Structure of the Heliosphere

Part II

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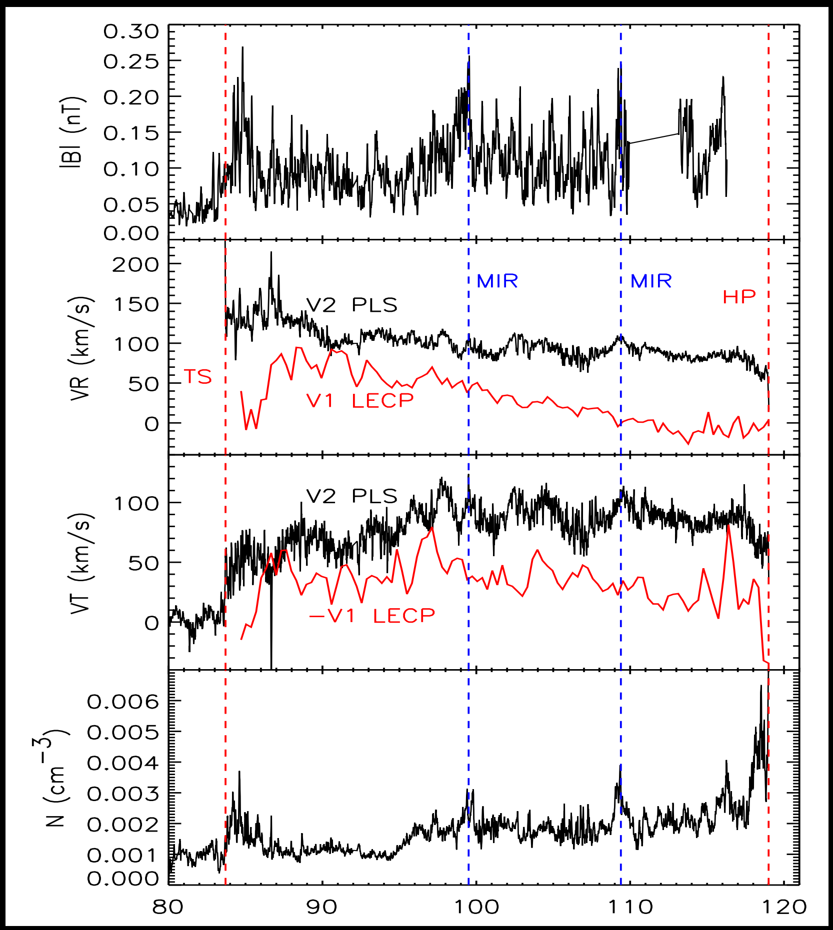
Opher et al. Nature Astronomy 2020

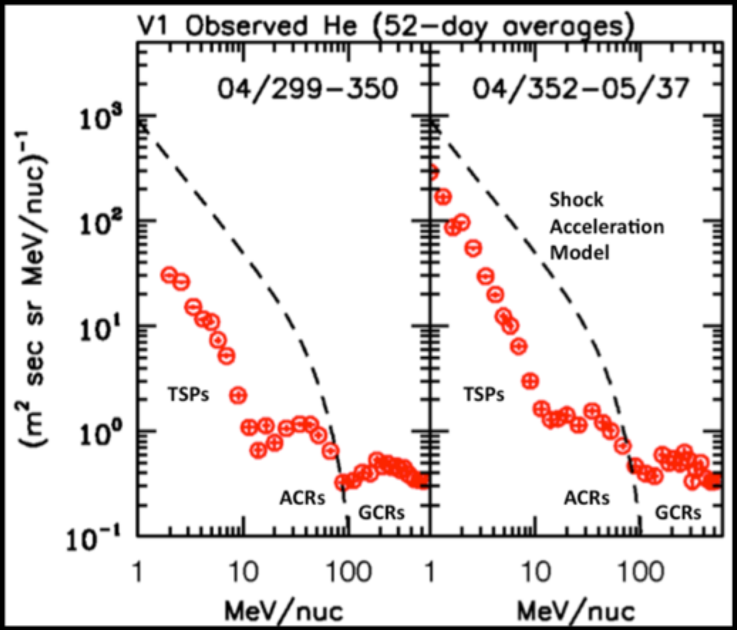
Our Current Models Failed to Explain Key Observations

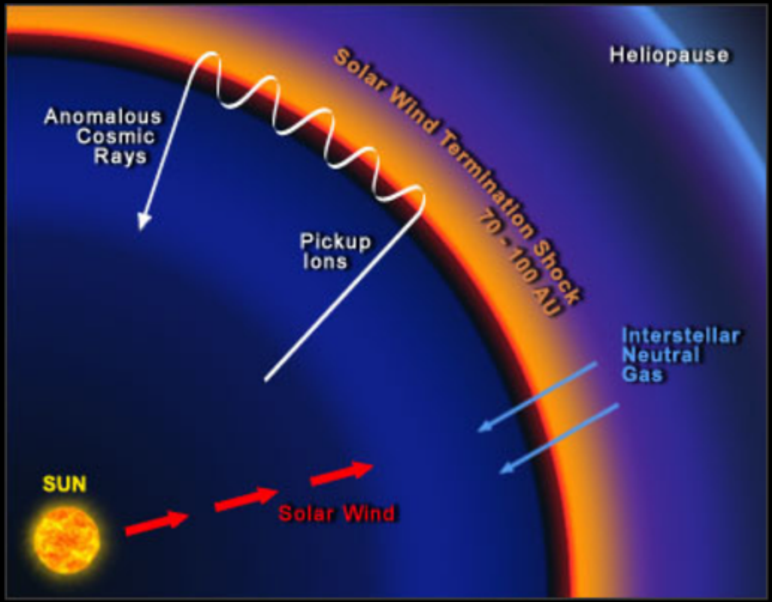


The differences are not understood and don't match current models

Voyager spacecrafts lack instrumentation capable to measure the weak magnetic fields in the heliosheath and a key component of the plasma

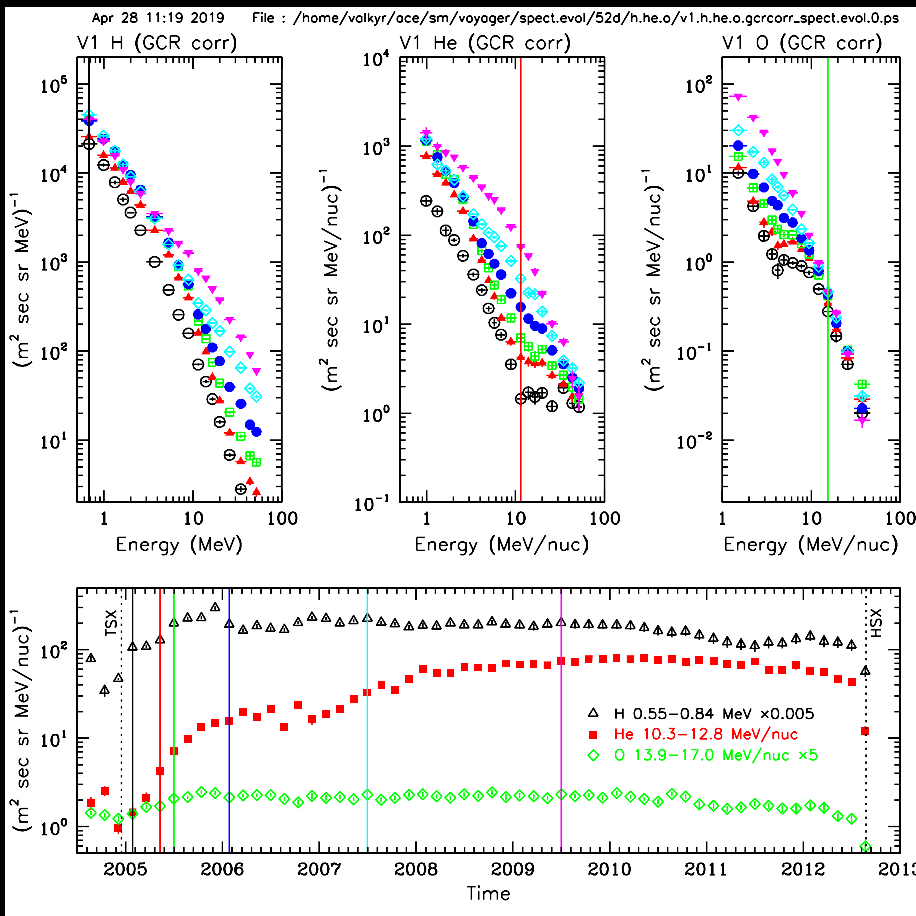
How and where the Anomalous Cosmic Rays (ACRs) accelerated?





Old paradigm: PUIs are accelerated at the Termination Shock to ACRs (MeV energies).
NOT seen at Voyager 1 and 2

ACRs intensities evolve throughout the Heliosheath



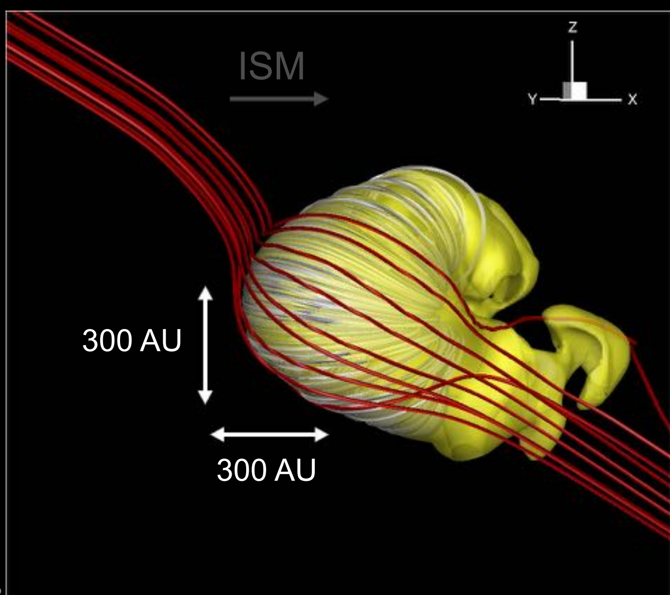
The intensity peaked just before the Heliopause

Broad Implications for acceleration of particles in space physics and astrophysics

Models predict a much thicker heliosheath than observations

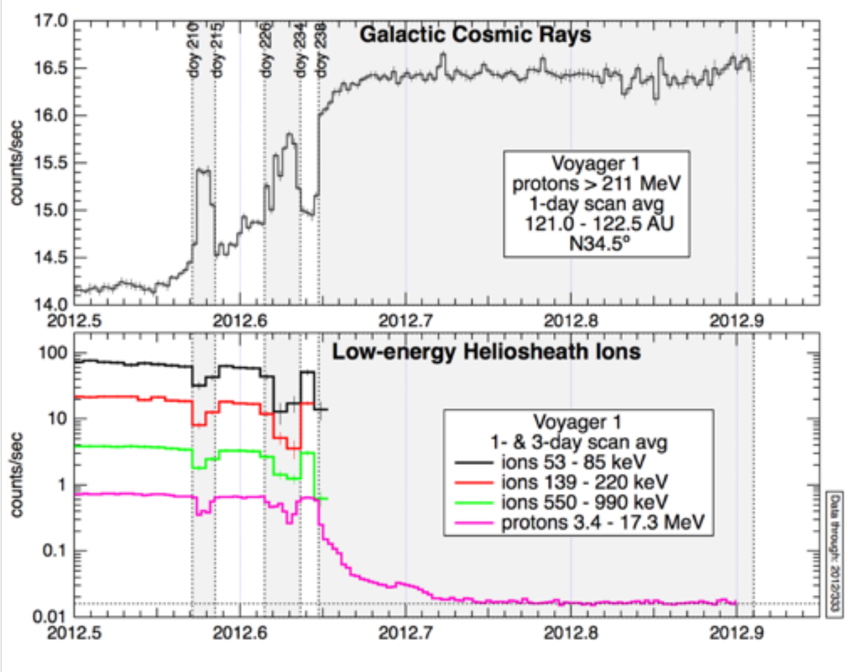
Models predict 60-70AU while thickness was 28AU at V1 and 35AU at V2

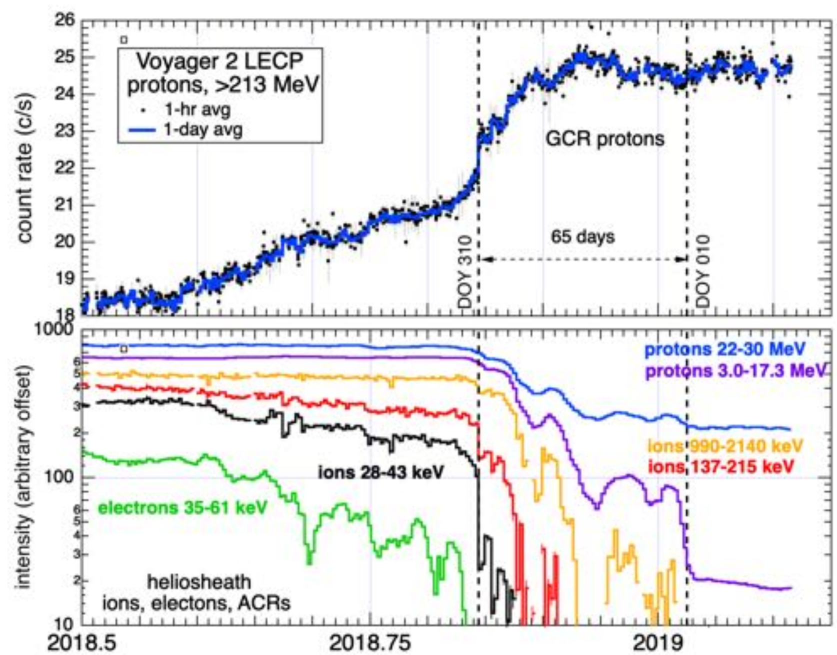
Time Dependent effects cannot reconcile these measurements
(Izmodenov et al. 2005; 2008)



Indicating that some
physics is missing in the models

How Porous is the Heliopause?

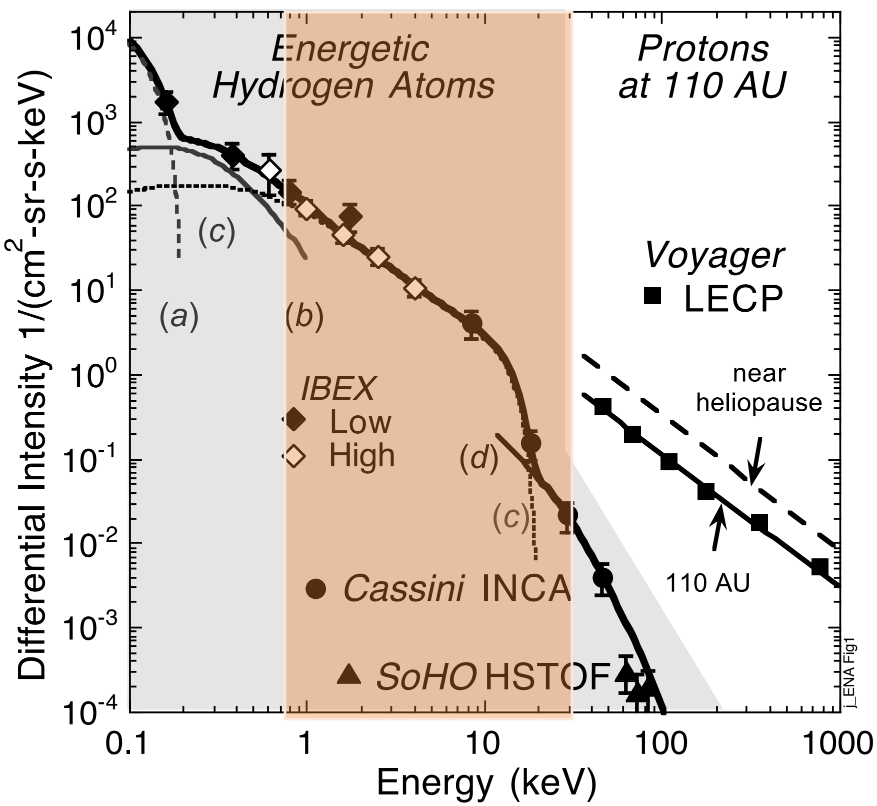




The Properties of the Heliopause are not understood

Science Question A:
What is the global structure of the heliosphere?

Science Question B:
How do Pick-Up Ions evolve from “cradle to grave”?



