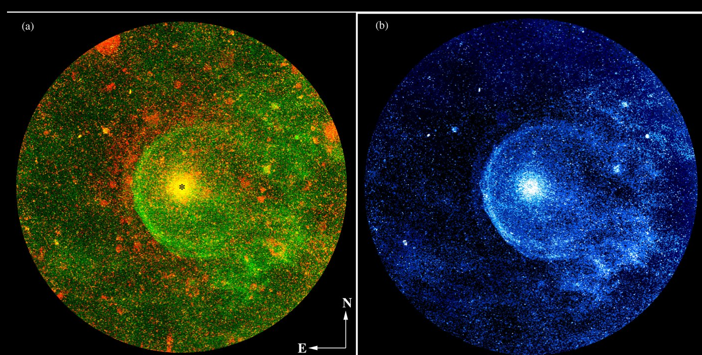
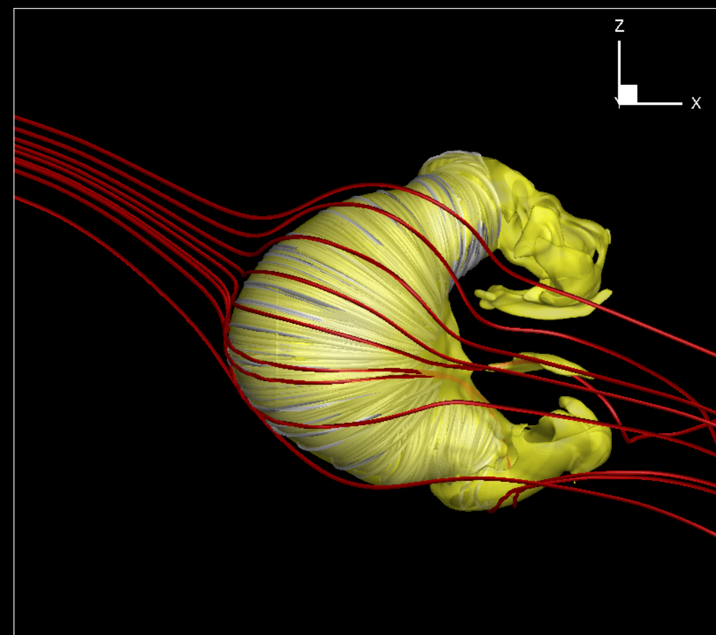
A Predicted Small and Round Heliosphere





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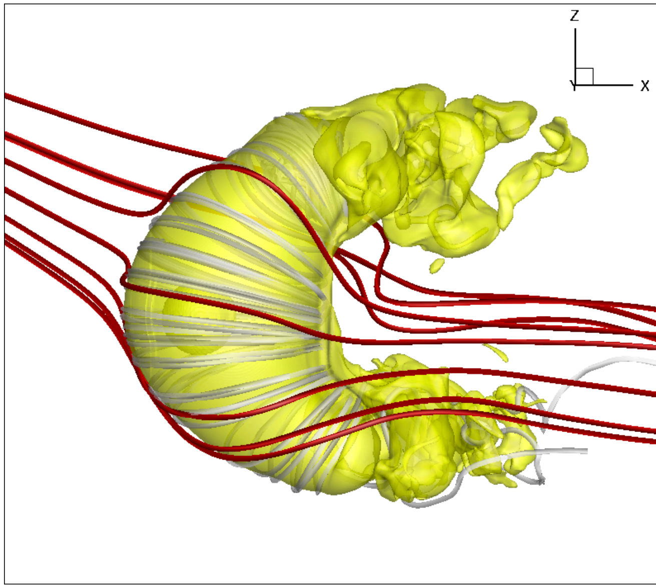
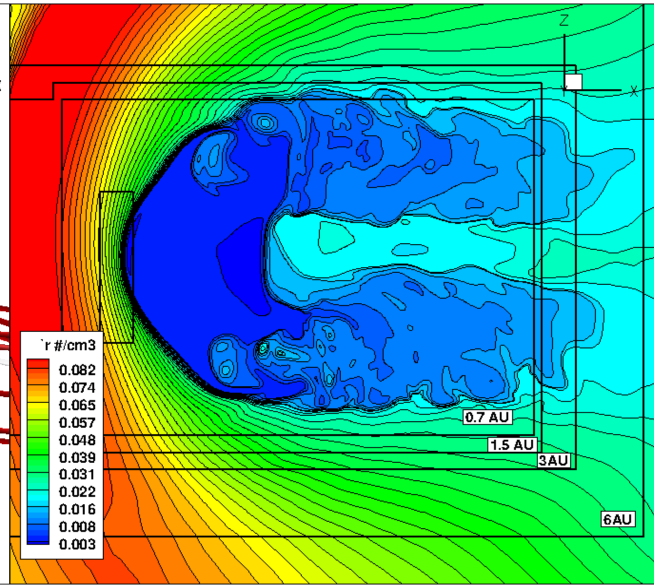
Abraham Loeb (Harvard), Jim Drake(UMD),
Gabor Toth (Univ. of Michigan)

BOSTON UNIVERSITY

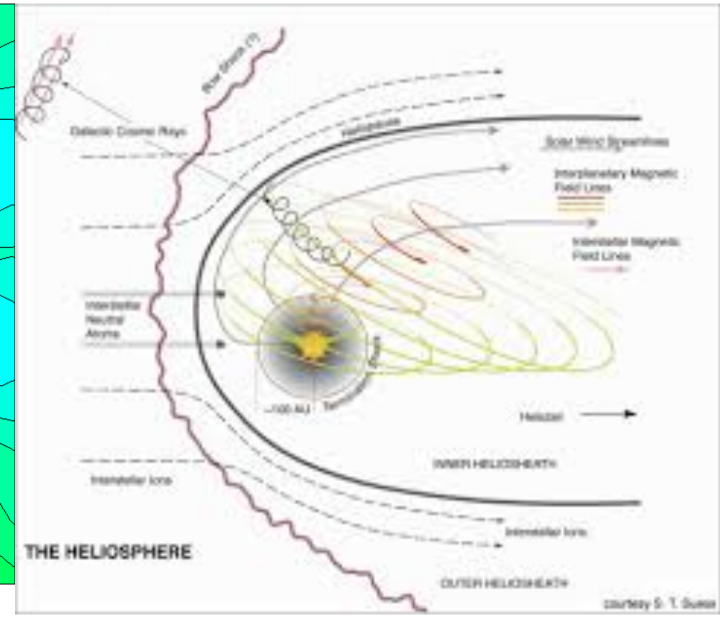
A new realization: the solar magnetic field is “slinky” and funnel the heliosheath flows



Opher et al. 2015



Deep blue: Heliosheath density



Old View: solar magnetic field being stretched back (yellow)

The Solar Magnetic field is not *passive* but instead (tension force) collimates the heliosheath flow in two jets

Resistance of the solar magnetic field to being stretched

The tension on a field line with a radius of curvature *R* is so

$$F_{tension} = \left|B \cdot \nabla B\right| / 4\pi \approx \left(B^2 / 8\pi\right)\left(2 / R\right) \qquad F_{tension} \approx 2P_B / R$$

