Reconstructing the 3D Solar Wind Speed in the Middle Corona with Metis

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Abstract

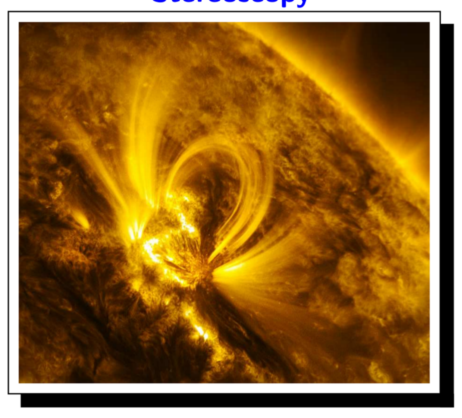
Determination of the three-dimensional (3D) thermodynamic structure of the solar corona by observational means is key to advance our understanding of the physical processes responsible of the heating and acceleration of the solar wind. Towards this end, solar rotational tomography uses time series of White Light (WL) and extreme ultraviolet (EUV) images of the solar corona to determine the 3D distribution of the electron density and temperature of the solar corona. The recently operational Metis space coronagraph, on board the Solar Orbiter mission, records both HI Lyman-α and WL images of the solar corona. Based on images from these spectral ranges, tomography allows construction of 3D maps of the Lyman-α Doppler dimming term. In combination with a global model of the coronal magnetic field and proton temperature, the reconstructions allow derivation of 3D maps of the solar wind speed. We describe the technique and show preliminary results based on simulations. *Keywords:* [Sun: Solar Wind — Sun: Corona — Sun: Fundamental Parameters]

What is Solar Corona Tomography?

2D versus 3D

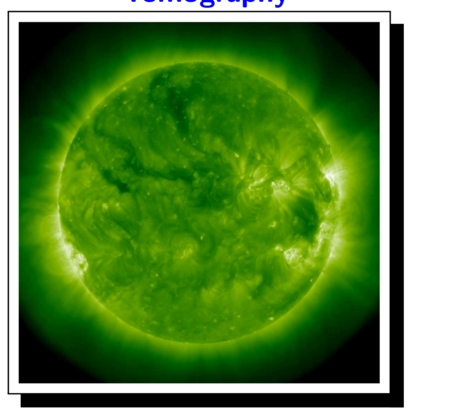
- The corona is optically thin in the UV, EUV, X, WL ranges. Images are thus 2D projections of the underlying 3D emitting structure.
- Advancement of physical models is in need of 3D information of the coronal fundamental parameters **B**, N_e, T_e.

Stereoscopy



By studying the 2D shape of EUV loops from 2 view points it triangulates the 3D geometry of the "frozen-in" magnetic field.

Tomography



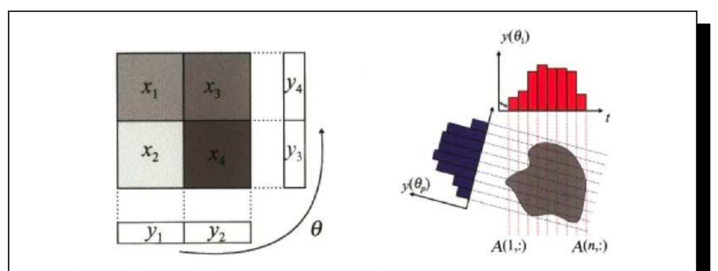
By inverting for the 3D EUV emissivity from time series of images it allows inferring the 3D N_e and T_e of the global corona.

Tomography

Unknown: 3D distribution of a certain quantity x_i (e.g. N_e) for each cell volume i within an object (e.g. the solar corona), under optically thin regime (e.g. coronal white light)

Knowns:

- Intensity vector $\mathbf{y}_j$: measured in each pixel j of each image in a time series taken from different view angles.
- *Proyection* matrix $\mathbf{A}_{ji}$: depending on the geometry (e.g. solar rotation, telescope orbit) and the involved physical process (e.g. Thomson scattering).

