Measuring Neutral Hydrogen Properties in the Interplanetary Medium

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Science Recommendations

The recommendation of this white paper is to support development and deployment-to-space of a high-resolution spectrograph in order to distinguish the different populations of H atoms that directly interact at the interface of the heliosheath, the region where the solar wind is subsonic. A required resolution of 3 – 10 km/s at H Lyman-α would suffice for spectrally resolving the line emissions from the local interstellar medium (LISM), inner and outer heliosheath populations, and enable characterization of these populations and their interactions from 1 – 1000 AU. This new science would directly complement the two Voyagers, IBEX, IMAP, New Horizons, and Interstellar Probe mission observations. The scientific yield would directly support NASA goals of understanding how the solar wind behaves near Earth; how the heliosphere interacts with the interstellar medium; and determining what boundaries of the heliosphere look like.

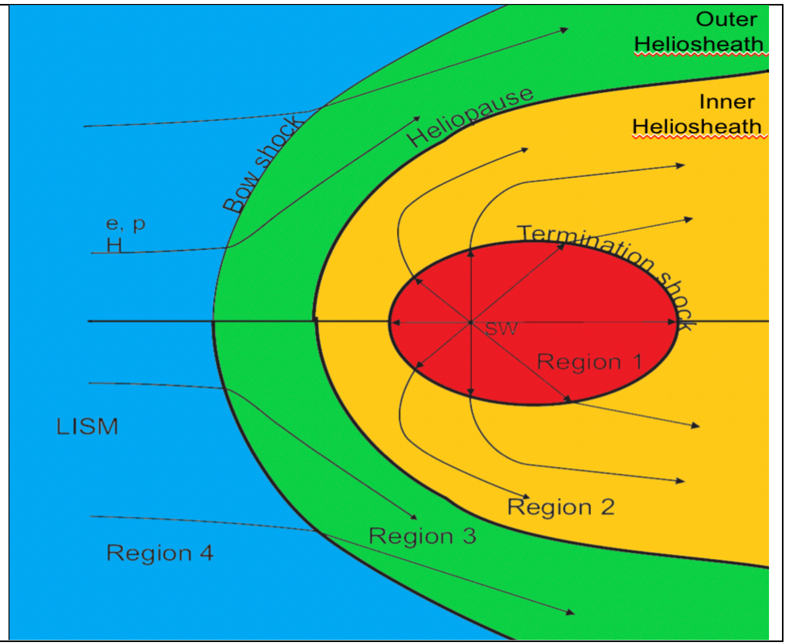
Brief Background & Knowledge Gaps

The motion of the solar system through the local interstellar medium (LISM) carves out a cavity around the Sun known as the heliosphere. The heliosphere is comprised of multiple regions and boundaries (Figure 1). The inner heliosphere contains a relatively hot population of H atoms produced by the Sun such as the solar wind. At the interface region between the heliosphere and the LISM, some neutral H atoms of interstellar origin directly penetrate into the heliosphere. Other interstellar protons charge exchange with interstellar neutral H atoms before entering the heliosphere. Additional populations of H atoms are produced by charge exchange throughout the heliosphere.

The different populations of neutral H atoms of solar and interstellar origin that occupy the heliosphere have conventionally been labeled as a single bulk population collectively referred to as Interplanetary Hydrogen (IPH) [Bertaux and Blamont, 1971; Thomas and Krassa, 1971; Quémerais, 2006 and references therein]. The individual populations that form IPH each have different dynamical and thermal properties, determined by their formation mechanisms [Quémerais and Izmodenov, 2002]. These properties are expected to vary with solar distance and solar activity. When monitored over a solar cycle, the differentiation of properties from each population can be used to identify variations in local (solar) processes as well as to determine dynamics of external (interstellar) interactions [e.g., Izmodenov, 2007, Vincent et al., 2014].

