What epoch and space region at the heliospheric boundaries are probing IBEX and IMAP observations of interstellar neutral gas populations?

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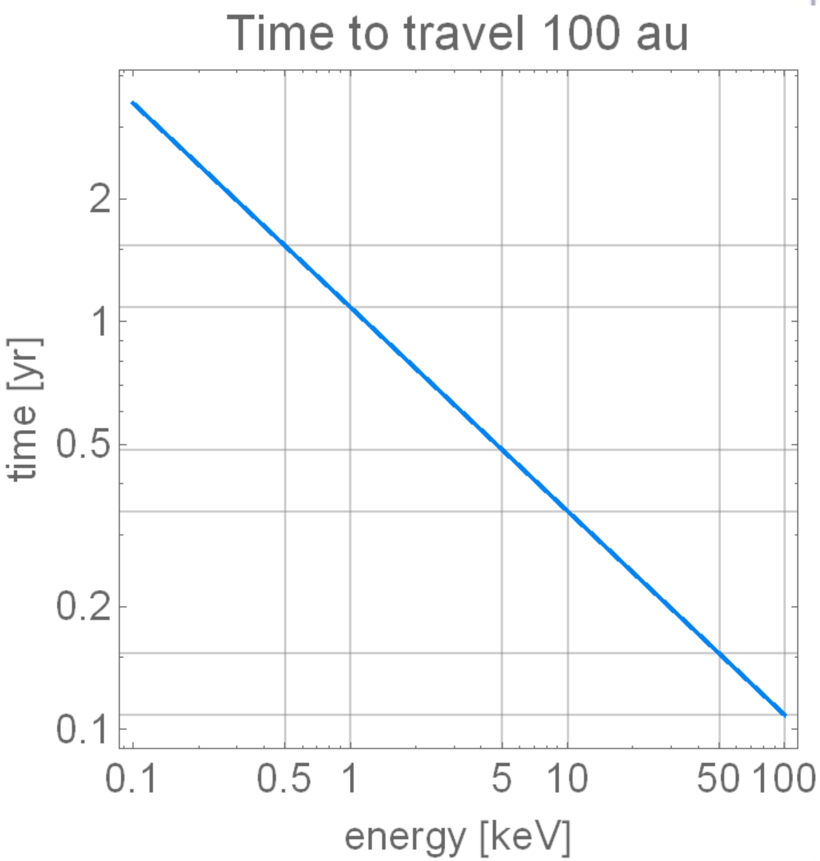
When we measure here and now, what do we study, in fact?

- Studying the heliosphere-LISM interaction is done
  - by in situ sampling (the Voyagers)
  - remotely by ENAs (from ~0.7 keV to ~100 keV)
  - remotely by ISN atoms (primary and secondary)
  - remotely by the helioglow
  - by pickup ions
- Interpretation requires understanding the time delays between source and detector for these different information sources
- Distances in the heliosphere:
  - inner heliosheath: ~ 80 – 130 au (upwind hemisphere)
  - outer heliosheath ~ 130 – 250 au (upwind hemisphere)
- These are regions where most of the interaction occurs

What is the epoch we obtain information from?

- in situ sampling (the Voyagers): now
- Heliospheric ENAs from ~0.7 keV to ~100 keV – run 100 au in 1.3 – 0.1 yr,
- ENA production modulated at the source due to solar wind modulation
- ENA modulation due to re-ionization relatively weak, strongest just before detection (< ~10 au, weeks–months)
- Heliospheric ENA delay shorter than the solar cycle length;



- An observation-based time-dependent model of the heliosphere will catch these details if the observed SW variations accounted for

What is the epoch we obtain information from?

- ISN atoms (primary and secondary) are:
  - directly sampled at 1 au and the
  - observed indirectly as the helioglow
- strongly modulated within ~10 au (i.e., within months from detection)
- production of the secondaries is and filtration of the primaries are modulated at the source in the outer heliosheath
- The secondaries bring the information on the OHS
- From what time ago?
- This can be answered by simulation. The answer is important but not a trivial one

Synthesizing the signal

- Simulating the IBEX signal $F(\psi)$ for spin angle ψ

$$\Phi(\psi,\alpha,t;\boldsymbol{\pi}) = \int_{u_{\min}}^{u_{\max}} u_{rel}\, \omega_{\text{He}}\left(\mathbf{r}_{obs}, \mathbf{v}_{obs}(\mathbf{u}_{rel}), t; \boldsymbol{\pi}\right) w\left(\mathbf{r}_{obs}, \mathbf{v}_{obs}; \boldsymbol{\pi}\right) u_{rel}^2\, du_{rel}$$

differential flux in the sky

$$F(\psi) = \int_{\Delta\Psi} \int_{\Delta\Omega} \Phi(\psi, t, \boldsymbol{\pi})\, d\Omega\, dt\, d\psi$$

