Expanding the Realm of Solar & Space Physics: Exploration of the Outer Heliosphere and Local Interstellar Medium

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Our Star is one of hundred billion stars in the galaxy that plows through the interstellar gas, plasma and dust made up from supernova remnants and condensed stellar outflows. With its dynamic solar wind, the Sun carves out the enormous habitable magnetic bubble harboring the solar system that we live in. The unique interaction responsible for upholding the boundary of the heliosphere, applicable to also the vast range of other astrospheres in our galaxy, represents one of the most outstanding problems in space physics today. Beyond the heliosphere, the unexplored local interstellar medium (LISM) presents a completely new territory that is decisive for the heliospheric interaction and holds the key for understanding our home in the galaxy.

Heliophysics is a unique discipline that has brought us, robotically, to the farthest reaches of space. Voyager 1 and 2 have pushed the boundaries of heliophysics across the threshold of interstellar space, where they have uncovered a new regime of space physics defined by the vast scales of the heliospheric boundary and the extreme mean-free paths of interstellar neutrals and energetic particles. Remote observations[1] have revealed global features from the heliospheric boundary that are still seeking explanations. Observations of absorption spectra have discovered that our Sun recently entered the Local Interstellar Cloud[2] and is now transitioning into a completely new environment of interstellar space[3]. With these discoveries, the quest of heliophysics to understand our home in the galaxy has expanded the frontier of space exploration and, inevitably is becoming agnostic of pre-defined scientific disciplines.

Already during the Termination Shock (TS) crossings, Voyager 1 and 2 revealed a completely new nature of shocks never encountered before. Instead of the anticipated heating of the solar wind plasma, most of the energy was transferred to the more energetic pick-up ions (PUIs) residing in an energy range not measured by the Voyager instruments[4], an interpretation also complicated by insufficient measurements of the plasma distribution. Therefore, the mechanisms responsible for upholding the force balance of the entire heliosheath (HS) against the LISM are still elusive. During the historical crossings of the Heliopause (HP), almost no change in the direction of the magnetic field was observed [5, 6]. Significant differences between the two crossings indicated also large-scale asymmetries of the HS and instabilities acting at the HP in only one of the crossings [6]. Hence, both the unperturbed Interstellar Magnetic Field (ISMF) and the fundamental nature of the HP remain unsolved puzzles. Now at 150 AU, Voyager 1 is still detecting variations in galactic cosmic ray anisotropies indicating solar disturbances propagating well beyond the HP, making it very likely that the projected end of Voyager 1 at around ~170 AU will not be able to determine how far the heliospheric influence extends.

All knowledge of the unperturbed LISM are *average* basic properties inferred from absorption spectra towards the nearest stars, and from measurements of interstellar gas, Pick-Up Ions (PUIs) and dust penetrating the heliosphere. New evidence is mounting that the heliosphere is in contact with four interstellar clouds with different properties and is leaving the Local Interstellar Cloud within relatively short galactic time scales [3] - a “galactic event” of sorts. Humanity’s step into this unexplored region of space would offer the first sampling of unprocessed particles and dust that hold the key to understanding the heliospheric interaction, the interstellar cloud environment, nucleosynthesis and generally the chemical evolution of the galaxy.

Several missions have been seeking remote information about the surrounding boundary and LISM from deep inside the heliosphere. Using Energetic Neutral Atom (ENA) imaging, IBEX and Cassini made the tantalizing discoveries of a “ribbon” or “belt” [7, 8], with some evidence for constraining the ISMF. The observations from the two instruments have resulted in seemingly contradictory conclusions on the global shape of the heliosphere[1, 9], which illustrates the difficult task of retrieving the 3D structure from a vantage point inside the heliosphere. From 1 AU, the IMAP mission will characterize the ENA morphologies and dynamics, and the interstellar neutral gas flow at unprecedented resolution, which will be critical in guiding the future exploration of the outer heliosphere and LISM. Imaging in the energy range of 0.2 – 10's keV are crucial for understanding the plasma processes responsible for and location of the enigmatic ribbon and belt. At higher energies, ENA imaging provides remote access to the crucial energy range that dominates the force balance in the heliosheath and is expected to reveal the global shape of the heliosheath due to the longer lifetimes of convecting ions. Therefore, ENA imaging from a changing vantage point along an outward trajectory to well beyond the HP would provide definitive observations of the global shape of the heliosphere[10] and also will be less affected by signal modulation caused by solar wind charge exchange and photo ionization.

Despite the governing importance of neutral H in forming the heliospheric boundary, the nature of interstellar H remains elusive. Voyager 1 and 2, and New Horizons have provided the first Ly-α intensity observations in the outer heliosphere revealing an excess emission that cannot be explained by these observations alone. Spectroscopic Ly-α measurements at large distances are needed to gain access to the vital charge-exchange processes by resolving the H density and velocity of the LISM and Hydrogen Wall[11] from the hotter components of the inner and outer heliosheath that represent an important diagnostic of the global structure and the existence of a Bow Shock[12].

Exploration at the heliospheric frontier and beyond is now becoming more accessible due to the availability of large launch vehicles. Using conventional propulsion and Jupiter gravity assist, the TS can be reached in less than 12 years followed by a four-year traversal of the HS in the general direction of the heliospheric nose. With spacecraft design lifetimes already in excess of 20 years and with 50 years realistically within reach, Heliophysics has therefore arrived at the opportunity to push its frontier in to interstellar space expanding the realm of Solar and Space Physics, and of Space Exploration itself.

Key Science Questions	**Key Measurements**
What constitutes the force balance in the heliosheath? What are the mechanisms acting at the TS, HS, HP, and beyond?	Magnetic fields, plasma, PUIs, energetic particles and Anomalous Cosmic Rays (ACR)
How do solar perturbations affect the TS, HS and HP? What is the nature of the Heliopause? How far in to the LISM does the heliospheric influence extend? How are Galactic Cosmic Rays (GCRs) shielded? Is there a Bow Shock?	Magnetic fields, waves, plasma, energetic particles, ACRs, GCRs and nanodust over multiple propagating interaction regions, Ly-α
What is the global shape and dynamics of the heliosphere? What does the ribbon/belt telling us about structure and interaction mechanisms?	Remote ENA imaging (~1 – 100 keV) from 5 to 250 AU over a significant part of the solar cycle. Plasma, PUIs, energetic ions and magnetic fields in the source region.
What is the neutral H distribution in the inner and outer heliosheath, Hydrogen Wall and LISM?	High-resolution Ly-α to separate local from galactic emission
What are the properties of the pristine LISM and how do they dictate the nature of the heliospheric interaction?	Plasma, neutrals, and dust composition; densities, flows and ionization state from inside the heliosphere to 300 AU and beyond

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