Interstellar MApping Probe (IMAP) mission concept: Illuminating the dark boundaries at the edge of our solar system

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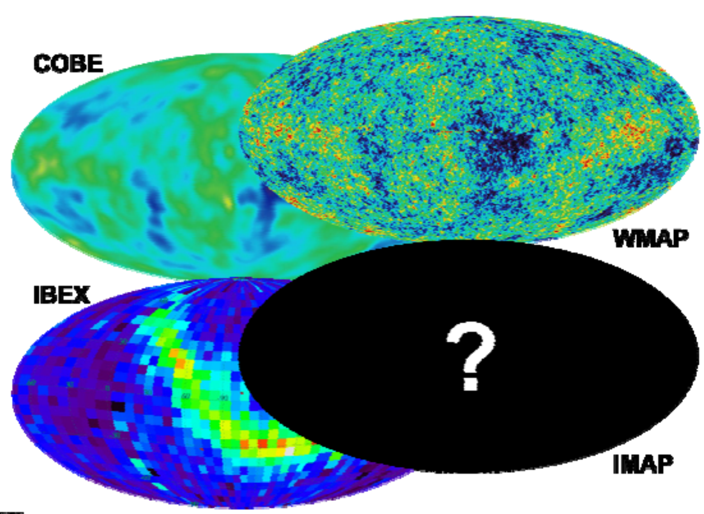
A. Introduction

Recent groundbreaking all-sky images of the heliospheric boundaries by the Interstellar Boundary Explorer (IBEX) mission and Cassini INCA instrument, in concert with dual point *in situ* observations of the inner heliosheath from both Voyager spacecraft, have made outer heliospheric science one of the most exciting and fastest developing areas in Heliophysics. The **Interstellar MApping Probe (IMAP)** is a mission concept that carries on from the highly successful first heliospheric mapping to enable the discovery of the detailed processes and interaction between the heliosphere and the local interstellar medium (LISM)[1]. IBEX discovered a completely unpredicted, narrow (~20º) ribbon of Energetic Neutral Atom (ENA) emissions coming from the outer heliosphere, which appear to be ordered by the magnetic field just outside in the LISM[2-5]. Even more surprisingly these emissions appear to be evolving on timescales as short as six months[6], demonstrating that the heliosphere's galactic interaction is more dynamic than anticipated. IBEX also made the first *in situ* detections of interstellar H and O, including a secondary O component, which stems from the outer heliosheath and contains information about deflection of the interstellar flow around the heliosphere[7].

Together, the IBEX and INCA ENA images and Voyager observations have proven that our current ideas are truly inadequate to understand the global interaction of our heliosphere. In addition, detailed analyses of interstellar H and O, along with He and Ne, from IBEX are forcing a reexamination of even what we thought we knew about the characteristics of the LISM. Thus, the scientific excitement and broad range of fundamental open issues exposed by these recent observations call out for an advanced and more capable mission – IMAP – which will provide ENA images over a broader energy range and with one to two decades better sensitivity/resolution. In addition, IMAP includes high resolution observations of all the other forms of interstellar matter that can be sampled directly in the inner heliosphere: pickup ions (PUIs), produced by ionization of incoming interstellar neutrals; Galactic Cosmic Rays; Anomalous Cosmic Rays, which are highly energized interstellar neutrals; and cosmic dust, which delivers grains whose chemical and isotopic composition exposes processes and their origins beyond our solar system. Finally, the IMAP concept includes observations of Ly-α backscatter, the interplanetary magnetic field, solar wind ions and electrons, and solar energetic particles, which are used to produce background free ENA observations – the last three of these time-critical space weather observations are provided through a real-time downlink.



What WMAP was to COBE, IMAP will be to IBEX - enabling a "quantum leap" forward in understanding, analogous to that which occurred from COBE to WMAP observations of the cosmic microwave background. With a factor of 10-100 enhanced sensitivity, higher angular and energy resolution and a broader energy range, IMAP will revolutionize our understanding of the heliosphere's interaction with, and our place in, the Galaxy.

All of the great IMAP science can be accomplished in a properly instrumented small-class (250-500M $FY10) mission based on a simple Sun-pointed spinning spacecraft, much like the Advanced Composition Explorer (ACE). As summarized in this white paper, IMAP promises to cost effectively 1) advance critical scientific objectives of understanding our home in the galaxy, 2) contribute to the fundamental understanding of the Sun-Earth system, and 3) produce secondary observations critical to space-weather related societal needs.

