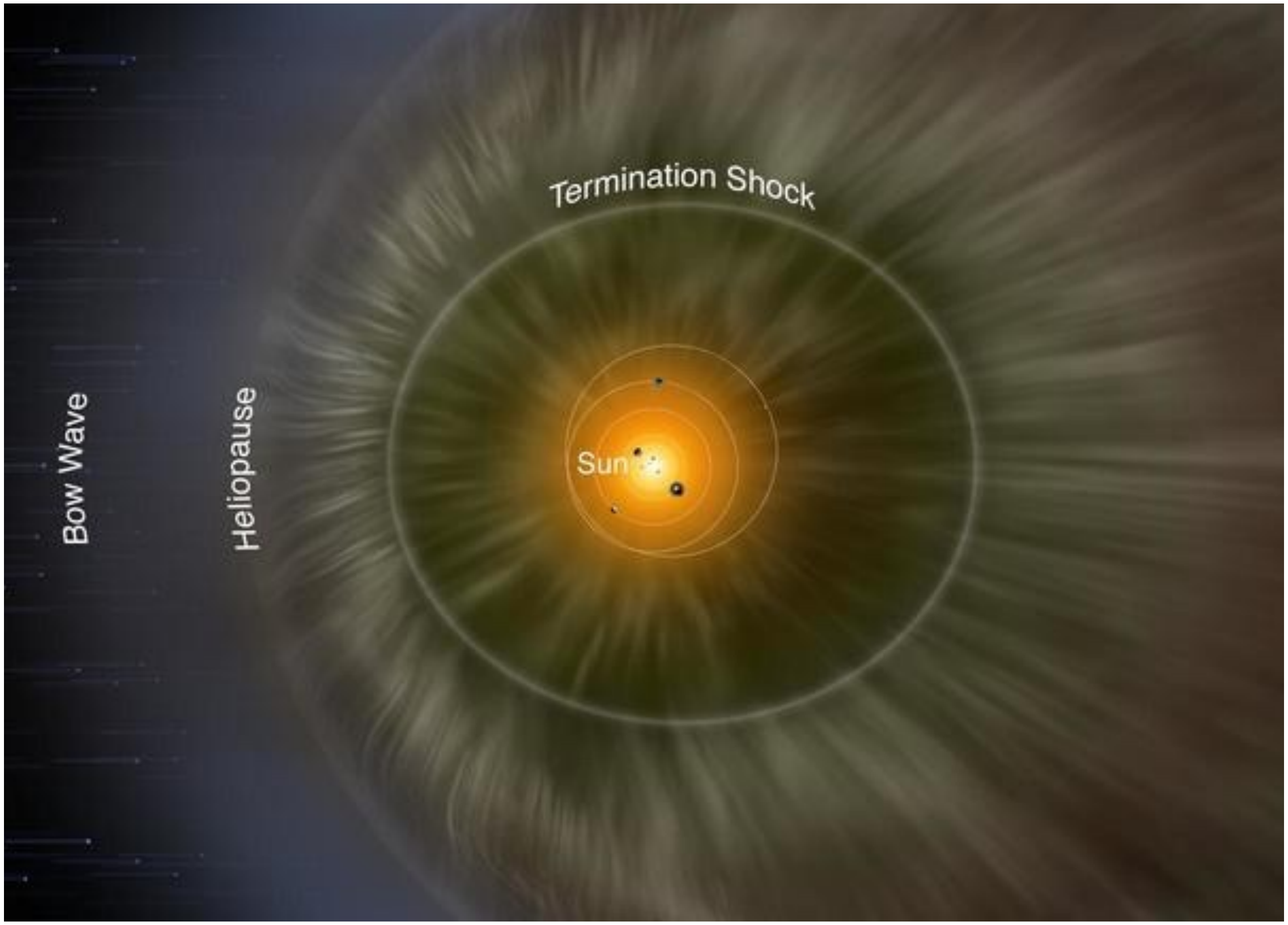
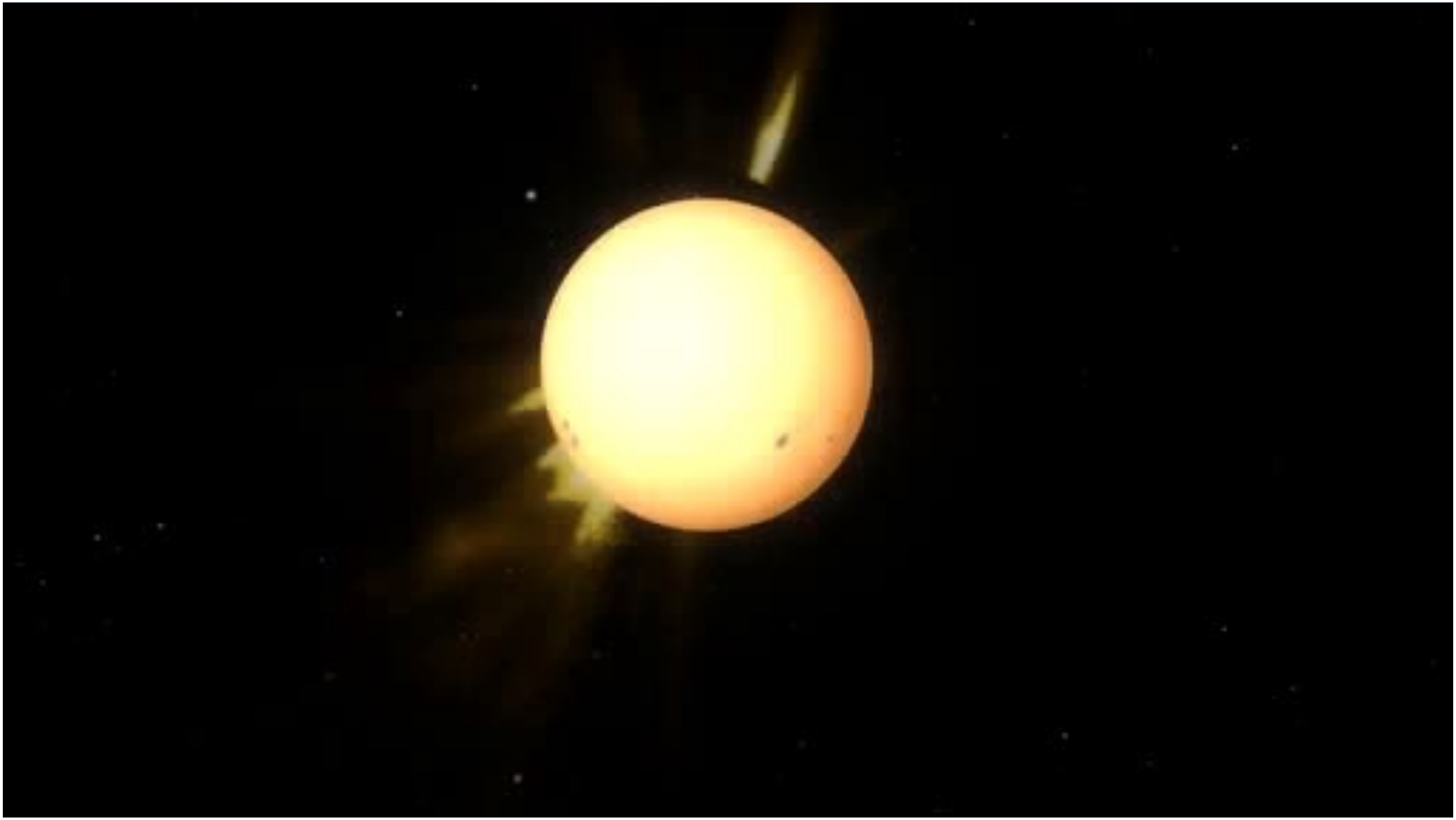
Outer Heliosphere

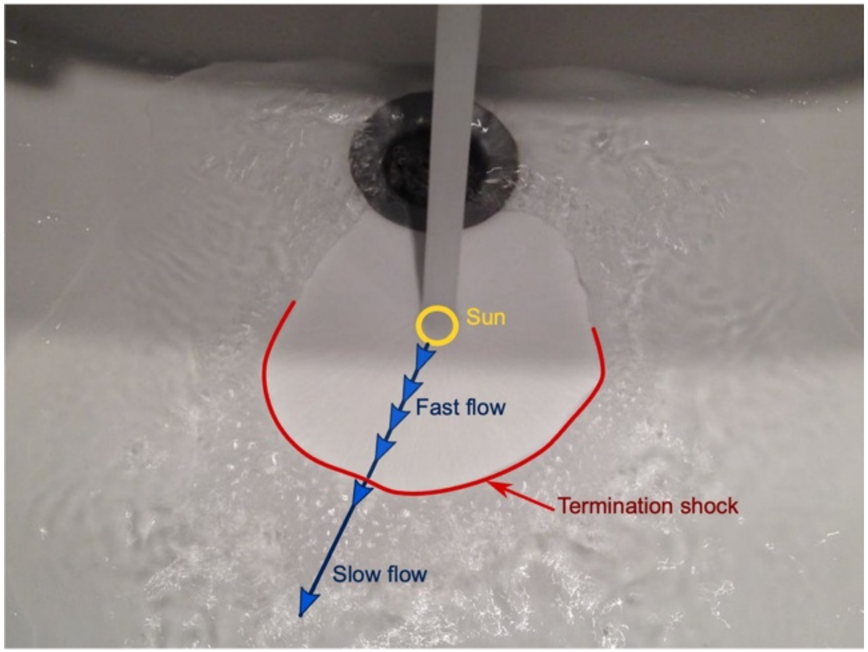
The Outer Heliosphere

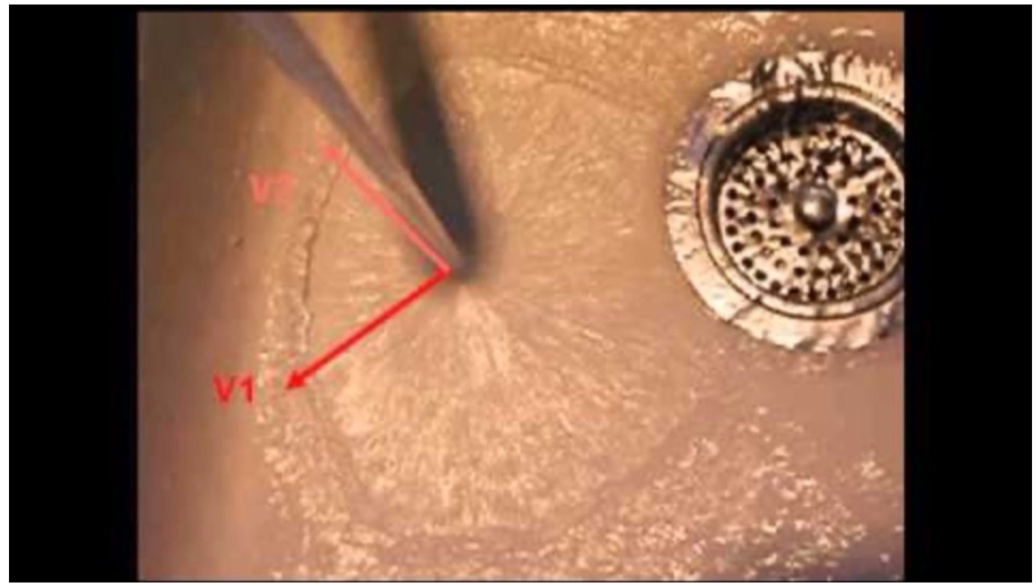


Modified Credit NASA/Adler Planetarium



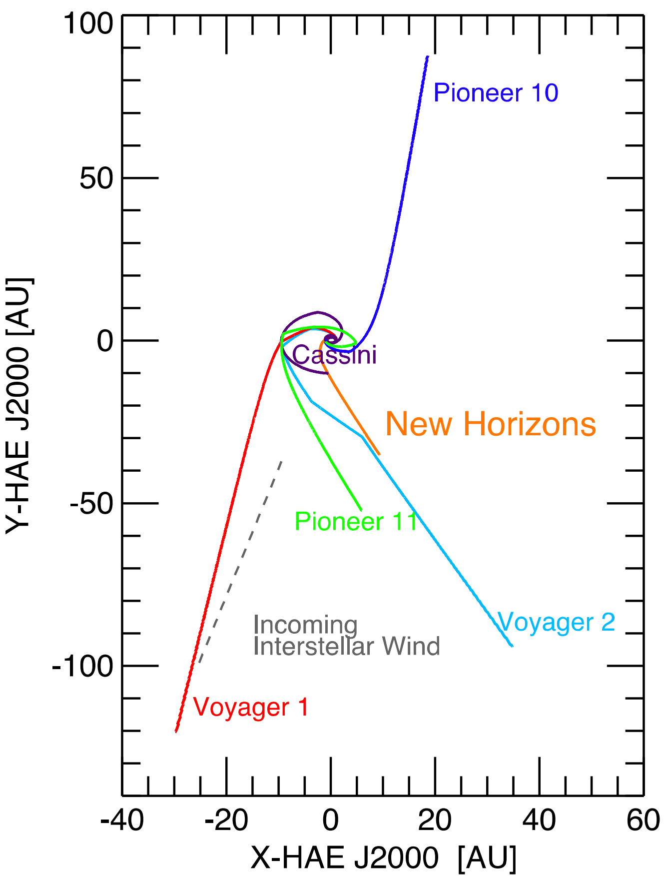
Sink Faucet Analogy For Termination shock



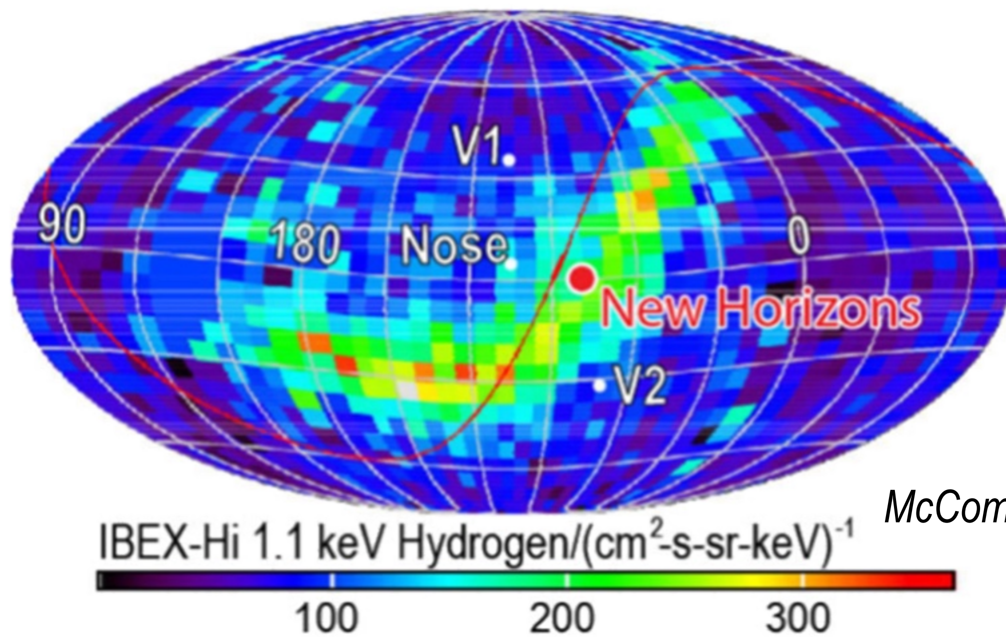


- https://commons.wikimedia.org/wiki/File:Heliosphere-washbasin.svg#/media/File:Heliosphere-washbasin.svg
- https://www.youtube.com/watch?v=z_Il8zTGkQk

Few Missions Have Explored the Outer Heliosphere



Elliott et al., 2016

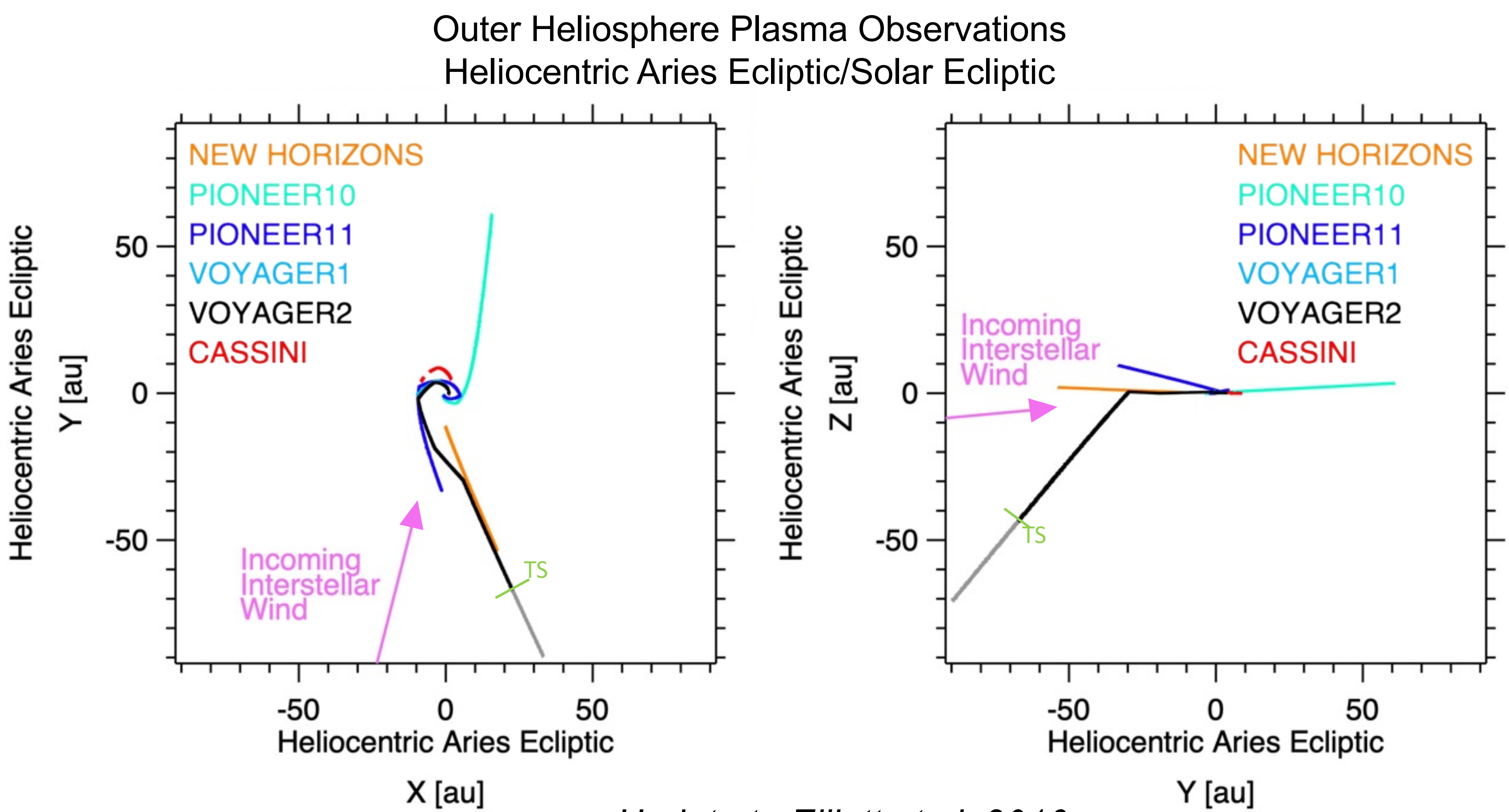


Adapted from McComas et al.,2009

New Horizons is moving along the same longitude as Voyager 2, but remaining in the ecliptic headed towards the ENA Ribbon.

