10th Metis Workshop

An iterative method for determining T_e in corona from Metis observations

- preliminary results-

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FEBRUARY
11-13, 2026

Agenzia Spaziale Italiana

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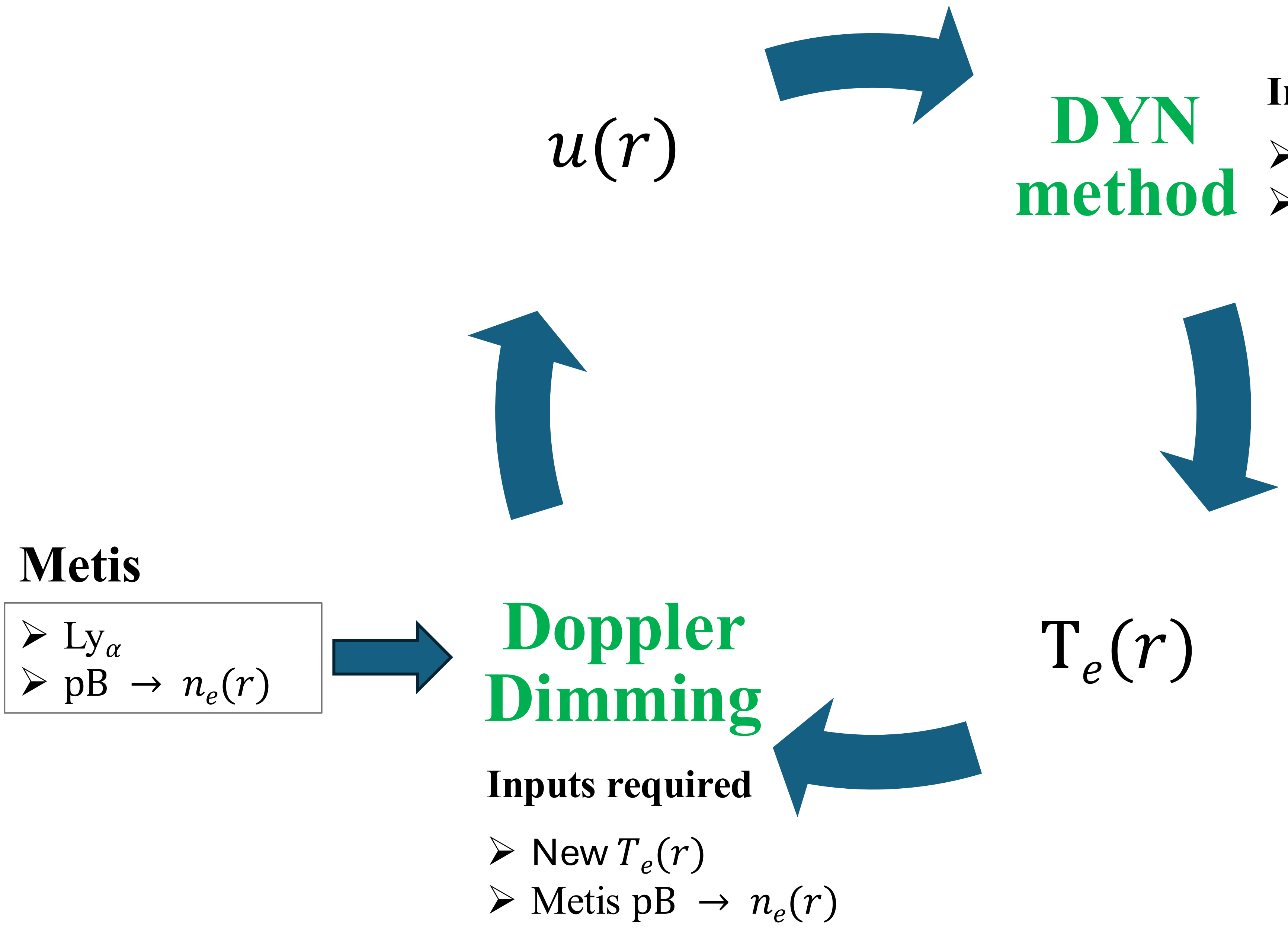
Evaluate electron temperature profiles using <u>Metis data</u> and <u>cycling</u> with a DDT & DYN model.



…convergence after a few cycle!

Summary

1

DYN model

- Overview
- Main profiles

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Preliminary Results

- T_e using DYN & Metis
- Iteration

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Other models

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- Comparison with DYN

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Future works

- WIP
- Possible improvements

DYN model

- [REF_1]: J.F. Lemaire and K. Stegen, Solar Phys (2016) 291:3659–3683; DOI 10.1007/s11207-016-1001-32016.
- [REF_2]: J.F. Lemaire and A.C. Katsiyannis, Solar Phys (2021) 296:64; DOI 10.1007/s11207-021-01814-4.

Solar Phys (2016) 291:3659–3683
DOI 10.1007/s11207-016-1001-3

CrossMark

Improved Determination of the Location of the Temperature Maximum in the Corona

J.F. Lemaire[1] · K. Stegen[2]

Solar Physics (2021) 296:64
https://doi.org/10.1007/s11207-021-01814-4

Check for updates

Radial Distributions of Coronal Electron Temperatures: Specificities of the DYN Model

Joseph F. Lemaire[1,2] · Athanassios C. Katsiyannis[3]

Received: 20 February 2020 / Accepted: 3 April 2021 / Published online: 12 April 2021

HST method:

[More details at Lemaire and K. Stegen, 2016]

[…] if the corona were in **hydrostatic equilibrium**, $T_e(r)$ would be the solution of the following equation:

$$\frac{dT_e}{dr} + T_e \frac{d \ln n_e}{dr} = -\mu\, m_H\, g_0\, R_\odot \,/\, \mathrm{k} r^2$$

boundary condition $T = 0$ at $\mathrm{r} = \infty$. Introducing a constant normalization temperature T^* (Alfvén, 1941) $\rightarrow$ $y = T/T^*$, the above equation becomes:

$$\frac{dy}{dr} + y \frac{d \ln n_e}{dr} = -\,1 \,/\, r^2$$

$$y(r) = -[1/n_e] \int_{\infty}^{r} [n_e(r')/r'^2]\, dr'$$

DYN method:

Continuous expansion of the solar corona is a well-established phenomenon

→ hydrostatic equation replaced by the hydrodynamic momentum-transport equation;

→ an inertial force term $[\rho du/dt]$ is added to the kinetic-pressure gradient term.

Some of the assumptions in DYN model

1. Expansion factor $f_{max} = 1$ in order to simulate radial expansion (Kopp and Holzer, 1976);
2. the $u(r)$ is stationary and the flux of particles is conserved along plasma flow tubes;
3. ignore the presence of He^{++} ions;
4. the plasma can be treated as a single fluid whose bulk velocity $[u(r) = u_e = u_i]$;
5. both the electron and the ion temperatures vary with r, but we will assume that their ratio $[T_p/T_e = \tau_p]$ is independent of r; it is assumed that $\tau_p = 1$.

…

Hydrodynamic momentum equation to be solved (see Appendix in Lemaire and K. Stegen, 2016):

$$\frac{dy}{dr} + y\,\frac{d\ln n_e}{dr} = -1/r^2\,[1 + F(r)]$$

where $F(r)$ is the ratio between the "inertial force" and the "gravitational force":

$$F(r) = r^2 u\left(\frac{du}{dr}\right)/g_0 R_\odot$$

Ignoring recombination processes, the steady-state distribution of $u(r)$ can be obtained **from the flux conservation equation and electron density profile**:

$$u(r) = u_E\,[A_E/A(r)][n_E/n_e(r)]$$

where A_E, u_E, and n_E are, respectively, the cross-section of flow tubes, the solar-wind bulk velocity, and density at 1 AU.

Solution HST:

$$y(r) = -[1/n_e] \int_{\infty}^{r} [n_e(r')/r'^2]\, dr'$$

Solution DYN:

$$y(r) = T(r)/T^* = -[1/n_e] \int_{\infty}^{r} [n_e(r')/r'^2]\,[1 + F(r')]dr'$$

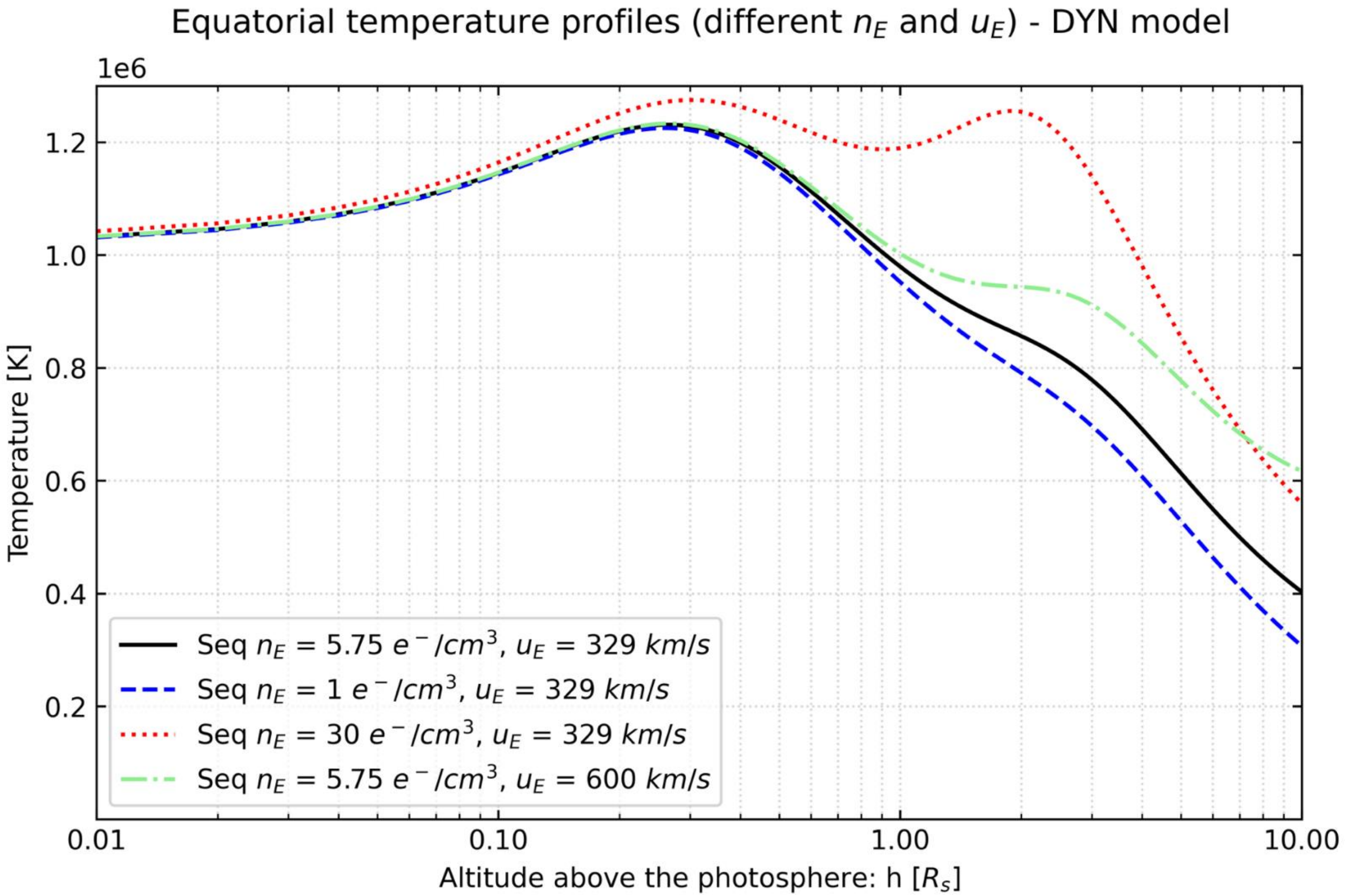
Goal:

coronal electron temperature profiles [$\mathrm{T}_e(r)$] from given radial distributions of the coronal solar wind [$u(r)$] and electron densities [$n_e(r)$].