The force stretching the magnetic field due to the flows is

so the ratio between the two forces is

$$F_{streatching} \approx \rho\left|\mathrm{v} \cdot \nabla \mathrm{v}\right| / 2 \approx \rho \mathrm{v}^2 \kappa_V \big/ 2 \approx \rho \mathrm{v}^2 \big/ 2R \approx P_{ram} \big/ R$$

$$F_{streatching} \big/ F_{tension} \approx P_{ram} \big/ 2P_B$$

Resistance of the solar magnetic field to being stretched

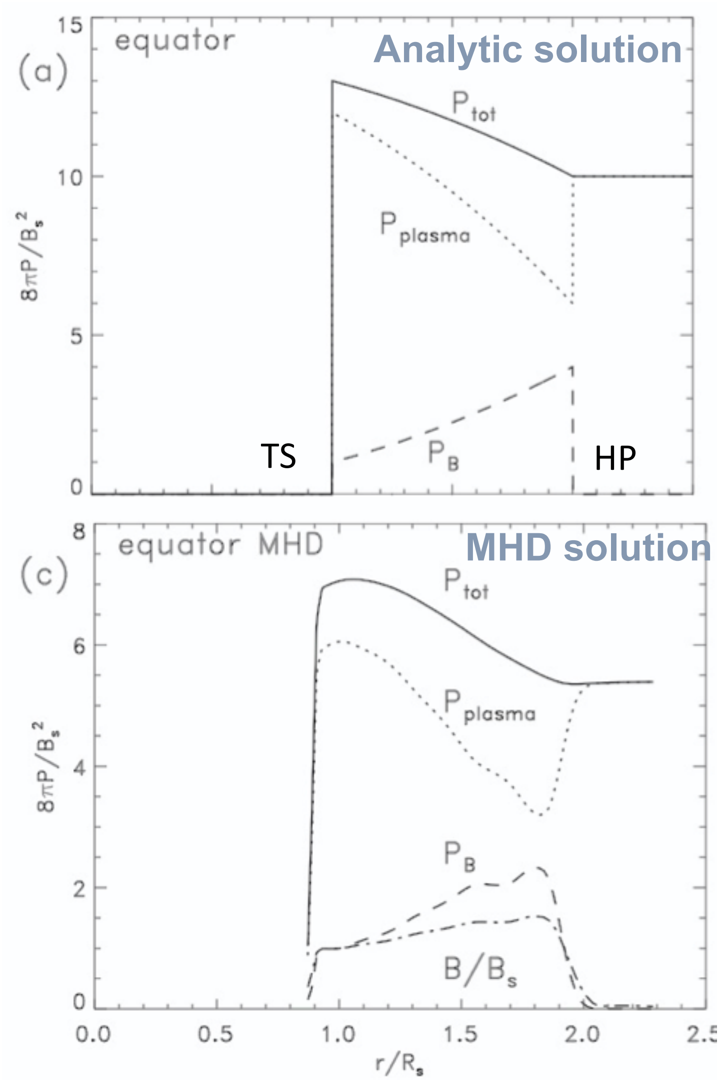
The ratio between the two forces is

$$\frac{F_{streatch}}{F_B} = \left(\frac{\rho(\#/cm^3)}{10^{-3}}\right)\left(\frac{u(km/s)}{50}\right)^2\left(\frac{0.1}{B(nT)}\right)^2 0.175$$

Taking nominal values u = 50km/s; ρ ~ 0.001#/cm^3

For B > 0.04nT = 0.4µG $\qquad F_B > F_{streatch}$

Analytic model



The gradient in the total pressure across the heliosheath is set by the

$$\frac{8\pi\Delta P}{B_s^2} = 2\frac{\tan^{-1}\left(\sqrt{2}c_{As}/V_s\right)}{\sqrt{2}c_{As}/V_s}$$

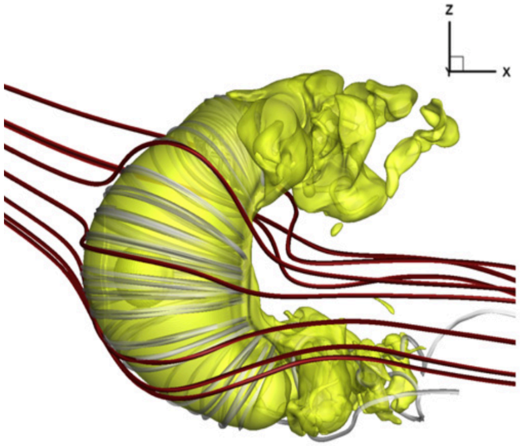
ratio of alfven speed to the flow speed at the termination shock V_s

This gradient is what drives the flows in the jet

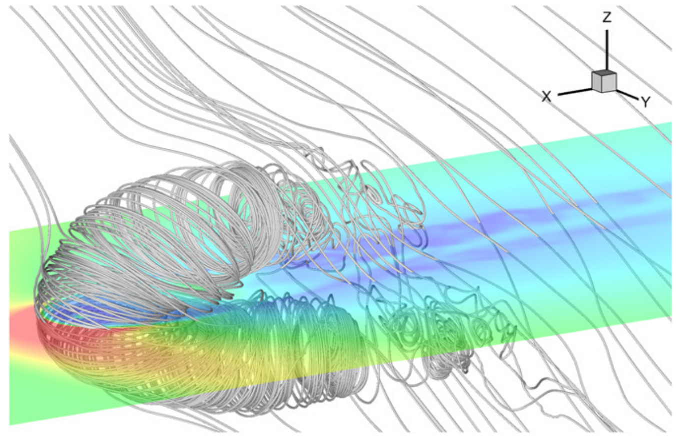
$$V_{0z} = -\frac{1}{n_s r}\frac{\partial\psi}{\partial r}$$

Drake et al. *ApJL* 2015

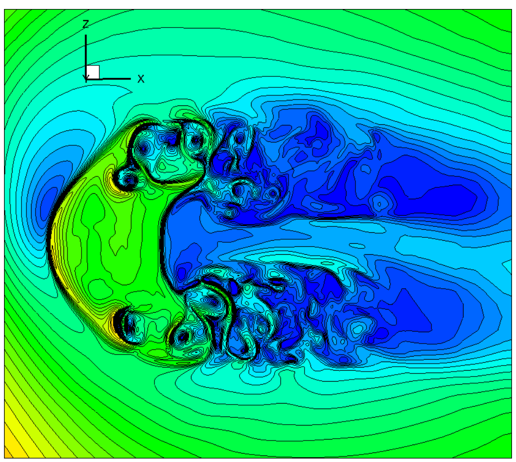
The largest turbulent structures in the heliosphere



