Interstellar Probe Study Webinar Series

Voyagers 1 and 2: Where are we now?

Presenters

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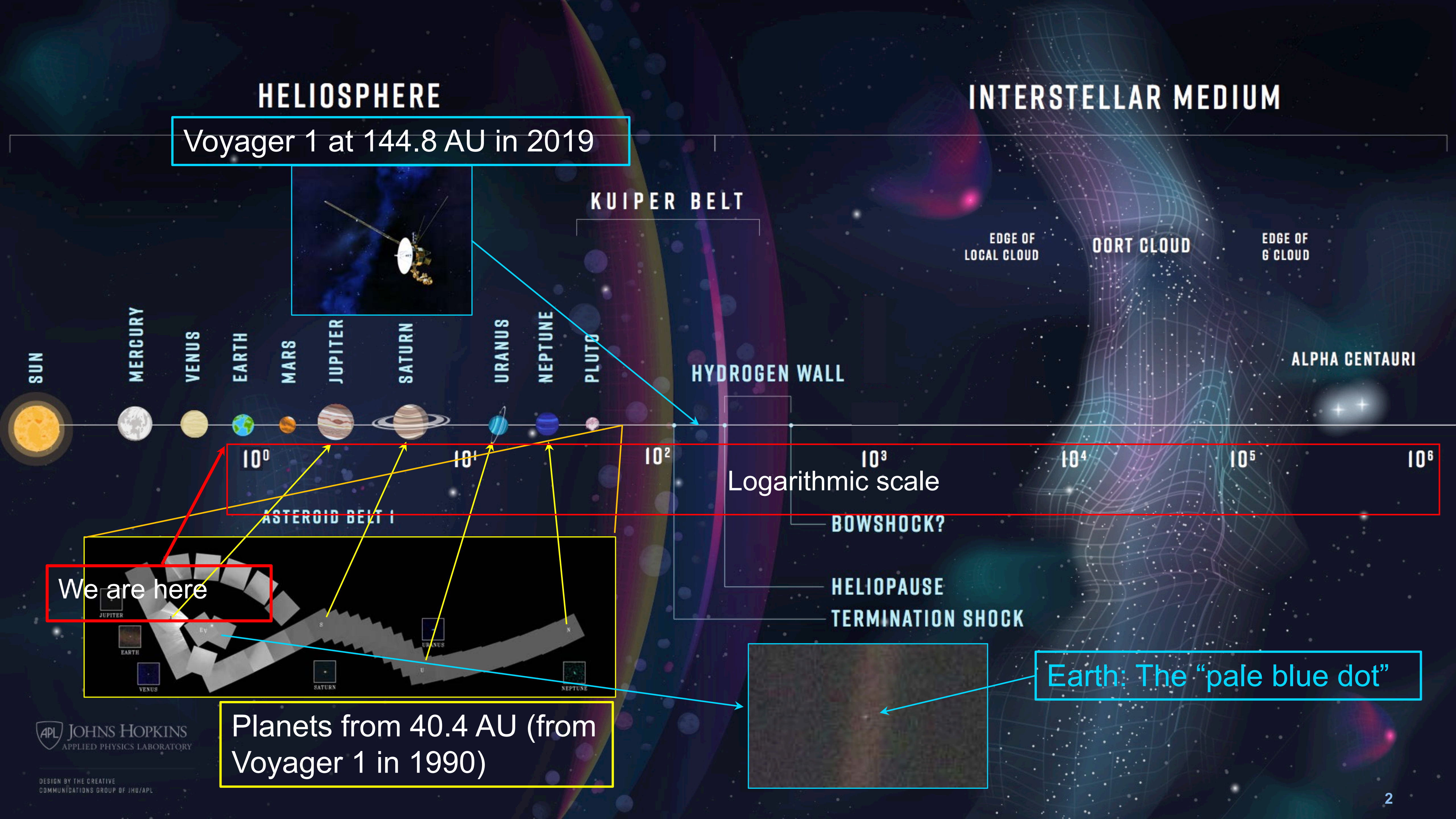
12:05 PM EDT Thursday, 20 August 2020