Electron density profile

[Saito (1970)]

$$n_e(r) = 10^8\left[3.09r^{-16}(1-0.5\sin\Phi) + 1.58r^{-6}(1-0.95\sin\Phi) + 0.0251r^{-2.5}(1-\sin^{0.5}\Phi)\right] + n_E(215/r)^2.$$

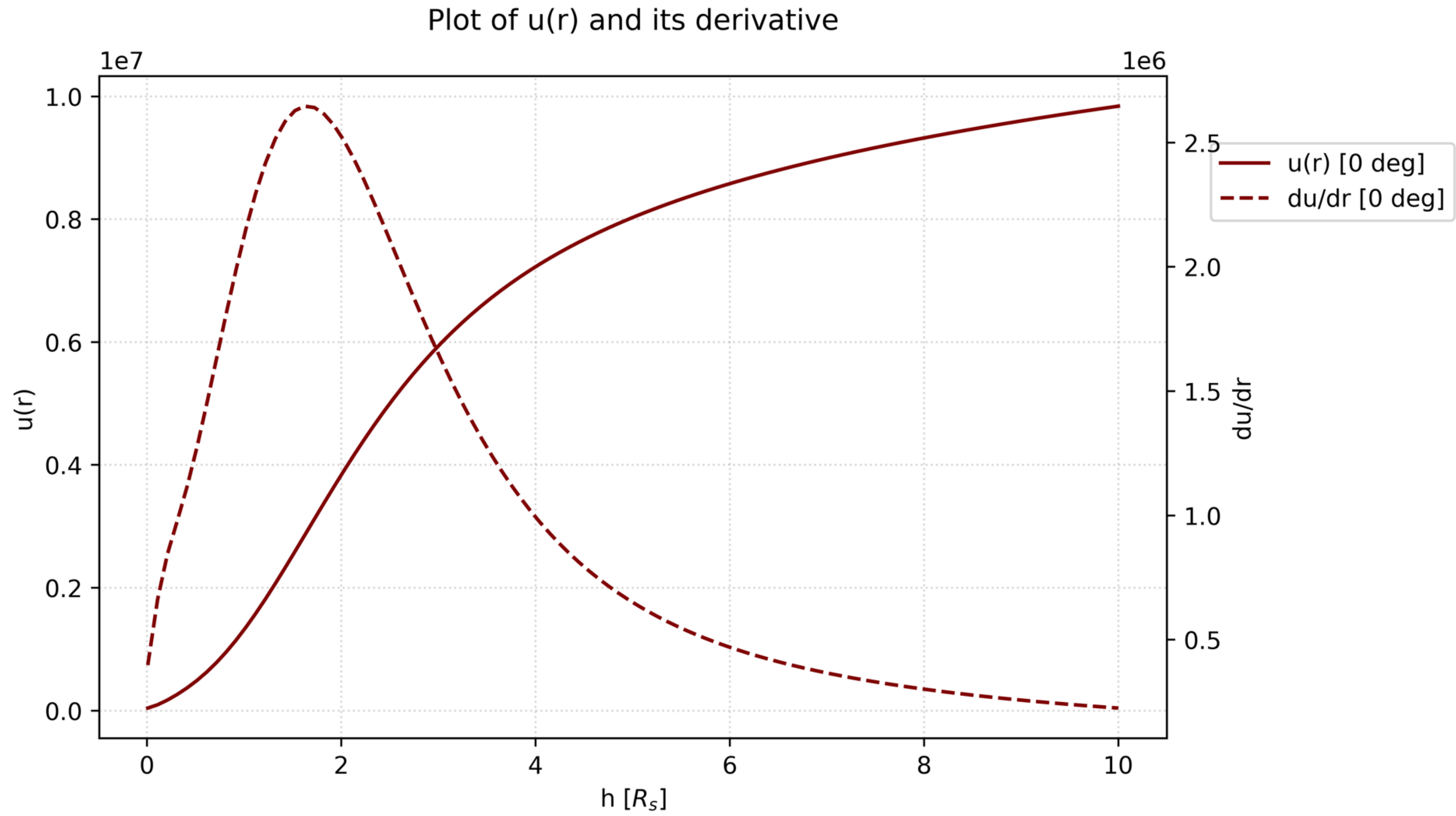


SW velocity profile

$$u(r) = u_E \, [A_E/A(r)][n_E/n_e(r)]$$

DYN model restricts calculations to **spherical expansions** of the SW

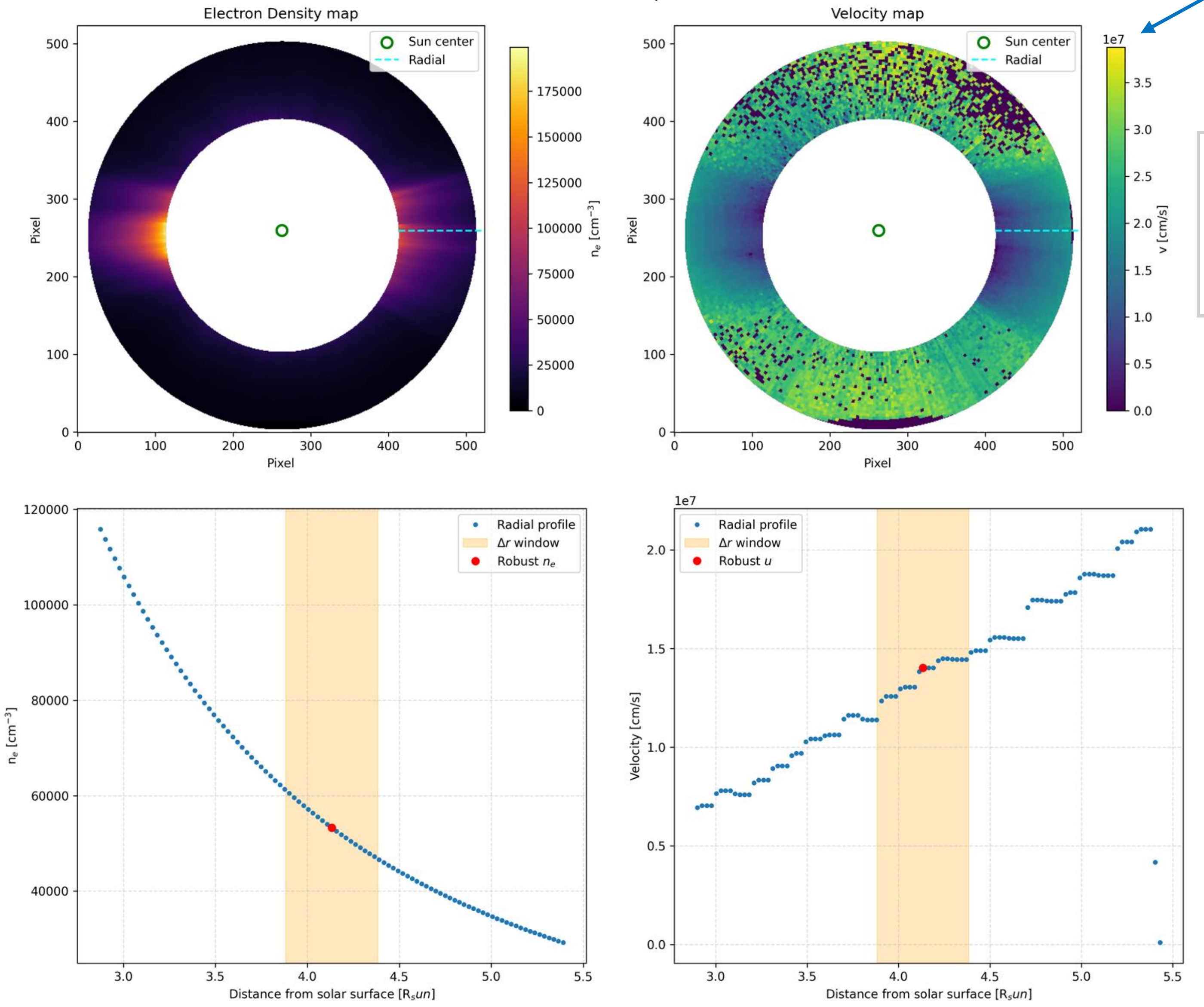
$\rightarrow A_E / A(r) = (215/r)^2$ …where A_E is the cross-section of the flow tube at 1 AU.



n_e and u_e Radial profiles with Metis

Map from S.Giordano , A&A, 701, A56 (2025);
DOI 10.1051/0004-6361/182554105.

Date Obs.: Jan 14, 2021



Electron density

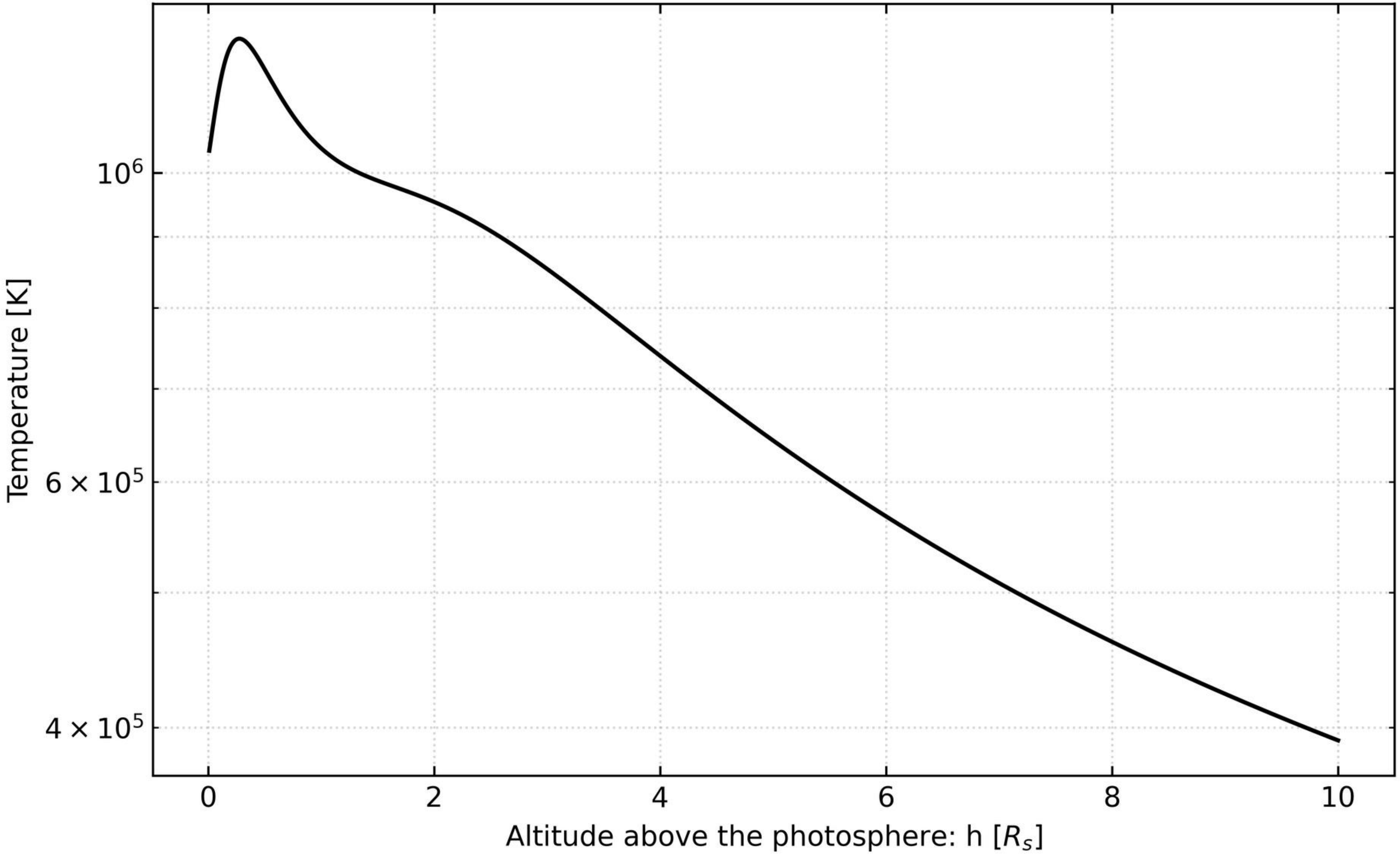
$$n_e(r) = 10^8\left[3.09r^{-16}(1-0.5\sin\Phi) + 1.58r^{-6}(1-0.95\sin\Phi) + 0.0251r^{-2.5}\left(1-\sin^{0.5}\Phi\right)\right] + n_E(215/r)^2.$$

SW velocity

$$u(r) = u_E\,[A_E/A(r)][n_E/n_e(r)]$$

...from 1 AU to $4R_\odot$

T_e combining DYN method & Metis observations



Doppler dimming

SW velocity from Metis through Doppler Dimming Technique (DDT)

Neutral hydrogen **ionization fraction** (depending on the coronal electron temperature $\mathbf{T}_e$) given by the equilibrium tables from CHIANTI database.

