Kinetic modeling of interstellar hydrogen and backscattered Ly-α emission

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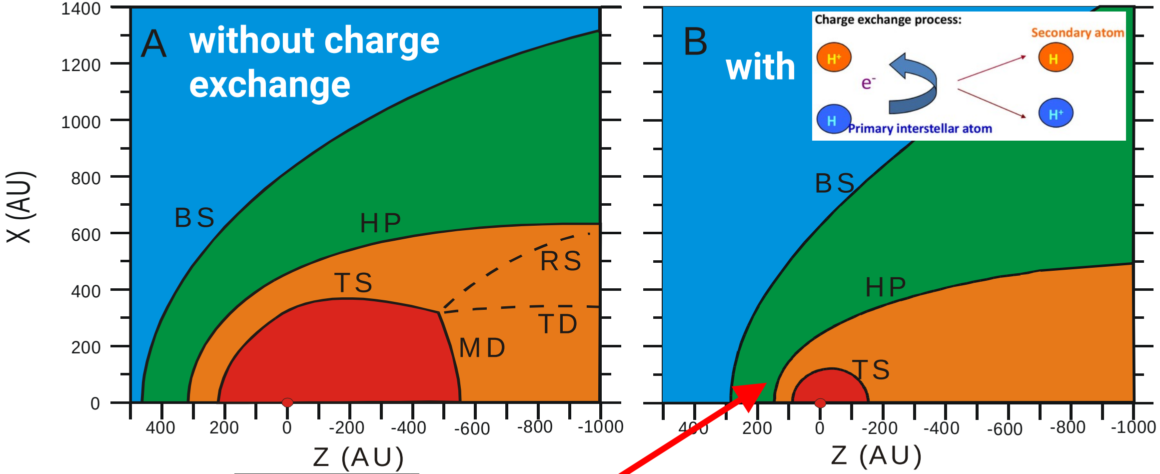
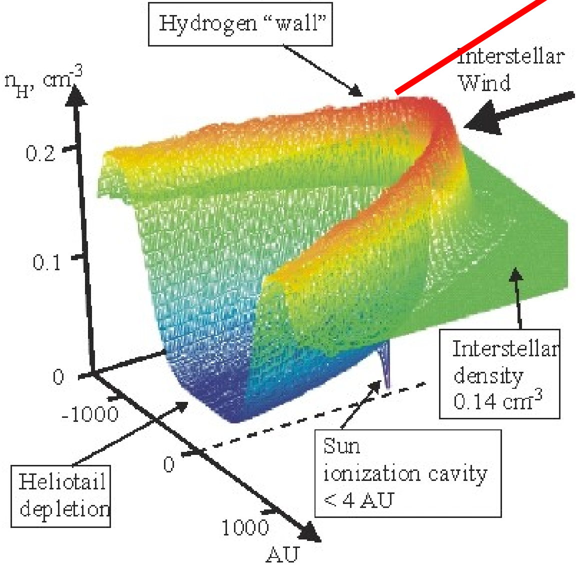
"H wall" is a manifestation of the charge exchange effect

Izmodenov (2000)



$$H + H^+ \leftrightharpoons H^+ + H$$

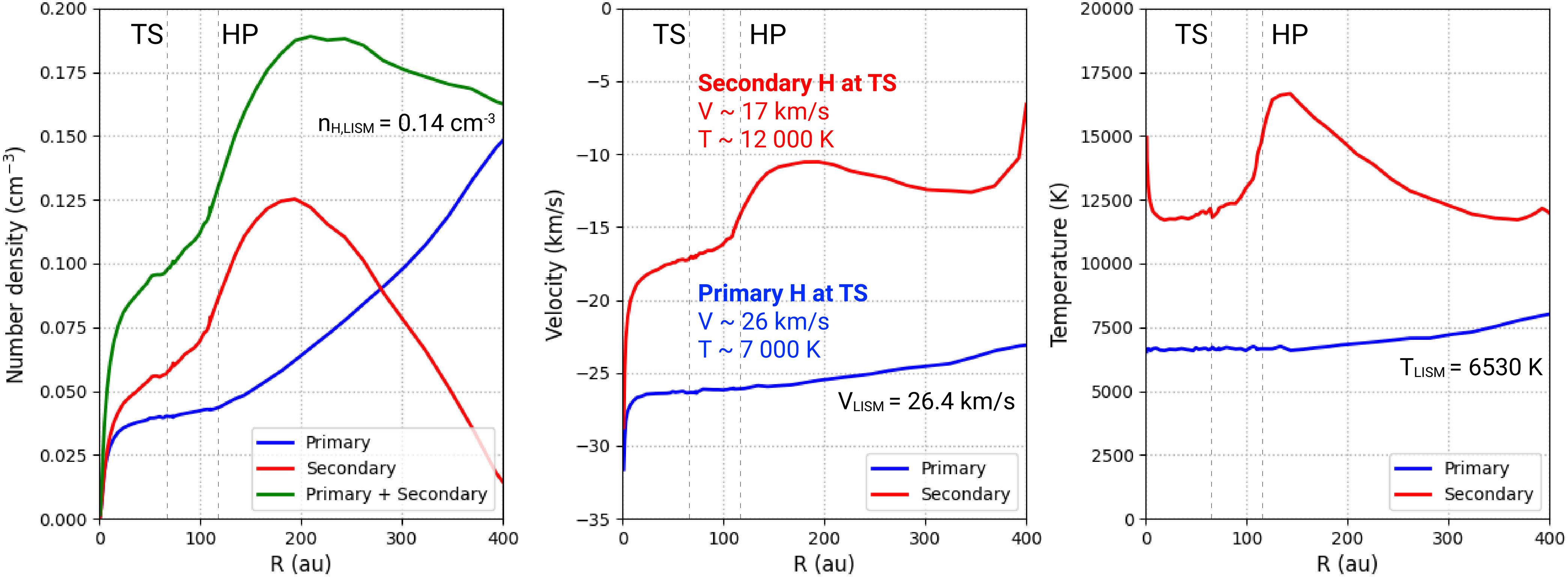
- Charge exchange provides exchange of **momentum and energy** between plasma and neutral components.
- It is very important dynamically.



Gruntman et al. (2001, JGR)

- "H wall" is a **moderate** (by factor of 2 or less) increase of the number density of interstellar H atoms in the vicinity of the heliopause.
- "H wall" consists of the **secondary** interstellar atoms that originated in the vicinity of the heliopause by charge exchange with decelerated and heated protons.
- **First time** the H wall was **predicted theoretically** by *Baranov, Lebedev, Malama (1991, ApJ)*. The **first self-consistent model**: *Baranov and Malama (1993, JGR)*.