PUIs are particles with energy > ~0.5 keV (hotter than the thermal component of the solar wind)

Voyager is “blind” to PUIs until 28keV

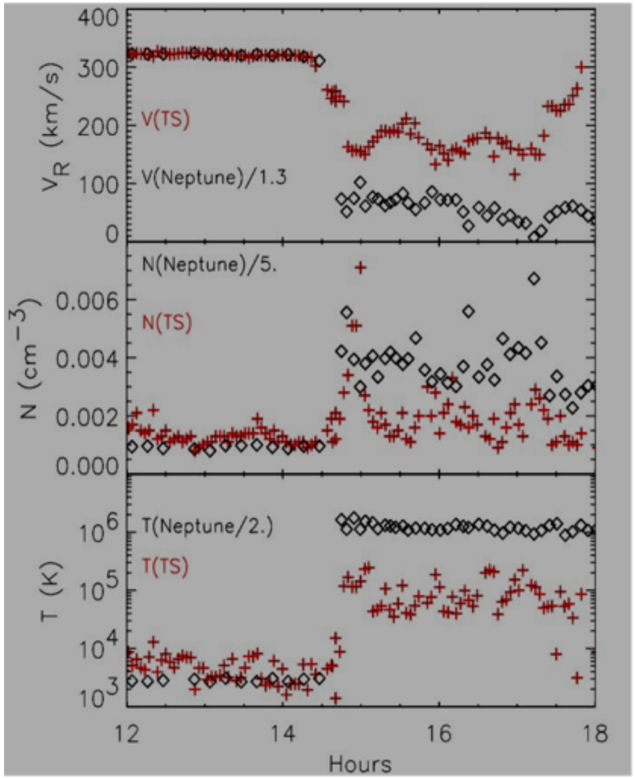
New Paradigm:

Realization that the Energetic Particles - created streaming of neutral H from ISM – *Pick-Up ions (PUIs)* are the dominant species in the distant solar wind

Voyager data of the crossing of the Termination Shock:

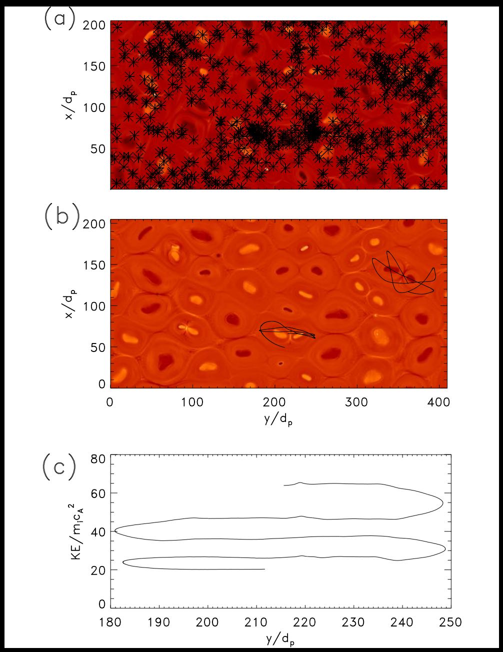
Plasma was colder by one order of magnitude the PUIs carry all the energy

Previous Global Models: Cold Solar Wind + PUIs = one fluid

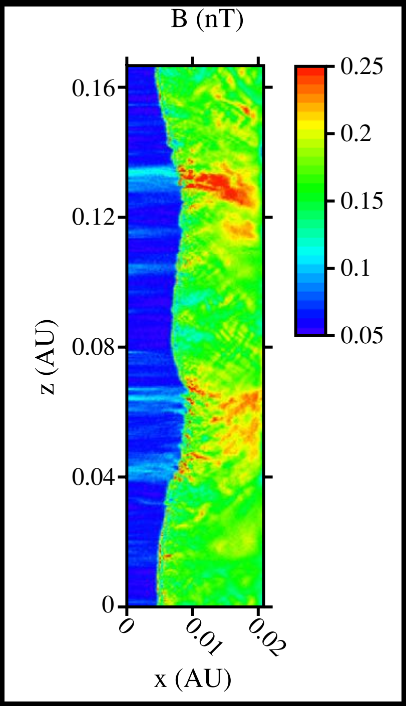


Richardson et al. Nature 2005

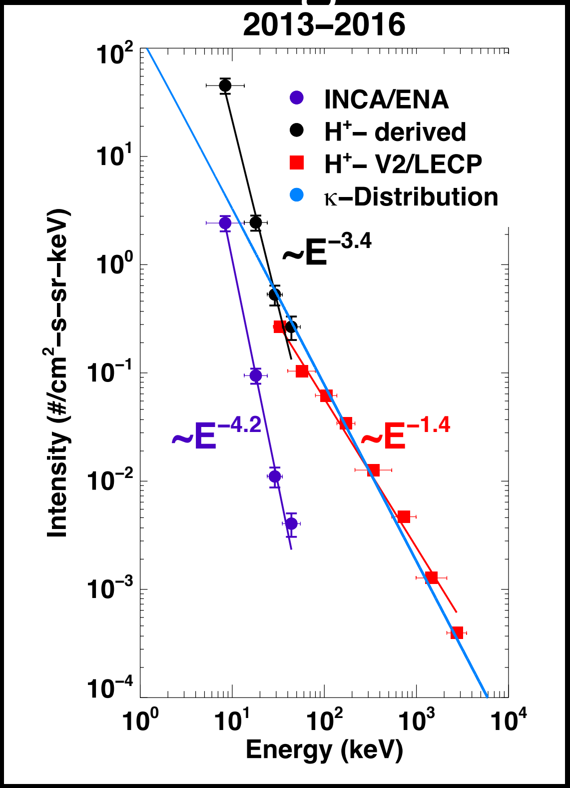
How the Pick-Up Ions evolve from “cradle to grave



Reconnection



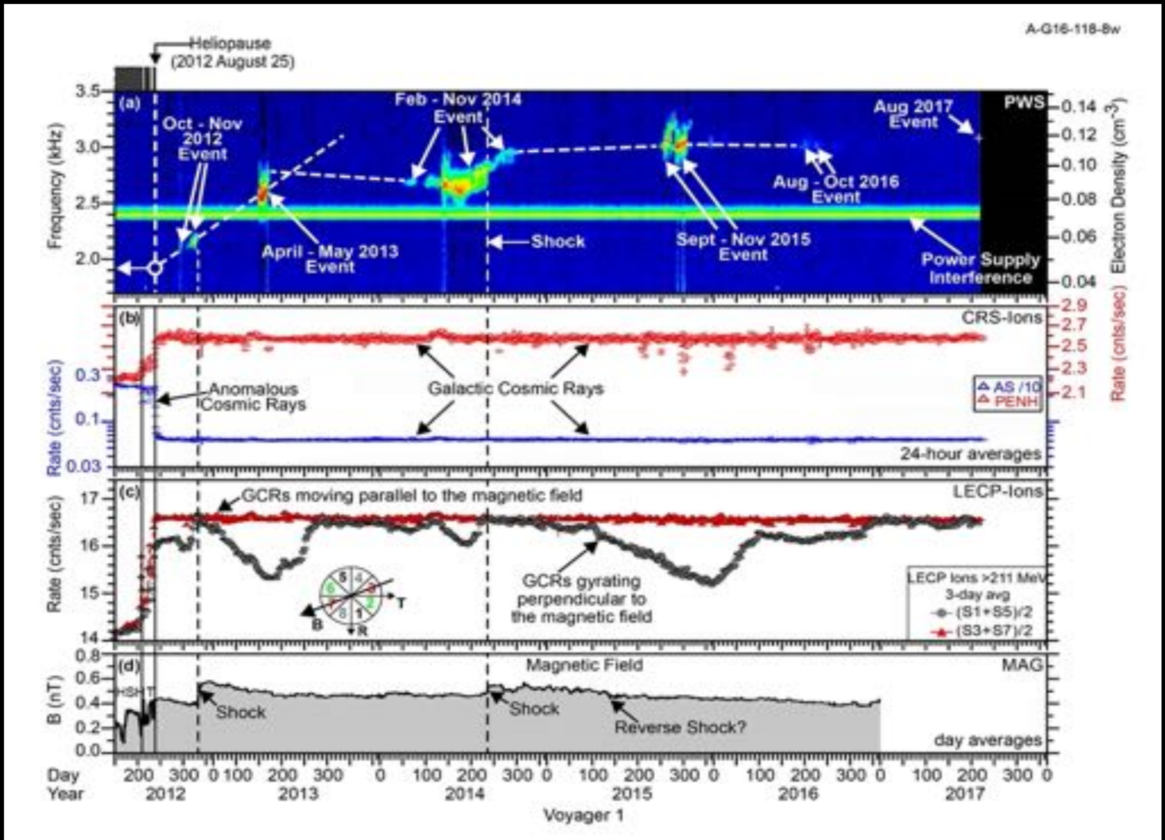
Turbulence



Dialyanas et al. 2019

Science Question C:
How does the heliosphere interacts with Interstellar Medium?

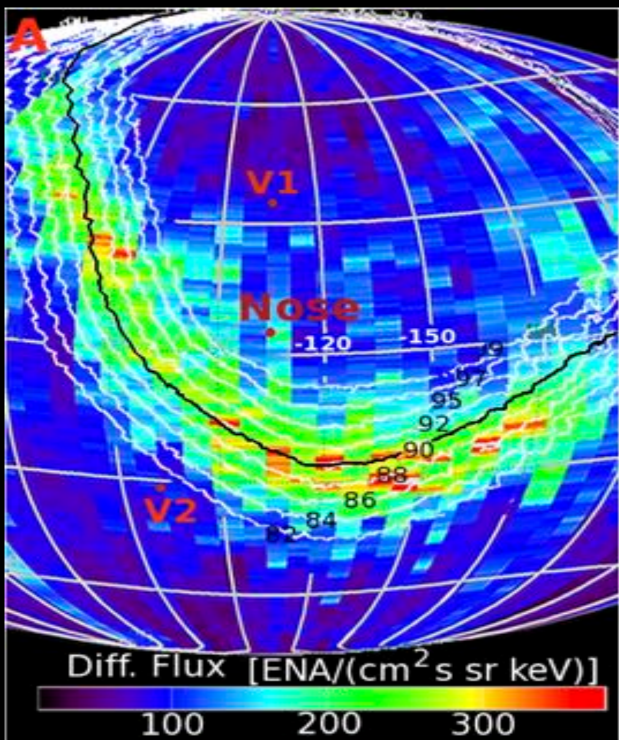
The medium ahead of the Heliosphere in the ISM is disturbed by the Heliosphere



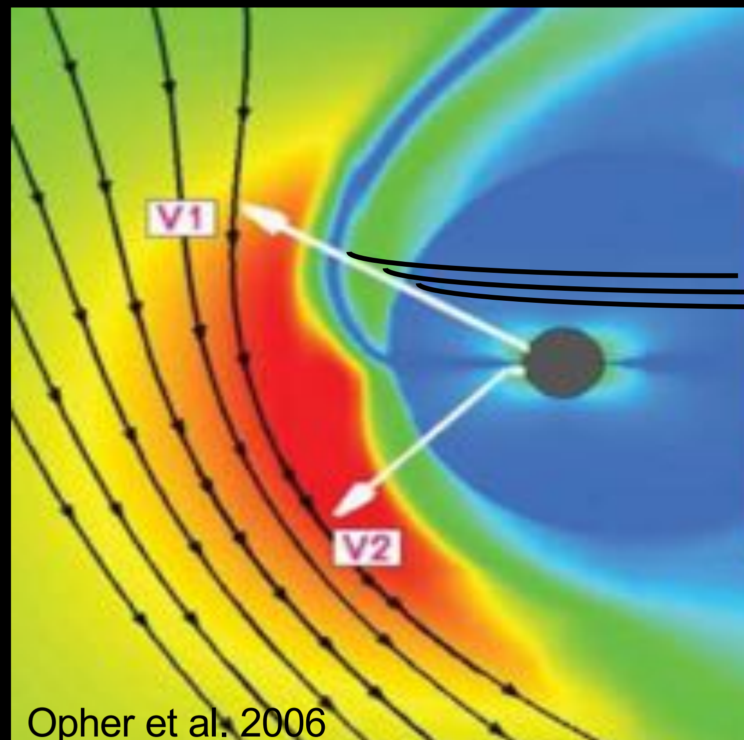
Gurnett et al.

How far does the heliospheric influence extends into the ISM?

Need to understand the draping of Interstellar Magnetic Field a round the heliosphere



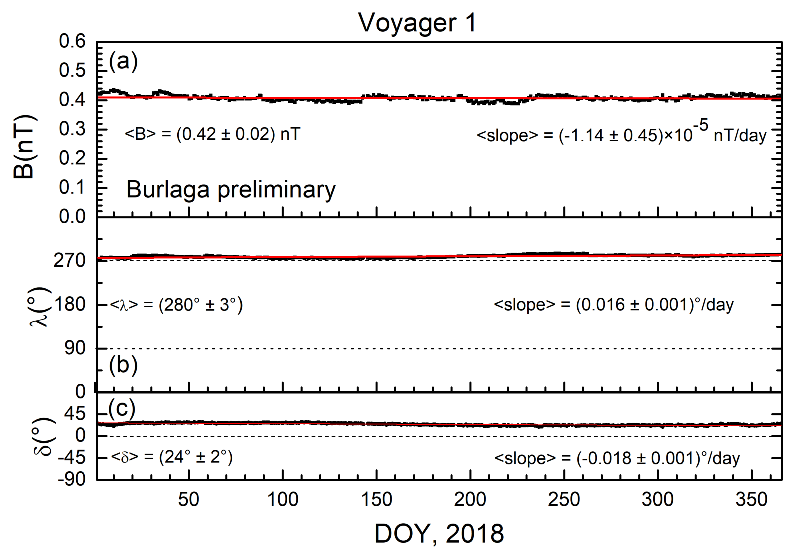
McComas et al. 2009

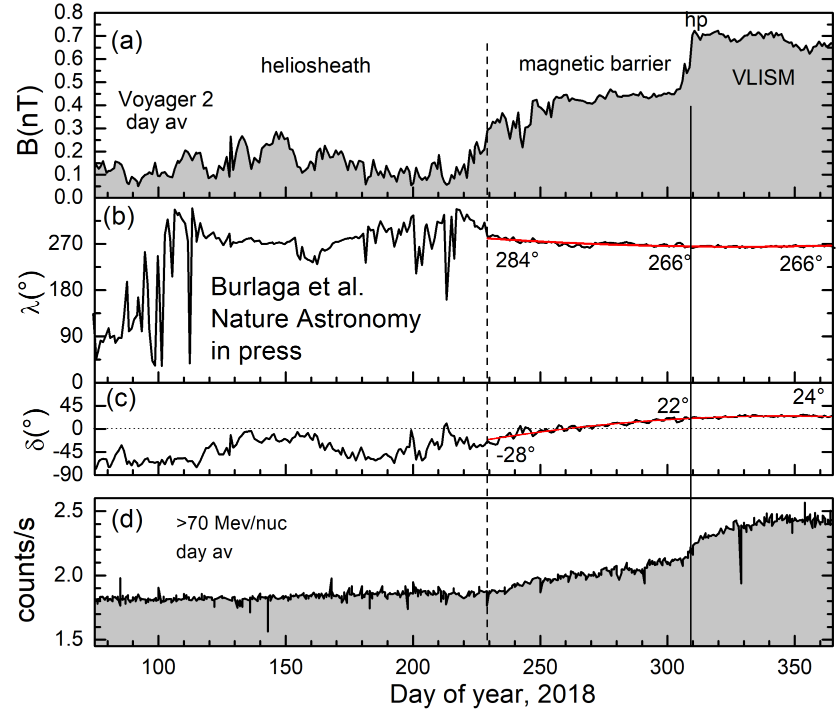


Opher et al. 2006

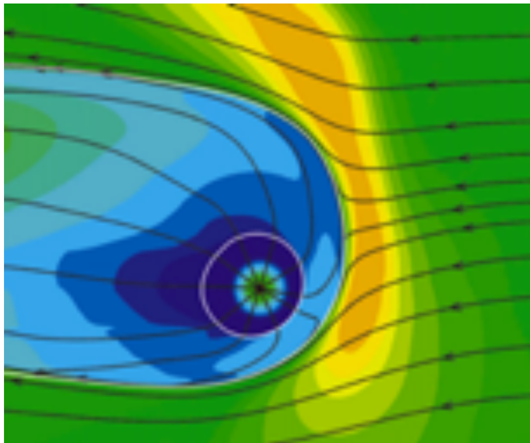
Models predicted a dramatic rotation of the magnetic field direction upstream of the Heliopause

