New Horizons Modeling Review:

Voyager Termination Shock Crossings

Marc Kornbleuth

Research Scientist

Deputy Director of SHIELD Global Heliosphere Team (RT1)

Boston University

Motivation for Global Heliosphere Models

- Allows for large-scale modeling of the heliosphere, which helps understand interplay of different processes within the global system
  - e.g., how the interstellar magnetic field affects the filtration of neutrals into the heliosphere and the distance of the heliopause/termination shock, etc.

- Allows community to better understand observations through direct/indirect comparisons and investigating differences
  - e.g., comparing modeled energetic neutral atom maps to IBEX/INCA observations

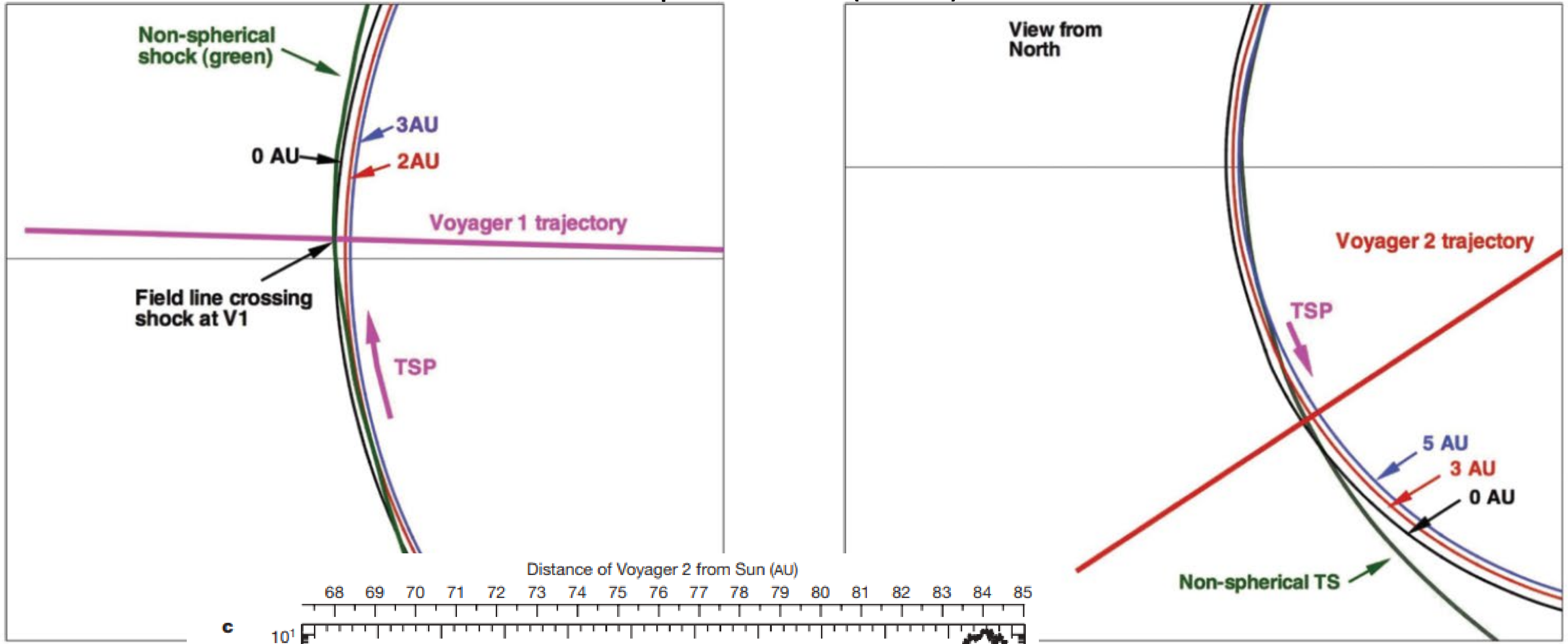
- Allows for modelers to make predictions for spacecraft observations
  - e.g., termination shock and heliopause crossing distances for Voyagers and New Horizons

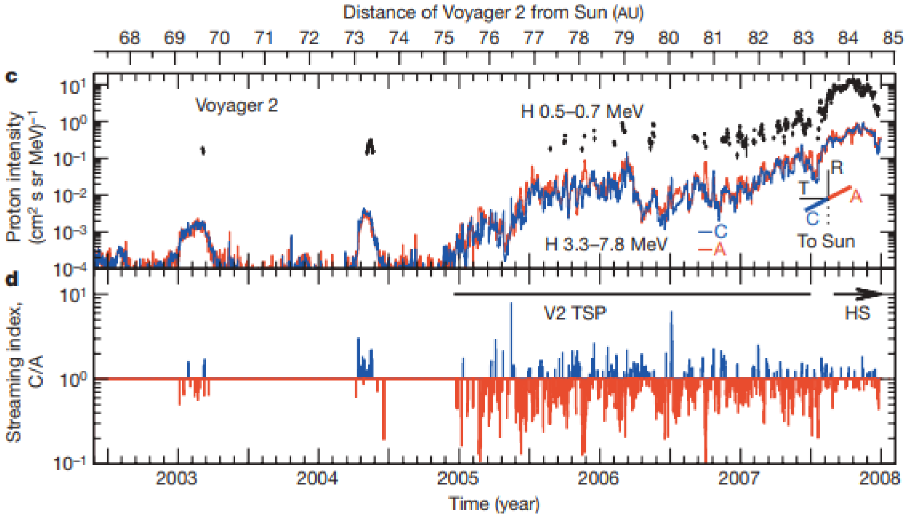
Early Modeling of the Voyager Termination Shock Crossings

One example of many: Opher et al. (2006)

- Opher et al. (2006) found that the interstellar magnetic field can produce a blunt termination shock, with a north-south asymmetry
- For a blunt termination shock, can have magnetic field lines crossing the shock connecting Voyager to shocked particles before crossing
- At Voyager 2, could be connected to the shock when it is within ~5 AU of the shock, but with particles from the shock streaming inward along the field
  - Predicted (correctly) Voyager 2 would encounter shock closer than Voyager 1

Opher et al. (2006)





Voyager 2 Particle Streaming: Stone et al. (2008)