B. IMAP Science Concept

IMAP combines ten state-of-the-art measurement capabilities (Table 1) to produce a) critical new observations of ENAs from the heliospheric boundary region over an extended energy range and with significantly enhanced sensitivity, and spatial and energy resolution, compared to prior observations (1-2); b) high sensitivity observations of the other direct samples of interstellar matter available in the inner solar system – interstellar neutral atoms (3), PUIs (4), GCRs and ACRs (5), and dust (6); and c) other supporting measurements required to monitor the solar wind input to the outer heliosheath, as well as understand and mitigate all backgrounds from the local environment around the spacecraft (7-10). This latter element of the IMAP payload will also provide societally important real-time solar wind (RTSW) monitoring.

Table 1. Nominal Payload for IMAP Mission	[kg]	[W]
High Sensitivity, High Resolution ENAs		
1. Solar Wind & PUI ENAs	20	18
2. High Energy ENAs	7	7
Other Samples of Interstellar Matter		
3. Interstellar Neutrals (w Low-E ENAs)	15	15
4. Pickup Ions	10	8
5. ACRs/GCRs	5	5
6. Interstellar Dust	8	16
In Situ/Background Payload with RTSW		
7. Ly-α Photometry	4	4
8. Interplanetary Magnetic Field	3	3
9. Solar Wind Ions & Electrons (two sensors)	7	7
10. Solar/Interplanetary Energetic Particles	3	3
Full Science Payload (CBE)	**80**	**86**
30% Contingency	24	26
TOTAL PAYLOAD ALLOCATION	**104**	**112**

1. Solar Wind & PUI ENAs - The critical energy range from ~0.3-20 keV covers hydrogen ENAs produced from the solar wind and interstellar PUIs, which mass load the solar wind as it travels out through the heliosphere. This energy range also spans the emissions from the IBEX ribbon. Observations of these ENAs with a factor of ~100x the combined sensitivity/duty cycle compared to IBEX-Hi will enable the extreme spatial and energy resolution needed to track the detailed processes and interactions at work in the inner heliosheath and outer heliospheric boundaries as well as fully resolve the time varying structure in the ribbon.

2. High Energy ENAs - The energy range ~3-200 keV covers ENAs that produce the majority of the particle pressure in the heliosheath, and are needed to understand the processes that accelerate solar wind and interstellar pickup ions to higher energies as a function of direction in the sky, where integration path lengths, termination shock strength, and angle to the interstellar field and flow vectors may all play important roles. All-sky ENA images at these energies with a factor of ~10x the angular resolution and ~100x the combined sensitivity/duty cycle of INCA, will resolve time variations on time scales of months, appropriate to the transit times of these particles through regions of interest.

3. Interstellar Neutrals/Low Energy ENAs - IMAP will make direct measurements (5-860 eV) of neutral matter (H, D, He, O, and Ne) from the ISM to determine their abundances, flow patterns (bulk velocity and temperature), and the filtration of the ISM neutrals in the outer heliosheath. By stepping the viewing direction, both direct trajectories of neutral atoms (before or at the atom's perigee) and indirect trajectories (after their perigee) are observed, providing direct information about the ionization rate that the atoms are exposed to. IMAP will have significantly higher sensitivity for O, Ne, and He than IBEX and high accuracy pointing knowledge (<0.05°) so that it can well separate the primary and secondary neutral populations, illuminating the interactions in the outer heliosphere. Finally, IMAP data will make fundamental measurements the LISM D/H, which requires ~10x the sensitivity of IBEX[8].

4. Pickup Ions - Velocity distributions of PUIs created from atoms at rest, range from zero to twice the solar wind speed. IMAP covers the energy range from 50 eV to 80 keV, which provides good coverage of light PUIs and sufficient coverage of heavier PUIs. In addition, supra-thermal tails in the PUI distribution of H and He will be studied. To infer the complete angular distributions a significant swath of the sky will be viewed (at least 150º x 60º). Finally, this sensor also measures the composition of solar wind ions, which "label" the solar wind sources.

