Measurements Beyond 1 au are Necessary for Exploration of the Outer Heliosphere and Local Interstellar Medium

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1. Synopsis

Heliospheric missions operating in the outer heliosphere and beyond are necessary for understanding the heliosphere and its interstellar neighborhood.

Interstellar neutrals (ISNs), pickup ions (PUIs; ionized ISNs picked up by the local plasma fields), and energetic neutral atoms (ENAs; neutralized PUIs and solar wind ions) provide information about the interstellar medium, the global heliosphere, and processes at the transition region between solar and interstellar environments. These heliospheric data are usually collected from the vicinity of the Earth. Thus, they require careful and thoughtful interpretation of the observed signals and implementation of proper corrections for modulation by the solar environment. Interpretation is complicated because the solar wind and solar extreme ultraviolet (EUV) radiation ionize the incoming flux of interstellar particles measured near the Earth’s orbit. The ionization rates vary depending on species and phase of solar activity. Hydrogen, the most abundant element, is the most prone to the modulation by the solar environment and undergoes the greatest losses inside the heliosphere. High ionization rates and radiation pressure create a density depletion region for ISN H at a few astronomical units from the Sun. The last decades provided strong arguments for measurements at least outside this cavity (beyond Jupiter’s orbit) to mitigate the adverse solar environment losses for the fluxes of interstellar-born particles. In-situ heliospheric measurements far beyond 1 au should be a priority for the heliospheric community in the coming decades to make progress in data interpretation, improve quality of the observations, and advance our understanding of the heliosphere and its interstellar neighborhood.
2. Background

The heliosphere, a result of solar plasma outflow from the Sun into the surrounding interstellar medium, is a fundamental subject of numerous studies and observations. Understanding our heliosphere through direct exploration provides means for reaching out to distant exoplanetary systems and their interpretation by remote observations. The advanced understanding of the heliosphere is achieved through a combination of both in-situ and remote observations from different vantage points across the heliosphere. Remote sensing of the heliosphere is a powerful diagnostic method; however, it is also limited because it is typically conducted from close distances to the Sun. With present-day technology, we are ready to leave 1 au and move our heliospheric laboratories to the outer heliosphere, where we are not blinded by the Sun and its environment.

Measurements from past and ongoing missions such as, e.g., Ulysses, Cassini, IBEX, New Horizons, and Voyager (to list only a few) expand our knowledge about the heliosphere, its structure and properties, solar wind and activity dependence, its interaction with the local interstellar medium (LISM), and the LISM itself. The solar environment, defined by processes in a space filled with solar wind plasma, electromagnetic field, and solar ultraviolet radiation, plays a crucial role in the planning of research targets, instrumentation design, and our interpretation of the measurements. Solar wind and EUV fluxes ionize interstellar atoms flowing into the heliosphere. The newly ionized atoms are then picked up by the solar plasma fields as PUIs. Both, ISNs and PUIs, have been measured close to Earth’s orbit by instruments onboard missions such as Ulysses, IBEX, ACE, and STEREO, to list just a few [1, 2, 36, 37, 38]. However, ionization losses vary depending on species and phase of solar activity [3]. Hydrogen, the most abundant species, is the most prone to the solar environment and undergoes the greatest losses. It also is sensitive to the (repulsive) radiation pressure which further depletes the incoming flux [4]. These two processes create a density depletion at a few astronomical units from the Sun [4, 5]. The density of interstellar hydrogen is significantly reduced from the values at the heliospheric termination shock, leaving only about 2% of the atoms at 1 au (Fig. 1) [5]. Among the other interstellar atoms observed at 1 au (e.g., He, Ne, O, D), oxygen is reduced to ~8%, neon to ~45%, and helium to ~82% (Fig. 1) [5]. These numbers are for the solar minimum conditions which are favorable for the measurements of ISNs from close distances to the Sun because of low ionization rates. During
solar maximum, when the solar environment is more active and the ionization rates are higher, the fluxes are further reduced. These severe losses significantly affect the scientific interpretation of the measurements [6, 7, 8, 16, 17, 18].