SHIELD

Basics of Global MHD Modeling

The MHD Equations

Single-Ion MHD: Combined thermals and PUIs

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = S_\rho,$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + \left(p + \frac{B^2}{2\mu_0}\right) \cdot \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi}\right] = \mathbf{S}_{\rho v},$$

$$\frac{\partial \epsilon}{\partial t} + \nabla \cdot \left[\mathbf{u}\left(\epsilon + p + \frac{B^2}{2\mu_0}\right) - \frac{(\mathbf{u} \cdot \mathbf{B})\mathbf{B}}{\mu_0}\right] = S_\epsilon,$$

$$\epsilon = \frac{\rho u^2}{2} + \frac{p}{\gamma - 1} + \frac{B^2}{2\mu_0}.$$

Multi-Ion MHD (Opher et al. 2020): Separate thermals and PUIs

$$\frac{\partial \rho_{\mathrm{SW}}}{\partial t} + \boldsymbol{\nabla} \cdot (\rho_{\mathrm{SW}} \mathbf{u}_{\mathrm{SW}}) = S_{\rho_{\mathrm{SW}}}$$

$$\frac{\partial \rho_{\mathrm{PUI}}}{\partial t} + \boldsymbol{\nabla} \cdot (\rho_{\mathrm{PUI}} \mathbf{u}_{\mathrm{PUI}}) = S_{\rho_{\mathrm{PUI}}}$$

$$\frac{\partial (\rho_{\mathrm{SW}} \mathbf{u}_{\mathrm{SW}})}{\partial t} + \boldsymbol{\nabla} \cdot \left(\rho_{\mathrm{SW}} \mathbf{u}_{\mathrm{SW}} \mathbf{u}_{\mathrm{SW}} + p_{\mathrm{SW}} \overleftrightarrow{I}\right) - \frac{\rho_{\mathrm{SW}}}{m_p} (\mathbf{u}_{\mathrm{SW}} - \mathbf{u}_+) \times \mathbf{B} - \frac{\rho_{\mathrm{SW}}}{n_e e} \mathbf{J} \times \mathbf{B} = S_{M_{\mathrm{SW}}}$$

$$\frac{\partial (\rho_{\mathrm{PUI}} \mathbf{u}_{\mathrm{PUI}})}{\partial t} + \boldsymbol{\nabla} \cdot \left(\rho_{\mathrm{PUI}} \mathbf{u}_{\mathrm{PUI}} \mathbf{u}_{\mathrm{PUI}} + p_{\mathrm{PUI}} \overleftrightarrow{I}\right) - \frac{\rho_{\mathrm{PUI}}}{m_p} (\mathbf{u}_{\mathrm{PUI}} - \mathbf{u}_+) \times \mathbf{B} - \frac{\rho_{\mathrm{PUI}}}{n_e e} \mathbf{J} \times \mathbf{B} = S_{M_{\mathrm{PUI}}}$$

$$\frac{\partial \mathcal{E}_{\mathrm{SW}}}{\partial t} + \boldsymbol{\nabla} \cdot [(\mathcal{E}_{\mathrm{SW}} + p_{\mathrm{SW}}) \mathbf{u}_{\mathrm{SW}})] - \frac{\rho_{\mathrm{SW}}}{m_p} \mathbf{u}_{\mathrm{SW}} \cdot (\mathbf{u}_{\mathrm{SW}} - \mathbf{u}_+) \times \mathbf{B} - \frac{\rho_{\mathrm{SW}}}{n_e e} \mathbf{u}_{\mathrm{SW}} \cdot \mathbf{J} \times \mathbf{B} = S_{\mathcal{E}_{\mathrm{SW}}}$$

$$\frac{\partial \mathcal{E}_{\mathrm{PUI}}}{\partial t} + \boldsymbol{\nabla} \cdot [(\mathcal{E}_{\mathrm{PUI}} + p_{\mathrm{PUI}}) \mathbf{u}_{\mathrm{PUI}})] - \frac{\rho_{\mathrm{PUI}}}{m_p} \mathbf{u}_{\mathrm{PUI}} \cdot (\mathbf{u}_{\mathrm{PUI}} - \mathbf{u}_+) \times \mathbf{B} - \frac{\rho_{\mathrm{PUI}}}{n_e e} \mathbf{u}_{\mathrm{PUI}} \cdot \mathbf{J} \times \mathbf{B} = S_{\mathcal{E}_{\mathrm{PUI}}} + H$$

Modeling of the Solar Wind Profile

Three methods for modeling solar wind profile in MHD:

1. **Uniform solar wind**

    -Time-independent solar wind conditions

    -Spherically symmetric solar wind (i.e. solar wind is uniform for all latitudes and longitudes at inner boundary)