Hydrogen parameters in the upwind direction



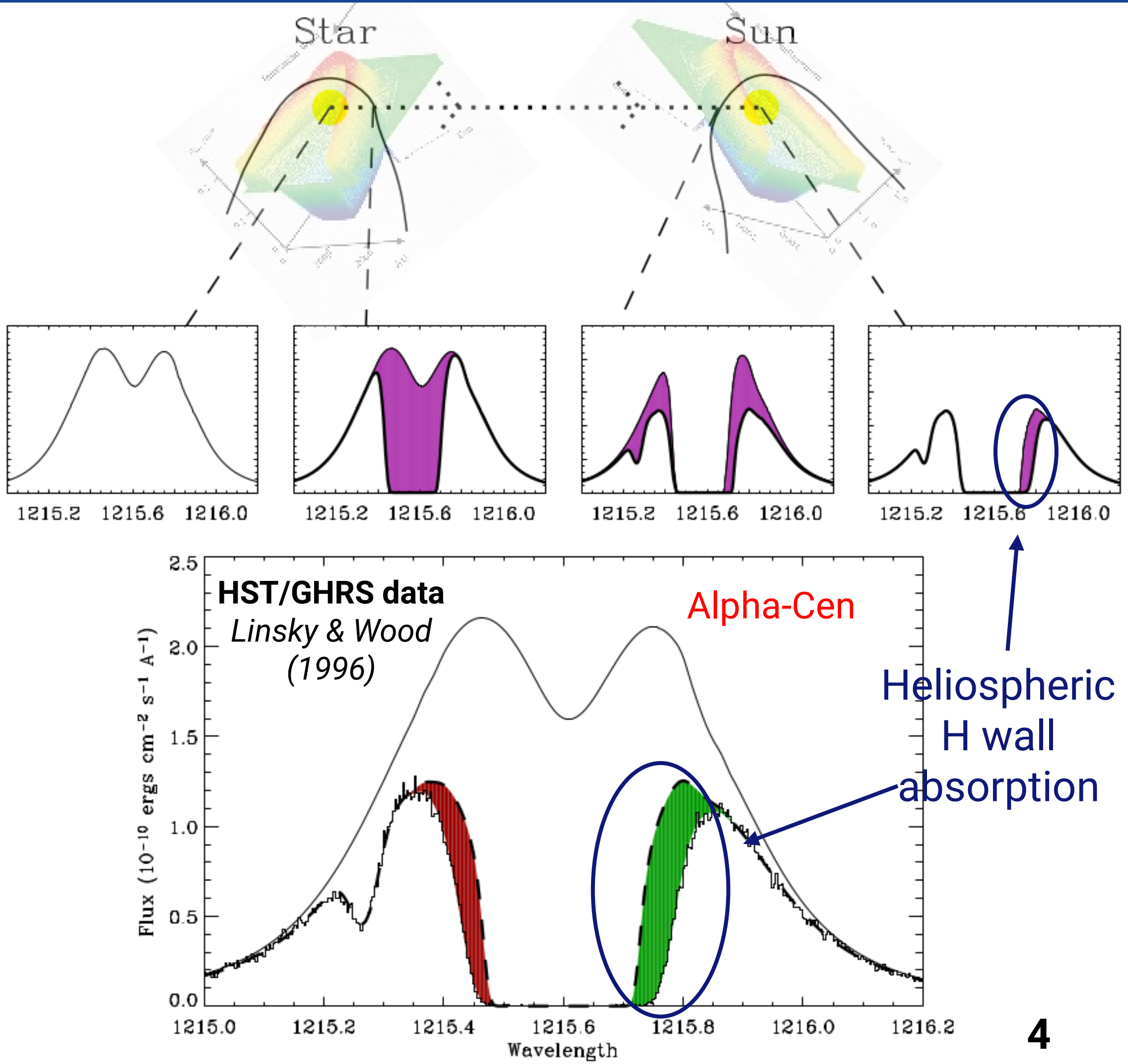
Secondary interstellar atoms are **slower** and **hotter** as compared with the primary interstellar component.

Model by Izmodenov & Alexashov (2020)

Observational proof of the H wall

- Secondary interstellar atoms are seen in absorption spectra towards nearby stars!

- H wall was discovered by *Linsky and Wood (1996, ApJ)* in **Ly-α absorption spectra** observed using HST/GHRS toward Alpha-Cen. It was confirmed by many other HST observations.

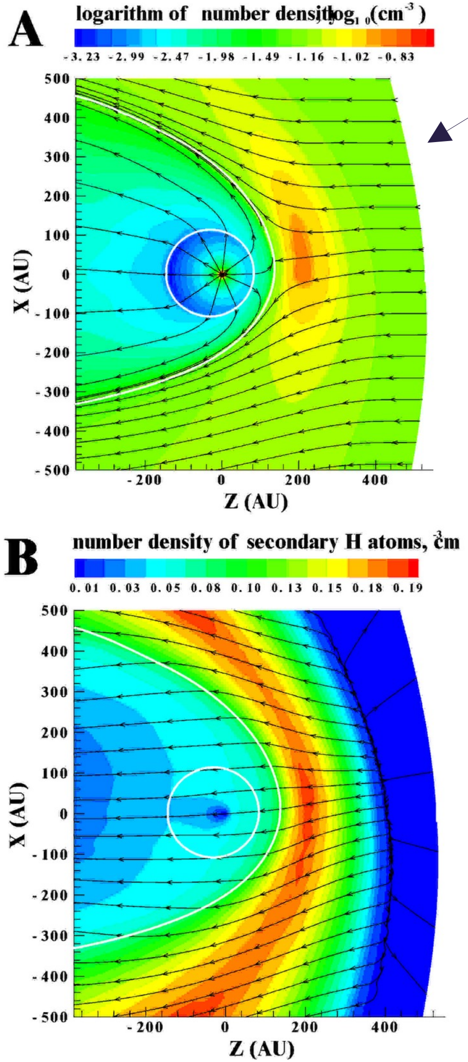


HST/GHRS data
Linsky & Wood (1996)

