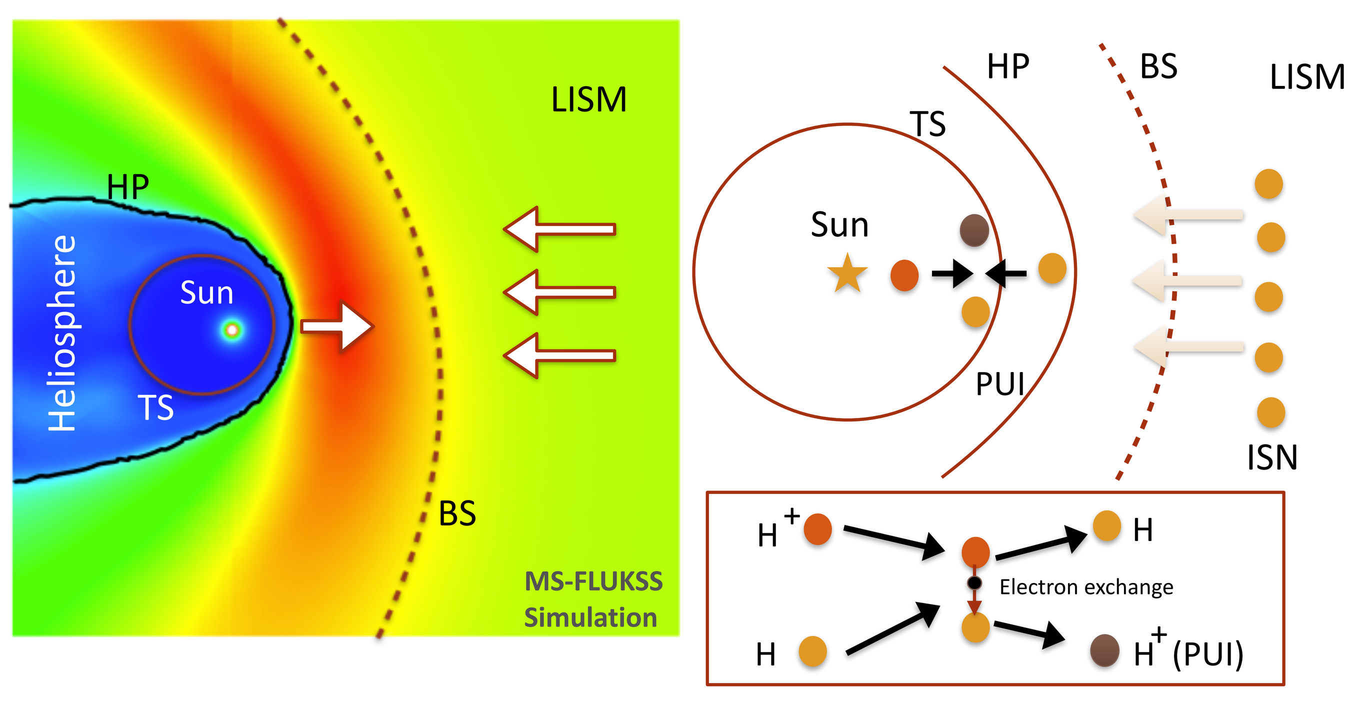
Towards Accurate Modeling of Pickup Ions in the Solar Wind Interaction with the Local Interstellar Medium

Ratan Kumar Bera[1], Nikolai V Pogorelov[2], Federico Fraternale[1], Michael Gedalin[3], and Vadim Roytershteyn[4]

[1] University of Alabama in Huntsville, Center for Space Plasma and Aeronomic Research, Huntsville, AL, United States
[2] University of Alabama in Huntsville, Department of Space Science, Huntsville, AL, United States
[3] Ben-Gurion University of the Negev, Beer Sheva, Israel
[4] Space Science Institute, Boulder, CO, United States

INTRODUCTION

Pickup ions (PUIs) are born when interstellar neutral (ISN) atoms resonantly exchange charge with the solar wind (SW) ions.