New Horizons is currently the only spacecraft exploring the outer heliosphere and Kuiper Belt.

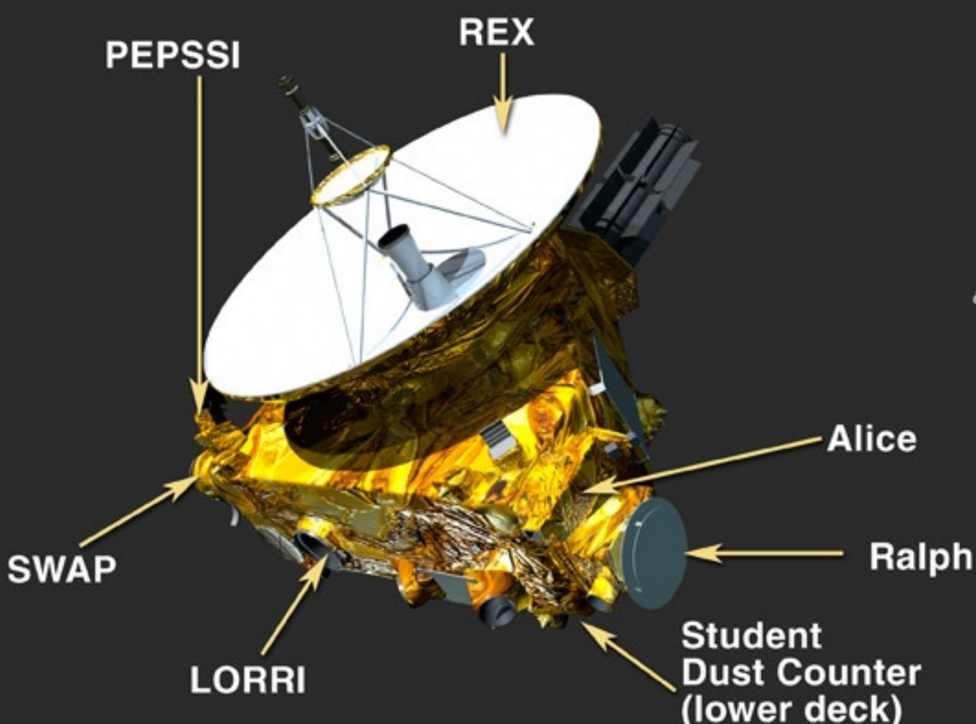
Outer Heliospheric Solar Wind Coverage



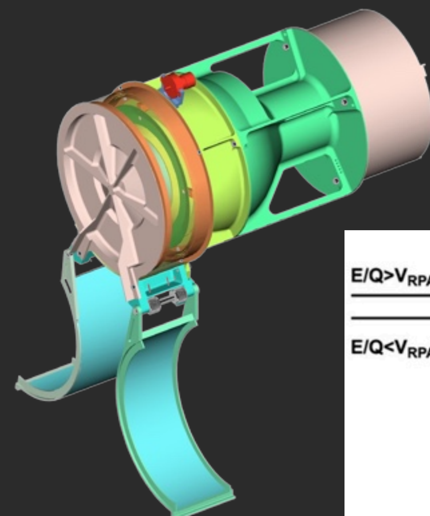
Update to Elliott et al. 2016

New Horizons Spacecraft and SWAP Instrument

New Horizons

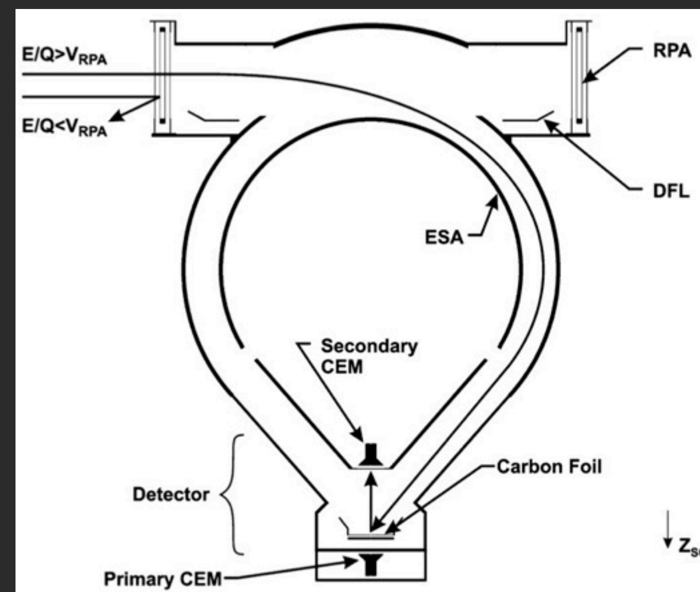


SWAP Instrument

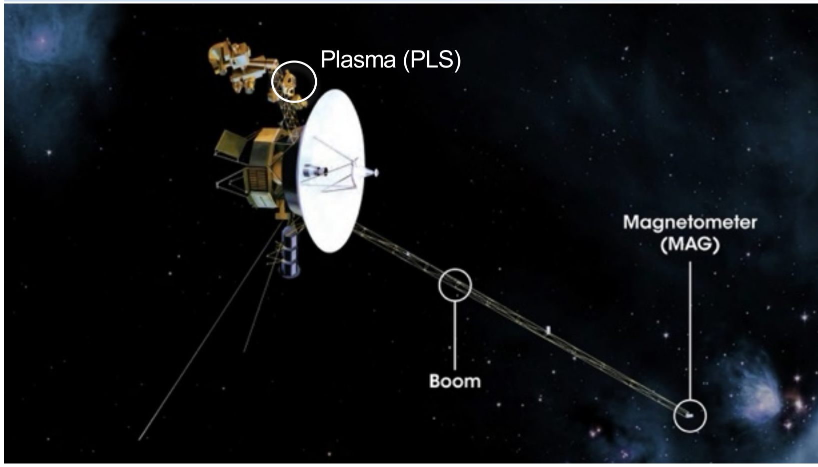


Xsc

Ion Measurements with SWAP

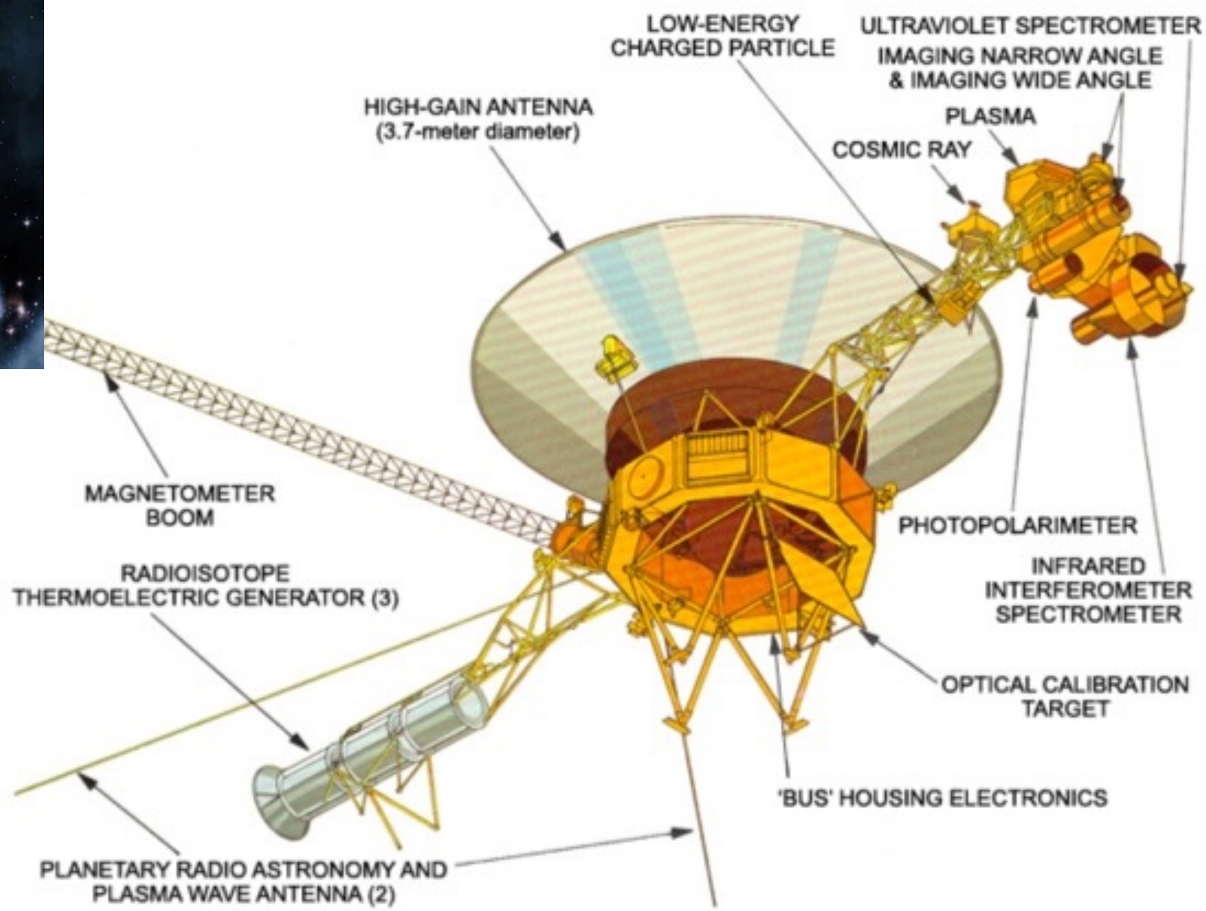


Voyager



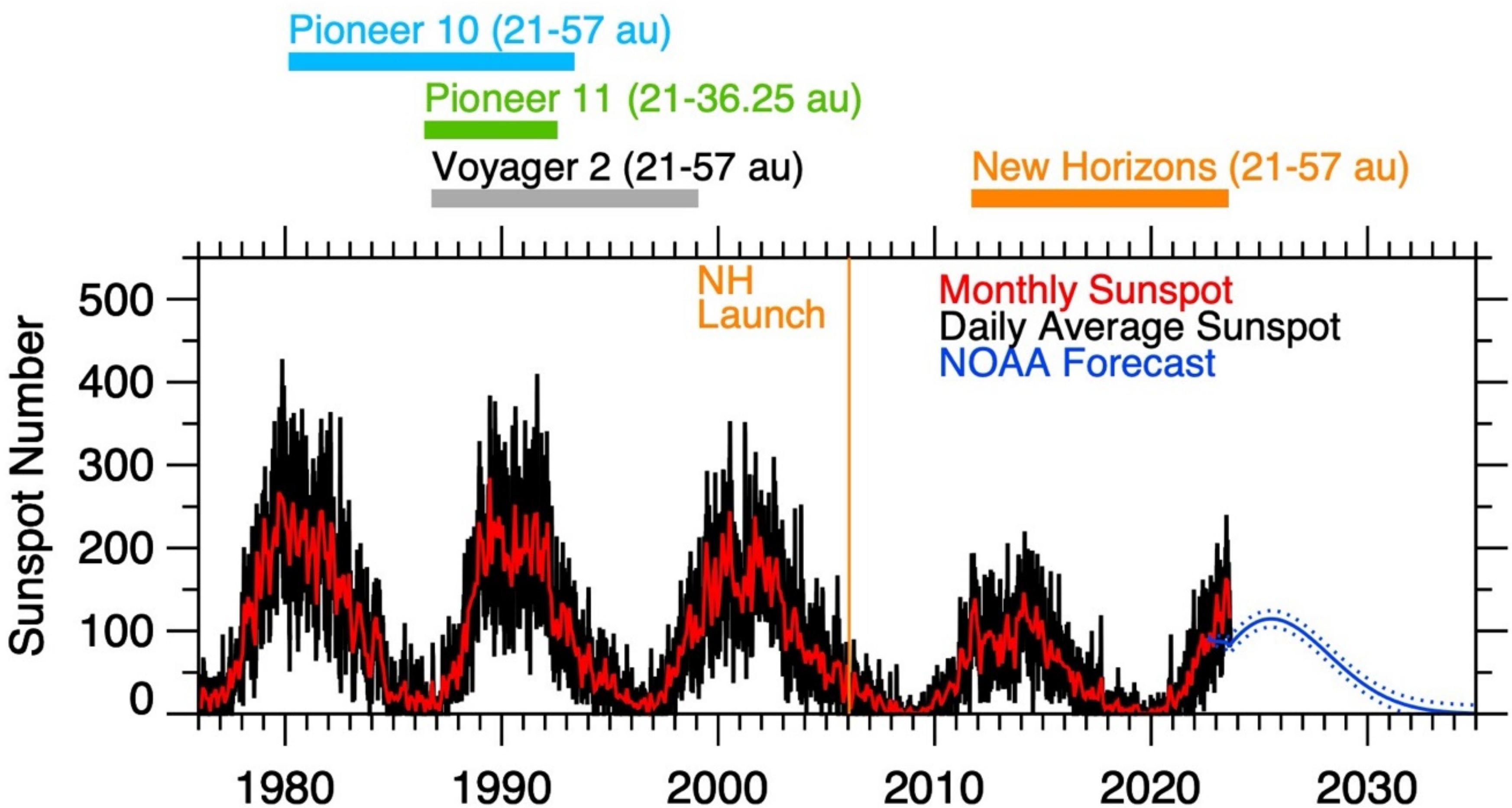
Plasma (PLS)
Magnetometer (MAG)
Boom

COSMIC RAY SUBSYSTEM (CRS)
PLASMA SCIENCE (PLS)
LOW-ENERGY CHARGED PARTICLES (LECP)



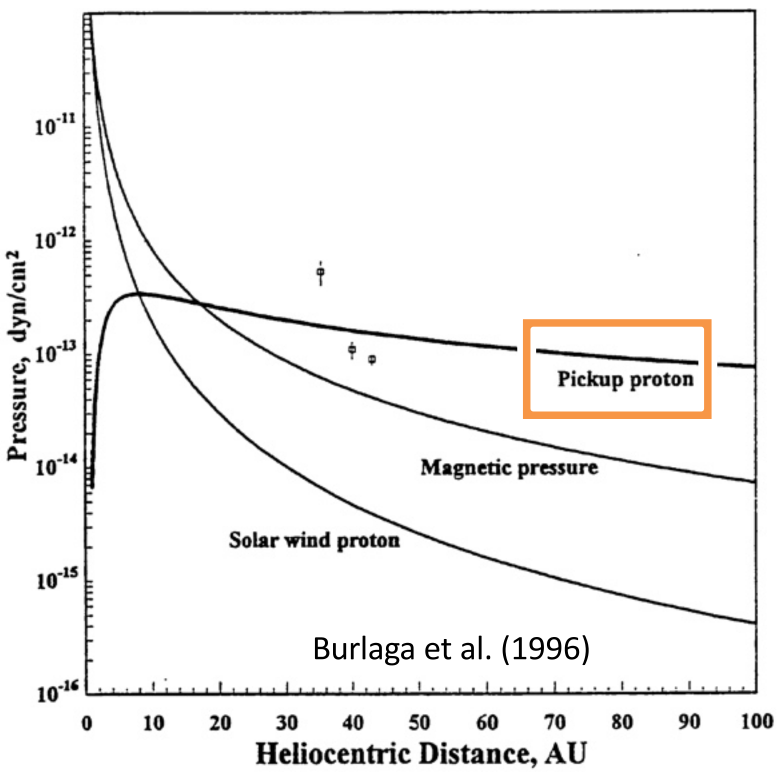
LOW-ENERGY CHARGED PARTICLE
ULTRAVIOLET SPECTROMETER
IMAGING NARROW ANGLE & IMAGING WIDE ANGLE
HIGH-GAIN ANTENNA (3.7-meter diameter)
PLASMA
COSMIC RAY
MAGNETOMETER BOOM
PHOTOPOLARIMETER
RADIOISOTOPE THERMOELECTRIC GENERATOR (3)
INFRARED INTERFEROMETER SPECTROMETER
OPTICAL CALIBRATION TARGET
'BUS' HOUSING ELECTRONICS
PLANETARY RADIO ASTRONOMY AND PLASMA WAVE ANTENNA (2)

Solar Cycle Phase of Outer Heliospheric Measurements

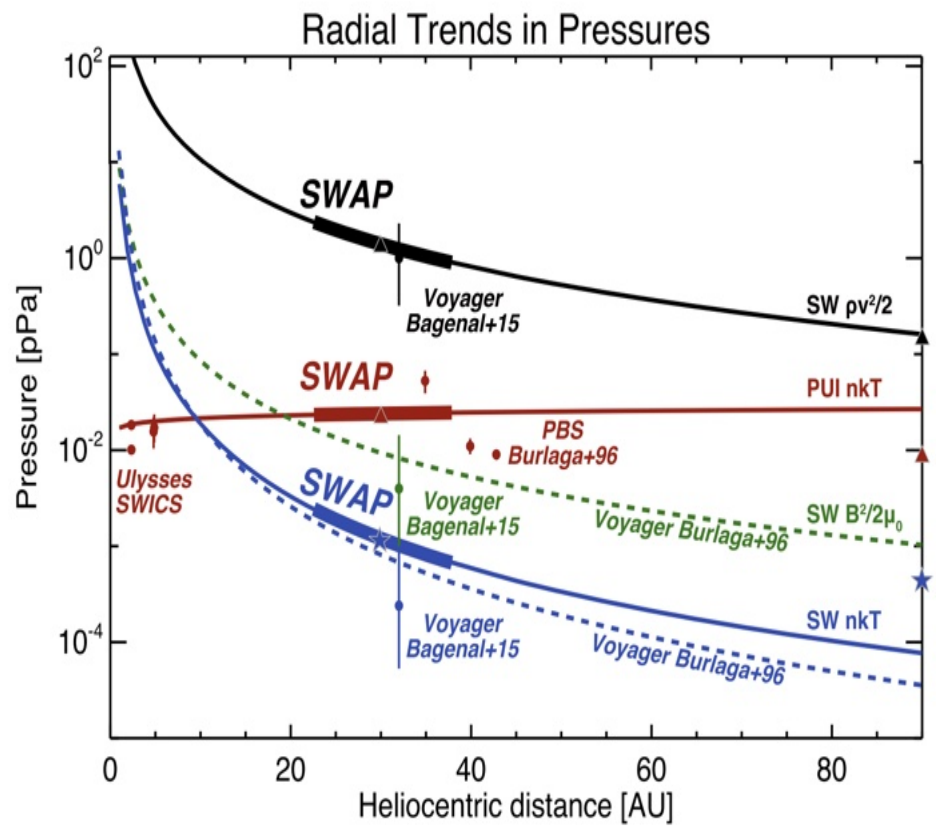


Importance of Interstellar Pickup Ions

- PUIs have the dominant pressure in the outer heliosphere.