5. Anomalous and Galactic Cosmic Rays – Anomalous cosmic rays (ACRs) are pickup ions that are accelerated in the heliosheath region where most of the ENAs measured by IMAP are formed. Understanding the physics of solar modulation depends on obtaining a long-term record of the temporal variations of both GCRs and ACRs near 1 AU. IMAP measurements utilize stacks of silicon solid-state detectors to measure ACRs and GCRs over the energy range from a few to >100 MeV/nuc. Particle trajectory measurements allow isotopes of He and Ne to be measured. The geometric factor is large enough to provide reasonably accurate monthly energy spectra of the rarer ACR species (e.g., Ar).

6. Interstellar Dust - Interstellar dust particles (ISD) flowing through the heliosphere are expected in the mass range (m) of $10^{-13}<m<10^{-10}$ g with a range of impact speeds (v) 20<v<70 km/s. Their unique identification requires <10% uncertainty in speed and <5° angular resolution. A dust telescope combining a trajectory sensor and an impact dust instrument will enable the high-fidelity identification of ISD, and the measurement of their chemical and isotopic compositions over 1<M<200 AMU with a mass resolution of $M/\Delta M>200$. Statistically meaningful observations are provided from an integrated exposure (target area x duration) of >500 cm^2year.

7. Ly-α Backscatter – Ly-α photometry provides a level of global solar wind imaging, including the out-of-ecliptic conditions, which are needed to assess the survival probabilities of both ENAs and interstellar neutrals measured by IMAP. Measurements similar to those from SOHO/SWAN image the neutral interstellar hydrogen distribution within a few AU from the Sun[9-10]. However, IMAP will employ a narrower (~2 Å) filter around the Ly-α line to eliminate the extraheliospheric "chaff" that plagues the SWAN observations. With this, IMAP will be able to provide remote-sensing information on neutral interstellar H supplemental and complementary to those obtained *in situ* via direct detection.

8. Interplanetary Magnetic Field - The local Interplanetary Magnetic Field (IMF) vector direction and magnitude will be measured at a cadence of at least 10 Hz by a magnetometer mounted on a short boom. Measurements cover a wide dynamic range up to several hundred nT (the largest fields observed in the solar wind at 1 AU) with an accuracy better than 0.1 nT.

9. Solar Wind Ions & Electrons - Energy per charge (E/q) ion spectra covering the solar wind beam direction, over the energy range of ~0.1-20 keV/q, are required with a one minute cadence to resolve solar wind structures. Electron energy spectra covering the majority of 4π sr (using the spacecraft spin), over the energy range of ~0.005-2 keV, are required with a cadence of one minute to resolve solar wind structures and suprathermal halo and strahl electron distributions. Such observations are routinely made with electrostatic analyzer based instruments, such as those flown on Ulysses[11] and ACE[12].

10. Solar/Interplanetary Energetic Particles – IMAP makes high sensitivity and temporal resolution (~1 minute) measurements of the differential fluxes of ions and electrons from ~2 keV up to ~1-2 MeV energy covering as much of 4π sr over a large dynamic range ($>10^5$) to identify the sources of background in the ENA detectors. Similar energetic particle observations are routinely made with solid-state detector based instruments[13-15].

Integrated Theory and Modeling

In addition to the revolutionary new IMAP observations, this mission concept includes an integrated and dedicated theory and modeling effort, which allows the "big picture" of our heliosphere's interaction with our galaxy to be synthesized. One of the possibly outstanding implications of the IBEX discovery of the ribbon is the first accurate estimate of the very local interstellar magnetic field orientation and strength, this derived from large-scale simulations of the global heliosphere coupled to detailed microphysical plasma processes[2,5,16,17]. The confrontation of IBEX observations with prior theory and modeling is forcing an extensive revision of current approaches, reinforcing the critical need to couple kinetic and macroscopic processes in the modeling of complex physical systems.

IMAP, by making measurements over a broader range of energies and with significantly higher sensitivity and resolution, will propel theory and modeling of the heliospheric boundary regions to address the critical microphysical/ kinetic processes and their coupling to the large-scale heliosphere that appear to define so much of the physics of this complex region. Finally, the extension of what we learn from IMAP will expand our knowledge of other astrospheres and the search for habitable zones of extra solar planets.