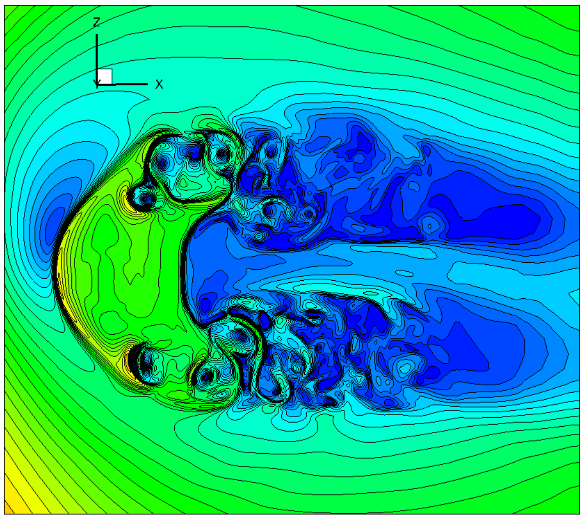
(a) Opher et al. 2015

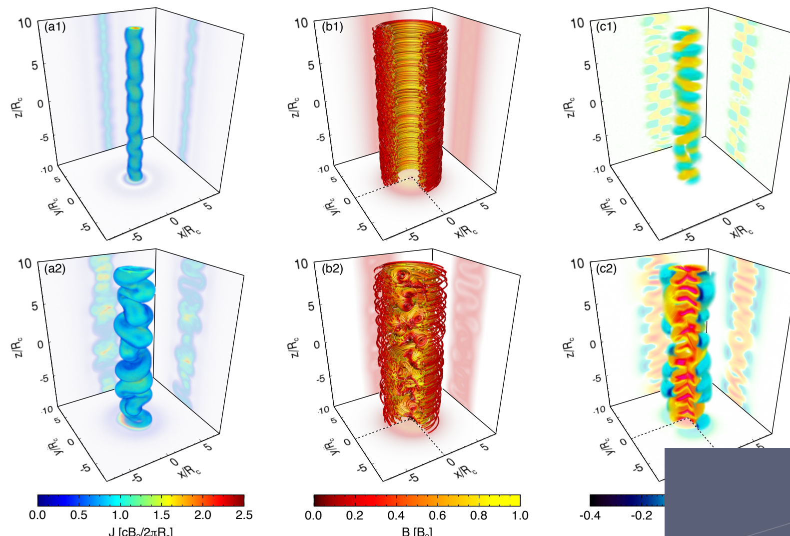


(b) Pogorelov et al. 2015



The turbulent jets

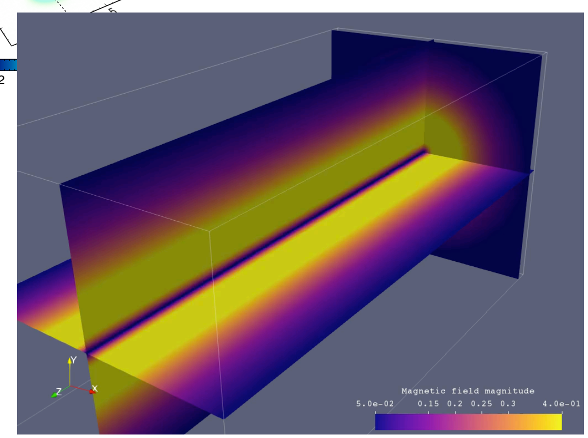




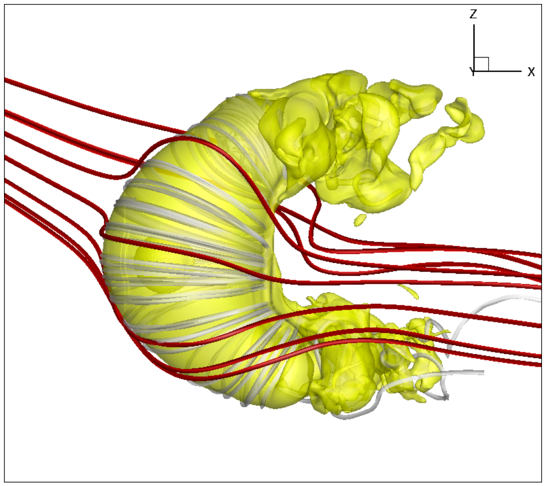
Alves, Zrake, and Fiuza (PRL, submitted), 2018

Turbulence in the jets likely to be the non-relativistic analogue of that in other astrophysical jets such as Blazar jets

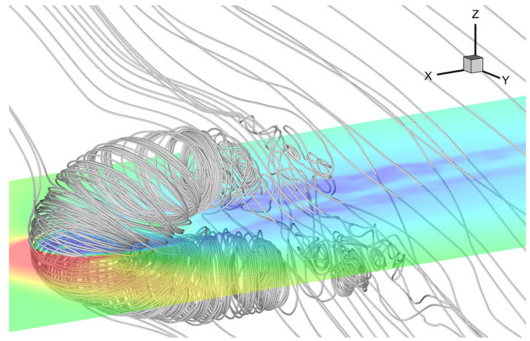
Zrake et al. Submitted '18



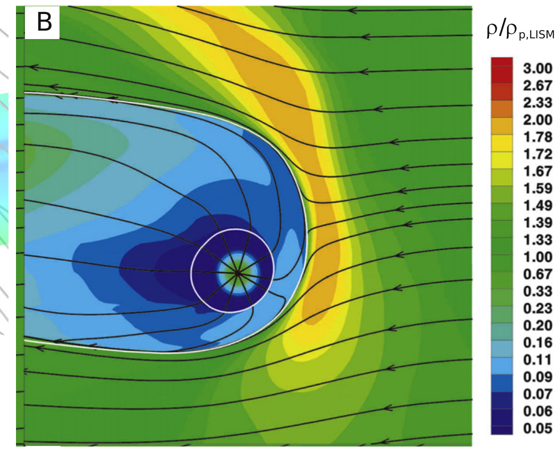
Previous 3D models: Single-Ion Approximation



Opher et al. *ApJL* 2015



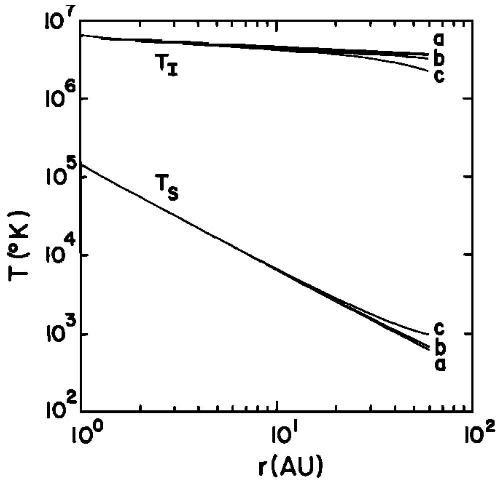
Pogorelov et al. ApJL 2015



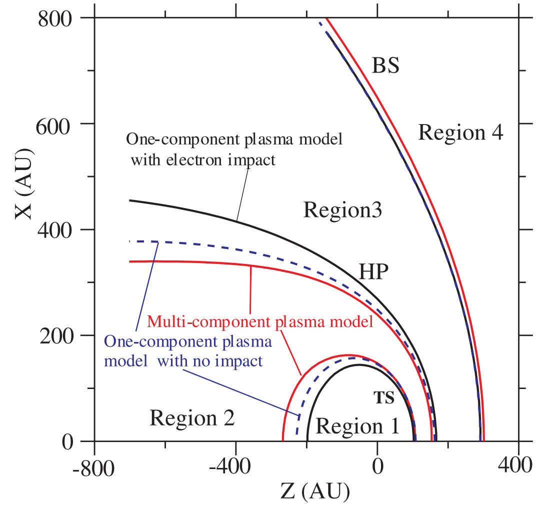
Izmodenov et al. 2015

Followed the pick-up ions and the thermal cold solar wind plasma using a *single-ion* fluid approximation

Previous Models that included PUIs



Isenberg, JGR 1986 (1-D)



Malama et al. 2006 (2-D)

Recent models : 3-D MHD - Pogorelov et al. 2016 ; Usmanov et al. 2016 -
Treating the PUIs and solar wind as co-moving; and low resolution of of the heliospheric tail, simplified treatment of n_H (Usmanov et al. 2016).