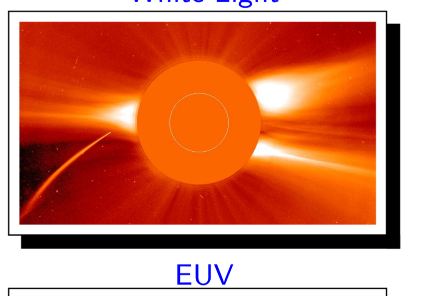


$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} \iff \mathbf{y} = \mathbf{A}\mathbf{x}$$

Solar Rotational Tomography (SRT)

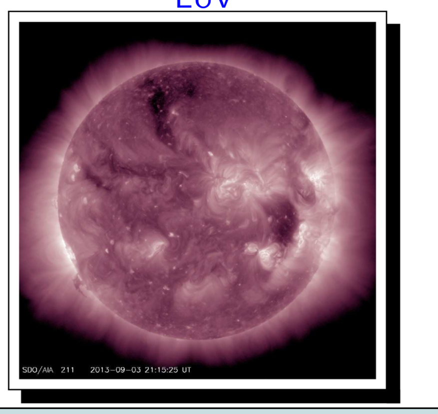
The solar rotation provides the needed 360° view angles.

White Light



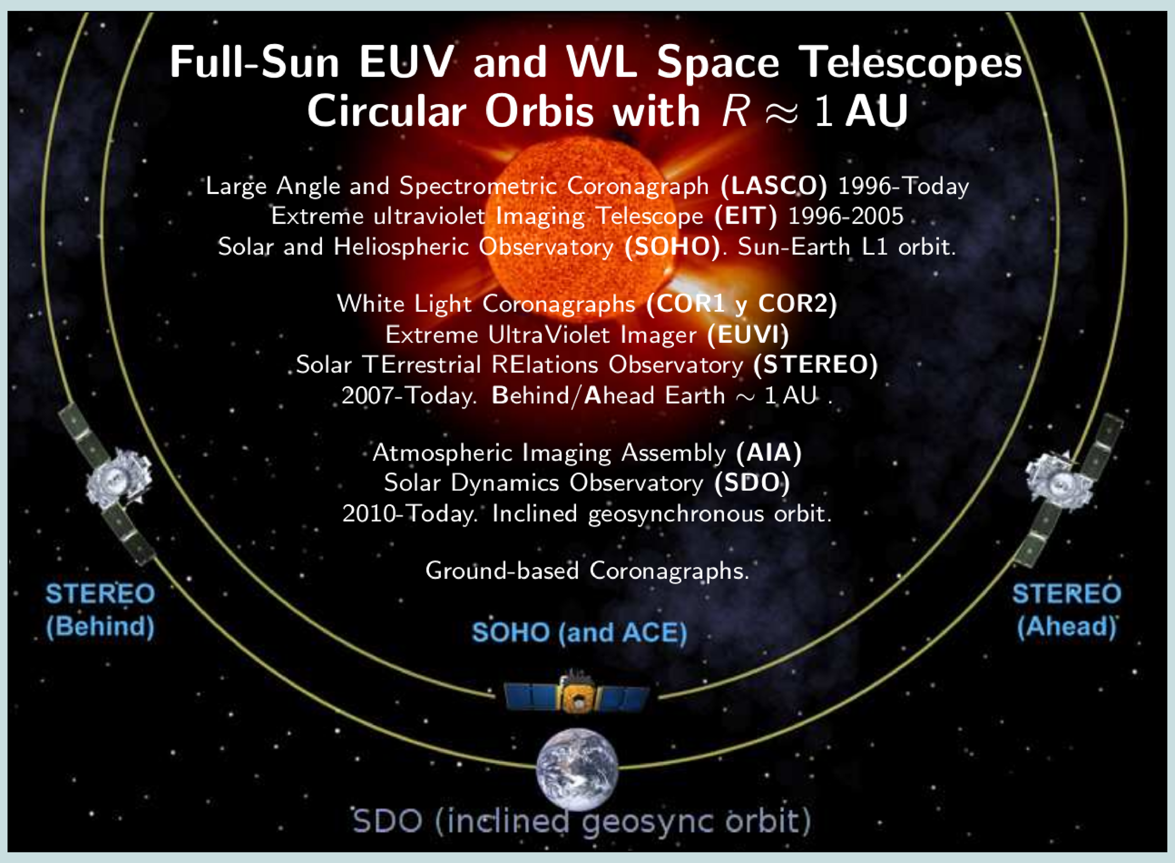
- Corona-K: Thomson scattering of photospheric white light (WL).
- SRT-WL → 3D N_e.
- 1st SRT-WL: Altschuler & Perry (1972)

