

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 three 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 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 ISP mission observations. The recommended science 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 interstellar medium (ISM) carves out a cavity in the plasma known as the heliosphere. Voyager 1 and 2 (V1 and V2), and Interstellar Boundary Explorer (IBEX)¹ missions have revolutionized our understanding of the physics of the heliospheric interface and of the interactions of stars with the interstellar medium. V1 observations showed a perplexing region of near-zero radial plasma velocity upstream of the heliopause within 10-15 AU where the solar wind slows², 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 wind³. An alternative explanation suggests the solar wind magnetic field reversal alters the flow abruptly as the radial velocity of solar wind becomes zero or negative⁴. However, current models and theories of observed flows do not reconcile with this (either in magnitude or direction⁵), highlighting our lack of understanding of the nature of the heliosheath.

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 models⁶. 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 heliosphere⁷.

The explanation for the excess Lyman- α emission considers a significant contribution from the galactic backgrounds⁸. The emission can be produced by ionization and subsequent recombination

¹ McComas *et al.* 2009

² Krimigis *et al.* 2011

³ Lallement *et al.*, 2012

⁴ Opher *et al.*, 2012

⁵ Opher *et al.* 2015

⁶ Katushkina *et al.*, 2017

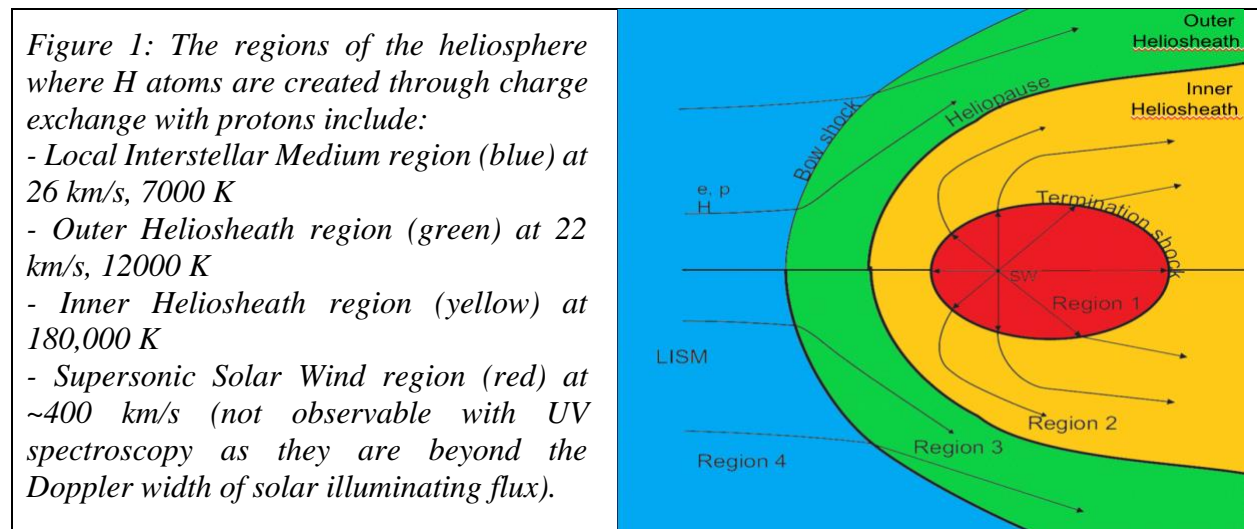
⁷ Zank *et al.*, 2013

⁸ Lallement *et al.* 2011

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 ISM. It is 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 data⁹. 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 km/s)⁶, 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

⁹ Quémérais *et al.* 2003

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 region¹⁰. 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 region¹¹. The inflowing IPH atoms are known to be a combination of unmodified ISM atoms and a second population modified by charge exchange between ISM neutrals and interstellar protons in the interface region.

Science Questions

The neutral IPH emissions from resonant scattering of solar Lyman-alpha have been mapped across the sky for decades. These maps, 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. 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.

- What is the Hydrogen atom number density in the Local Interstellar Medium?
- What is the Hydrogen distribution in the outer heliosheath?
- What is the Hydrogen hot population distribution in the inner heliosheath?
- How is momentum exchanged between these populations?
- What do these properties signify about the interactional dynamics of the three populations?

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 3-5 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.

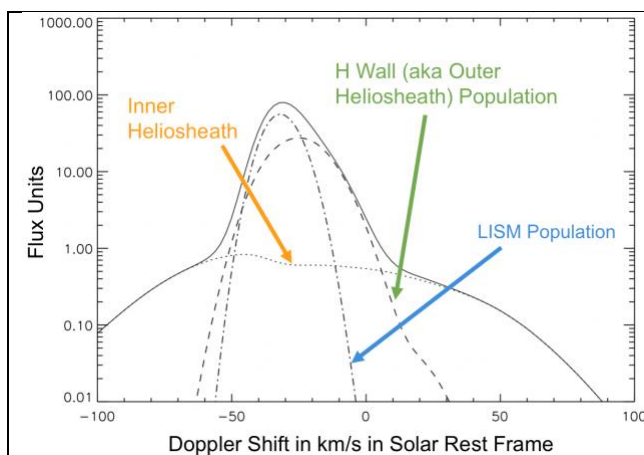


Figure 2: High resolution line profile of IPH¹², in km/s, for an observer at 1 AU, looking upwind. The populations contributing to the total (solid) line shape are: the inner heliosheath atoms (dotted), the outer heliosheath atoms (dash), and the local interstellar medium atoms (dash-dot). Supersonic 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.

¹⁰ Lallement *et al.* 1993

¹¹ Clarke *et al.* 1995

¹² Quémerais and Izmodenov, 2002