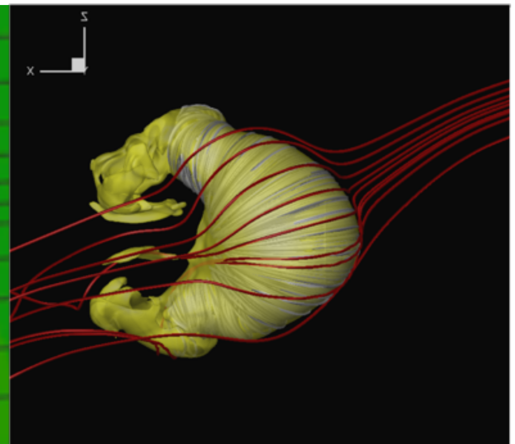
The Interstellar Magnetic Field is Solar Ahead of the Heliosphere at Voyager 1 and 2

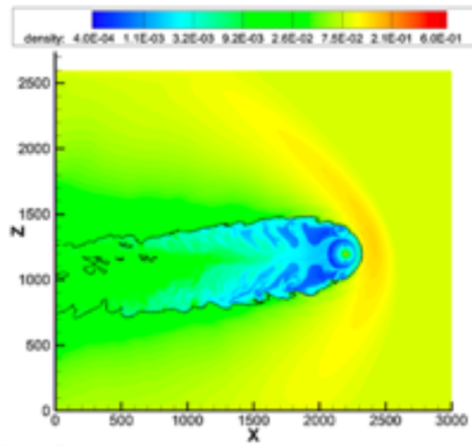


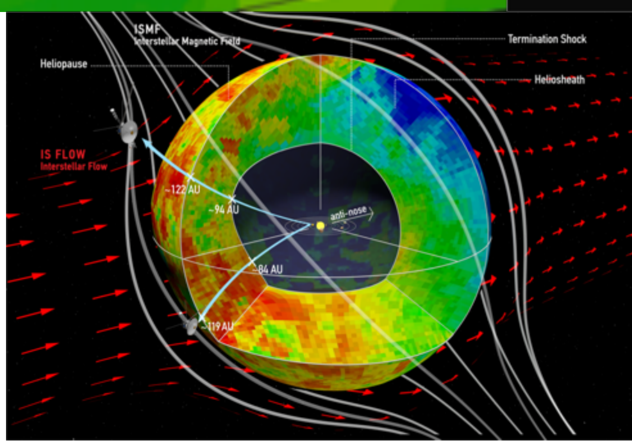


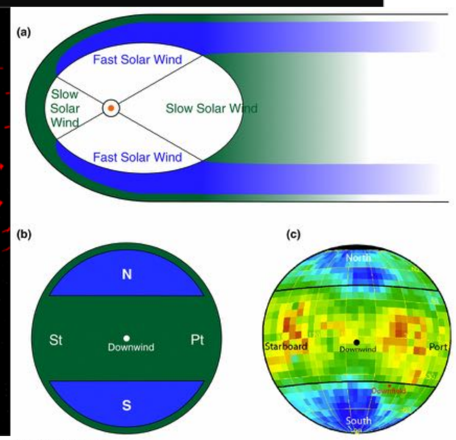
There is a Current Debate on Shape of the Heliosphere







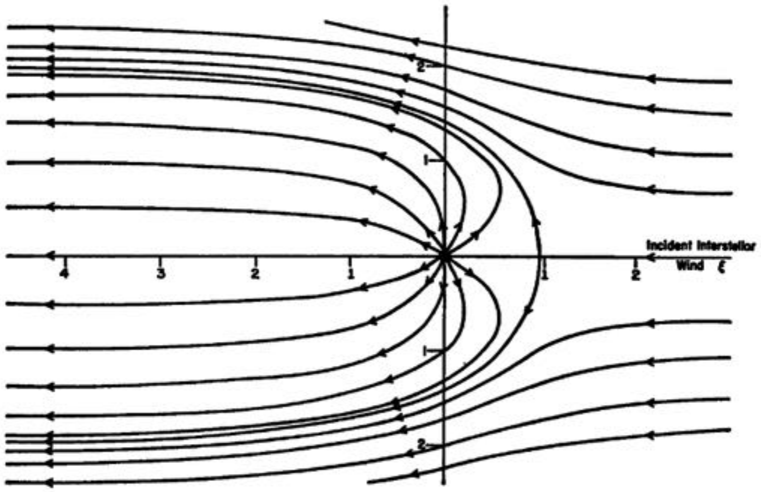




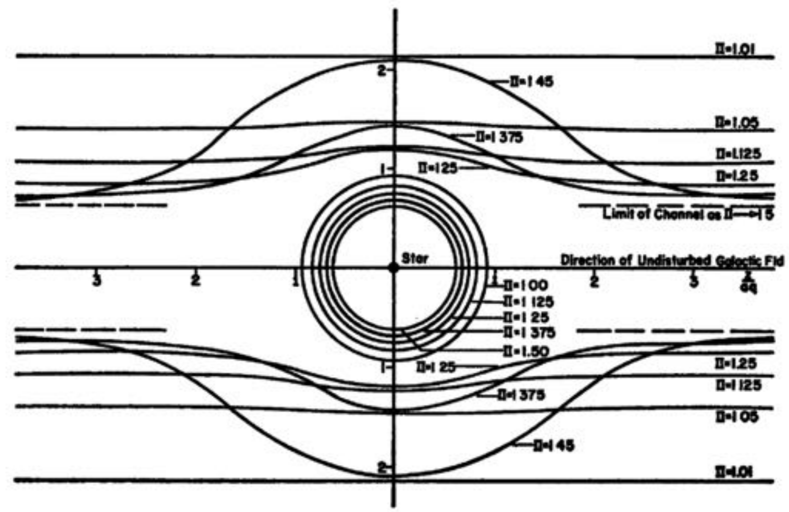
This question is one that will be addressed in

SHIELD

Concepts of the Heliosphere: Classic works of 50-60’s



Weak Interstellar Magnetic Field



Strong Interstellar Magnetic Field

Parker (1961)

Working Paradigm: Long Comet-like Tail

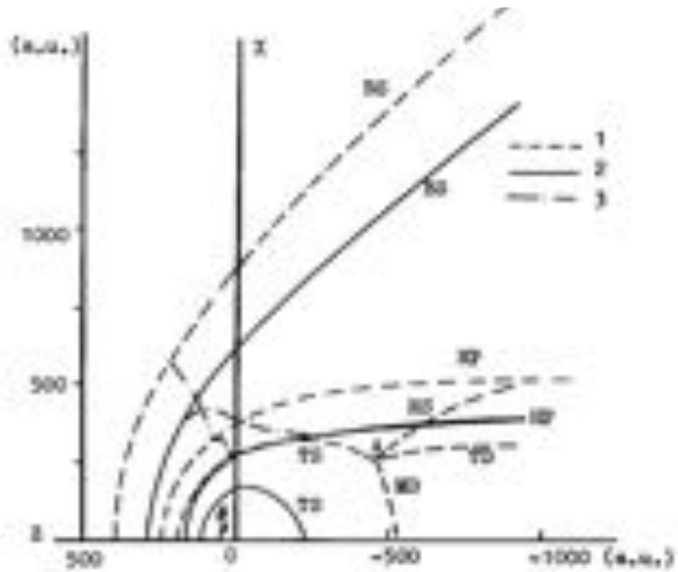
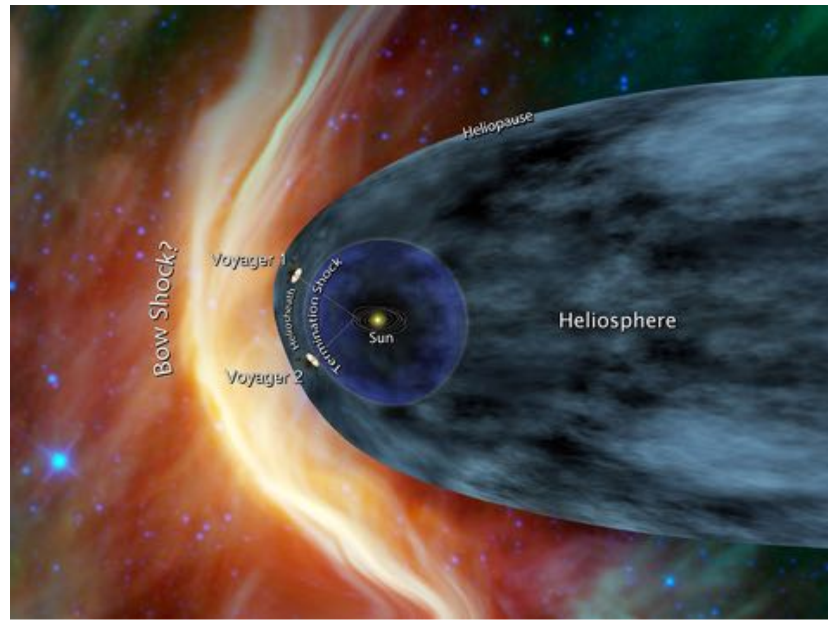
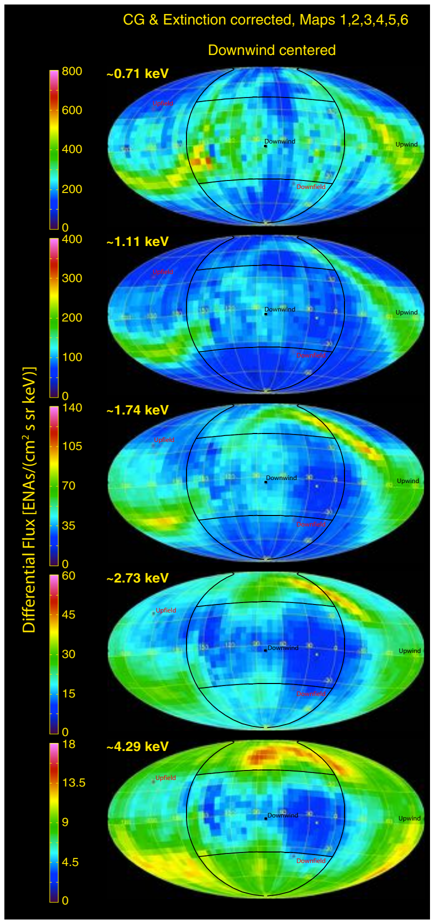


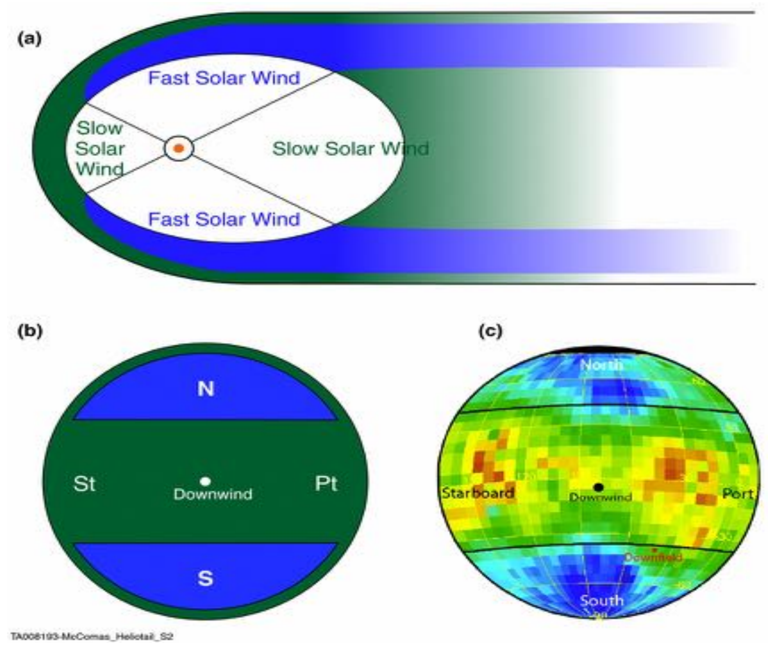
Fig. 2. Geometrical pattern of the interface. Results of the numerical calculations for $n_{H\infty} = 0$ (1) and $n_{H\infty} = 0.14\ cm^{-3}$ (2); curves (3) are the sonic lines. Positions of bow shock (BS), termination shock (TS), heliopause (HP), reflected shock (RS), tangential discontinuity (TD), and Mach disc (MD) are shown.



Baranov & Malama (1993) – Hydrodynamic calculations

First ENA images of the Heliospheric Tail



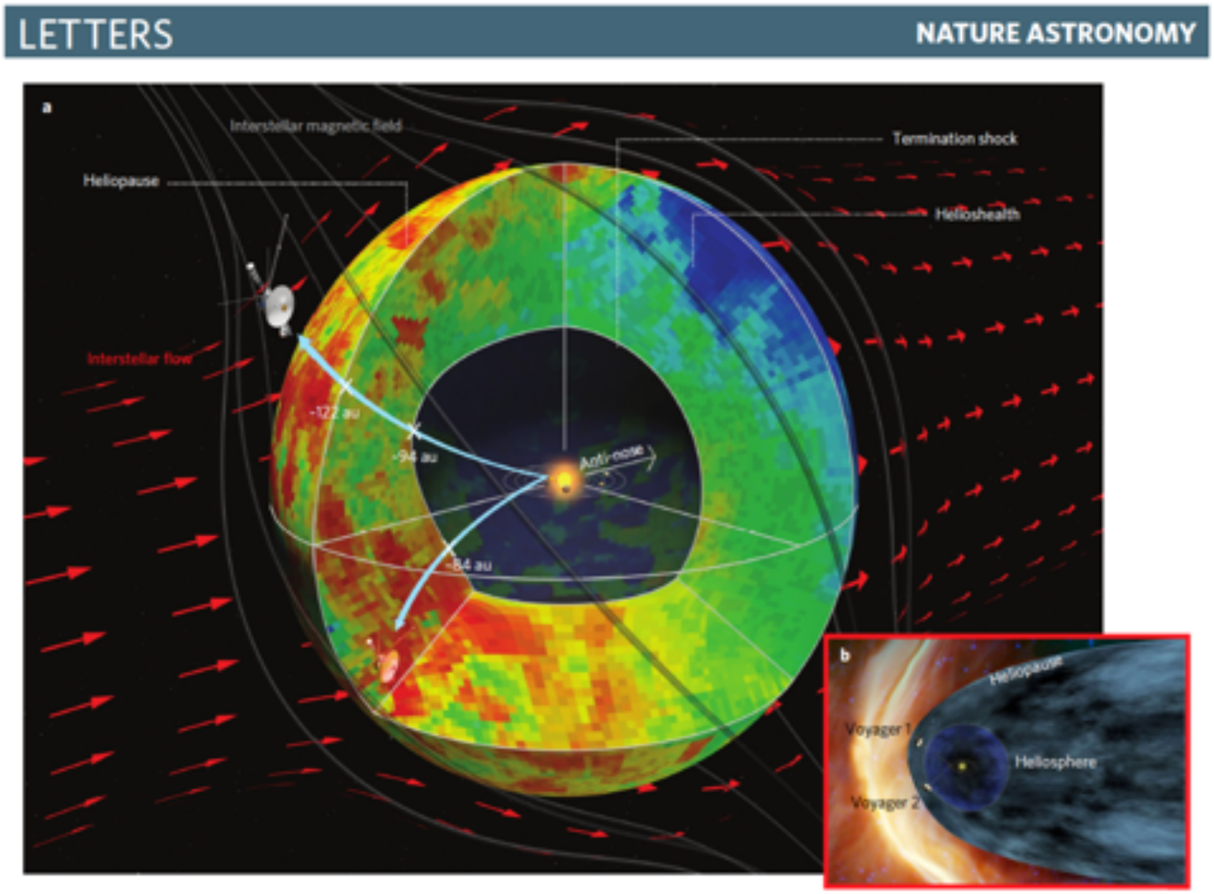


IBEX; ENA images
Around 1-6keV

McComas et al. 2013

Interpretation of the signal from a long comet like heliospheric tail filled with slow and fast solar wind