PUIs quickly acquire the velocity of the ambient ions but are never form a single equilibrated distribution with the ambient ions. The PUI pressure soon becomes dominant inside the supersonic SW and in the heliosheath as compared with the thermal SW ion pressure and magnetic pressure.

Understanding the behavior of PUIs at the heliospheric termination shock (TS) is of major importance in the SW-LISM interaction process , as they are highly anisotropic near TS.

They play important role for the interpretation of the puzzling data from the Voyager 1 and 2 space crafts.

PICKUP IONS IN MS-FLUKSS

Multi Scale-Fluid Kinetic Simulation Suite (MS-FLUKSS) is a fully 3D, parallel, explicit space plasma modeling tool that uses Adaptive Mesh Refinement (AMR) technique implemented using "Chombo" software package [1,2]

In MS-FLUKSS, the flow of plasmas is described by the ideal magnetohydrodynamics (MHD) equations and neutrals are treated hydrodynamically by solving Euler equations (or kinetically). PUIs are treated as a separate fluid component, the distribution function of which is isotropic away from TS [2].

Mixture

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0=D_\Sigma,$$
$$\frac{\partial\rho\mathbf{u}}{\partial t}+\nabla\cdot\left(\rho\mathbf{u}\mathbf{u}+p^*\mathbf{I}-\frac{1}{4\pi}\mathbf{B}\mathbf{B}\right)=\mathbf{M}_\Sigma,$$
$$\frac{\partial E}{\partial t}+\nabla\cdot\left((E+p^*)\mathbf{u}-\frac{1}{4\pi}(\mathbf{B}\cdot\mathbf{u})\mathbf{B}\right)=E_\Sigma,$$
$$\frac{\partial\mathbf{B}}{\partial t}+\nabla\cdot(\mathbf{u}\mathbf{B}-\mathbf{B}\mathbf{u})=0.$$

Neutrals

$$\frac{\partial\rho_a}{\partial t}+\nabla\cdot(\rho_a\mathbf{u}_a)=D_a,$$
$$\frac{\partial\rho_a\mathbf{u}_a}{\partial t}+\nabla\cdot(\rho_a\mathbf{u}_a\mathbf{u}_a+p_a\mathbf{I})=\mathbf{M}_a,$$
$$\frac{\partial e_a}{\partial t}+\nabla\cdot((e_a+p_a)\mathbf{u}_a)=E_a.$$

PUIs:

$$\frac{\partial\rho_\mathrm{I}}{\partial t}+\nabla\cdot(\rho_\mathrm{I}\mathbf{u})=D_\mathrm{I},$$
$$\frac{\partial p_\mathrm{I}}{\partial t}+\nabla\cdot(p_\mathrm{I}\mathbf{u})+(\gamma-1)p_\mathrm{I}\nabla\cdot\mathbf{u}=P_\mathrm{I}$$

OBJECTIVE

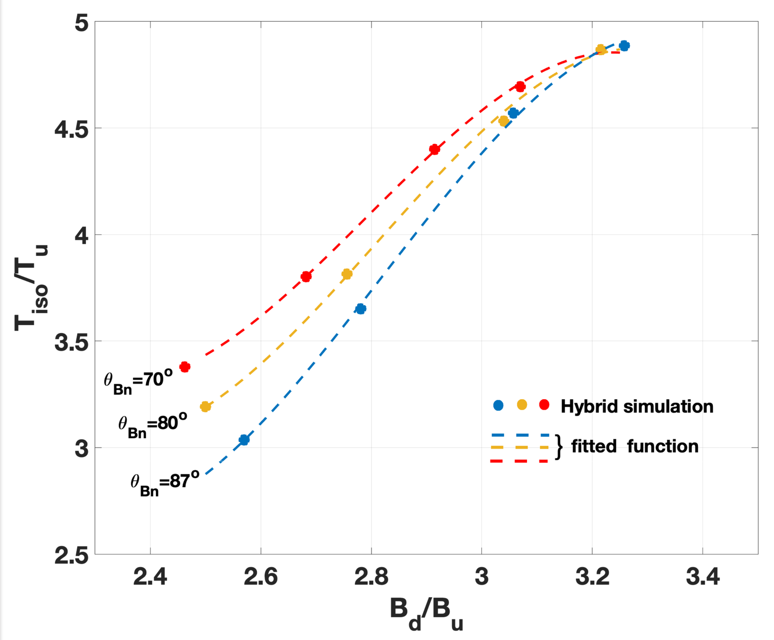
The standard Rankine-Hugonoit (RH) for PUIs are not suitable for describing TS crossing as they are intrinsically non-isotropic, non-maxwellian near TS. RH conditions are the consequences of the global, MHD conservations laws of mass, momentum, energy, and magnetic flux at shocks in plasma [2,6]

