Estimation of the 3D electron density distributions in the solar corona for more realistic solar wind modelling

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Abstract

We estimate the electron density (N_e) distribution in the solar corona

- for the last two recent minima of solar activity, with LASCO
- using a new time-dependent tomography method.

(1) Do we have realistic N_e distributions at the equator and in the coronal holes?
(2) How is the temporal evolution of the N_e distributions during the last two solar minima?
(3) Does the position of the maximum N_e follow the streamer belt?

1. Solar Coronagraph Images

Polarized brightness images (PB) from SOHO/LASCO-C2.

- The PB are dominated by Thompson Scattering.
- We mask strong temporal change produce by Coronal Mass Ejections (CME)

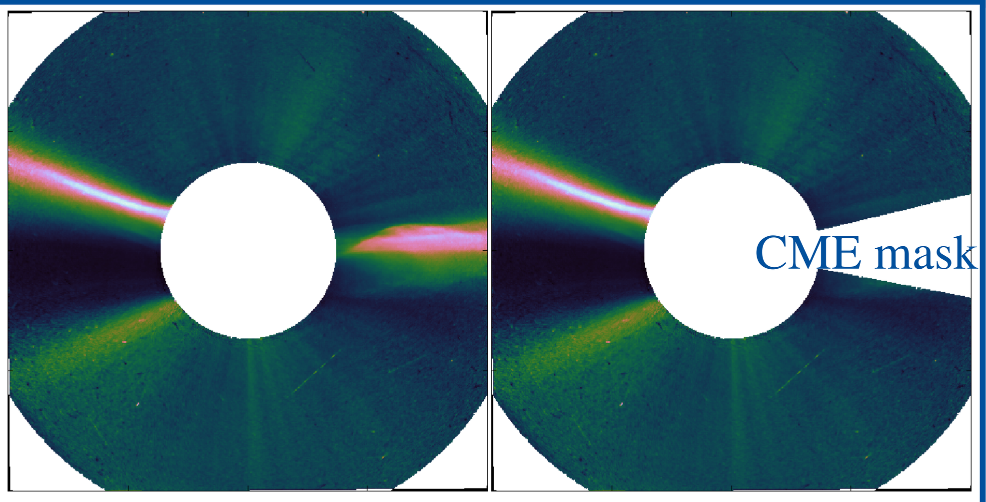

Fig.1: PB images with a background subtraction and a contrast enhancement (26-Mar-2008). Field of View: 2 R$_\odot$ to 6.5 R$_\odot$.

2. Tomography reconstruction method

Electron density of the corona: $N_e(r,\theta,\varphi,t) = \underset{\mathbf{x}\geqslant b}{\operatorname{argmin}} \left\| \begin{pmatrix}\mathbf{y}\\ \mathbf{0}\end{pmatrix} - \begin{pmatrix}\mathbf{A}\\ \mathbf{R}\end{pmatrix} \mathbf{x} \right\|_2^2$

- **y** contains pixels of the PB images;
- **x** contains the bins of the N_e, with the constraint of positivity: $\mathbf{x} \geqslant b$ and $b = 0$.
- **A** is the projection matrix determined by the physics and the geometry of the problem.
- **R** is the regularization matrix. Usually, only a spatial regularization is used $\mathbf{R} = \lambda_s \mathbf{R}_s$.

In the new method, we add a temporal and co-rotating regularization [1]:

$$\mathbf{R} = (\lambda_s \mathbf{R}_s,\ \lambda_t \mathbf{R}_t,\ \lambda_c \mathbf{R}_c)^T$$

Time series of density reconstructions:

Each reconstruction: half a rotation $\simeq$14 days $\simeq$13-15 images.
Period of time: the two recent solar minima, *i.e.*, **1996–1997** & **2008–2010**.
Time series: One full 3D reconstruction every 4 days.