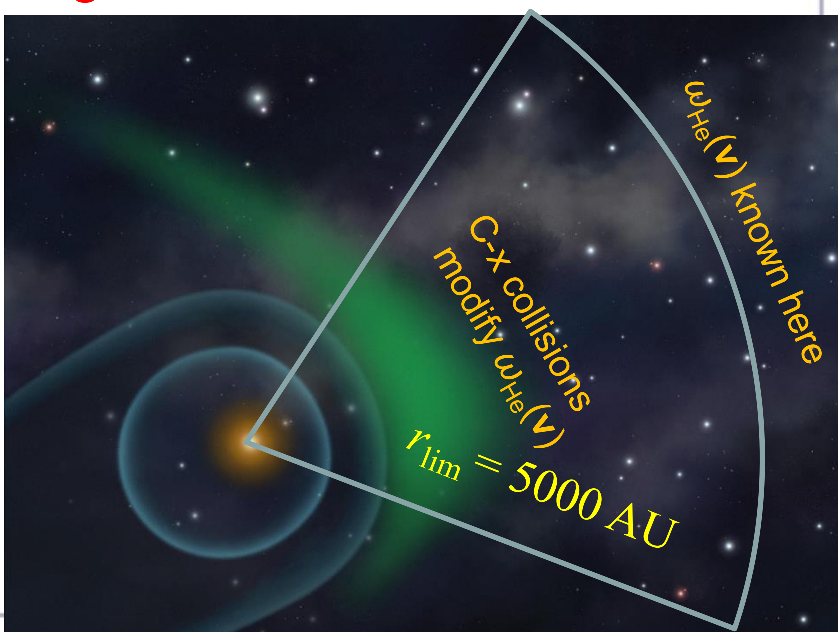
flux integrated over the collimator, spin bin, good times

- the statistical weight $\omega_{\text{He}}(\boldsymbol{r}_{\text{obs}}, \boldsymbol{v}_{\text{obs}}; \boldsymbol{\pi})$ is calculated as due to a balance between production and losses at a given Keplerian trajectory:

$$\frac{d\omega_{\text{He}}}{ds} = \beta_{\text{prod}}(s) - \omega_{\text{He}}(s)\beta_{\text{loss}}(s); \quad ds = r\, d\theta$$

statistical weight

- Initial conditions: assumed as known at r_{lim} = 5000 AU
- Sought: $\omega_{\text{He}}(\boldsymbol{r}_{\text{HP}}(\lambda_{\text{HP}}, \varphi_{\text{HP}}))$



Gain and loss terms

- Gain and loss terms: solely due to resonance c-x collisions:
  $\mathrm{He} + \mathrm{He}^+ \rightarrow \mathrm{He}^+ + \mathrm{He}$
- He+ fully thermalized with IS protons everywhere: follows density, velocity, and temperature changes of IS plasma
- ISN He isothermal, uniform density, constant velocity
- c-x with no momentum transfer
- More complex interactions can be added:
  - elastic collisions,
  - c-x interaction with protons and H atoms, … (you name it)

$$\beta_{\mathrm{prod}}(t) = n_{\mathrm{He}}\, n_{\mathrm{He}^+}\, f_{\mathrm{He}^+}(\boldsymbol{v}, \boldsymbol{u}_{\mathrm{He}^+}, u_{\mathrm{T,He}^+})\, u_{\mathrm{rel}}^{\mathrm{prod}}\, \sigma_{\mathrm{cx}}\left(u_{\mathrm{rel}}^{\mathrm{prod}}\right);$$

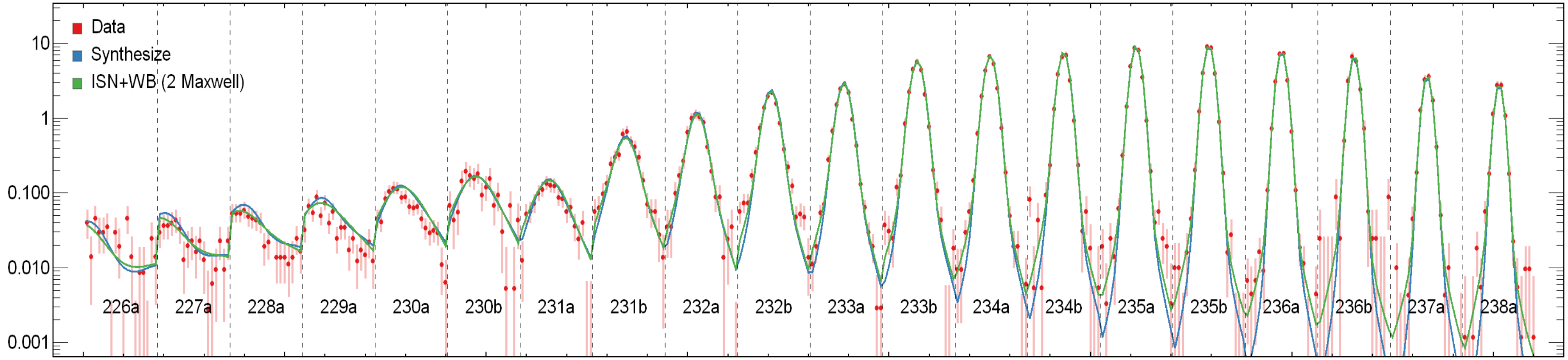
$$\beta_{\mathrm{loss}}(t) = n_{\mathrm{He}^+}\, u_{\mathrm{rel}}^{\mathrm{loss}}\, \sigma_{\mathrm{cx}}\left(u_{\mathrm{rel}}^{\mathrm{loss}}\right);$$

$$u_{\mathrm{rel}}^{\mathrm{prod}} = u_{\mathrm{rel}}(\boldsymbol{v}, \boldsymbol{u}_{\mathrm{He}}, u_{\mathrm{T,He}})$$

$$u_{\mathrm{rel}}^{\mathrm{loss}} = u_{\mathrm{rel}}(\boldsymbol{v}, \boldsymbol{u}_{\mathrm{He}^+}, u_{\mathrm{T,He}^+})$$