Voyager 1 and 2 (V1 and V2), and Interstellar Boundary Explorer (IBEX) [McComas et al. 2009] missions have revolutionized our understanding of the physics of the heliospheric interface and of the interactions of stars with the interstellar medium. Recent investigations have shown discrepancies between observations and theoretical models of interplanetary H atoms. V1 observations showed a perplexing region of near-zero radial plasma velocity upstream of the heliopause within 10-15 AU where the solar wind slows [Krimigis *et al*. 2011], reaching a 'stagnation region'. There have been several explanations for the existence of the stagnation region, such as momentum loss due to charge-exchange reactions of ions with interstellar H atoms that collectively decelerate the inner heliosheath solar wind [Lallement et al., 2014]. An alternative explanation suggests the solar wind magnetic field reversal alters the flow abruptly as the radial velocity of solar wind becomes zero or negative [Opher et al., 2012]. However, current models and theories of observed flows do not reconcile with this (either in magnitude or direction [Opher et al., 2015]), highlighting our lack of understanding of the nature of the heliosheath.

Figure 1: The regions of the heliosphere where H atoms are created through charge exchange with protons include:
- Local Interstellar Medium region (blue) at 26 km/s, 7000 K
- Outer Heliosheath region (green) at 22 km/s, 12000 K
- Inner Heliosheath region (yellow) at 180,000 K
- Supersonic Solar Wind region (red) at ~400 km/s (not observable with UV spectroscopy as they are beyond the Doppler width of solar illuminating flux).



The existence of this region can be mitigated by the presence of an additional neutral H population that originates from charge exchange of LISM protons with neutral H atoms at the stagnation region of the interstellar interface with the outer heliosheath region of the heliosphere (referred to as the 'Hydrogen Wall') [Baranov et al., 1991; Baranov & Malama, 1993, Linsky and Wood, 1996, Wood et al., 2004].

V1 data show a constant Lyman-α intensity measured over ~90-115 AU from the Sun, where one expects a decreasing brightness with increasing distance due to the decreasing solar flux. Voyager and New Horizons both showed an excess of 20-25 R in the Lyman-α emission not predicted by current models [Katushkina et al., 2017]. This excess is not absorbed by interplanetary hydrogen (IPH); therefore, it must consist of high velocity atoms outside the IPH absorbing spectral range. Such a phenomenon could be attributed to a Doppler-shifted population of H atoms with a position and thickness that are consistent with the stagnation region. One explanation for this is to invoke a dense layer of hydrogen at 115-122 AU. This hydrogen population has not been comprehensively considered in models of the heliosphere [Zank et al., 2013].

The explanation for the excess Lyman-α emission considers a significant contribution from the galactic background [Lallement et al., 2011]. The emission can be produced by ionization and subsequent recombination of ISM H atoms either by stellar UV radiation in H^+ regions and/or by collisions in interstellar shocks, and should be concentrated near the galactic plane. Its spectrum and intensity are key parameters to understand the ionizing radiation field in the galaxy, to understand its application as an indicator of star formation rates in other galaxies, and to understand the amount of shocked gas in the LISM.

The IPH spectral features are also key to identifying the interaction of H Lyman-α emission with the well-studied H 21 cm radiation through the Wouthuysen-Field effect. Recent work has set an upper limit to the galactic emission intensity of 40 Rayleighs from modeling of various spacecraft data [Quémerais et al., 2003]. This emission should exhibit two broad peaks (up to 2-3 Angstroms wide) on either side of a saturated core. This theoretical hydrogen population would create emissions on the edge of the red wing spectrum of the IPH line via resonant scattering of solar emission.

Proposed Solutions

The inconsistencies in total H emission brightness between observations and models resulted in a theory of the various populations of neutral H atoms in our heliosphere (Figure 1). An IPH emission in the range of 800-1000 R at 1 AU (lower value near solar minimum), would include multiple spectral components corresponding to: a primary interstellar population, with a bulk velocity of 26 km/s and a temperature close to 7000 K; a secondary population created by charge exchange in the outer heliosheath, with a bulk velocity of 22 km/s and a temperature around 12,000 K; and a tertiary component red-shifted from the main line with a brightness of 25 R.

These inconsistencies around the heliospheric interface can be observationally constrained by new approaches to observations, namely, from high spectral resolution UV measurements that build on knowledge gained from existing UV mapping of H Lyman-α across the sky. This whitepaper is motivated to close the knowledge gaps by consideration of a high-resolution spectrometer (~3 – 10 km/s) [Quémerais et al., 2003], to be flown on a mission to map the heliosphere at H Lyman-α. These measurements would be capable of resolving the momentum exchange in the reactions between the solar wind and Energetic Neutral Atoms (ENAs) that are key to identifying the most important processes and how solar wind flow is modified. This can be done by measuring the velocity spectrum of interplanetary H (IPH) atoms in the Lyman-alpha emission spectral profile. This science is synergistic with IMAP observations of ENA's.

