Sensing the Shape and Global Structure of the Heliosphere

R. DeMajistre, P.C. Brandt, D.G. Mitchell, R. McNutt, E.C. Roelof, E. Provornikova, M. Gkioulidou, P.S. Mostafavi, R. Nikoukar, J. Westlake, M. Opher, K. Dialynas, M. Kornblueth, A. Galli, M. Gruntman, D. Reisenfeld, M. Kubiak, J. M. Sokół, S. Fuselier

The solar system is encased in a magnetic bubble created by the expanding solar wind. As it plows through galactic space, the properties of the solar wind and the interstellar environment shape this heliosphere (or more generally, astrosphere). The complex processes at its interface shield the solar system from the very high energy cosmic rays that otherwise would have bombarded and affected the chemical evolution of the planetary atmospheres. Despite its crucial importance for understanding the physics and habitability of our astrosphere and others out there, its global structure and plasma processes continue to be mysteries.

Current status

The first direct measurements of the heliosheath region were made by the Voyagers – Voyager 1 crossed the termination shock (the inner boundary of the heliosheath) in late 2004 when the spacecraft was 94 Astronomical Units (AU) from the Sun, followed by Voyager 2 in 2007 at 84 AU. They traveled through the heliosheath and crossed into the interstellar medium at around 120 AU from the Sun (Voyager 1 in 2012, Voyager 2 in 2018). Both Voyagers are headed in the upwind direction and have revealed a rather thin (25-35AU) heliosheath in this direction (towards the so-called 'nose'). The Voyager data, however, provides us no direct measurements of the shape of the heliosphere towards the tail or the flanks.

For more than a decade, the technique of Energetic Neutral Atom (ENA) imaging has been brought to bear on mapping the structure of the outer heliosphere from vantage points relatively close to the Sun. The first mission dedicated to measuring ENAs from the outer heliosphere, the Interstellar Boundary Explorer (IBEX), was launched in late 2008 and has provided full-sky maps of ENA heliospheric emission for more than a decade. These maps have yielded new information about structures in the outer heliosphere. The INCA instrument aboard the Cassini spacecraft at Saturn (9.5 AU) was also able to provide ENA maps in a different energy range than IBEX. The INCA maps show similar structures as the IBEX data where the energy ranges are close, but at higher energies, the heliosheath appears much more symmetric than in the IBEX-HI range. The Interstellar Mapping and Acceleration Probe (IMAP) mission is currently being developed with a planned launch in 2024. The IMAP spacecraft will host a full suite of ENA measurements covering the energy range of both IBEX and INCA at higher spatial resolution and higher sensitivity from a single vantage point at 1 AU. IMAP will provide definitive maps of ENA fluxes from the heliosheath from 1 AU, and will likely strengthen constraints on its shape made by IBEX and INCA. However, its vantage point close to the Sun will make unambiguous determination of the shape of the heliosphere very difficult –similar to the difficulty in determining the shape of a cloud from an airplane flying through it.

Perhaps the most conspicuous and unexpected feature in the IBEX data is the so-called 'ribbon', which is a circular region of ENA emission, most likely due to a secondary charge exchange interaction beyond the heliopause, nominally perpendicular to the interstellar magnetic field. To date, the mechanism that produces the ribbon has still not been quantified. A mechanism consistent with our understanding of plasma processes has not been found, and data from vantage points other than near the Sun, which is at the center of the system, will be very helpful to refine our understanding of this feature and the processes that cause it.

Current measurements and modeling of the outer heliosphere put important constraints on its shape, though we are still not able to say unambiguously whether it is cometary, bubble shaped, 'croissant-like' shaped - whether it is closed or open, or what processes are operating on different parts of its boundary. Making ENA measurements from beyond the heliopause will allow us to answer these questions directly.

