Interstellar Probe: Humanity`s Journey to Interstellar Space Begins

Lecture at NASA Heliophysics Summer School, 25 June 2021

Elena Provornikova, P. C. Brandt, R. L. McNutt, Jr., J. Kinnison, K. Runyon, C. Lisse, A. Rymer, R. Stought, M. V. Paul
and 476 experts and enthusiasts around the world

The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA
NASA Marshall Space Flight Center, SLS Office, Huntsville, AL, USA

Elena.Provornikova@jhuapl.edu
interstellarprobe.jhuapl.edu
Current understanding of the heliosphere

Unexpected discoveries that remain challenging to explain

- Voyager 1 and 2 are the only spacecraft to have traversed the Heliopause. With limited payload they left a range of mysteries.

- IBEX and Cassini have imaged the boundaries from inside and have brought the best global understanding to date, but still lack consistent interpretations.

- SOHO, Ulysses, New Horizons brought remote information on interstellar neutrals and their critical interaction with the heliosphere.

- IMAP (launch 2025) will provide order-of-magnitude better ENA imaging capabilities from 1 AU and guide further formulation of the Interstellar Probe Science Investigation.
What is Interstellar Probe?

**Achieving a Dream:** A mission to the Interstellar Medium has been discussed since 1960

**The First Step:** Interstellar Probe is a mission concept through the boundaries of the heliosphere, into the Local Interstellar Medium

**Not A Starship:** Uses available or near-term technologies to achieve asymptotic speeds larger than those of past missions

**The Science:** Our heliosphere as a habitable astrosphere, the unexplored interstellar medium beyond, and opportunities for planetary science and astrophysics

**Paving the Way:** Interstellar Probe paves the way scientifically, technically and programmatically for longer interstellar journeys that would require future propulsion systems
Interstellar Probe mission concept study

• 4-year study funded by NASA led by JHU APL and supported by more than 470 scientists, engineers and enthusiasts around the world

• “Pragmatic” mission concept

• Technology ready for launch by 2030

• Capability to operate and downlink out to 1000 AU

• Mission lifetime no less than 50 years

• “Menu” approach
The Team Journey
Primary Goal
Our Habitable Astrosphere and its Home in the Galaxy

Astrophysics Supporting Goal
Formation of Early Galaxies and Stars

Planetary Supporting Goal
Evolution of Planetary Systems

Interstellar Probe
Humanity’s Exploration of Interstellar Space Begins

KBOs  Dwarf Planets  Dust Disk
Goal 1: Objective 1: A Heliosphere Shaped by the Sun

Unknown Global Structure

Processes Upholding the Heliosphere:

gap in understanding the critical pick-up-ion population
Goal 1: Objective 1: A Heliosphere Shaped by the Sun

The Termination Shock: the largest shock in the heliosphere and not like others

Acceleration of Anomalous Cosmic Rays: still unsolved

Instabilities at the Heliopause and Magnetic Draping

Richardson et al. 2008

McComas and Schwadron 2006

Pogorelov et al. 2017

Opher et al. 2015
Goal 1: Objective 2: A Variable Sun in a Changing Interstellar Environment

The Breathing Heliosphere Harboring a Variable Sun

The Changing Heliosphere Through an Inhomogeneous ISM

Highly Dynamic Heliosheath

Tiny heliosphere in a dense interstellar cloud

Large heliosphere in Local Bubble plasma

McComas 2020

Washimi et al. 2011

Muller et al. 2008
Goal 1: Objective 2: A Variable Sun in a Changing Interstellar Environment

How far does the influence of our Sun extends into the interstellar space?

Connecting the dynamic Sun with shocks in the interstellar medium
The first direct sampling of density, temperature, ionization, state, composition and fields beyond the heliopause would provide decisive information on the heliospheric interaction, and also on the chemical evolution of the galaxy.
**Goal 1: Objective 3: Into the Unknown Local Interstellar Cloud**

**Hydrogen Wall: Discovered remotely but unexplored**

**Interstellar Dust: disconnect between ISM dust measurements from remote sensing and in-situ measurements**

**New Galactic Cosmic Ray science: sources and origin of GCRs <1 GeV**

---

[Images and graphs related to the topics mentioned.]
Unique Opportunities for Planetary Science and Astrophysics

The Origin of Planetary Systems
Dwarf Planets and KBOs

130 dwarf planets and over 4000 KBOs. Any direction defined by Heliophysics offers at least one compelling flyby.

Imprint of Solar System Evolution
Circum-Solar Dust Disk

Discovery of the solar dust disk is critical for understanding the evolution of planetary systems.

Understand Galaxy and Star Formation
Extragalactic Background Light (EBL)

Uncovering the Extragalactic Background spectrum, a key in our understanding of early galaxy formation.