Synthesis method successful

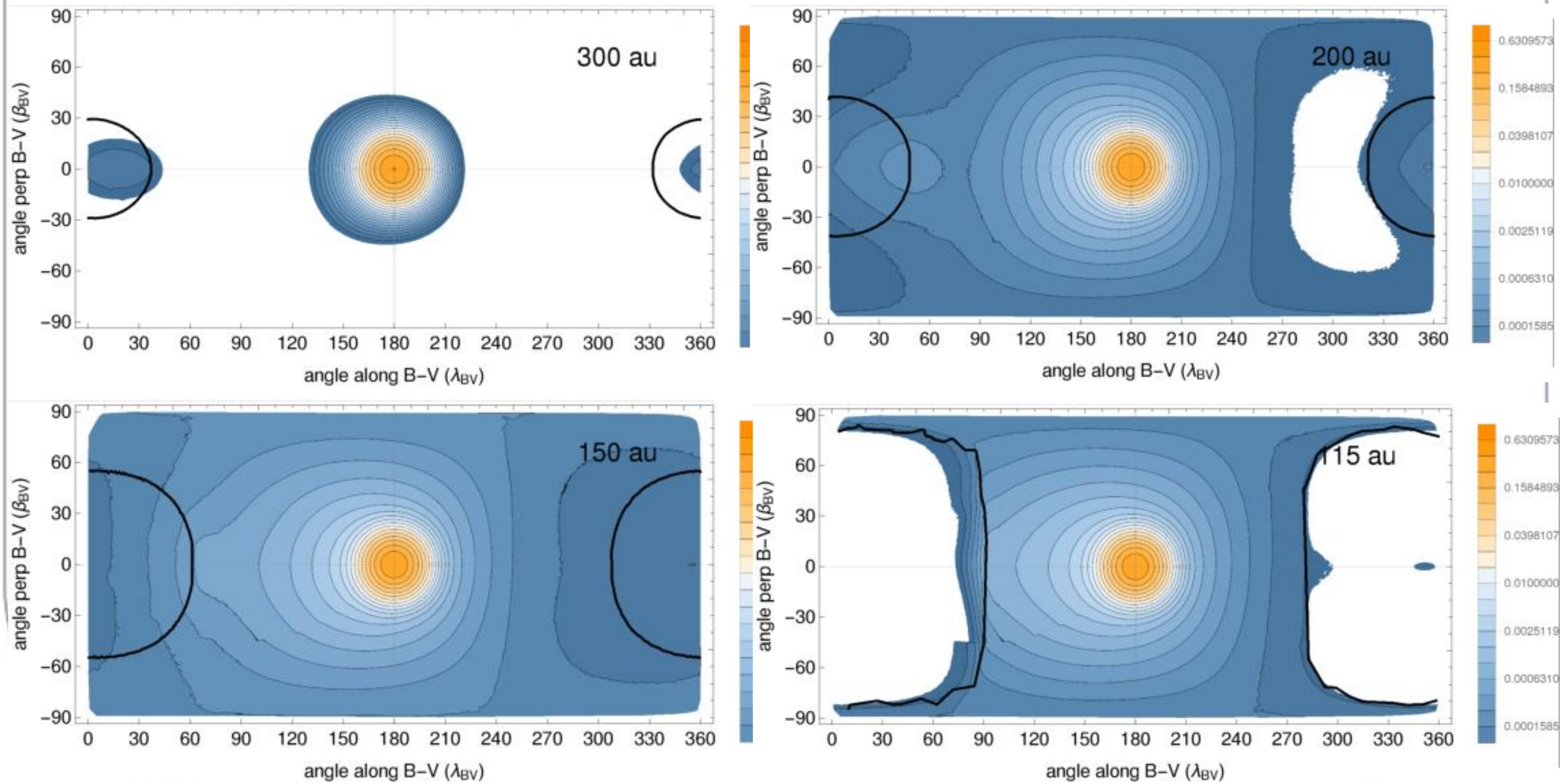
- Using this method, we can simulate the IBEX-Lo signal and compare it with observations
- Bzowski et al. (ApJ 882:60, 2019) determined He^{+} density in the VLISM (~1000 au ahead of the Sun)



- While the chi-square magnitude is better than for the model with two independent Maxwell-Boltzmann populations, it is statistically too large – we are missing something

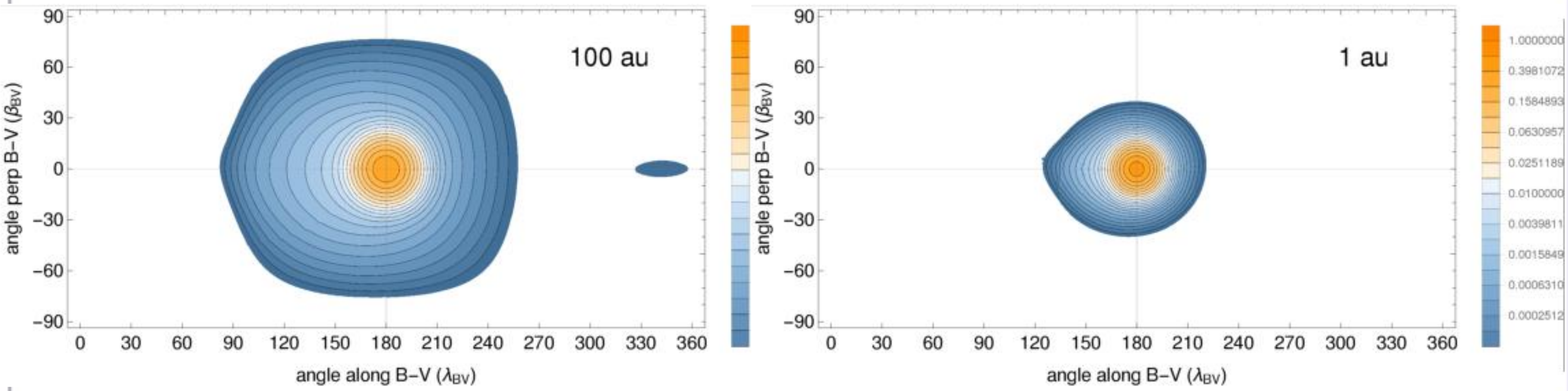
Where are the secondaries produced?