2. **Latitudinally-varying solar wind**

    -Time-independent solar wind conditions

    -Solar wind at inner boundary varies with latitude

    -Assume longitudinal symmetry

3. **Time-dependent solar wind**

    -Time-varying solar wind conditions based on data or empirical fits to data

    -Solar wind at inner boundary varies with latitude

    -Typically assume longitudinal symmetry for global heliosphere modeling

SHIELD

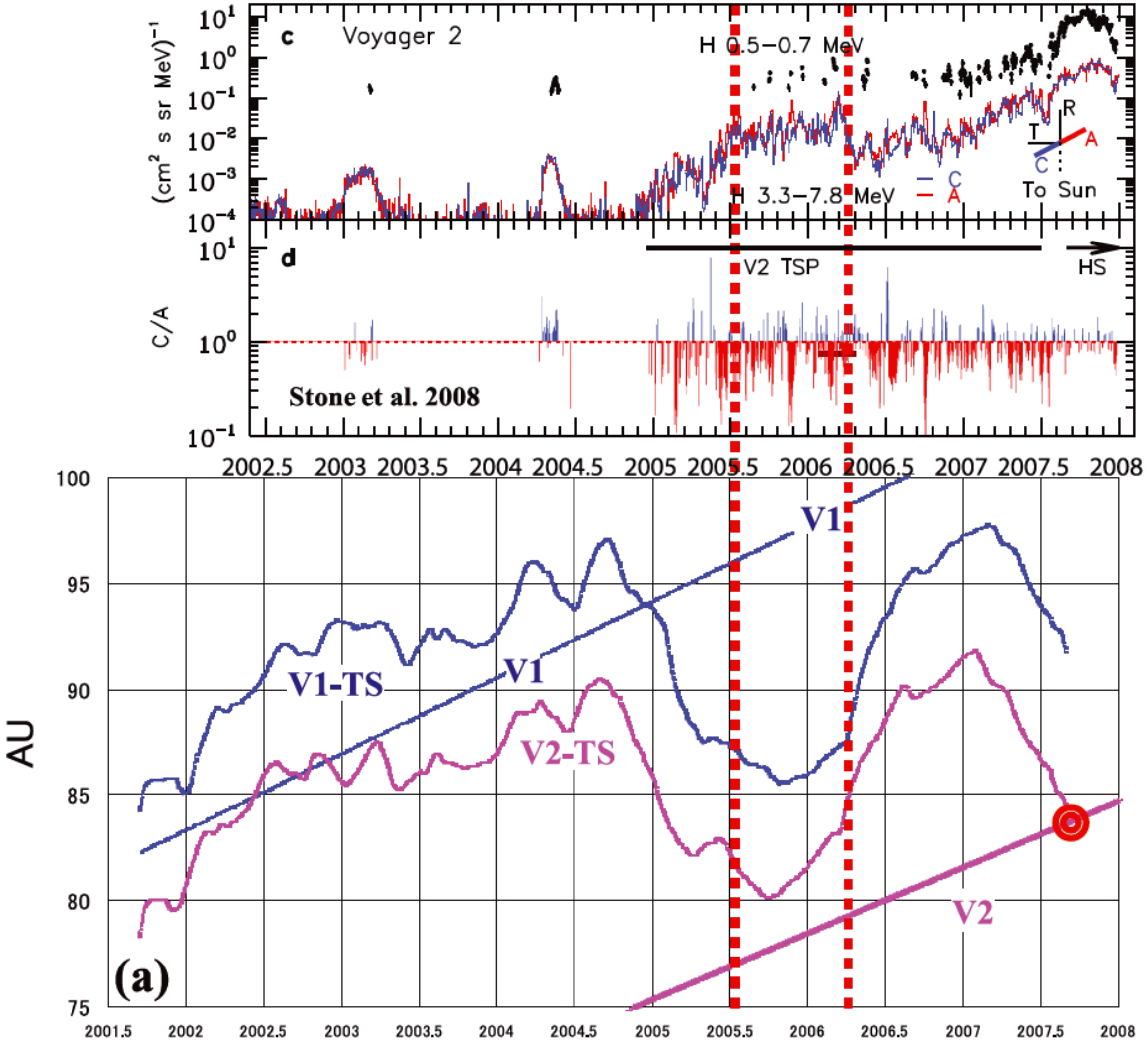
Modeling of the Voyager Termination Shock Crossings:

The Alabama Group

Time Dependent Modeling: Movement of the Termination Shock

SHIELD

- Washimi et al. (2011) used simplified time dependent modeling of the heliosphere
    - Able to match Voyager 1 and 2 termination shock crossings
    - Not able to compare well with Voyager 2 observations of the solar wind plasma in the heliosheath
- Find the termination shock position increases whenever a solar-wind high-ram-pressure pulse collides with the shock
- Termination shock shown to vary on the order of ~10 au over the solar cycle for both Voyager 1 and 2

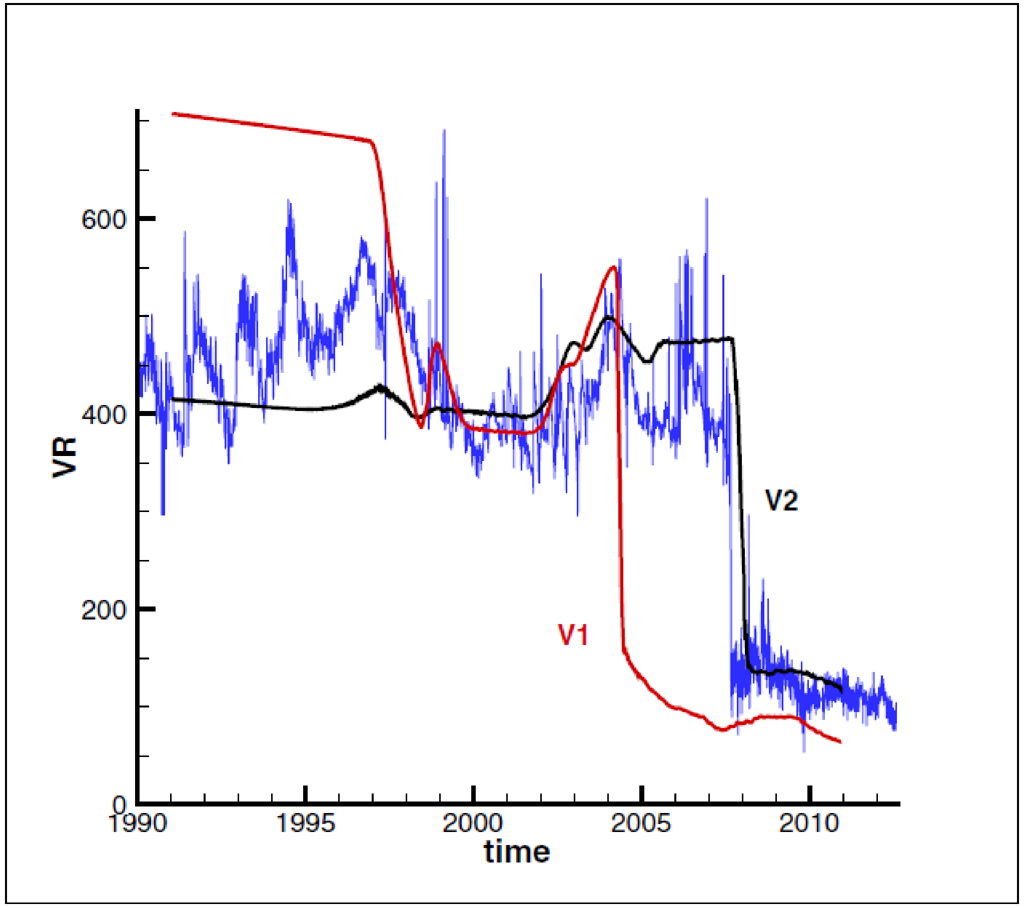


Washimi et al. (2011)