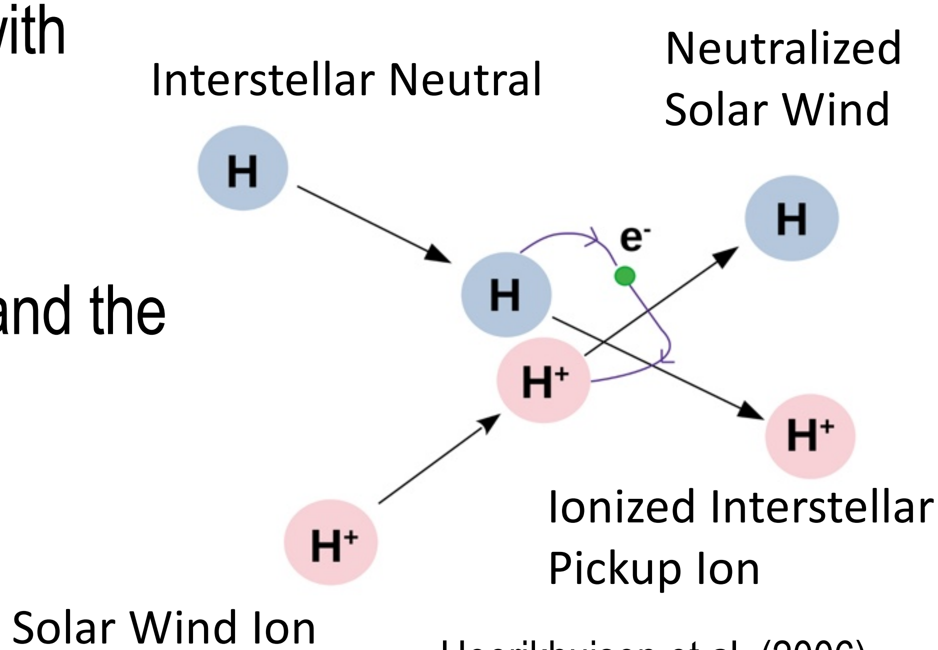


Burlaga et al. (1996)



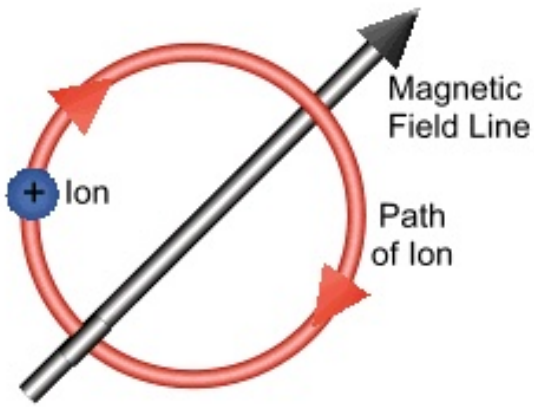
Interstellar Pickup Ions

- Interstellar Pickup Ions (PUIs) created when interstellar neutrals charge exchange with solar wind ions.
- The solar wind ion becomes a neutral and the interstellar neutral becomes an ion.

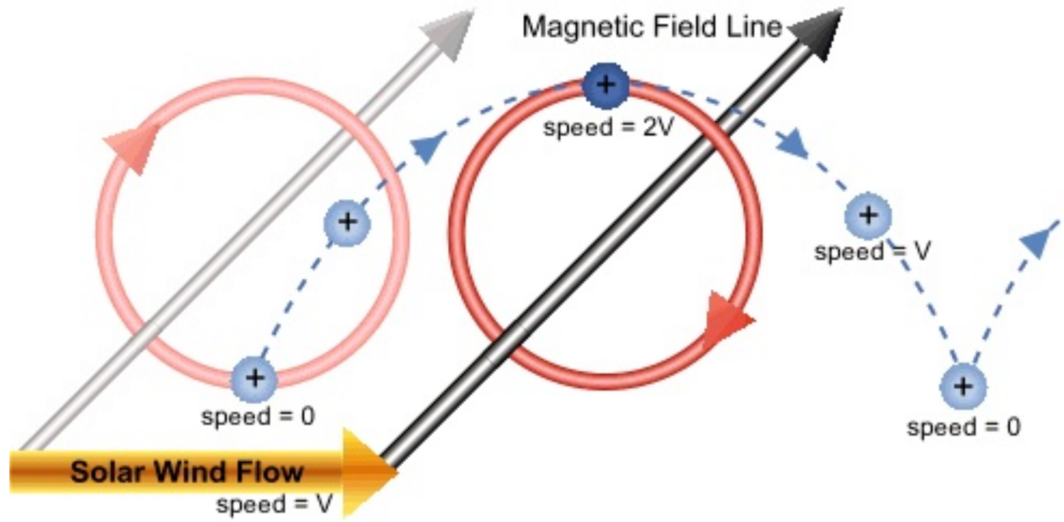


Heerikhuisen et al. (2006)

Pickup Ion Motion



Gyration of an ion around magnetic field line

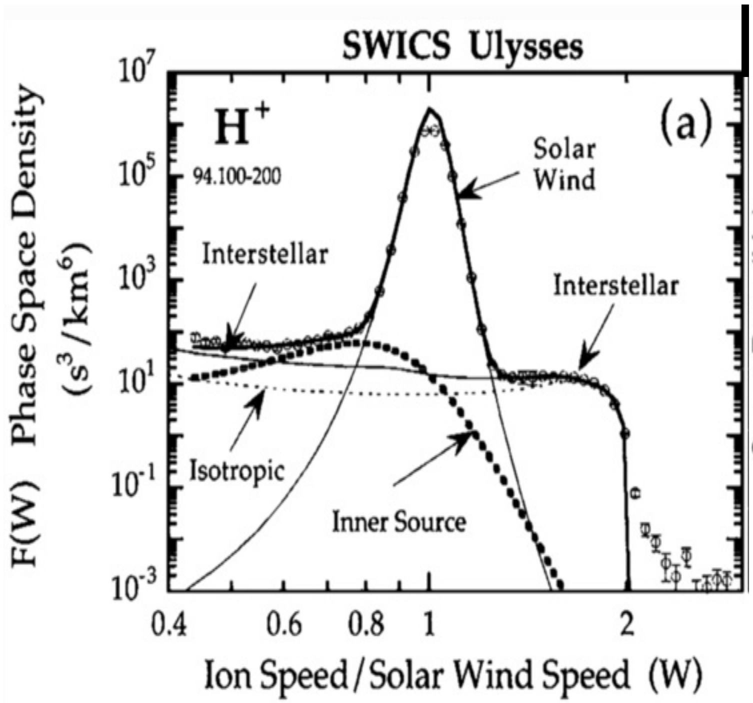


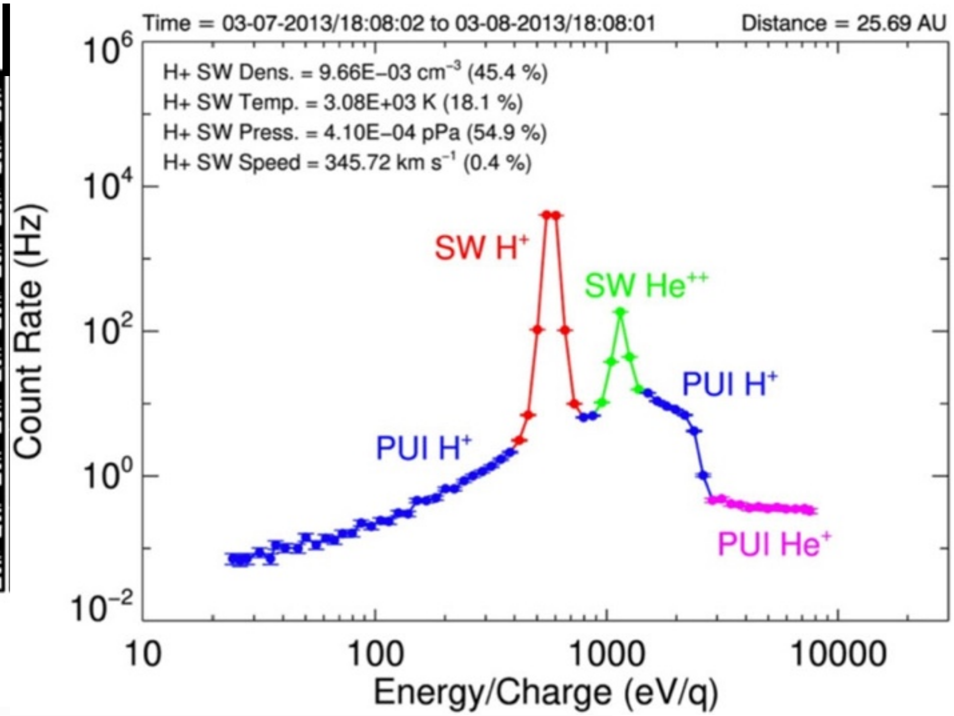
Ionized interstellar material the interstellar pickup Ions move around the field lines that are being carried by the solar wind motion.

PUI can have up to twice the solar wind speed.

http://www-ssg.sr.unh.edu/index.html?tof/Outreach/interstellarmain.html

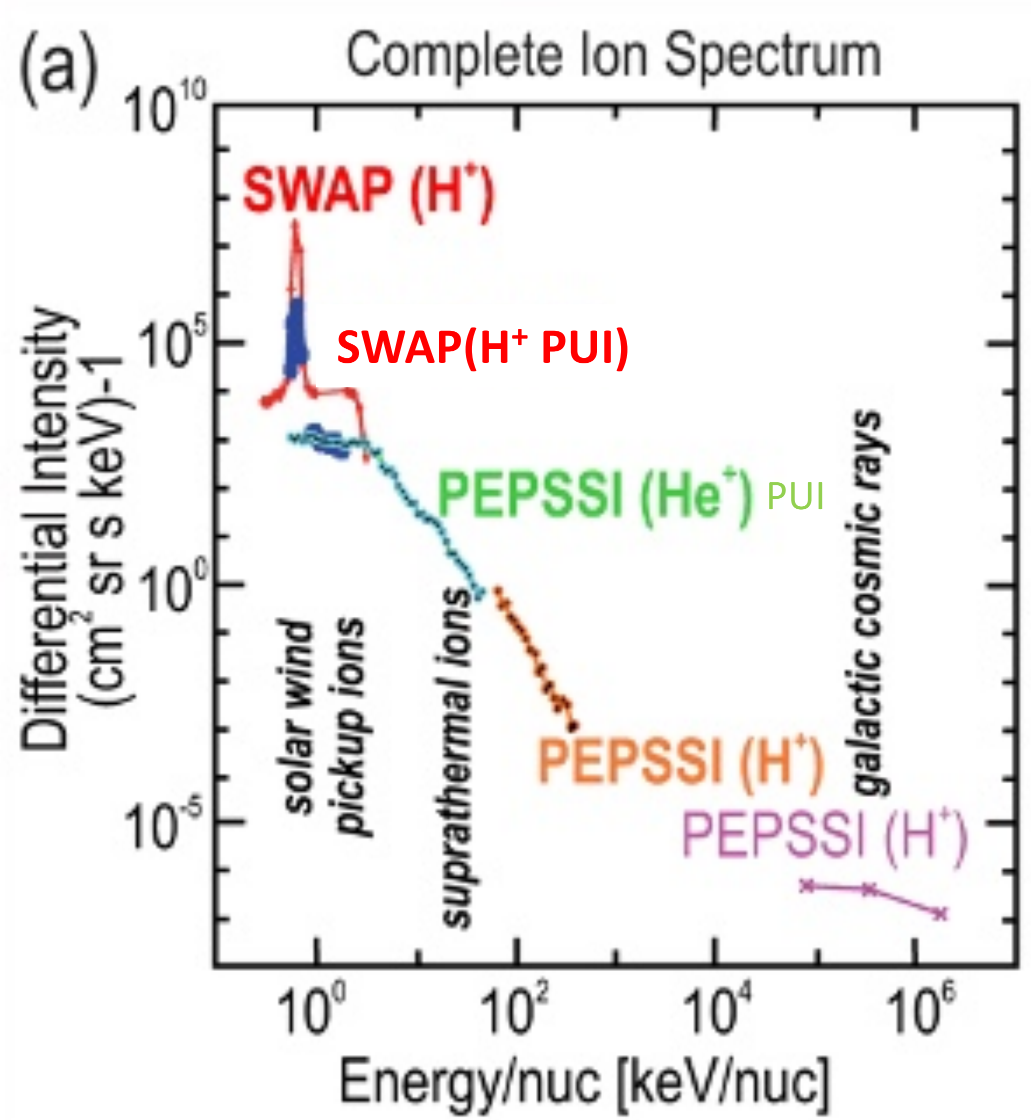
Distribution Solar Wind and Interstellar Picukp Ions



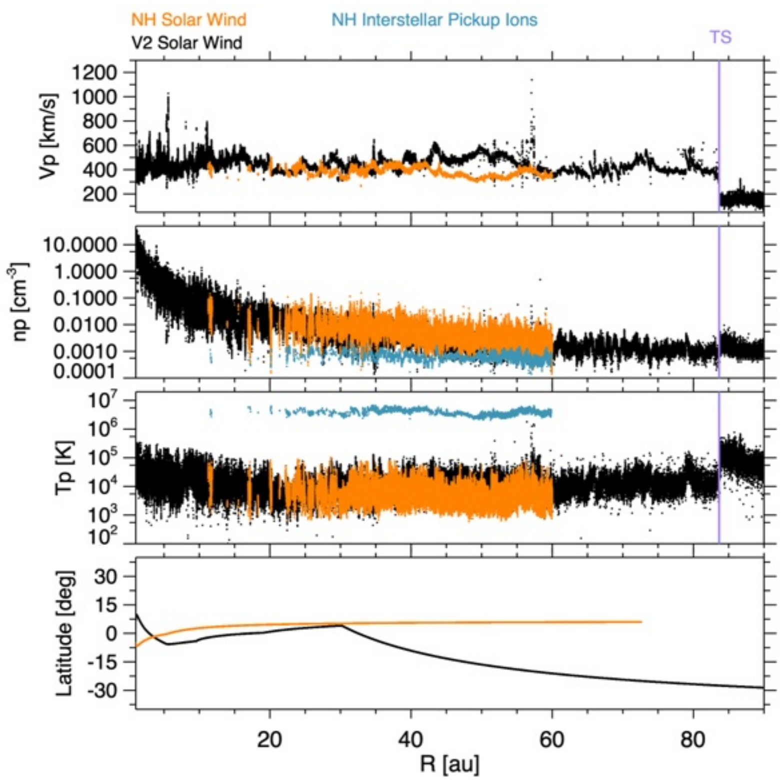


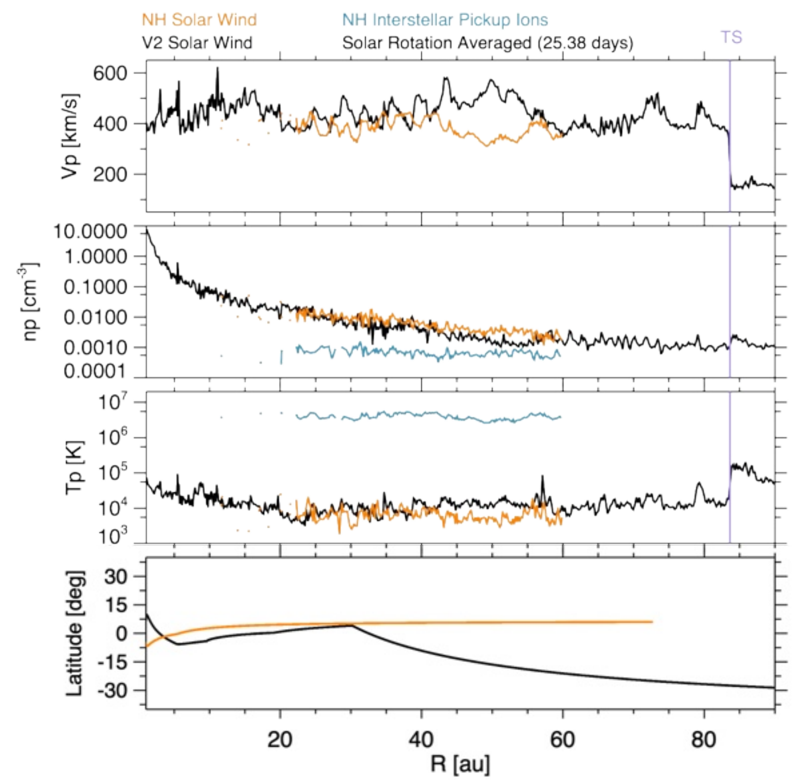
Suprathermal Tails and GCRs

The PEPSSI Instrument measures the Interstellar He+ PUI, Suprathermal Tails, And Galactic Cosmic Rays.