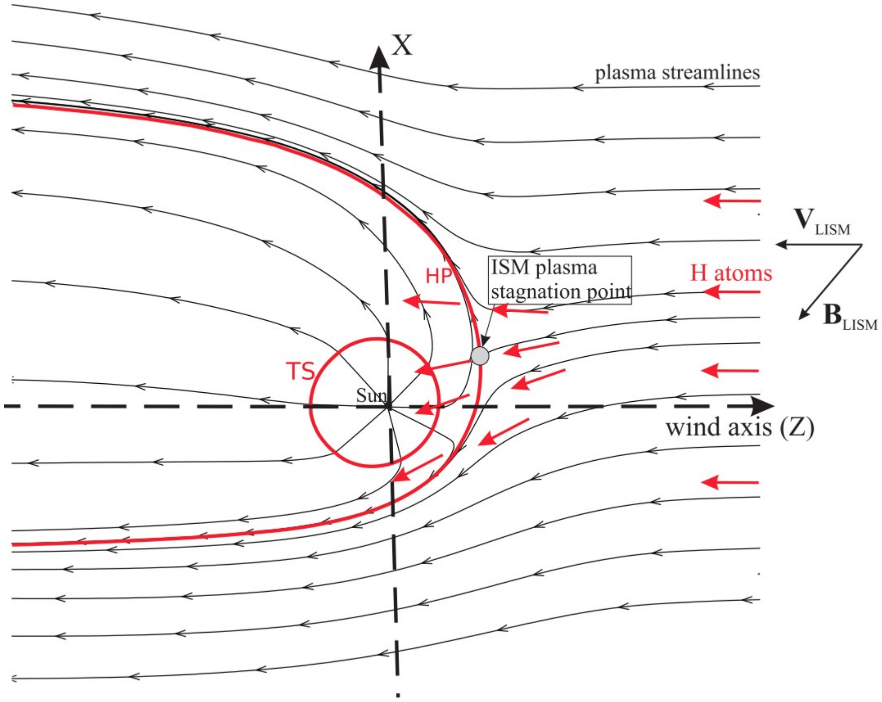
Alpha-Cen

Heliospheric H wall absorption

Effect of the interstellar magnetic field on the “H wall”



Izmodenov et al. (2005, A&A) – the first self-consistent global model of SW/LISM interaction with the interstellar magnetic field taken into account



Katushkina et al. (2015)

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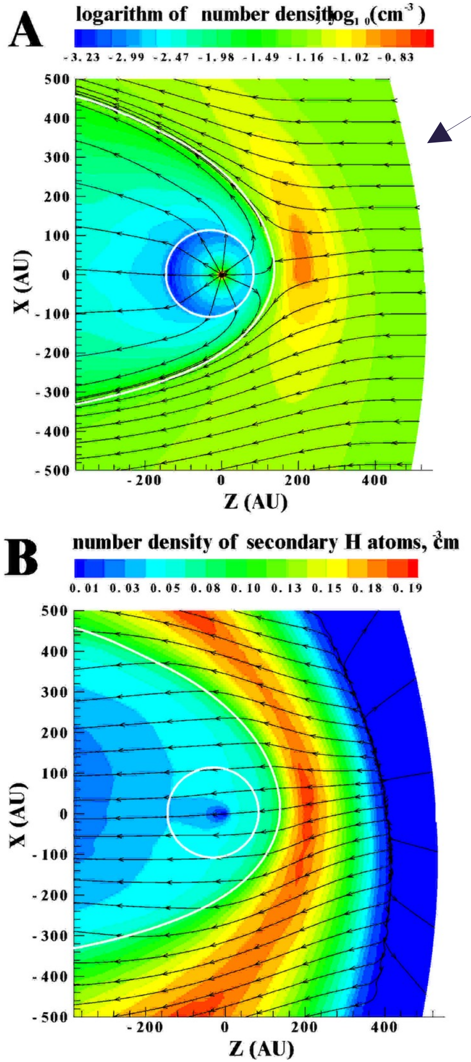

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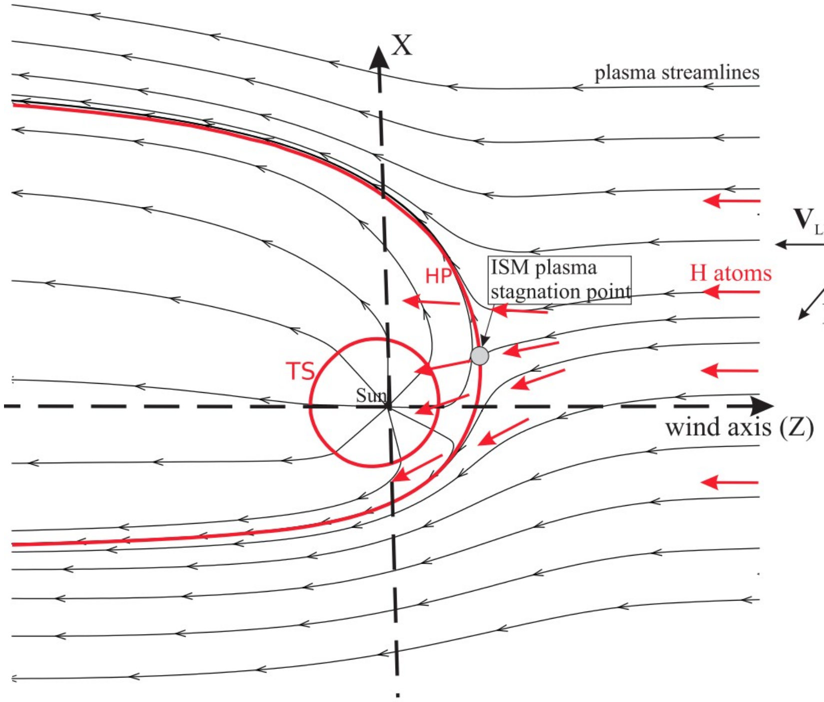

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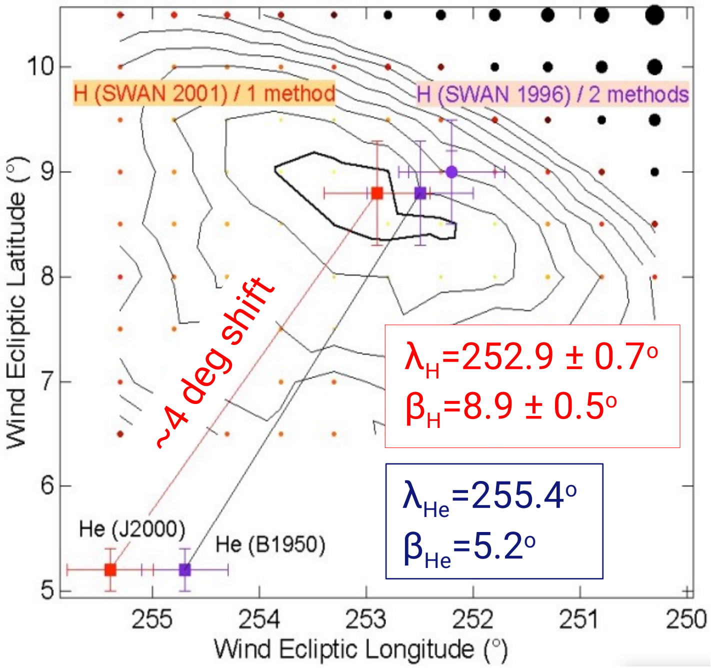


$\lambda_H = 252.9 \pm 0.7^o$
$\beta_H = 8.9 \pm 0.5^o$

$\lambda_{He} = 255.4^o$
$\beta_{He} = 5.2^o$

Lallement et al. (2005, Science), 2010

Kinetic modeling of H atoms

Difficulty in the modeling of the interstellar hydrogen is the large mean free path (Kn~1).