3. Density reconstruction *vs.* PFSS *vs.* PredSci MHD Model

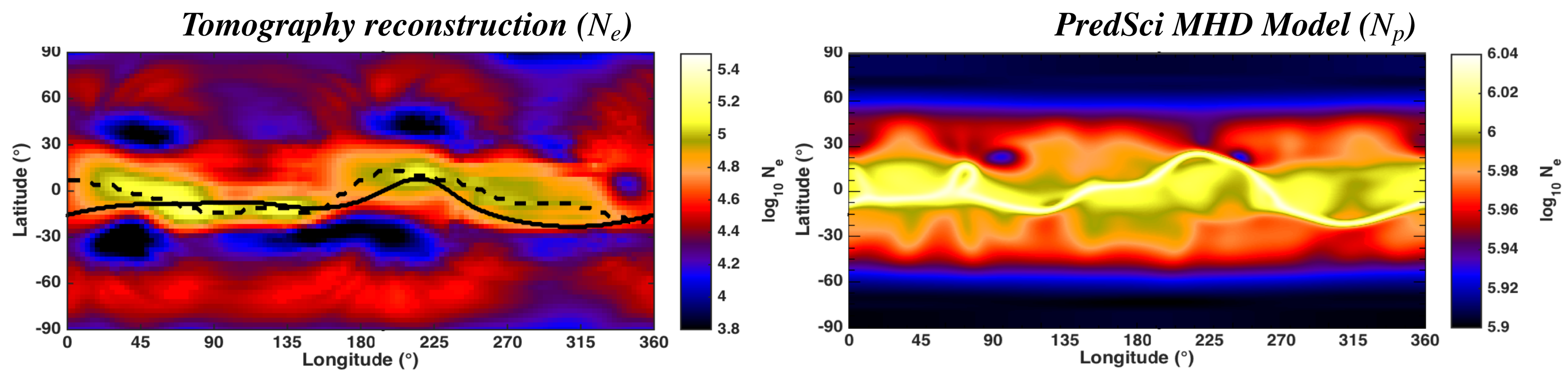

Fig.2: Spherical plane at 3.5R$_\odot$. 180°long corresponds to Dec 28, 2008 (Carrington Rotation 2077).

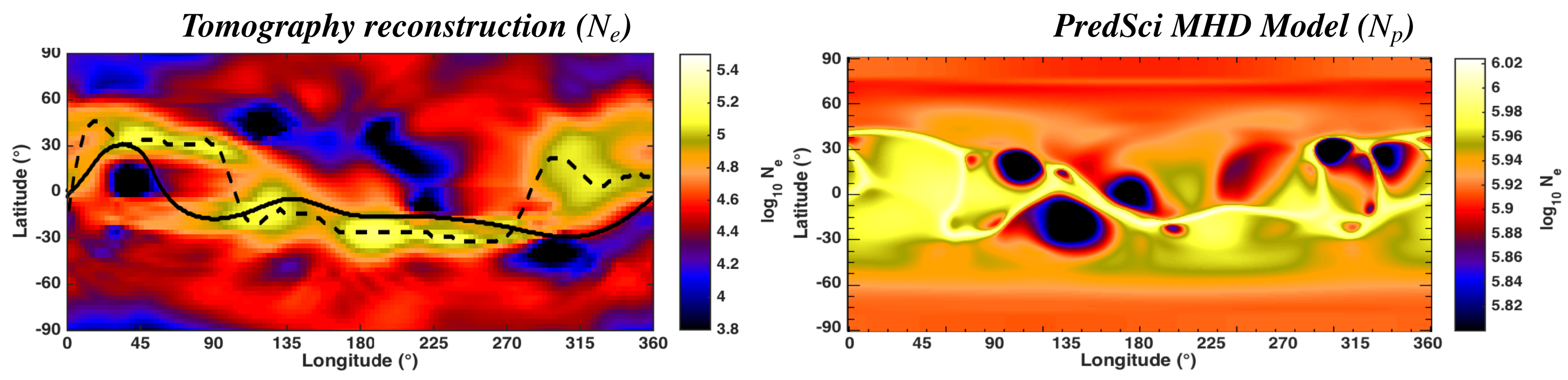

Fig.3: Spherical plane at 3.5R$_\odot$. 180°long corresponds to Jun 17, 2010 (Carrington Rotation 2098).

Black line: Heliospheric Magnetic Equator (HME) from PFSS model (coronal fields extrapolated from SOHO/MDI magnetograms) [2]. **Dashed line:** Maximum N_e from tomography shows a mismatch with PFSS/HME.

PredSci MHD Model: polytropic MHD simulation (based on same magnetogram as for the PFSS) [3], provides the coronal plasma density ($N_p = N_e$).