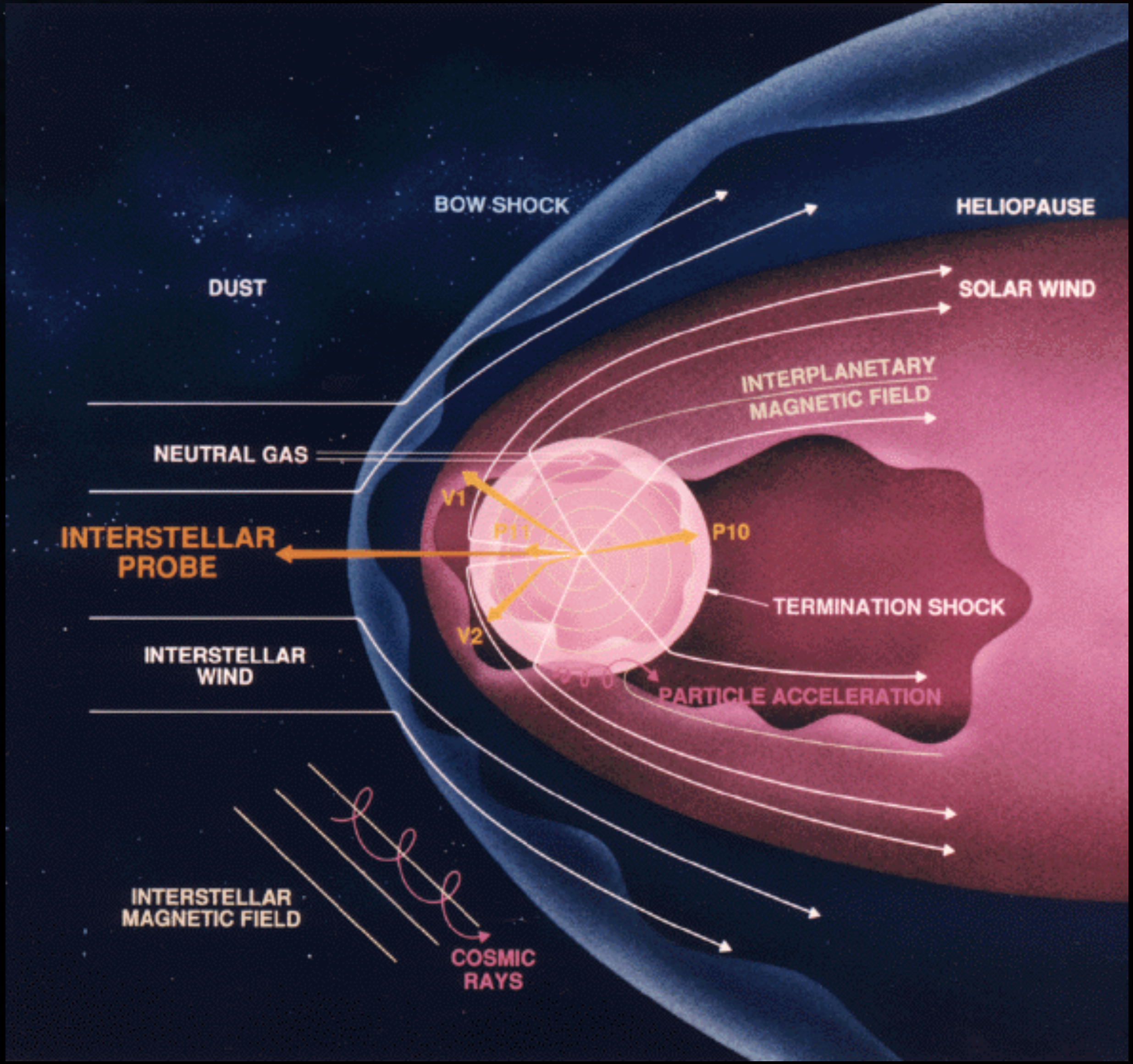
Interstellar Probe Study Website

http://interstellarprobe.jhuapl.edu


HELIOSPHERE
INTERSTELLAR MEDIUM
Voyager 1 at 144.8 AU in 2019
KUIPER BELT
EDGE OF LOCAL CLOUD
OORT CLOUD
EDGE OF G CLOUD
ALPHA CENTAURI
SUN
MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
PLUTO
HYDROGEN WALL
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Logarithmic scale
ASTEROID BELT
BOWSHOCK?
HELIOPAUSE
TERMINATION SHOCK
We are here
JUPITER
EARTH
VENUS
SATURN
URANUS
NEPTUNE
Earth: The "pale blue dot"
Planets from 40.4 AU (from Voyager 1 in 1990)
APL JOHNS HOPKINS
APPLIED PHYSICS LABORATORY
DESIGN BY THE CREATIVE COMMUNICATIONS GROUP OF JHU/APL

Where are Voyager 1 and 2 now?