In order to be consistent with the weak shock observed by V2,
it is crucial to heat up the PUIs to high temperatures upstream the shock

Our 3D MHD Model

Two ionized fluids (thermal and PUIs) interacting with 4-neutral fluids

Opher et al. 2018;
eprint arXiv:1808.06611

$$\frac{\partial \rho_{SW}}{\partial t} + \vec{\nabla} \cdot (\rho_{SW}\vec{u}_{SW}) = S_{\rho_{SW}} \tag{1}$$

$$\frac{\partial \rho_{PUI}}{\partial t} + \vec{\nabla} \cdot (\rho_{PUI}\vec{u}_{PUI}) = S_{\rho_{PUI}} \tag{2}$$

$$\frac{\partial (\rho_{SW}\vec{u}_{SW})}{\partial t} + \vec{\nabla} \cdot \left(\rho_{SW}\vec{u}_{SW}\vec{u}_{SW} + p_{SW}\overleftrightarrow{I}\right) - \frac{\rho_{SW}}{m_p}(\vec{u}_{SW} - \vec{u}_{+})\times\vec{B} - \frac{\rho_{SW}}{\rho_{SW}+\rho_{PUI}}\vec{J}\times\vec{B} = S_{M_{SW}} \tag{3}$$

$$\frac{\partial (\rho_{PUI}\vec{u}_{PUI})}{\partial t} + \vec{\nabla} \cdot \left(\rho_{PUI}\vec{u}_{PUI}\vec{u}_{PUI} + p_{PUI}\overleftrightarrow{I}\right) - \frac{\rho_{PUI}}{m_p}(\vec{u}_{PUI} - \vec{u}_{+})\times\vec{B} - \frac{\rho_{PUI}}{\rho_{SW}+\rho_{PUI}}\vec{J}\times\vec{B} = S_{M_{PUI}} \tag{4}$$

$$\frac{\partial \mathcal{E}_{SW}}{\partial t} + \vec{\nabla} \cdot [(\mathcal{E}_{SW} + p_{SW})\vec{u}_{SW})] - \frac{\rho_{SW}}{m_p}\vec{u}_{SW} \cdot (\vec{u}_{SW} - \vec{u}_{+})\times\vec{B} - \frac{\rho_{SW}}{\rho_{SW}+\rho_{PUI}}\vec{u}_{SW} \cdot \vec{J}\times\vec{B} = S_{\mathcal{E}_{SW}} \tag{5}$$

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

S: source terms due to charge exchange

Our 3D MHD Model

The neutral component

$$\frac{\partial \rho_H(i)}{\partial t} + \vec{\nabla} \cdot (\rho_H \vec{u}_H) = S_{\rho_H}(i)$$

$$\frac{\partial \rho_H \vec{u}_H}{\partial t} + \vec{\nabla} \cdot \left(\rho_H \vec{u}_H \vec{u}_H + p_{PUIH} \overleftrightarrow{I}\right) = S_{M_H}(i)$$

(9)

$$\frac{\partial \mathcal{E}_H}{\partial t} + \vec{\nabla} \cdot [(\mathcal{E}_H + p_H)\vec{u}_H)] = S_H\ (i)$$

MHD simulation: no kinetic effects - Giacalone and Decker [2010], 2-D hybrid code using core pickup protons (25% of the total ion density) and a supra-thermal power law tail with form v^-5, reproduce the lower energy Voyager 2 Low-Energy Charged Particle Experiment (LECP) data.

Regarding the Perpendicular Speeds of PUIs and Solar Wind

For example, large gradients of PUI pressure can make the perpendicular speeds of the PUIs different than the solar wind ions. The term responsible for that, in the momentum equation Eq. 4 is ∇p_{PUI}. Comparing that term with $\vec{u}\times\vec{B}$ the ratio is

$$\frac{\nabla p_{PUI}}{ne\vec{u}\times\vec{B}} \sim \frac{v_{diamag}}{U_{flow}} \sim \frac{v_{th(PUI)}}{U_{flow}} \frac{r_L}{L_p} \qquad (1)$$

where $r_L = \frac{mv_{th(PUI)}}{|q|B}$ is the Larmor radius for the PUI; L_p the length of the gradient of pressure. v_{diamag} and $v_{th(PUI)}$are, respectively the diamagnetic and thermal speeds of the PUIs,

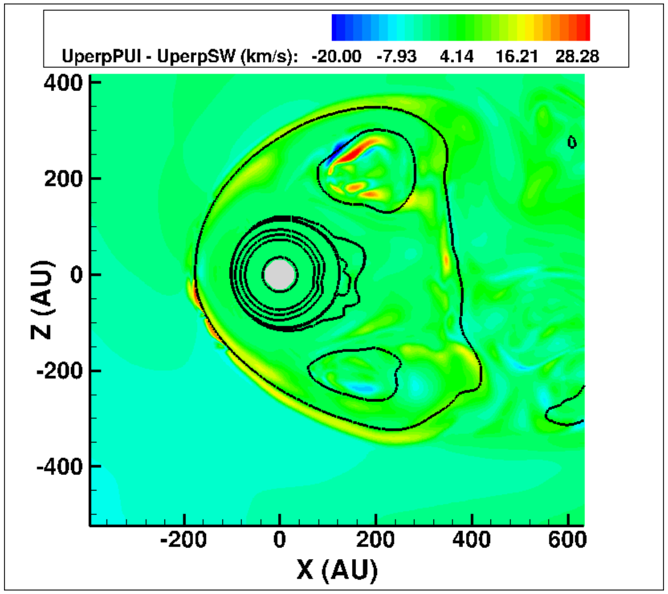
$$v_{diamg} = \frac{v_{th(PUI)}}{L_p} \frac{mv_{th(PUI)}}{|q|B} \sim \frac{p_{PUI}}{n_{PUI}} \frac{1}{|q|BL_p}$$

Regarding the Perpendicular Speeds of PUIs and Solar Wind

The ratio in Eq. (1), $\frac{v_{th(PUI)}}{U_{flow}} \sim 7$ from mid heliosheath to ~ 30 near the heliopause.

The Larmor radii $r_L \sim 2x10^{-3}\ AU$ while the PUI pressure drops length in the heliosheath is $L_p \sim 25AU$. So $\frac{\nabla p_{PUI}}{ne\vec{u}\times\vec{B}} \sim 6x10^{-4}$ and the perpendicular speeds for the PUIs and solar wind ions should be the same.

At the Termination Shock, as shows in Zieger et al. 2015, L_p is small (<r_L) there should be a difference in the perpendicular speeds in PUI and solar wind.