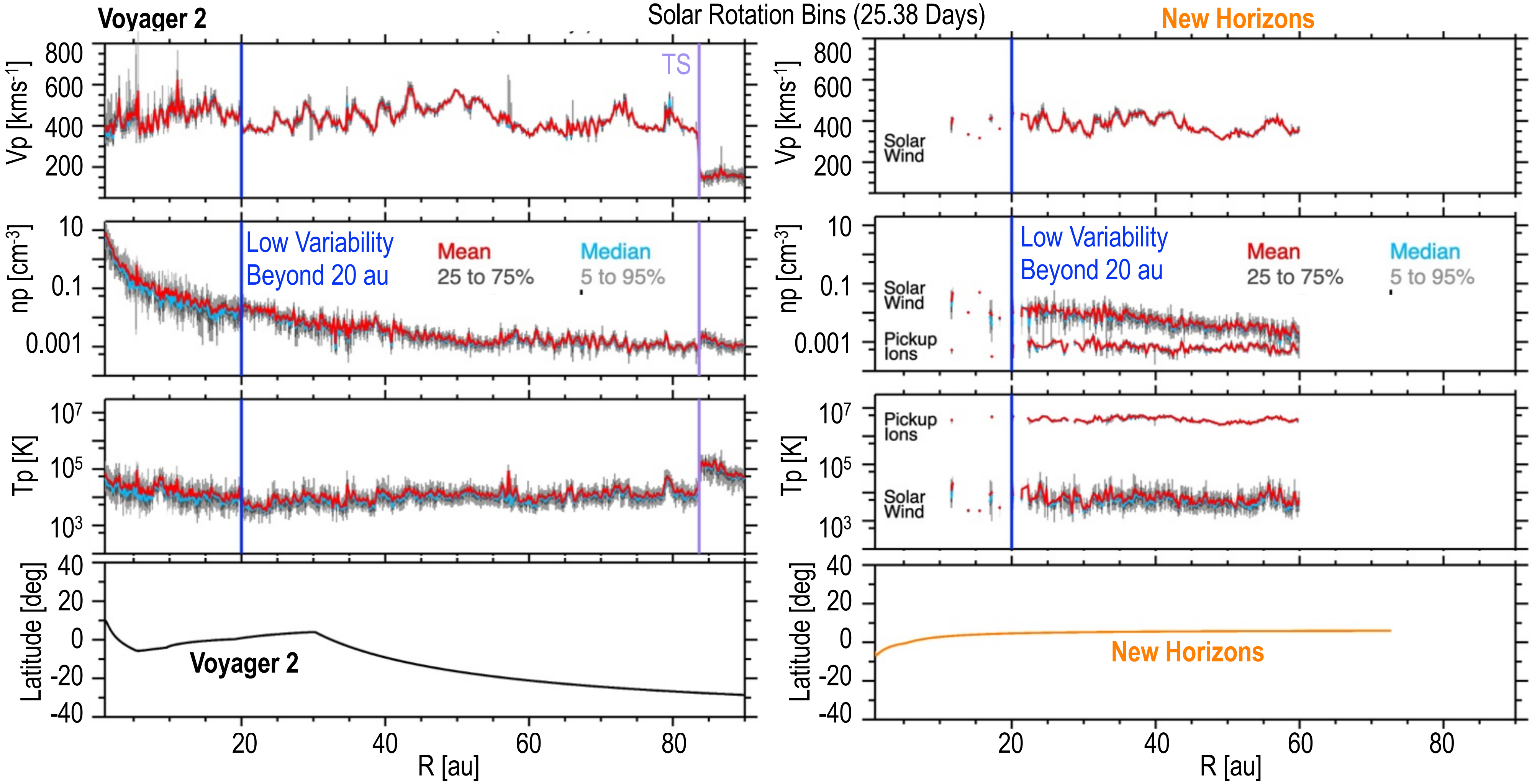


Radial Profiles: Solar Wind Parameters

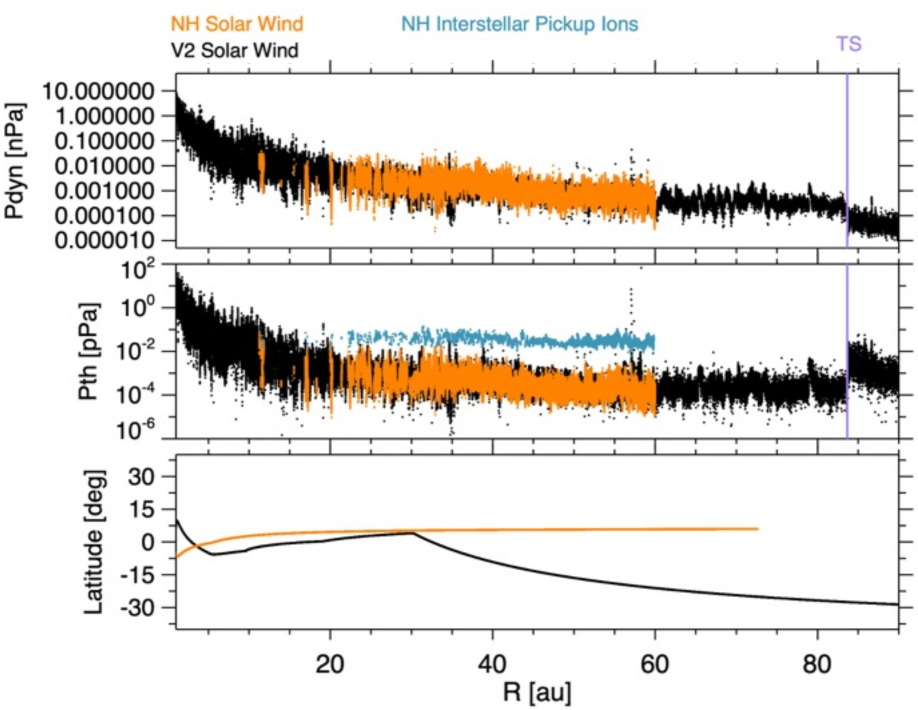


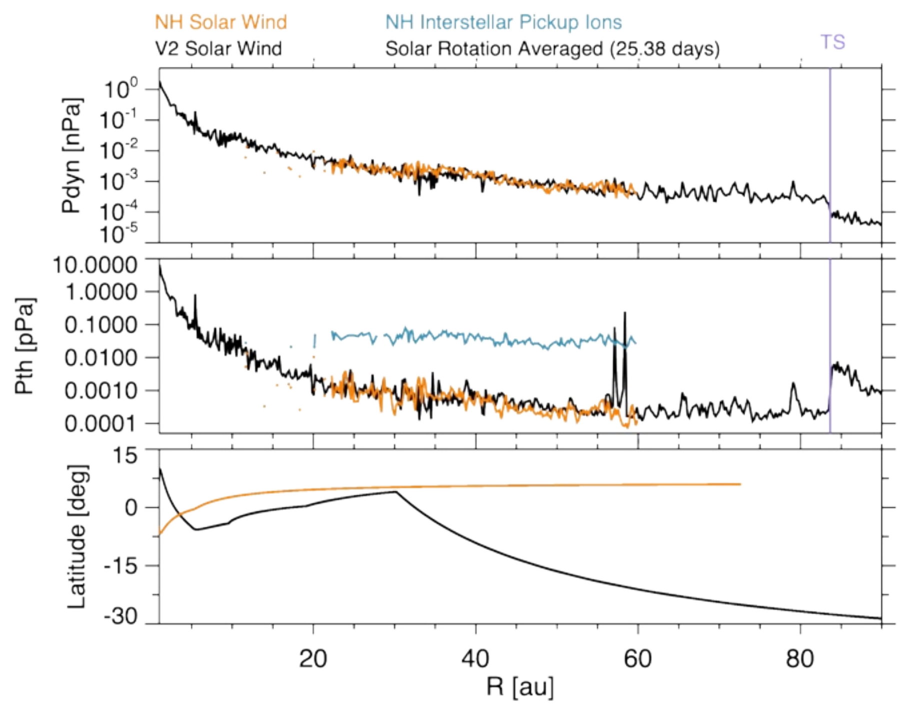


Radial Profiles of Solar Wind Parameters

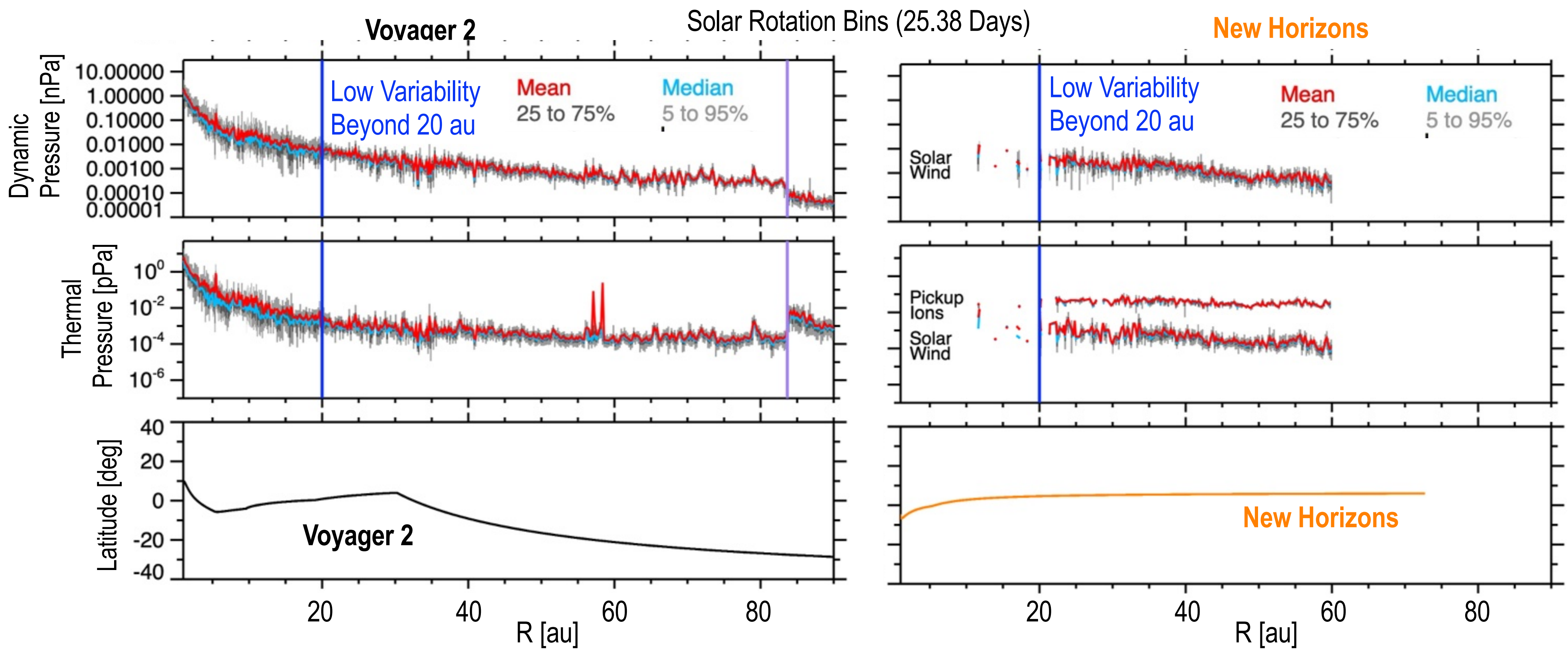


Overlay Radial Profiles of Solar Wind Pressures



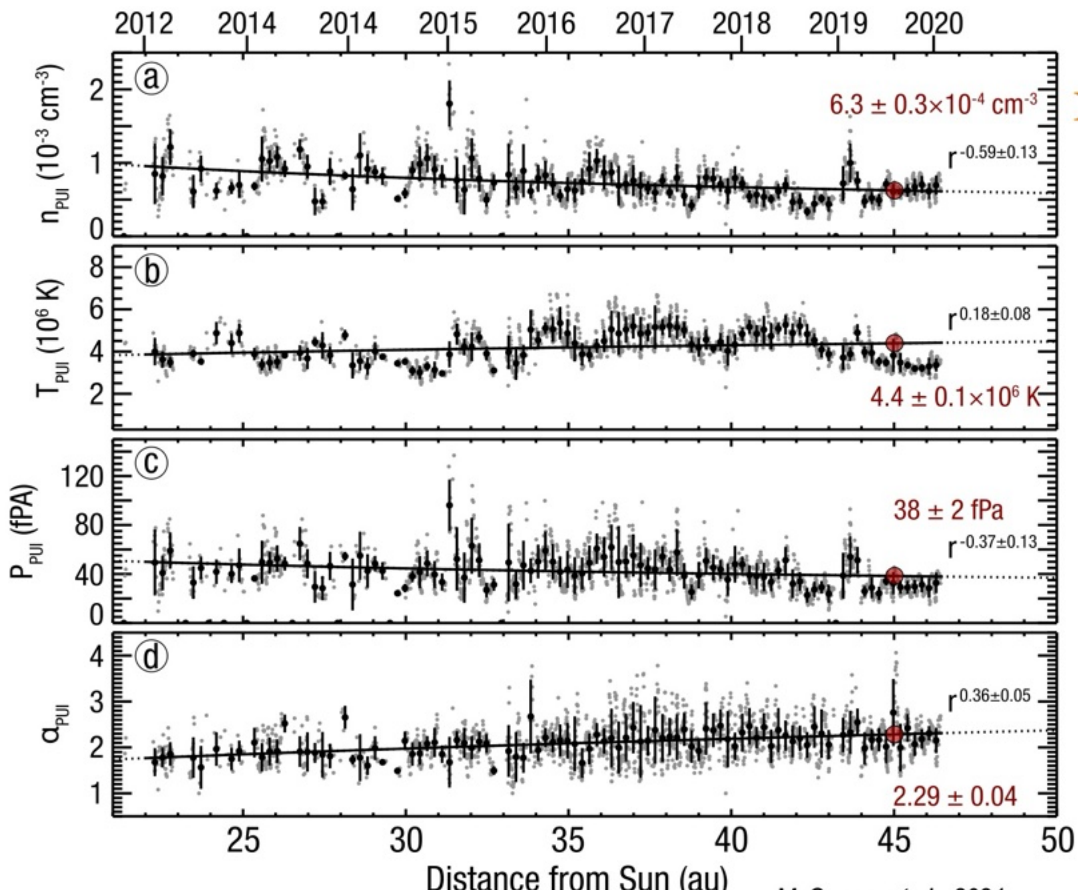


Radial Profiles of Dynamic and Thermal Pressure



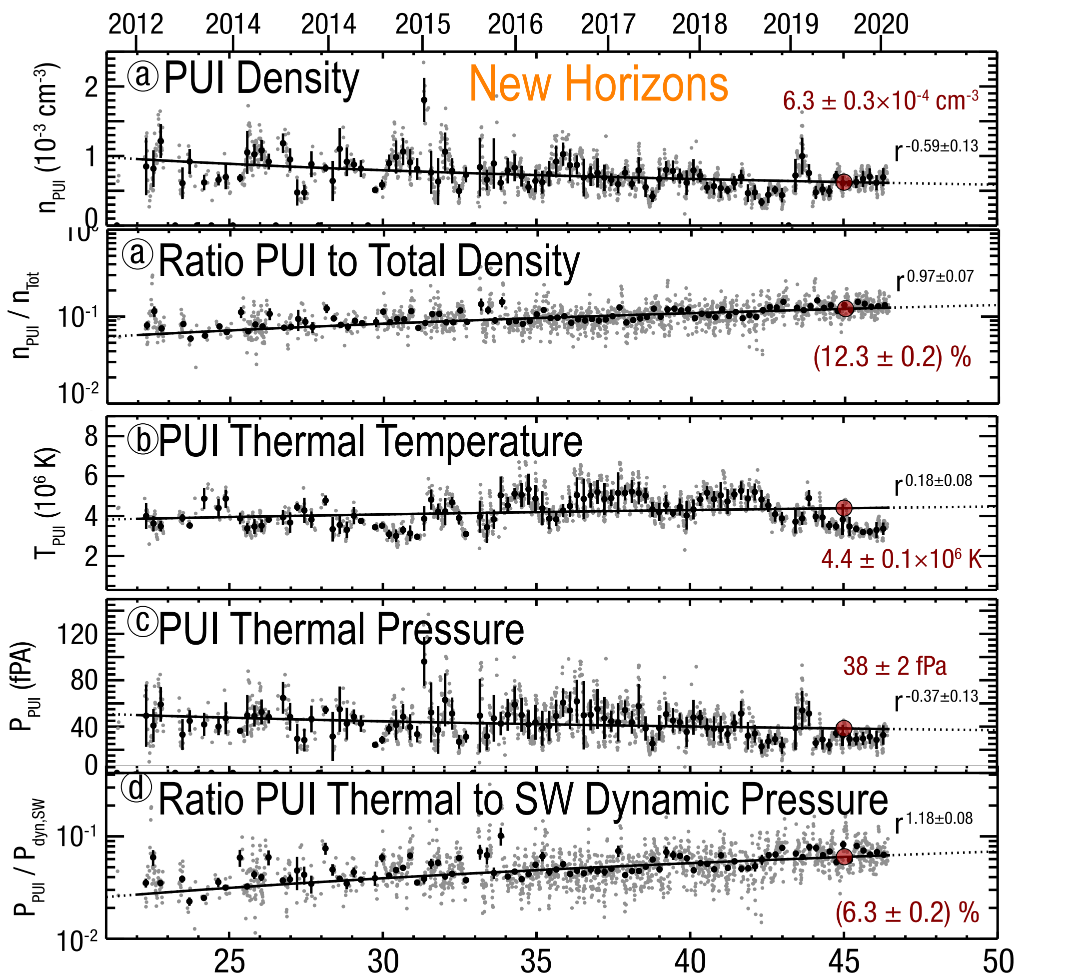
Radial Profiles of Interstellar Pickup Ion Properties

- PUI H^+ density, temperature, thermal pressure, and cooling index as a function of heliocentric distance.
- The black solid lines show power-law fits of the radial profiles.
- The PUI density and thermal pressure both drop off with heliocentric distance. In contrast, the PUI temperature and cooling index increase with distance.
- **Stronger cooling** when $\alpha < 3/2$
- **Additional heating** of the particle distribution when $\alpha > 3/2$.
- Values at 45 au in red.