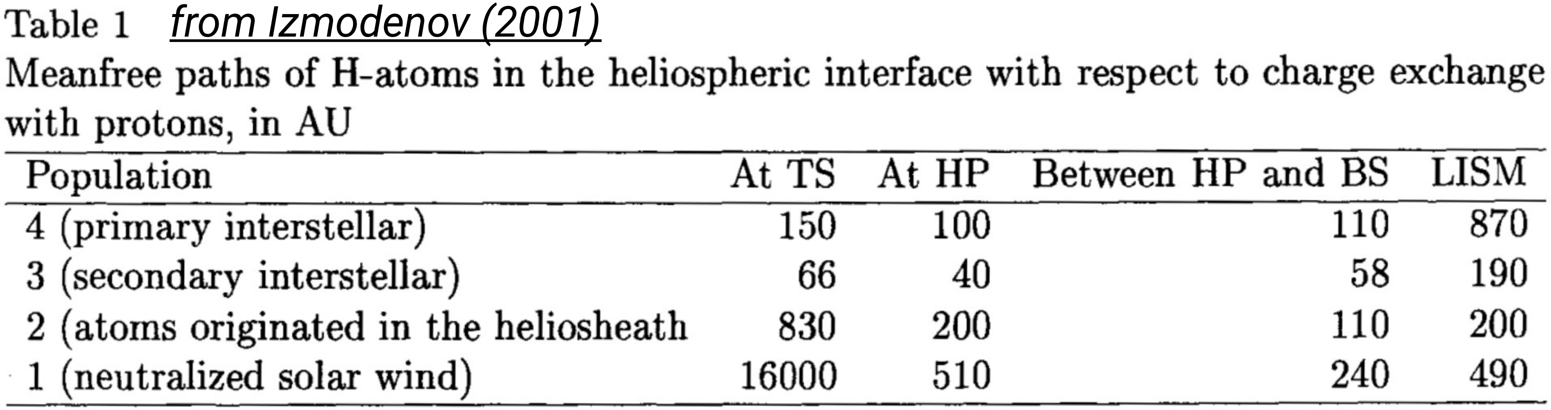


Table 1 *from Izmodenov (2001)*

Meanfree paths of H-atoms in the heliospheric interface with respect to charge exchange with protons, in AU

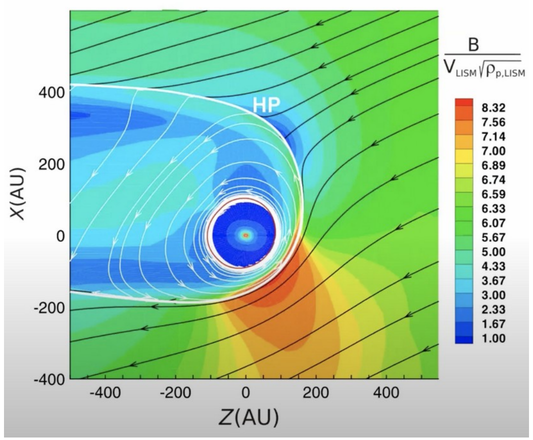
Population	At TS	At HP	Between HP and BS	LISM
4 (primary interstellar)	150	100	110	870
3 (secondary interstellar)	66	40	58	190
2 (atoms originated in the heliosheath	830	200	110	200
1 (neutralized solar wind)	16000	510	240	490

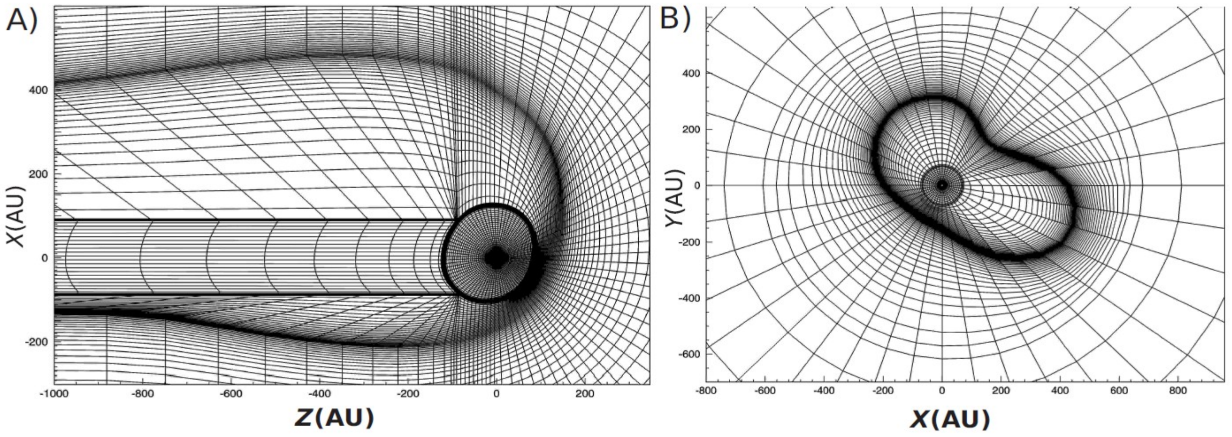
(minimum) Requirements for the SW/LISM interaction models:

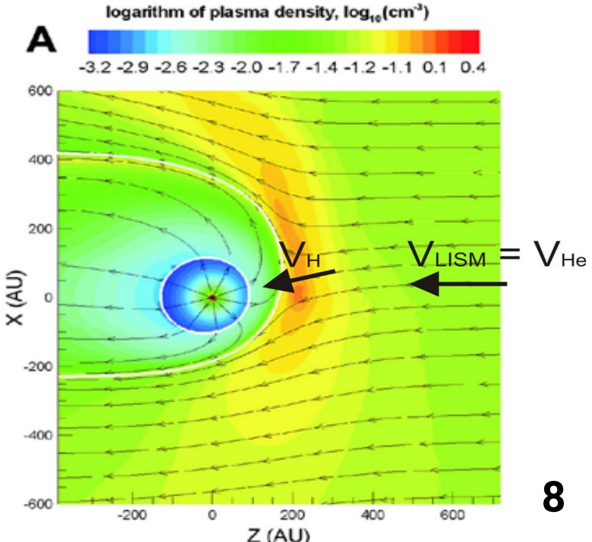
- Kinetic equation for interstellar neutral component – collision integral depends on the plasma parameters.
- MHD equations for plasma component – right parts of the momentum and energy equations are the integrals of the H velocity distribution function.
- Kinetic and MHD equations should be solved self-consistently.