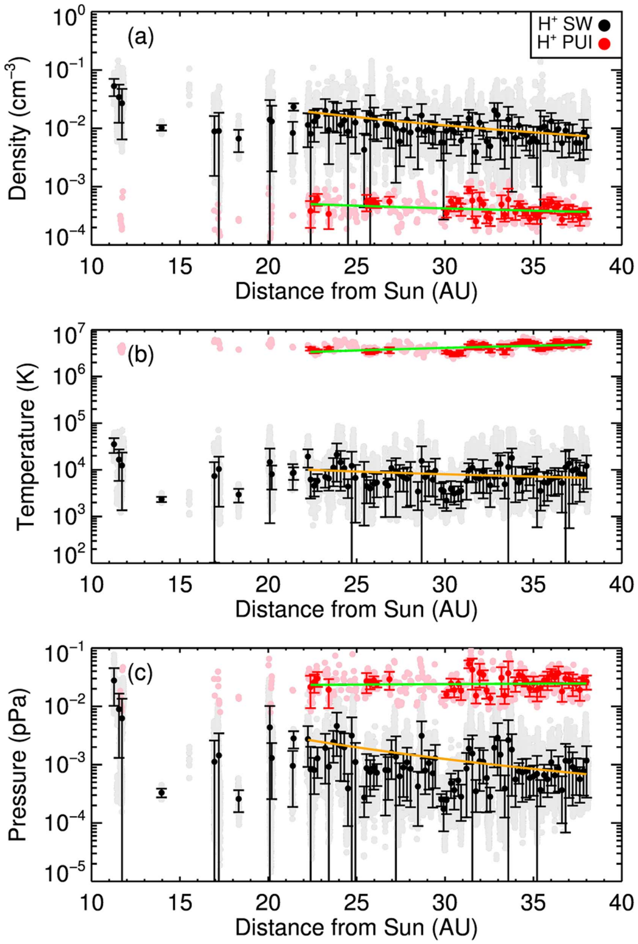
Regarding the Parallel Speeds of PUIs and Solar Wind

Along the magnetic field, the PUI and solar wind fluids are decoupled and can attain significantly different ion velocities. In reality, two-stream instabilities physically restrict the relative ion velocities parallel to the magnetic field. This two-stream instability is a kinetic phenomenon that cannot be represented in multi-ion MHD, therefore (Glocer et al. 2009) used a nonlinear artificial friction source term in the momentum equation to limit the relative velocities to realistic values,

$$S_M^{friction} = \frac{\rho_{PUI}}{\tau_c}(\vec{u}_{PUI} - \vec{u}_{SW})\left(\frac{|\vec{u}_{PUI} - \vec{u}_{SW}|}{u_c}\right)^{\alpha_c}$$

where τ_c is the relaxation time scale, u_c is the cutoff velocity, and α_c is the cutoff exponent.

New Horizon Measurements indicate that PUI thermal pressure is A substantial fraction of the pressure upstream of the TS



New Horizon measurements at 30AU and 38 AU shows that the PUI temperature is increasing with distance as $r^{0.68}$;
and density of PUIs is decreasing as $r^{-0.6}$

Expectation that upstream the Termination Shock the PUI temperature is $T \sim 8.7x10^6$ K

and PUI density $n_{PUI} \sim 2.2x10^{-4} cm^{-3}$.

McComas et al. 2017

PUI Heating Term

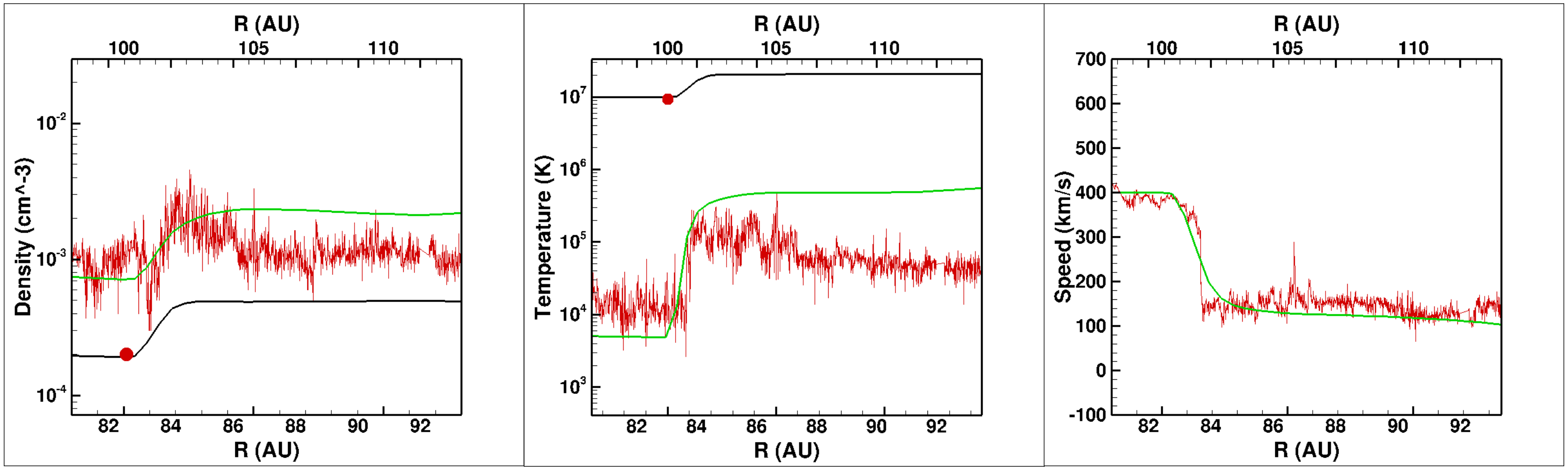
The increase of PUI pressure in the supersonic solar wind could be due to several reasons: co-rotating interaction regions that merge and drive compression and heating; etc.

We adopt an *ad-hoc* heating of the PUI in the supersonic solar wind to bring their temperature close to 10^7K upstream of the TS.

$$H = \rho_{PUI}(T_{PUI} - 10^7)(r - 30.) * 10.$$

Distance	New Horizons Density (cm^{-3})		Model Density (cm^{-3})		New Horizons Temperature (K)		Model Temperature (K)	
	SW	PUI	SW	PUI	SW	PUI	SW	PUI
30AU	1.1×10^{-2}	4.2×10^{-4}	9.4×10^{-3}	9.4×10^{-4}	8.0×10^{3}	4.1×10^{6}	1.4×10^{4}	8.1×10^{6}
90 AU	1.6×10^{-3}	2.2×10^{-4}	8.9×10^{-4}	2.0×10^{-4}	3.6×10^{3}	8.7×10^{6}	5.5×10^{3}	1.0×10^{7}
Radial Dependence	-1.8	-0.58			-0.74	0.68		