Len Fisk
University of Michigan



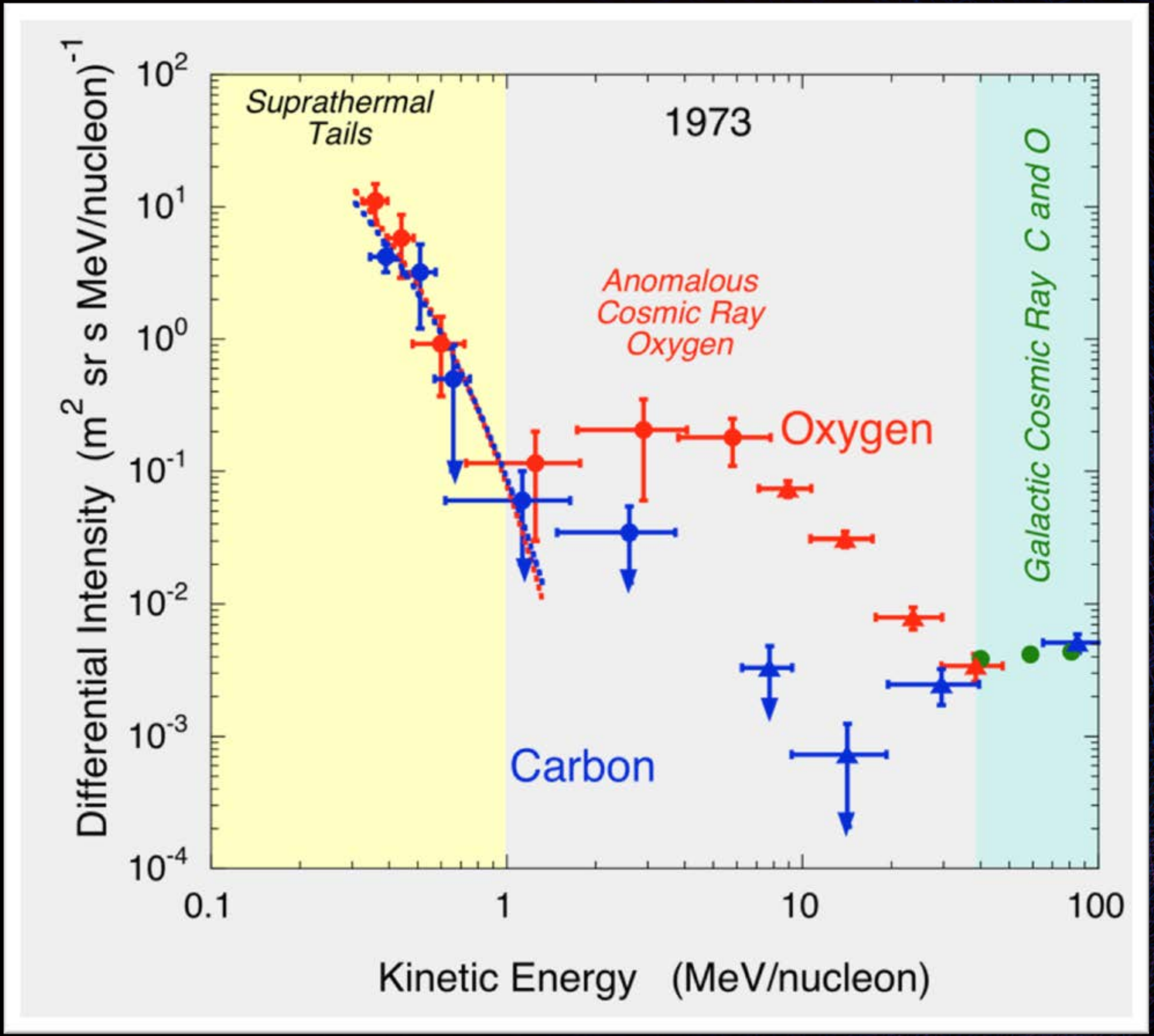
The region we will be talking about today lies between the termination shock of the solar wind and the heliopause. It is known as the heliosheath.
We will confine ourselves to the nose region of the heliosheath, which lies in the direction of motion of the solar system through the local interstellar medium

The Voyager investigators, and for that matter essentially all numerical models of the heliosheath have overlooked and ignored a fundamental property of the heliosheath.

- The dominant particle pressure in the heliosheath resides in a particle population known as interstellar pickup ions, and in accelerated pickup ions.
  - Interstellar neutral gas penetrates into the heliosphere and is ionized by photoionization and charge-exchange, picked up by the solar wind, and convected outward into the heliosheath.
  - The pickup ions can be accelerated and form a particle population, which I will refer to using the historic term, Anomalous Cosmic Rays, or ACRs.