- The synthesis method used to simulate the distribution function of ISN gas within the OHS (Kubiak et al., Ap.J. 882:114, 2019)



Where are the secondaries produced?

- The secondaries originate between HP and ~1.75 x HP distance



- Inside HP, ballistic selection effects kick in and the distribution function gradually loses the imprinted details of the plasma source population
- Effectively, the c-x production of the secondaries and losses of the primaries operate between HP and ~1.75 HP distance
- This holds along and across the upwind line

How old are the secondary ISN atoms observed at 1 au?

- We simulate the time of flight using WTPM + synthesis method

$$\Phi(\psi,\alpha,t;\boldsymbol{\pi})=\int_{u_{\min}}^{u_{\max}} u_{rel}\,\omega_{\mathrm{He}}(\mathbf{r}_{obs},\mathbf{v}_{obs}(\mathbf{u}_{rel}),t;\boldsymbol{\pi})\,w(\mathbf{r}_{obs},\mathbf{v}_{obs};\boldsymbol{\pi})\,u_{rel}^2\,du_{rel}$$

$$T(\psi,\alpha,t;\boldsymbol{\pi})=\int_{u_{\min}}^{u_{\max}} \tau\,u_{rel}\,\omega_{\mathrm{He}}(\mathbf{r}_{obs},\mathbf{v}_{obs}(\mathbf{u}_{rel}),t;\boldsymbol{\pi})\,w(\mathbf{r}_{obs},\mathbf{v}_{obs};\boldsymbol{\pi})\,u_{rel}^2\,du_{rel};\ \tau:\text{calendar time at source}$$

$$T^2(\psi,\alpha,t;\boldsymbol{\pi})=\int_{u_{\min}}^{u_{\max}} \tau^2\,u_{rel}\,\omega_{\mathrm{He}}(\mathbf{r}_{obs},\mathbf{v}_{obs}(\mathbf{u}_{rel}),t;\boldsymbol{\pi})\,w(\mathbf{r}_{obs},\mathbf{v}_{obs};\boldsymbol{\pi})\,u_{rel}^2\,du_{rel}$$

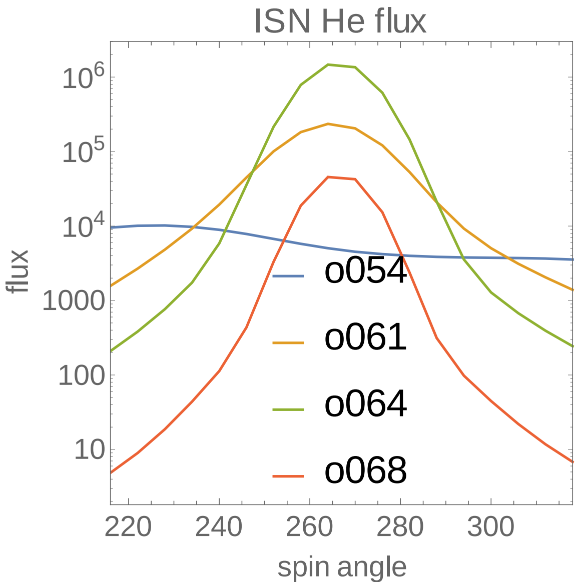
$$\langle\tau(\psi,\alpha,t;\boldsymbol{\pi})\rangle=T(\psi,\alpha,t;\boldsymbol{\pi})/\Phi(\psi,\alpha,t;\boldsymbol{\pi})$$

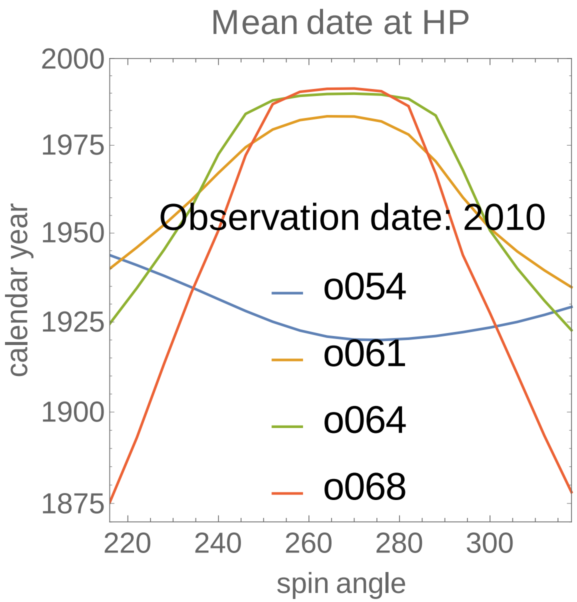
$$\langle\tau^2(\psi,\alpha,t;\boldsymbol{\pi})\rangle=T^2(\psi,\alpha,t;\boldsymbol{\pi})/\Phi(\psi,\alpha,t;\boldsymbol{\pi})$$

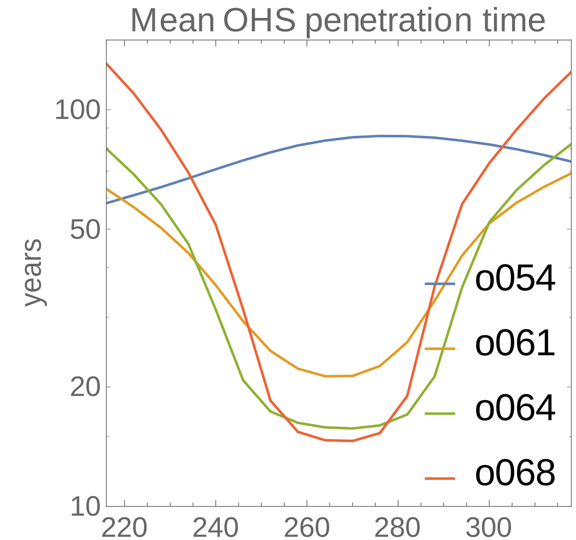
$$ToF=t_{obs}-\langle\tau\rangle\pm\Delta\tau$$