The higher the energy of atoms, the smaller the ionization losses for them, because the travel time of these atoms through the heliosphere is short and subsequently the exposure to the solar ionizing radiation is low. However, as H ENA observations show, solar wind affects the production of ENAs significantly. Solar wind shapes the heliosphere (shape, size, structure) and organizes the processes in its boundary regions. The latitudinal variation of the solar wind outflow and the variation due to the solar activity cycle is reflected in the global structure of the heliosphere observed by ENAs [9, 10, 11, 27, 28, 32]. The dual role of the solar environment in the study of the global heliosphere is unquestionable.

3. Key Drivers

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<td>Predicted by models and measured by Cassini [12], Voyager [13], New Horizons (distance dependence, [14, 15]), and IBEX-Lo (solar cycle dependence, [16])</td>
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<td>Interpretation of heavy element species of ISNs measured at 1 au is sensitive to details of ionization models [8, 19, 20]. Determination of the Ne/O and D/H ratios from 1 au is difficult and uncertain [20, 21].</td>
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**Hydrogen Depletion Region:** A region around the Sun where the solar environment significantly depletes the flux of interstellar hydrogen has been estimated to expand from about 4 au upwind to several au downwind from the Sun [4, 5]. Cassini measured the depletion region for interstellar hydrogen through H$^+$ PUIs on its way through the focusing cone to the outer heliosphere (Fig. 2) [12]. Since 2009, IBEX-Lo has measured the ISN H at 1 au and has observed a significant decrease in its flux during the solar maximum, when the ionization rates and the radiation pressure are the highest [16]. New Horizons observes a continuous increase of H$^+$ PUIs at increasing distances from the Sun [14, 15]. The solar environment significantly limits the capability to measure the ISN H at 1 au, and measurements from greater distances confirm that we need to move our instrumentation to at least outside Jupiter’s orbit.

**ISN H Density in the Outer Heliosphere:** New Horizons, which currently operates in the outer heliosphere at ~54 au in an excellent condition, has successfully surveyed the outer heliosphere at solar distances greater than 20 au from the Sun [35]. Its measurements of H$^+$ PUIs indicate that ISN H density is higher by ~40% than the values determined from Ulysses' observations at 5 au.
This finding indicates that measurements at the boundary of the density depletion region (e.g., 1 to 5 au) result in large uncertainties in data interpretation. The farther away from the Sun, the more accurate the data interpretation and our understanding of the processes in the heliosphere.

**ISN H Observations vs. Models:** *IBEX-Lo* successfully measures H ENAs and ISNs. However, the models to interpret the data do not support the observations [18, 25]. The inability to fully reconstruct the observations indicates that either the measured fluxes are too low to provide reliable scientific interpretation of the data (e.g., ISN H) or the models are missing some components that impede data reproduction (e.g., H ENA). *Conducting observations at distances where the flux is not severely depleted by the solar environment should resolve numerous issues.*

**Radiation Pressure Affects the Data:** As highlighted by the study of ISN H flux measured by *IBEX-Lo*, solar radiation pressure in the Lyman-alpha line plays a crucial role in understanding the data [17, 18, 25]. However, the most significant changes in the flux due to the radiation pressure occur a few astronomical units before the detection. *Thus, moving observations outside the significant influences of the radiation pressure should improve both data quality and model interpretation.*

**Interstellar Elements Other Than H:** In addition to H and He, the interstellar wind through the heliosphere contains small amounts of Ne, O, and D, which are detectable from 1 au, as *IBEX-Lo* demonstrated [19, 20, 21]. However, the fluxes are either too low to detect [21] or sensitive to details of models used to interpret them, e.g., the adopted model of ionization rates affects the results [8, 19, 20]. *Thus placing detectors at distances from the Sun where the particle fluxes are less depleted and the ionization losses are negligible increases the scientific success of the multi-area studies including on the origin and the interstellar neighborhood of the Solar System through the study of abundances of various elements (e.g., D/H).*