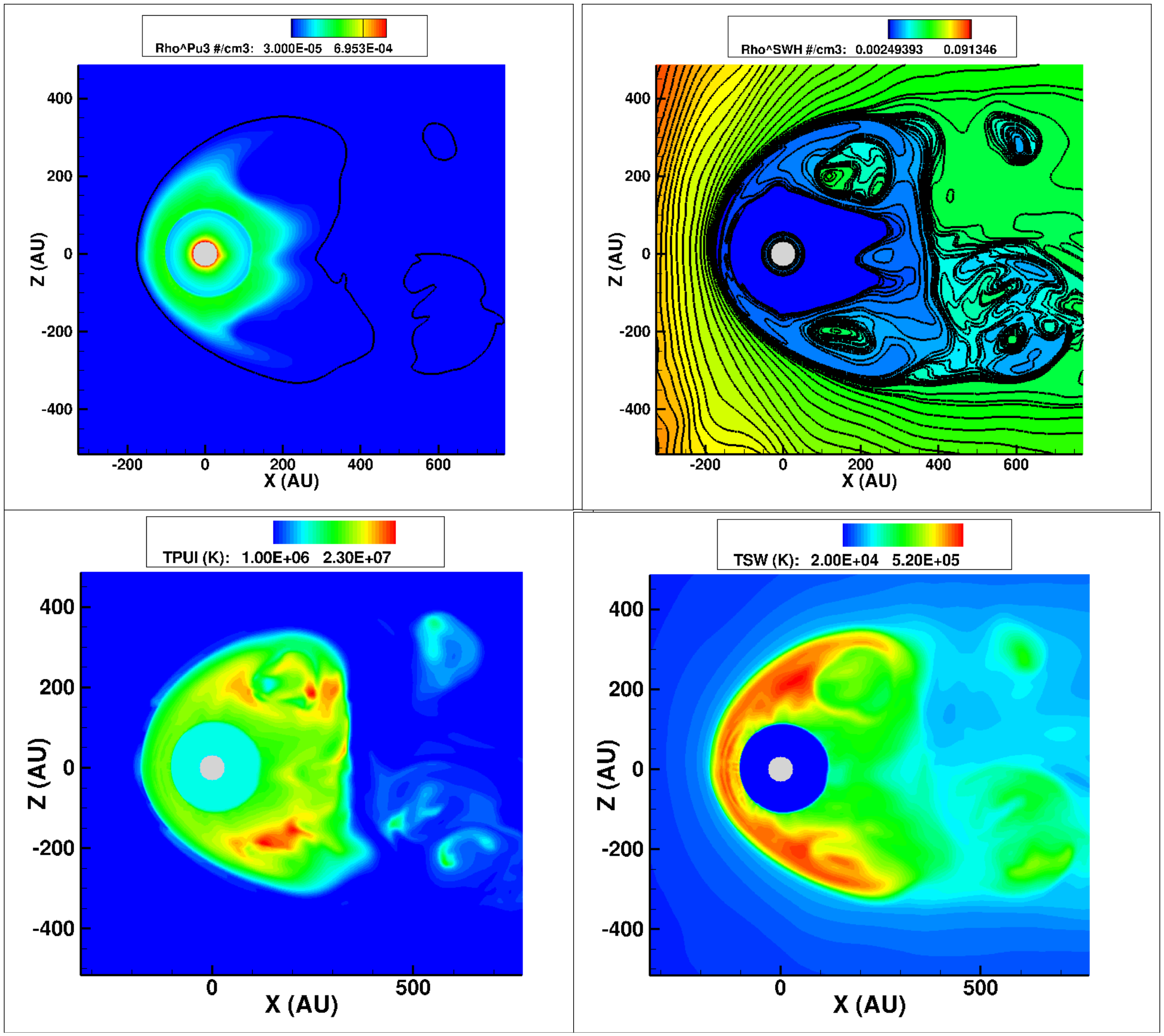
V2 TS Crossing



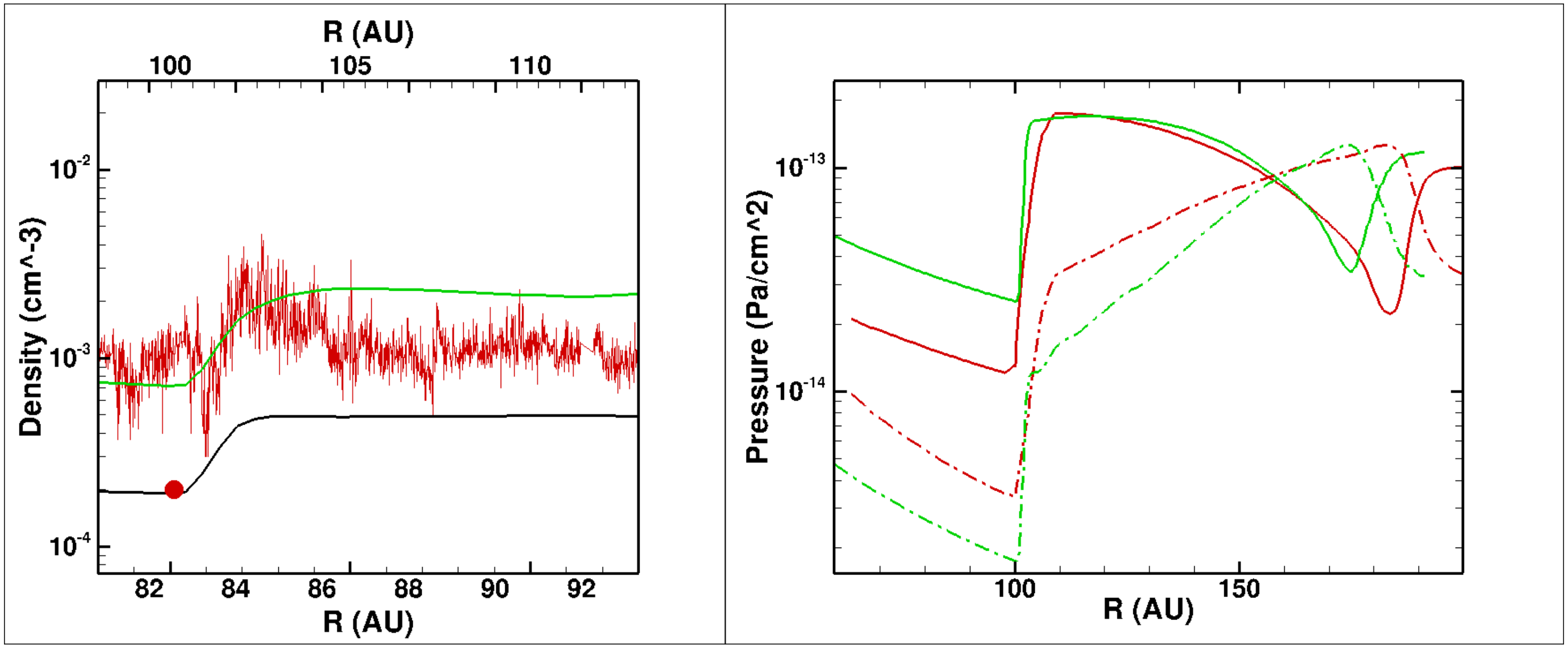
Model: green and black lines
V2 data: red line
New Horizon predictions: red dots