Real Time Solar Wind – The Magnetospheric Connection

IMAP makes upstream solar wind observations to provide multi-point viewing of the "magnetosphere-scale" features in vast solar wind disturbances impacting Earth and serves as a critical supplier of observations in the era beyond ACE. The ever-changing solar wind and IMF observed by IMAP drive space weather disturbances at Earth. In contrast to tropospheric weather, these drivers are more important than initial conditions in determining the state of the geospace-atmosphere system making IMAP observations critical to holistic studies that promise breakthroughs in understanding the interconnected Sun-Earth system.

Even during quiet solar times, the conditions in the solar wind can conspire to produce space weather that can affect our space systems. An example of this is the recent failure of the Galaxy 15 Communication satellite that occurred when a powerful susbstorm was triggered by a strong solar wind pressure increase when the IMF was already southward. IMAP will observe the solar wind and IMF disturbances that trigger catastrophic reconfigurations of magnetospheric structures with consequences throughout geospace and the upper atmosphere, and feed models, which rely on real-time knowledge of upstream solar wind conditions for prediction. Developing a space weather prediction capability is a national priority [*National Space Weather Program Strategic Plan, FCM-P30-2010, Washington, DC, June 2010*] made more urgent by our growing awareness that complex interdependencies increase the vulnerability of societal infrastructures that are affected by space weather [*NAS*, *Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report, 2008*] and knowledge of the changing upstream environment is an integral component of space situational awareness and treaty verification crucial to our national security.

C. How IMAP Will Advance Solar and Space Physics Science

Understanding the myriad of interactions at the outer boundaries of the solar system is critical for understanding the radiation and space environment throughout our inner solar system. The interstellar interaction leads to the compression of magnetic fields and plasmas in the inner and outer heliosheath. The compressed magnetic fields, in turn, lead to the deflection of the majority of GCRs (~90% at 10-100 MeV) around the heliosheath. These complex interactions cause:

- charge-exchange between incoming interstellar neutral atoms with the plasma of the outer heliosheath. This leads to the depletion (or filtration) of neutral atoms entering the solar system, which, in turn, modifies the composition of the interstellar gas flow entering the heliosphere and thus that of pickup ions born from interstellar neutral atoms. Studies using interstellar pickup ions and/or interstellar neutral atoms to determine the isotopic and elemental composition of the LISM utilize filtration models based on our understanding of the global heliosphere and charge-exchange interactions within the heliosheath. These filtration factors will reach a new level of accuracy once the interstellar boundary conditions of the MHD heliosphere models are better constrained. A precise understanding of the elemental and isotopic composition of the LISM also has fundamental implications for Big Bang cosmology, stellar nucleosynthesis and galactic evolution.

- interstellar pickup ions to form a source of anomalous cosmic rays that are accelerated at the termination shock, through stochastic processes in the heliosheath, or through magnetic reconnection. The study of interstellar pickup ion acceleration to anomalous cosmic ray energies provides a progenitor for understanding particle acceleration in diverse astrophysical environments ranging from the shocks, turbulence and dynamic magnetic structures that surround black holes and supernova remnants.
- modification of the population of interstellar dust grains from the interstellar medium into the heliosphere. The strong magnetic fields of the inner heliosheath cause filtration of interstellar grains, allowing only large grains (>0.2 μm) in. More accurate information about the interstellar interaction will allow us to unfold physical and compositional properties of the interstellar grains in the solar system to understand their sources in the interstellar medium. Finally, the large interstellar dust grains that reach the inner heliosphere create a gravitational focusing tail that links the LISM with dust grains of molecular cloud cores.
- the formation of a neutral population that generates the IBEX ribbon. One of the great discoveries of IBEX is the ENA ribbon nearly circling the heliosphere. While the heliospheric community is still grappling with the source of the ribbon, it is clear that it must be controlled, in part, by the local interstellar magnetic field. Both time-variations in the ribbon and more accurate measurements of fine-structure will yield critically needed insights into its origin, and ultimately help probe the magnetic and plasma properties of the LISM.
- the modulation of Galactic Cosmic Rays. The compression of plasma in the inner heliosheath causes intense magnetic fields that modulate as much as 90% of GCRs at tens of MeV. Understanding how this modulation changes with time is important for assessing how our solar system's radiation environment has changed in the past and how it will change in the future. GCRs pose one of the most stringent factors affecting possibilities of long-term human exploration and may have other effects on life on Earth and even, possibly, terrestrial climate.