The inflowing ISM neutral atoms can be observed through resonant scattering of solar H Lyman-α emission to determine both the line of sight speed and the velocity distribution of the inflowing atoms after modification by charge exchange in the interface region [Lallement et al. 1993]. These observable characteristics have been used to measure the flow speed of H and He atoms, and to identify line broadening associated with charge exchange reactions in the interface region [Clarke et al., 1995]. The inflowing IPH atoms are known to be a combination of unmodified ISM atoms, the primary population, and a second population created by charge exchange between ISM neutrals and interstellar protons in the interface region, as demonstrated in Figure 2.

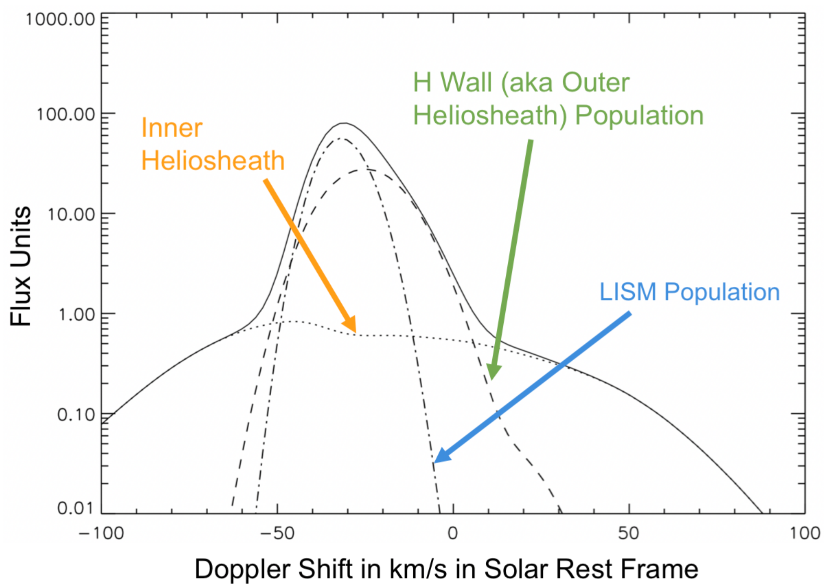


Figure 2: High resolution line profile of IPH [Quémerais and Izmodenov, 2002], in km/s, for an observer at 1 AU, looking upwind. The populations contributing to the total (solid) line shape are: the inner heliosheath atoms (dotted), the outer heliosheath atoms (dash), and the local interstellar medium atoms (dash-dot). Supersonic Solar Wind H population moves at ~400 km/s and is not observable with UV spectroscopy as they are Doppler shifted beyond the width of solar illuminating flux.

A key consideration for these high-spectral resolution observations is their vantage point. Earth-orbiting spacecraft looking away from the planet with UV remote sensing capabilities have an added challenge of mitigating contamination from terrestrial emissions. The geocoronal Lyman-α emission is variable, relatively bright compared with the IPH emission, and is presently uncharacterized. The upcoming Global Lyman-alpha Imagers of the Dynamic Exosphere (GLIDE) mission will be hopping on a ride share on IMAP to the L1 Lagrange point to investigate and identify the properties of geocoronal H[*]. For the recommendation of this whitepaper, a mission targeted beyond the geocorona and headed far from the Sun would be optimal for obtaining the most reliable and revealing signal from IPH emissions. Such an opportunity will be made available with the Interstellar Probe (ISP) mission.

Science Questions

The neutral IPH emissions from resonant scattering of solar Lyman-alpha have been mapped across the sky for decades [e.g., Bertaux et al., 1995; Katushkina et al., 2019]. These maps (shown in Figure 3, for example), coupled with models, have led to valuable findings about the nature of the ISM flow through the heliospheric interface, and of interactions with the solar wind [e.g., Kubiak et al., 2021a; 2021b]. However, the spectral shape of the IPH emission is currently unknown, and holds key information about the properties and various interactions of the different populations of H atoms.