Bubble-like shape

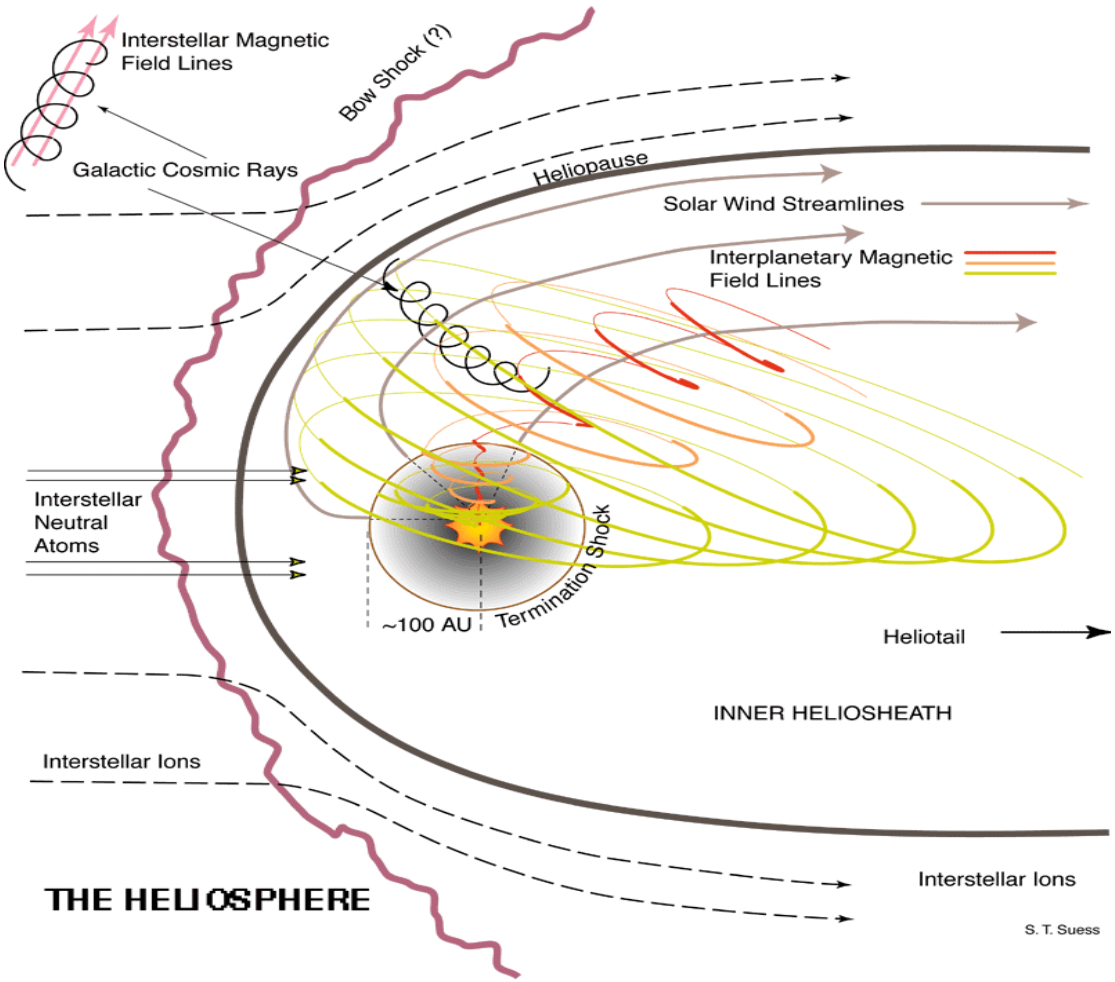


CASSINI/INCA; ENA images 5.2keV-55keV

Interpretation based on the signal being the same at the nose and tail

Diaylinas et al. 2017

ISSUE OF CONFINEMENT by the Solar Magnetic



Assumption is that the solar magnetic field has a negligible role

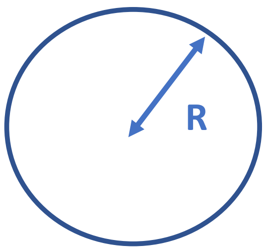
Probably because in the heliosheath, the plasma $\beta = P_T/P_B >> 1$

$$B = B_0 \left(\frac{R_0}{r}\right)^2 e_r - B_0 \left(\frac{R_0^2}{r}\right) \frac{\Omega \sin \Theta}{v_{SW}} e_\phi,$$

Ω: stellar rotation rate
Θ: polar angle

Interplanetary Magnetic Field

Issue of Confinement: Resistance of the solar magnetic field to being stretched



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

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

The force stretching the magnetic field due to the flows is

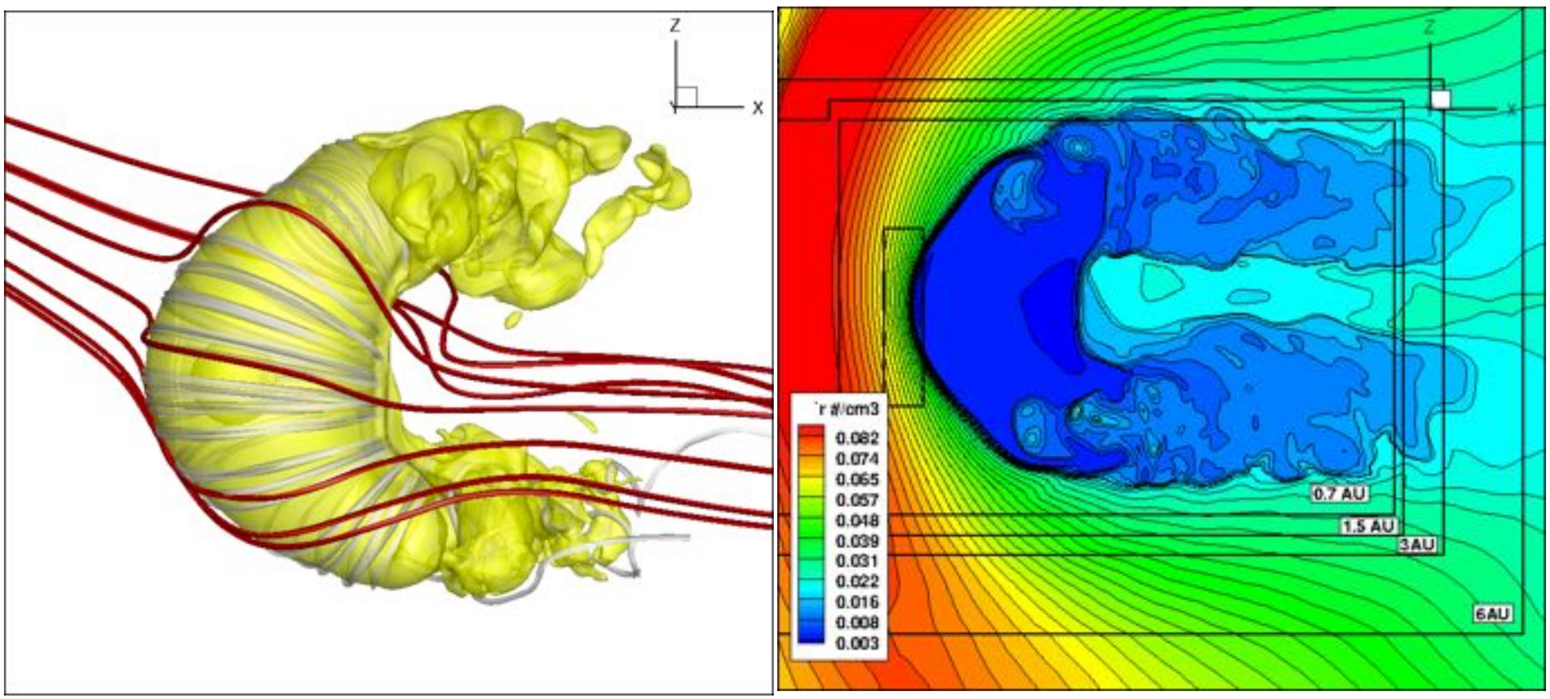
$$F_{streatching} \approx \rho|\mathrm{v} \cdot \nabla \mathrm{v}|/2 \approx \rho \mathrm{v}^2 \kappa_V / 2 \approx \rho \mathrm{v}^2 / 2R \approx P_{ram}/R$$

so the ratio between the two forces is

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

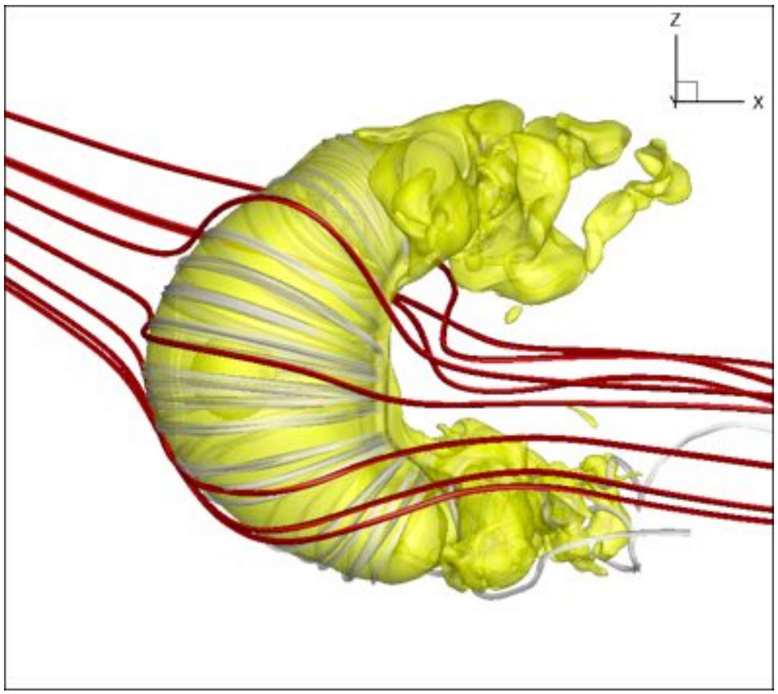
For the Heliosheath nominal values $F_{streatching}/F_{tension} < 1$

Solar Magnetic Field is the backbone of the heliosphere: “Croissant-Like” Heliosphere

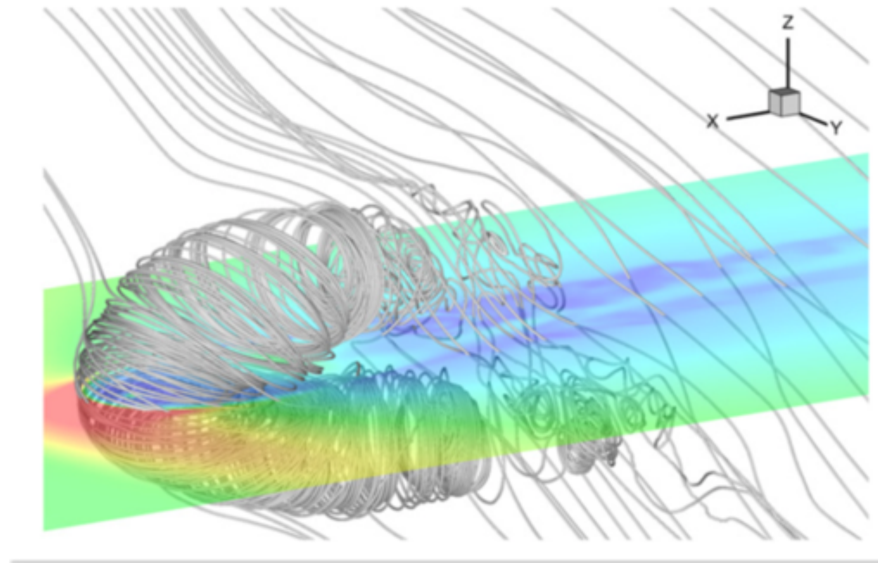


Tension force collimates the heliosheath flow in two jets
(Opher et al. 2015; Drake et al. 2015)

Realization: The magnetic tension of the solar magnetic field organizes the solar wind into two jet-like structures