McComas et al., 2021

Increasing Interstellar H+ Pickup Ions Importance



McComas et al., 2021

- The proton interstellar PUI density gradually decreases with distance, but the fraction relative to the total increases with distance.
- The interstellar PUI thermal temperature increases with distance.
- The interstellar PUI thermal pressure decreases slightly with distance, but the fraction relative to the solar wind dynamic pressure increases.

Ratios Extrapolated to Termination Shock

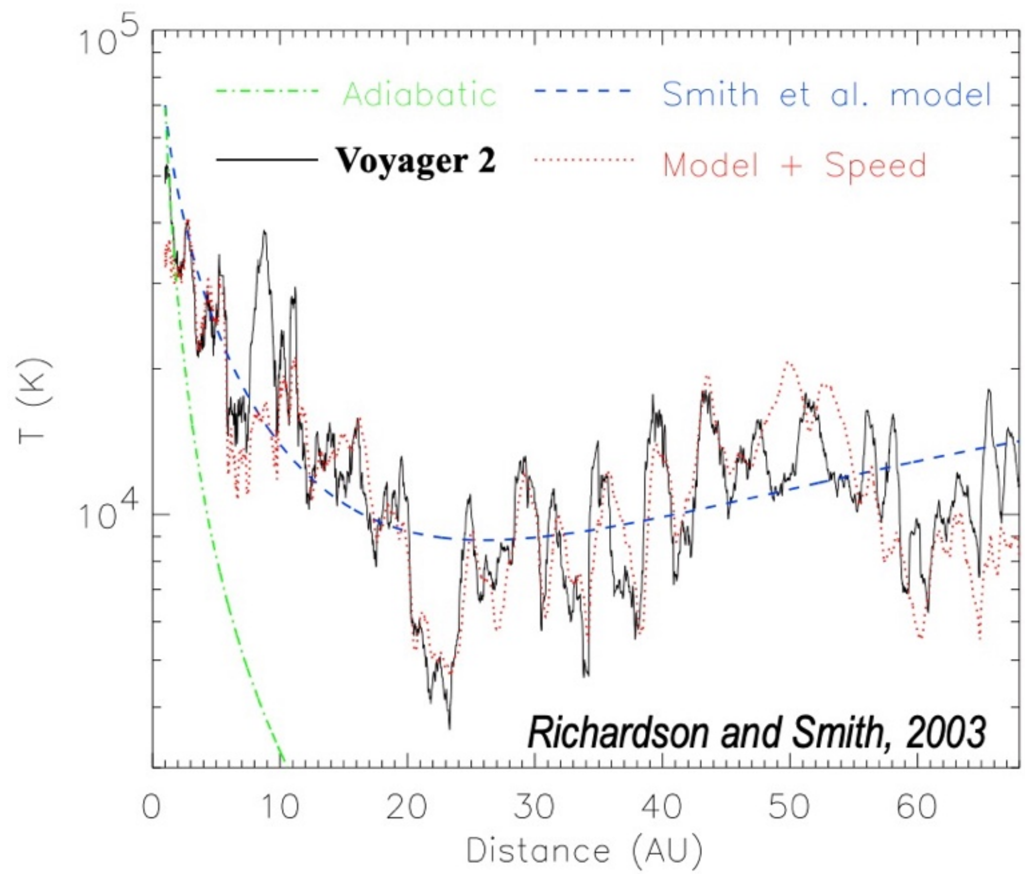
PUI Properties at 45 au, Radial Dependences, and Extrapolated Values at 90 au

	Value at 45 au	Extrapolated to 90 au	Radial Exponent
$n_{\rm PUI}$	$(6.3 \pm 0.3) \times 10^{-4}$ cm^{-3}	$(4.1 \pm 0.6) \times 10^{-4}$ cm^{-3}	-0.59 ± 0.13
$T_{\rm PUI}$	$(4.4 \pm 0.1) \times 10^{6}$ K	$(5.0 \pm 0.4) \times 10^{6}$ K	0.18 ± 0.08
$P_{\rm PUI}$	38 ± 2 fPa	30 ± 4 fPa	-0.37 ± 0.13
α	2.29 ± 0.04	2.9 ± 0.2	0.36 ± 0.05
$n_{\rm PUI}/n_{\rm Total}$	$(12.3 \pm 0.2)\%$	$(24 \pm 2)\%$	0.97 ± 0.07
$T_{\rm PUI}/T_{\rm SW}$	603 ± 35	716 ± 124	0.25 ± 0.18
$P_{\rm PUI}/P_{\rm SW}$	78 ± 5	173 ± 32	1.15 ± 0.20
$P_{\rm PUI}/P_{\rm SW-Dyn}$	$(6.3 \pm 0.2)\%$	$(14 \pm 1)\%$	1.18 ± 0.08

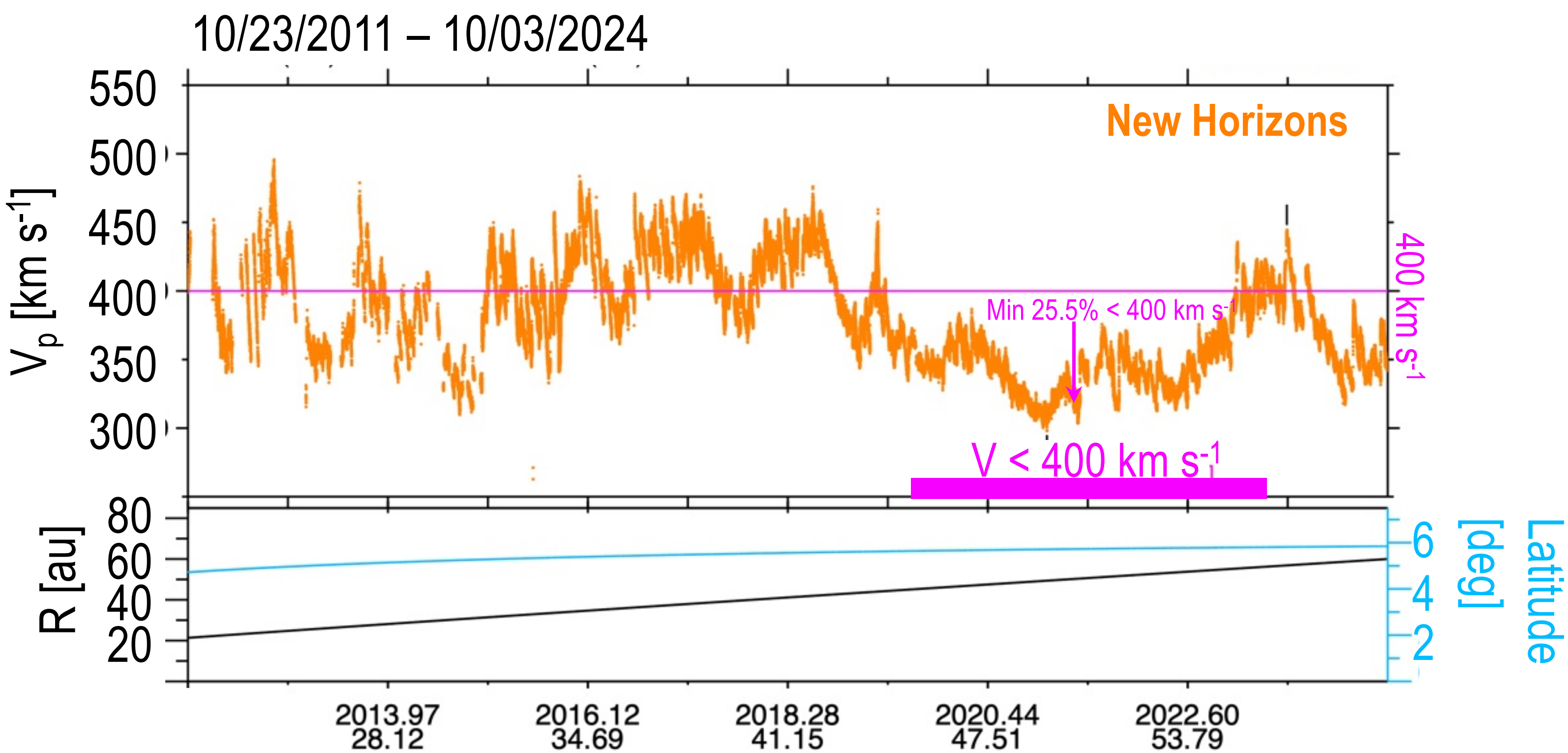
McComas et al., 2021

Heating of Solar Wind at Large Distances (Voyager 2)

- Some of the increase in V2 temperatures is related to V2 observing more fast wind as it moves to higher latitudes where fast wind is more common.
- Fast wind is hotter than slow wind.
- In the outer heliosphere the solar wind temperature is well above what would be expected for adiabatic expansion.
- Even though the solar wind is expanding, it maintains its temperature well above the temperature expected for an expanding plasma that cools adiabatically.

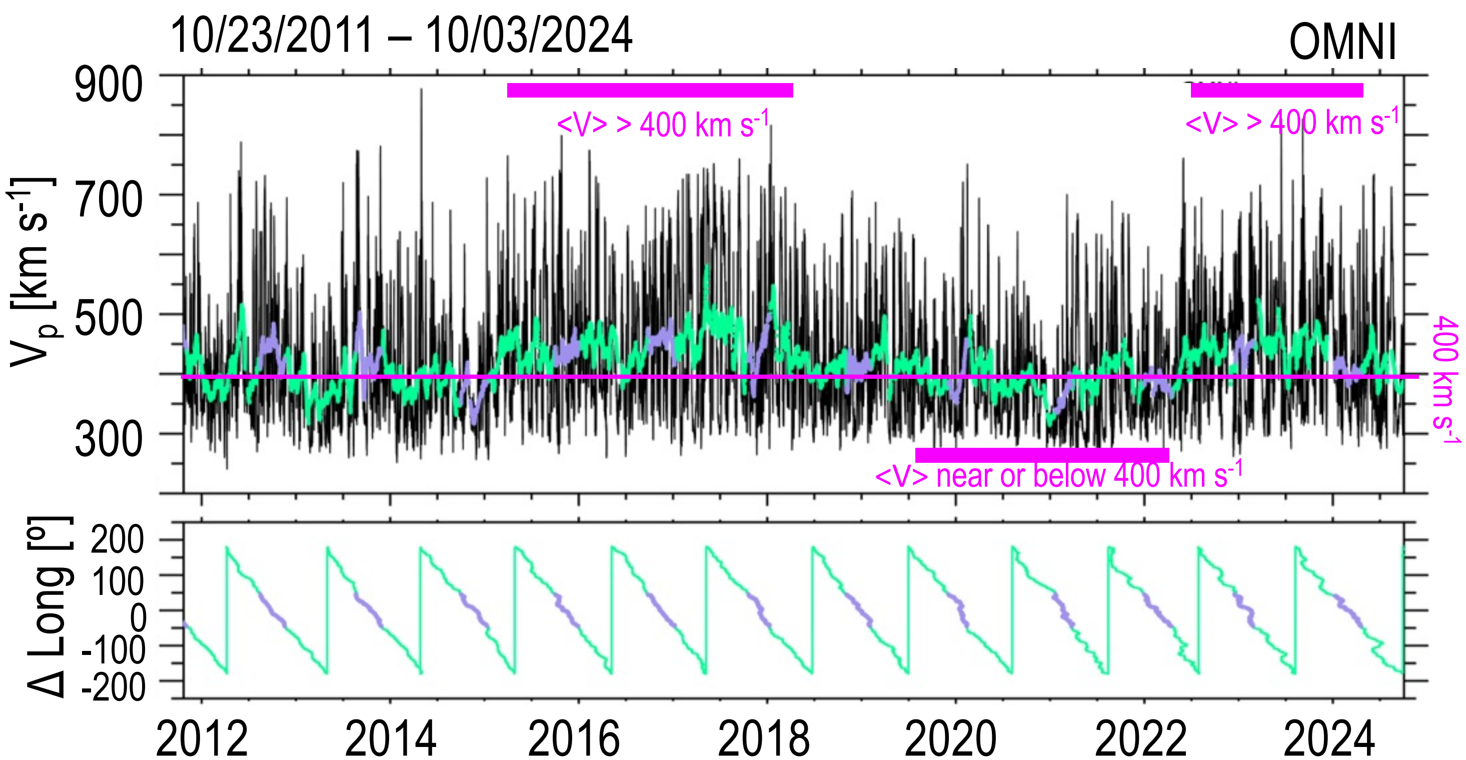


New Horizons Solar Wind Time Series



Elliott et al., 2025 Submitted

OMNI Speed Measurements at 1 au

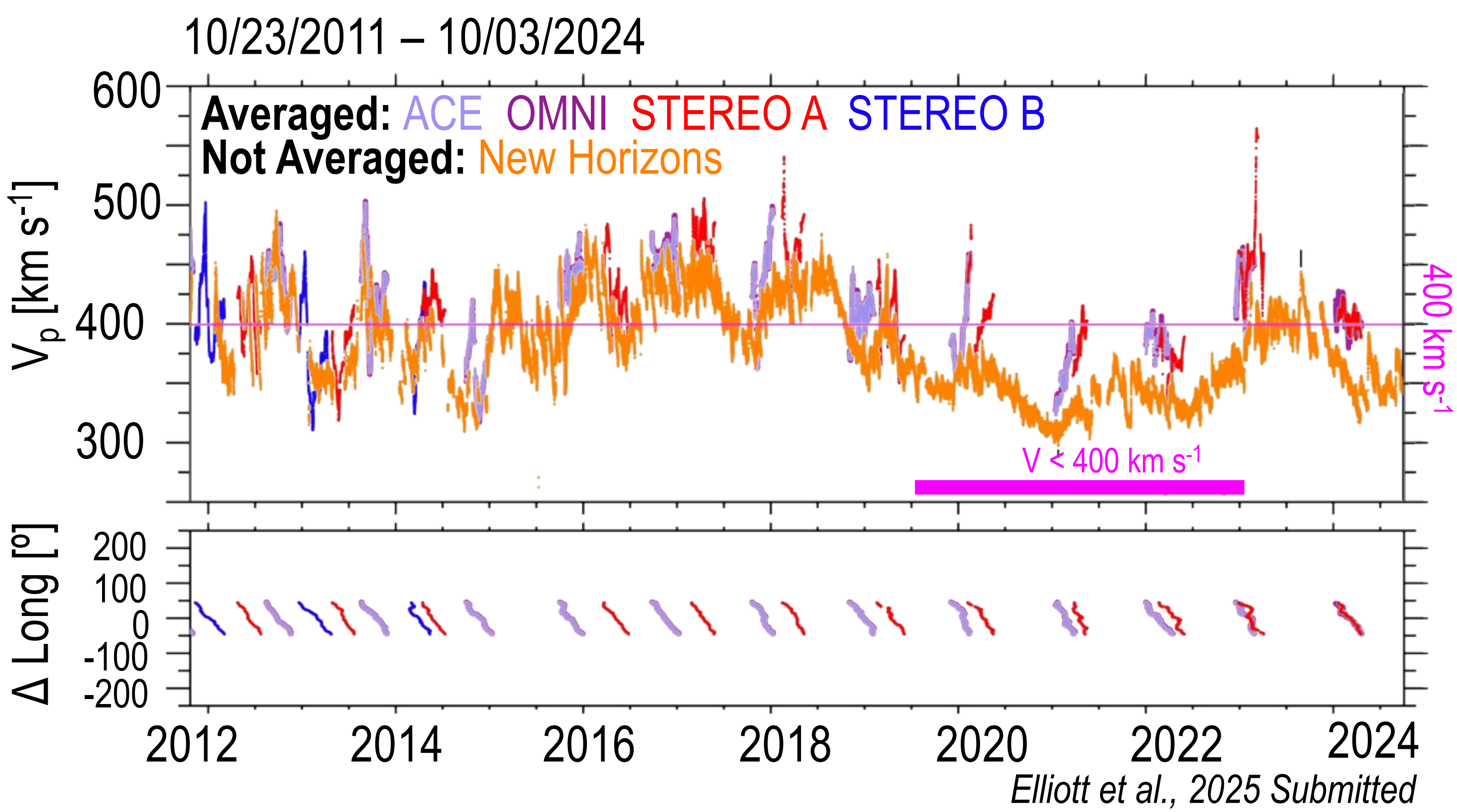


Elliott et al., 2025 Submitted

- Many structures merge prior to reaching the outer heliosphere.