Time-dependent Modeling: Importance of Input Data

- Pogorelov et al. (2013) used realistic time dependent modeling of the heliosphere to investigate effects on flows and Voyager termination shock crossings
  - Used empirical fits to replicate Ulysses solar wind observations in modeling

- Showed that a substantial decrease in the solar wind ram pressure observed by *Ulysses* between the termination shock crossings by *Voyager 1* and *2* contributes to the differences in the crossing distances



Pogorelov et al. (2013)

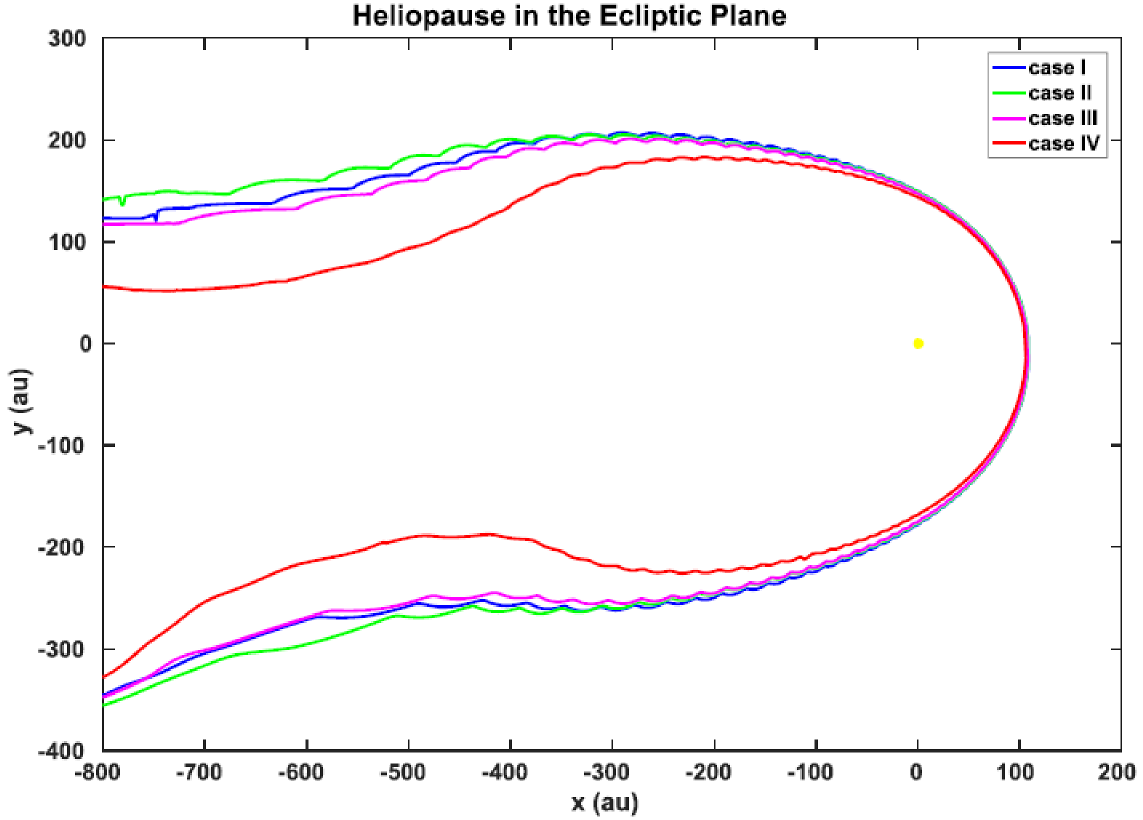
Effect of Suprathermal Ions and Electrons on the Heliosphere

SHIELD

- Heerikhuisen et al. (2019) considered the effect of suprathermal ions and cool electrons in MHD modeling with a uniform solar wind

- Modeled single-ion plasma with MHD, but when modeling charge exchange source terms considered four cases with varying ion/electron treatment

- Effect of ion treatment largely affects the heliotail, but cooler electrons (Case IV) appears to have the largest effect in shrinking the heliosphere



Case	Heliosheath *V1*	Heliosheath *V2*
I	44.7 au	41.4 au
II	43.0 au	39.9 au
III	42.8 au	39.8 au
IV	41.0 au	38.3 au

