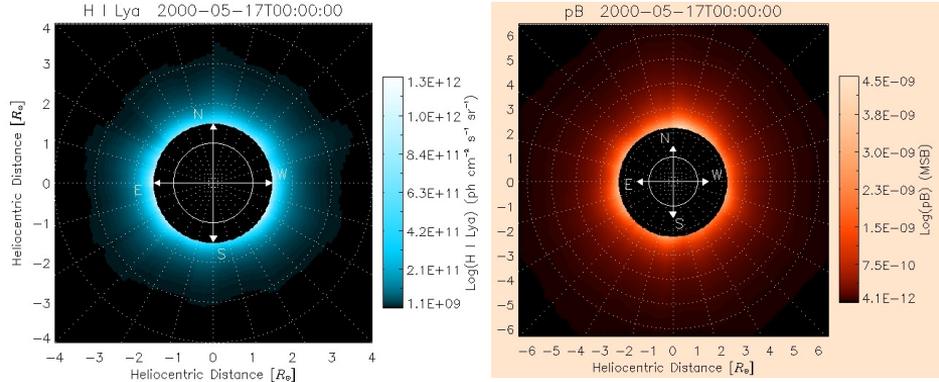
Giordano et al. in preparation

Conclusions

Solar wind speed maps from Metis coronagraph observations

The solar wind speed maps are crucial
>   for studying the mechanisms of wind acceleration and
>   for defining the environment in which CMEs expand
>   are also important for validating MHD simulations

Solar wind speed maps from the Metis coronagraph observations

S. Giordano[1,*], D. Spadaro[2], R. Susino[1], R. Ventura[2], L. Zangrilli[1], V. Andretta[3], Y. De Leo[2,4], M. Romoli[5,6], L. Teriaca[7], M. Uslenghi[8], S. Fineschi[1], D. Telloni[1], F. Landini[1], G. Nicolini[1], M. Pancrazzi[1], and C. Sasso[3]

✓ Metis provide maps of solar wind speed in the corona from ≈ 1.7 to 10 Rsun

❑ The maps <u>will</u> be released in FITS format as L3 products in the Solar Orbiter data archive.
❑ Now, maps, for a specific periods can be requested
   at Marco Romoli (marco.romoli@inaf.it), (Metis PI) or at Silvio Giordano (silvio.giordano@inaf.it).

➢ The tool for creating maps from Metis data is intended to be released,
   although at least initially, its use will need to be supervised by the team that developed it.

➢ Next steps:
   1. Python version of the code package
   2. Apply technique to UVCS data over a full solar cycle
   3. Go beyond the cylindrical geometry
   4. Wind speed diagnostics to constraint Electron Temperature
   5. Use of Kinetic Temperature from UVCS measurements to improve coronal model