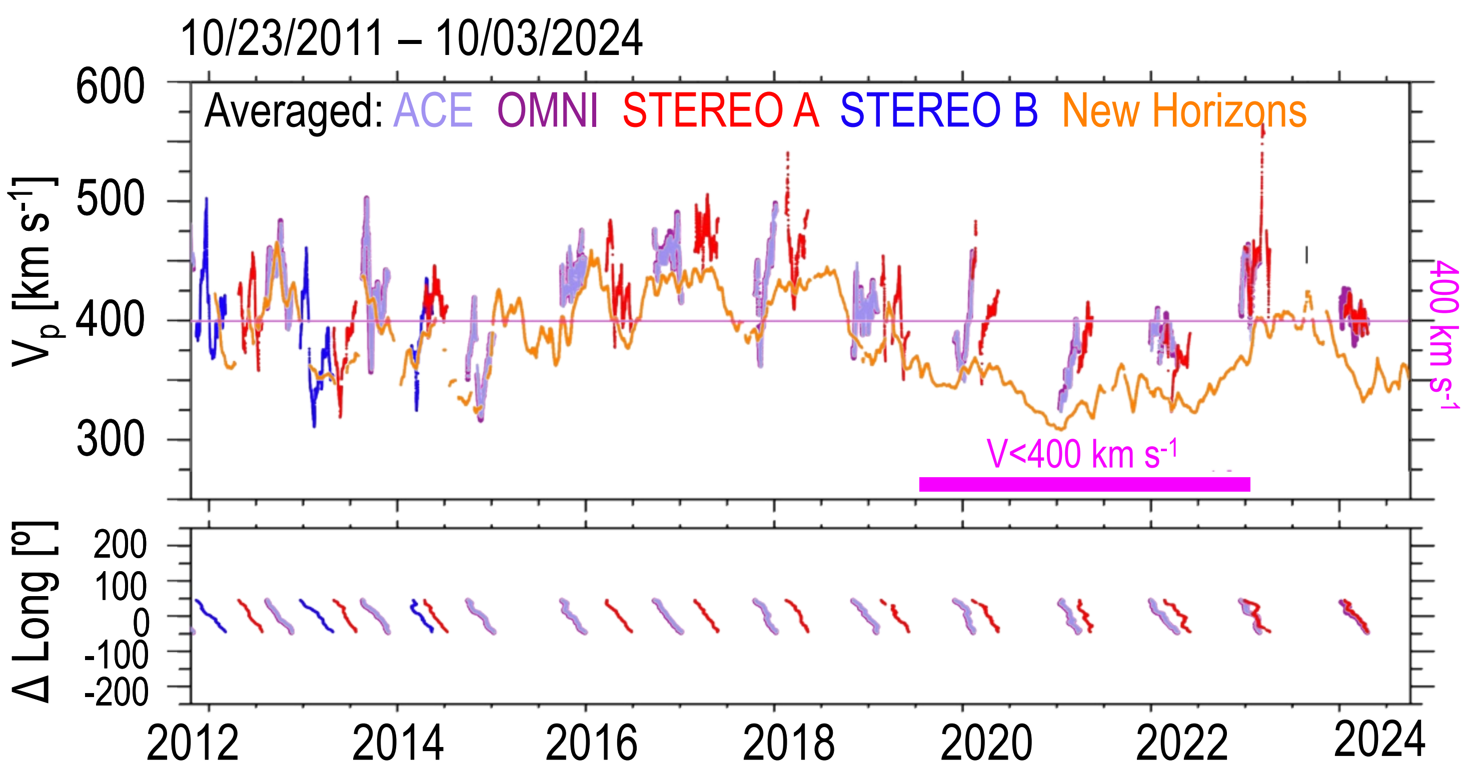
- 1 hour averages black.
- Green and purple are running solar rotation averages (25.38 days) where purple indicates NH & ACE are within +/- 45º.
- OMNI observations at L1 near Earth (1 au) indicate the average solar wind speed decreased in 2018 and stayed low until late 2022.
- From late 2022 through July of 2023 the wind speed increased.

NH - 1 au Speed Comparison (NH No Averaging)



- Running solar rotation averages (25.38 days) of the 1 au observations are show in purple (ACE), red (STEREO A) and blue (STEREO B).
- Averaging the 1 au observations matches the New Horizons speeds fairly well without averaging (at recorded cadence) because the solar wind structures merge and are worn down as they propagate away from the Sun.

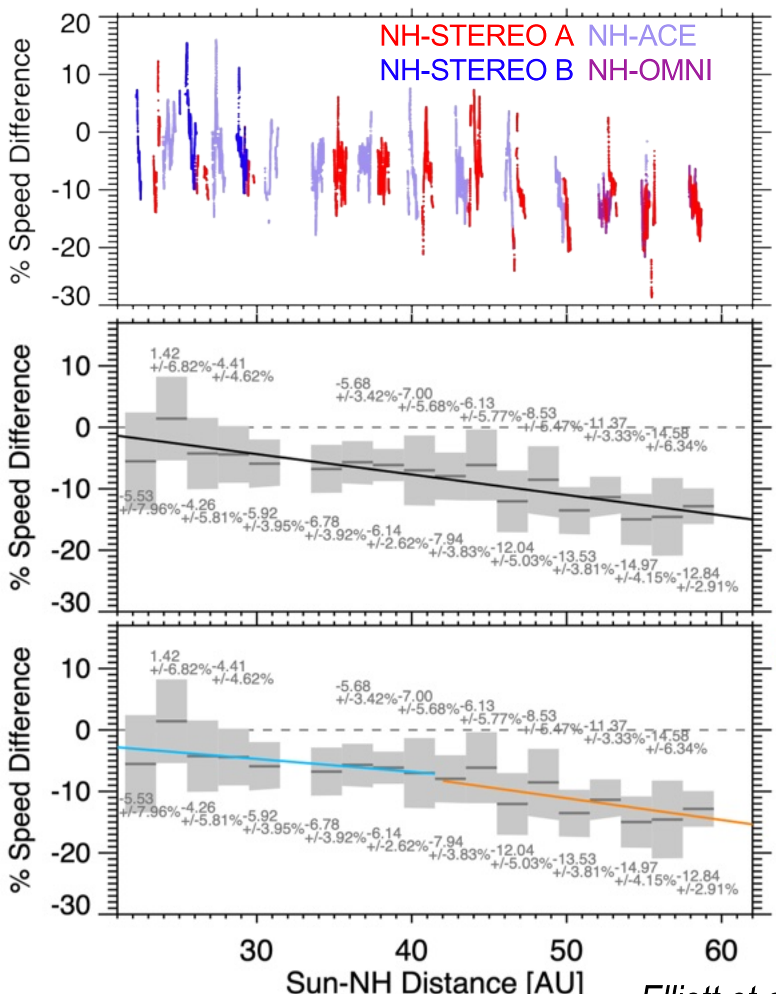
NH - 1 au Speed Comparison (NH With Averaging)



Elliott et al., 2025 Submitted

- Using the running solar rotation averages (25.38 days) on the New Horizons observations, it is clear that the solar wind at NH is consistently slower than at 1 au.

Percent Slowing Relative to 1 au



- Between 30-43 au the solar wind at NH was 5-7% slower than at 1 au (Elliott et al. 2019).
- Recently, the amount of slowing has increased to be ~13 to 15% slower that at 1 au.
- The amount of slowing in the solar wind owing to picking up interstellar material is gradually increasing.

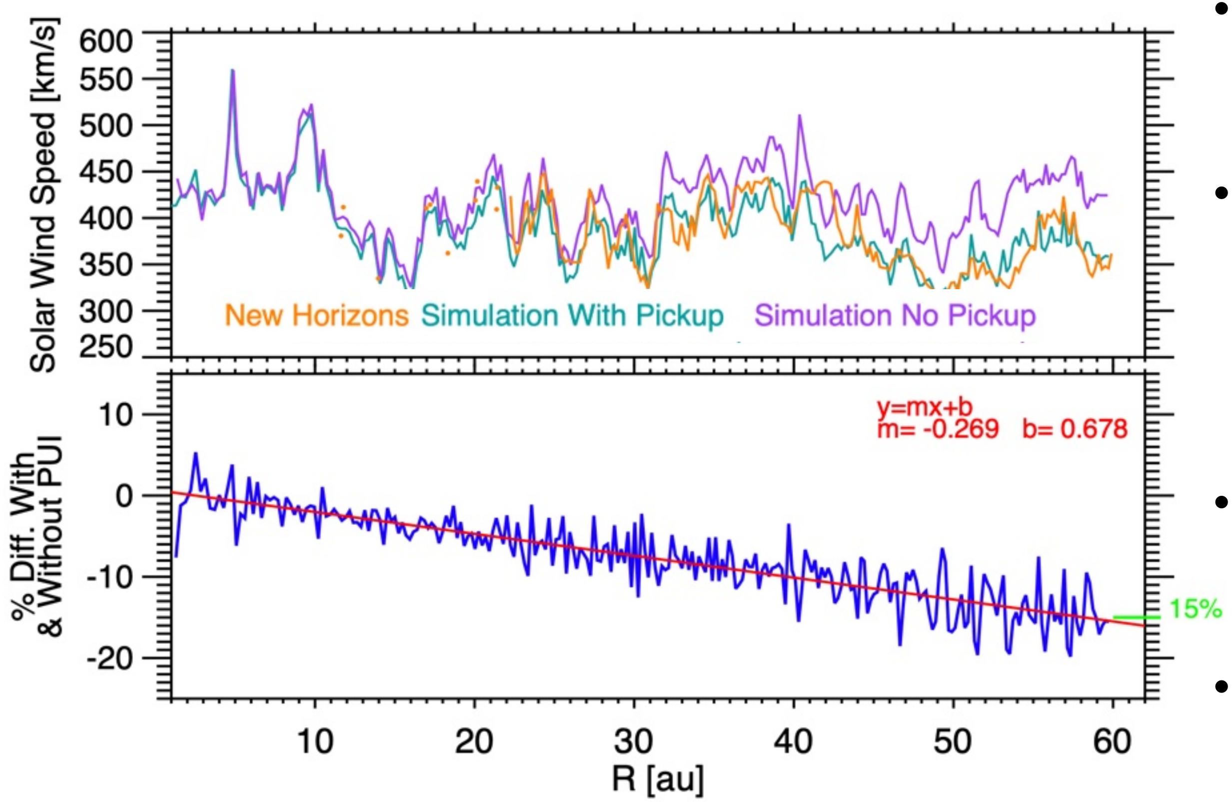
$y=mx+b$
$m=-0.3326\ \%\ au^{-1}$ $b=5.6206\%$

$R < 42$ $y=mx+b$
$m=-0.2103\ \%\ au^{-1}$ $b=1.5958\%$

$R >= 42$ $y=mx+b$
$m=-0.3539\ \%\ au^{-1}$ $b=6.5880\%$

Elliott et al., 2025 Submitted

Radial Speed Profile Comparison
Percent Difference Between With & Without Pickup Ions

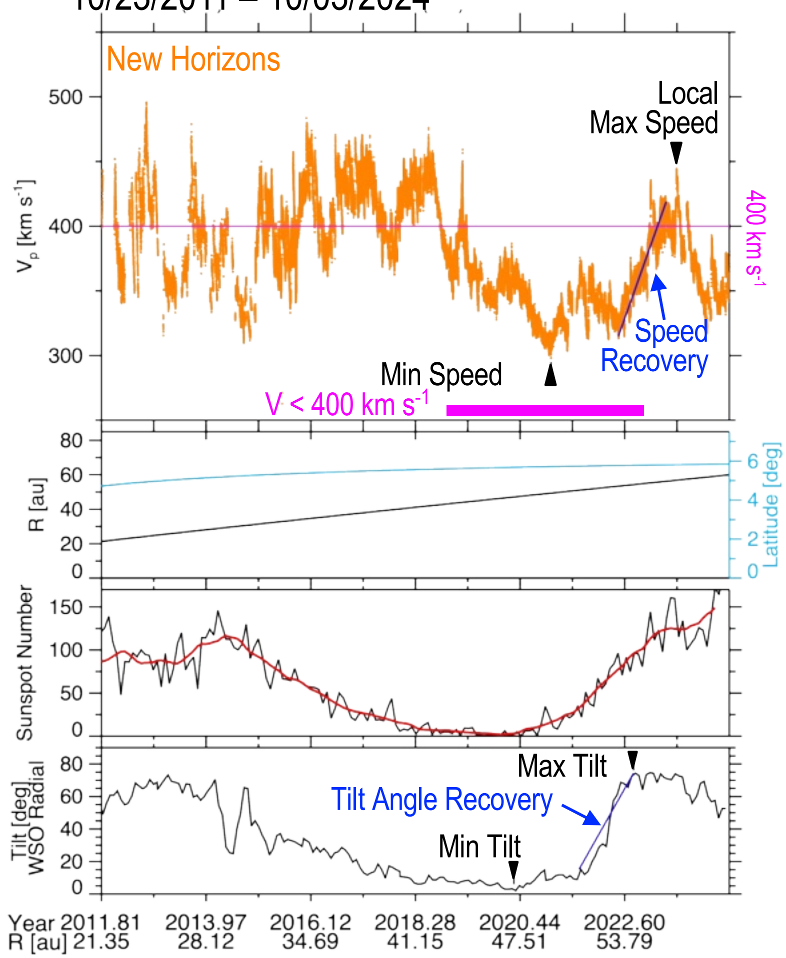


Elliott et al., 2024 Submitted; simulation by Tae Kim

- Multi-scale Fluid-kinetic Simulation Suite (MS-FLUKSS) model (Borovikov et al., 2013; Pogorelov et al., 2014).
- Solar wind and pickup ions treated as a single fluid governed by the MHD equations. The interstellar neutral hydrogen atoms determined using mulit-component Euler equations.
- The inner boundary at 1 au is driven using the OMNI solar wind observations (Kim et al., 2016).
- The simulation & observation speeds match well with pickup ions included.
- The speeds with PUI included in the model between 50 & 60 au are about 15% slower than without PUI.

Long Interval of Slow Steady Wind At New Horizons

10/23/2011 – 10/03/2024



Elliott et al., 2025 Submitted

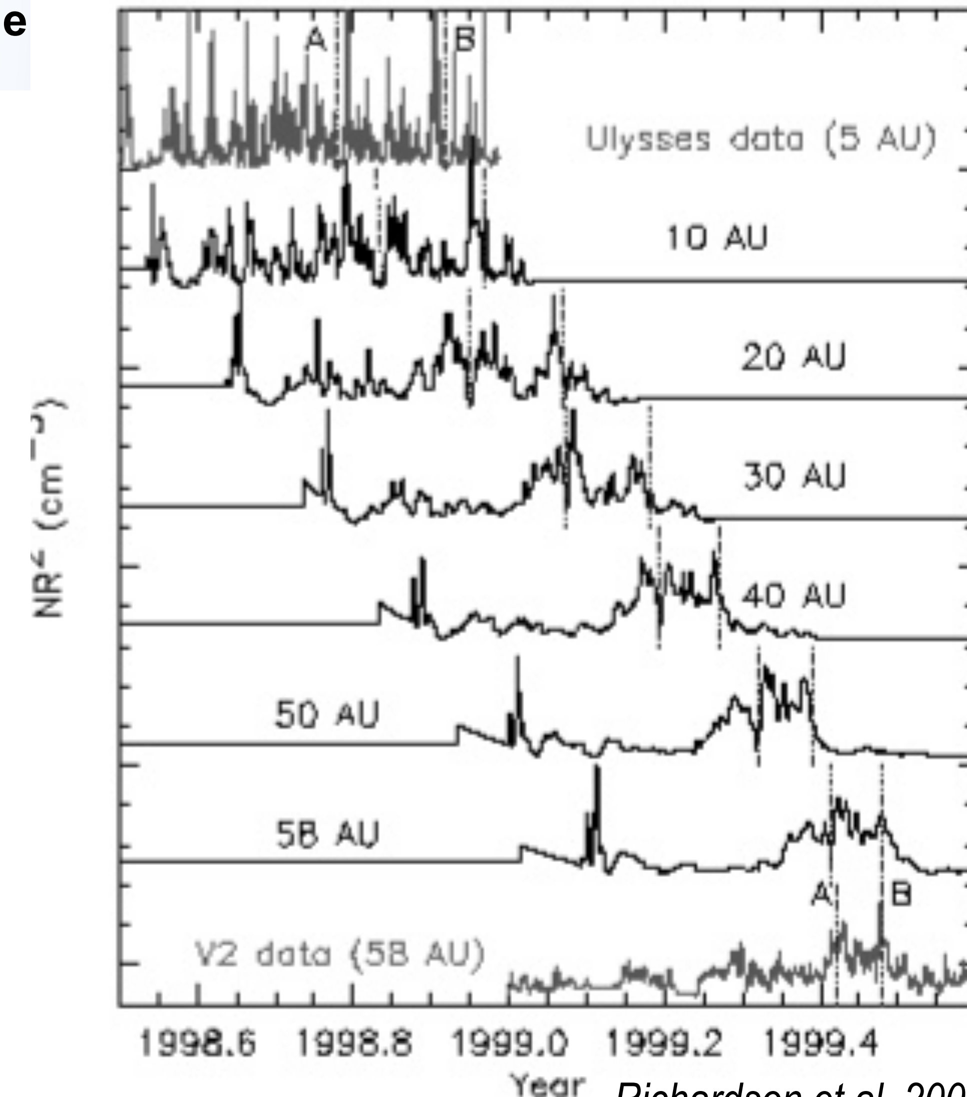
- Interval of very slow wind at New Horizons from 2019 through early 2023.
- Began in late 2018 at solar minimum and continued into the early rising phase of the solar cycle until late 2022.