Overview of the latest version of Moscow model of the SW/LISM interaction [Izmodenov & Alexashov 2015, 2020, 2023]

- Plasma component (protons, electrons, solar α-particles):
  ideal MHD (3D + time) + sources of momentum and energy due to charge exchange: $H + H^+ \rightarrow H^+ + H$
- Neutral component (interstellar hydrogen):
  kinetic equation taking into account charge-exchange (Kn ~ 1)
  (Monte Carlo method with splitting of trajectories)
- Magnetic field – heliospheric and interstellar (frozen into plasma component)
- Heliolatitudinal and non-stationary behavior of the solar wind
- Additional components: α-particles, minor interstellar components (He, He^+, O)
- Electron thermal conduction in the inner heliosheath





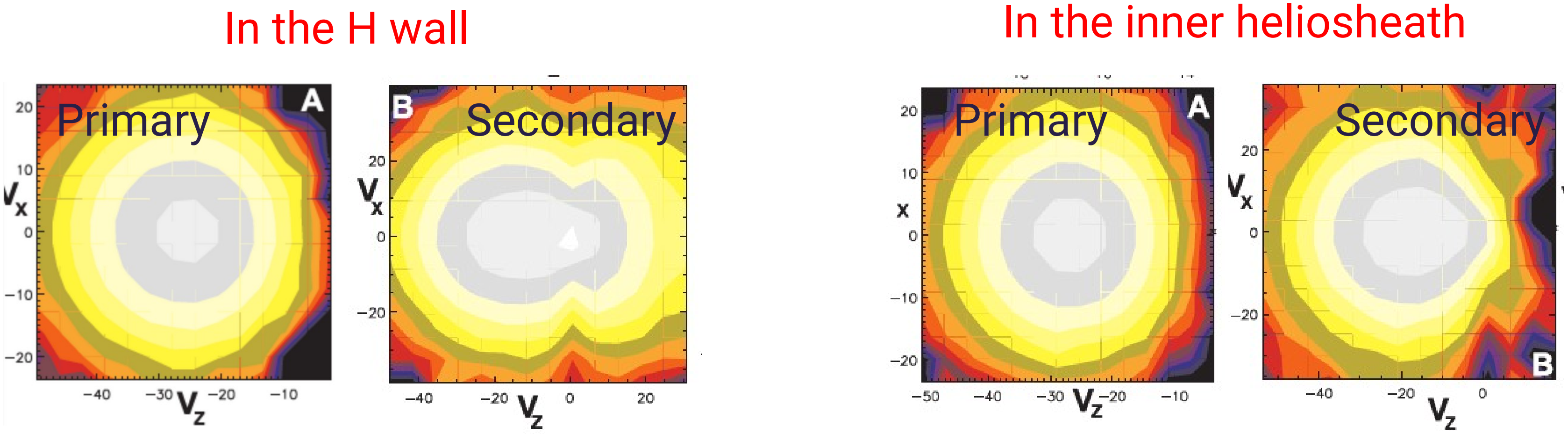


3D time-dependent local kinetic model of the H atoms distribution inside the heliosphere

Hydrogen distribution in the heliosphere is effected by:

1. Global effects: distribution function of H atoms is distorted in the heliospheric interface due to charge exchange → **distribution function is not Maxwellian** (Izmodenov et al. 2001).

Velocity distribution of primary and secondary interstellar atoms



In the H wall

In the inner heliosheath

Izmodenov, Gruntman, Malama (2001, JGR)

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2. Local effects are important near the Sun (solar gravitation F_g, radiation F_{rad} and ionization β_E). **Model is 3D and time-depended** due to detailed description of these effects.

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Kinetic equation:

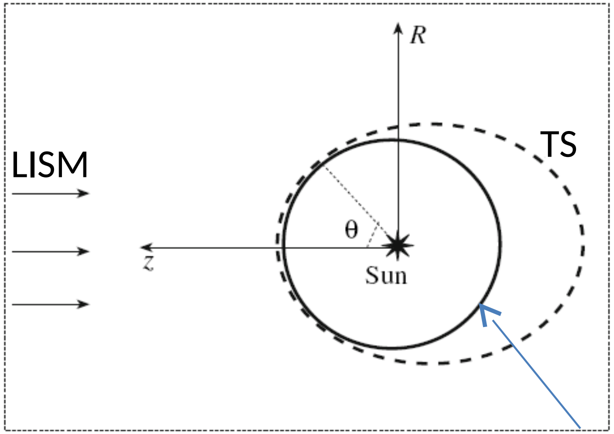
$$\boxed{\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial t}+\mathbf{w}\cdot\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial \mathbf{r}}+\mathbf{F}(r,\lambda,v_r,t)\cdot\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial \mathbf{w}}=-\beta(r,\lambda,t)\cdot f(\mathbf{r},\mathbf{w},t)}$$

$$\boldsymbol{F}=\boldsymbol{F}_g+\boldsymbol{F}_{rad}=-\frac{G\cdot M_s\cdot(1-\mu)}{r^2}\cdot\frac{\boldsymbol{r}}{r}$$, where $\mu = |\boldsymbol{F}_{rad}|/|\boldsymbol{F}_g| = \mu(t, \lambda, v_r)$

μ is taken from the analysis of disk-integrated solar Ly-α line profiles from SUMER/SOHO by Kowalska-Leszczynska et al. (2018, 2020).