EUV

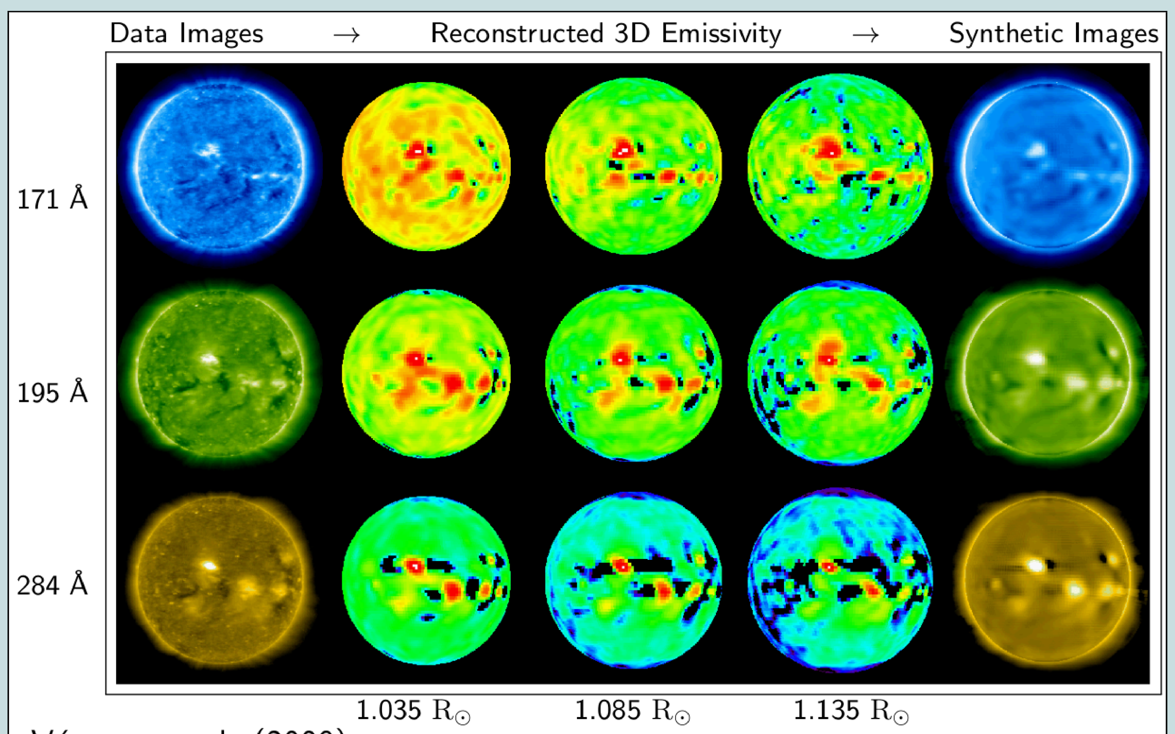


- Corona-E: True coronal emission by ions UV, EUV y X.
- SRT-EUV → 3D EUV emissivity → 3D Differential Emission Measure → 3D N_e y T_e
- 1st SRT-EUV (DEMT): Frazin, Vásquez & Kamalabadi (2009)