- PFSS and PredSci use a full rotation, while tomography requires only half rotation.
- Tomography reconstruction is more detailed at the poles and at the equator compared to PredSci.
- Mismatch between max N_e and the PFSS/HME could be due to pseudo-streamer.

4. Latitude of the current sheet and the density maximum

How does the position in latitude of the PFSS/HME, N_e maximum in the MHD model and N_e maximum in the tomography reconstruction, vary with time?

PFSS and PredSci show similar result since they both use Magnetogram Synoptic Maps.

Location of the maximum N_e does not always follow the HME.

→ Pseudo-streamer could be denser than the streamer belt?

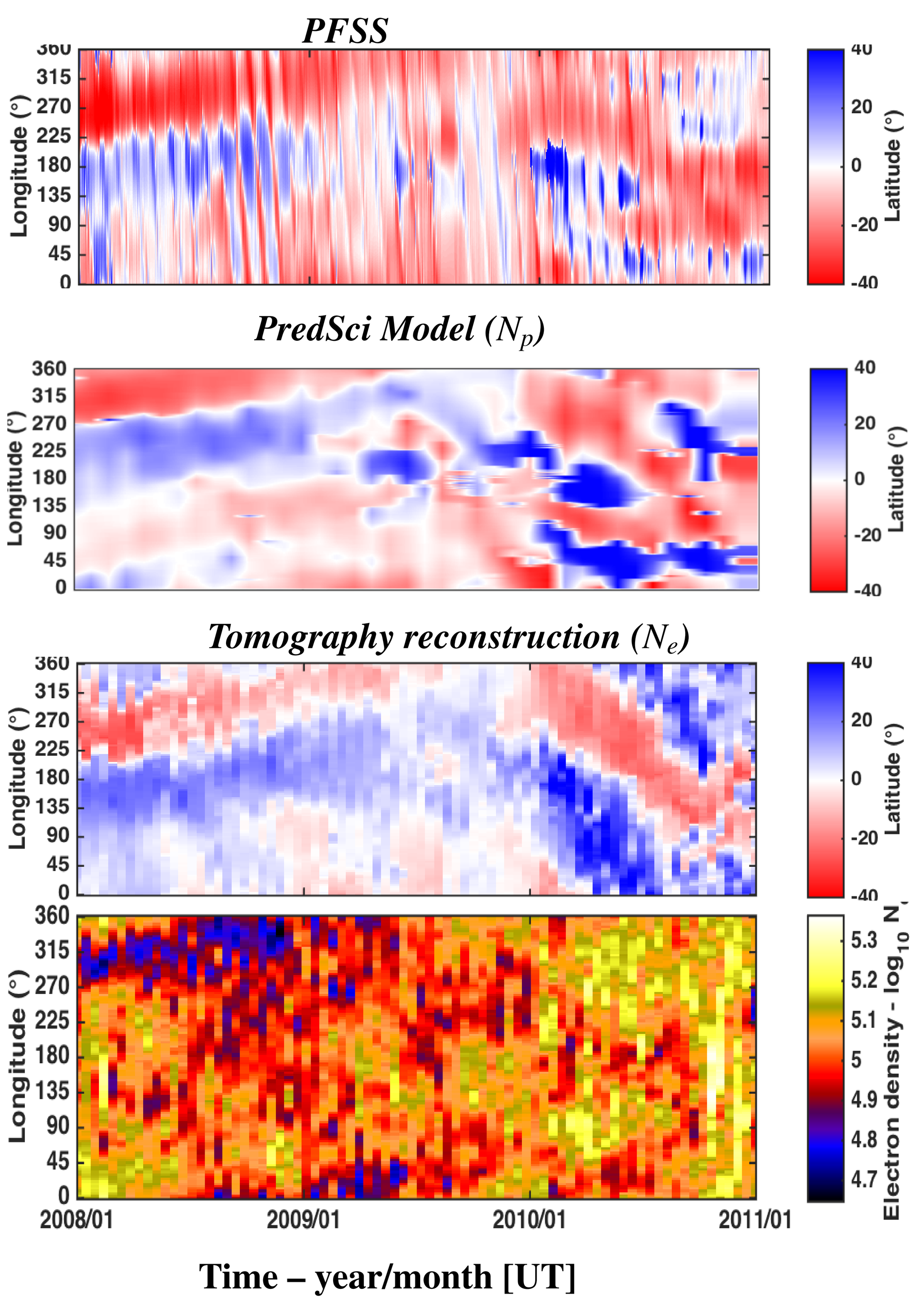

Fig.4: Latitude of the HME and N_e maximum at 3.5R$_\odot$ during the solar minimum, 2008–2010.