Opher et al. 2015; Drake et al. 2015

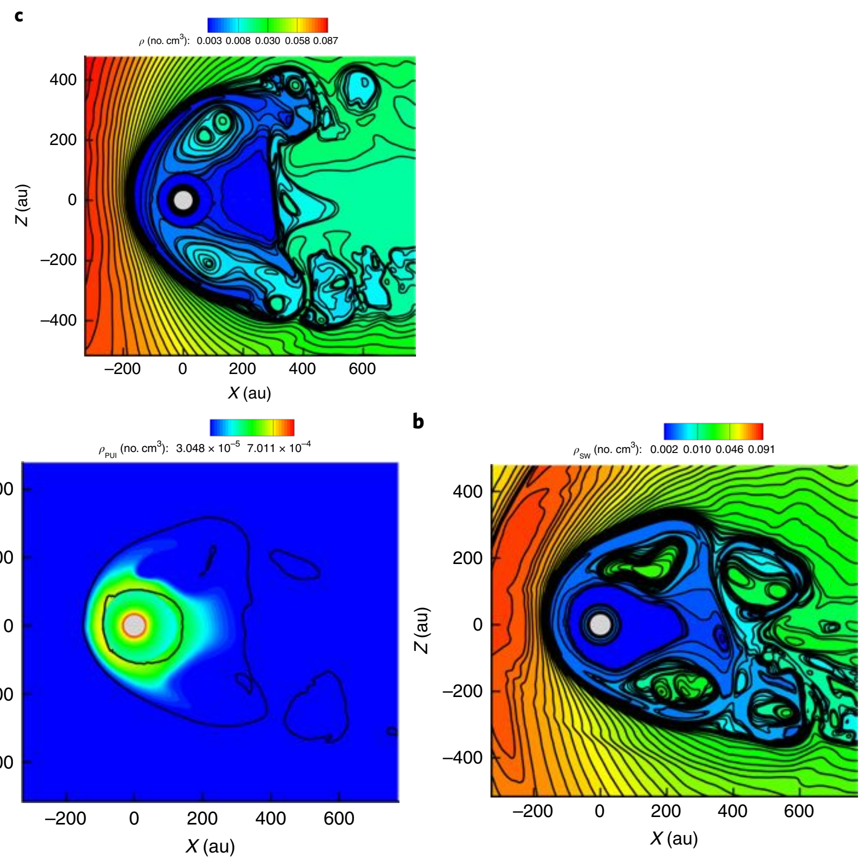


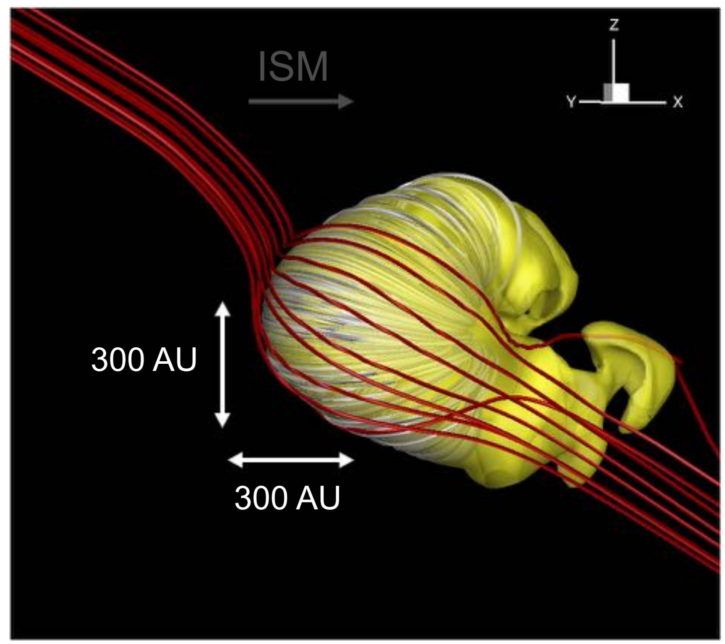
Pogorelov et al. 2015

New Global Model: Cold Thermal Solar Wind and PUIs treated separately

Old Model: Single Ion

New Model: Multi Ion

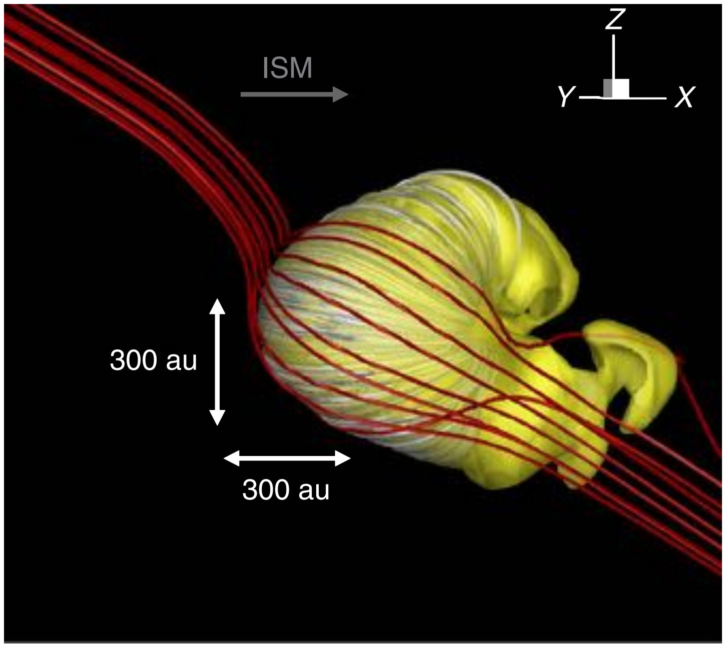




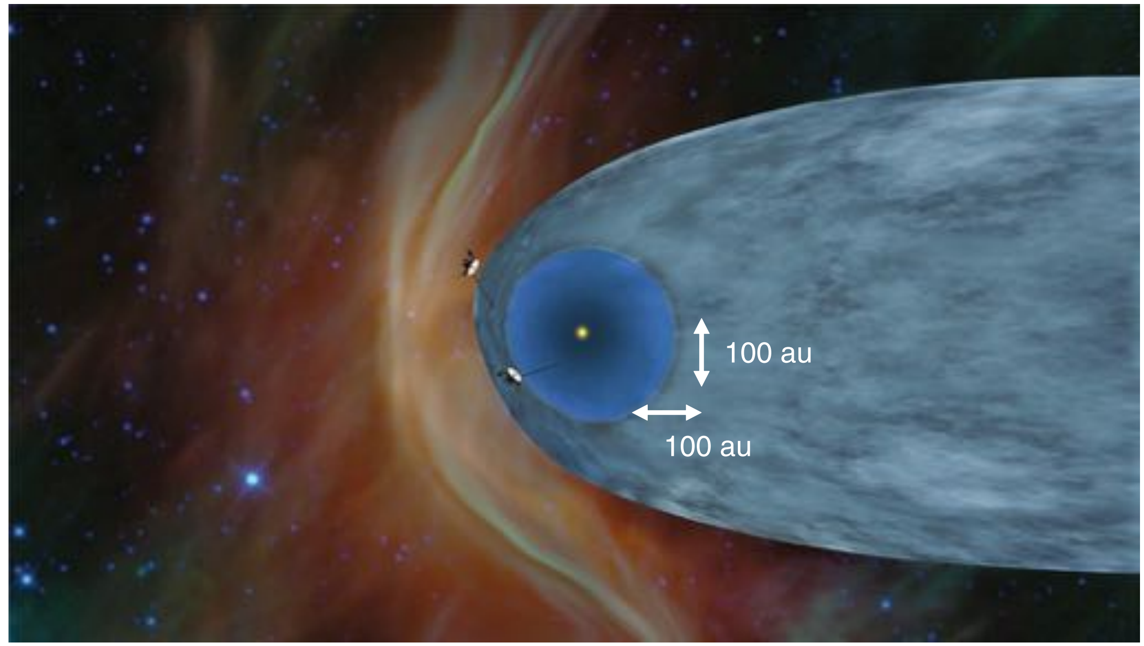
Opher et al. Nature Astronomy 2020

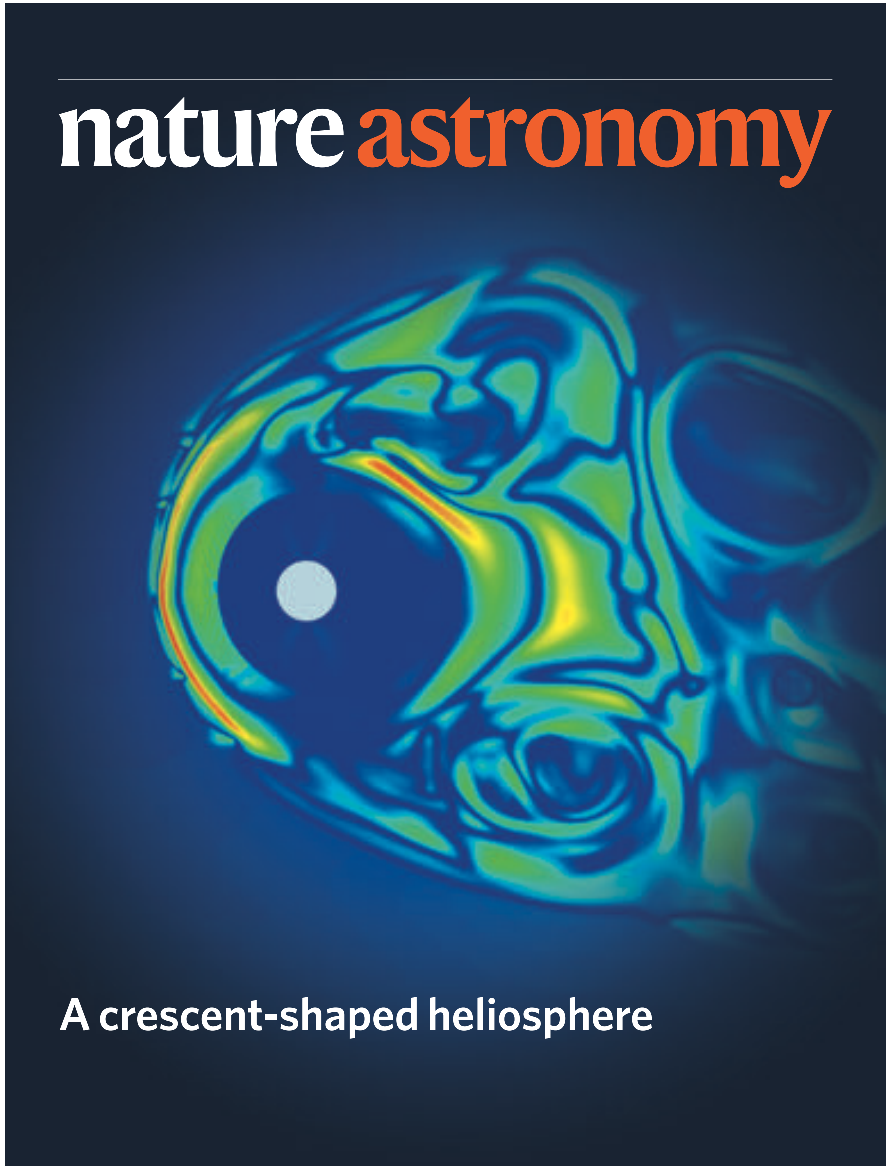
New Heliosphere

a

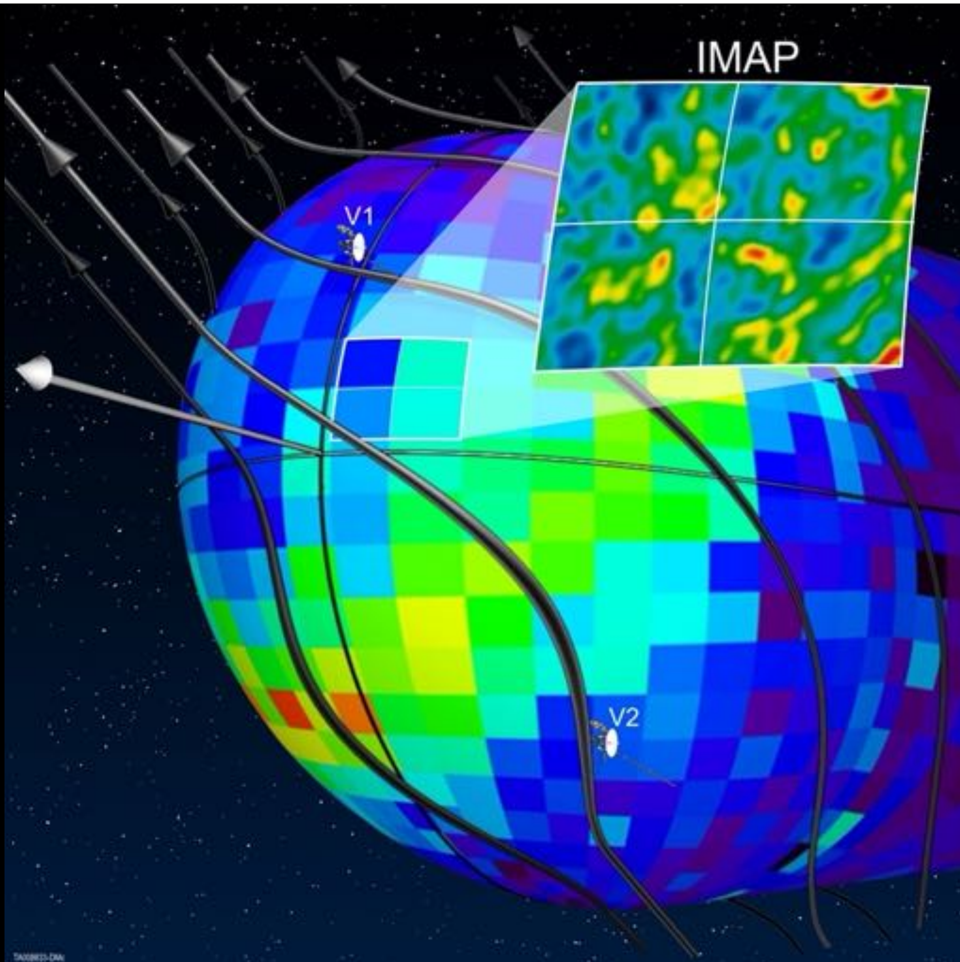


b





Cover of July issue, 2020



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+ NASA SMD Home
+ Solar Terrestrial Probes (STP) Program

NASA NATIONAL AERONAUTICS and SPACE ADMINISTRATIONS

LaRC Science Office for Mission Assessments

STP-5

Solar Terrestrial Probes

Interstellar Mapping and Acceleration Probe (IMAP)

++ Home

IMAP

Community Announcements

Final AO

Draft AO

IMAP Q&A

IMAP Program Library

IMAP Teaming Interest

IMAP Evaluation Plan

Pre-proposal Conference

IMAP (STP-5): Interstellar Mapping and Acceleration Probe

iMAP INTERSTELLAR MAPPING AND ACCELERATION PROBE

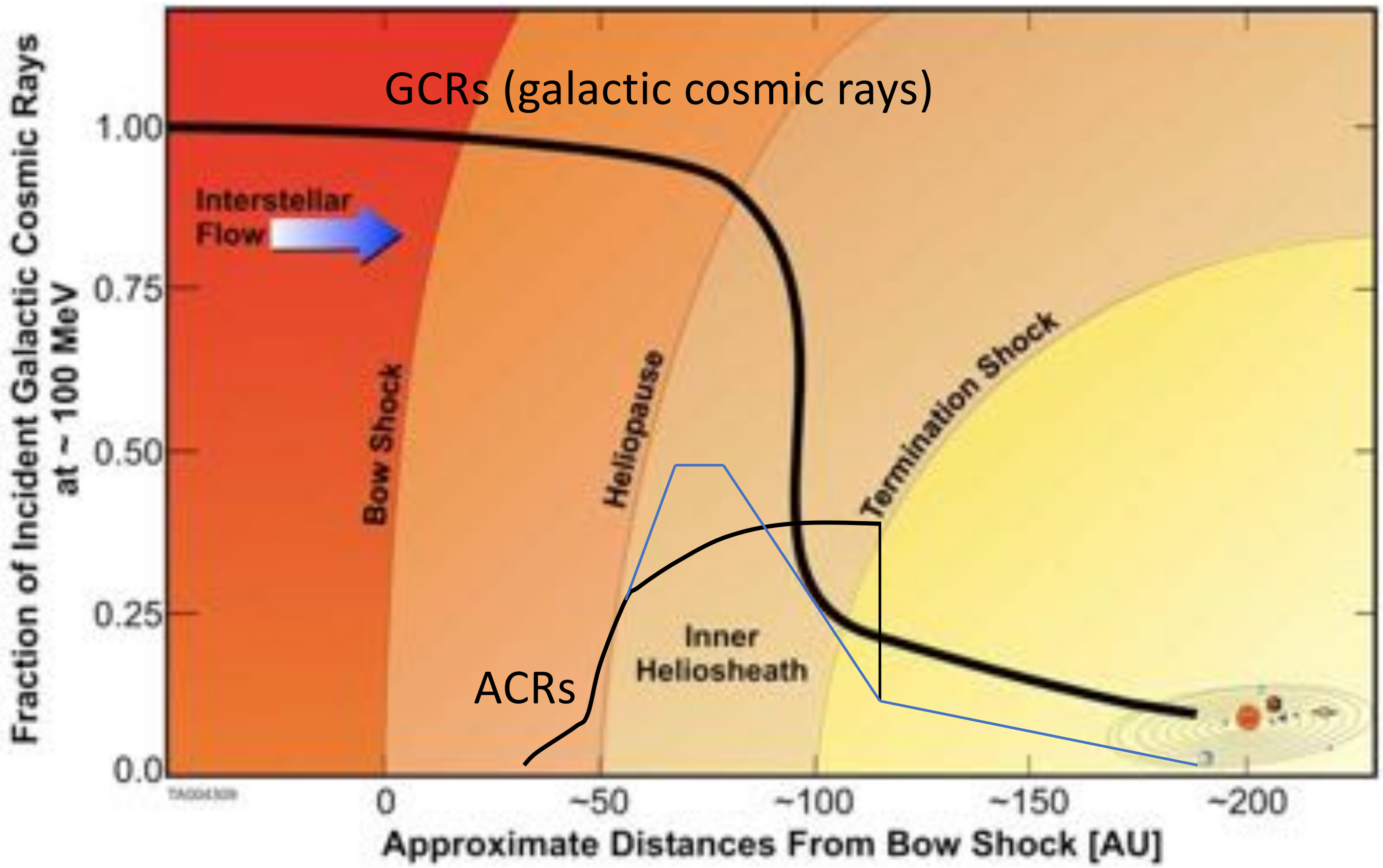
The Heliophysics Division of NASA's Science Mission Directorate plans on implementing the next Solar Terrestrial Probes (STP) mission. Following the recommendation of the 2013 National Research Council Decadal Strategy for Solar and Space Physics report, Solar and Space Physics: A Science for a Technological Society (www.nap.edu/catalog.php?record_id=13060), the fifth in a series of STP missions will be the "Interstellar Mapping and Acceleration Probe" or IMAP. It will "target the understand[ing of] the outer heliosphere and its interaction with the interstellar medium."

IMAP science priorities are enumerated as follows:

1: What is the spatio-temporal evolution of heliospheric boundary interactions?

2: What is the nature of the heliopause and of the interaction of the solar and interstellar magnetic fields?

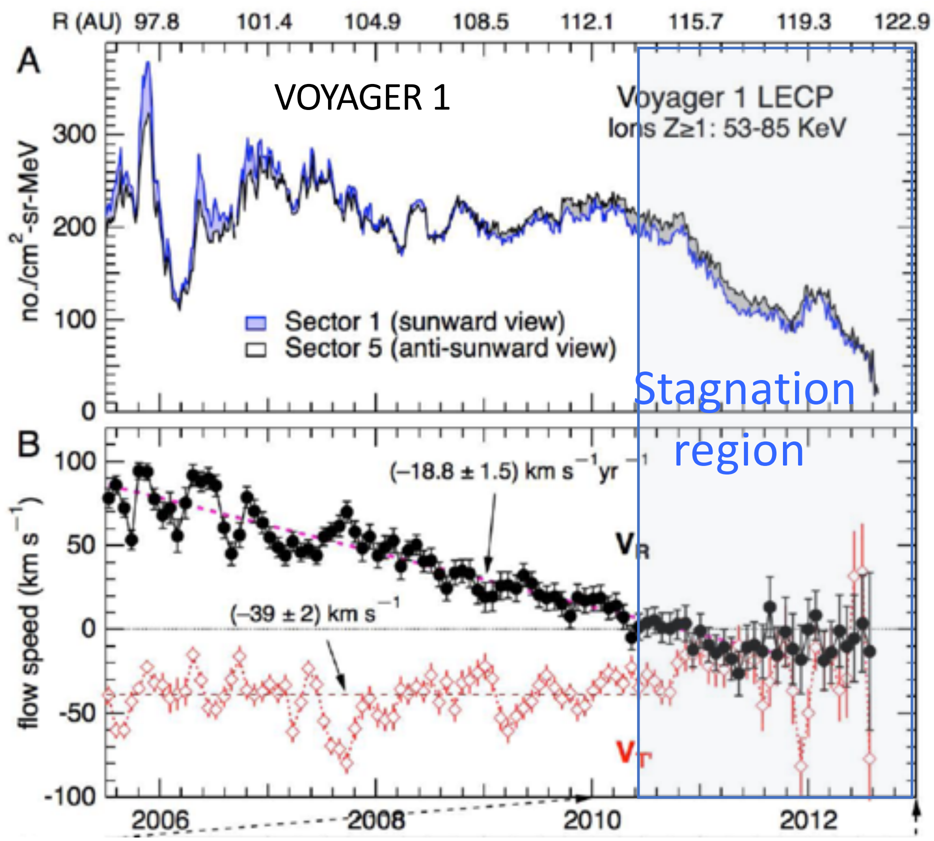
3: What are the composition and physical properties of the surrounding interstellar medium?



Heliopause signatures: predicted at 135-155 AU

Galactic cosmic rays increase and heliosheath particles decrease.