Tomography with Previous Instrumentation

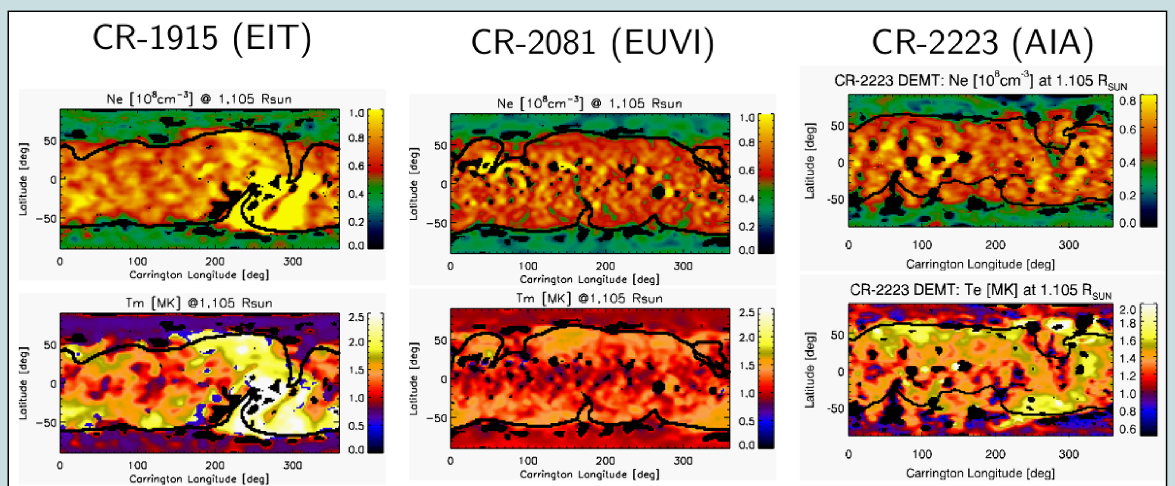


Using EUV images taken over 1/2 solar rotation (≈ 14 days) with space telescopes (SOHO/EIT, STEREO/EUVI, SDO/AIA), SRT allows 3D reconstruction of the coronal emissivity in their various bands.



Vásquez et al. (2009)

Based on the temperature response of the bands, 3D reconstruction of N_e and T_e is then possible.



Lloveras et al. (2017,2020,2022)

Highlights

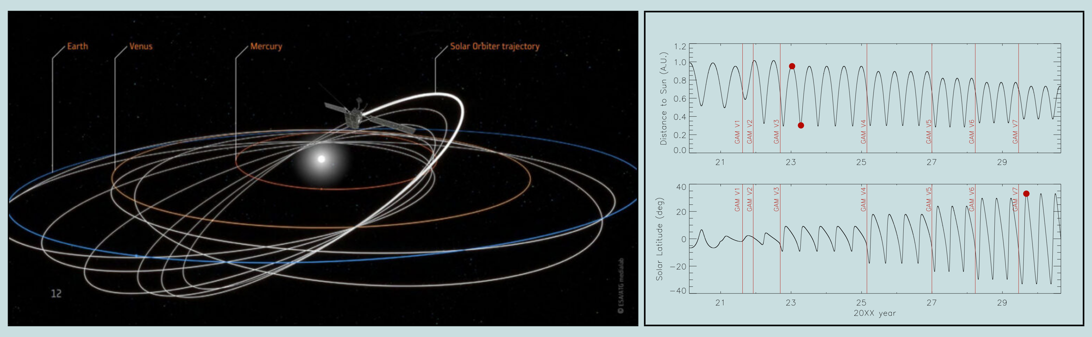
- SRT is a powerful observational technique able to provide global constraints for 3D-MHD models of the solar corona and the solar wind.
- As new space instrumentation becomes available opportunities for development and application of SRT arise.
- The Metis coronagraph, on board the Solar Orbiter mission, is the first space instrument to perform simultaneous imaging of the solar coronal in the WL and HI Lyman-α wavelenghts. Combination of tomography based on the two spectral ranges, with a global model for the magnetic field and the proton temperature, allows in principle reconstruction of the 3D wind speed.
- To probe the concept we first applied it to synthetic images computed from 3D-MHD simulations of the solar corona.

References

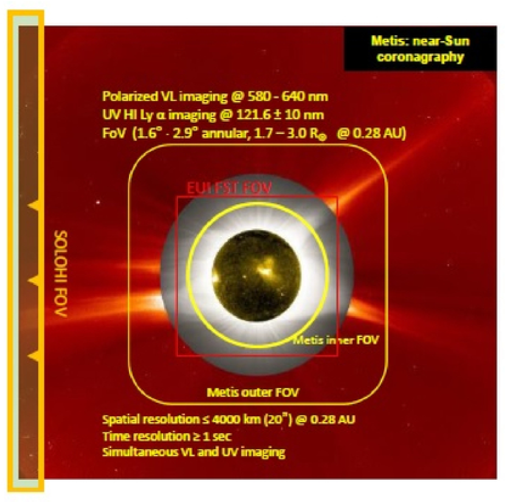
- **Metis Tomography:** Vasquez et al. (2019, 2022).
- **Tomography:** Frazin and Janzen (2002), Frazin et al. (2009), Vasquez et al. (2009, 2016), Lloveras et al. (2022).
- **Ly-α and Wind Speed:** Noci et al. (1987), Vásquez et al. (2003), Bemporad et al. (2021).