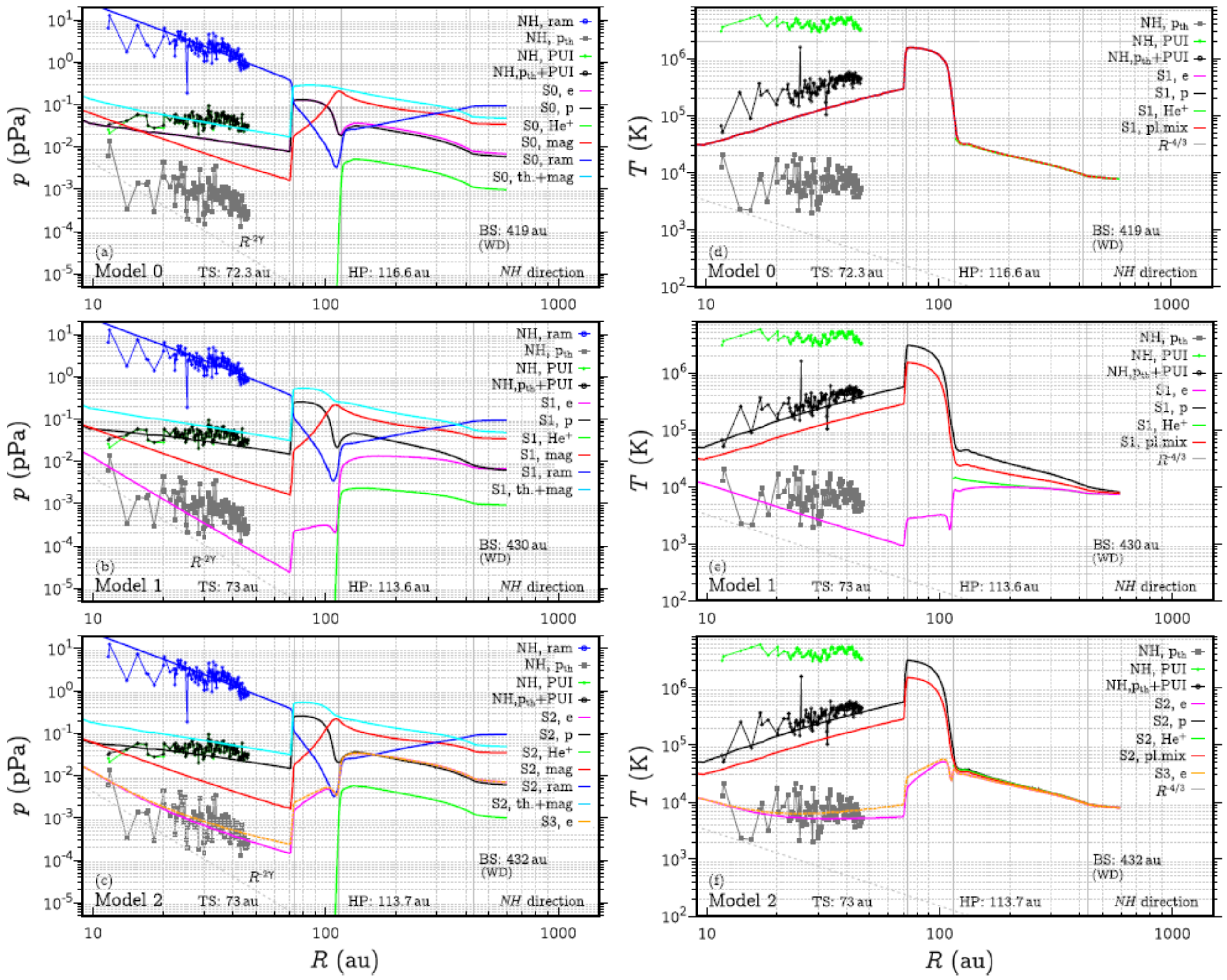
Heerikhuisen et al. (2019)

Effect of Coulomb Collisions on the Heliosphere

- Fraternale et al. (2023), using a uniform solar wind profile, considered the effect of Coulomb collisions with hot/cold electrons on the heliosphere and compared with New Horizons data

- Finds in the supersonic solar wind cooler electrons better match New Horizons observations, whereas in the ISM the protons and electrons are in thermal equilibrium

- Treating electrons as a separate, cooler fluid allows for charge-exchange driven cooling which decreases the heliosheath thickness and moves the heliopause inwards
    - Termination shock distance less affected



Fraternale et al. (2023)

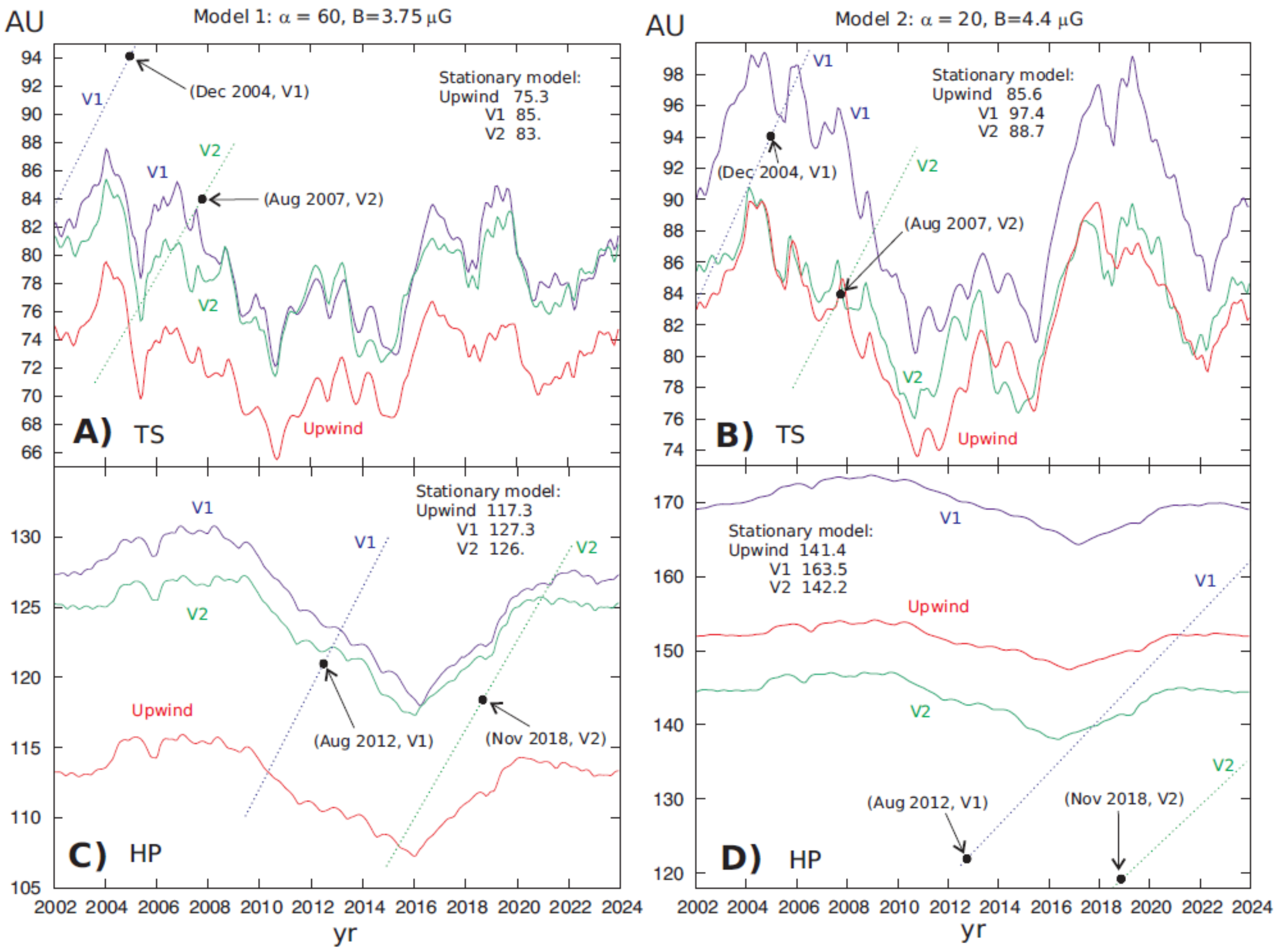
SHIELD

Modeling of the Voyager Termination Shock Crossings:

The Moscow Group

Moscow Time-dependent Modeling: SOHO/SWAN Data

- Izmodenov & Alexashov (2020) considered time-dependent MHD modeling and the effect of the interstellar magnetic field on the heliospheric boundaries
- Find termination shock fluctuations on the order of 12-15 au
- The angle between the interstellar magnetic field and interstellar flow largely influences the heliopause asymmetries
  - Find large angle best reproduces asymmetries, with similar heliopause crossings for Voyagers and ~6 au asymmetry in termination shock crossings
  - Higher time resolution could resolve data discrepancy

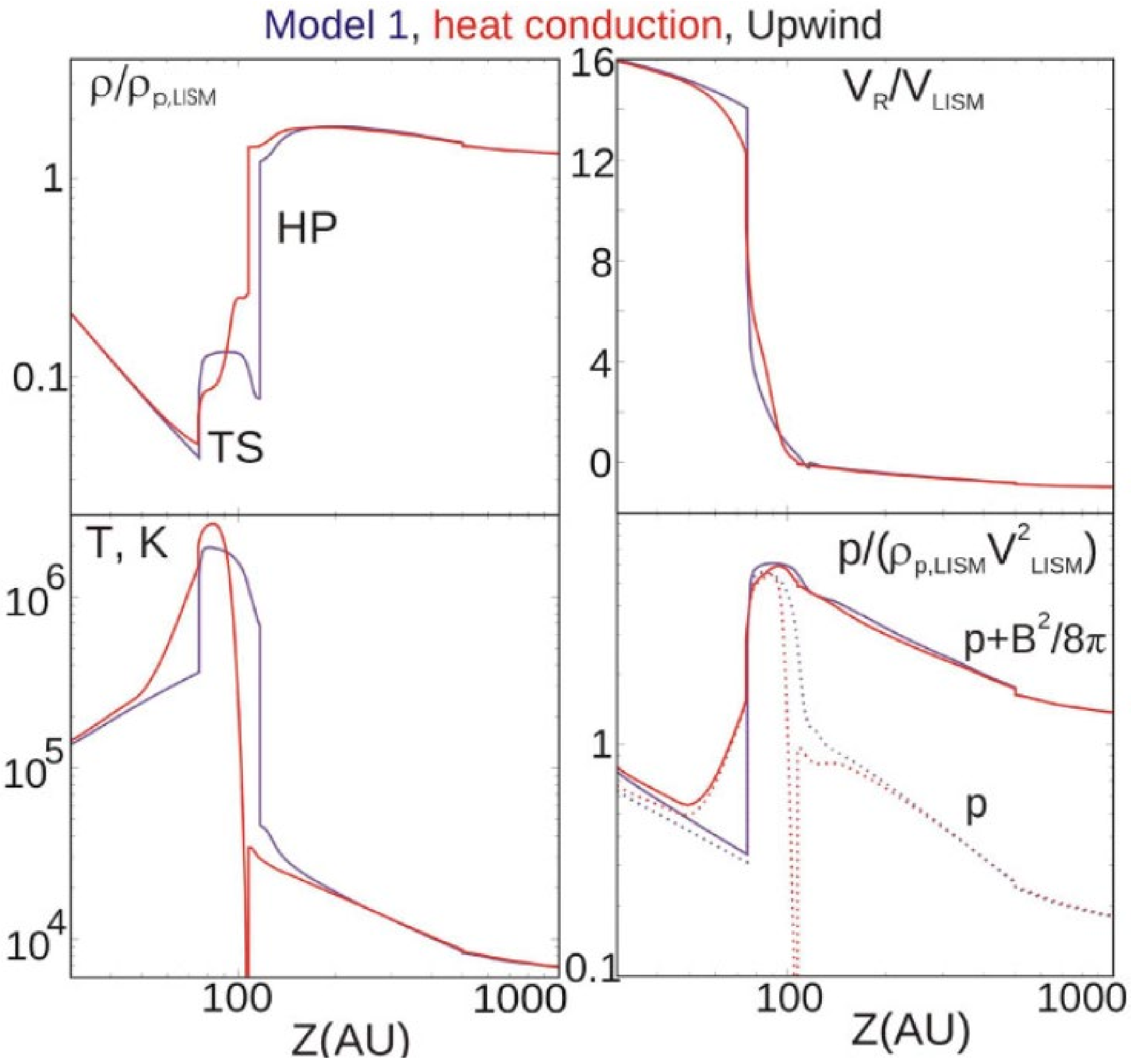


Izmodenov & Alexashov (2020)

Effect of Electron Thermal Conduction on the Heliosphere

SHIELD

- Izmodenov & Alexashov (2023) followed a study from Izmodenov et al. (2014) to explore effect of electron heat conduction on the heliosphere and understand overprediction of heliosheath thickness in models
- Used latitudinally-varying solar wind with interstellar magnetic field from Izmodenov & Alexashov (2020)
- Thickness of heliosheath reduced by 20% in the solar equator, and by 50% at the poles
- Leads to strong depletion of plasma temperature towards the heliopause and an increase in plasma temperature in supersonic solar wind upstream of the termination shock



Izmodenov & Alexashov (2023)