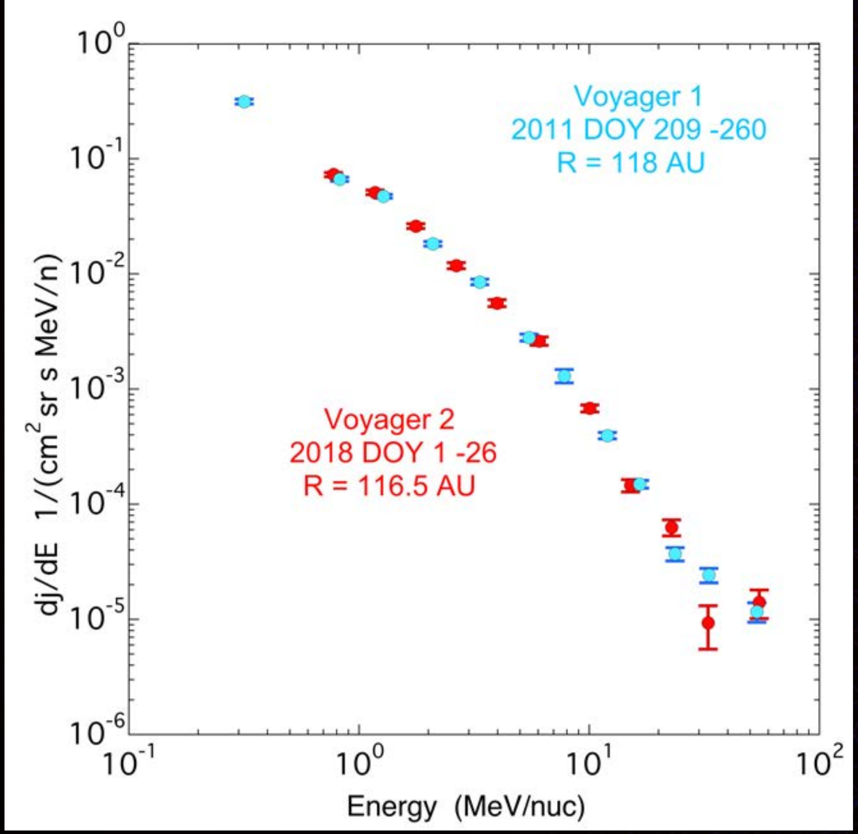
- The pickup ions and the ACRs need to be treated as separate gas from the thermal solar wind.

- The ACRs, with their unusual composition, enhanced in oxygen, not carbon, the composition of interstellar neutral gas, were discovered in the inner heliosphere in the early 1970s.
- Pickup ions are generated in the inner heliosphere, convected outward with the solar wind, accelerated to ACR energies somewhere in the outer heliosphere, and then propagate back to Earth to be observed as ACRs.
- There was a concern that as the pickup ions are convected outward with the solar wind, they will be assimilated into the solar wind.
- Papers were written showing that would not occur.



Voyager Observations

- When Voyager 2 with its working plasma detector crossed the termination shock, it observed that the solar wind was not heated.
- Upstream from the termination shock the pressure in the pickup ions is much larger than the thermal solar wind. The pickup ions are heated at the termination shock, and as a separate gas from the the thermal solar wind, the pickup ions are the dominant pressure throughout the heliosheath.
- Contrary to expectations, the ACRs were not accelerated to high energies at the termination shock where Voyager 1 and 2 crossed.
- Rather, as both Voyager 1 and Voyager 2 penetrated deep into the heliosheath, the full ACR spectra were observed.



The pressure in these spectra are in the higher energy ACRs and including all ACR species is equal to half of the pressure in the pickup ions at the termination shock

- ACRs are highly mobile and a completely separate gas from the thermal solar wind.
- The pickup ions are a separate gas from the solar wind
- Collectively the pickup ions and ACRs are the dominant pressure in the heliosheath.

- The pickup ions and ACRs are of course coupled to the magnetic field.
- The pressure in the pickup ions and ACRs plus the pressure in the magnetic field must balance the pressure exerted on the heliosheath by the local interstellar medium.

$$P_{pu} + P_{ACR} + \frac{B^2}{8\pi} = \text{constant}$$

- The sum of the pressure in the pickup ions and ACRs must be approximately constant, which places constraints on how the ACRs are accelerated in the heliosheath.
- The ACRs must be accelerated out of the pickup ions as they are convected radially outward with the solar wind.

- In the heliosheath, the pickup ions and ACRs are a single gas, which is separate from the solar wind.