Solar Orbiter (SolO and Metis)

Launched 10 February 2020, the Solar Orbiter's journey from 2020 to 2030 involves highly eccentric orbits with increasing off-ecliptic inclination $\approx 0 \to 33°$, with gravitational assistance manouvers (GAM) flying by Venus (V) and Earth (E).

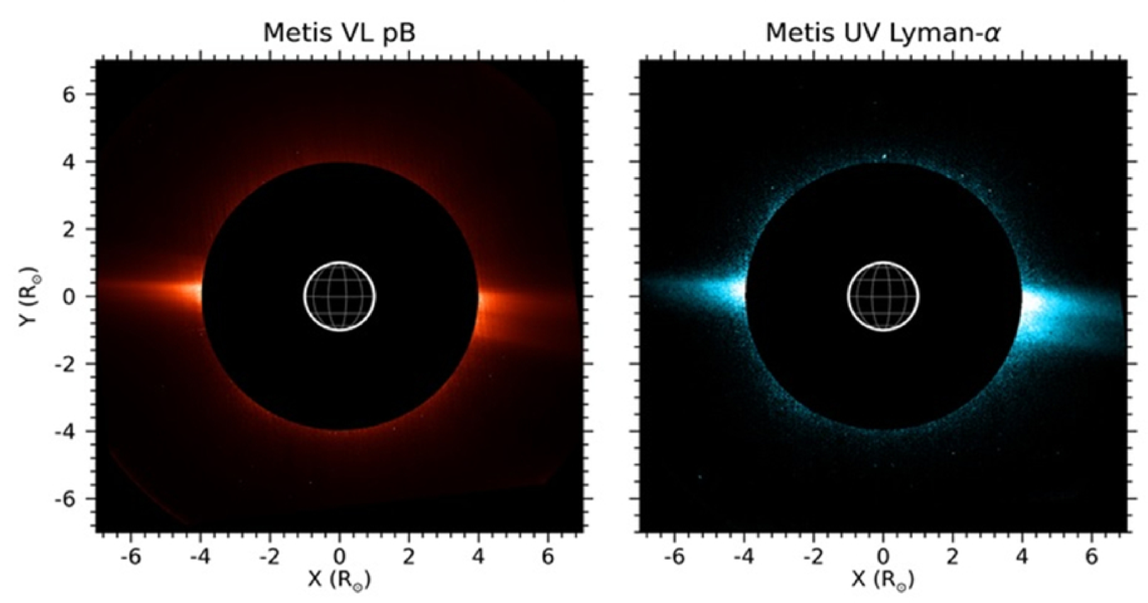


As SOLO flies the *Metis* FOV varies from $\approx 5.8 - 10.2$ R$_{SUN}$ at its maximum aphelion ≈ 1 au, down to $\approx 1.7 - 3.0$ R$_{SUN}$ at its minimum perihelion ≈ 0.28 au.



SolO-Sun Distance (AU)	Min FOV	Max FOV	Corner FOV
0.28	1.7 R☉	3.0 R☉	3.9 R☉
0.3	1.75 R☉	3.3 R☉	4.0 R☉
0.4	2.2 R☉	4.4 R☉	6.2 R☉
0.5	2.8 R☉	5.4 R☉	7.7 R☉
0.8	4.3 R☉	12 R☉	17 R☉

Metis simultaneously records coronal images in both White Light (580-640 nm, left) and Lyman-α (UV121.6 nm, right).



Metis first-light on 15 May 2020, from a distance to the Sun ≈ 0.6 au, and a FOV of $\approx 4.0 - 7.0$.

3D Wind Speed from WL and Lyα Tomography

Being radiatively excited by chromospheric emission, the Lyman-α emission of coronal neutral Hydrogen (a very small fraction of H is non-ionized even in the million degree corona) provides a diagnostic of the wind speed. The faster a solar wind plasma parcel moves away from the Sun the smaller its radiative excitation is, an effect known as "Doppler dimming".

Being the corona optically thin in Lyman-α, SRT can be applied to sequences of its images to reconstruct the 3D distribution of the the quantity D_H (defined below) which, combined with reconstructions of N_e based on SRT applied to WL images, allows determination of the 3D distribution of the "Doppler dimming term" D (defined below).