Proper boundary conditions derived from kinetic analysis/simulations are required to describe PUIs across TS.

The goal is to perform simulations using kinetically derived boundary conditions (BCs) for PUIs at TS, based on test particle, fully Particle-In-Cell (PIC) and hybrid simulations.

PROBLEM SETUP

The downstream isotropic temperature (T_{iso}) for PUIs is obtained from the hybrid simulations as function of magnetic compression (B_d/B_u) and θ_{Bn}, angle between shock normal and magnetic field.



$$\frac{T_{iso}}{T_u}=\frac{2}{3}\frac{T_\perp}{T_u}+\frac{1}{3}\frac{T_{||}}{T_u}$$

$$\frac{T_{iso}}{T_u}=f(B_d/B_u,\theta_{Bn})$$

$$p_{PUI}=n_{PUI}k_BT_{iso}$$

The simulations are performed in the heliospheric co-ordinate system (x,y,z), where the z-axis is aligned with the Sun's rotation axis and x axis belongs to the plane formed by the z-axis and LISM velocity vector and directed upstream into the LISM.

Boundary Conditions

1 au

SW : OMNI (2012-2020)]

$n=9.1cm^{-3}$
$V=420km/sec$
$T=90000K$
$B=39\mu G$

PUI: SWAP, NH [4]

$n_{PUI}=0.0015cm^{-3}$
$T_{PUI}=3.36\times10^6K$

LISM

$n=0.054cm^{-3}$
$V=25.4km/sec$
$T=7500km/sec$
$B=3.5\mu G$
$n_{PUI}=0.00001cm^{-3}$
$T_{PUI}=7500K$