Heliophysics has yielded a wealth of information about our magnetosphere, its associated shocks, the similar boundaries that surround other planets, comets, asteroids, the shocks and boundaries surrounding Coronal Mass Ejections (CMEs) as they plow through the heliosphere, and the shocks associated with Co-rotating Interaction Regions (CIRs) in the solar wind. These are all forms of magnetohydrodynamic (MHD) shocks and plasma boundaries that benefit greatly from comparative studies as they inform our understanding of MHD structures that pervade our cosmos and have critically important effects for the formation of energetic particles, the modification of the composition of astrophysical plasmas, the radiation environments of astrospheres and the evolution of planetary environments and atmospheres. Advanced understanding of the plasma boundaries of our heliosphere, the least understood boundaries in Heliophysics, enables generalized understanding of plasma boundaries in the cosmos.

Understanding the time variation of our heliosphere on short and long time-scales has fundamental implications for the history and future of our home in space. By comparing our heliosphere to astrospheres, we may learn how GCR radiation, stellar winds and astrospheres play into the habitability zones surrounding other stars. Our heliospheric boundaries help control, regulate and change the particle and dust populations through the heliosphere: neutral atoms, pickup ions, grains, GCRs and ACRs are all regulated and controlled, in part, by these boundaries. A thorough understanding of the changing Sun and its effects cannot be complete until we develop a comprehensive understanding of how the solar wind and interstellar medium interact to create the complex boundaries and the myriad of associated interactions to form our heliosphere and regulate our space environment. IMAP is a critical next step in the exploration and discovery of our global space environment.

D. Estimated IMAP Cost (FY10 Dollars) – Small Mission

The full IMAP science can be carried out in a straightforward way on a small spacecraft stationed in a halo orbit about the Sun-Earth Lagrangian - L1 point, ~$1.5x10^6$ km sunward of the Earth. IMAP fits readily into the small-class (250-500M $FY10) mission size because it is based on a simple Sun-pointed spinning spacecraft, similar to the highly successful ACE spacecraft, which has remained in such an orbit for over a decade. Sun-pointed, deploy-once solar arrays provide ample power for all spacecraft subsystems and for continuous observations by all instruments. The roughly Sun-pointed configuration also provides an optimum configuration for a single high-gain antenna mounted on the aft side of the spacecraft to provide continuous low power, low rate RTSW data in addition to periodic high-rate telemetry of the stored science observations.

From a cost standpoint, the cost for IMAP can also be estimated from the extremely analogous ACE mission, which was launched in August 1997: IMAP has 10 instruments with a nominal payload mass of 104 kg and power of 112 W, ACE had a payload of nine largely similar type instruments of comparable complexity and resources, with resources of 156 kg and 102 W. The IMAP spacecraft is very similar to the ACE spacecraft with the same orbit and essentially identical technical and environmental requirements. ACE was launched on a Delta II which by the time of the IMAP launches should be replaced with a Taurus II. As such, we developed a Rough Order of Magnitude (ROM) cost estimate for IMAP using actual costs from the ACE mission plus the current Launch Vehicle (LV) costs. The cost data are partially reproduced in the Table below. Phase E operations, science, and theory and modeling costs will be highest in the first two years of operations (~$18M/year) and decrease annually (down to ~$6M/year) by the end of the decade of operations to achieve an average ROM cost of $12M/year over 10 years for a well funded, high science return mission.

Table 2. ROM Costs	ACE Pre-Launch Actuals (FY95 M$)[18]	ACE Actuals Inflated to FY10 M$	Estimated IMAP Costs FY10 M$
Project Management	5.1	8.1	10
Spacecraft	47.0	74.8	90
Science Payload	50.2	79.9	100
Ground Systems	1.5	2.4	4
Performance Assurance	1.2	1.9	5
Flight Operations	1.8	2.9	4
Total w/o LV&Phase E	106.8	169.9	213
Phase E Estimate			120
Taurus II Cost		65.0[19]	75
TOTAL IMAP cost w/ Phase E & Taurus LV			**408**
Note that the ACE actual costs[18] are real year and include civil servant cost. We assumed them to be at the mid-year of the development and production or FY95 M$. Using the NASA inflation factor of 1.591, we obtained the cost in FY10 M$ shown in the third column.			