5. Density radial profile

Red N_e maximum at the equator.
Blue N_e average over the poles above $\pm 65°$.
Dashed line: First solar minimum.
Continuous line: Second solar minimum.
Squares: Saito model [4].
Dots: PredSci MHD model during the second minimum.

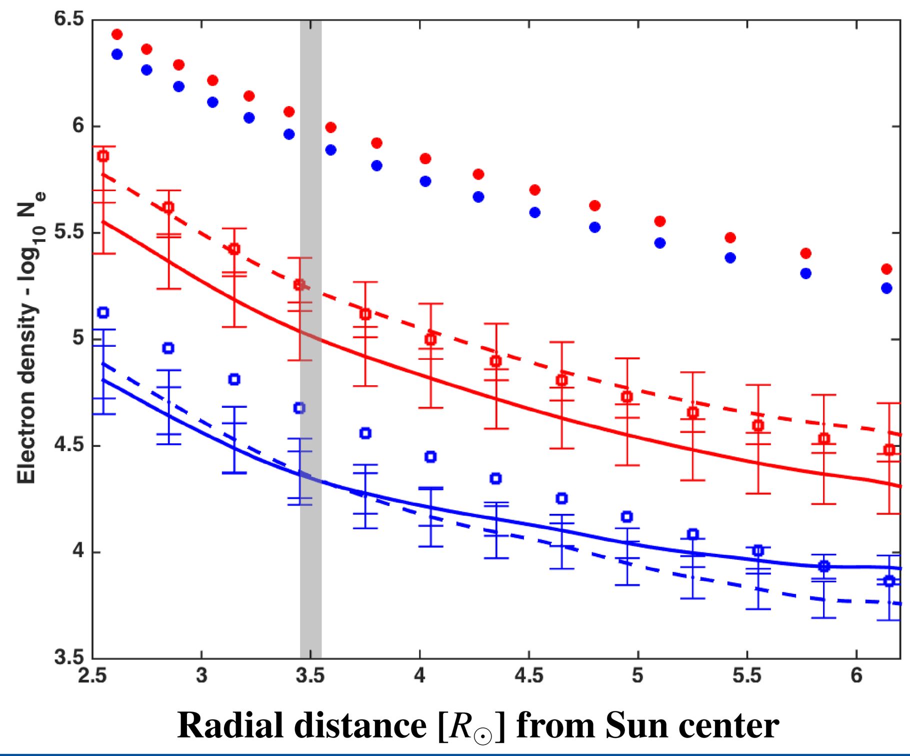

Fig.6: Electron density, N_e, at the current sheet (red) and the poles (blue).

6. Temporal evolution of the electron density at 3.5$R_\odot$

Black Sunspots Number (SIDC).
Red N_e maximum at the equator.
Blue N_e average over the poles above $\pm 65°$.

- Good agreement with the Sunspots number (SSN).
- At the poles N_e is similar for two minima.
- At the equator N_e is lower for the second minimum.