Pickup Ions

Solar Wind



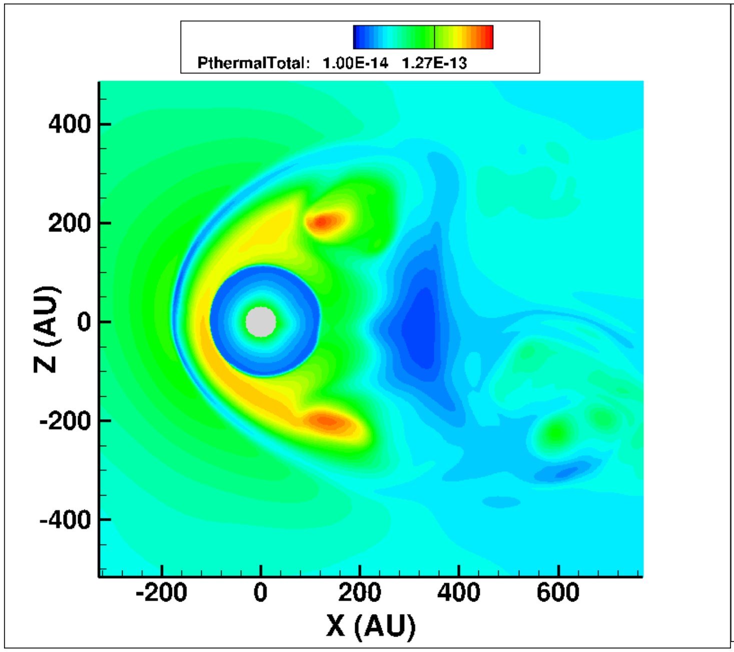
The presence of PUIs weaken the Termination Shock



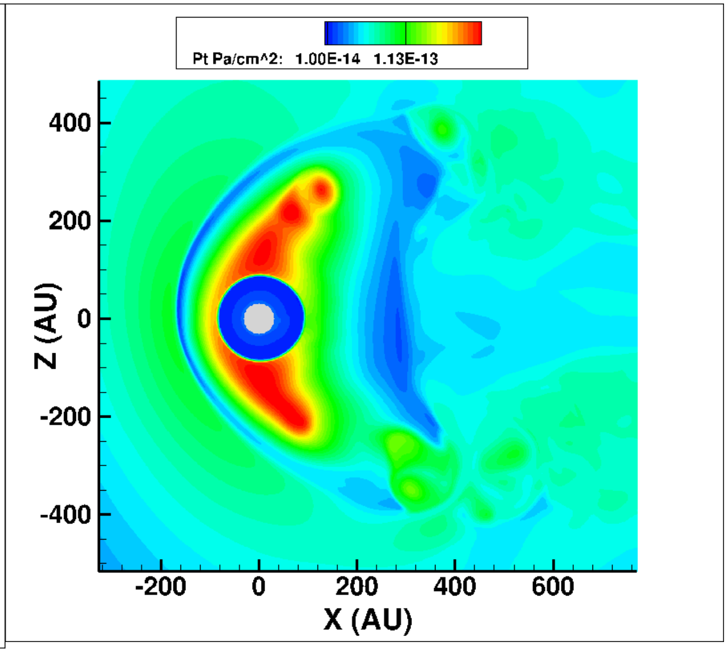
Green line (new model)
Red line (old single ion model)

A weaker shock means that the overall power going into the HS and the magnetic field in the HS is weaker than the old single-ion models

Colder Heliosheath



Multi Fluid Model

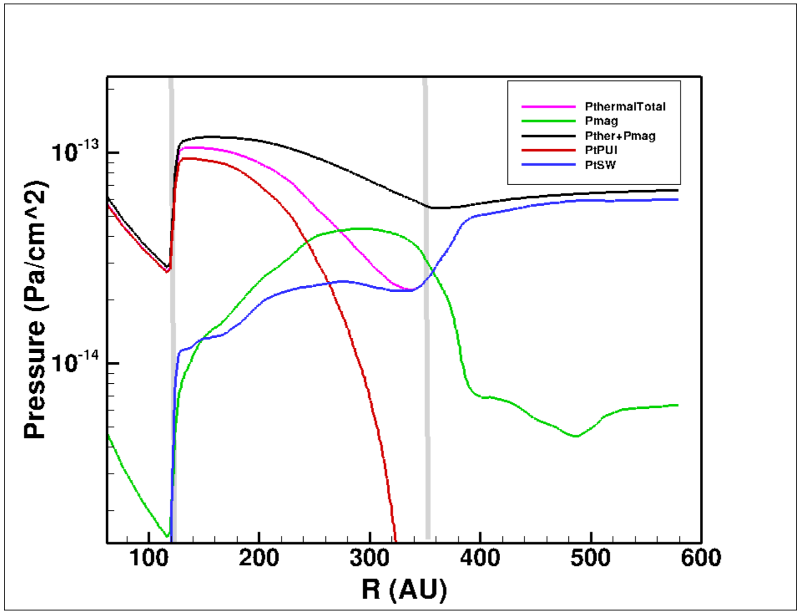


Single Ion Model

As the PUIs charge exchange, they become energetic neutral atoms and leave the system and deflate the heliosphere.

Enhanced magnetic field near the Heliopause

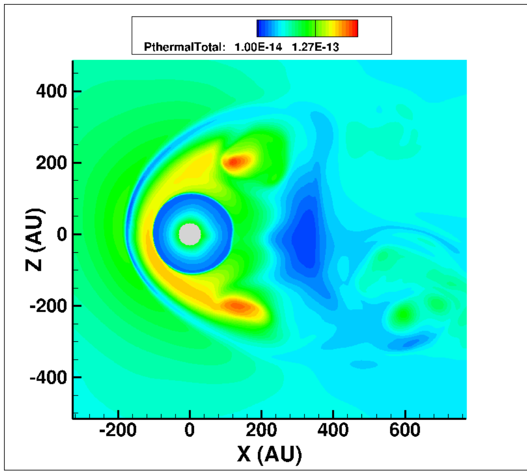
The drop in the PUI pressure compresses the magnetic field further downstream the TS near the Heliopause



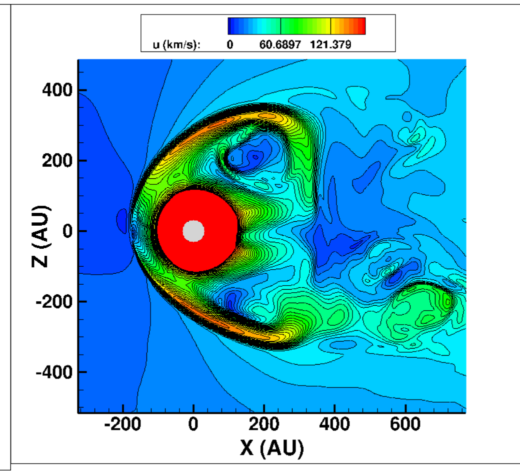
TS HP

Red: PUI pressure
Blue: Solar Wind pressure
Green: Magnetic Field pressure
Black: Total pressure