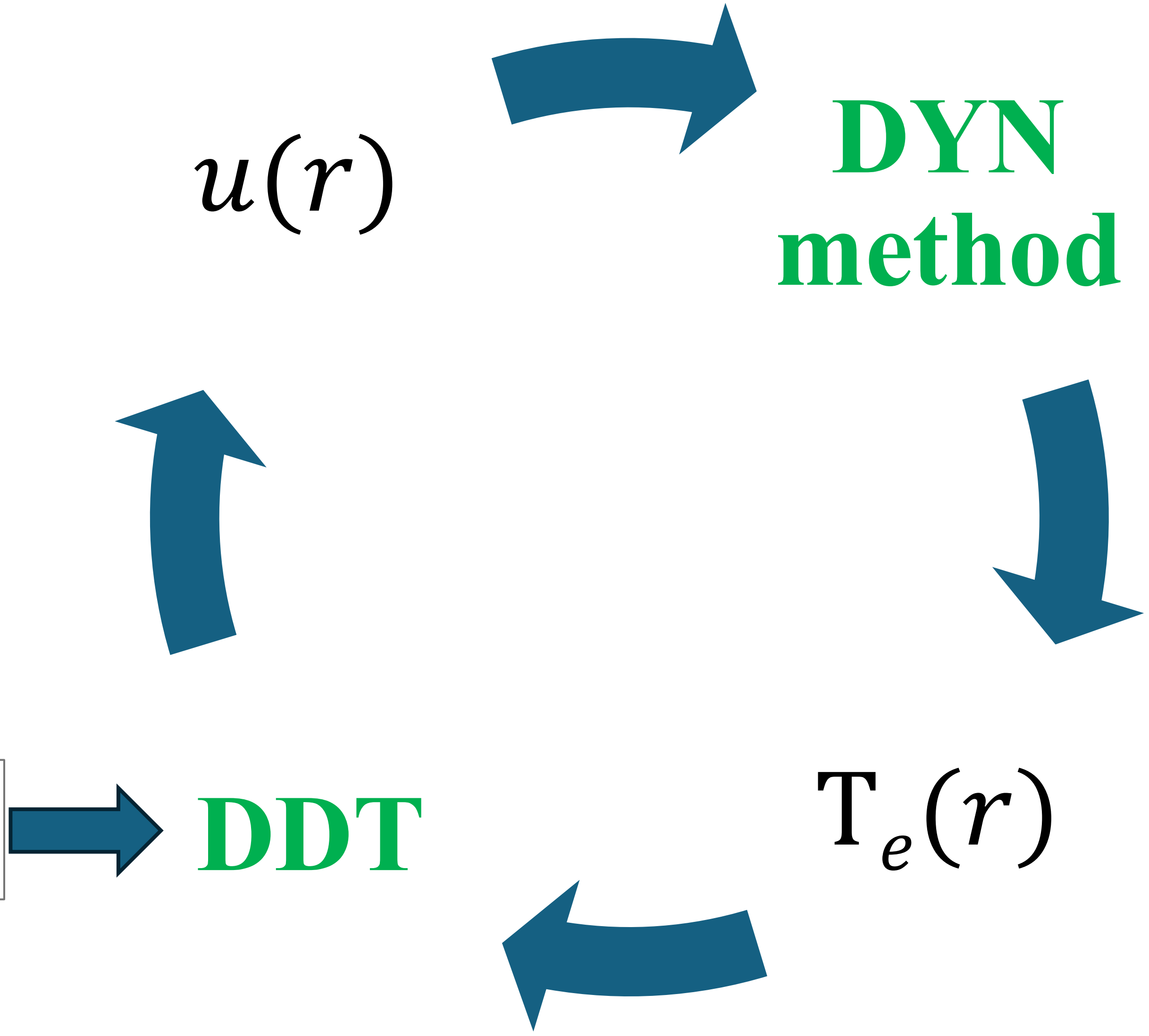
$$I_r(\mathbf{n}) = B_{12}\frac{h\,\lambda_0}{4\pi}\,n_{pe}\int_{-\infty}^{+\infty} n_e R_{HI}\,dx \int_\theta \int_\phi p(\mathbf{n}\cdot\mathbf{n}')\sin\theta\,d\theta\,d\phi$$

$$\int_{-\infty}^{+\infty} I_{ex}(\lambda-\lambda_0,\mathbf{n}')\int_{-\infty}^{+\infty} f(\mathbf{v})\,\delta\!\left(\lambda-\lambda_0-\frac{\lambda_0}{c}\mathbf{v}\cdot\mathbf{n}'\right)d\mathbf{v}\,d\lambda$$

- More details at: S.Giordano , A&A, 701, A56 (2025); DOI 10.1051/0004-6361/182554105.

Iteration cycle

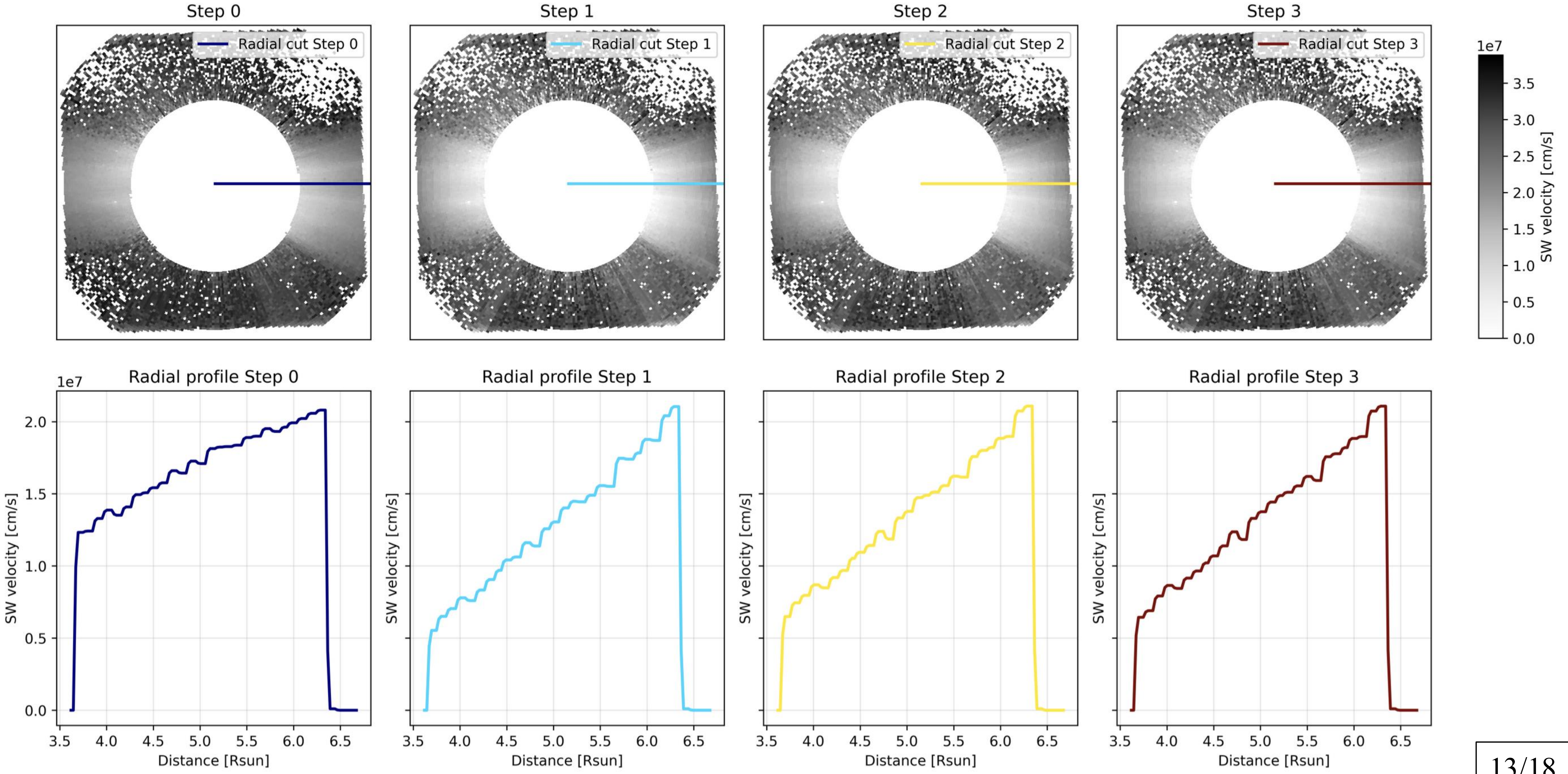
- **DDT $\mathbf{u}(\boldsymbol{r})$**
- Metis pB $\rightarrow n_e(r)$



- Ly$_\alpha$
- Metis pB $\rightarrow n_e(r)$

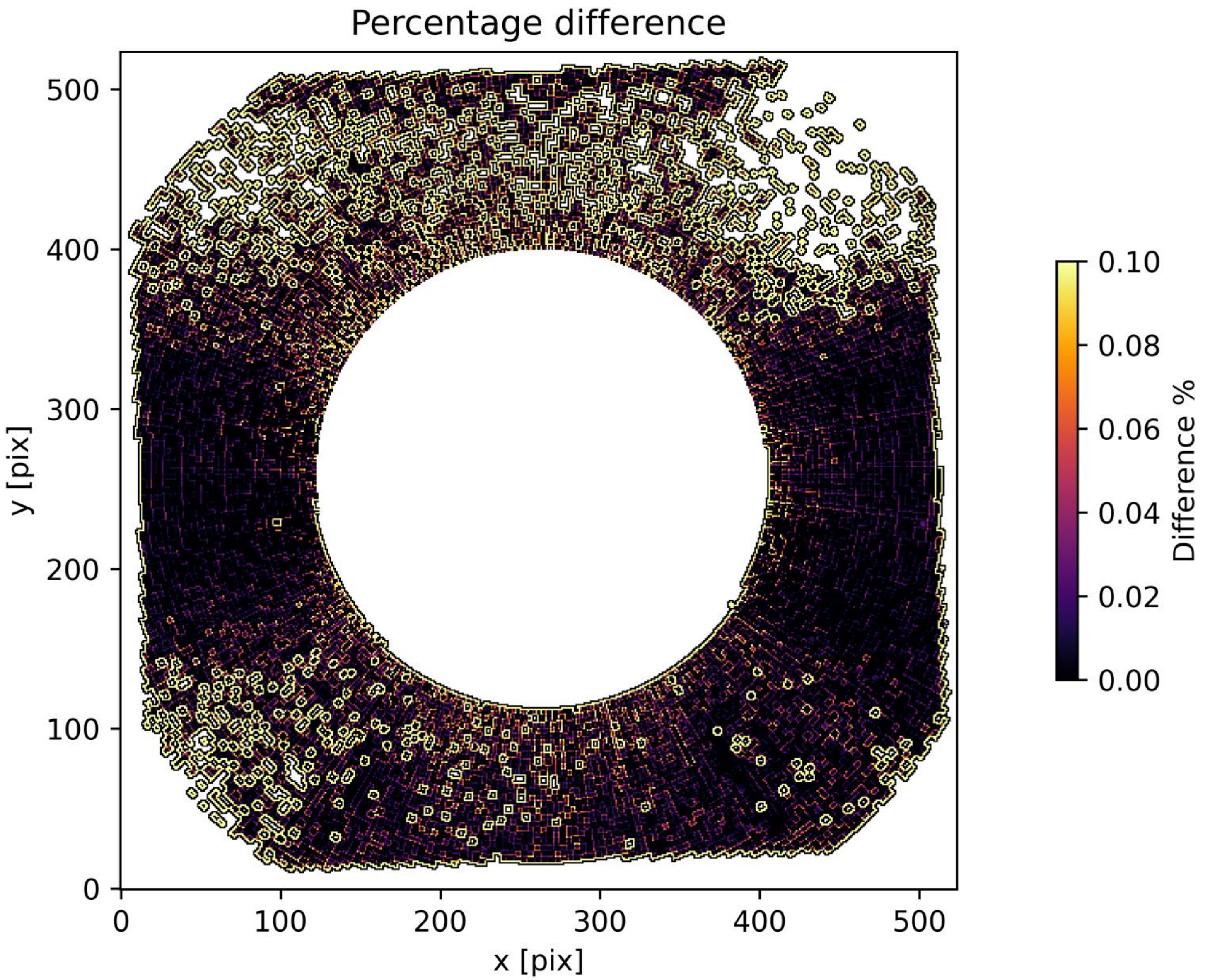
- $\boldsymbol{T_e(r)}$
- Metis pB $\rightarrow n_e(r)$