Coronal Lyα emitted by neutral H **radiatively excited** by the photospheric emission:

$$\mathrm{I}_{\mathrm{Ly}\alpha} = \int_{\mathrm{LOS}} \mathrm{d}l \ \Gamma(l) \ \mathrm{D_H}(l) \quad \to \quad \mathrm{I} = \mathrm{A} \cdot \mathrm{D_H}$$

Electron density where the geometrical dilution factor $\Gamma(\mathbf{r})$ is known and:

$$\mathrm{D_H} \equiv \mathrm{N_H} \ \mathrm{D}, \quad \text{"Doppler dimming" term:} \quad \mathrm{D} \equiv \int d\nu \ I_\odot(\nu + \delta\nu) \ \phi(\nu - \nu_0)$$

$$\mathrm{N_H} \approx 0.8 \ R(T_e) \ \mathrm{N_e} \quad \to \quad \mathrm{D} = (1/0.8 \ R(T_e)) \ \mathrm{D_H}/\mathrm{N_e}$$

$\mathrm{D_H}$ and $\mathrm{N_e}$ are respectivelly obtained from Lyα and WL tomography.

The reconstructed D can be related to the solar wind velocity and T_H as:

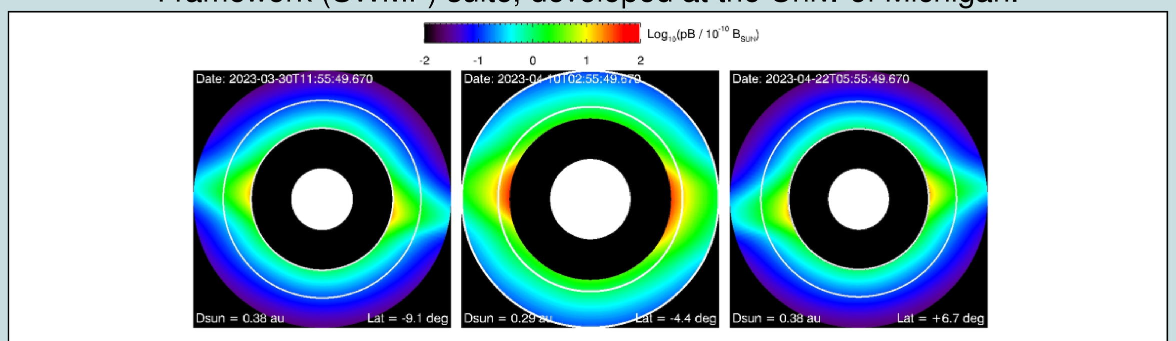
$$D(v_r) = I_0 \ \lambda_0 \ \frac{1}{\sqrt{\sigma^2_{\rm disk} + \sigma^2_{\rm cor}}} \ \exp\left[-\frac{v_r^2}{(\sigma^2_{\rm disk} + \sigma^2_{\rm cor})}\right]$$

$$\sigma_{\rm cor} = \sqrt{(\cos\beta \ V_{\rm th\parallel})^2 + (\sin\beta \ V_{\rm th\perp})^2} \quad \text{and} \quad \beta \equiv \cos^{-1}(B_r/B)$$

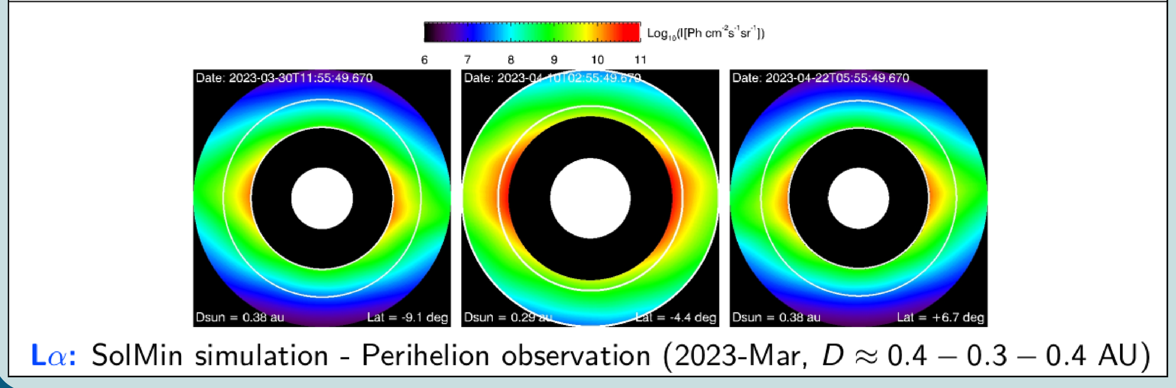
Under several simplifying assumptions (see references) the Doppler dimming term $D(v_r)$ can be analytically expressed in terms of the direction of the local magnetic field β, the paralel and perpedicular coronal Hydrogen temperature $v_{\rm th\parallel,\perp}$, and the radial component of the solar wind speed v_r, as written above.