Puzzle: why a stagnation region?   V ~ 0



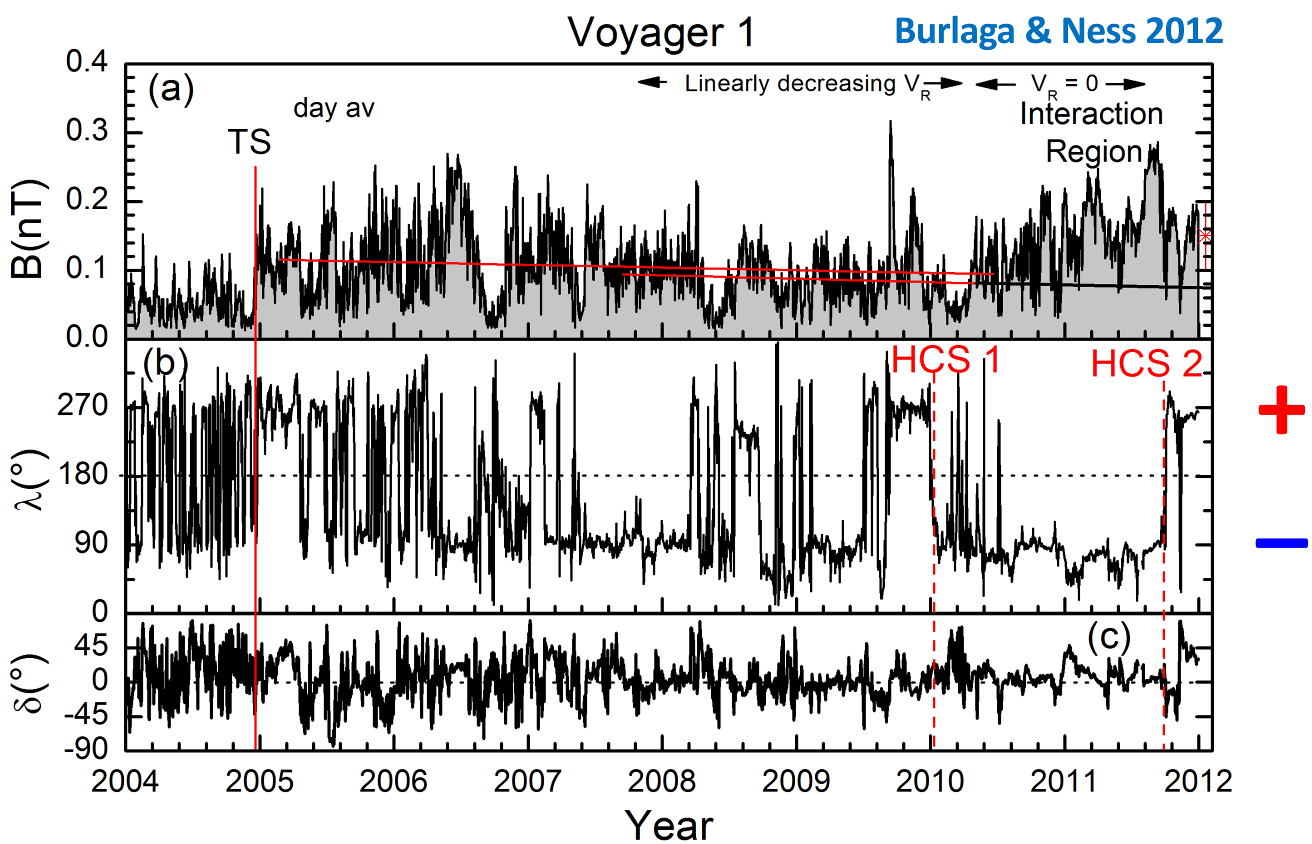
Flow expected to turn tailward as it moves across HSH; VR to ~0 at HP

Intensity ~constant from 94-115 AU, then decreased from 2010 to dropout in 2012.

Radial speed near zero from early 2010 to dropout: **113-121 AU**

Other flow components also small:
Stagnation region

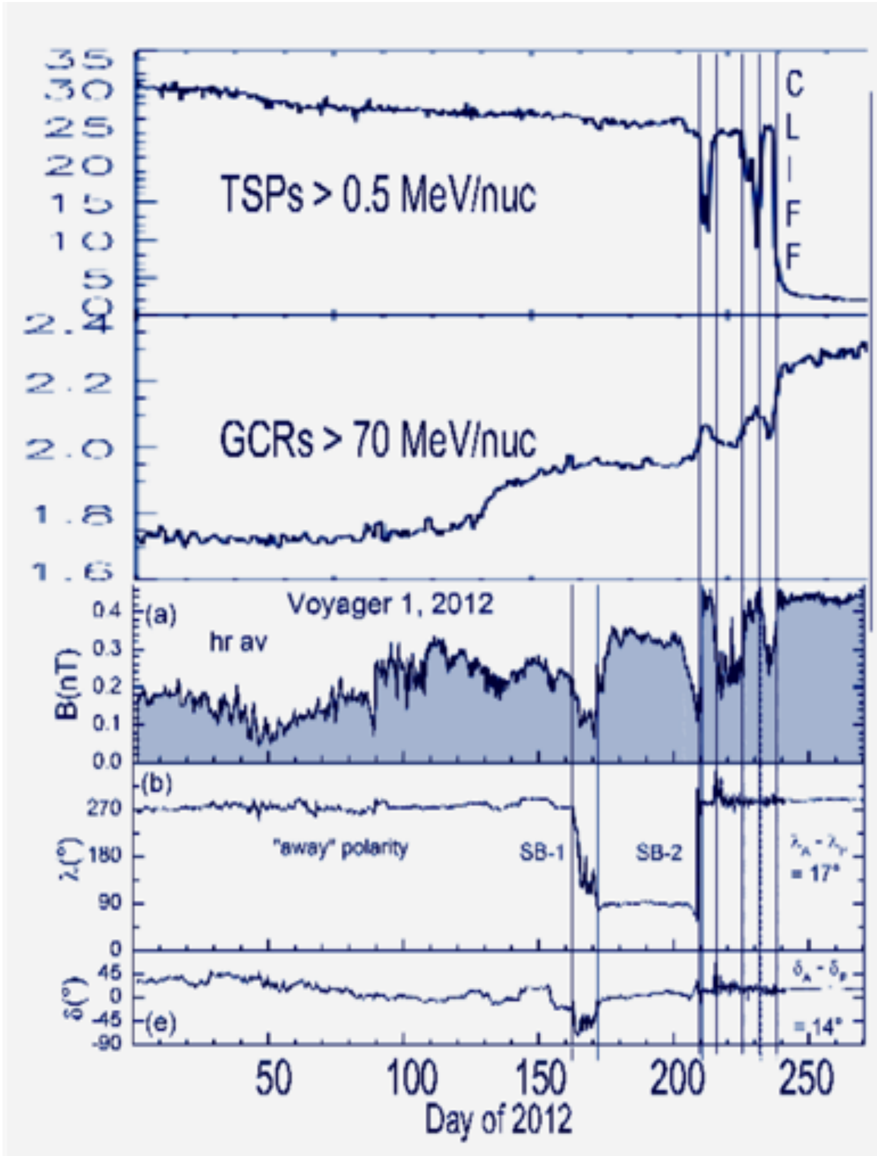
Krimigis et al. (2013)



- **Strong magnetic fields were observed in the stagnation region from 2010.3 to 2012.1.**
- **B in Parker direction (inside HP). Sector structure still observed.**

Burlaga & Ness

HELIOCLIFF



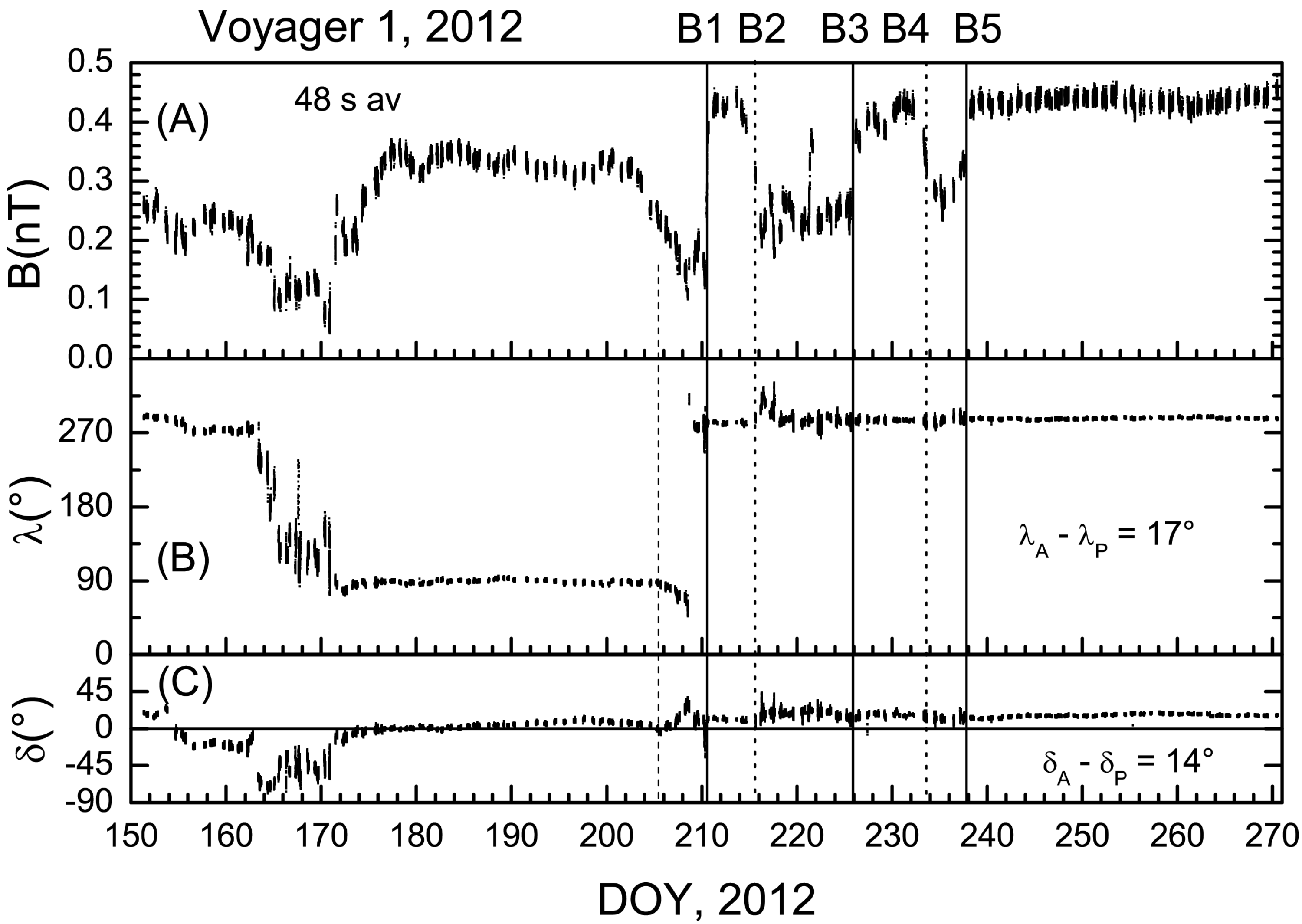
Heliosheath particles disappear

Galactic cosmic rays increase

Magnetic field increases

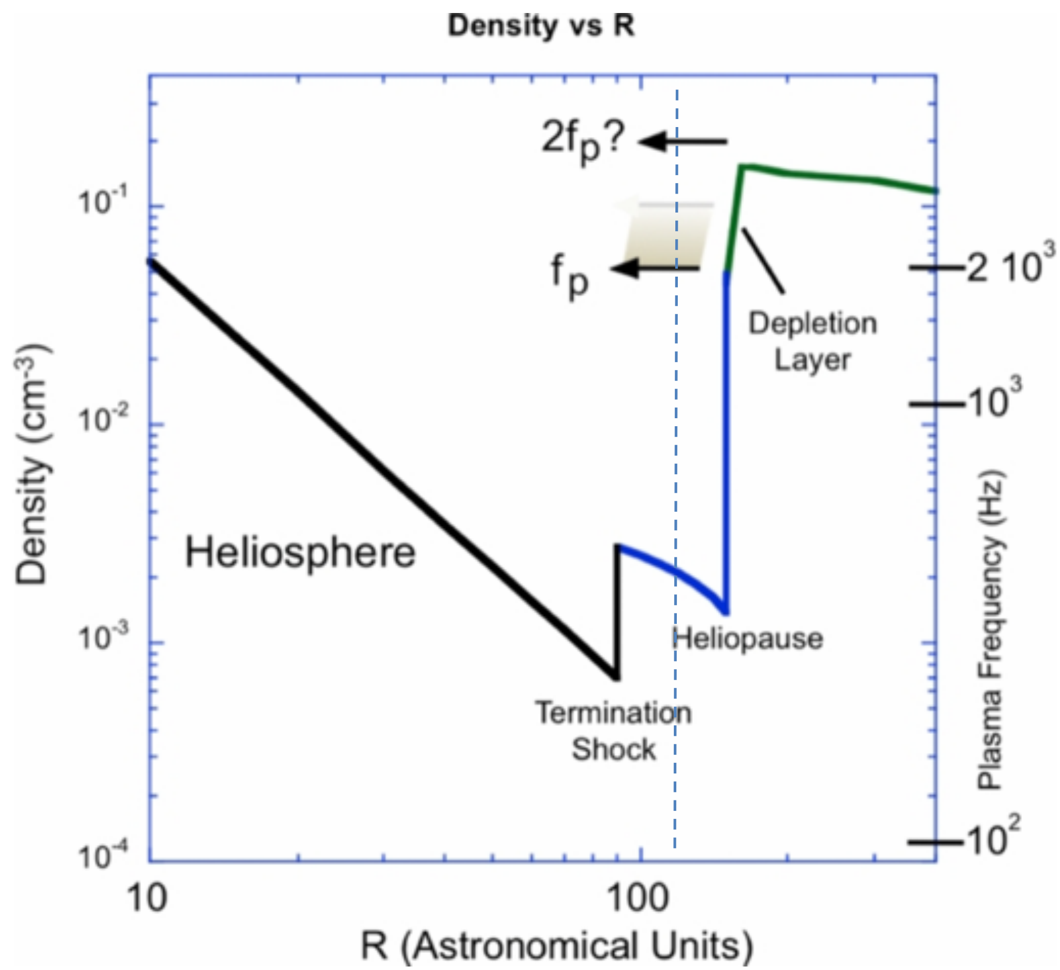
Magnetic field direction does NOT change

Still inside heliopause?