Iteration: SW map

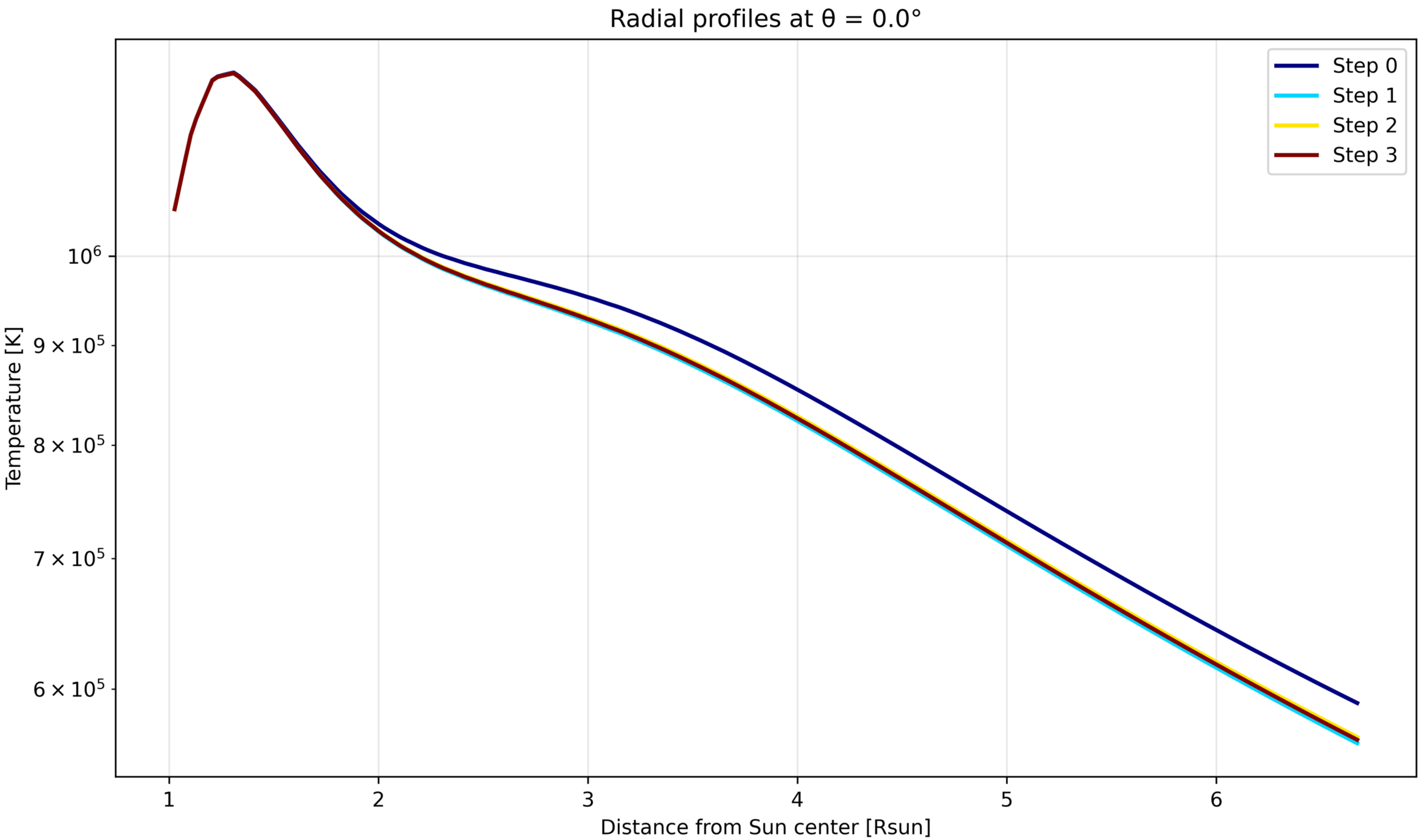


Iteration SW map

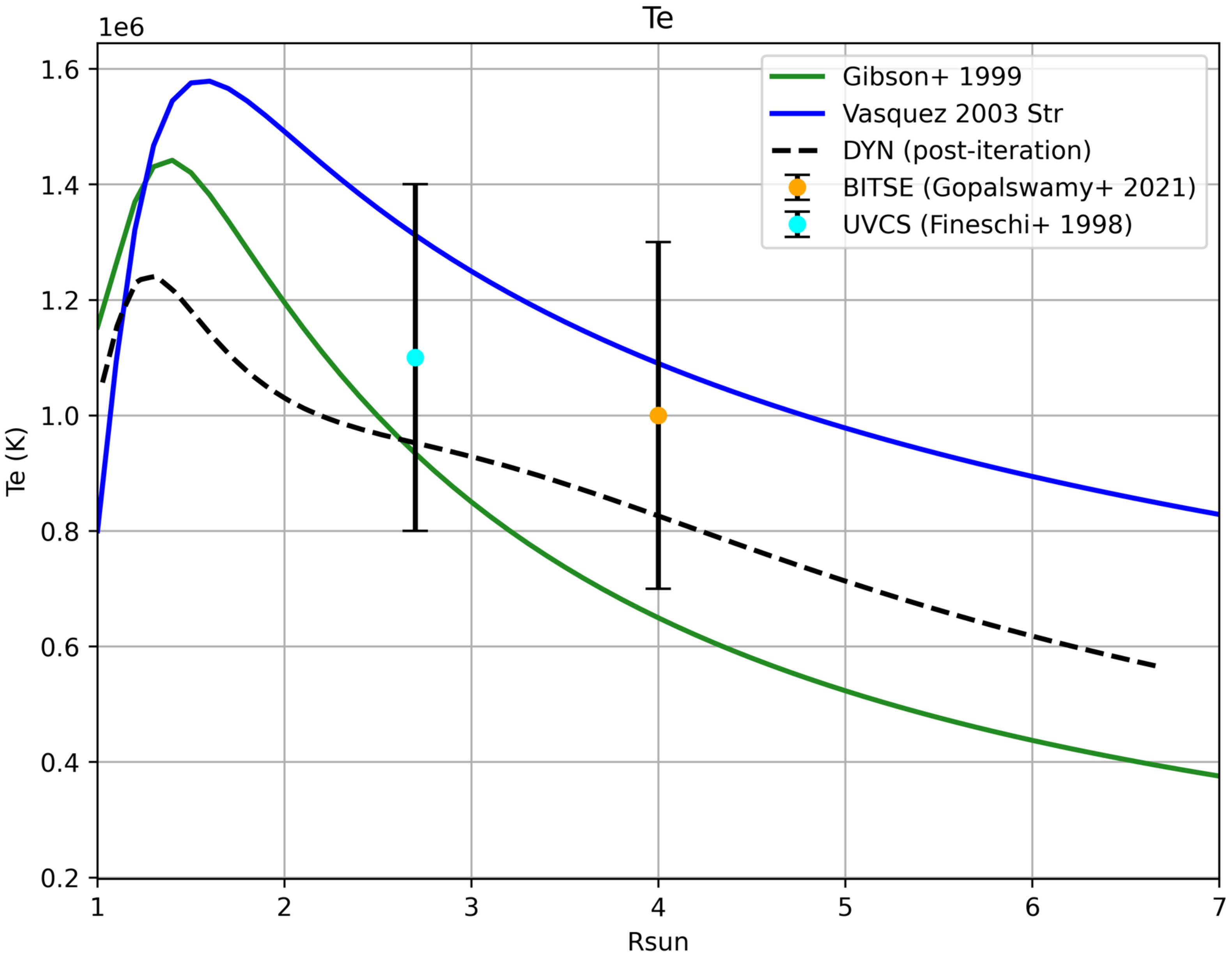
We stop when:



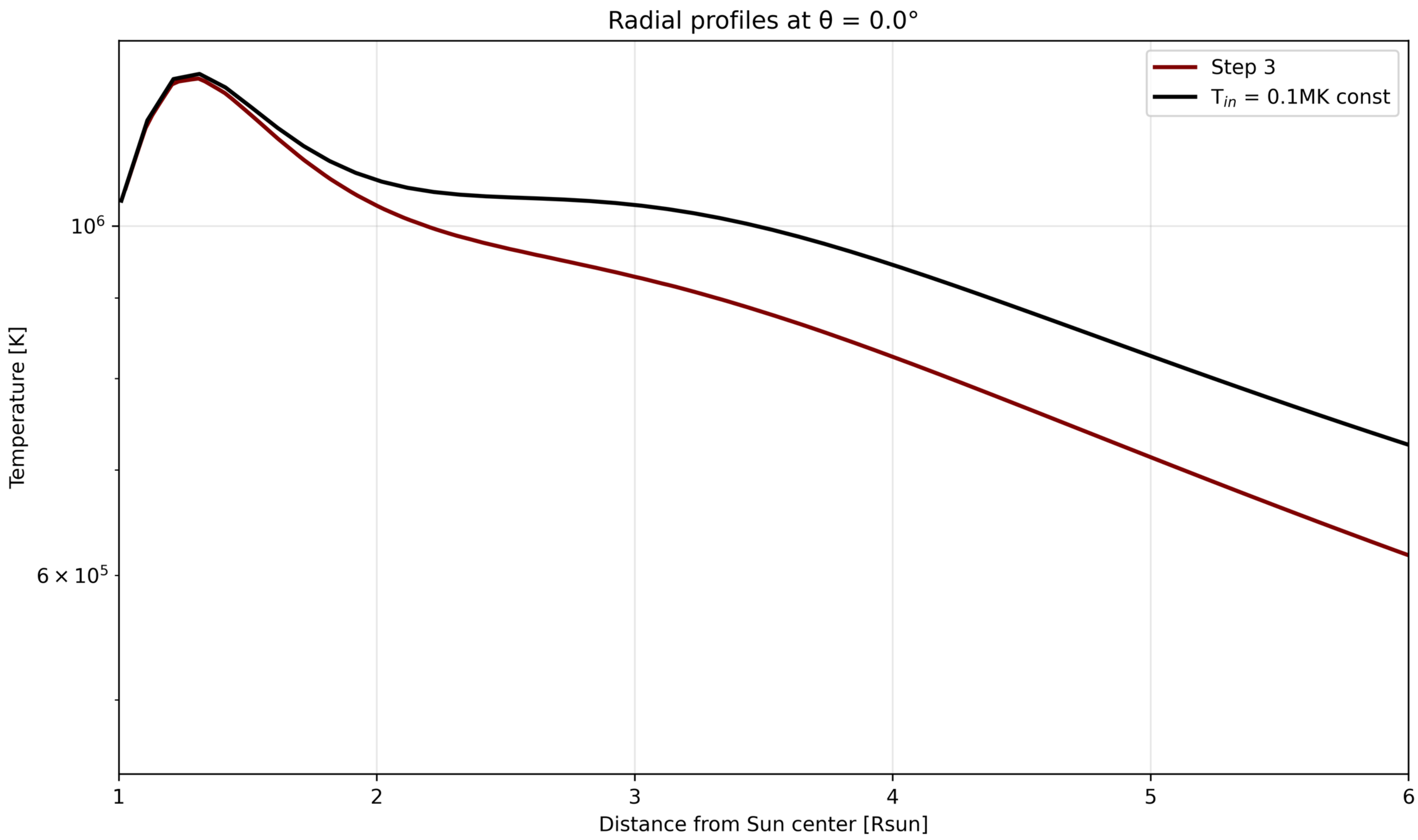
Iteration: $T_e(r)$ profile



Comparison with other $T_e(r)$ profiles

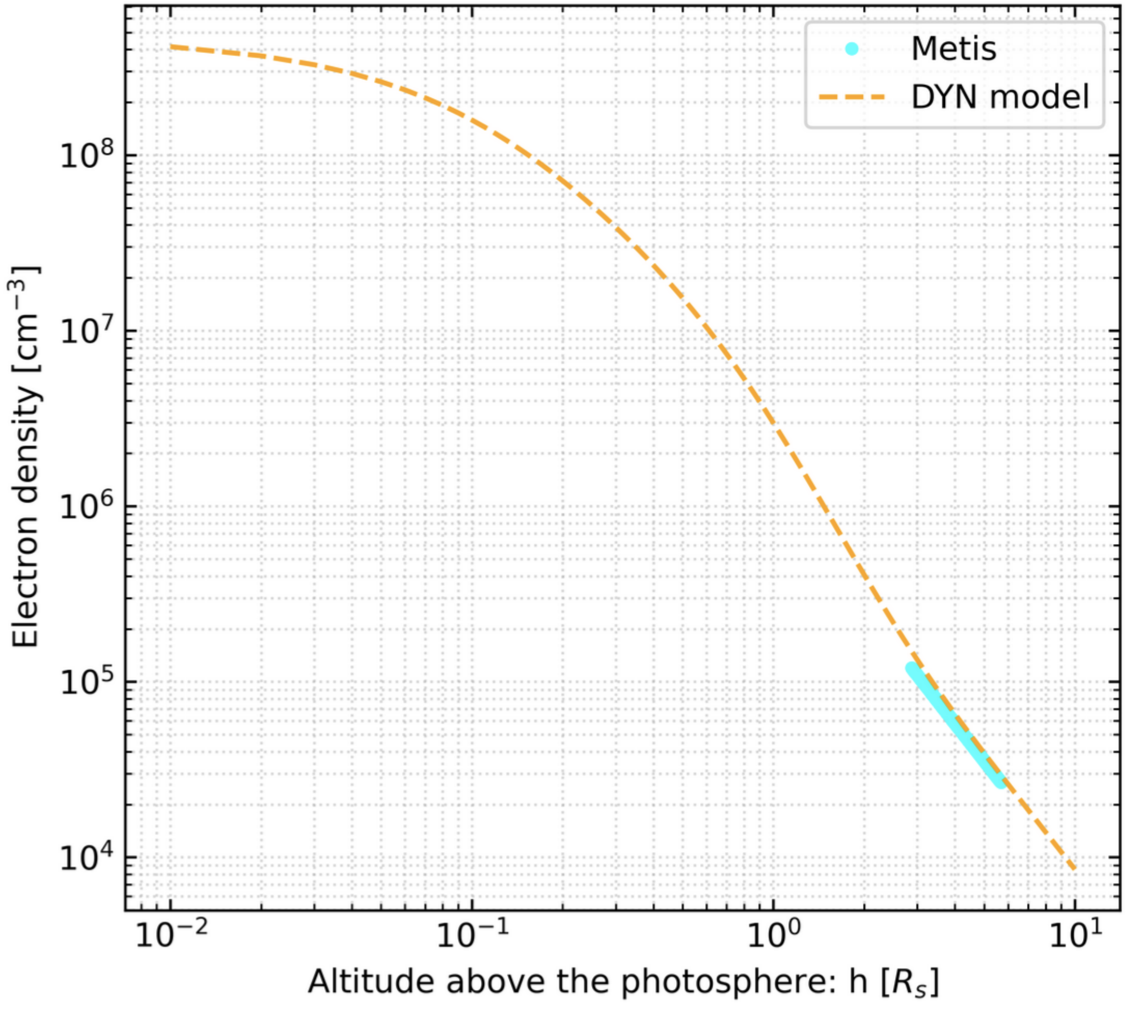


$T_e(r)$ profiles starting with different input



Future work

- New electron density profile →
- Relax some assumptions
  e.g., expansion factor $f_{max} \neq 1$
- Different latitudes → map of T_e
- Different input T_e
- Test with other S/C profiles
  e.g., pB from **PROBA-3/ASPIICS**



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Methods overview

- DYN method is a new tool to evaluate the range of altitudes where the heating rate is maximum in the solar corona when the electron-density distribution is obtained from WL coronal observations.

- Assuming spherical symmetry for the polarized WL brightness (pB), empirical radial distributions of the coronal electron density have been obtained by several authors [e.g., Baumbach (1937), Allen (1947), van de Hulst (1950; 1953), Saito (1970), Pottasch (1960), Koutchmy (1977), Munro and Jackson (1977), Fisher and Guhathakurta (1995), and Gibson et al. (1999)].

- From the radial gradients of such empirical density profiles $n_e(r)$ coronal electron temperatures $T_e(r)$, have also been determined by using the popular scale-height method (**SHM**) reviewed by van de Hulst (1950). These SHM temperature profiles exhibit a maximum above $h > 0.3R_{\odot}$, *i.e.,* well above the base of the solar corona ($r_{TR} \sim 1.0036R_{\odot}$). The existence of a temperature peak T_{max} invalidates, unfortunately, the application of the SHM method (indeed, the method is based on the implicit assumption that the corona is isothermal, which is not true, and that $n_e(r)$ does not decrease exponentially with r). [Note: $h = r + 1$]

- Two improved methods are proposed to determine $T_e(r)$: the hydrostatic (**HST**) method and the hydrodynamic (**DYN**) method. Unlike the SHM method, these alternative methods are adequate when the corona is actually either in hydrostatic equilibrium or alternatively in hydrodynamic equilibrium. The radial temperature profiles derived by these two other methods tend asymptotically to zero when $r \to \infty$.

- In general: $T_e(r \to \infty) \to 0$; T_{max} value ranges between 1 – 3 MK; the peak of temperature is located at a different h.

SHM method

When a planar atmosphere is in hydrostatic equilibrium, and when the temperature gradient is everywhere equal to zero, the number density of particles is distributed according to an exponential function of the altitude [h]:

$$n(h)/n(h_o) = \exp\left[-(h - h_o)/H)\right]. \quad (1)$$

Here, $n(h_o)$ is the density at a reference altitude [h_o], and H is then the constant density scale height:

$$H = (-\mathrm{d}\ln n/\mathrm{d}h)^{-1} = \mathrm{k}T/\mu \mathrm{m_H} g, \quad (2)$$

where k is the Boltzmann constant; g is the gravitational acceleration: a constant in a planar atmosphere; $\mathrm{m_H}$ is the mass of hydrogen atom; μ is the mean molecular mass of the gas, and T is its constant temperature.

$$n_e(r)/n_e(1) = \exp\left[-(\mathrm{R}_\odot/H_o)(1/r - 1)\right]$$

(spherical symmetry)

$$T_e(r) = \mu \mathrm{m_H} g_o \mathrm{R}_\odot/\mathrm{k}\left[-\mathrm{d}\ln n_e/\mathrm{d}(1/r)\right].$$

HST method

If the corona were in hydrostatic equilibrium, $T_e(r)$ would be the solution of the following equation:

$$\frac{dT_e}{dr} + T_e \frac{d \ln e}{dr} = -\mu \, m_H \, g_0 \, R_\odot \, / \, \mathrm{k} r^2 \qquad \text{(Eq. 8)}$$

To solve this, a first-order ordinary differential equation, a boundary condition has to be given at a reference level $[r_1 : T(r_1) = T_1]$, or for instance $T = 0$ at r = ∞. The SHM temperature is recovered from this equation only when dT_e/dr = 0 at all altitudes, i.e., if the corona were strictly isothermal.

Alfvén (1941) introduced a *constant* normalization temperature T^* and, using a dimensionless temperature variable, $y = T/T^*$, the above equation becomes:

$$\frac{dy}{dr} + y \frac{d \ln e}{dr} = -1/r^2$$

The solution of this first-order differential equation, for which y(r) = 0 when r → ∞ is:

$$y(r) = -[1/n_e] \int_\infty^r [n_e(r')/r'^2] \, dr'$$

DYN method

Since the continuous expansion of the solar corona is a well-established phenomenon, the hydrostatic equation must be replaced by the more general hydrodynamic momentum-transport equation; the inertial force term [$\rho \, \mathrm{d}u/\mathrm{d}t$], must then be added to the kinetic-pressure gradient term in the left-hand-side of Equation (8).

Let us assume that $u(r)$, the radial component of coronal expansion velocity, is stationary, and that the flux of particles is conserved along all plasma flow tubes. The cross-section of these flow tubes is a prescribed function of r that we assume to be the function introduced by Kopp and Holzer (1976) and often adopted to model the geometrical expansion rate of coronal flow tubes. In our study, we will first assume $f_{max} = 1$ in order to simulate radial expansion.

Assumptions

- Let us first ignore the presence of He++ ions.
- Let us also consider that the plasma outward bulk velocity of the electrons [u_e] is equal to the bulk velocities of all ions species [u_i], as generally postulated. This implies that there is no net electric current in the radial direction, and no diffusion of particle species with respect to each other.
- Based on these usual restrictive conditions, the plasma can be treated as a single fluid whose bulk velocity [$u(r) = u_e = u_i$] is a solution of the single-fluid-mass and momentum-transport equations
- Both the electron and the ion temperatures vary with r, but we will assume that their ratio [$T_p/T_e = \tau_p$] is independent of r. In a first set of calculations, it is assumed that $\tau_p = 1$.
- Furthermore, the kinetic-pressure tensors of the coronal electrons and ions will be assumed to be isotropic. This implies that their velocity distribution functions (VDF) are isotropic in the frame of reference co-moving with the bulk speed [$u(r)$].

Ignoring recombination processes, the steady-state distribution of $\mathrm{u}(r)$ can be obtained from the given empirical density profile $[n_e(r)]$, and the equation of conservation of mass flow:

$$u(r) = u_E\ [A_E/A(r)][n_E/n_e(r)]$$

where A_E, u_E, and n_E are, respectively, the cross-section of flow tubes, the solar-wind bulk velocity, and density at 1 AU.

The hydrodynamic momentum equation to be solved is derived in the Appendix of the paper and is:

$$\frac{dy}{dr} + y\,\frac{d\ln n_e}{dr} = -1\,/\,r^2\,[1 + F(r)] \qquad \text{(Eq. 14)}$$

where $F(r)$ is the ratio between the "inertial force" and the "gravitational force":

$$F(r) = r^2 u\left(\frac{du}{dr}\right)/g_0 R_\odot$$

Note that $F(r \to \infty) = 0$ for all well-behaved distributions of $\mathrm{u}(r)$ when $r \to \infty$.

The solutions of the first-order differential Equation (14) depend on the initial condition taken at some reference level: $r = r_b$.