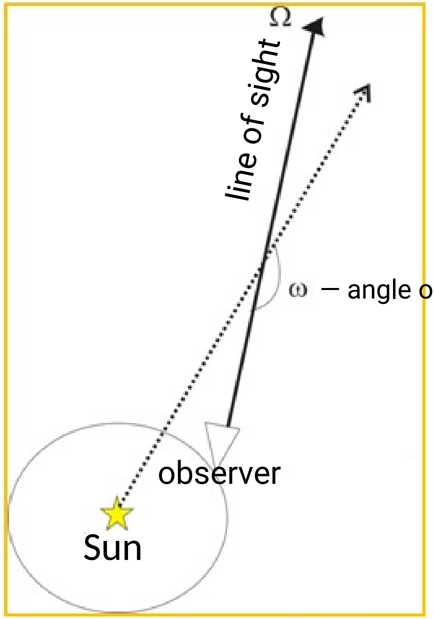
$$\beta(r,\lambda,t)=(\beta_{ex,E}(\lambda,t)+\beta_{ph,E}(\lambda,t))\left(\frac{r_E}{r}\right)^2=\beta_E(\lambda,t)\left(\frac{r_E}{r}\right)^2$$, r_E=1 AU

$\beta_{ex,E}$ is estimated using the inversion procedure (Quemerais et al. 2006) that is applied to the SWAN/SOHO Ly-α data.



Outer boundary for the local model is 70 AU

Radiative transfer model



The Sun is the source of the solar Ly-α photons. λ_0 = 121.567 nm at the line center.

Radiative transfer equation:

$$\boxed{\mathbf{\Omega} \cdot \nabla I(r, \Omega, \nu) = -\sigma(\nu)\ N(r)\ I(r, \Omega, \nu) + N(r)\ j(r, \Omega, \nu)}$$

$N(r + s\Omega)$ — number density of H atoms

$\sigma_\lambda(\mathbf{r}', \lambda) = k_0 \cdot \hat{f}_p(\mathbf{r}', u)$ — differential scattering cross section

$j(r, \Omega, \nu)$ — atomic emission coefficient

Formal solution
(integral along line of sight):

$$\boxed{I(\mathbf{r}, \nu, \mathbf{\Omega}) = \int_0^\infty N(\mathbf{r} + s\mathbf{\Omega})\, \underset{\uparrow}{\phi(\omega)}\, j(\mathbf{r} + s\mathbf{\Omega}, \nu, -\mathbf{\Omega})\, \underset{\uparrow}{e}^{-\tau_\nu(\mathbf{r}, \mathbf{r}+s\mathbf{\Omega})} ds}$$

local emissivity

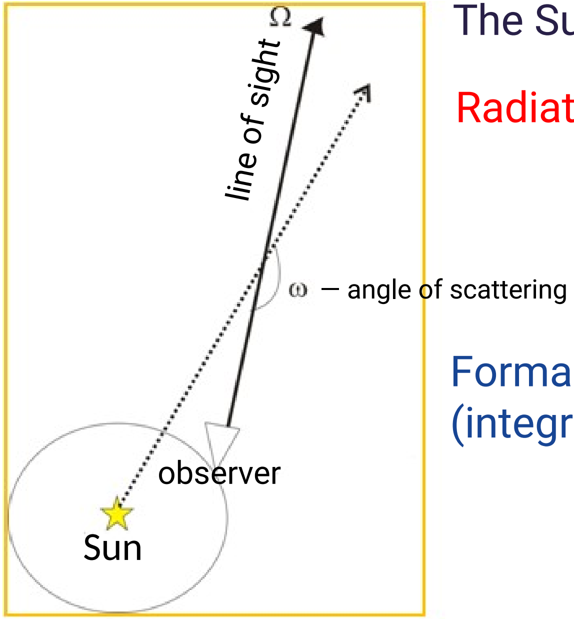
absorption

Methods:

- Analytical solution for single-scattered photons (primary term)

$j(\mathbf{r}', \nu, -\mathbf{\Omega}) = F_S(\mathbf{r}', \nu)\, \sigma_\nu(\mathbf{r}', \nu)$, where $F_S(\mathbf{r}', \nu) = F_E(\nu)\, \frac{r_E^2}{r'^2}$ — solar Ly-α flux

Radiative transfer model



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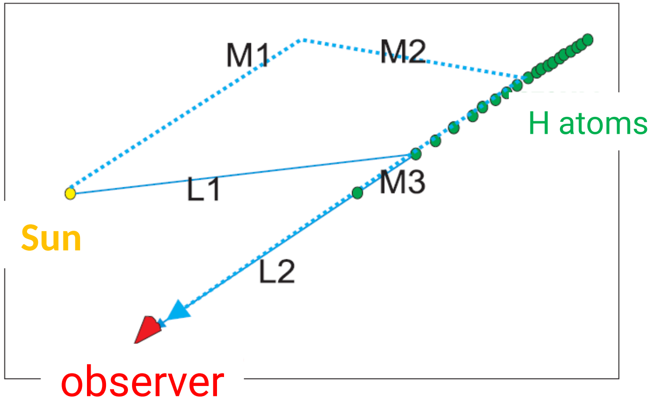


Methods:

- Analytical solution for single-scattered photons (primary term)

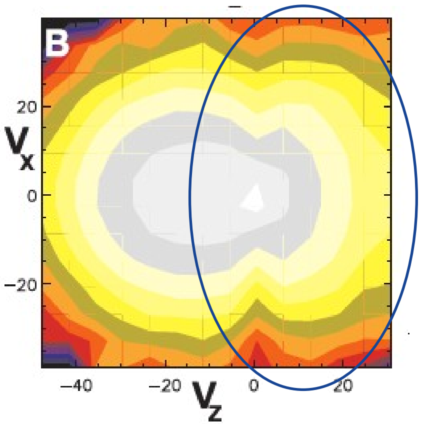
  $j(\mathbf{r}',\nu,-\Omega) = F_S(\mathbf{r}',\nu)\,\sigma_\nu(\mathbf{r}',\nu)$, where $F_S(\mathbf{r}',\nu) = F_E(\nu)\,\dfrac{r_E^2}{r'^2}$ – solar Ly-α flux
- Monte Carlo method for multiple scattering term (Quemerais 2000)

Radiative transfer code (Quemerais 2000): spectra of backscattered Ly-α radiation are calculated from known H distribution and solar Ly-α flux.

Multiple scattering is important in the outer heliosphere!
(optical thickness ~ number density along LOS, and $\tau \sim 1$ at 10 AU for $\lambda = \lambda_0$)

Could the H wall be detected in backscattered solar Ly-α?