The pickup ions and ACRs alter the observed magnetic field

- A separate gas of pickup ions and ACRs will experience gradient and curvature drifts that generate currents, and since the pressure is large, the pickup ions and ACRs will generate a significant magnetic field.
- The magnetic field that is observed in the heliosheath consists of two components.
  1. The magnetic field that is convected across the termination shock
  2. The magnetic field that is caused by currents produced by gradient and curvature drifts of the separate gas of pickup ions and ACRs.
- Fisk and Gloeckler (2016) provide a method for unraveling the observed magnetic field, $\boldsymbol{B}$, to find the magnetic field that is embedded in and convected outward with the solar wind, $\boldsymbol{B}_{sw}$.

$$\nabla B = \frac{\nabla B_{sw}}{\left(1 + B/B_{sw}\right)}$$

- The pressure in the magnetic field embedded in the solar wind is the principal force controlling the flow velocity and density of the solar wind in the heliosheath.

In a self-consistent model for the heliosheath:

The pressure in the pickup ions and ACRS is in equilibrium with the pressure in the observed magnetic field, and satisfies:

$$P_{pu,ACR} + \frac{B^2}{8\pi} = \text{constant}$$

The observed and embedded magnetic field satisfy:

$$\nabla B = \frac{\nabla B_{sw}}{\left(1 + B/B_{sw}\right)}$$

The solar wind flow velocity and density and embedded magnetic field satisfy the standard MHD equations

$$\nabla \bullet \left(\rho \mathbf{u}\right) = 0$$

$$\nabla \bullet \left(\rho \mathbf{u} \left(\frac{u^2}{2} + \frac{5}{2} \frac{P_{sw}}{\rho} \right) - \frac{1}{4\pi} \left(\mathbf{u} \times \mathbf{B}_{sw} \right) \times \mathbf{B}_{sw} \right) = 0$$

- There are some important simplifications available:
- When you start from approximately constant pressure in the pickup ions and ACRs, the flow of the solar wind must be in a plane that contains the magnetic field. Gradients in the pressure in the pickup ions and ACRs, the dominant pressure force. can be relieved only along the magnetic field.
- The magnetic field in the heliosheath lies primarily in the azimuthal direction, *T,* of the Voyager *R-T-N* coordinate system.
- Strong polar flows are not allowed.
- Neither Voyager 1 nor Voyager 2 see significant polar flows.

- The requirement that strong polar flows are neither allowed nor observed in the heliosheath eliminates every model for the heliosheath with a heliopause that is a hard barrier with the interstellar medium, i.e., a heliopause that is a tangential discontinuity.
- Also, the requirement that the pickup ions and ACRs must be treated as a separate gas invalidates essentially all numerical models of the heliosheath. Most current models are single-fluid models.

- In Fisk & Gloeckler (2014) and (2016) present an analytic model for the flow of the solar wind that satisfies all the constraints discussed.