We introduce here a different procedure providing directly the unique regular solution of Equation (14) that tends asymptotically to $y = 0$ for $r \to \infty$.

$$y(r) = T(r)/T^* = -[1/n_e] \int_{\infty}^{r} [n_e(r')/r'^2] [1 + F(r')] dr'$$

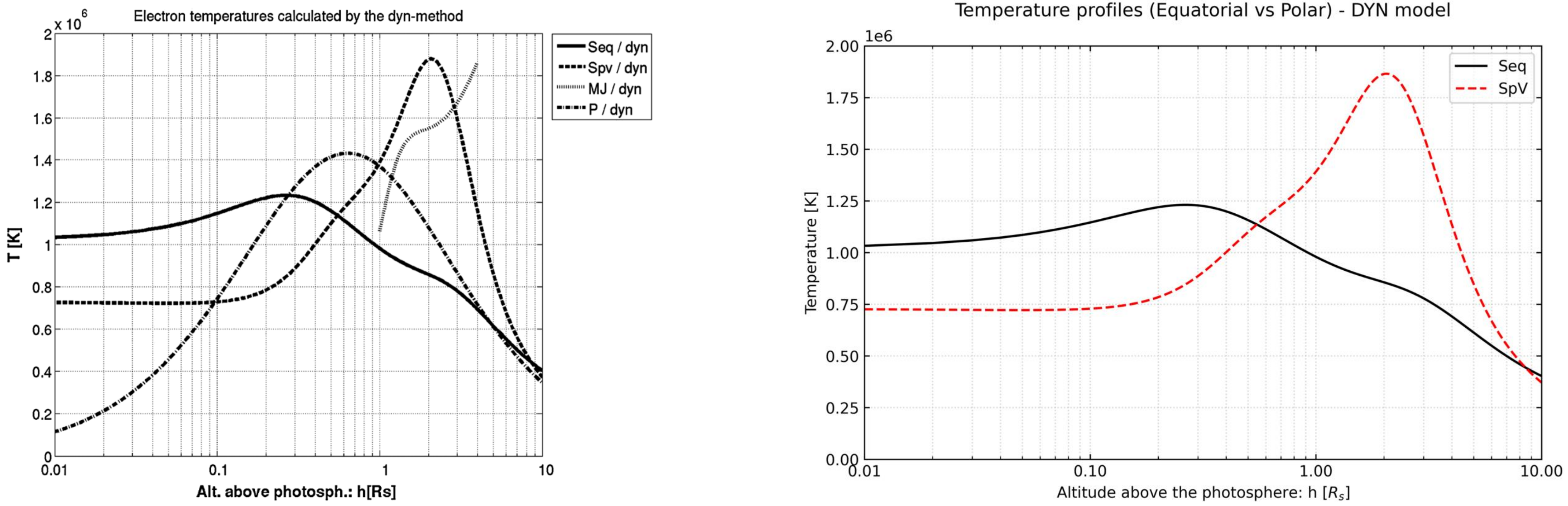
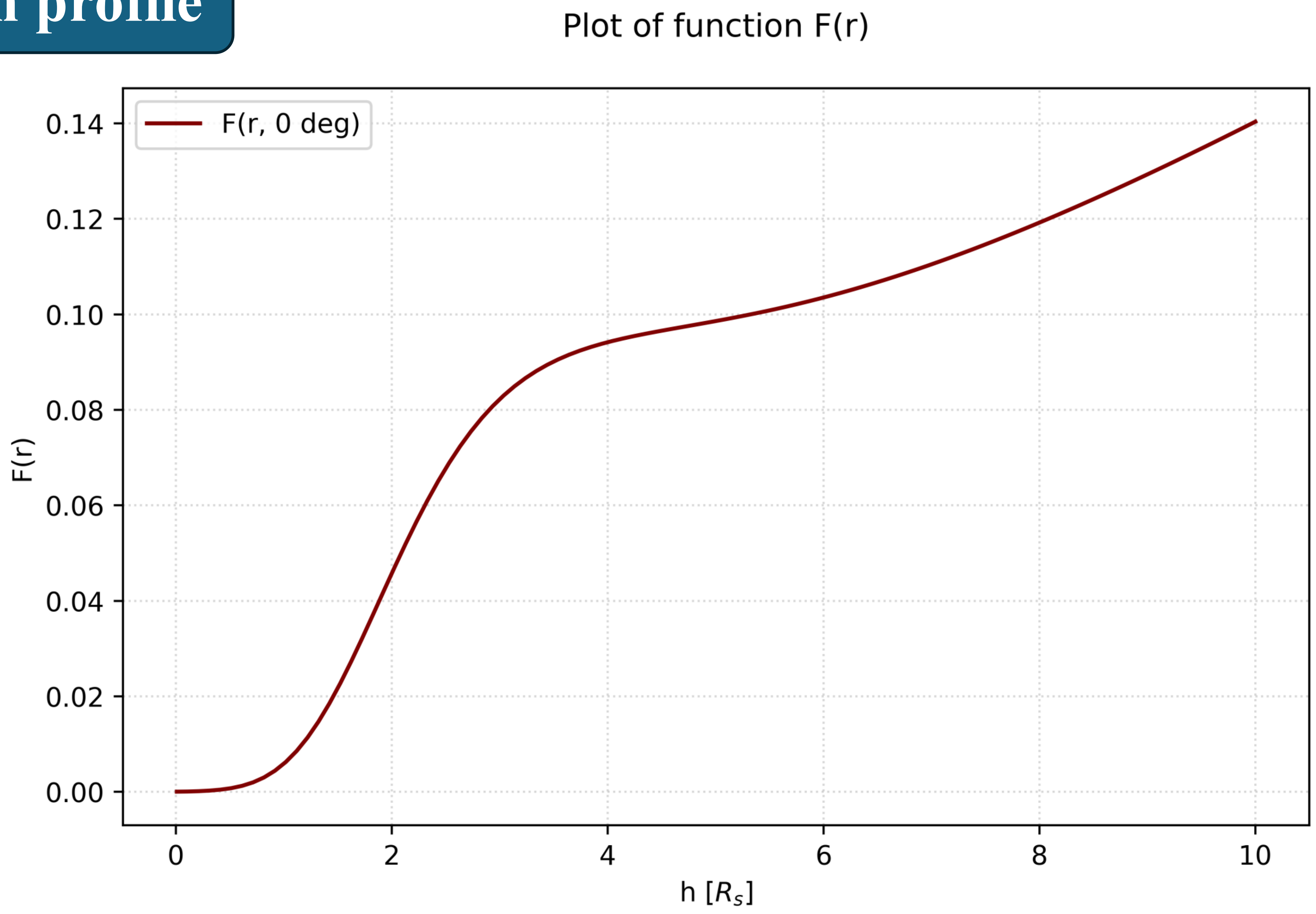
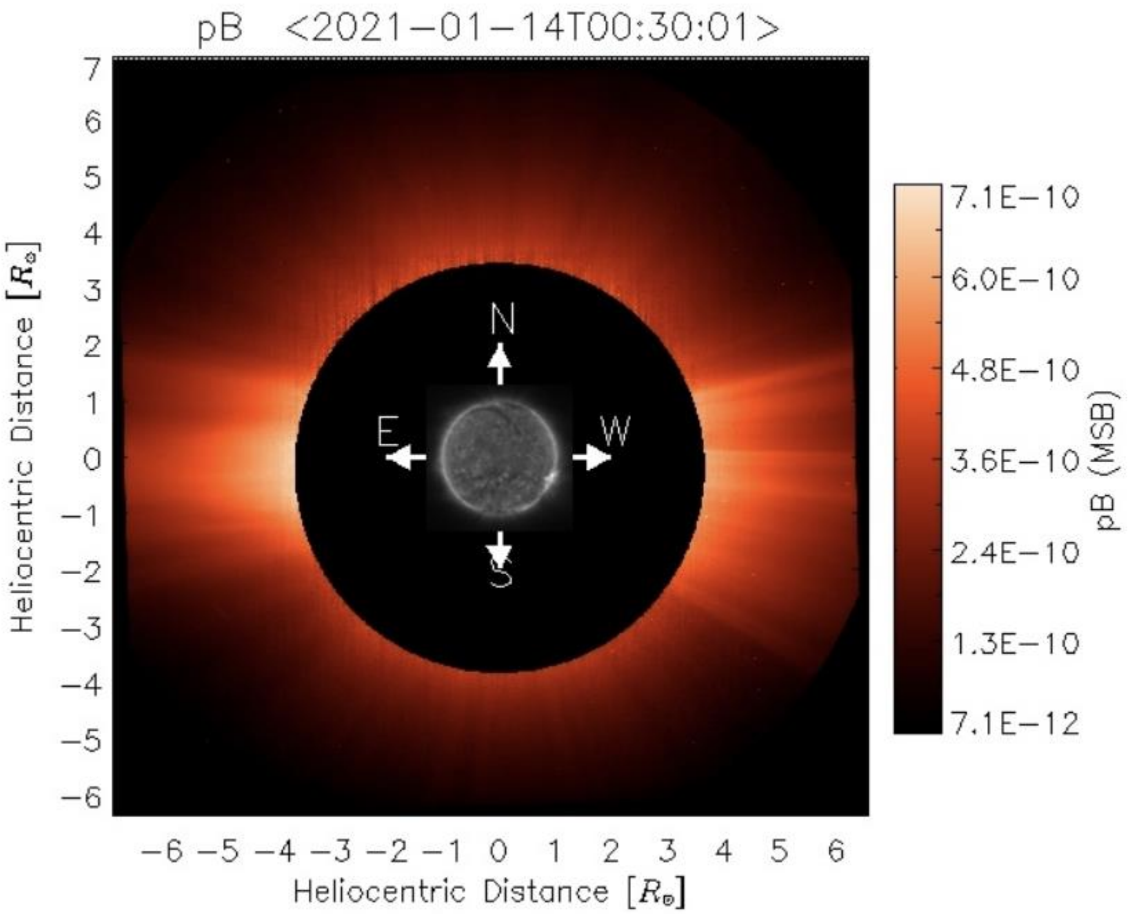


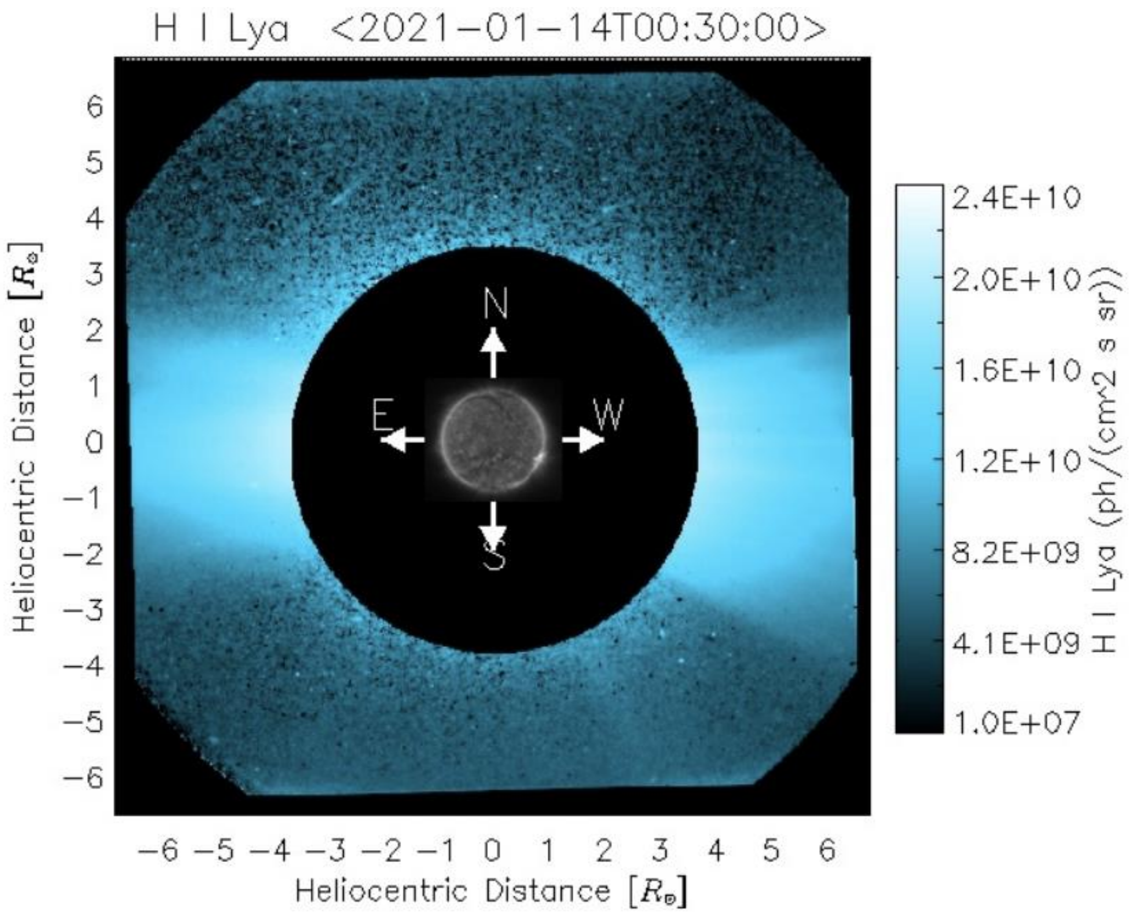
Figure 4 Coronal electron-temperature distributions calculated using the DYN method (Equation (16)). The input parameters for the electron-density models (Seq; Spv; MJ; P) are listed in Table 1. The calculated temperature maximum [$T'_{\max}$], altitude [$h'_{\max}$], and half-width range [Δr] are given in Table 2 for each case. The values of $T'_{\max}$ obtained using the DYN method are not equal to those obtained using the HST method unless solar-wind expansion velocity at 1 AU is smaller than 150 km s^{-1}. In addition, the altitude of the temperature peaks [$h'_{\max}$] determined using the DYN method are higher up in the corona than those obtained using the HST method (see Table 2). Consequently, the DYN method must be used instead of the HST method to determine the altitudes where the maximum energy is deposited to heat the coronal plasma.