[*] https://www.nasa.gov/press-release/nasa-selects-heliophysics-missions-of-opportunity-for-space-science-research-and

- What is the Hydrogen atom number density in the Local Interstellar Medium?
- What is the Hydrogen velocity distribution in the outer heliosheath?
- What is the Hydrogen secondary (hot) population number density in the inner heliosheath?
- What is the Hydrogen hot population velocity distribution in the inner heliosheath?
- How is momentum exchanged between these populations?
- What do these properties tell us about the interactional dynamics of the individual populations?

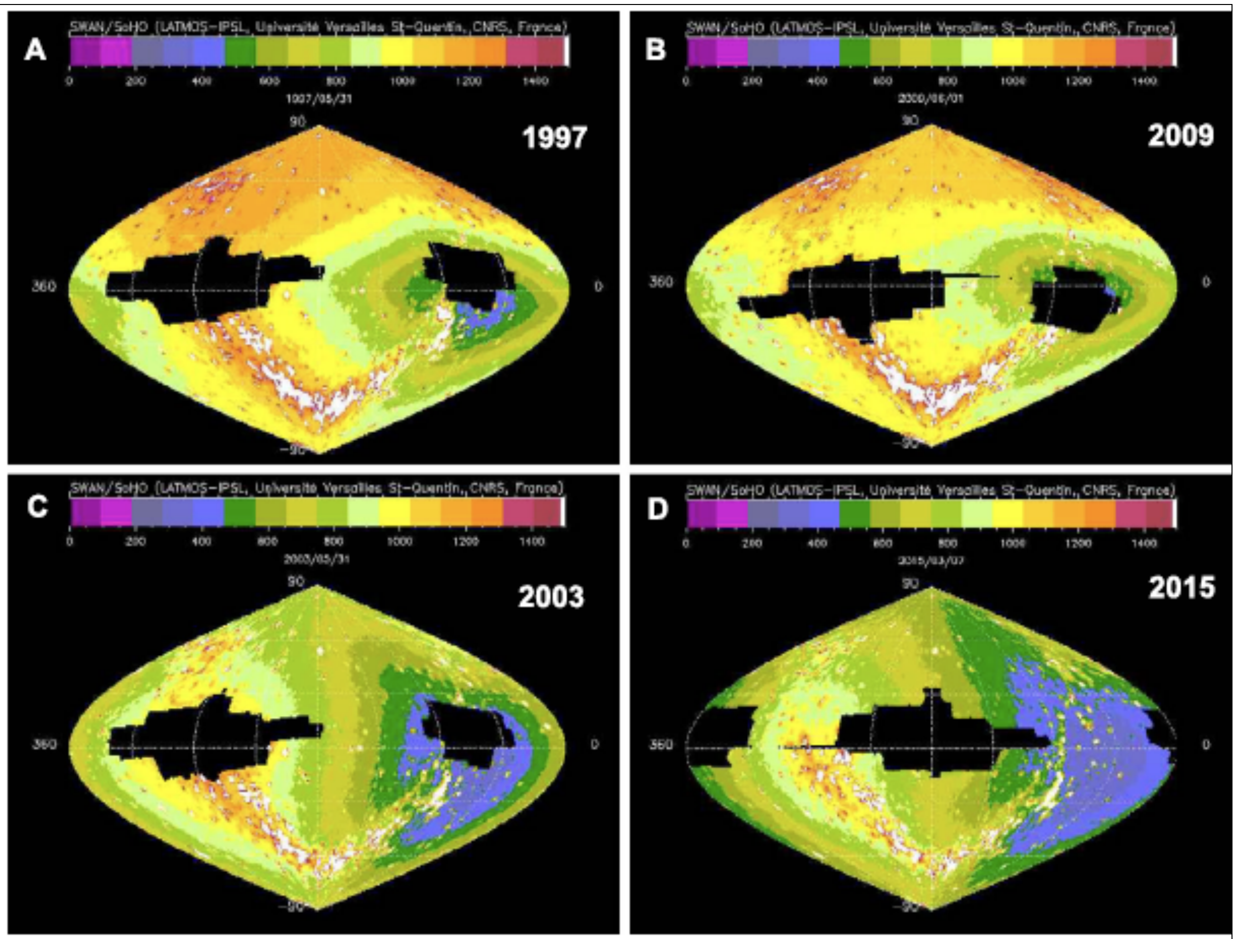


Figure 3. SOHO/SWAN full-sky maps of the backscattered solar Lyman-α intensity, shown for four years of solar activity extrema. Top row shows solar minimum scenarios from 1997 and 2009. Bottom row shows solar maximum scenario from 2003 and 2015. Figure from Katushkina et al., 2019. Maps also available online at http://swan.projet.latmos.ipsl.fr.