Source of Slow Wind:

- Not an indication of proximity to the termination shock.
- Low current sheet tilt directed slow wind from coronal streamers towards New Horizons which was in the ecliptic.
- Amount of slowing owing to the pickup of interstellar material on par with Voyager 2.

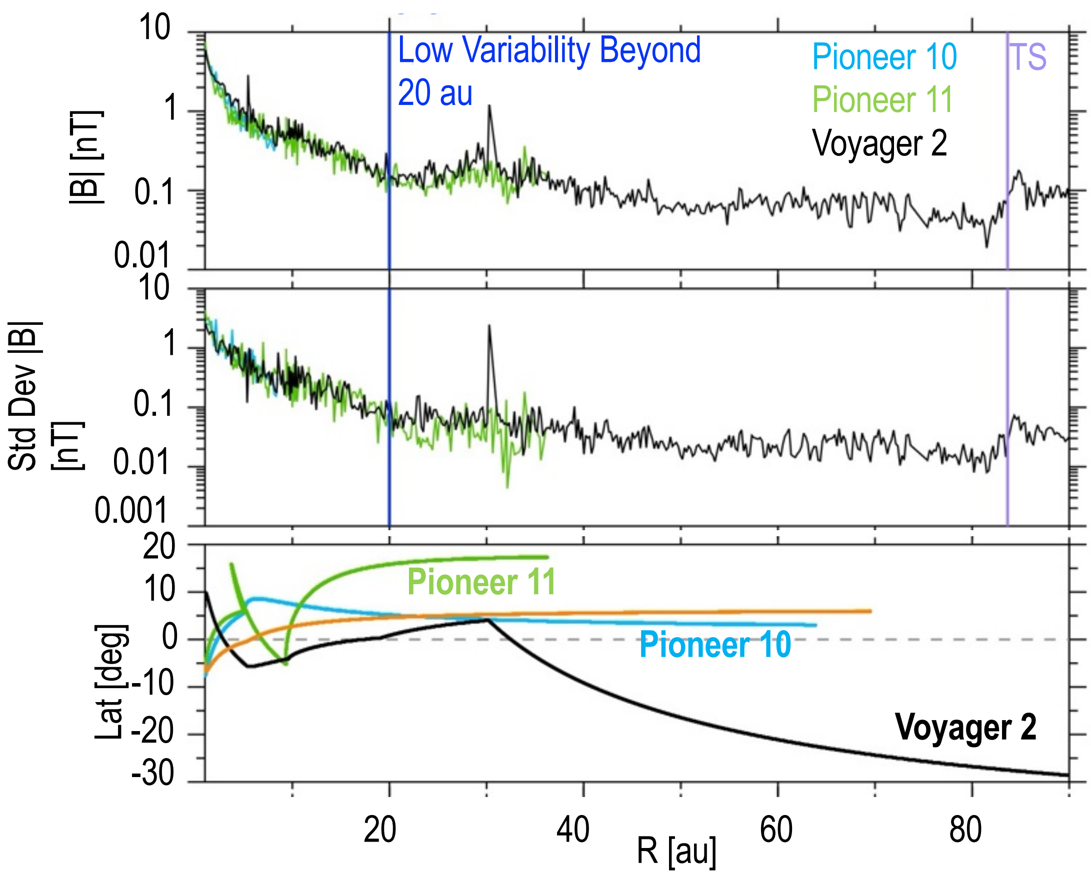
Structures in Solar Wind Density Merge and Are Worn Down with Distance

- Many structures in the inner heliosphere merge to for one larger scale feature with a smaller amplitude.
- The amplitudes decreases significantly inside of 20 au.
- All the structures between A and B have merged into one another by 40 au



Richardson et al. 2004

Interplanetary Magnetic Field Radial Profile



The field strength and the field variability decrease with increasing distance.

The variability of the field strength decreases rapidly inside of 20 au.

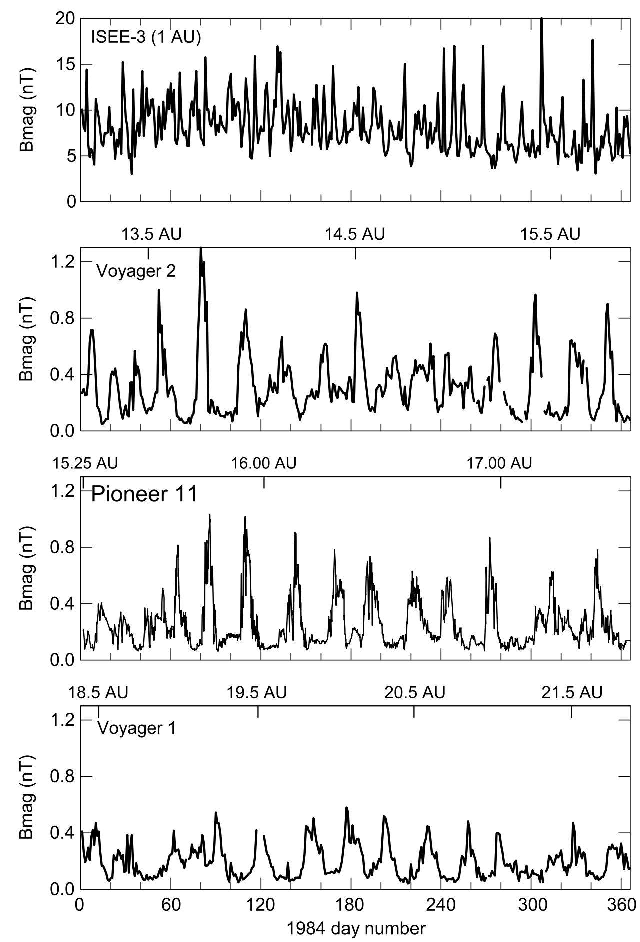
Then field strength variability decreases less rapidly to ~50 au where it levels off until reaching the termination shock

Structures in Magnetic Filed Merge and Are Worn Down with Distance

- The amplitude of the field structure decreased significantly between 1 au and 20 au.

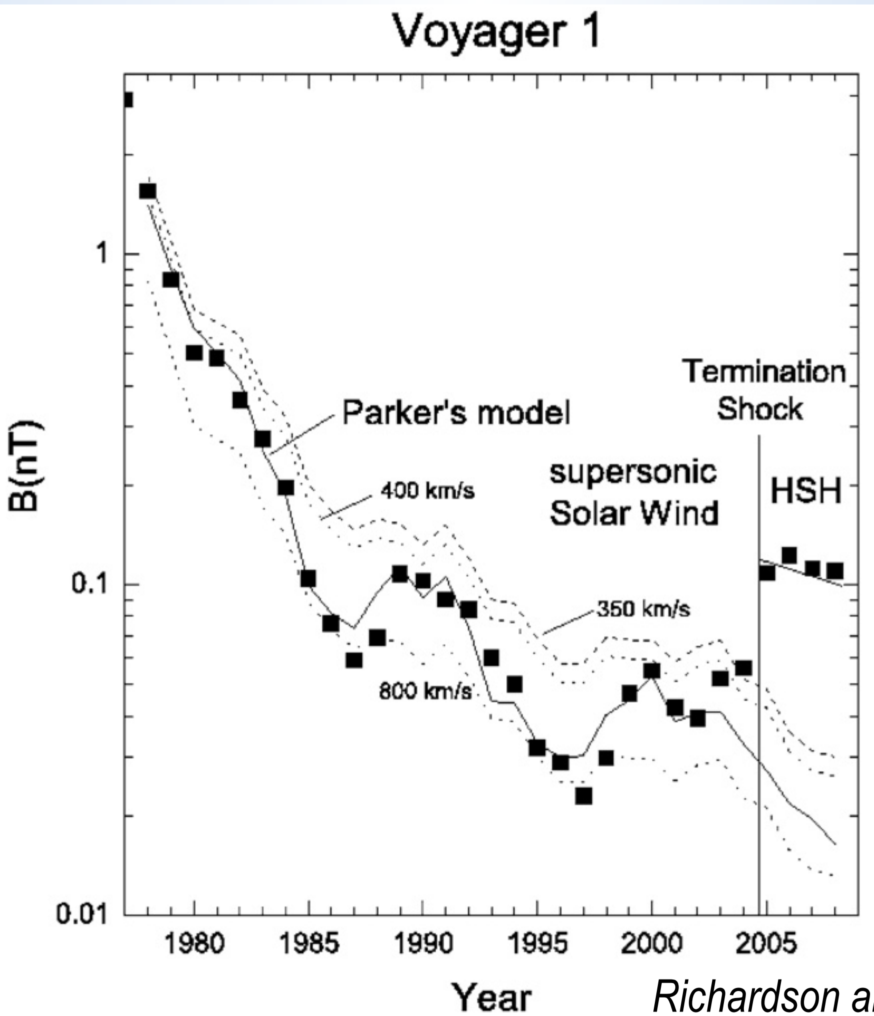
192 A. Balogh, G. Erdős

Fig. 11 The magnetic field magnitude measured through 1984 at four different heliocentric distances between 1 AU and 21 AU. The stream interaction regions at 1 AU (represented by their corresponding magnetic compression regions) merge into consolidated compression regions by the time the solar wind propagates to ∼13 AU. Although more dynamic interactions between streams may occur between 13 and 20 AU, the general pattern of about one large-scale compression region per solar rotation remains qualitatively unchanged



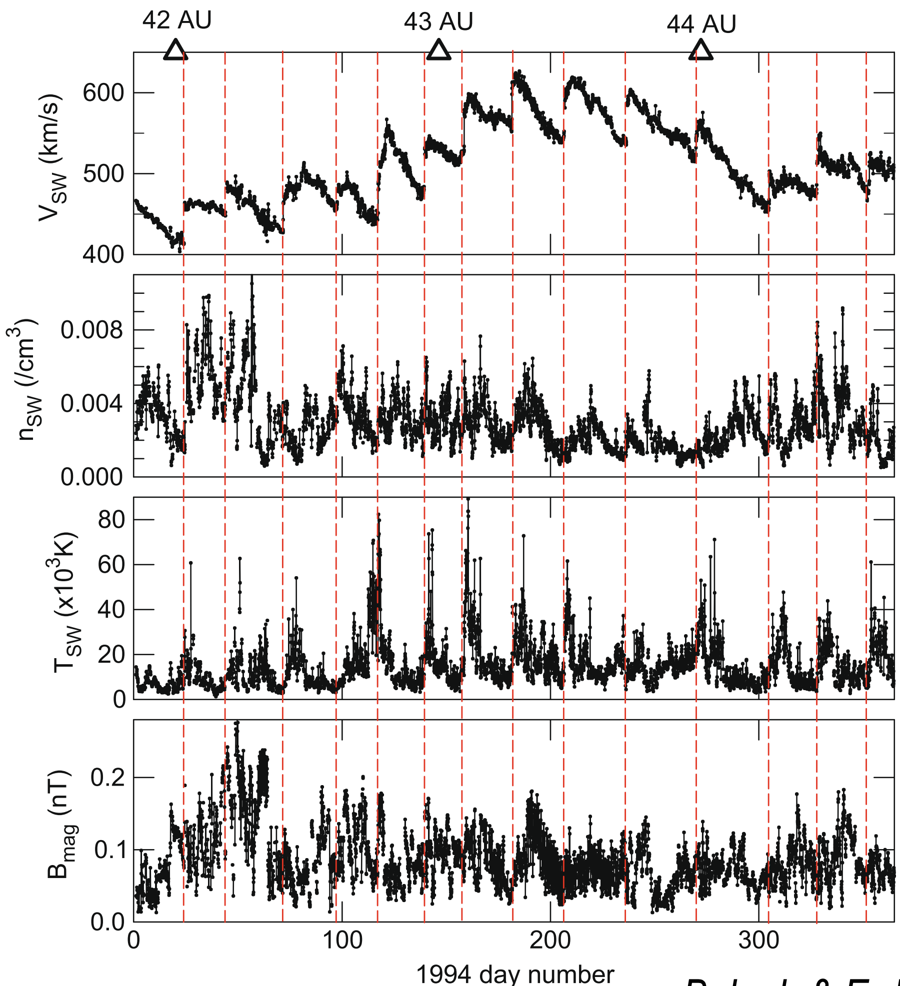
Balogh & Erdōs 2013

Magnetic Field Strength Radial Variation



Richardson and Burlaga, 2013

Shocks In Outer Heliosphere



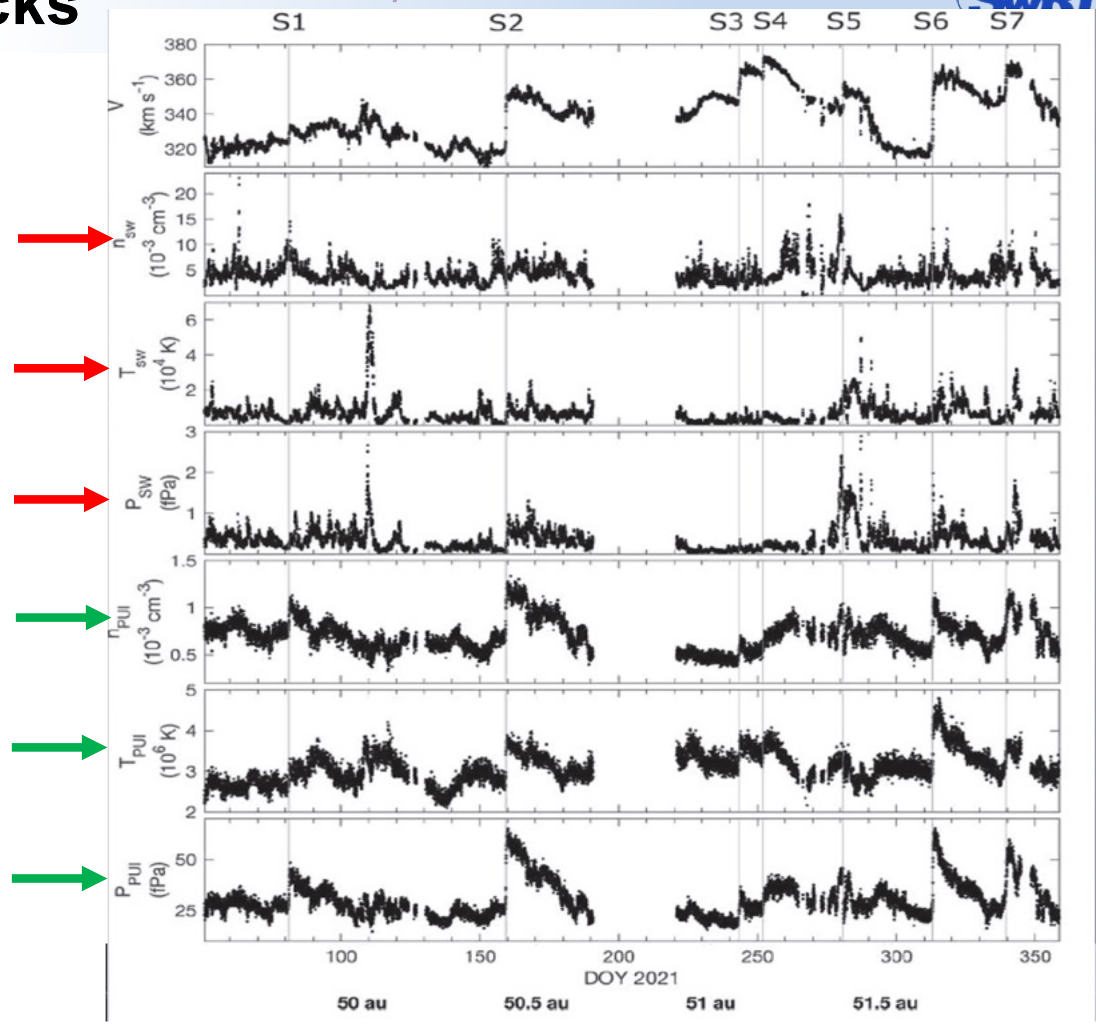
Balogh & Erdōs 2013

The classic compression signature where the density and field are enhanced on where the speed jumps does not always occur in the outer heliosphere.