F function profile

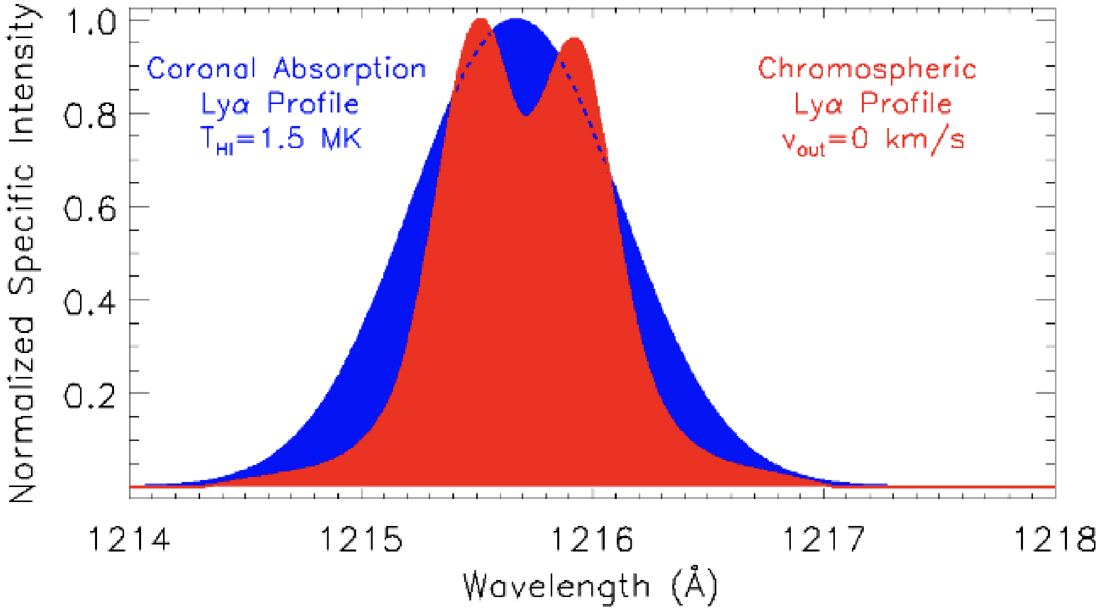


Data from Giordano+ 2025

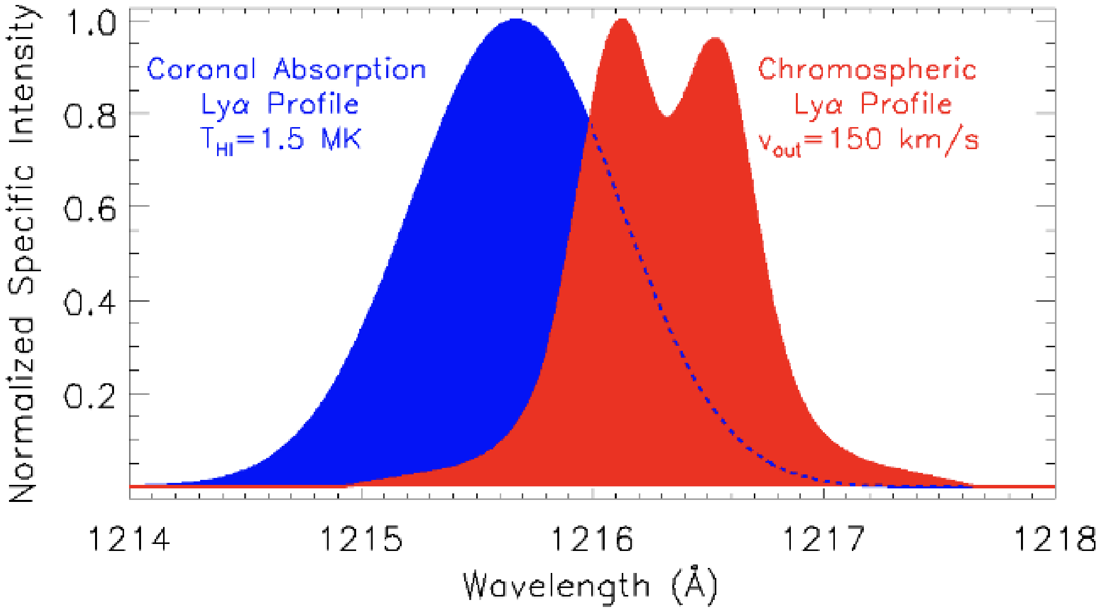




About DDT



Coronal Absorption
Lyα Profile
T_HI=1.5 MK
Chromospheric
Lyα Profile
v_out=0 km/s
Normalized Specific Intensity
Wavelength (Å)
1214
1215
1216
1217
1218



Coronal Absorption
Lyα Profile
T_HI=1.5 MK
Chromospheric
Lyα Profile
v_out=150 km/s
Normalized Specific Intensity
Wavelength (Å)
1214
1215
1216
1217
1218

About Expansion Factor f

Following Kopp and Holzer (1976), it has become a common practice to approximate $A(r)$ by an exponential function of r:

$$\begin{aligned} A(r)/A(1) &= r^2 f(r) \\ &= r^2\{f_{\max}\exp[(r-r_1)/\sigma]+f_1\}/\{\exp[(r-r_1)/\sigma]+1\}, \end{aligned}$$

where $f_1 = 1 + (1 - f_{\max})\exp[(1-r_1)/\sigma]$; where $f_{\max}$ is the total geometrical expansion rate, r_1 is the heliocentric distance of most rapid geometrical expansion, and σ is the range over which this takes place in the corona. When $f_{\max} = 1$, then $f(r) \equiv 1$ and the radial expansion is then recovered, as in early hydrodynamic and kinetic models of the solar wind.

About $T_p/T_e = \tau_p = 1$

$u(r) = u_E\,[A_E/A(r)][n_E/n_e(r)]$ (Eq. 18)

When the average bulk velocities of the electrons and ions are all equal to u, and they are determined by Equation (18), the radial component of the steady-state momentum-transport equations for electrons, protons, and α-particles are, respectively,

$$n_e m_e u\,du/dr + dp_e/dr = -n_e m_e g - n_e e E, \tag{20}$$

$$n_p m_H u\,du/dr + dp_p/dr = -n_p m_H g + n_p e E, \tag{21}$$

$$4n_\alpha m_H u\,du/dr + dp_\alpha/dr = -4n_\alpha m_H g + 2n_\alpha e E, \tag{22}$$

About $T_p/T_e = \tau_p = 1$

Concatenation of Equations (20), (21), and (22) leads to the familiar (single-fluid) hydrodynamic momentum equation adopted in hydrodynamic models,

$$\rho u \mathrm{d}u/\mathrm{d}r + \mathrm{d}p/\mathrm{d}r = \rho g. \tag{23}$$

In Equation (23), the total kinetic pressure $[\Sigma_j p_j = \Sigma_j n_j \mathrm{k} T_j]$ is given by $p = p_\mathrm{e} + p_\mathrm{p} + p_\alpha = \nu_\mathrm{p} n_\mathrm{e} \mathrm{k} T_\mathrm{e}$ where

$$\nu_\mathrm{p} = (1 + 2\alpha + \tau_\mathrm{p} + \alpha \tau_\alpha)/(1 + 2\alpha) \tag{25}$$

Further generalizations of Equation (30) can be envisaged by assuming anisotropic pressures and temperatures for the coronal ions and electrons, as well as non-uniform distributions for the relative concentrations of the minor ions $[\alpha = n_\alpha(r)/n_\mathrm{p}(r)]$ or of the temperature ratios $[\tau_{\mathrm{p}(\alpha)} = T_{\mathrm{p}(\alpha)}/T_\mathrm{e}]$.

DYN method scheme

- Metis (Inner FoV_{min}: 1.7 $R_\odot$)
- ASPIICS (Inner FoV_{min}: 1.09 $R_\odot$)

Electron density [n_e]

- Metis (Inner FoV_{min}: 1.7 $R_\odot$)

SW bulk velocity [$u(r) = u_e = u_i$] → see: Abbo+2016

DYN model

$$T_e = -\frac{T^*}{n_e(r)} \int_\infty^r \frac{n_e(r)}{r^2} [1 + F(r)] \, dr$$

$$F(r) = r^2 u (du/dr)/g_o R_\odot$$

Temperature $T_e(r)$

About Vasquez profile

A pressure balance is considered between the tube and the ambient (Vekstein & Katsukawa 2000).

$$\underbrace{-\nabla\left(p + \frac{B^2}{8\pi}\right)}_{\text{The gradient of total pressure}} + \underbrace{\frac{1}{4\pi}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}}_{\text{The magnetic tension}} = 0. \quad (2)$$

The vertical flux tubes are assumed not to be curved and thus do not have magnetic tension (neglecting the second term of the Equation (2)). Then, the pressure balance requirement is

$$2Nk_BT = \frac{B^2}{8\pi} \quad (3)$$

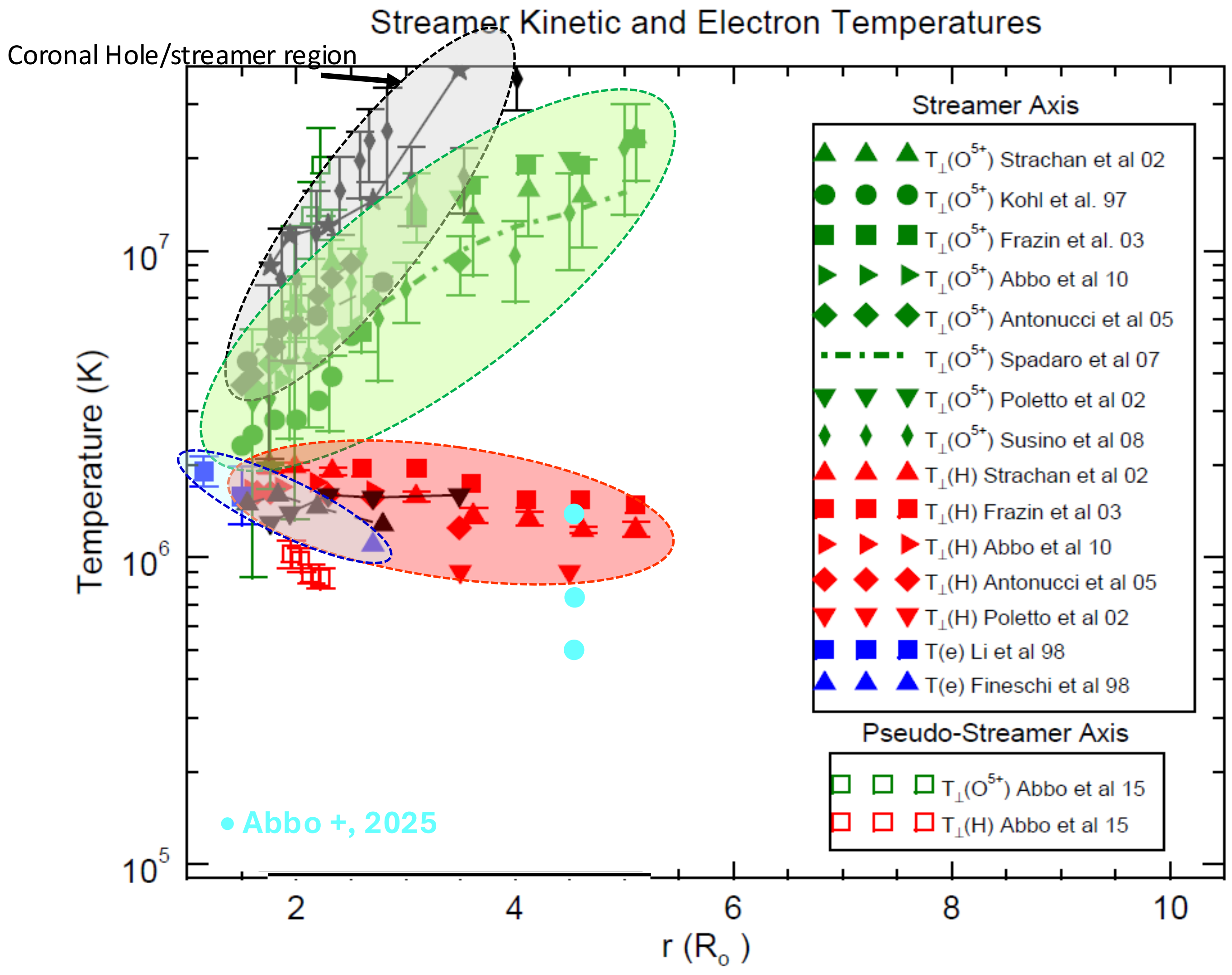
where $N\,[\mathrm{cm}^{-3}]$ is the electron density, $k_B\,[\mathrm{erg\,K}^{-1}]$ is the Boltzmann constant, $T\,[\mathrm{K}]$ is the temperature, and $B\,[\mathrm{G}]$ is the magnetic field. Also, the plasma β ($\approx 8\pi NK_BT/B^2$) from the Equation (3), is assumed to be small enough for the plasma to be effectively confined by the magnetic field (Emslie & Brown 1980).