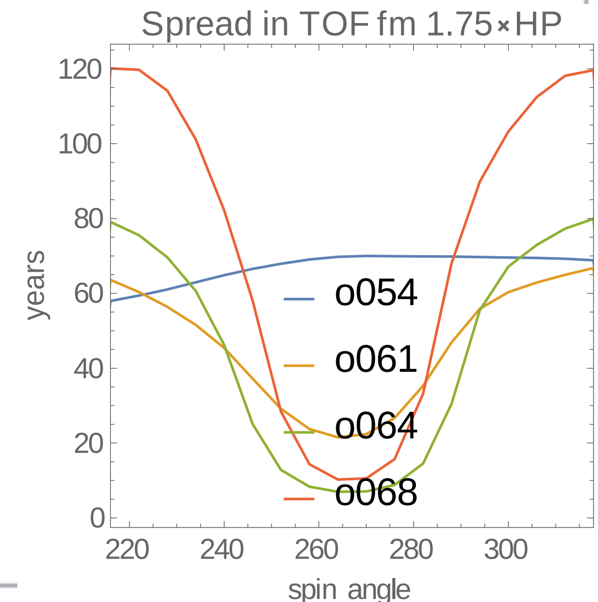
$$\Delta\tau=\sqrt{\langle\tau^2\rangle-\langle\tau\rangle^2}$$

How old are the ISN atoms observed at 1 au?





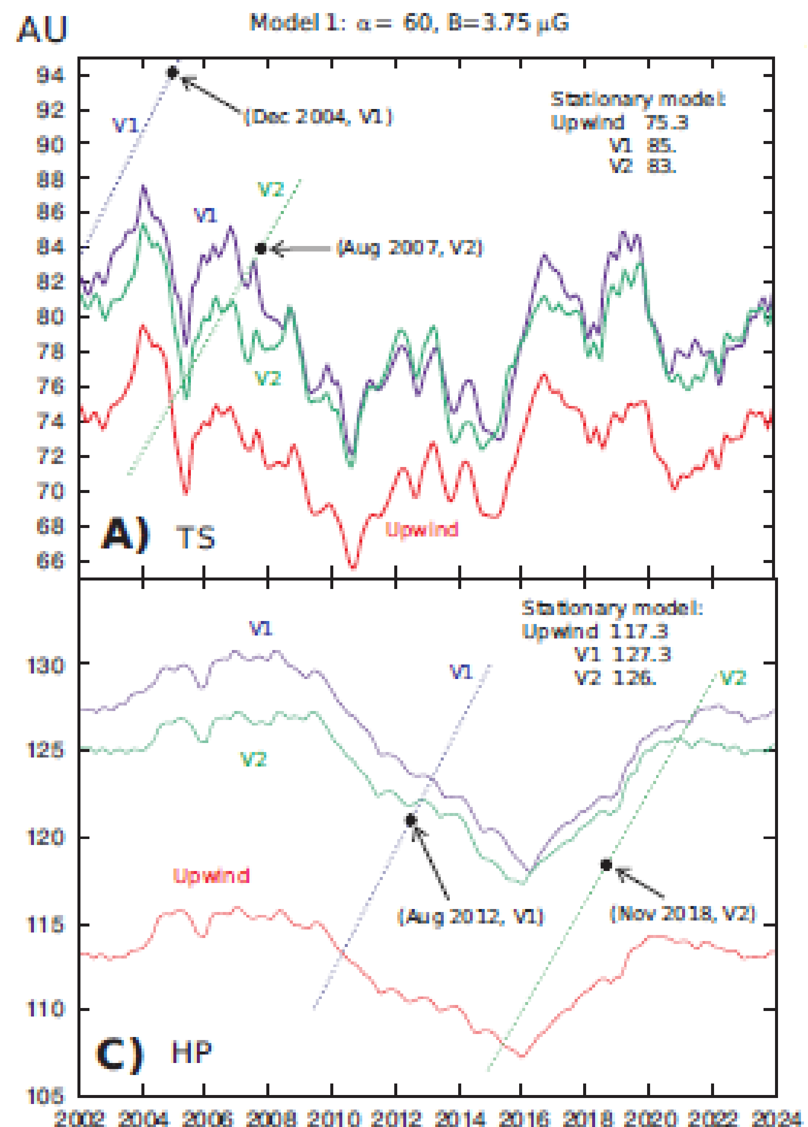




- TOF for ISN and secondary atoms are very different
- Primaries crossed the interaction region during 70-ties and 80-ties, with a spread of ~10 years
- Secondaries crossed the interaction region in the second half of 19th /beginning of 20th century!!!
- The penetration time is several solar cycle lengths
- Analysis done for He, conclusions for H similar

How far backward should SW coverage extend?

- Thus, a model with solar wind coverage backwards at least to the turn of 19/20 century is needed – clearly not available
- Izmodenov & Alexashov (2020) showed that a MHD-kinetic heliosphere model with a measurement-based 3D time-dependent SW is potentially able to reproduce the Voyager TS & HP crossings
- Amplitudes of HP and TS motions is ~8 and ~10 au, respectively



How to model SW for secondary ISN analysis?