RESULTS

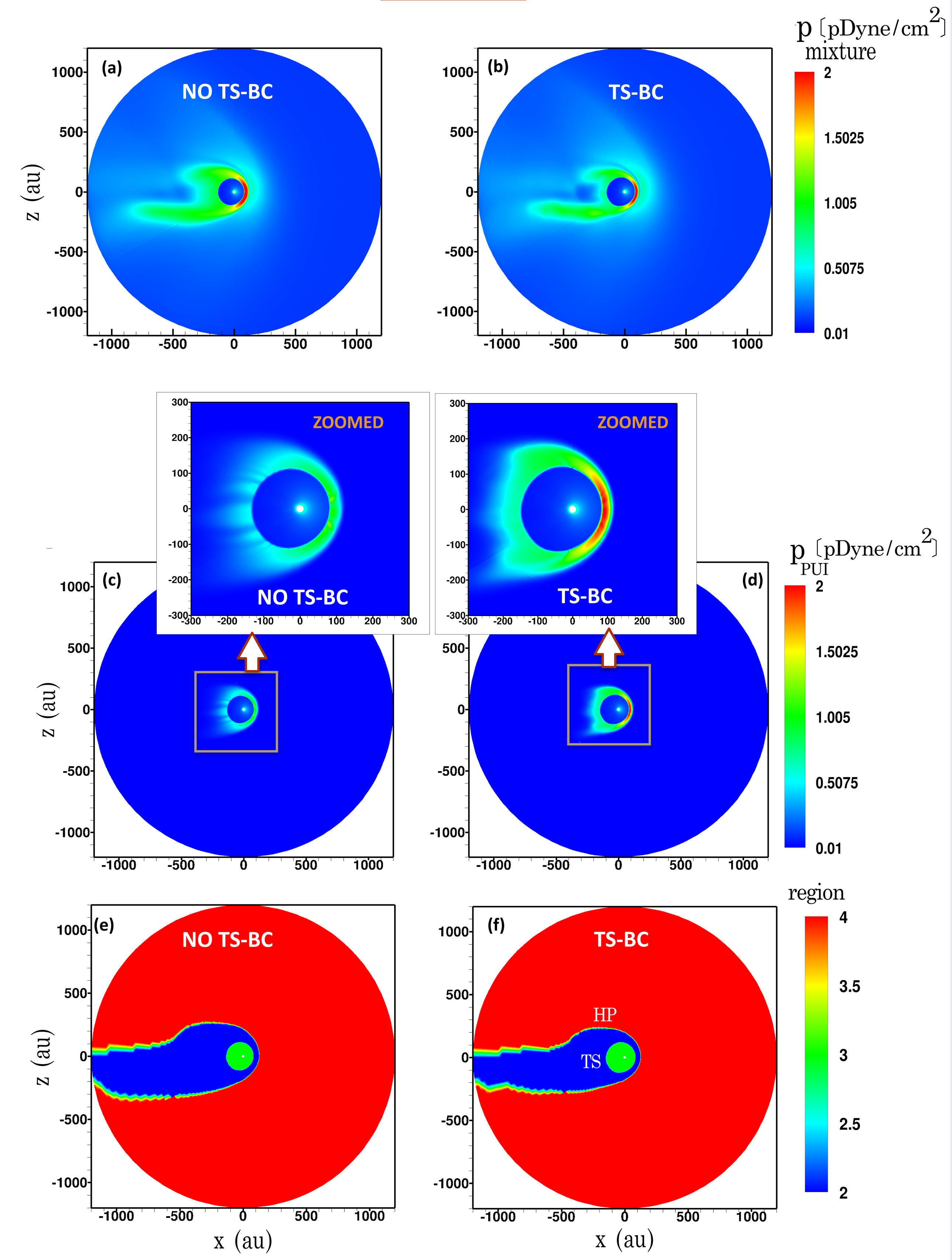


Fig 1: Meridional plane distributions of mixture pressure (top panel (a), (b)), PUIs pressure (mid panel (c), (d)) and region (bottom panel (e), (f)) for "NO TS-BC" case (left) and for "TS-BC" case (right).