Metis Synthetic Images from 3D-MHD Model

Based on 3D-MHD simulations of the solar minimum corona, we compute Metis synthetic images in both WL and Lyman-α. The simulation is performed using the Alfven Wave Solar Model (AWSoM), part of the Space Weather Modeling Framework (SWMF) suite, developed at the Univ. of Michigan.



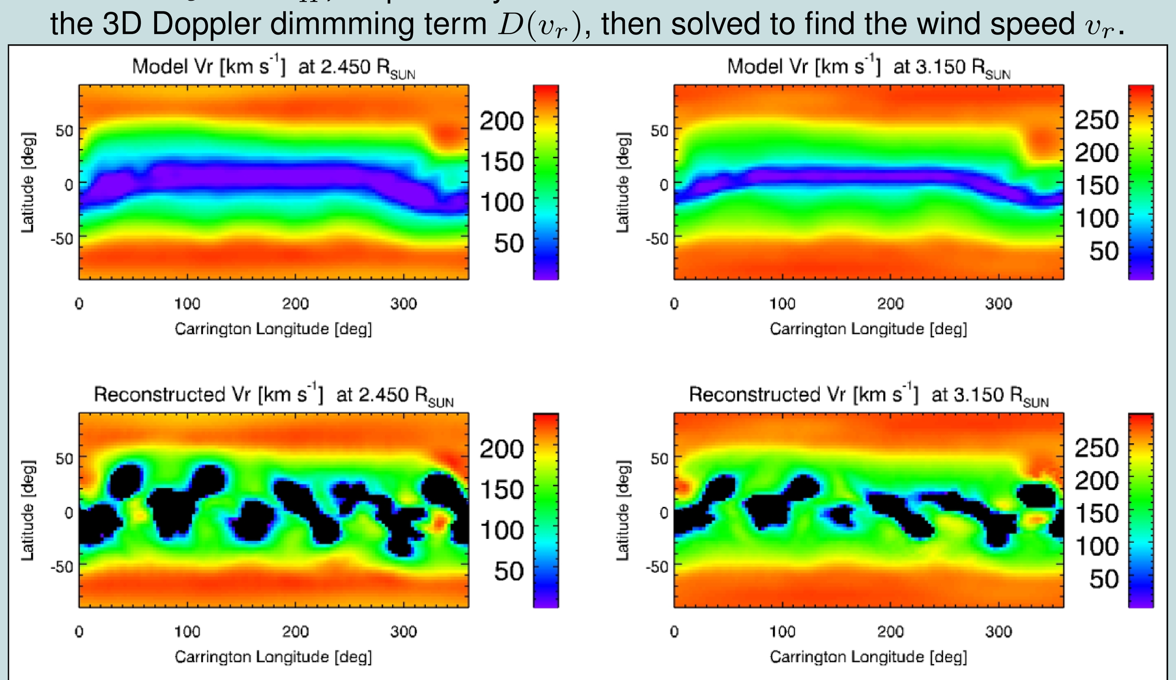
WL: SolMin simulation - Perihelion observation (2023-Mar, $D \approx 0.4 - 0.3 - 0.4$ AU)



Lα: SolMin simulation - Perihelion observation (2023-Mar, $D \approx 0.4 - 0.3 - 0.4$ AU)