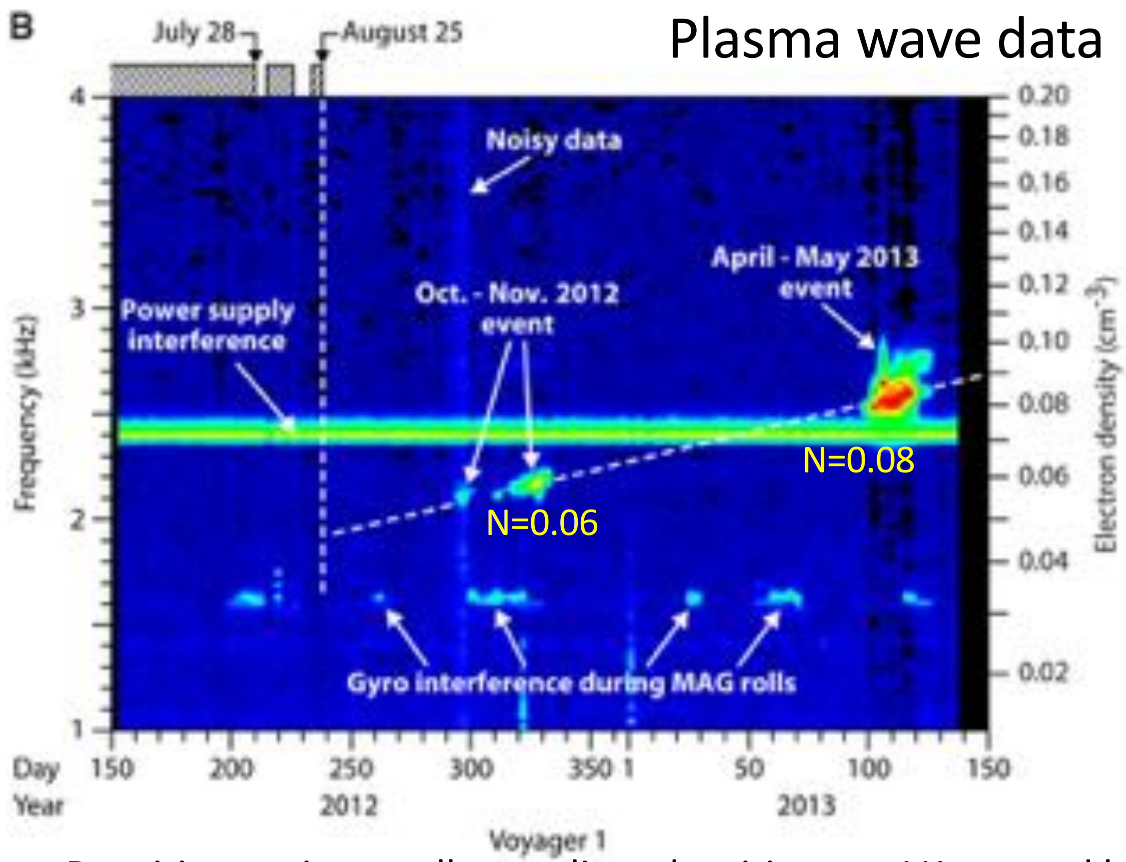
Burlaga et al. 2013

Question: Why is the heliopause so close? At 121 AU, it is only 27 AU from TS. Models predict HP is 40-60 AU from TS



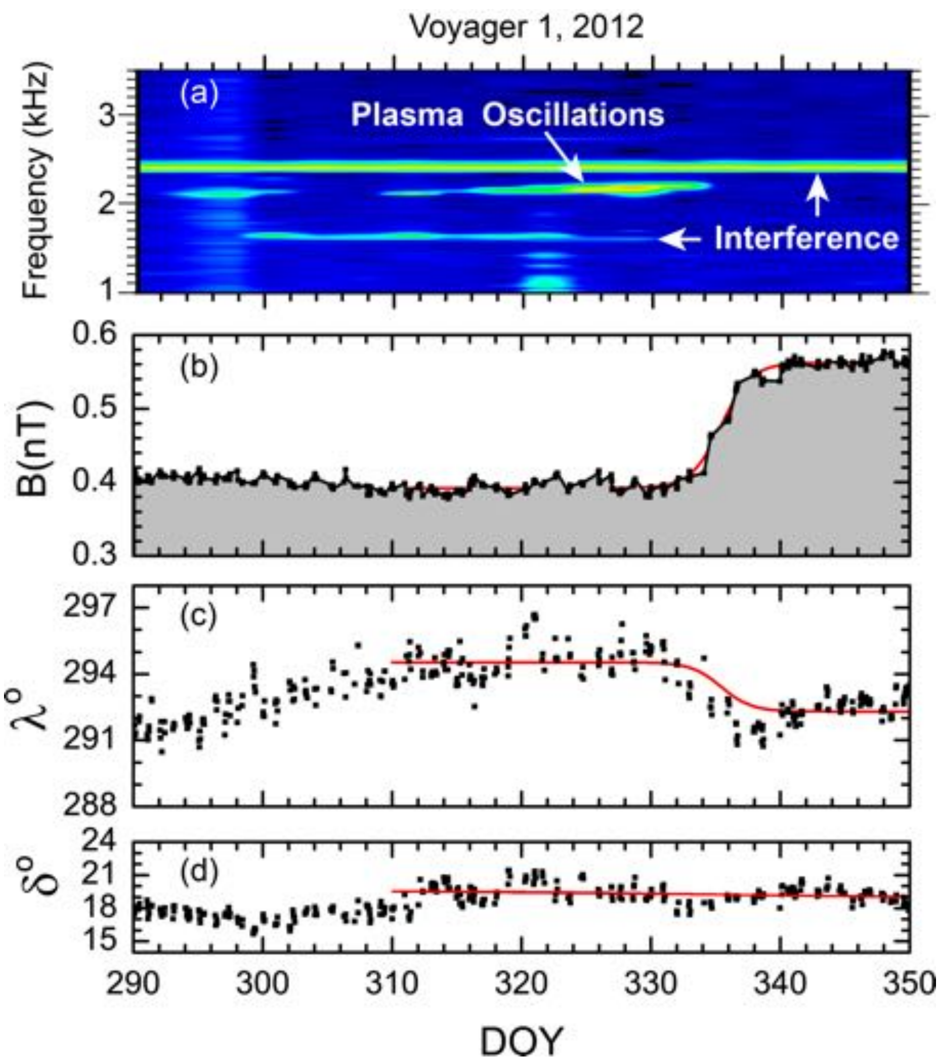
Pogorelov et al

Plasma wave data



Densities are interstellar medium densities – so V1 crossed heliopause!
Emissions excited when ICMEs hit heliopause and accelerate electron beams.

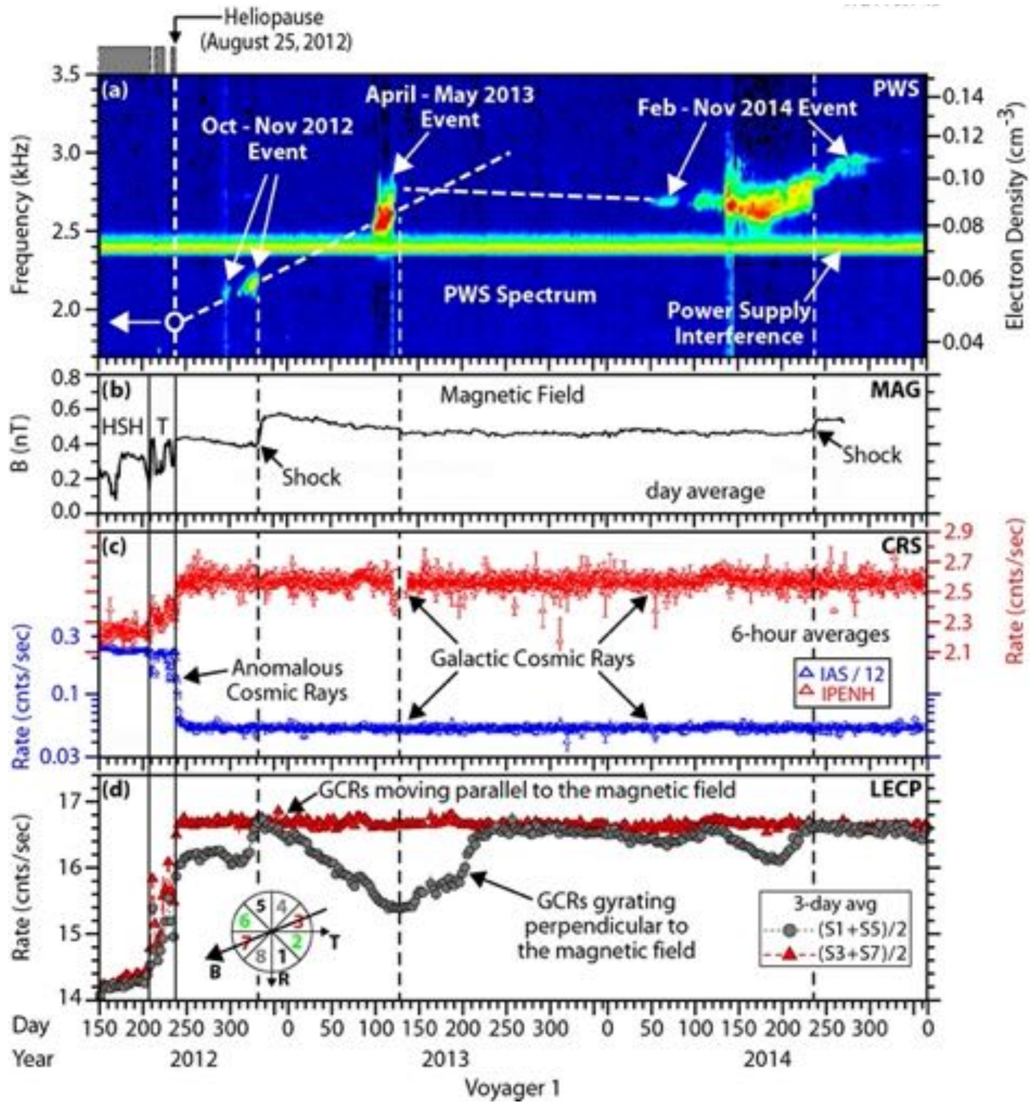
Gurnett et al., Science, 2013



Voyager 1, 2012
Frequency (kHz)
(a)
Plasma Oscillations
Interference
B(nT)
(b)
λ°
(c)
δ°
(d)
DOY

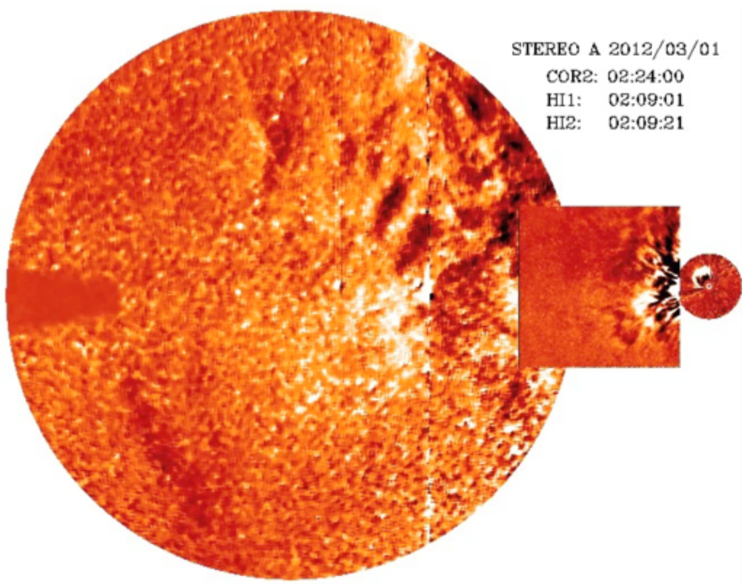
Overview of Interstellar Disturbances Detected by Voyager 1.

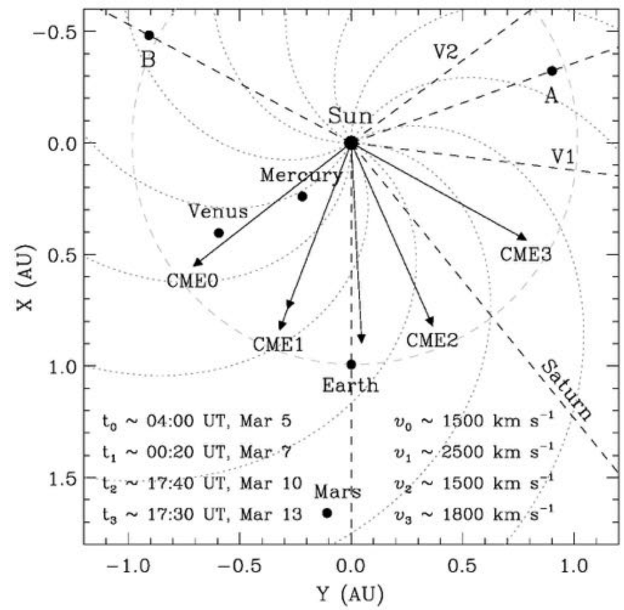
MIRs drive pressure waves Through LISM



2, CME interaction with the heliosphere

- A series of M/X class flares and large CMEs were produced from AR 11429 in 2012 March, as the AR was rotating with the Sun from east to west;

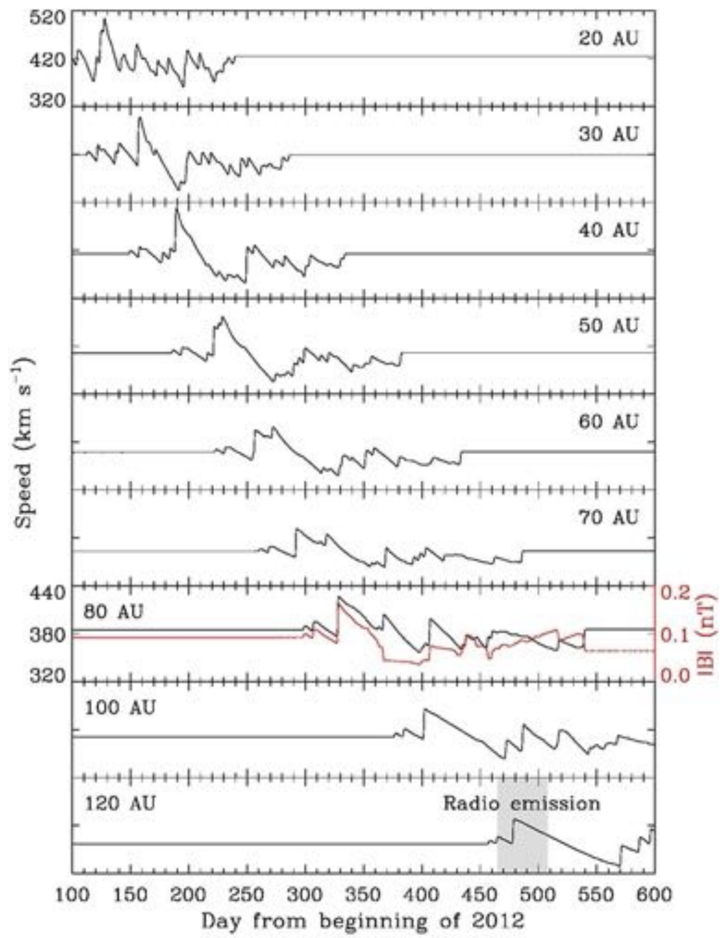




- These sustained eruptions are expected to generate a global shell of disturbed material sweeping through the heliosphere.

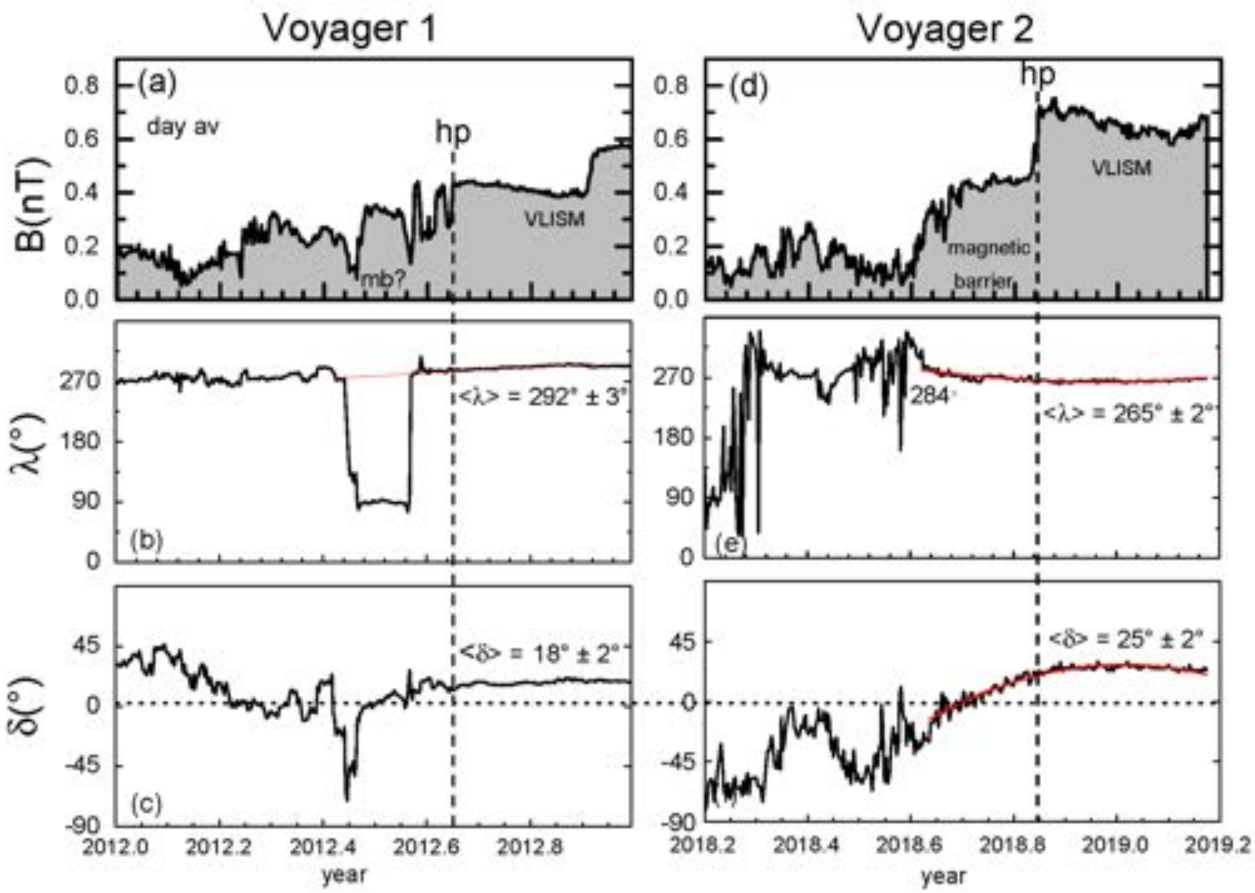
2, CME interaction with the heliosphere

- Propagate the solar wind disturbance outward from 1 AU using an MHD model (Wang et al.2000);
- The transient streams interact with each other, which erases memory of the source and results in a large merged interaction region (MIR) with a preceding shock;
- The shock and MIR would reach 120 AU around 2013 April 22, consistent with the period of radio emissions;
- These results reveal the "fate" of CMEs in the outer heliosphere and provide confidence that the heliopause is located around 120 AU from the Sun.