Then, considering the magnetic field:

$$B(r, \theta, \phi) = \sqrt{((B_r(r, \theta, \phi))^2 + (B_\phi(r, \theta, \phi))^2 + (B_\theta(r, \theta, \phi))^2)} \quad (4)$$

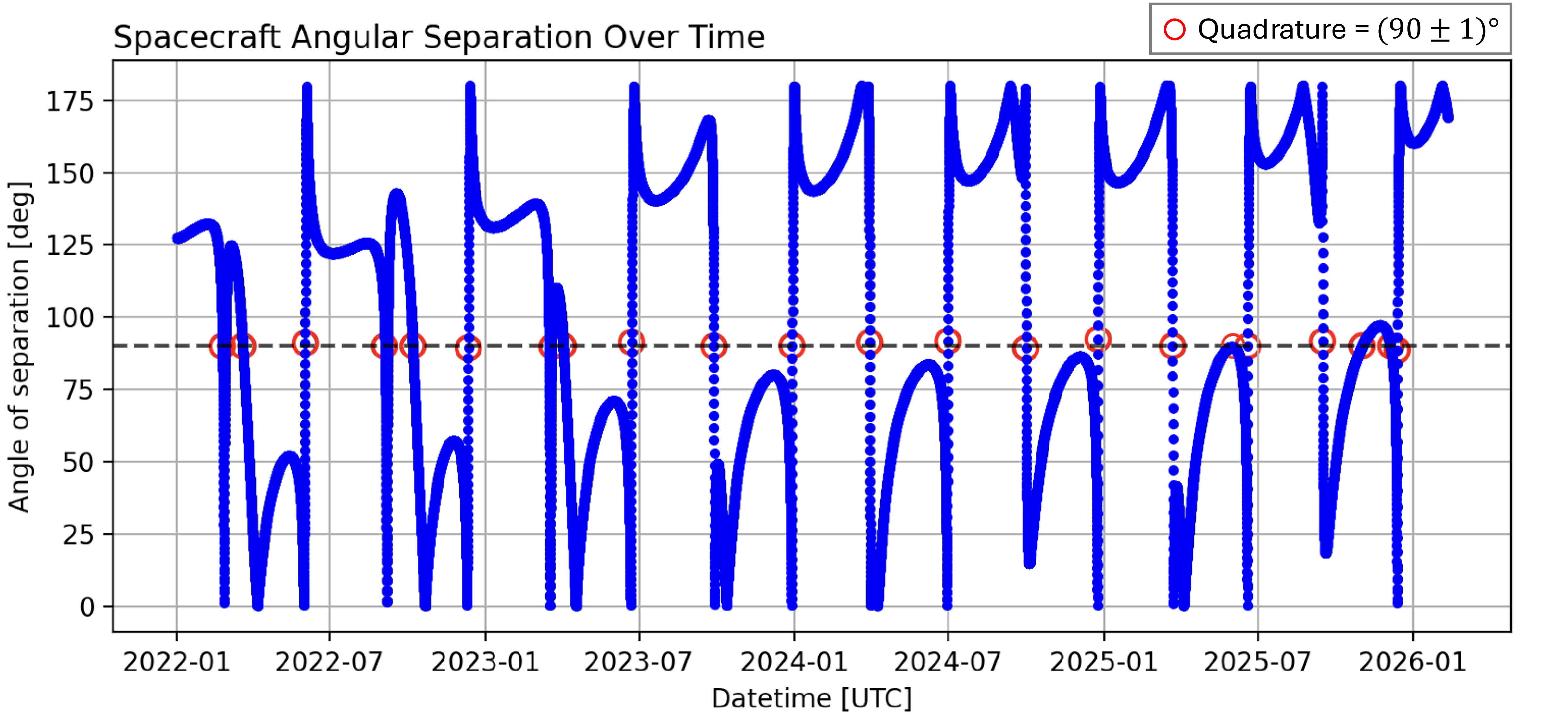
where $B_r(r, \theta, \phi)$, $B_\phi(r, \theta, \phi)$, and $B_\theta(r, \theta, \phi)$ are the magnetic field components from PFSS. The magnetic field B is measured in [G] units. We consider $B(r, \theta, \phi) = B$ in the following description.

T_e results from Metis and comparison with literature

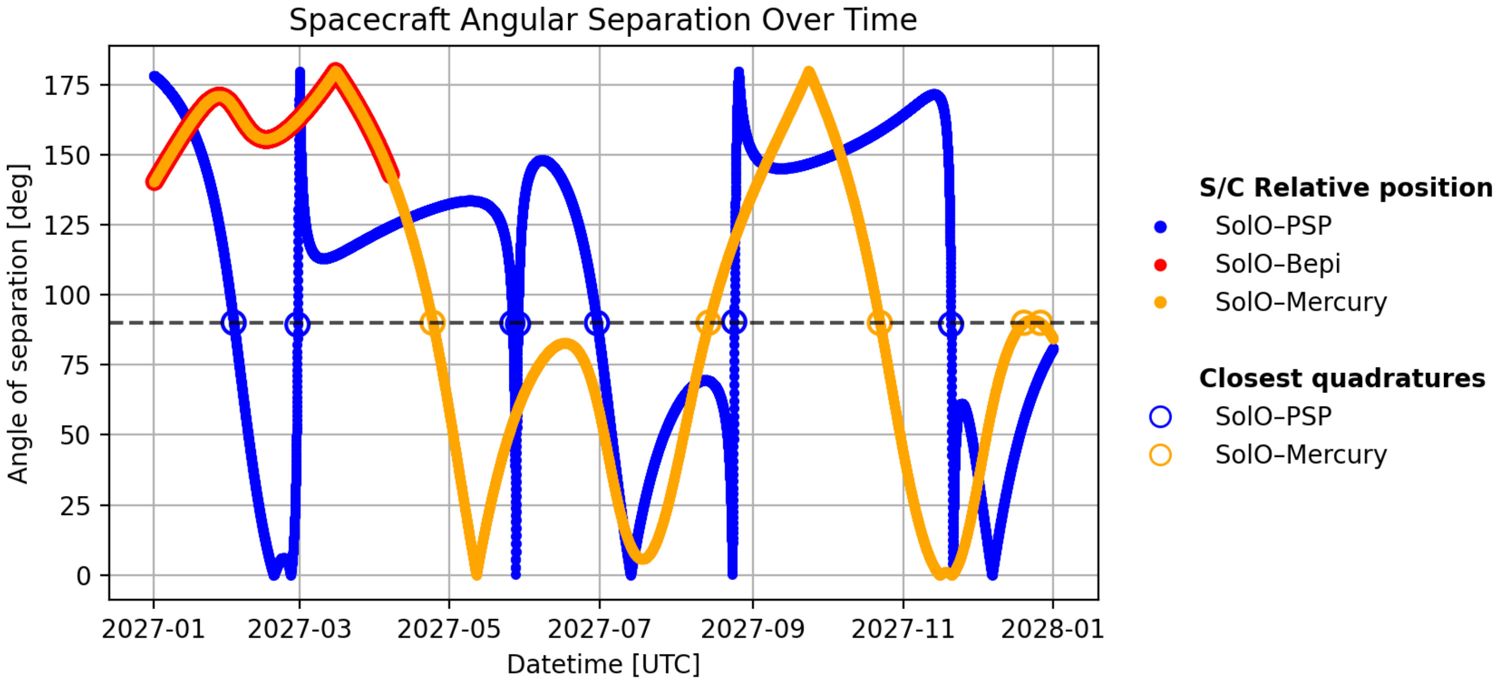


Abbo+ 2016, SSRv, Fig.3 adapted

SolO-PSP quadratures 2022-2026



Quadrature between Spacecraft 2027

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SolO–PSP quadrature events:
```

	datetime	angle_solo_psp	delta_90
1	2027-02-02 08:30:00.021	90.030	0.030
2	2027-02-28 06:00:00.037	89.361	0.639
3	2027-05-26 11:00:00.094	89.912	0.088
4	2027-05-28 17:30:00.095	89.602	0.398
5	2027-06-29 18:30:00.116	89.953	0.047
6	2027-08-24 11:00:00.152	90.365	0.365
7	2027-11-20 10:00:00.208	89.437	0.563

```
SolO–Mercury quadrature events:
```

	datetime	angle_solo_bepi	delta_90
1	2027-04-24 01:59:59.964	90.035	0.035
2	2027-08-14 00:59:59.928	90.011	0.011
3	2027-10-22 12:59:59.905	89.977	0.023
4	2027-12-19 23:59:59.886	90.013	0.013
5	2027-12-26 15:59:59.884	90.002	0.002

Quadrature between Spacecraft - overview

Quadrature Events with Full Info - SkyCoord (lon, lat, dist) in Heliographic Stonyhurst (deg, deg, AU)

SolO - PSP

#	datetime	angle_solo_psp	delta_90	solo_lon	solo_lat	solo_dist	psp_lon	psp_lat	psp_dist	Δt (days hh:mm:ss)
1	2027-02-02 08:30:00	90.030	0.030	113.021	-20.079	0.299	-156.949	3.808	0.648	0 days 00:00:00
2	2027-02-28 06:00:00	89.361	0.639	-131.366	23.455	0.500	-42.004	-2.581	0.048	25 days 21:30:00
3	2027-05-26 11:00:00	89.912	0.088	-111.522	-4.514	0.699	158.566	2.034	0.105	87 days 05:00:00
4	2027-05-28 17:30:00	89.602	0.398	-110.874	-5.703	0.681	-21.272	-1.899	0.075	2 days 06:30:00
5	2027-06-29 18:30:00	89.953	0.047	-48.462	-22.714	0.320	41.491	3.460	0.699	32 days 01:00:00
6	2027-08-24 11:00:00	90.365	0.365	104.436	17.865	0.749	-165.198	-3.858	0.047	55 days 16:30:00
7	2027-11-20 10:00:00	89.437	0.563	137.16	-22.506	0.394	47.723	-1.947	0.051	87 days 23:00:00

SolO - Mercury

#	datetime	angle_solo_bepi	delta_90	solo_lon	solo_lat	solo_dist	bepi_lon	bepi_lat	bepi_dist	Δt (days hh:mm:ss)
1	2027-04-24 02:00:00	90.035	0.035	-111.845	8.89	0.823	158.12	2.336	0.342	0 days 00:00:00
2	2027-08-14 01:00:00	90.011	0.011	101.052	20.891	0.676	-168.936	-0.208	0.351	111 days 23:00:00
3	2027-10-22 13:00:00	89.977	0.023	103.579	-4.149	0.704	13.602	3.259	0.317	69 days 12:00:00
4	2027-12-20 00:00:00	90.013	0.013	-75.018	22.212	0.438	-165.031	-2.424	0.456	58 days 11:00:00
5	2027-12-26 16:00:00	90.002	0.002	-61.662	23.538	0.522	-151.663	-1.464	0.434	6 days 16:00:00

BackUp End