SHIELD

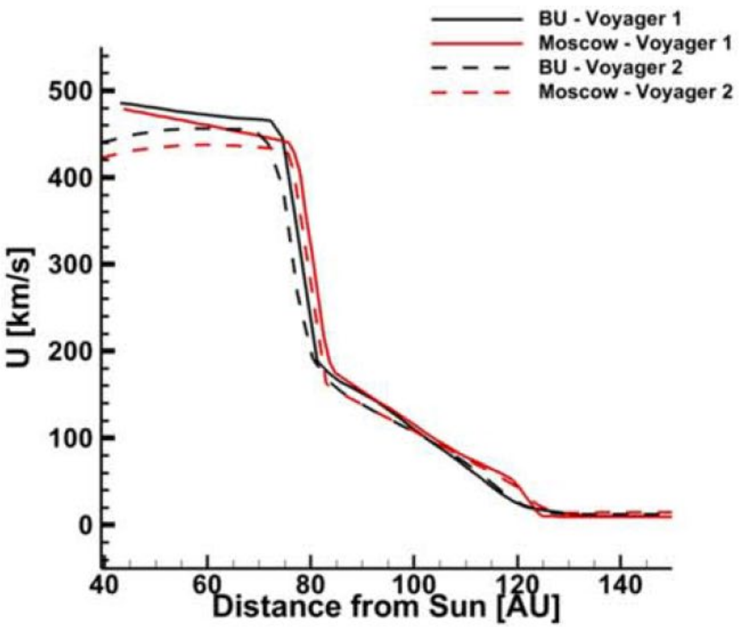
Modeling of the Voyager Termination Shock Crossings:

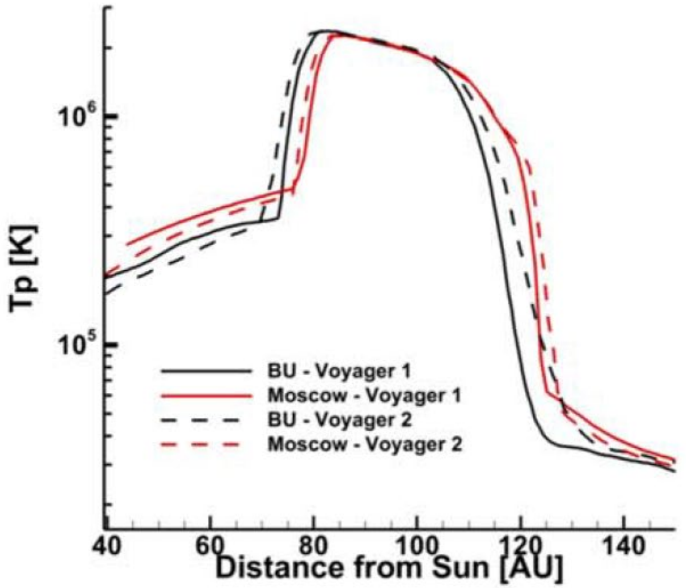
The Boston Group

A Comparison of the Boston and Moscow Single-ion Models

- Kornbleuth et al. (2021) performed a comparison of Boston and Moscow MHD models with latitudinally-varying solar wind
  - Primary difference between models is shape of the heliotail and communication between ISM and solar wind at the heliopause
- For the Voyager 1 and 2 directions, see very similar termination shock and heliopause distances
  - Reconnection at the heliopause and shape of heliotail do not strongly affect boundary locations in the upwind hemisphere

Kornbleuth et al. (2021)





Comparison of Termination Shock (r_{TS}) and Heliopause (r_{HP}) Locations for the Voyager 1 and 2 Directions between the BU and Moscow Models, and the Heliosheath Thicknesses (d_{HS})

	BU (V1)	Moscow (V1)	BU (V2)	Moscow (V2)
r_{TS}	82 ± 4 au	80 ± 1 au	82 ± 4 au	80 ± 1 au
r_{HP}	121 ± 1 au	123 ± 1 au	126 ± 1 au	124 ± 1 au
d_{HS}	39 au	43 au	44 au	44 au

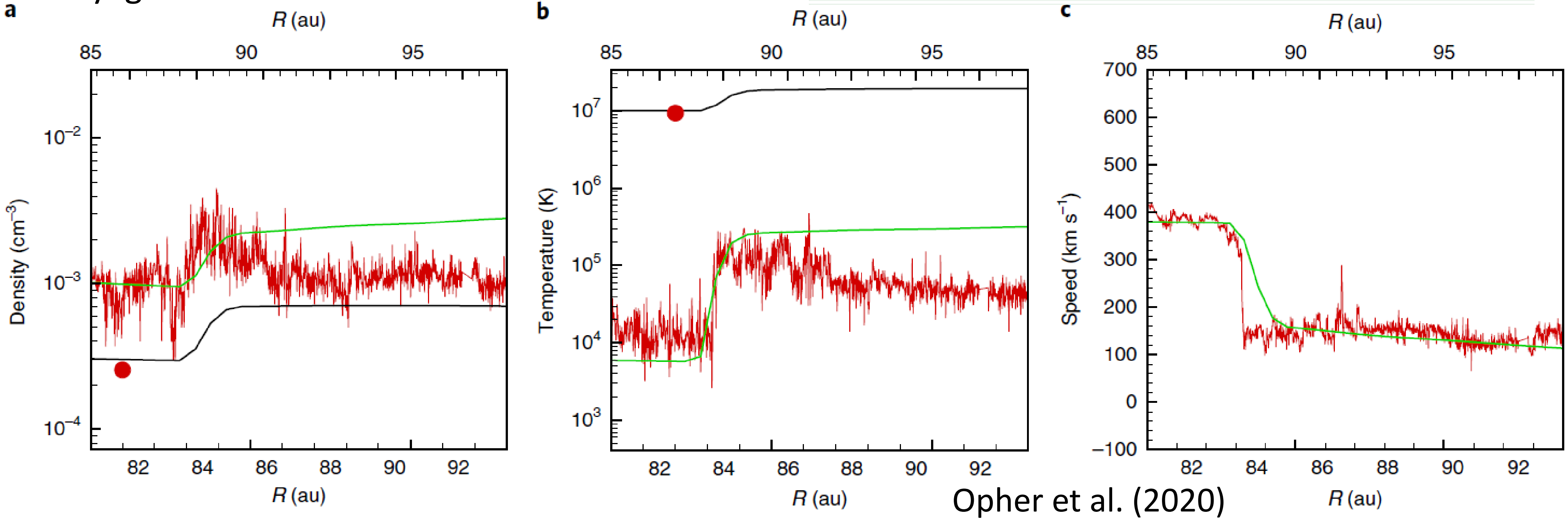
Pick-up Ions Play a Critical Role in Deflating the Heliosphere