- Ideally, studies of secondary ISN neutrals need observations of solar wind > 150 au backwards
- These would be used in a 3D time dependent MHD-kinetic model of the heliosphere to provide a plasma flow in the OHS
- Analysis of observations should be done with a SW and EUV modulation of ISN neutrals within ~months prior to detection – this is now available
- With a 150-year SW history not available, it is recommended to use SW conditions averaged over as many full solar cycles as available
- However, to model the secondary production – how good or how bad is the c-x cross section we use?

What is the good H – H^+ c-x cross section for the OHS?

- Everybody uses the Lindsay & Stebbings 2005 cross section
- Apparently, in the low-energy region, L&S used data from Belyaev et al., JETP 25, 777, 1965
- In the low-energy portion, L&S 2005 disagree with models and a measurement by Newman et al., Phys.Rev.A., 25, 2976, 1982
- The latter one was used in the formula by Barnett et al. 1990 (ORNL), „The Red Book”
- Look at the data…

What is the good H – H$^+$ c-x cross section for the OHS?

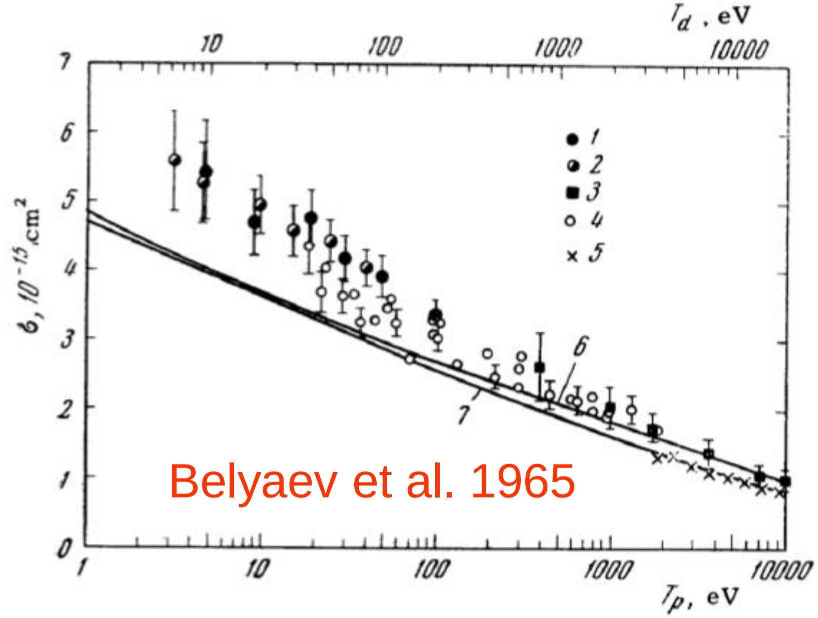


FIG. 3. Cross sections for resonance charge exchange o protons in hydrogen atoms (1, 3–7) and deuterons in deuteri atoms (2) as a function of the collision energy: 1, 2 – prese work, 3 – [10]; 4 – [11]; 5 – [12]; curves – theoretical: 6 – ac cording to [4], 7 – according to [3]. The values of proton en- ergy T_p and deuteron energy T_d, which coincide on the plot correspond to the same relative velocities of the particles i H^+–H and D^+–D collisions.