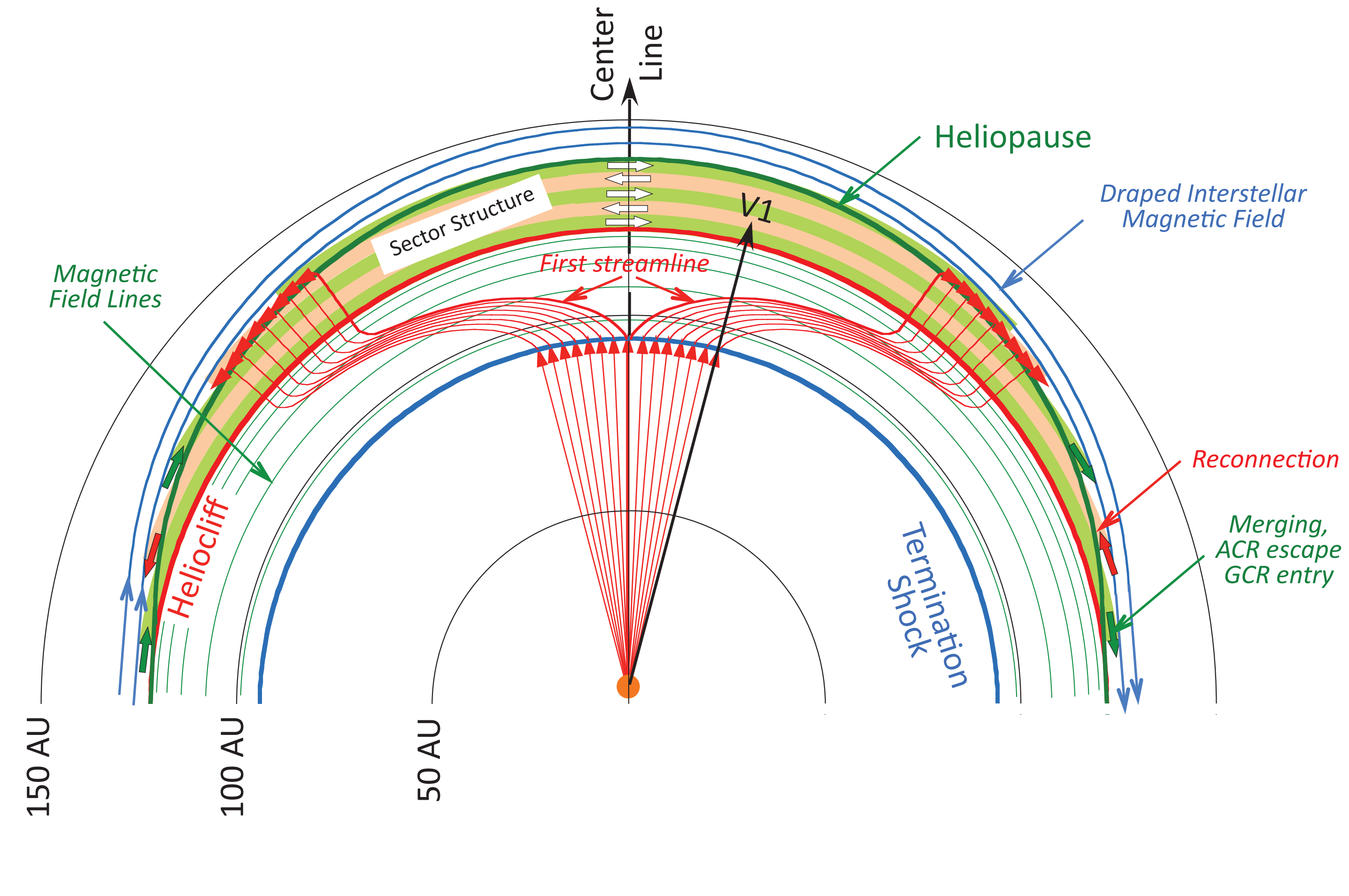
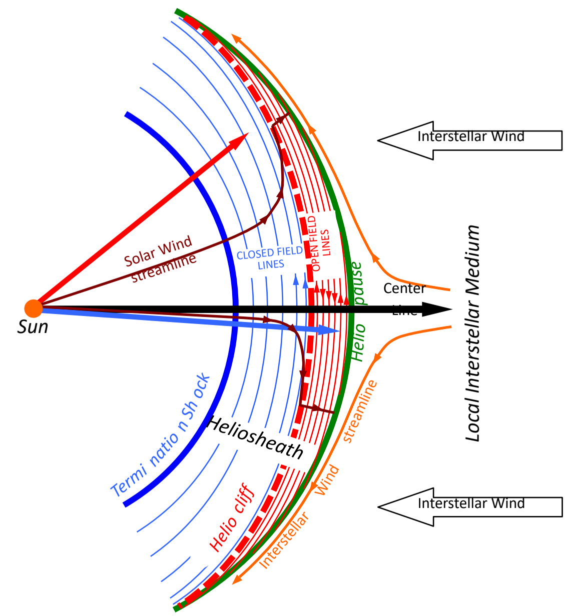