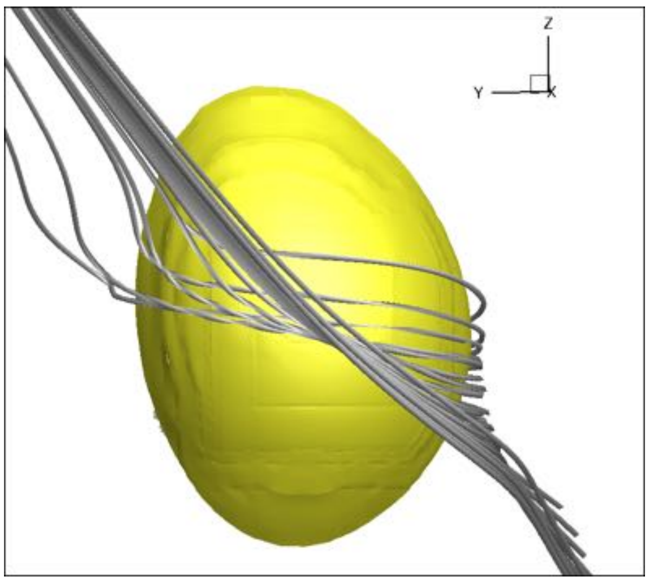


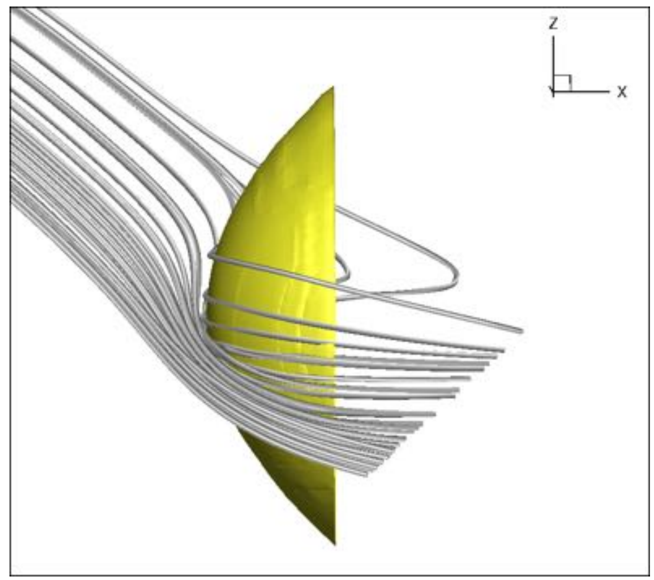
NASA press conference, Sept. 12, 2013: V1 is in interplanetary space!

The Interstellar Magnetic Field is Solar Ahead of the Heliosphere at Voyager 1 and Voyager 2!



We suggested that the draping of the interstellar magnetic field around the heliopause is strongly affected by the solar magnetic field although the physical mechanism for such behavior was not understood.





Opher & Drake *ApJL* 2013

Diamagnetic Drift Suppress Reconnection at the Nose

$$\mathbf{v}_{*,j} = -c\frac{\nabla p_j \times \mathbf{B}}{q_j n_j B^2},$$

Diamagnetic drift

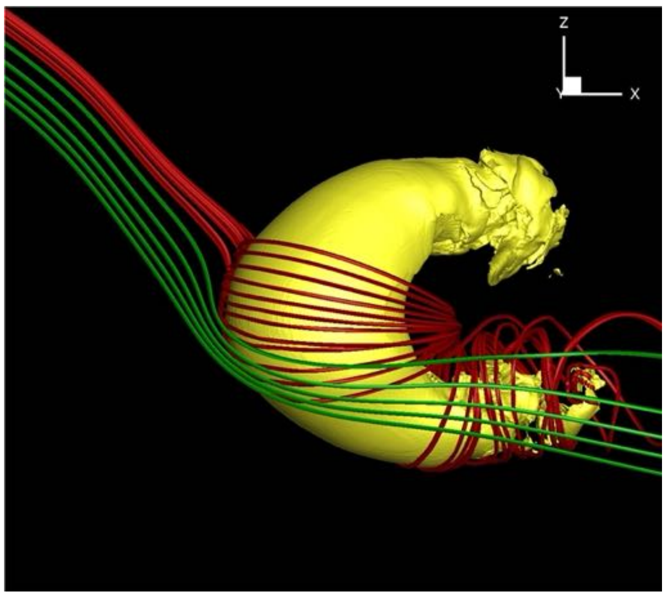
Reconnection will be suppressed if $v_{*,j} > v_{A,j},$

Can be re-written as $\Delta\beta_j > \frac{2L_p}{d_i}\tan(\theta/2),$ Swisdak et al. 2003; 2010

This condition was applied for Magnetosphere (Phan et al. 2011); Saturn; Jupiter (Desroche et al. JGR 2012); Neptune (Masters et al. 2015); Outer Heliosphere (Swisdak et al. 2010)

Across the heliopause there is a large jump of plasma β so reconnection will be suppressed. In the flanks there should be a smaller jump (less PUIs than the nose) and more favorable location for global reconnection

Reconnection in the flanks predicts no field rotation at the HP At V1 and V2

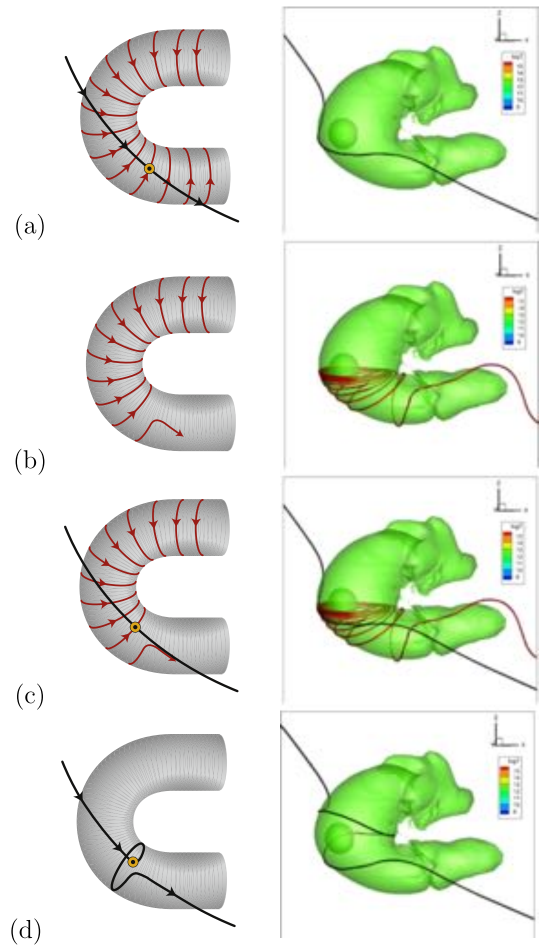


Opher et al. 2017

Two family lines:

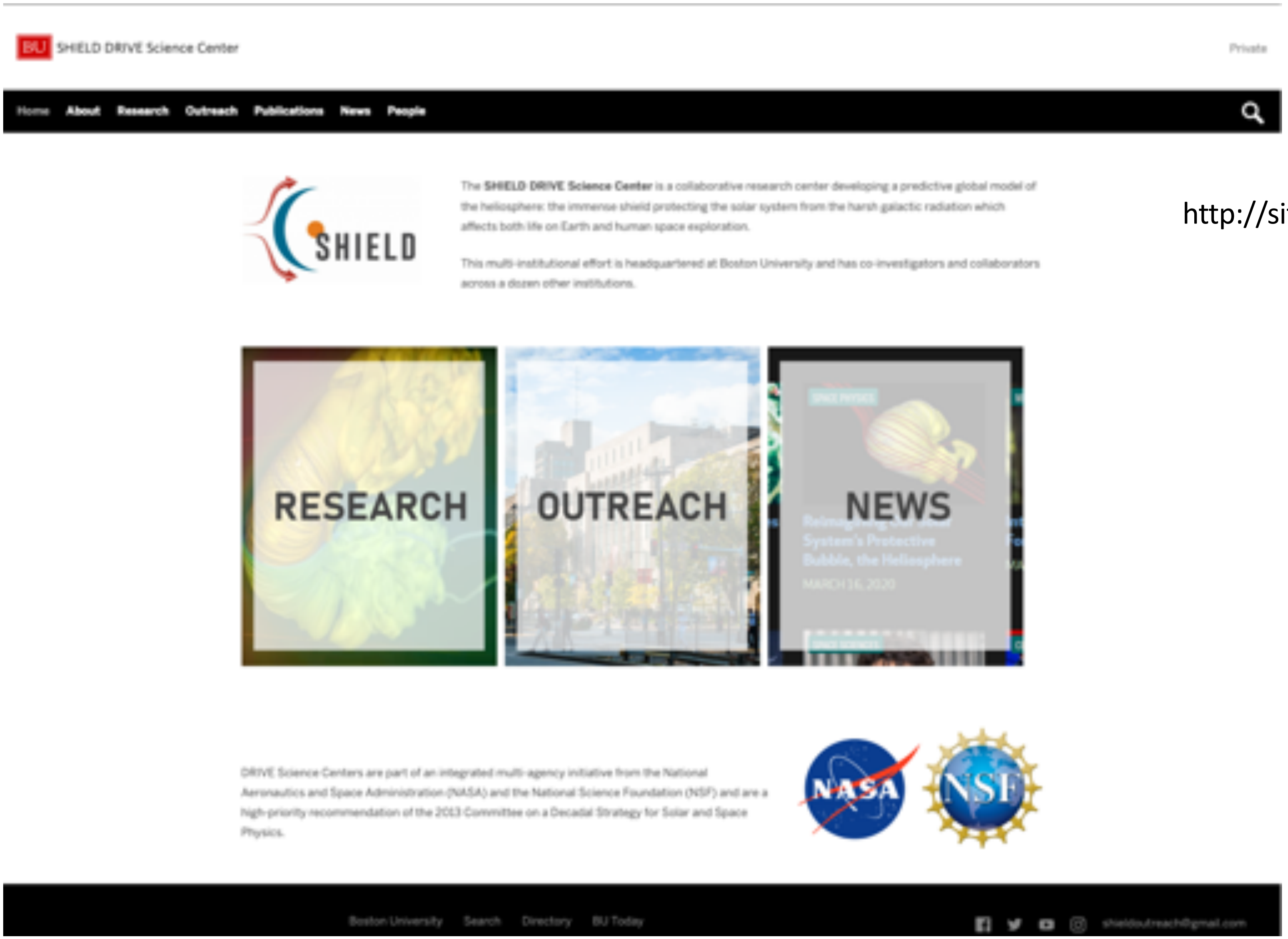
Red: connected to reconnection site in the flanks

Green: rotation towards the BISM

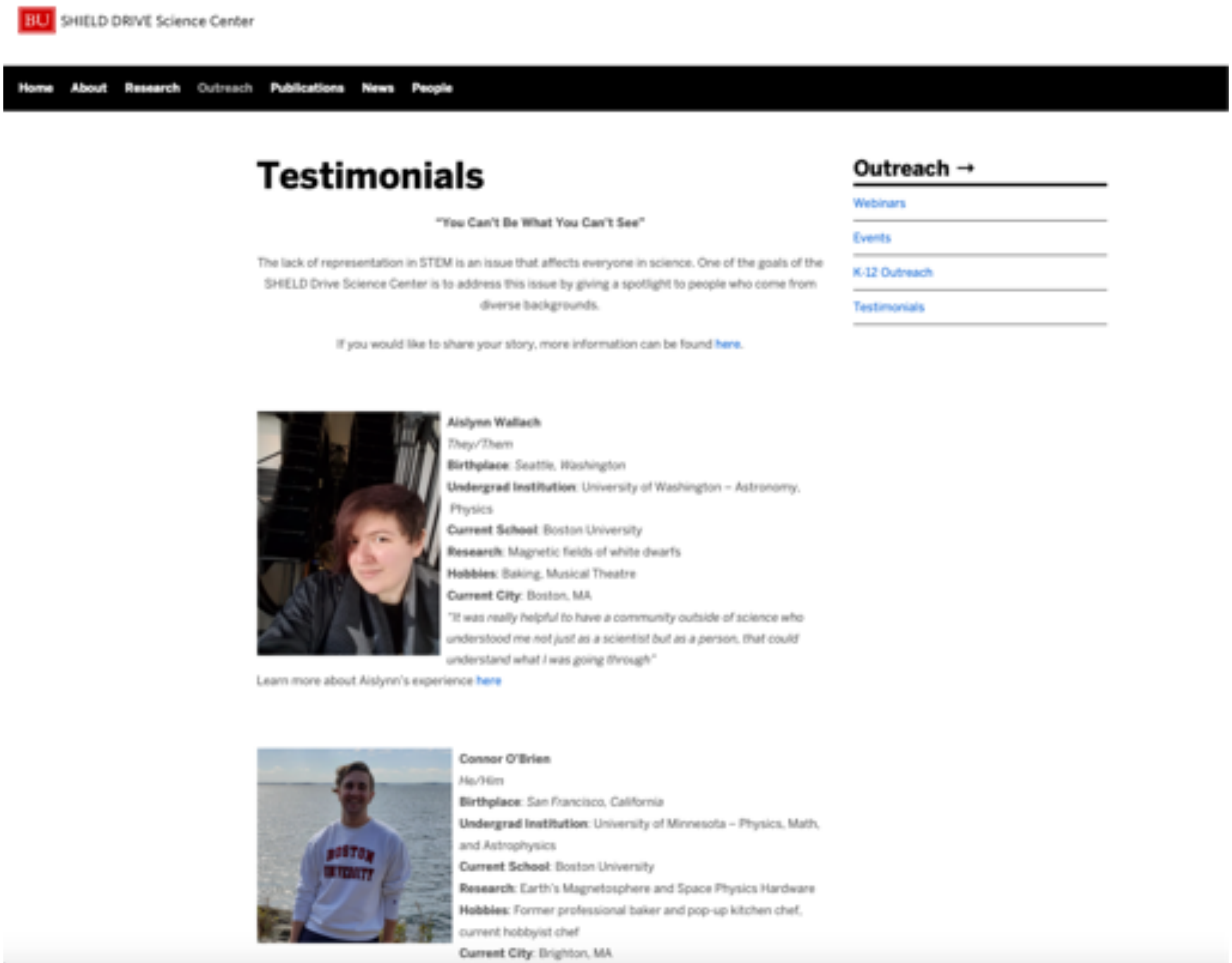


Reconnection Re-Arrange the Interstellar Magnetic Field ahead of the Heliopause to be solar like

Issue is how the field will drape from the HP to the pristine direction and value



http://sites.bu.edu/shield-drive/


BU SHIELD DRIVE Science Center

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"You Can't Be What You Can't See"

The lack of representation in STEM is an issue that affects everyone in science. One of the goals of the SHIELD Drive Science Center is to address this issue by giving a spotlight to people who come from diverse backgrounds.

If you would like to share your story, more information can be found here.

Aislynn Wallach
They/Them
Birthplace: *Seattle, Washington*
Undergrad Institution: University of Washington – Astronomy, Physics
Current School: Boston University
Research: Magnetic fields of white dwarfs
Hobbies: Baking, Musical Theatre
Current City: Boston, MA
"It was really helpful to have a community outside of science who understood me not just as a scientist but as a person, that could understand what I was going through"
Learn more about Aislynn's experience here

Connor O'Brien
He/Him
Birthplace: *San Francisco, California*
Undergrad Institution: University of Minnesota – Physics, Math, and Astrophysics
Current School: Boston University
Research: Earth's Magnetosphere and Space Physics Hardware
Hobbies: Former professional baker and pop-up kitchen chef, current hobbyist chef
Current City: Brighton, MA

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Please contact us if you
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Or

mopher@bu.edu

The Future

- Sufficient power until the year 2030
- Voyagers will then wander the Milky Way
  - Voyager 1 within 1.6 light years of the star Gliese 445 in 40,000 years
  - Voyager 2 within 1.7 light years of Ross in 40,000 years


THE SOUNDS OF EARTH
PLANET EARTH

UN/DPI PHOTO

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