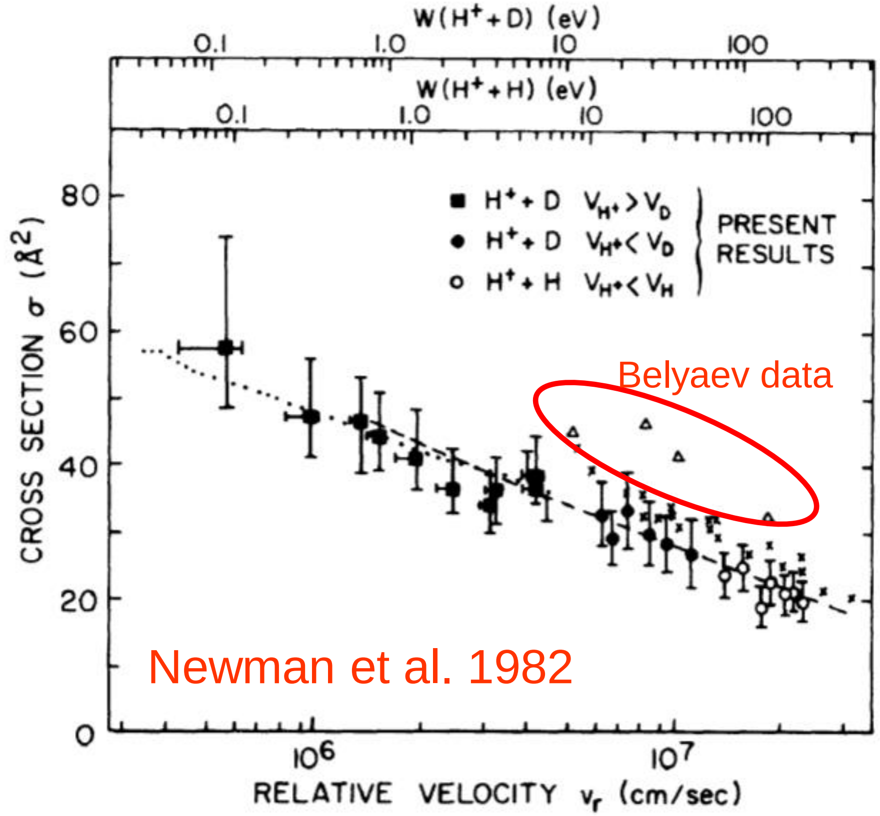
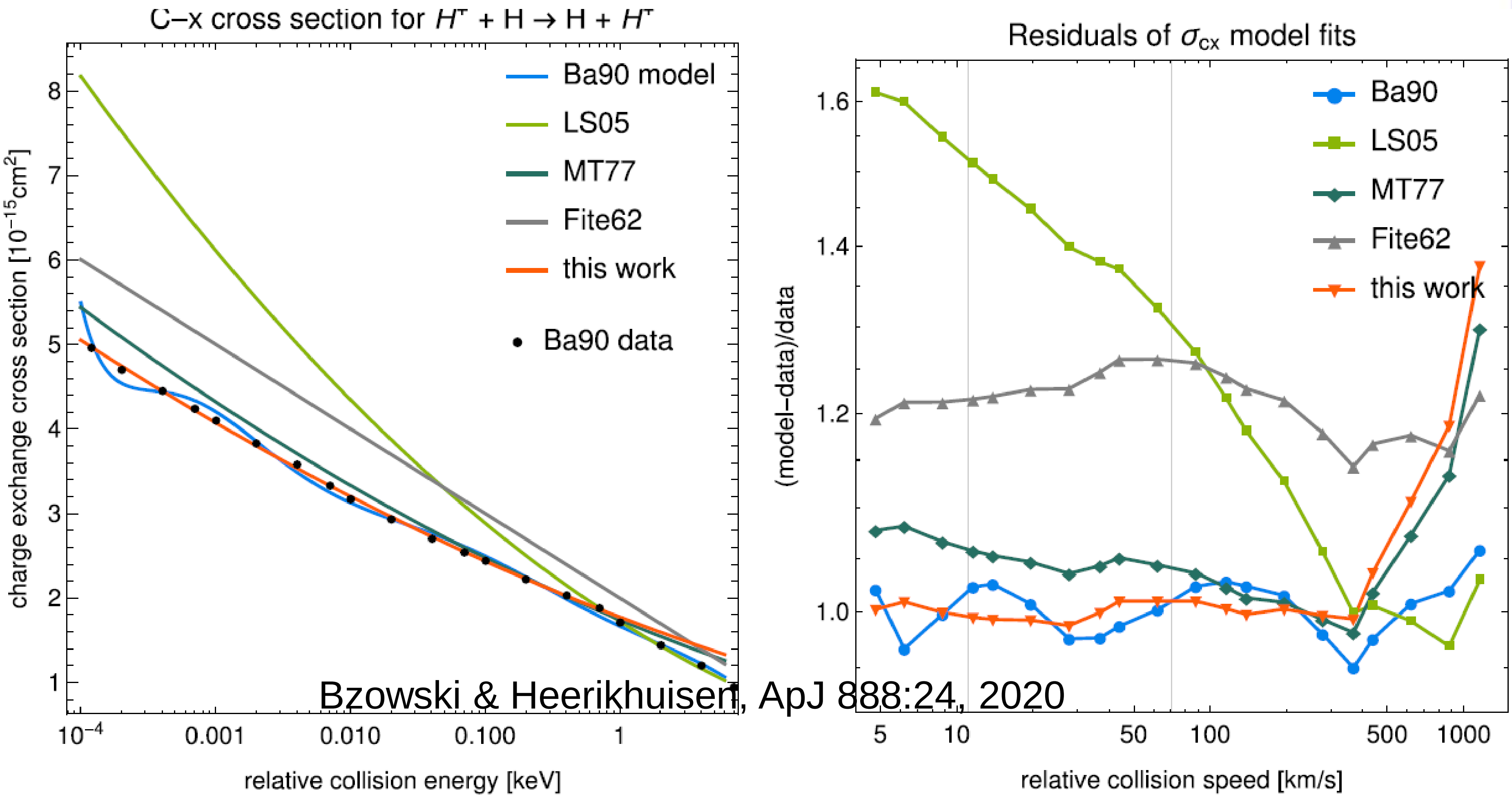


FIG. 5. Results for present study of $H^+ + H \rightarrow H + H^+$ and $H^+ + D \rightarrow H + D^+$. Other experimental results: ×, Fite, Smith, and Stebbings (Ref. 14); △, Belyaev, Brezhnev, and Erastov (Ref. 15). Theoretical results: — — —, $H^+ + H \rightarrow H + H^+$, Dalgarno and Yadav (Ref. 13); · · · ·, $H^+ + D \rightarrow H + D^+$, Hunter and Kuriyan (Ref. 11).

What is the good H – H+ c-x cross section for the OHS?



Bzowski & Heerikhuisen, ApJ 888:24, 2020

Figure 1. Comparison of measurements of the H + H^+ charge-exchange cross-section as a function of collision energy, recommended by Barnett et al. (1990; black dots) with approximation formulae from Barnett et al. (1990, Ba90), Lindsay & Stebbings (2005, LS05), Maher & Tinsley (1977, MT77), Fite et al. (1962, Fite62), and this work corresponding to Equation (2) (left panel) and the residuals of these formulae as a function of collision speeds (right panel). The energy scale in the left panel precisely corresponds to the collision speed scale in the right panel.

What is the good H – H^+ c-x cross section for the OHS?