SHIELD

- Opher et al. (2020) treated thermal solar wind ions and PUIs as separate fluids in MHD modeling with uniform solar wind
- Found treating PUIs separately led to a cooling of the heliosheath through charge exchange, leading to a decrease in the heliosheath thickness
- By matching New Horizons inferred PUI temperature and density at termination shock, able to reasonably replicate Voyager 2 observations

Table 1 | Distances to TS and HP and the thickness of the HS

Case A			Case B	
	Single ion	Multi-ion	Multi-ion	Observations
TS (V1)	85 ± 3 au	96 ± 3 au	90 ± 3 au	95 au
HP (V1)	187 ± 3 au	171 ± 3 au	146 ± 3 au	122 au
HS (V1)	102 au	75 au	56 au	28 au
TS (V2)	80 ± 3 au	91 ± 3 au	88 ± 3 au	85 au
HP (V2)	162 ± 3 au	153 ± 3 au	141 ± 3 au	119 au
HS (V2)	82 au	62 au	53 au	35 au



Opher et al. (2020)

SHIELD

Global Heliosphere Modeling

Future Efforts

Model Comparisons and Updates

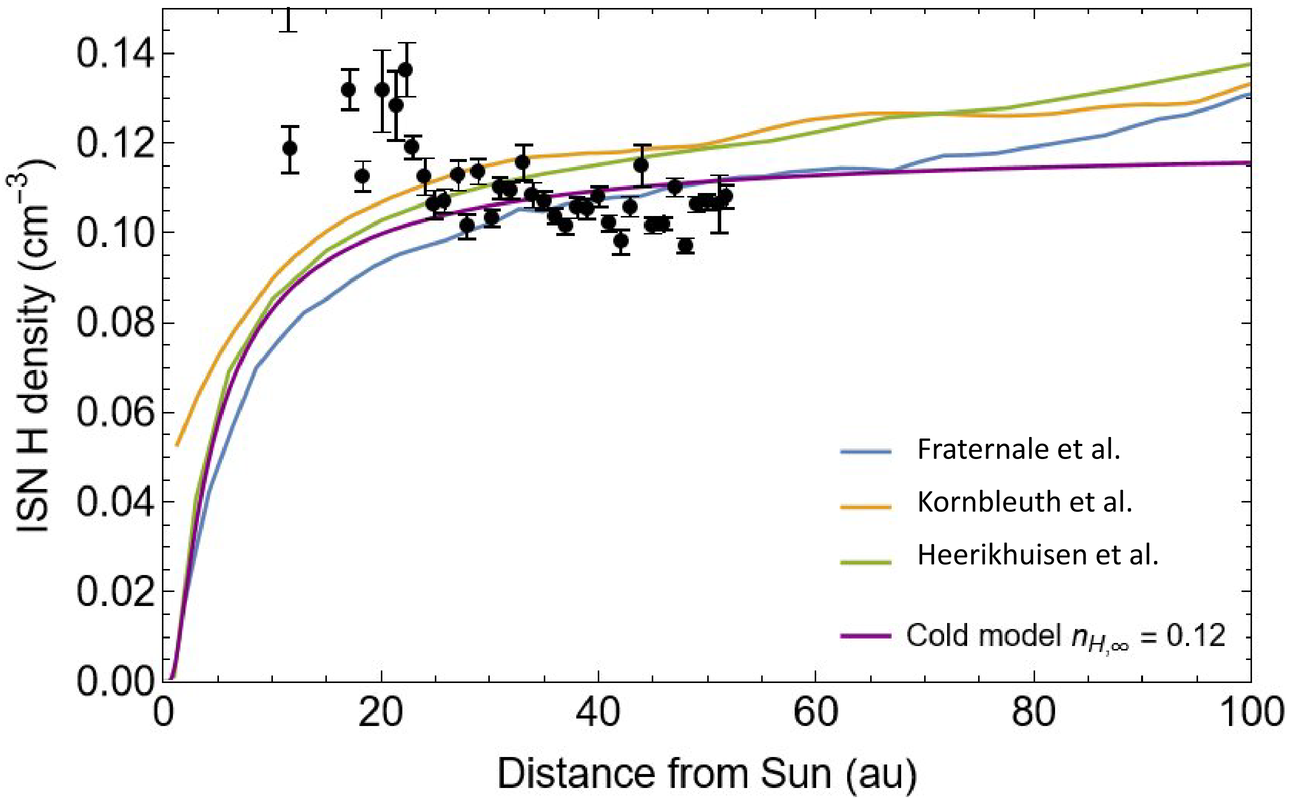
SHIELD

Ongoing model comparison:

- Swaczyna et al. (in prep) is comparing the Boston and Alabama models to understand which provides best fit to inferred neutral H observations from New Horizons
  - Models generally show reasonable agreement with each other, but disagree with New Horizons observations – needs to be reconciled

Ongoing model updates:

- The Boston (SHIELD) multi-ion model is currently being upgraded to include a time dependent solar wind and electron thermal conduction
  - Combines the most important contributors that regulate the heliosheath thickness, and therefore the boundaries



Swaczyna et al. (in prep)

Summary

SHIELD

- **MHD models have difficulty replicating both the observed Voyager termination shock and heliopause distances**

- **A time dependent solar wind is important** in MHD modeling as the termination shock can move on the order of 10-15 au over the course of a solar cycle

- **Electrons play a critical role** in regulating the thickness of the heliosheath, and need to be considered when modeling the heliospheric boundaries

- A **multi-ion MHD treatment**, which separates thermal solar wind ions and PUIs is key in matching Voyager observations and properly capturing the dynamics of the heliosheath

- **No current MHD model currently includes all of the above factors**, however models are being developed to incorporate all of the important physics for properly matching Voyager observations and for making New Horizons predictions

SHIELD

THANK YOU!

https://shielddrivecenter.com