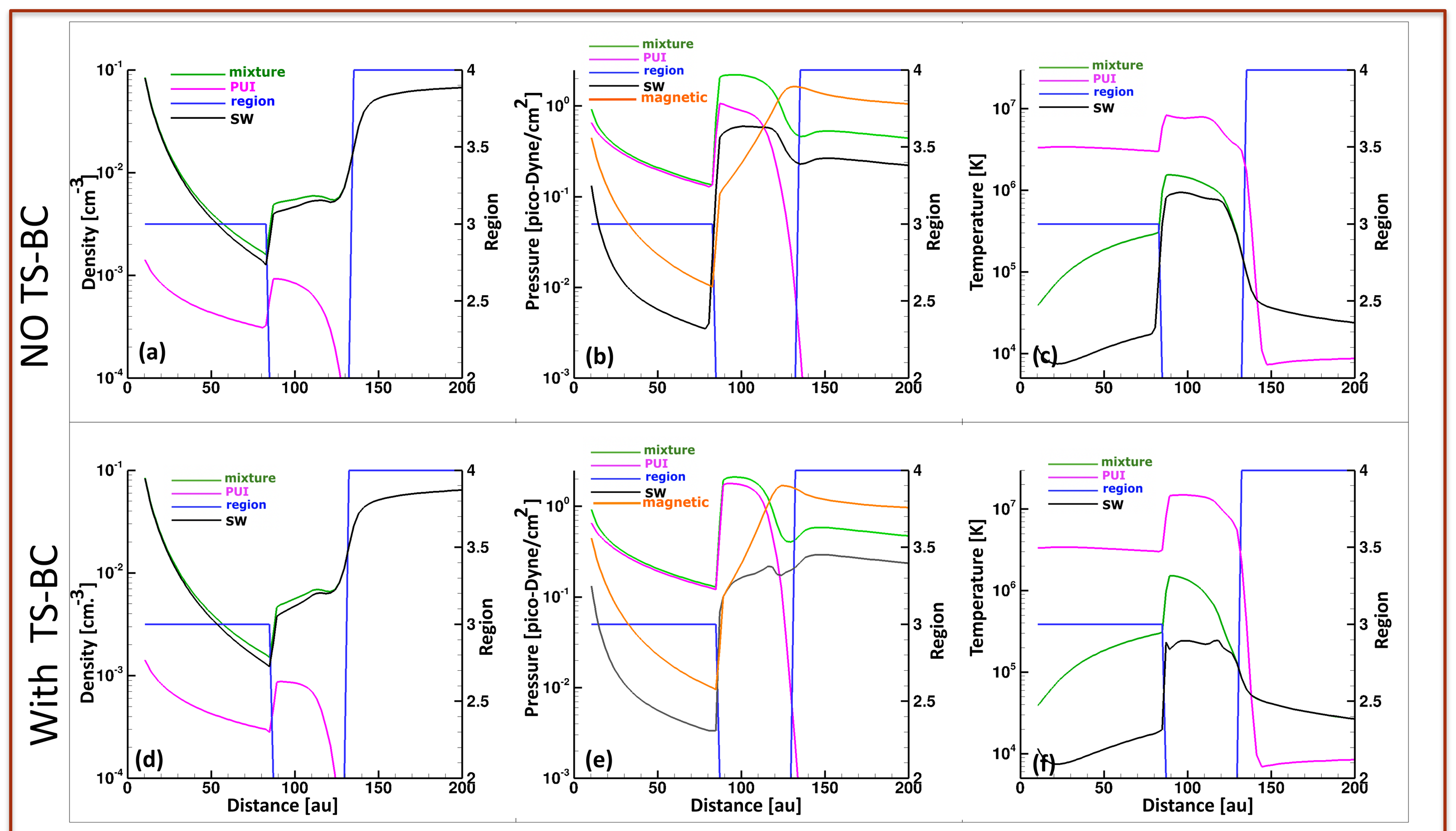


Fig 2: Linear distributions of density, pressure, and temperature of mixture, PUIs, and SW along V2 direction. Top panel ((a), (b), and (c)) shows the distributions for "NO TS-BC" case and bottom panel (d), (e) and (f) shows for "TS-BC" case.

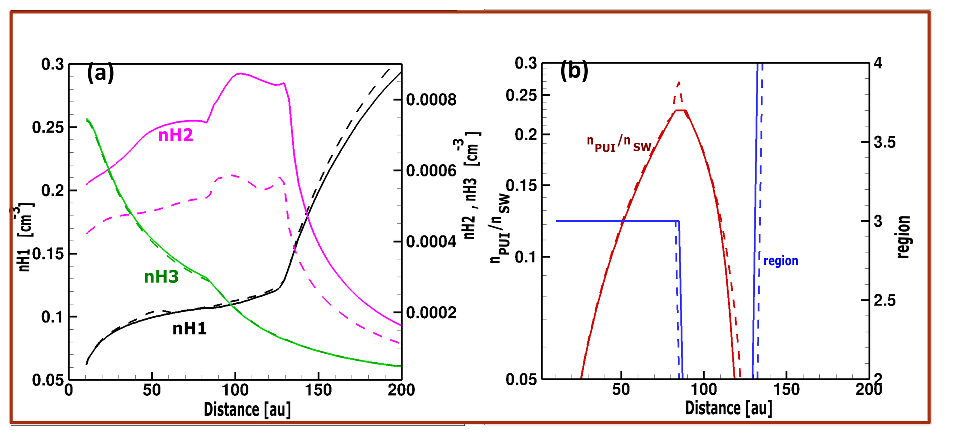


Fig 3: Linear distributions of (a) three different neutral populations (nH1, nH2, nH3) and (b) ratio of n_{PUI}/n_{SW} along V2 direction. Solid lines show the distributions for "NO TS-BC" case and dashed lines show for "TS-BC" case.