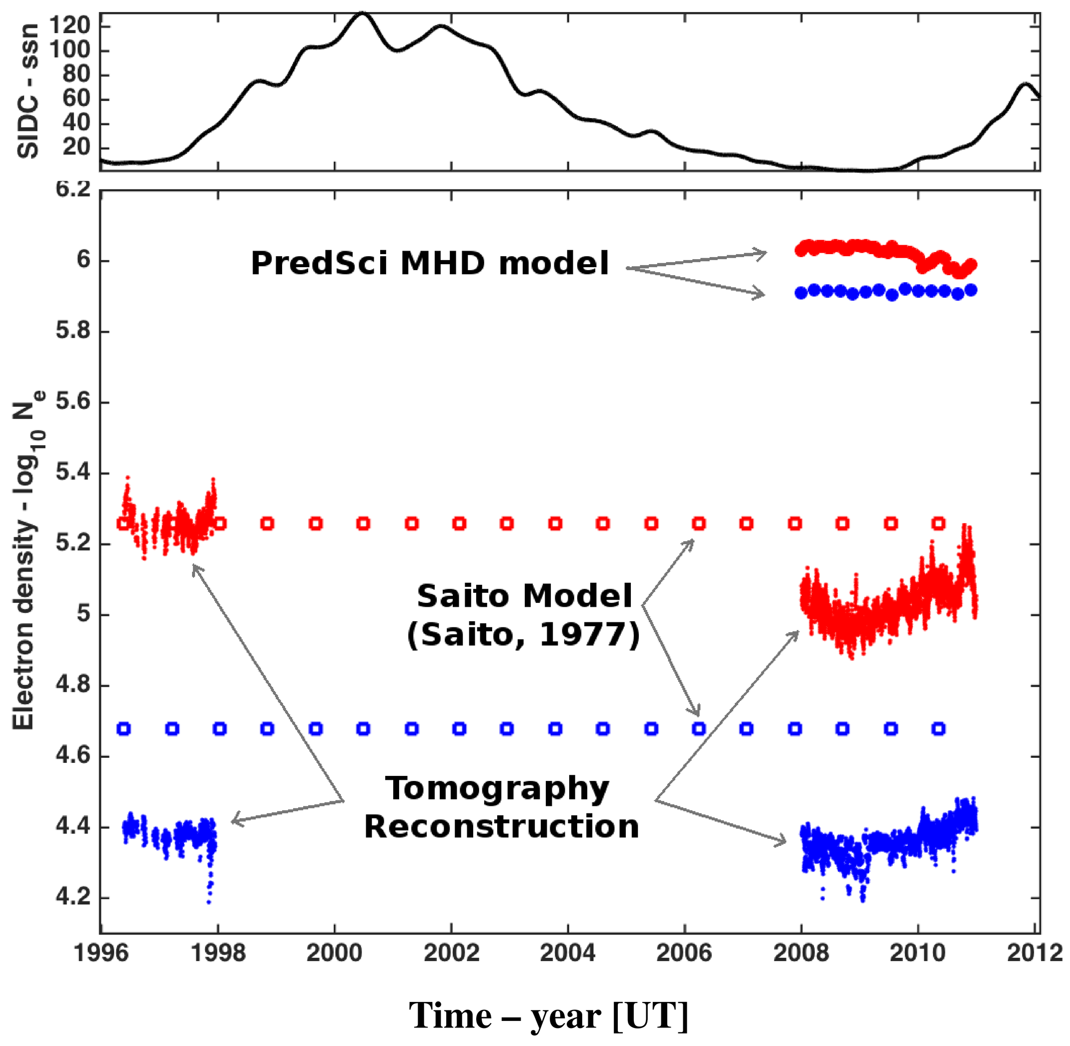

Fig.5: N_e estimation at 3.5$R_\odot$.

Summary & Conclusion

- **Realistic values? Time evolution?** The value range of PredSci/N_e is shorter and over-estimates the tomography results by an order of magnitude. Temporal variations in the 3D N_e distribution from tomography are non negligible.
- **Realistic radial profiles?** Deviation in N_e between Saito model and tomography at the poles for distance $\leq 5R_\odot$; Radial profile changes between solar minima: at the poles they cross at 3.5$R_\odot$, at the equator they differ by $\sim 10^5 \mathrm{cm}^{-3}$
→ Saito model cannot be used realistically for solar activity evolution.
- **Realistic positions?** Positions of PFSS/HME and PredSci/$N_e$max are usually similar and follow the streamer belt. However, positions of $N_e$max from tomography do not always follow the predicted streamer belt.
- **The results provide important constraints and initial conditions** for a realistic and running time models of the solar corona and solar wind. So far, time-dependent MHD models suffer from realistic initial conditions (density, temperature, velocity) close to the surface and are not well constrained outward (radial profile).

[1] Peillon et al., *Sol.Phys.* in prep.
[2] Schatten, et al., *Sol.Phys.* 1969
[3] Predictive Science: *www.predsci.com* (Riley, et al., *JGR* 2001)
[4] Saito, et al., *Sol.Phys.* 1977

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