Velocity distribution of **secondary** interstellar atoms in the H wall

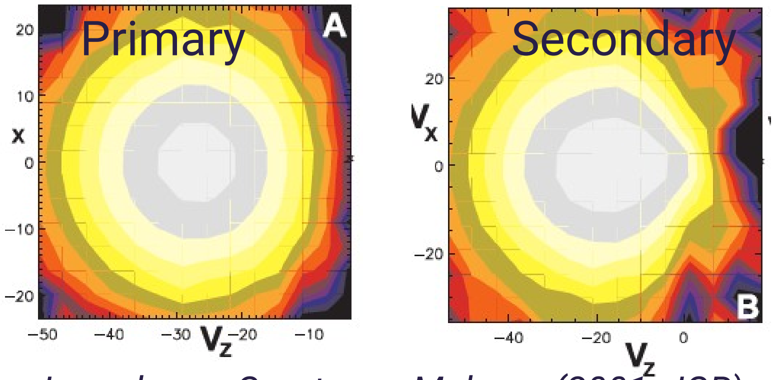


$V_r = c\,(1 - \lambda_0/\lambda)$

Photons with the wavelengths $V_r > 0$ are not scattered inside the heliosphere but are scattered by the atoms inside the H wall.

The (relative) increase in the upwind direction **should be seen** when an observer is approaching the H wall.

Primary and secondary interstellar atoms inside the heliosphere

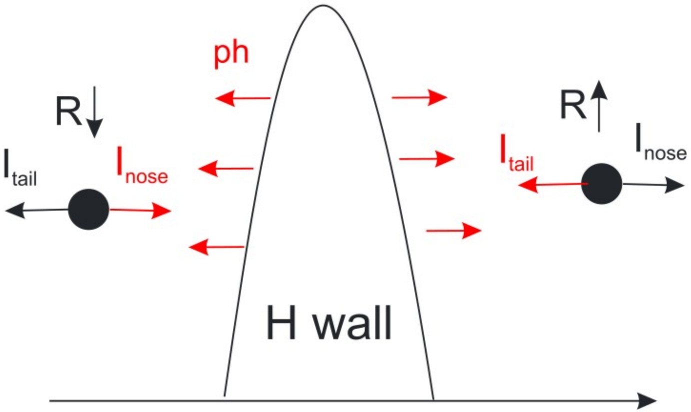


Izmodenov, Gruntman, Malama (2001, JGR)

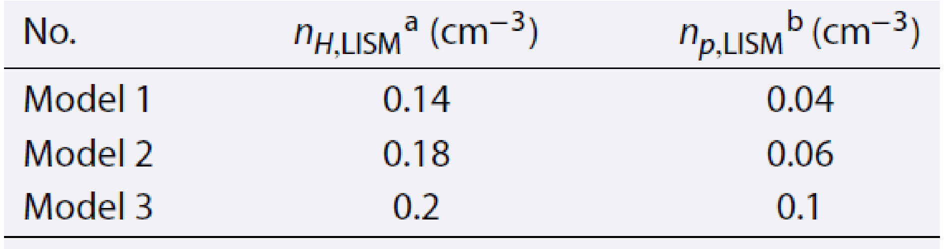
Modeling results

The ratio of intensities in the “tail” and “nose” directions is an effective tool for remote diagnostic of the H wall (its height and location):

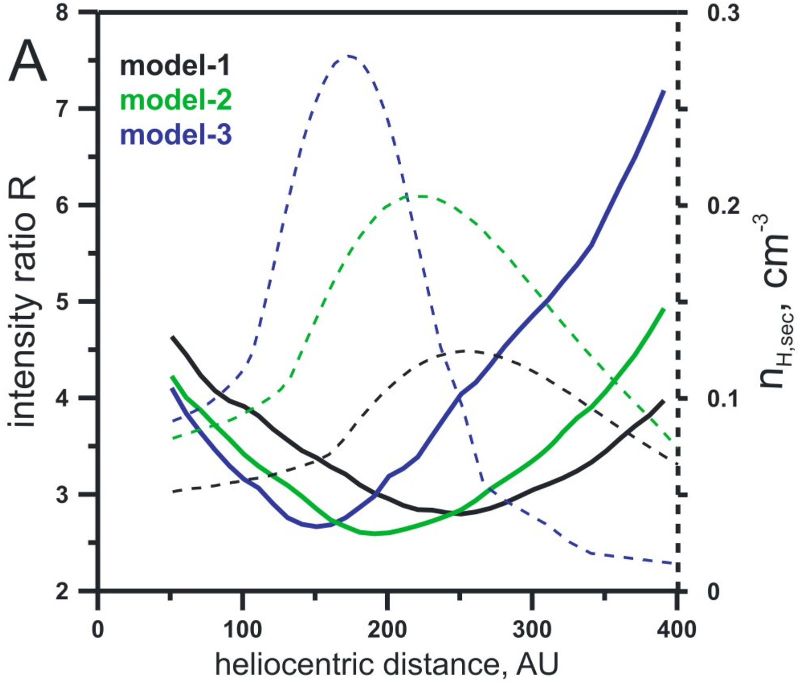
$$R = I_{tail} / I_{nose}$$



- independent of the instrument absolute calibration
- independent of the solar Ly-α flux variations
- minimum of the ratio corresponds to the maximum of the H wall



No.	$n_{H,LISM}$[a] (cm^{-3})	$n_{p,LISM}$[b] (cm^{-3})
Model 1	0.14	0.04
Model 2	0.18	0.06
Model 3	0.2	0.1



Katushkina et al. (2016, JGR)

Voyager/UVS: Remote sensing of the H wall

Katushkina et al. (2016, JGR)

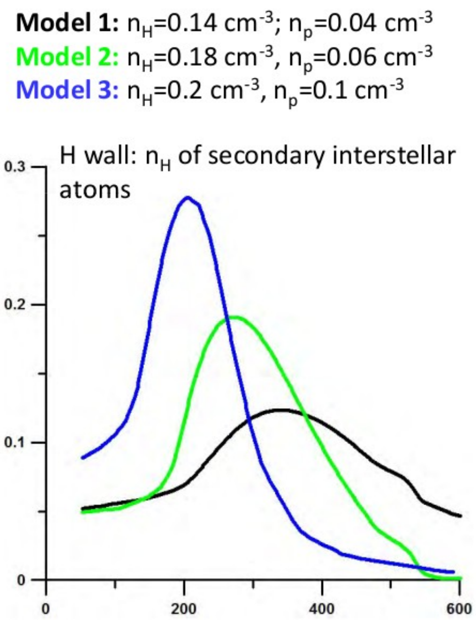
DATA: Voyager 1/UVS intensity measurements in 1993-2003 (scanning regime from nose to tail) at 53–88 AU from the Sun