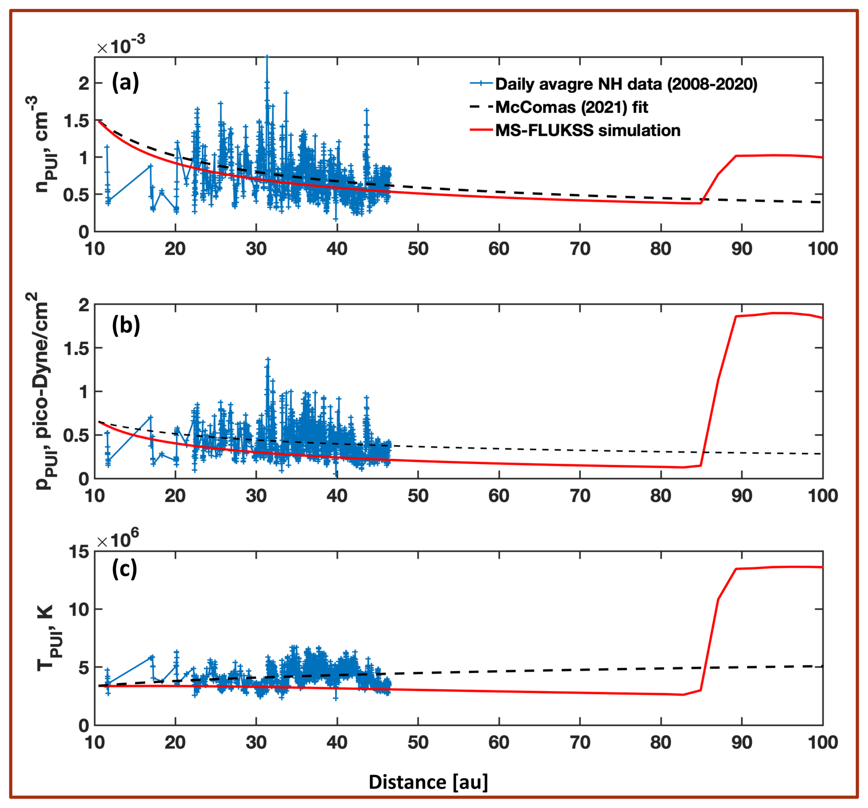


Fig 4: Comparison of MS-FLUKSS results with the NH observations [4]

PUIs parameters in-front of TS (~90 au) from the simulation

$n_{PUI}=3.8\times10^{-4}cm^{-3}$
$p_{PUI}=15fPa$
$T_{PUI}=3\times10^6K$

CONCLUSION

- The simulations are performed using kinetically derived BCs for PUIs near TS
- It is observed that the width of the heliosheath is reduced by approx 7 au when kinetic BCs are applied for PUIs
- The flow of the interstellar neutral atoms inside the heliosphere changes with the behavior of PUIs at TS
- The simulation results show a good agreement with the observations made by NH

REFERENCES

1. N. V. Pogorelov *et al* 2017 *ApJ* **845** 9
2. N. V. Pogorelov et al 2016 J. Phys.: Conf. Ser. **767** 0120202.
3. Arcadi V. Usmanov et al., 2016 *ApJ* ***820*** *17*
4. D. J. McComas *et al* 2021 *ApJS* **254** 19
4. Ming Zhang *et al* 2020 *ApJ* **889** 97
5. P. Swaczyna *et al* 2020 *ApJ* **903** 48
6. Michael Gedalin *et al* 2020 *ApJ* **889** 116
7. D. J. McComas *et al* 2017 *ApJS* **233** 8

ACKNOWLEDGEMENT

Resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center.