Hydrogen atoms are observed by solar resonant scattering of photons at Lyman-α (1215.67 Å). By obtaining and analyzing the UV emission spectra of IPH, one can determine the number density, flow velocity and thermal broadening of H atoms in the heliosphere. In theory, and with fine spectral resolution, the different H populations within the collective interplanetary flow should be resolvable. Figure 2 shows a theoretical depiction of the main H atoms populations that contribute to the total IPH Lyman-α spectrum, when looking upwind into the bulk IPH flow.

The upwind direction of this flow is the ‘nose’ of the heliosphere, at ~250° ecliptic longitude and ~5° ecliptic latitude [McComas et al., 2015; Witte, 2004].

Relative to the solar rest frame, H atoms in the local interstellar medium (LISM) flow at ~26 km/s, with a temperature of ~7000 K [Vincent et al., 2011]. H atoms from the outer heliosheath (aka, hydrogen wall) that have charge exchanged with interstellar protons in the interface region travel at ~22 km/s, with a temperature of ~12000 K [Katushkina et al., 2016; 2017; Gladstone et al., 2018]. H atoms in the inner heliosheath reach temperatures of ~180000 K, and encompass a broad range of velocities [Quémerais and Izmodenov, 2002]. Solar wind H atoms are generated by charge exchange with solar wind protons and are supersonic (~450 km/s). At these velocities, the solar wind H atoms are Doppler shifted out the solar Lyman-α line and cannot be detected via IPH spectral observations.

The high-resolution spectra, simulated in Figure 2, will tackle these questions. The H number density from each population (LISM, outer heliosphere, and inner heliosphere) can be separated from the galactic emission with a resolution of 3 – 10 km/s. The line profile measurements would provide the distribution of atoms from each population, thereby quantifying: number density, velocity distribution, temperature, and subsequently, the momentum exchange in the reactions that identify how the flow is modified.

Goals for Scientific Community Diversity

The Heliophysics program at NASA has been a leader in constructing paradigms that are oriented toward limiting implicit bias. Implementation of dual-anonymous reviews in select program calls has been an excellent starting point. However, there remains much to be done to ‘level the playing field’. It is critical over the next decade to continue to improve diversity in NASA-sponsored program PIs as well as the greater scientific community.

Recommended initiatives to support the goal of community diversity include:
- further expansion of dual-anonymous reviews into other Heliosphysics program elements,
- publicizing data for funding selections’ PI demographics to support further improvements,
- establishing program elements that specifically support under-represented communities, and
- encouraging education and public outreach to diverse communities as a fundamental component of sponsored programs.

Synergies within the Heliophysics Community

Many of the scientific recommendations described in this White Paper are synergistic with ideas articulated in several other community whitepapers submitted to this decadal survey. At the time of this writing, specific synergistic ideas include:

- Solar Environment as Driving and Constraining Factor in the Study of the Heliosphere and the Local Interstellar Medium, by *Justyna M. Sokół et al.*

- Expanding the Realm of Solar and Space Physics: Exploration of the Outer Heliosphere and Local Interstellar Medium, by *Pontus Brandt et al.*
- The potential of the Interstellar Probe for measuring in-situ interstellar neutrals, by *Andre Galli et al.*
- What Lies Outside of the Heliopause: Connecting the Outer Heliosphere with the Interstellar Medium, by *Linsky and Redfield*

Visions for the next Decade

- Support research and development of space-ready instruments capable of making remote sensing measurements of the outer heliosphere neutral H population.
- Support flight opportunities for such instrumentation throughout the heliosphere.
- Support design and development of empirical-based numerical models that use multi-point spacecraft measurements.
- Support research opportunities, training, and development of a diverse community of NASA-funded scientist. Diversity includes individuals of various gender identities, ethnic identities, social identities, economic backgrounds, religious identities, chronological ages, sexual identities, career stages, etc., to more reasonably reflect population demographics.

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