Science Progression – Outstanding science questions

Objective	Measurement	Rational
Unambiguous characterization of the global shape of the heliosphere and its change over solar cycle timescales.	ENA images taken from outside of the heliosheath (>250 AU from the Sun) at energies greater than 40 keV, along a trajectory toward the flank of the heliosphere (see Figure 1.). Further, Imaging of the structure near the ecliptic poles will help us understand how the structure is influenced by the opening of polar coronal holes during the solar cycle.	ENA images taken from a remote vantage point immediately reveal the plasma boundary of the heliosphere (see Figure 1). The source of the ENA emission is charge exchanged non-thermal ions embedded in the plasma. To sense the shape farther away from the nose of the heliosphere, it is necessary to measure ENA from ions that have traveled large distances, that have long charge exchange lifetimes (see Figure 2). The simulations in Figure 1 show that the more remote parts of the heliosheath are most visible at energies > 40 keV.
Identify plasma acceleration regions and other processes that support the shape of the heliosphere.	ENA images taken from outside the heliosheath at energies near 10 keV, where the charge exchange lifetime is relatively short. Images at lower energies (0.1 – 1.0) keV are also useful for evaluating pressure balance in the downwind and flank direction.	The simulated images shown in Figure 1 assume no acceleration sources beyond the termination shock. For this reason, the lower energy images, i.e., where the charge exchange lifetime is relatively short, dim rapidly away from the termination shock. Any regions where plasma might be accelerated beyond a few keV will appear as bright spots against this dim background.
Determine the mechanisms and plasma processes responsible for the IBEX ribbon	ENA measurements of the ribbon near 1 keV (0.1 to 2 keV) at various distances from the Sun	There are several hypotheses for the location and cause of the IBEX ribbon, ranging from near the termination shock to a broad region beyond the heliopause (Figure 3 shows the extent of the source region for the proposed neutral solar wind hypothesis). Observations of the ribbon away from 1 AU will allow us to distinguish between hypotheses through geometric arguments.
	In situ Velocity Distribution Functions near 1 keV in the ribbon source region	The ENA measurements can provide a location of the ribbon emission given multiple vantage points over time, though the mechanisms for this emission (for many of the hypotheses) can only be studied and quantified by in situ measurements

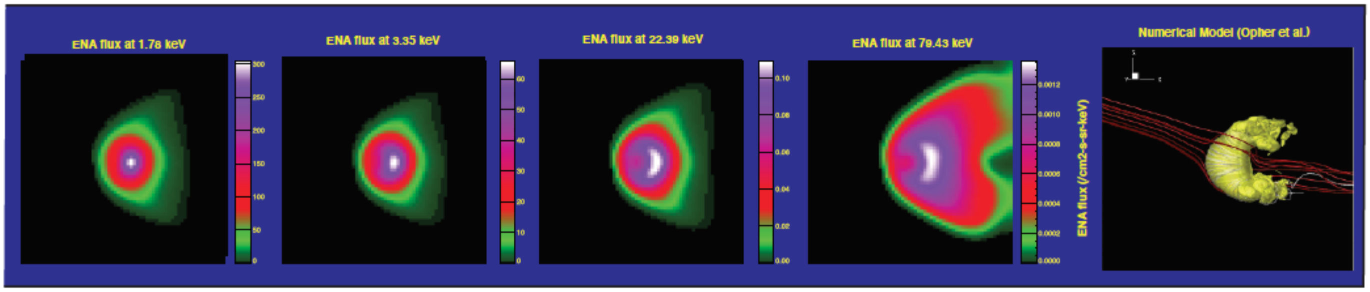

Figure 1. ENA images simulated at various energies from a vantage point on the port flank. The rightmost panel shows the model heliosphere (Opher et al.) used in the simulation. The simulation is based on the (likely oversimplified) assumption that the nonthermal ions are advected along plasma flow lines and simply decay via charge exchange. No sources of acceleration beyond the termination shock included.

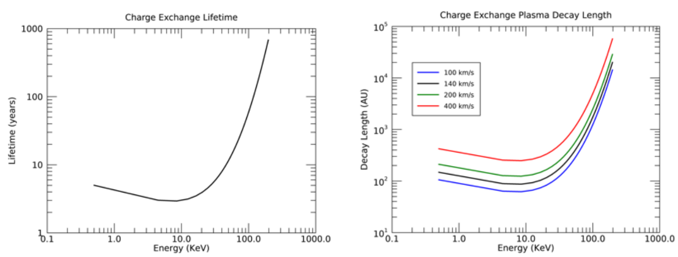

Figure 2. Charge exchange lifetime and plasma decay lengths for various plasma flow velocities in the outer heliosphere

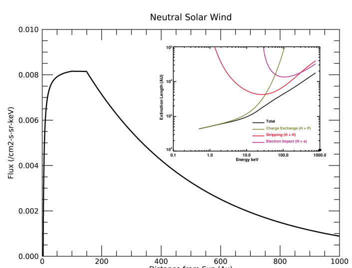

Figure 1. Simple model of Neutral Solar Wind flux in the heliosphere and beyond

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