E. How IMAP Meets the Evaluation Criteria

a. IMAP observations are high priority/requirements in previous studies or roadmaps. The fundamental questions addressed by IMAP are of central importance for Heliophysics in our continued quest to understand how the solar wind interacts with the LISM to form our heliospheric boundaries and the plasma and radiation environments contained by them. The related science questions have been highlighted in the previous NRC decadal survey:

The Sun to the Earth – and Beyond: A Decadal Research Strategy in Solar and Space Physics (2002). *Challenge 2: Understanding heliospheric structure, the distribution of magnetic field and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.* "The boundary between the solar wind and the local interstellar medium (LISM) is one of the last unexplored regions of the heliosphere. Very little is currently known about this boundary or the nature of the LISM that lies beyond it. … certain aspects of these regions can be studied by a combination of remote sensing and in situ sampling techniques."

b. IMAP makes a significant contribution to more than one of the Panel themes. IMAP is poised to make major advances in our understanding of the heliosphere and its particle, dust and plasma environments. IMAP is equipped with instruments to measure the solar wind, suprathermal populations, energetic particles, magnetic fields, and cosmic rays. With its RTSW data, the mission will also provide a required element for magnetopsheric, ionospheric, thermospheric and mesospheric science, serving as the future L1 monitor.

c. IMAP contributes to important scientific questions facing solar and space physics today. Understanding the global heliosphere and its complex interactions will lead to major advances in understanding particle acceleration at the termination shock, at traveling interplanetary shocks and disturbances, the evolution of MHD structures on global scales, the kinetic physics measured through *in situ* plasma, field, suprathermal and energetic particle measurements. The measurements will continue to provide insights into traveling plasma waves and shocks, the incident structures at the magnetosphere, and reconnection exhausts measured in the solar wind.

d. IMAP contributes to applications and/or policy making related to operations, applications, and societal benefits. IMAP's comprehensive measurements will untangle the influence of changes in the heliosphere on the hazard posed by GCRs to astronauts and provide direct measurements of space weather hazards at L1. The societal relevance of delivering both RTSW and comprehensive measurements is demonstrated by ACE, which is a critical asset in space weather networks.

e. IMAP complements other observational systems or programs available. IMAP complements the operational missions, IBEX, Cassini/INCA and Voyager, by taking the next steps in our exploration of the global heliosphere. IMAP advances the measurement of interstellar neutral atoms and PUI composition, complementing the ongoing ACE and earlier Ulysses missions, by measuring the velocities of interstellar neutrals so that heliospheric data on the ISM can be compared with interstellar data from the Hubble Space Telescope. Finally, IMAP provides a cornerstone to the Heliophysics Great Observatory by providing a critically needed L1 replacement mission.

f. IMAP is affordable, providing great benefit for modest costs. IMAP is highly affordable, and fits well within the small-class mission size. The science per dollar ratio is extremely high. The mission takes fundamental steps in the exploration and discovery of our heliosphere, and provides extensive practical benefits.

g. IMAP has an appropriate degree of technical, resource, and expertise readiness. IMAP requires no significant technical developments. All instruments are natural extensions of existing instruments flown on previous successful 1 AU missions and the spacecraft requirements are very similar to the cost effective ACE spacecraft. The L1 orbit and associated mission operations are well-known and readily achievable within budgeted resources; the mission is categorically low risk.

h. IMAP fits with other national and international plans and activities. The call to understand the complex and interconnected system from the Sun to the interstellar medium is also clearly articulated in the 2010 Science Plan for NASA's Science Mission Directorate:

"An effective plan requires viewing the Sun, heliosphere, and planetary environments as elements of a single interconnected system—one that… evolves in response to solar… and interstellar conditions."

"We know that the Sun, the solar system, and the region of the galaxy just outside the solar system present us with a complex, interacting set of physical processes. But it is also the part of the cosmos accessible to *in situ* scientific investigation; it is a hands-on astrophysical laboratory."

F. Conclusion

Our piece of cosmic real-estate, the heliosphere, is the domain of all human existence. Its history and future in the galaxy is key to understanding the conditions on our evolving planet and future expansion across the solar system. As we ask about the habitability of other planets surrounding other stars, we grapple with understanding the complex environments and interactions in the local parts of the galaxy where these stars exist. Our own heliosphere is an astrophysical case-history of the successful evolution of life in a habitable system. By exploring our global heliosphere and its myriad interactions, we develop key physical knowledge of the interstellar interactions that influence exoplanetary habitability as well as the distant history and destiny of our solar system and world.

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