MU69 "Arrakoth" (25 km)
New Horizons 1 Jan 2019

Pluto

MU69 "Arrakoth" (25 km)
New Horizons 1 Jan 2019

First Stars & Galaxies ~13 Gya

Big Bang 13.7 Gya

Today

Sol 4.6 Ga

HL-Tau 1 Ma!
Notional Operations Scenario
Driving Mission Architecture Designs

Baseline Scenario
(concluding now)
- Spin stabilized
- 50m PWS wire antennas

Inner Heliosphere Phase
1-90 AU
- In-situ measurements of magnetic fields, solar wind and PUI
- ENA and Ly-α imaging from a changing vantage point
- PWS observations of 2.5 kHz emission

Heliosheath Phase
90-120 AU
- In-situ measurements through boundary region
- ENA and Lyα imaging
- PWS Observations

Interstellar Phase
>120 AU
- In-situ measurements of ISM gas, neutrals and dust
- External ENA and Lyα imaging
- In-situ measurements of ribbon
### Baseline: Goal 1 (Primary)

<table>
<thead>
<tr>
<th>Goal</th>
<th>Science Objectives</th>
<th>Specific Questions</th>
<th>Measurement Objectives</th>
<th>Measurements (Supporting)</th>
<th>Mission Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Physical Processes and Global Manifestation</td>
<td>Global Structure; Force Balance</td>
<td>In-situ particle spectra and fields across HS and into LISM, flows, Remote wave, Ly-α and ENA imaging.</td>
<td>MAG, PLS, PUI, EPS, CRS, ENA, PWS, LYA</td>
<td>Spinning: imaging from ~250 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ribbon/Belt</td>
<td>ENA imaging; In-situ within ribbon.</td>
<td>ENA, PLS</td>
<td>Spinning: trajectory through ribbon to ~300 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACRs, shocks, reconnection, TS, HP</td>
<td>Fields, e/ion plasma to ACRs across TS, HS; Fields, waves, particle spectra for HP instabilities</td>
<td>MAG, PLS, PUI, EPS, CRS, PWS</td>
<td>Spinning: through HP ~130 AU; spend sufficient time in HS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neutrals in the Heliosphere</td>
<td>LOS velocity and temperature of H</td>
<td>LYA, NMS</td>
<td>Through HP ~130 AU</td>
</tr>
<tr>
<td></td>
<td>Dynamics and Evolution</td>
<td>Solar Wind Effects on the Boundary</td>
<td>In-situ ~day variations in HS; ENA and wave variations remotely</td>
<td>MAG, PLS, PUI, EPS, CRS, ENA, PWS</td>
<td>Spinning: spend sufficient time in HS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shock Propagation and Turbulence</td>
<td>Fields, e/ion plasma to GCR anisotropies; fields turbulent spectra Earth to LISM</td>
<td>MAG, PLS, PUI, EPS, CRS, PWS</td>
<td>Spinning: sufficient time beyond HP out to ~400 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GCR Modulation/Shielding</td>
<td>GCR e/ion composition, fields out to LISM</td>
<td>MAG, CRS</td>
<td>Spinning: sufficient time beyond HP out to ~400 AU</td>
</tr>
<tr>
<td></td>
<td>Properties of the Unexplored VLISM</td>
<td>Nature of Bow Shock</td>
<td>In-situ fields, plasma, PUI for sound speed</td>
<td>MAG, PLS, PUI</td>
<td>Spinning: ≤300 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen Wall</td>
<td>LOS H; In-situ H and composition</td>
<td>LYA, NMS</td>
<td>≥300 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neutrals/Dust Filtration</td>
<td>In-situ elemental and isotopic out to LISM</td>
<td>NMS, IDA</td>
<td>~400 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LISM gas and plasma</td>
<td>Density, temp., composition, ionization</td>
<td>MAG, PLS, NMS</td>
<td>Spinning: ~400 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LISM Inhomogeneities</td>
<td>Variability of properties on 100’s AU</td>
<td>MAG, PLS, NMS</td>
<td>Spinning: ~400 AU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Origin of GCRs</td>
<td>Elemental/isotopic abundances, spectra</td>
<td>MAG, CRS</td>
<td>Spinning: sufficient time beyond HP</td>
</tr>
</tbody>
</table>

**Instruments:**
- MAG: Magnetometer
- PLS: Plasma System
- CRS: Cosmic Ray System
- EPS: Energetic Particle System
- PWS: Plasma Wave System
- ENA: Energetic Neutral Atoms
- IDA: Interstellar Dust Analyzer
- IDC: Interstellar Dust Counter
- NMS: Neutral Mass Spectrometer
- LYA: Ly-Alpha Spectrograph
### Example Model Payloads