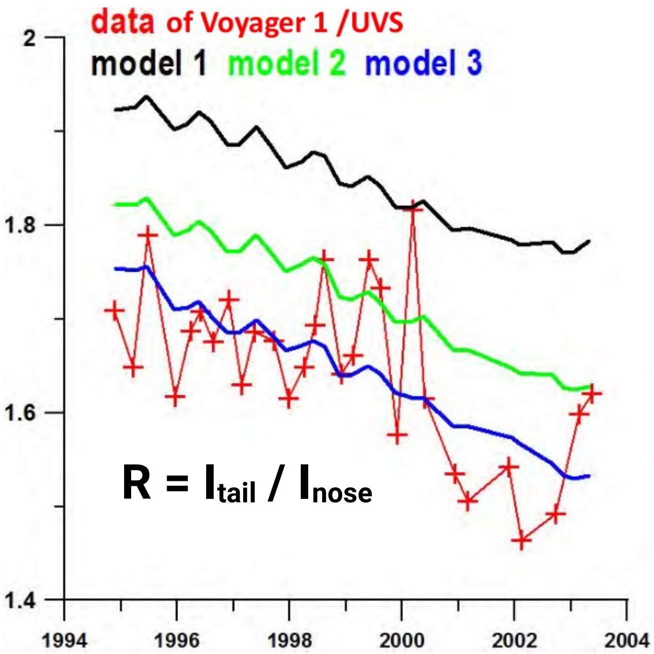
RESULTS:

- **Model 1** provides a systematically larger downwind to upwind intensity ratio compared to the data.
- To decrease the ratio, a higher and/or closer H-wall is needed.

Local emissivity(r, t) ~ $n_H(r) \times F_{S,E}(t)/r^2$

- Higher n_H inside the H wall → higher local emissivity → higher I_{nose} → lower ratio
- Closer H wall → higher local emissivity → higher I_{nose} → lower ratio





Model 1 – Izmodenov & Alexashov (2015)

Model 3 (n_H = 0.2 cm^{-3}, n_p = 0.1 cm^{-3}) provides a good agreement with the data. However, in this model the TS is located closer to the Sun than it was observed by V1.

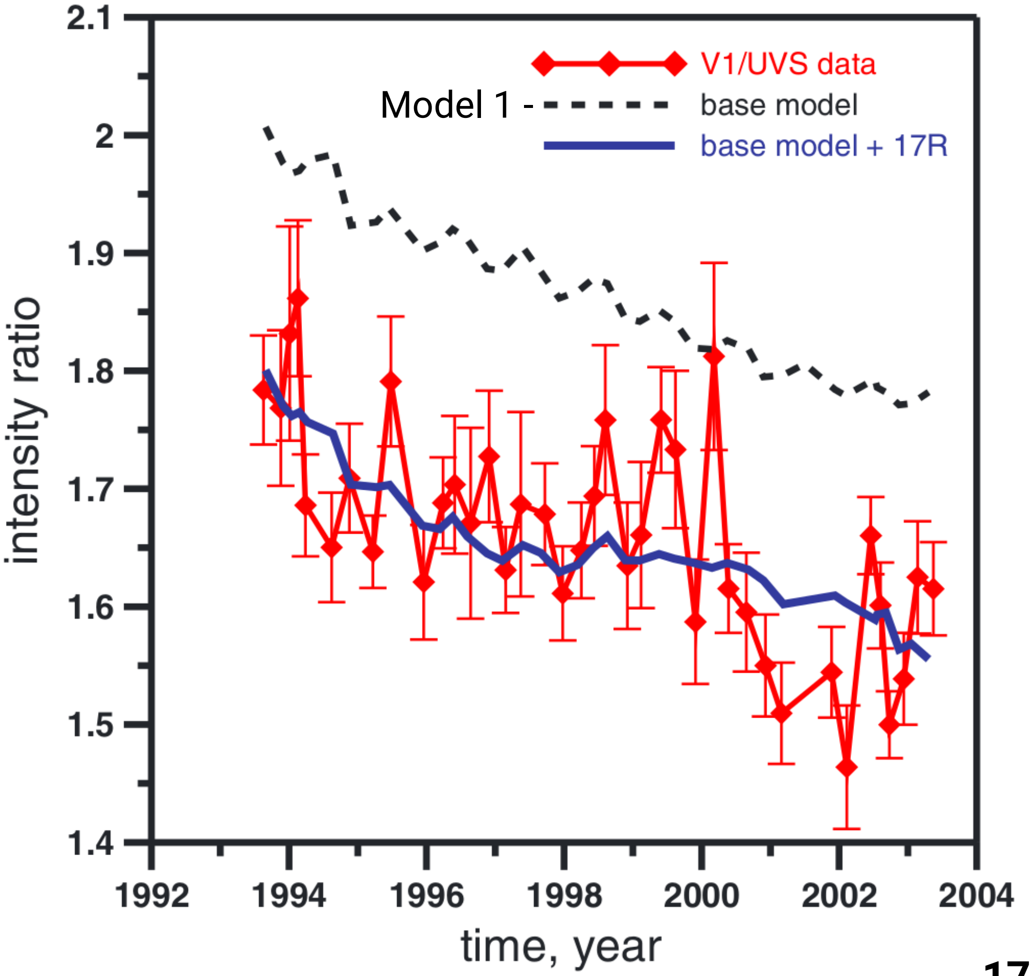
Voyager/UVS: Unknown Source of Additional Emission

Katushkina et al. (2017, JGR)

RESULT:

The additional constant emission of ~15-20 Rayleigh leads to a good agreement with the Voyager data in 1993-2003 as well (even without higher/closer H wall, suggested by Katushkina et al. 2016).

$$\hat{R} = \frac{I_{tail} + I_{add}}{I_{nose} + I_{add}} < \frac{I_{tail}}{I_{nose}} = R$$



Summary

- **H wall** consists of the **secondary interstellar atoms**, which have smaller bulk velocity and larger dispersion of the individual velocities ("effective" temperature) as compared with the primary component.
- The absorption produced by the H wall is observed in Ly-α spectra measured toward nearby stars.
- **Kinetic approach is needed** for modeling of the secondary component and should be used for the data analysis.
- **H wall should be seen** in the distant measurements of backscattered solar Ly-α emission.
- Analysis of the intensities ratio **$R = I_{tail} / I_{nose}$** is a tool for remote sensing of the H wall (its peak value and location). The ratio is not dependent on the instrument calibration and modulations of the solar Ly-α flux, so it is a **robust diagnostic**. Although an accurate consideration of an instrumental and **physical background** is needed.