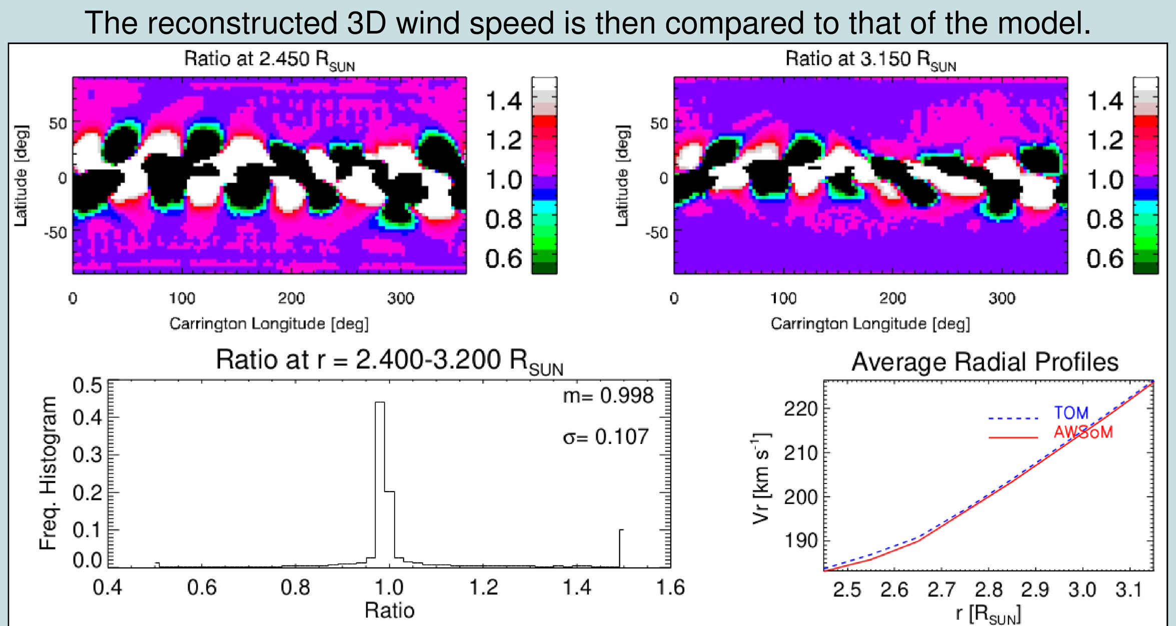
3D Wind Speed: Reconstruction versus Model

The WL and Lyman-α images are used to carry out tomographic reconstruction of the model N_e and D_H, respectively. The reconstructions are then combined to infer the 3D Doppler dimmming term $D(v_r)$, then solved to find the wind speed v_r.



$$V_r = \sqrt{\sigma^2_{\rm disk} + \sigma^2_{\rm cor}} \ \sqrt{\ln\left(\frac{I_0 \lambda_0/\sqrt{\pi}}{\sqrt{\sigma^2_{\rm disk} + \sigma^2_{\rm cor}}} \ \frac{1}{D}\right)} \qquad \left(D \leq \frac{I_0 \lambda_0/\sqrt{\pi}}{\sqrt{\sigma^2_{\rm disk} + \sigma^2_{\rm cor}}}\right)$$

The reconstructed 3D wind speed is then compared to that of the model.



Conclusions

- The wind-speed sensitive HI Ly-α *Doppler dimming* term can be written as: $\mathrm{D} = (1/0.8 \ R(T_e)) \ \mathrm{D_H}/\mathrm{N_e}$.
- The 3D $\mathrm{D_H}$ and $\mathrm{N_e}$ can be reconstructed from Lyα and WL tomography, respectively. We used AWSoM to simulate this for a solar minimum corona.
- The Doppler dimming reconstruction, combined with the 3D model for **B** and T_H, allows reconstruction of the 3D distribution of the wind speed:

$$D(v_r) = I_0 \ \lambda_0 \ \frac{1}{\sqrt{\sigma^2_{\rm disk} + \sigma^2_{\rm cor}}} \ \exp\left[-\frac{v_r^2}{(\sigma^2_{\rm disk} + \sigma^2_{\rm cor})}\right]$$

$$\sigma_{\rm cor} = \sqrt{(\cos\beta \ V_{\rm th\parallel})^2 + (\sin\beta \ V_{\rm th\perp})^2} \quad \text{and} \quad \beta \equiv \cos^{-1}(B_r/B)$$

- Non reconstructed regions (black color in the maps above) correspond to $V_r \ll \sqrt{\sigma^2_{\rm disk} + \sigma^2_{\rm cor}} \to D_{\rm recons} > D_{\rm model}$. We are able to reconstruct the fast/slow transition though.
- Next steps: solar maximum simulation, and application to actual data from Metis.