Opening a New Window on Our Global Heliosphere

... IBEX

... the Voyagers

... and the next steps (IMAP)

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University of New Hampshire

NEROC– Nov 2018
The Sun and Local Interstellar Medium (LISM)
ASTROSPHERES

LL Orionis
Visible
Hubble

BZ Cam
Visible
R. Casalegno

Mira
Ultraviolet
GALEX
Timeline of the Interstellar Discovery

2002

Schwadron et al., GRL, 2002
Timeline of the Interstellar Discovery

Voyager 1 and Voyager 2 remain inside the termination shock

Distance to TS **unknown**

Heliosheath **unmeasured**

Global properties of heliosphere **unknown**

Only indirect evidence from Anomalous Cosmic Rays, radio emissions, neutral populations and lyman alpha
Timeline of the Interstellar Discovery

Dec 2004

Voyager 1’s first crossing of the termination shock

Distance, properties known at one location and at one time

Exploration of Heliosheath begins
Timeline of the Interstellar Discovery

- Dec 2004: Discovery of termination shock (and heliosphere) asymmetries
  - Richardson et al., 2008
- Aug 2007: Voyager 2’s second crossing of the termination shock
  - Distance, properties known at two locations and at two times
  - Discovery of termination shock (and heliosphere) asymmetries
Timeline of the Interstellar Discovery

- Dec 2004: Richardson et al., 2008
- Aug 2007: Properties of LISM
- Dec 2009: Global structure of Heliosheath, termination shock
- Existence of Bow Wave
- Pickup ions, Suprathermal population critical to plasma pressure
- Discovery of IBEX ribbon
- Possible link between Ribbon and interstellar magnetic field
Timeline of the Interstellar Discovery

2002

Dec 2004

Richardson et al., 2008

Aug 2007

Dec 2009

Voyager 1 enters the local galactic medium

Aug 2012

In situ galactic exploration begins

Aug 2007

Dec 2009

Science

Richardson et al., 2008

IBEX and the heliosphere's boundary

2012
Timeline of the Interstellar Discovery

Ribbon Ordering by LISM Magnetic Field confirmed by TeV anisotropies

Journey continues

Dec 2004
Richardson et al., 2008

Aug 2007
Dec 2009
Aug 2012
2014-2016

Richardson et al., 2008

Dec 2009

Science

Aug 2007

Effects of interstellar magnetic field on global heliosphere, plasma and neutral populations

• Two huge aperture single pixel ENA cameras:
  – IBEX-Lo (~10 eV to 2 keV)
  – IBEX-Hi (~300 eV to 6 keV)
• Simple sun-pointed spinner (4 rpm)
IBEX Orbit Raising Approach

- No mission has ever used a Pegasus LV to achieve orbit higher than LEO (few hundred km)!
- IBEX apogee \( \approx 50 \, R_E \)
- New approach combines 3 orbit-raising methods
  - Pegasus launch vehicle
  - IBEX-supplied Solid Rocket Motor (SRM)
  - Hydrazine Propulsion System finishes orbit raising and trims out delta-V dispersions from solid rocket motors
Ribbon Correlates with $\mathbf{B \cdot r}=0$

- **A:** 1.1 keV Map with contours $\mathbf{B \cdot r}$ angle from Model 2 and the LOS over 10 AU outside heliopause
- **B:** Flux as function of LOS angle from $\mathbf{B}$
- **C:** Global structure of heliopause and $\mathbf{B \cdot r}=0$ surface

Schwadron et al., Science, 2009
Possible Sources of IBEX Ribbon [McComas et al., *Science*, 2009]

1) Max Pressure/Stagnation

Max Pressure - Stagnation

2) Primary ENAs from Compression

3) Secondary ENAs

Solar Wind ENAs

4) ENAs from Magnetic Reconnection

5) ENAs from Shock Accelerated PUIs

6) ENAs from HP Instabilities

SW Flow

Max Pressure: J x B + RAM

Compressed ISM B-field

ENAs from Inner Heliosheath

ENAs from Inner Heliosheath

ENAs from Inner Heliosheath

Hot Ion Leakage into Outer Heliosheath

Instabilities RT or KH

Motion away from nose
Spatial Retention Region

- Instability within retention region
  - Stronger isotropization of distribution functions
  - Reduced ion mobility
- Ion streaming outside retention region
  - Waves propagate toward retention region

Subscale process?

Schwadron and McComas, 2013
Comparison of Observed TeV Anisotropies

Schwadron et al., Science, 2014
Schwadron et al., ApJS, 2018
“L’essential est invisible pour les yuex”

Advancement requires that we understand and move beyond hidden boundaries.