**Interstellar PUIs:** Interstellar neutral atoms enter the heliosphere and through interaction with the solar environment are converted to PUIs. So far, only H$^+$ and He$^+$ PUIs have been explored. The maximum densities for Ne$^+$ and O$^+$ PUIs are expected beyond the Earth’s orbit (Fig. 2) [5]. *To thoroughly study heavy species coming from LISM, and thus to investigate the composition of LISM, measurements far beyond 1 au are needed.*

**ENA Image of the Heliosphere:** Observations of ENA fluxes by *IBEX* at 1 au [9, 22] and *Cassini/INCA* at 10 au [23] allows for remote sensing of the processes at the heliospheric
boundaries. They both provide full-sky images of ENA flux although in different energy ranges [29, 30]. However, the conclusions about the global shape of the heliosphere from their measurements are different. *INCA* observed high energy ENAs at distances from the Sun where the solar environment has negligible impact on the measured fluxes. *IBEX* operates closer to the Sun and collects atoms at an energy range that requires them to have been on a journey from the ENA source from a few months (*IBEX-Hi*) to years (*IBEX-Lo*) before detection. This means that the ENA flux measured by *IBEX* is modulated by the solar environment more than on *Cassini*. Do these differences in exposure to the solar environment create a gap in our understanding of the heliosphere?

In addition, the measurements of ENAs are affected by geometric ambiguity. The available ENA measurements provide sampling points of a 3D object (i.e., the shape of the heliosphere) from the inside of its gravity center. These ENA measurements are line-of-sight integrated measurements, and it is very difficult to distinguish their brightness from the thickness of their source. Consequently, we do not know where along the line of sight the emission is the strongest. **Simultaneous observations from different vantage points along an outer heliosphere or interstellar probe could resolve these ambiguities.**

**Hydrogen Helioglow Sky Maps:** The backscatter solar Lyman-alpha radiation measured by *SOHO/SWAN* reveals unexpected behavior of solar wind mass flux during solar maximum [24]. An enhancement of intensity appears at mid-latitudes at both hemispheres and its cause remains unclear when compared to the models and independent data. *Is there missing physics in our understanding of the hydrogen distribution inside the heliosphere, when interpreting measurements from 1 au?*

**Take away:** The last decades brought a number of breathtaking discoveries in the exploration of the heliosphere. They also opened new exciting science questions which await answering. For many of these questions, only **measurements from the outer heliosphere will provide satisfactory answers (Fig. 3).**

![Figure 3](image-url)

**Figure 3:** It is time to move the exploration of the heliosphere beyond 1 au. *With a combination of in-situ and remote sensing observations at different vantage points and distances from the Sun, we can study the heliosphere as one complete system.*
4. Science Questions

**To What Extent Does The Solar Environment Affect Heliospheric Observations?**

The solar environment affects the interstellar particles inside the heliosphere by continuous temporal and spatial modulation. **To find out how the Sun affects the dynamics of the heliosphere, we need a combination of in-situ and remote sensing measurements from different locations throughout the heliosphere.** Progress in this avenue is attainable only by mitigating the adverse modulation of the measured signal by the solar wind and EUV radiation which are very significant at 1 au. For ISNs and ENAs, the farther away from the Sun they are measured, the less the fluxes are attenuated and modulated by the solar environment. The fluxes of interstellar PUIs have their maxima at several au from the Sun depending on species and phase of solar activity. In addition, having simultaneous observations from 1 au and further distances from the Sun (e.g., 10, 30, 50, 70 au) allows us to distinguish between local variation which depends on the solar environment, and the variations typical for the source of the measured particles.