#### Heliophysics Baseline

<table>
<thead>
<tr>
<th>Instrument (Heritage)</th>
<th>Measurement Requirements</th>
<th>Mission Requirements</th>
<th>Science Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnetometer (MAG)</strong> (NKS/DFG)</td>
<td>0.01 - 100 nT; 0.01 nT (10^-1 nT/Hz turb.)</td>
<td>&lt;60 s; (100 Hz)</td>
<td>Two FB, 10m boom</td>
</tr>
<tr>
<td><strong>Plasma Waves (PWS)</strong> (Van Allen/EFW)</td>
<td>~1 Hz – 1 MHz; Δf/Δt 14%</td>
<td>&lt;60 s (&lt; 4 s at TS)</td>
<td>4x50 m wire; spin plane</td>
</tr>
<tr>
<td><strong>Plasma Subsystem (PLS)</strong> (PSP/SWP/SWAP)</td>
<td>~eV to 10’s keV e, He, C, N, O, Mg, Si, Fe (charge states)</td>
<td>~4π; ±60 s</td>
<td>Spinning</td>
</tr>
<tr>
<td><strong>Pick-up Ions (PUI)</strong> (Olysses/SPICE)</td>
<td>0.5-78 keV/e</td>
<td>iFOV: 60°</td>
<td>Spinning</td>
</tr>
<tr>
<td><strong>Energetic Particles (EPS)</strong> (PSP/EPI-Lo)</td>
<td>10’s keV – Fe MeV H, He, C, O, Ne, Mg, Si, Fe (Li/BeB)</td>
<td>iFOV: 60°</td>
<td>Spinning</td>
</tr>
<tr>
<td><strong>Cosmic Rays (CRS)</strong> (PSP/EPI-Hi, new development)</td>
<td>H to Sn; ≤1 GeV/nuc; Δm= 1 amu electrons; ≤10 MeV</td>
<td>x2 directions; daily</td>
<td>Spinning</td>
</tr>
<tr>
<td><strong>Interstellar Dust Analyzer (IDA)</strong> (IMAP/IDEX, new development)</td>
<td>1-500 amu; m/Δm &gt; 200</td>
<td>iFOV: 90°</td>
<td>Ram direction</td>
</tr>
<tr>
<td><strong>Neutral Mass Spectrometer (NMS)</strong> (LunaResurs/NGMS, JUICE/NMS)</td>
<td>H to Fe, m/Δm &gt; 100 (1σ)</td>
<td>iFOV: 10°; weekly</td>
<td>Ram direction</td>
</tr>
<tr>
<td><strong>ENA (ENA)</strong> (IMAP/IDEX, new development)</td>
<td>~1-100 keV H (He, O goal)</td>
<td>iFOV: 170° x 90°</td>
<td>Spinning, 2 heads</td>
</tr>
<tr>
<td><strong>Lyman-Alpha Spectrograph (LYA)</strong> (MAVEN/IDYS, new development)</td>
<td>120-130 nm; 0.004 nm</td>
<td>iFOV: 5°; 14° monthly</td>
<td>Spinning</td>
</tr>
</tbody>
</table>
Example Accommodation

**Baseline:** Snapshot (not all completed yet)

- **MAG:** 2 per 10-m boom
- **CRS:** Perpendicular telescopes on forward deck (not visible)
- **PLS:** Mounted on pedestal for 4π coverage
- **PUI:** Mounted on pedestal for unobscured coverage
- **EPS:** Mounted on pedestal for 4π coverage
- **ENA:** Mounted on pedestal for maximum coverage
- **RTGs:**
- **IDA:** Forward deck in ram direction
- **PWS:** Four 50-m spin plane wire antennas
- **NMS:** Forward deck in ram direction, co-aligned with IDA
- **LYA:** Side deck (not visible)

*interstellarprobe.jhuapl.edu*
Concluding Remarks

Galactic Supercluster Laniakea

The Orion Spur

The Local Clouds

Home
- Join the team at interstellarprobe.jhuapl.edu
- Student Program is under development
- White Papers for the Heliophysics Decadal
- https://www.lpi.usra.edu/decadal_whitepaper_proposals/heliophysics/

To join the journey: interstellarprobe.jhuapl.edu
Question and Answer Session
Baseline Trajectory

Optimized Example Baseline Direction
7.6 AU/year

Direction Trades from 2019 Workshop

<table>
<thead>
<tr>
<th>Direction</th>
<th>Heliophysics Trades</th>
</tr>
</thead>
</table>
| ~45° off nose | • Through ribbon (~285° ELOM)  
|             | • Good for imaging from outside  
|             | • Good for ISD |
| Nose        | • Fast way to LISM  
|             | • Stagnation, high-pressure region, force balance  
|             | • Good for ISD  
|             | • Not through max ribbon  
|             | • Not optimal for imaging from outside |
| Flank (~90°) | • HP data point important for shape  
|             | • ACR acceleration  
|             | • May be longer to reach LISM  
|             | • Not in the ribbon  
|             | • Dust duty cycle limited |
| ~135° off Nose | • Problematic for dust  
|             | • Sufficiently close to the direction of CMA  
|             | • Maximum outbound speed area |
| Tailward    | • Problematic for dust  
|             | • Sufficiently close to the direction of CMA |
| Off Ecliptic (U/N) | • Jets, turbulence  
|             | • Towards EUV ionizing stars (CMA)  
|             | • Not through ribbon (tailward) |