Outer heliospheric shocks

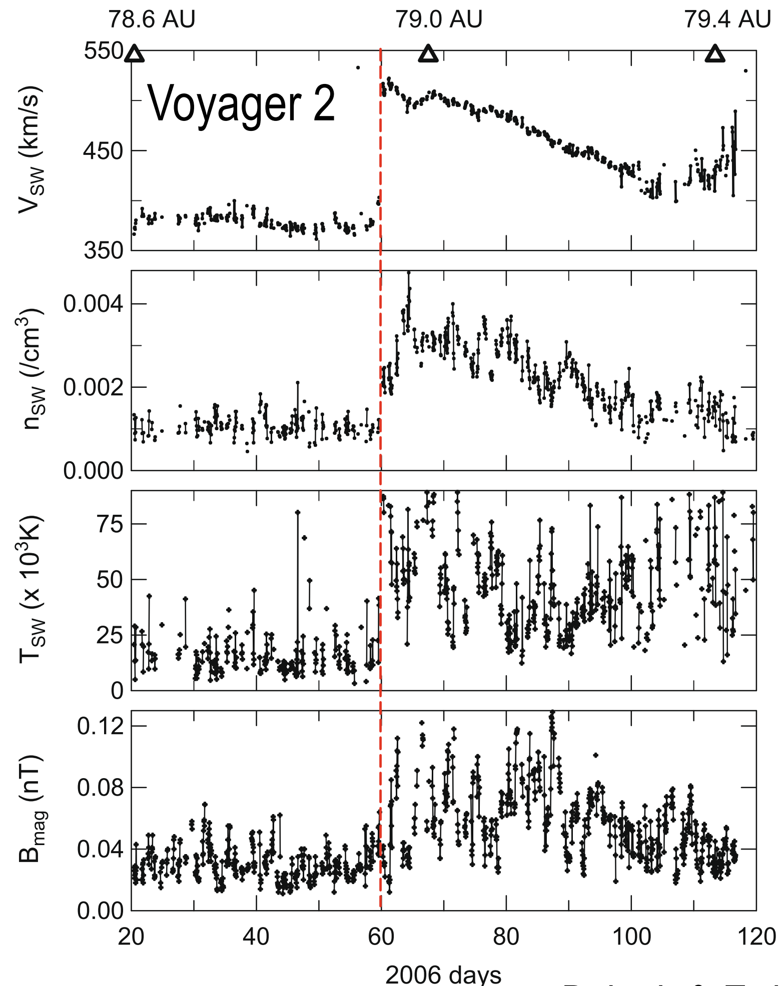
- Shocks observed by New Horizons
- PUIs have the dominant pressure in the outer heliosphere. Thus shocks in this region are mediated by these non-thermal energetic PUIs.
- ➔ PUI-mediated shocks
- Core solar wind properties did not show consistent changes across the shocks, indicating that these particles.
  - Need to measure the PUI to understand the shocks

NH/SWAP observations



Large Merged Interaction Region

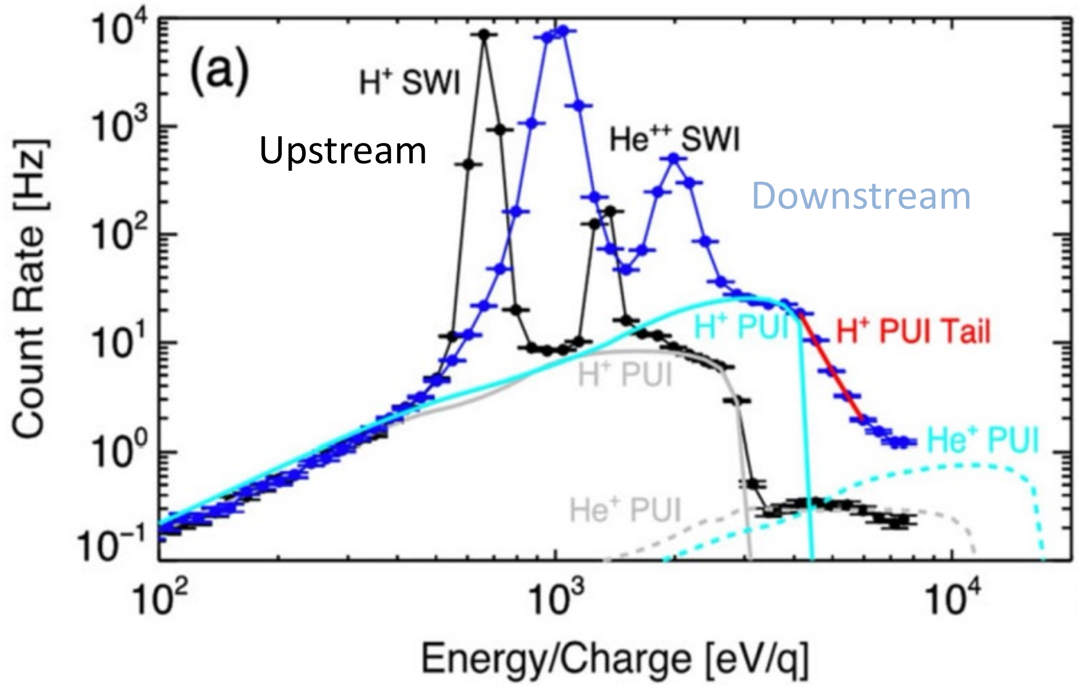
- In this very large Merged Interaction Region (MIR) the density and field strength are elevated after the shock.
- At 1 au the density typically peaks just before the rise in the speed.



Balogh & Erdōs 2013

Interstellar PUIs at the shocks

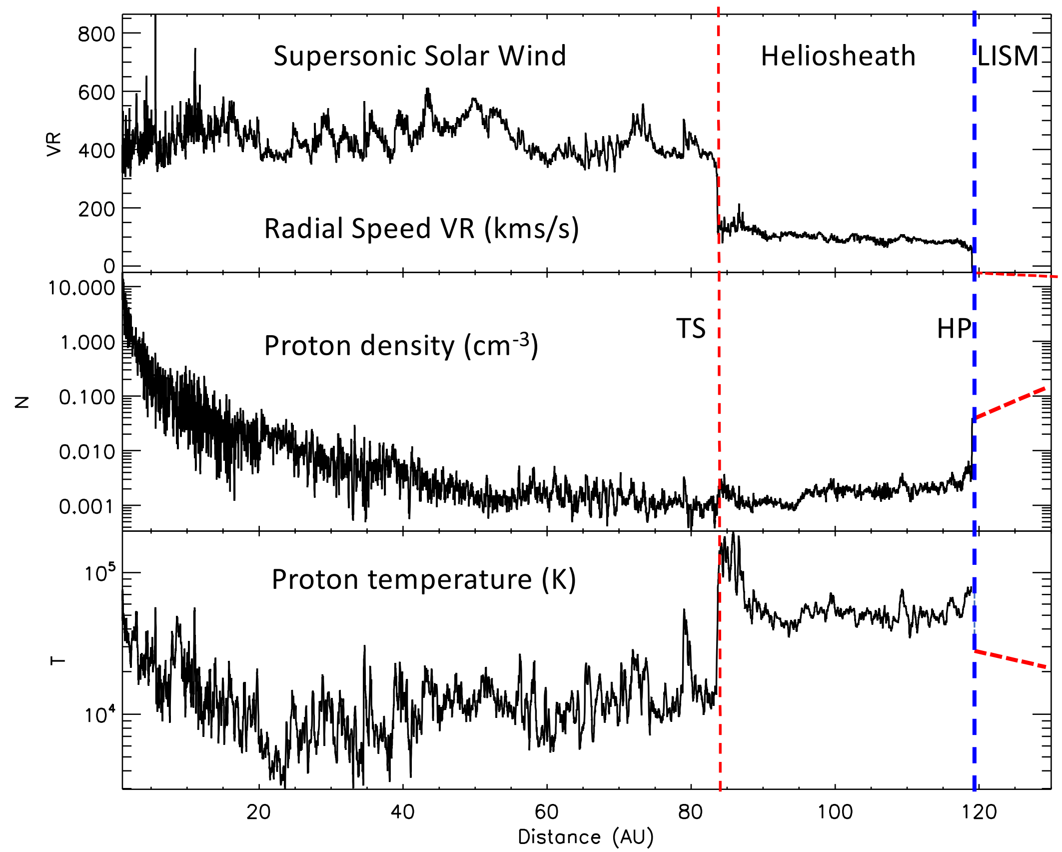
- Before the shock: SW proton and alpha are relatively cold. Proton PUI distribution is well represented by a filled-shell function with cutoff at $2V_{SW}$.
- After the shock, proton SWIs, alphas, and proton PUIs are all **hotter and denser.**
- But there is a suprathermal PUI tail downstream of the shock: The relatively steep PUI tail is a result of **preferential acceleration** at the shock, consistent with **PUI reflection at the cross-shock potential.**



Zirnstein et al. (2018)

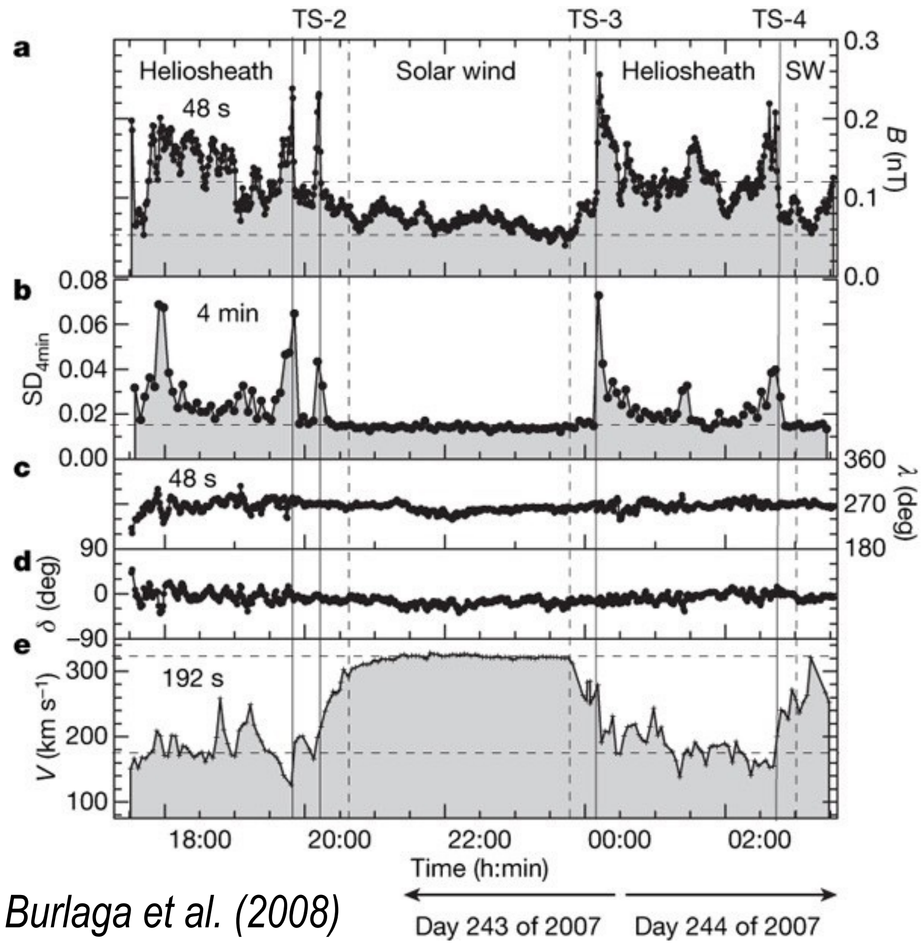
Termination Shock Crossing

- V1: at **94** AU in 2004
- V2: at **84** AU in 2007
- Termination shock is the largest fast reverse shock in our heliosphere.



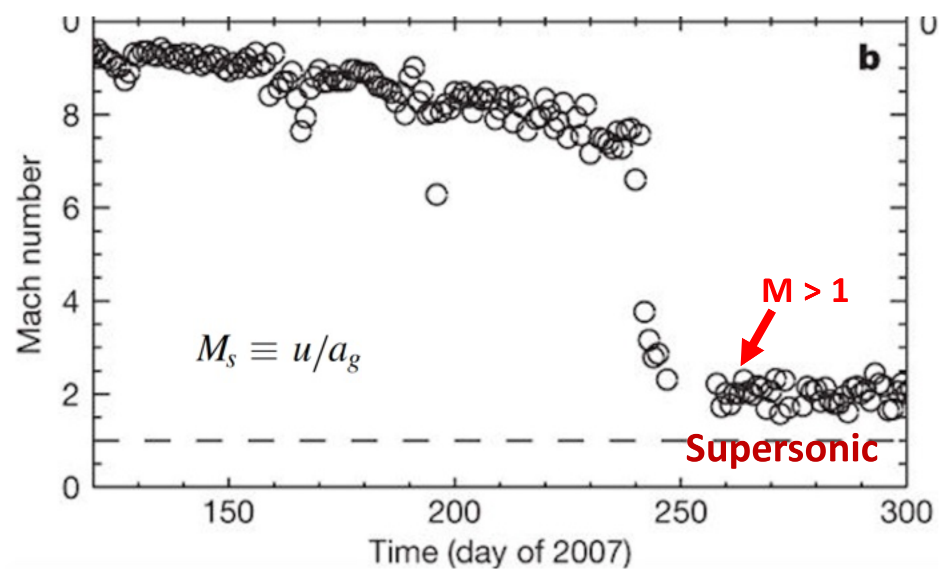
Multiple Crossing of the Termination Shock

- V1: does not have a working plasma instrument.
- V2: has a working plasma instrument.
- It showed multiple crossing ➔ **5 times!**
- The termination shock moved back and forth which caused multiple crossings of the termination shock by Voyager 2.

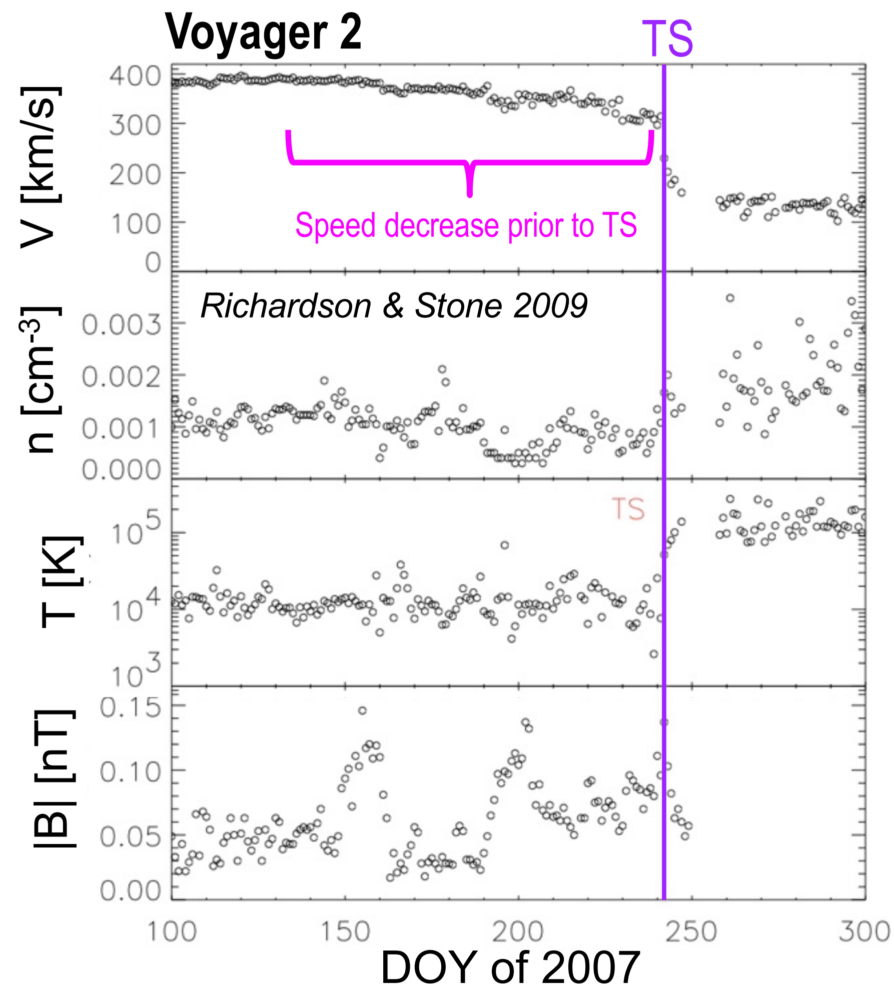


Burlaga et al. (2008)

Termination Shock Crossing

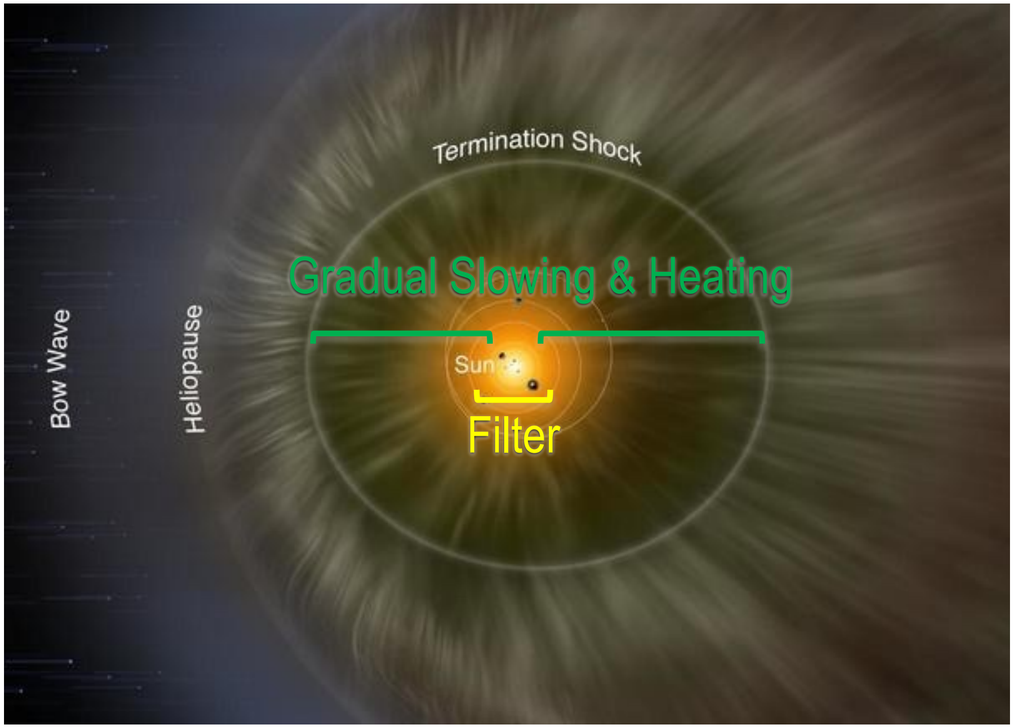


Richardson et al. (2008)



Outer Heliosphere: Summary and Conclusions

1. The pickup ion thermal pressure is very important in the outer heliosphere.
2. The slowing and heating of the solar wind in the outer heliosphere owing to the pickup of interstellar material is a gradual process.
3. To clearly observe and quantify the slowing, we need to compare outer heliospheric observations to inner heliospheric observations.
4. The amount of slowing in the solar wind in the outer heliosphere compared to 1 au was 5-7% slower from 30-43 au, and is 13-15% slower from 50 - 60 au.
5. The changes in the solar wind temperature and density relationship could be used to determine when New Horizons is getting close to the termination shock



Modified Credit NASA/Adler Planetarium

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