- Two discrepant views on the magnitude of H + H^+ cross section in the OHS, affect the plasma flow & heating, secondary H production
- The differences are 40% and larger
- We do not feel confident to tell which one is the more correct but a gut feeling tells me it's the one from Newman et al.
- If so, the cross section used in the OHS (and to a lesser extent to produce ENAs with energies << 1 keV in the IHS) are too large
- We devised a tentative c-x cross section formula in agreement with Newman et al. and checked how the simulated heliosphere changes

$$\sigma_{cx}(E) = (6.384 \times 10^{-8} - 3.14 \times 10^{-9} \ln E)^2 \quad \text{for} \quad 10^{-4} < E < 1\,\text{keV}.$$

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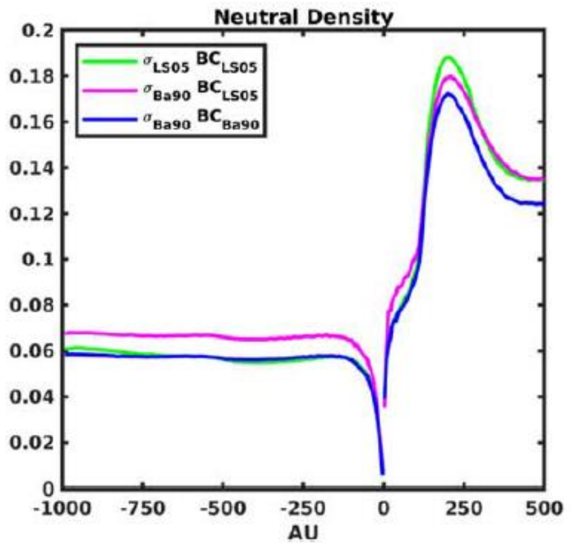
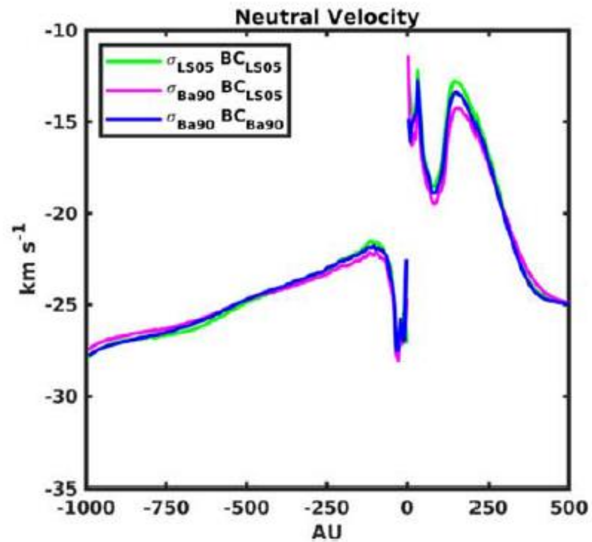
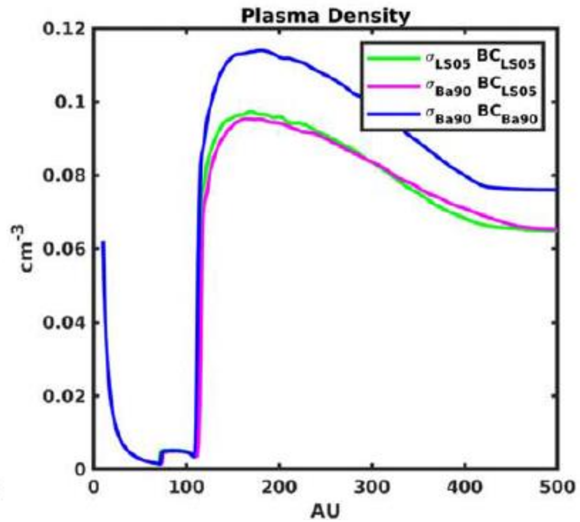
How does the c-x enigma affects modeling of the heliosphere?







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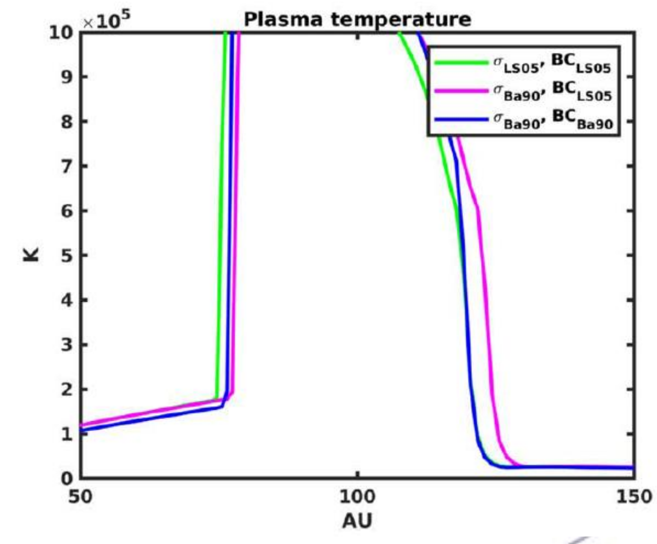
- We run the Huntsville model differing only by the c-x formula
- Compare green vs blue
- Results show a significant sensitivity to a c-x uncertainty of this magnitude (~40%)



Conclusions

- Neutral atoms bring information on the plasma state in remote locations with a delay due to Energy-dependent travel time
- Time delays for ENAs (E > ~200 eV) are inside the solar cycle length
- Hence, a sufficient solar wind measurement coverage is available to model the interaction
- Unlike ENAs, interstellar neutral (ISN) atoms (primary and secondary) feature time delays much longer than the solar cycler length
- Primary ISN atoms were filtered within OHS 2—3 solar cycles prior to detection, with a spread of ~1 solar cycle period
- Secondary ISN atoms were created in the OHS at the turn of 19/20 centuries
- Large spread in their times of flight (~5 solar cycles)

Conclusions

- Modeling OHS conditions for appropriate epoch using a time-dependent model requires solar wind data coverage from the turn of centuries – not available
- A feasible option is to use a time-stationary model for solar wind conditions averaged over several solar cycles
- Most likely, production of the secondaries in the OHS has been overestimated in the heliospheric models (all of them!)
- Reason: the Lindsay & Stebbings model likely overestimates the c-x cross section for OHS conditions by ~40%
- This affects also the plasma flow and heating
- The cross section issue needs to be resolved