**What Are The Preferred Locations For Observations From Inside The Heliosphere?**

Going outside the density depletion region reduces the uncertainties from model-dependent data interpretation and opens new possibilities. Additionally, it provides a link for the study of the heliosphere where gaps still exist (solar distances greater than 1 au). **Missions operating at distances greater than Jupiter's orbit seem to be most suitable for future heliospheric observations (Fig. 1).** Beyond 20 au, the variability in the solar wind parameters (density, speed, and temperature) is very low because the solar wind structures have been worn down and merged [33, 34]. Therefore, observations at about 30 au and beyond seem to be preferable for measurements of the steady solar wind, PUIs, ENAs, and ISNs. Moreover, simultaneous observations from multiple locations at different distances from the Sun will allow for disentanglement of the ionization processes and densities of ISN atoms and their influence on PUIs and the PUI mediation of the plasma inside the heliosphere. Moreover, they will provide data about the radial dependence of the solar wind and the solar environment, providing answers to the question of the global nature of the heliosphere. The preferred locations for the direct and remote observations depend on the scientific objective. The question then remains: Which locations are the best for which particles?

**What Drives ISN Density Variations in the Heliosphere’s Surroundings?**

The density of ISNs is an elementary parameter in the study of the heliosphere’s nature, properties of the LISM, and processes in the heliosheath. Without it, we will keep struggling with the model-dependent understanding of the heliosphere where a slight change of one parameter reorganizes the whole picture and we will not be able to unravel the nature of the nearby interstellar medium.
5. Recommendations

**RECOMMENDATIONS**

- **Observations from the Outer Heliosphere and LISM**
  A combination of in-situ and remote sensing observations of ISNs, PUIs, ENAs, and the solar wind throughout the heliosphere toward the LISM are necessary to advance our understanding of the heliosphere and the local interstellar environment, e.g., those proposed by the Interstellar Probe mission concept [26, 31]. At a minimum, measurements at distances at least greater than 5 au are necessary; however, continuous measurements far beyond 1 au up to the LISM would greatly advance the physics of the heliosphere as a one system. The regions of the outer heliosphere, in and beyond the orbits of the giant planets provide easy access to remote sensing of the heliosphere and interstellar medium free from obstacles present at 1 au.

- **Multi-Vantage Point Observations**
  Simultaneous measurements from several spacecraft radially and spatially distributed in the outer heliosphere (from 1 au up to the LISM) will provide information about spatial variation of the solar environment, e.g., the solar wind slow-down and heating, fading out of the effective ionization rates, and radial dependence of the radiation pressure. Measurements at multiple locations are needed to understand the overall size and shape of the heliosphere, as well as the processes throughout the heliosphere and the interconnection between them.

- **Interdisciplinary Opportunity**
  Observations from distances from Jupiter’s (~5 au) out to Uranus’ (~20 au) and Neptune’s (~30 au) orbits will explore the region of the heliosphere hitherto almost unexplored for ISNs, PUIs, and ENAs. This region is strategic for a heliospheric mission, because it allows measurements beyond the density depletion region, in reduced solar ionization, and in high fluxes of interstellar particles. One possibility would comprise a constellation of small spacecraft (heliosats) with similar heliospheric payload necessary to study the solar and interstellar plasma distributed throughout the outer heliosphere in the upwind hemisphere. Heliospheric mission in the outer heliosphere also is an opportunity to link heliospheric goals with planetary and astrophysics goals and move our space laboratories to the distances of the giant planets and beyond toward the interstellar medium.

- **Measurement Recommendations**
  Heliospheric mission operating in the outer heliosphere and beyond will provide scientific success with a payload including ISN and ENA detectors (to probe energies from 10 eV and above), neutral gas mass spectrometer [28], PUI detector, proton and electron probes, and electromagnetic field measurements.
References:

21. Rodríguez Moreno et al. 2014, Entropy, 16(2), 1134-1168, 10.3390/e16021134
23. Dialynas et al. 2017, Nat Astron 1, 0115, 10.1038/s41550-017-0115
34. Richardson et al. 2019, SSRv, 218, 4, 10.1007/s11214-022-00899-y
35. Stern et al. 2018, SSRv, 214, 4, 10.1007/s11214-018-0507-4
36. Gleocker et al. 1998, SSRv, 86, 497, 10.1023/A:1005036131689
37. Gleocker et al. 1998, SSRv, 86, 127, 10.1023/A:1005019628054