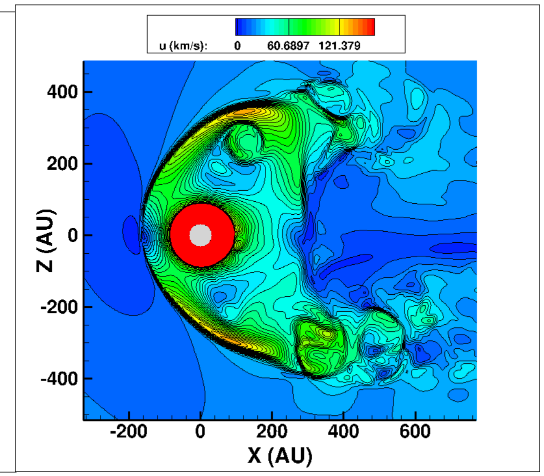
Thinning of the Heliosheath



Thermal Pressure



Multi Ion Model

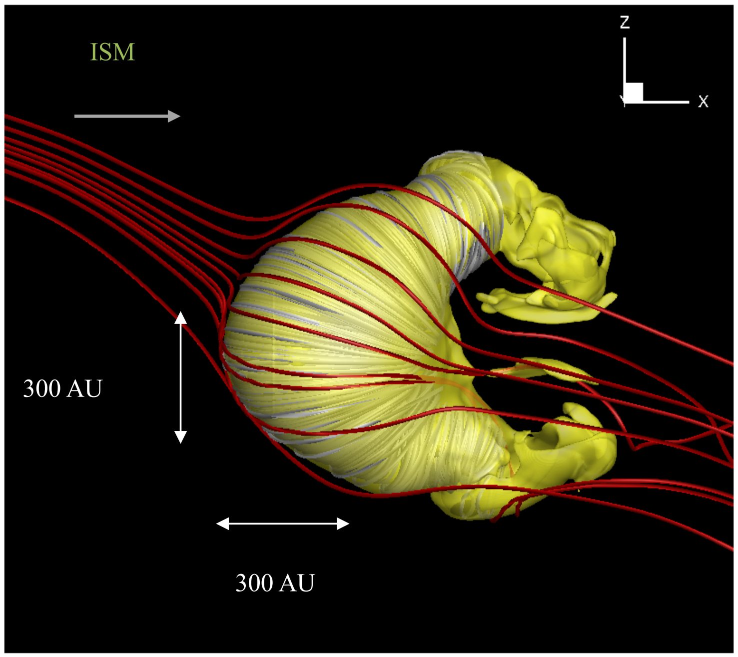


Single Ion Model

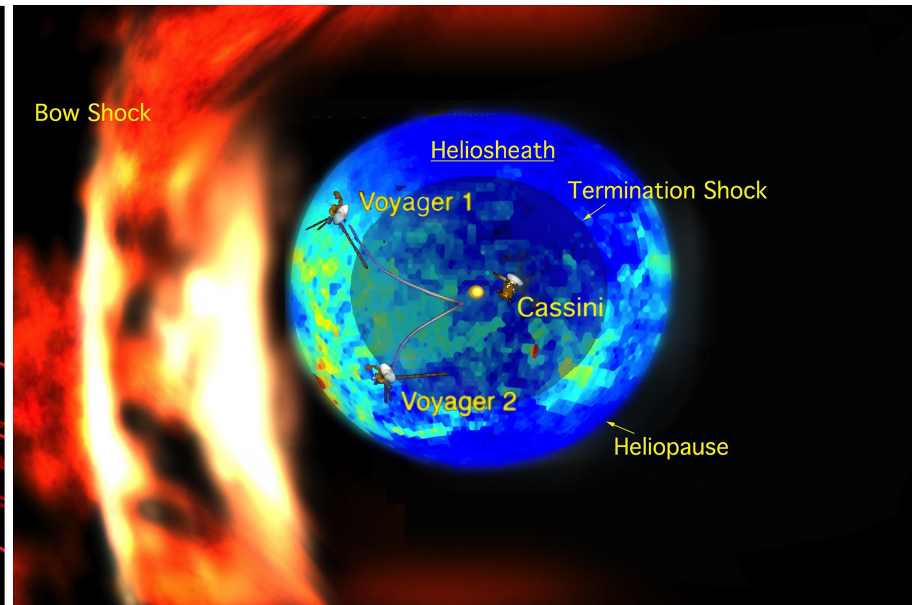
Strong gradients of the PUI thermal pressure within the HS drives faster polarward flows

The HS thickness is controlled by the continuity requirement: plasma flows across the TS must be balanced by flow down the tail within the heliosheath. Stronger flows in the HS therefore reduce the thickness of the heliosheath (Drake et al. 2015)

The Pick-up Ions deflate the heliosphere: Predicted Smaller Rounder Heliosphere



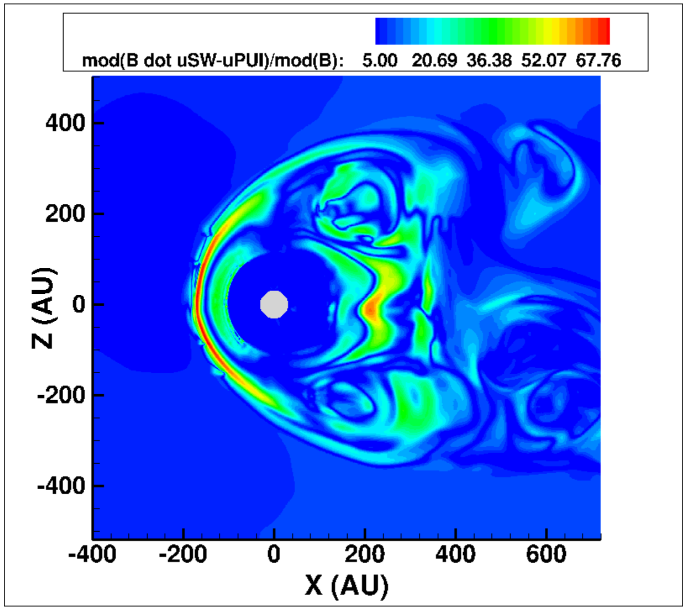
Opher et al. 2018;
eprint arXiv:1808.06611

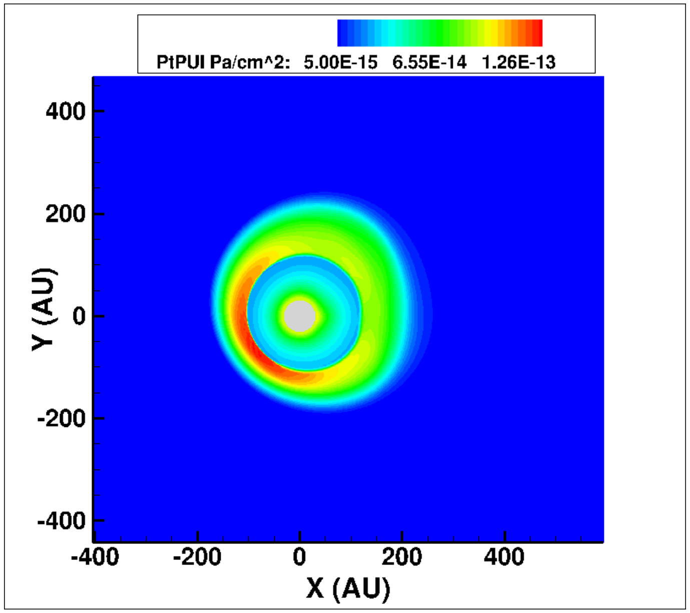


Dialynas et al. 2017

The round heliosphere has distances from the Sun to the heliopause similar in all directions

Faster streaming of PUIs along magnetic field lines





The large difference in velocity is driven by the large drop in the PUI pressure towards the flanks