Figure 1

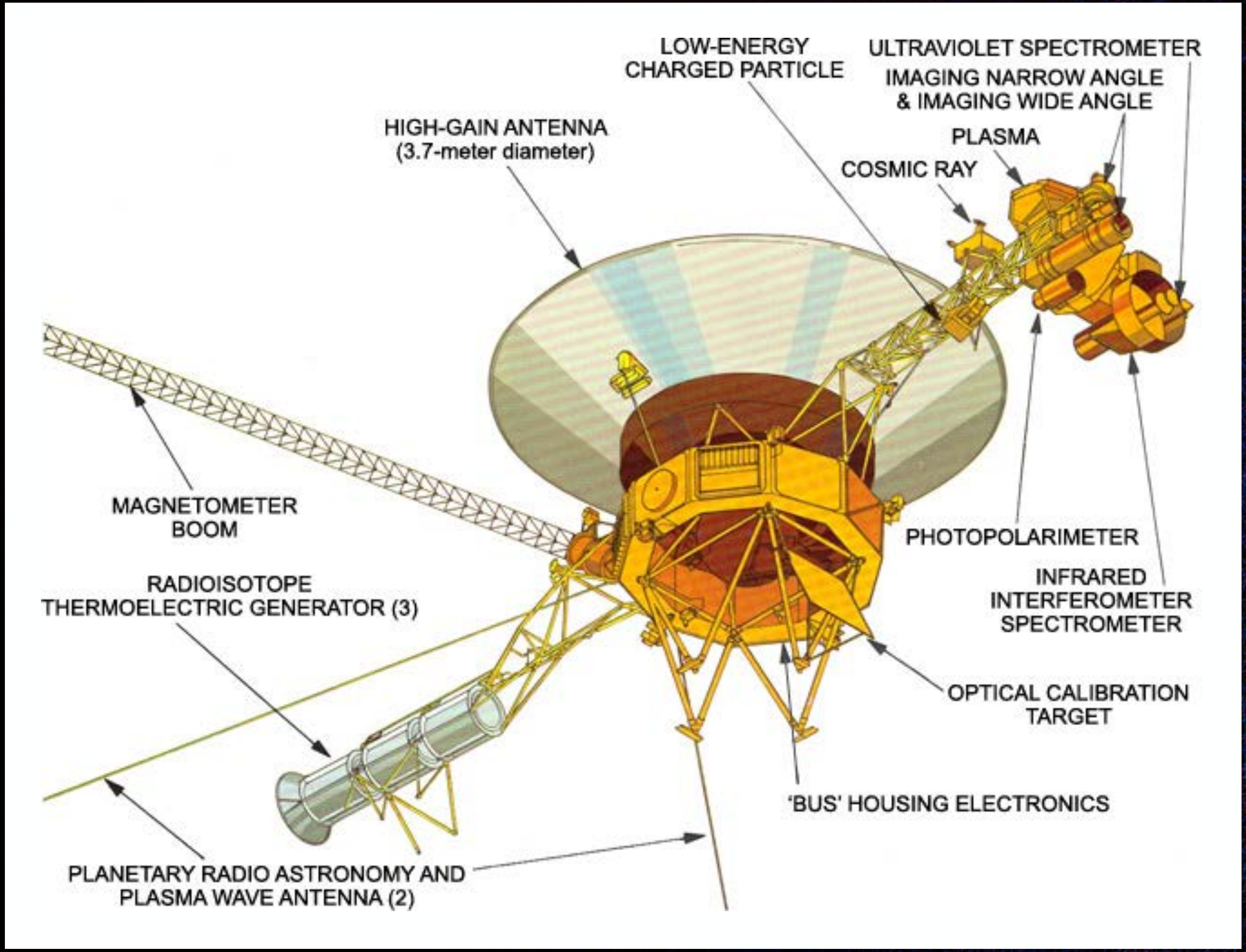
Figure 3. A simplified schematic of the nose region of the heliosheath.



So what were the observations of Voyager 1 that caused the Voyager investigators to conclude they had crossed the heliopause?

The Voyager Investigators

1. LECP and CRS (Krimigis at al., Stone, et al.) observed a precipitous decrease in ACR intensity and abrupt increase in the GCRs.
2. MAG (Burlaga & Ness) observed no change in the field direction. [initially decide not heliopause]
3. MAG (Burlaga & Ness) noted magnetic field magnitude and turbulence level changes at boundary
4. PLS (Gurnett, et al.) determined the plasma density, using plasma wave observations, find density comparable to what expect interstellar density to be.
5. MAG (Burlaga & Ness) find a sector boundary they claim is the heliopause



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The F&G Model

1. Voyager 1 crossed onto field lines that intersect the actual heliopause. ACRs escape, GCRs enter.
2. No change in magnetic field direction is expected as solar wind is convected across boundary.
3. The presence or absence of ACRs dramatically changes the observed magnetic field.
4. The increased density is simply compressed solar wind.
5. Burlaga & Ness uses incorrect analysis to determine transit time of sector boundaries in the heliosheath

So what were the observations of Voyager 2 that caused the Voyager investigators to conclude they had crossed the heliopause?

- There was a decrease but not as precipitous in the ACRs, consistent with the location of Voyager 2 on the flanks of the heliosheath.
- The magnetic field strength increased, but no change in field direction.
- Gurnett et al. had plasma density measurements just beyond boundary, and found values similar to those of Voyager 1.

- It appears as if the Voyager Investigators looked at the observations of the Voyager 2 crossing of the boundary and decided it looked very similar to the Voyager 1 crossing. And since they had decided (incorrectly) that the Voyager 1 boundary is the heliopause, then the Voyager 2 boundary must also be the heliopause.

- There is no conclusive evidence that Voyager 1 crossed into the interstellar medium in 2012. Nor that Voyager 2 crossed into the interstellar medium in late 2018.

So where are Voyager 1 and 2 now?

- Voyager 1 has been cruising through the heliosheath beyond the heliocliff since 2012, heading for the actual heliopause.
  - Why haven't we seen the heliopause yet?
    - Is anyone watching?
    - Maybe its more complicated than the simple model, with a clean rotational discontinuity
  - There is a simple little model you can build, based in Faraday's Law and the shape of the nose region of the heliosheath, which argues that the distance from the termination shock to the heliocliff is equal to the distance from the heliocliff to the heliopause.
  - The simple model predicts that Voyager 1 will encounter the heliopause at 150 AU, this September
- There is no simple model for Voyager 2, but you can use ENA observations along the line of sights of Voyager 1 vs Voyager 2 to predict that Voyager 2 will encounter the heliopause at the end of this year.

