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EDITED BY
Alexa Jean Halford,
National Aeronautics and Space
Administration, United States

REVIEWED BY
Martin Snow,
South African National Space Agency,
South Africa

*CORRESPONDENCE
Majd Mayyasi,
majdm@bu.edu

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Using Lyman- α to probe the interior and edges of the heliosphere

Majd Mayyasi^{1*}, Eric Quémerais², Olga Katushkina³,
John Clarke¹, Vlad Izmodenov^{1,3}, Pontus Brandt⁴,
Justyna Sokol⁴, Jeffry Linsky⁵ and Igor Baliukin³

¹Center for Space Physics, Boston University, Boston, MA, United States, ²LATMOS/IPSL, Guyancourt, Paris, France, ³Space Research Institute of Russian Academy of Sciences, Moscow, Russia, ⁴Johns Hopkins University Applied Physics Laboratory, Laurel, MD, United States, ⁵University of Colorado Boulder, Boulder, CO, United States

Understanding the role of neutral atoms in the heliospheric interface (between the bow shock and heliopause) is critical to identifying dynamics within our local bubble. This article recommends building upon existing measurements with new, high-spectral resolution observations of H Lyman- α , from a heliospheric mapping mission, to resolve the momentum exchange in reactions between the solar wind and energetic neutral atoms that are key to identifying the most important heliospheric processes.

KEYWORDS

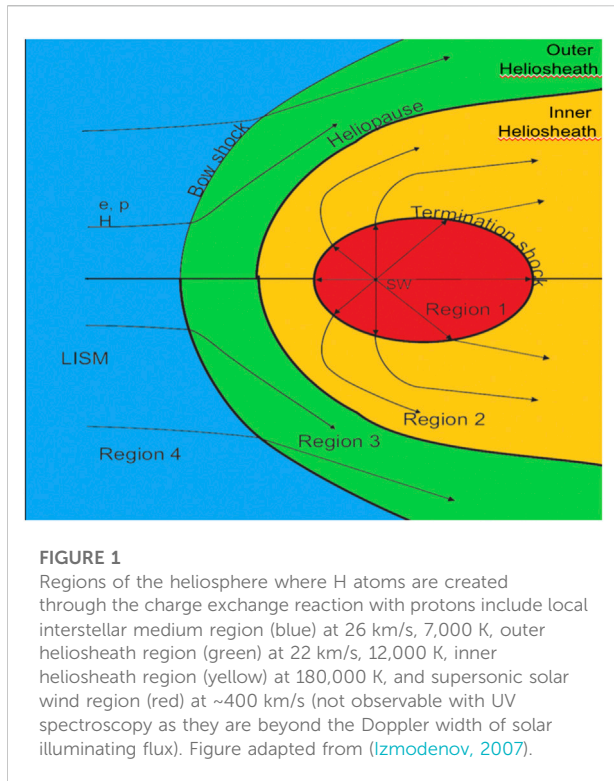
heliosphere, spectrograph, interplanetary hydrogen, Lyman alpha, Sun

Introduction

The motion of the Solar System through the interstellar medium (ISM) carves out a cavity in the plasma known as the heliosphere. Voyagers 1 and 2 (V1 and V2) and Interstellar Boundary Explorer (IBEX) (Broadfoot et al., 1977; McComas et al., 2009) missions have revolutionized our understanding of the physics of the heliospheric interface and 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 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., 2012). An alternative explanation suggests that 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.

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 our galaxy, to understand its application as an indicator of star formation rates that can be extrapolated to inform us of 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 Rayleigh from modeling of various spacecraft data (Quémerais et al., 2003). This

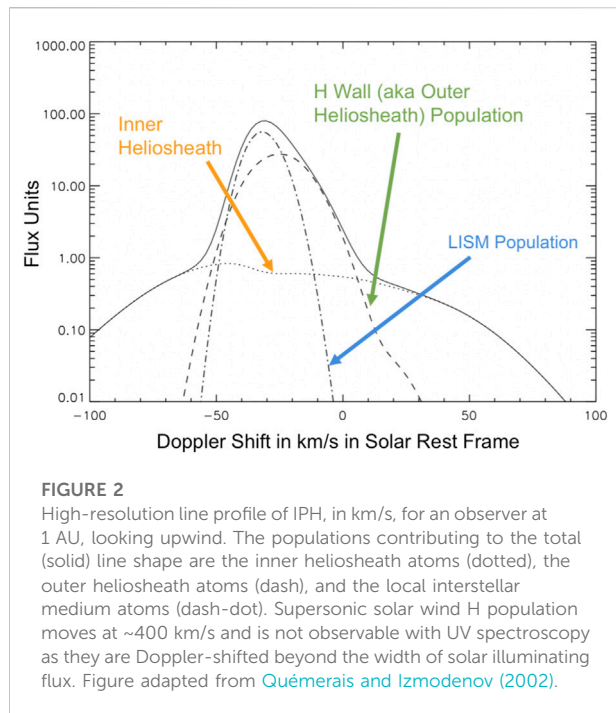
emission should exhibit two broad peaks (up to 2–3 Å wide) on either side of a saturated core. This theoretical hydrogen population would create emissions on the edge of the red wing spectrum of the IPH line *via* the resonant scattering of solar Lyman- α .

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 800–1,000 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 7,000 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 article motivates closing the knowledge gaps by considering a high-resolution spectrometer (~3 km/s) (Katushkina et al., 2017) to be flown on a mission to map the heliosphere at H Lyman- α . Such a spectrometer would be effective when placed at various locations (e.g., low Earth orbit or the L1 Lagrange point) and would be optimal on a cross-solar system mission, where IPH properties would vary as the measurements progress from inner to outer heliospheric distances. The resulting measurements would be capable of resolving the momentum exchange in the reactions between the solar wind and energetic neutral atoms (ENAs) which are key to identifying the most important processes and how solar wind flow is modified. This can be carried out by measuring the velocity spectrum of interplanetary hydrogen (IPH) atoms in the Lyman- α emission spectral profile. This science is synergistic with IMAP observations of ENAs.

The inflowing ISM neutral atoms can be observed through the 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 the 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 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 the resonant scattering of solar Lyman- α 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](#), would 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 the number density, velocity distribution, temperature, and, subsequently, the momentum exchange in the reactions that identify how the flow is modified.

Conclusion

The recommendation of this article is to support the 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) and inner and outer heliosheath populations, allowing characterization of these populations and their interactions from 1–1,000 AU. This new science would be highly suitable for a future interstellar probe mission and would directly complement observations from the two Voyagers, IBEX, IMAP, and New Horizons ([Brandt et al., 2022](#); [McNutt et al., 2022](#)). The recommended science yield would directly support NASA's goals of understanding how the solar wind behaves near Earth, how the heliosphere interacts with the interstellar medium, and determining what the boundaries of the heliosphere look like.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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