Entering a new realm of galactic exploration.
Interstellar Mapping and Acceleration Probe (IMAP)

A mission to discover the Origin of Particle Acceleration and its Fundamental Connection to the Global Interstellar Interaction

Proposed: Oct 2017
Selected: 1 June 2018
Launch: 2024
Interstellar Mapping & Acceleration Probe

Hi-Resolution ENA Images of the Heliosphere Boundary
Detailed Analysis of the ISM Flow for H, D, He, O & Ne with Neutral Atoms and Pickup Ions
Study Interstellar Dust Flow and its Composition

Study Source Populations for SEPs Including Suprathermal Tails as well as Acceleration at Hi-Res
Monitor Space Weather from L1
# Comprehensive Science Payload

## Suite of Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMAP-Lo</td>
<td>Energetic Neutral Atoms (Increasing Energy) Interstellar Neutral Atoms</td>
</tr>
<tr>
<td>IMAP-Hi</td>
<td>Interplanetary or Vector Magnetic Fields</td>
</tr>
<tr>
<td>IMAP-Ultra</td>
<td>Solar Wind Electrons</td>
</tr>
<tr>
<td>MAG</td>
<td>Solar Wind, Pickup, Suprathermal, and Energetic Electrons</td>
</tr>
<tr>
<td>SWE</td>
<td>Solar Wind, Pickup, Suprathermal, and Energetic Electrons</td>
</tr>
<tr>
<td>SWAPI</td>
<td>Energetic Ions; Energetic Electrons</td>
</tr>
<tr>
<td>CoDICE</td>
<td>Dust</td>
</tr>
<tr>
<td>HIT</td>
<td>UV</td>
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<tr>
<td>IDEX</td>
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</tr>
<tr>
<td>GLOWS</td>
<td></td>
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Interstellar Mapping and Acceleration Probe (IMAP)

.. Civilizations next step into Galactic Exploration
Summary

– IBEX + Voyagers provide a new paradigm of our Magnetically Influenced Heliosphere
– Interstellar O + He Warm Breeze add new dimensions to understanding of filtration + B-V orientation
– 7 Year study underway in our time-evolving heliosphere

– Preparing IMAP, next step in Ed Stone’s Expedition
  • IMAP Fundamental and highly relevant scientific questions
    – Interstellar Interactions – Heliospheric Frontier
    – Acceleration of energetic particles and propagation of cosmic rays
    – Interstellar Conditions
    – L1 Science – Geospace Inputs and Responses
  • Societally critical and urgent
    – Voyager synergy
    – Most unique solar conditions in 80 years
  • Broad scientific engagement
  • IMAP Low cost and ready for implementation!
What are the Physical Properties and the Composition of the ISM?

- IMAP provides ISM Composition
  - First direct measurements of interstellar Deuterium with ISM neutrals (Implications for Big Bang Cosmology)
  - High-precision observations of ISM $^3\text{He}/^4\text{He}$ and $^{22}\text{Ne}/^{20}\text{Ne}$ ratio with pickup ions to better than 5% accuracy
- IMAP enables detailed study
  - H, He, O, and Ne ISM flow
  - Outer heliosheath with O and He secondary flow
- Simultaneous Global properties of Ly-\(\alpha\) backscatter, evolution of neutral H inflow
- Composition and properties of interstellar grains

Gloeckler et al. 1998

Möbius et al. Science 2009

Boston University, Sept 17, 2015
Criteria: IMAP Answers Vital and Urgent Scientific Problems

- Area of rapid discovery and progress at the Outer Frontier
  - Discovering our evolving home in the local galactic environs
- Urgency
  - Synergy with Voyager 1 and 2
  - Changes in the space environment allow extremely good imaging, time dependence of interstellar boundaries and changes in cosmic rays
- Fundamental Scientific Discovery of the Composition and Properties of Local Interstellar Medium
  - IMAP/Voyager co-temporal observations fundamentally enabling
- Discovery of the Fundamental Physical Processes that Control Particle Acceleration throughout the Cosmos
  - Underlying variations and sources of ubiquitous suprathermal ions
  - Injection of seed populations into particle acceleration
  - Particle injection and acceleration in TS and heliosheath
- Fundamental Scientific Implications for Exoplanetary Habitability and Future of our World
  - History and future within our galaxy key to understanding the conditions on our evolving planet over time and as prerequisite for future expansion across the solar system
  - Understanding our global heliosphere, physical interactions
  - Understanding of interstellar interactions that influence exoplanetary habitability
IBEX Mission

• Small Explorer
  – Smallest and cheapest type of full NASA mission
  – Foreign contributions: Swiss (hardware) and many country (science) contributions

• Fast Track Schedule
  – Selected: January 2005
  – Mission PDR: January 2006
  – Confirmation Rev: March 2006
  – Mission CDR: September 2006
  – Payload Delivery: September 2007
  – VAFB Delivery: July 2008
  – Launch: 19 October 2008
ENAs Illuminate the Heliosheath

- Supersonic SW must slow down and heat before it reaches the interstellar medium
- Large numbers of interstellar neutrals drift into heliosphere
  - Ly-α backscatter
  - interstellar pickup ions
- Hot SW charge exchanges with interstellar neutrals to produce ENAs
- Substantial ENA signal from outside the TS guaranteed from first principles

$$J_{ENA} = \int dx \ n_H \ J_{ION} \ \sigma$$
IBEX and the heliosphere's boundary
Heliotail Observed

- Influence of Solar Wind
- Port and Tail Lobes
- Twisting by external field influence

McComas et al., 2013
LISMF Twists Heliotail
Our Heliosphere

Termination Shock

Heliopause

Bow Shock

Interstellar Medium

Earth-Sun = 1 AU

~100 AU?

Distance unknown

Distance & existence unknown
Interstellar Magnetic Field Influence

- Interstellar magnetic field deflected around our heliosphere
- Affects TeV cosmic rays with ~100 AU gyroradii
- Controls structure of the IBEX ribbon

Schwadron et al., 2014, 2015
Solar and Space Physics 2013 Decadal Survey

- Interstellar Mapping & Acceleration Probe

2012-2013

SOLAR AND SPACE PHYSICS
A Science for a Technological Society

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