- If we are ever going to agree on the global structure of the heliosheath and its interaction with the local interstellar medium, we need better data, with modern instrumentation.

  - Over to you Interstellar Probe!

Question and Answer Session

Interstellar Probe Study Webinar Series

Engineering Discussion
Mission Trade Space

Presented by

- **Interstellar Probe Study Engineering Team**

12:05 PM EDT Thursday, 3 September 2020

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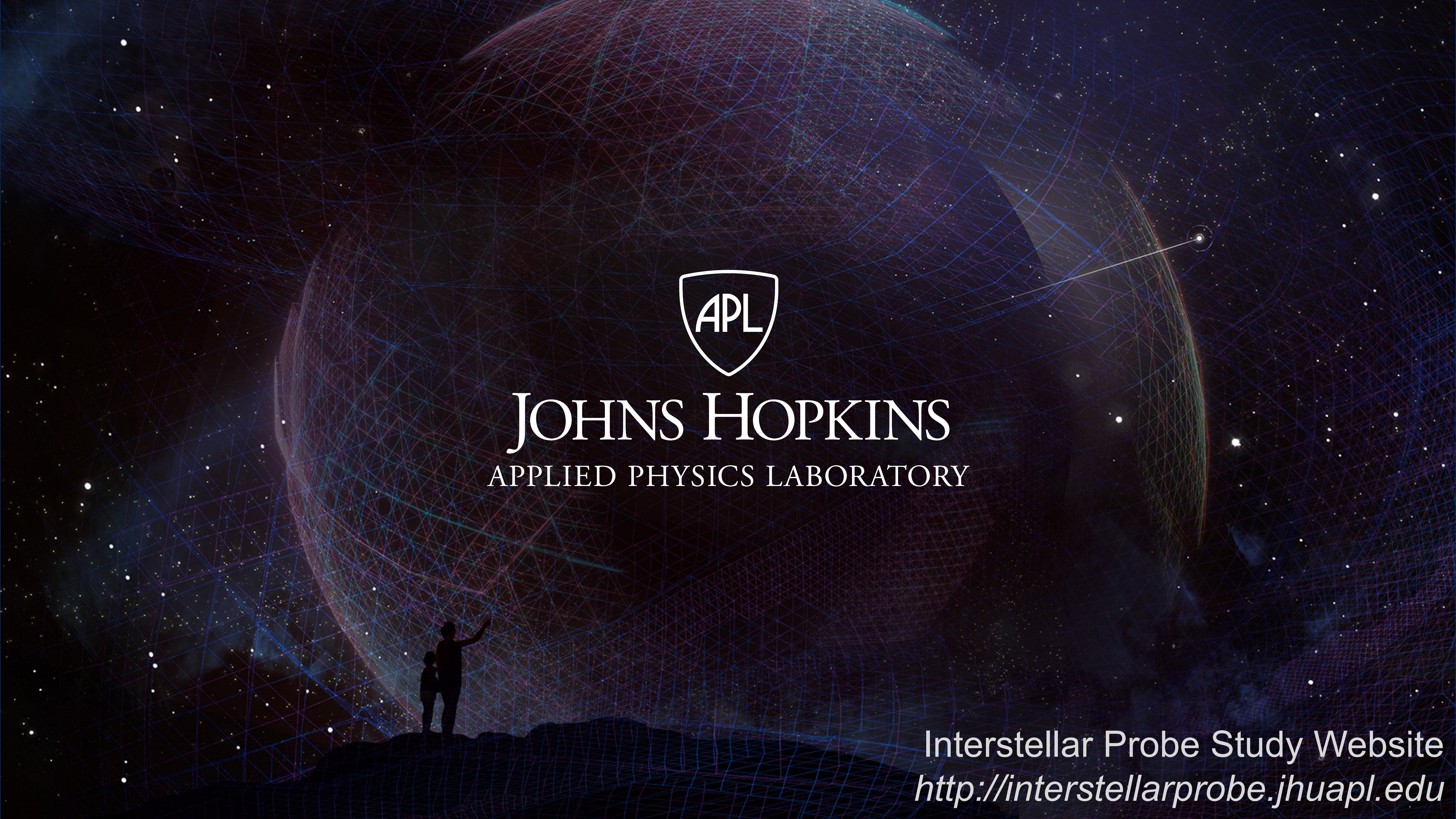
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