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Title:	Discovering the 3D Structure and Dynamics of the Sun-Interstellar Medium System on a Global Scale Los Alamos LDRD Report
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Discovering the 3D Structure and Dynamics of the Sun-Interstellar Medium System on a Global Scale
Los Alamos LDRD Report

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ABSTRACT

We discover the 3D plasma structure of the Sun-interstellar medium interaction region, called the heliosheath. This is enabled by (1) the completion of a full solar cycle of observations of hydrogen energetic neutral atoms (ENAs) emanating from this region and detected by the Los Alamos-led IBEX-Hi ENA imager on NASA's Interstellar Boundary Explorer (IBEX) mission, and (2) the development of tools to fully exploit all data from the IBEX-Hi imager, leading to a significant increase in the effective instrument sensitivity. This effort prepares us for optimizing the design and data exploitation of the IMAP-Hi imager, the Los Alamos-led next generation imager that will fly on the Interstellar Mapping and Acceleration Probe (IMAP) mission, currently under production. This project realized its goals as evidenced by two main outcomes: (1) The publication of the first-ever empirical 3D map of the interstellar boundary, and (2) the development and release of a new validated ENA data set that has tripled the amount of data available for scientific analysis of the outer heliosphere.

TECHNICAL GOALS

This project has two main research goals that utilize data from IBEX [1], and specifically, observations made by the Los Alamos-led IBEX-Hi ENA imager, which images atomic hydrogen emitted from the distant interaction of solar wind plasma with the interstellar medium (ISM) [2].

Our primary science goal is to empirically derive for the first time the 3D shape of the outer surface of the heliosheath, the region that surrounds our solar system and acts as the boundary between the solar system and the ISM. We can use IBEX observations of the ENA flux coming from the heliosheath to determine the boundary based on a technique described in the next section.

The second goal of this project is to develop a new data set from heretofore unutilized IBEX observations. The ENA emission features from the boundary layer are extraordinarily dim; on average, the standard IBEX-Hi data product consists of detections of ENA from this region every ~3 sec at a signal-to-noise ratio of ~1. We will develop and validate a "double-coincidence" (or "doubles") data product that was recently found to have better signal-to-noise and more counts than the standard "triple coincidence" (or "triples") data product. Combined, these data provide the potential to increase the effective sensitivity of the IBEX-Hi instrument by *a factor of three*.

SCIENTIFIC APPROACH AND RESULTS

The determination of the shape of the heliosphere is accomplished using a method we have pioneered by which we "sound" the depth of the heliosheath by comparing the outgoing solar wind observed near Earth to its return signal, which is the ENA flux imaged by IBEX-Hi [3-5]. We have determined that the temporal variation of the ENA signal follows the periodicity and intensity of the solar wind over the 11-year solar cycle [6]. By measuring the time delay between when features observed in the outgoing solar wind appear in the returning ENA signal, we can determine the distance to the ENA source in multiple directions, and thus map the shape of the heliosphere. This is much the same as the way bats determine the distance to objects in their surroundings using sonar pulses, except the Sun is providing the outgoing pulses, and IBEX "listens" for the return.

Figure 1 shows the fundamental result of this work, the first-ever map of the shape of the heliosphere. This work was published as part of a special section of the Astophysical Journal celebrating a full solar cycle of IBEX observations [7]. The LANL press office also did a news release regarding this, which was picked up by numerous science reporting outlets, including Live Science, Science Alert, Space.org, Sky and Telescope, and MIT Techincal Review.

The task of developing a new data set from the unutilized doubles data required multiple steps, including re-analysis of calibration data taken at LANL prior to the launch of IBEX, determination of the background correction factors to the raw count rates, and validating the new data set through a study comparing ENA fluxes derived from the new doubles and the standard triples data to demonstrate that the resulting ENA flux maps are statistically the same. The new data set is complete (see Figure 2) and we are currently finalizing the process of incorporating it into the IBEX data archive. The validation study is near completion and will be presented at the upcoming 2021 Fall Meeting of the American Geophysical Union, by postdoc Thomas Kim. He is also writing it up for publication.

MISSION AGILITY

The Sun-ISM interaction is a coupled, complex system, and the heliosheath acts as a shield against galactic cosmic rays (GCRs), which can damage the national space infrastructure, and are a high risk associated with human space flight. Determining the shape of the heliosheath is a critical step advancing our understanding of how harmful GCRs are modulated by the heliosheath. This project also develops LANL capability for taking a leadership role in the science of the IMAP mission, the follow-on to IBEX, for which Los Alamos is providing two of the 10 instruments that comprise the IMAP payload. This work has also played an instrumental role in establishing science capability which has led to the award of an FY22 LDRD Directed Research project to further explore the outer heliosphere by exploiting IBEX data.

TECHNICAL VITALITY

Understanding the 3D structure of the heliosheath, the plasma boundary between our solar system and the interstellar medium, is a fundamental goal of the IBEX mission with far-reaching impact not only on understanding the nature of our heliosphere, but on how the dynamics of the solar cycle modulates the Sun's interaction with the interstellar medium. As evidenced by the strong public interest in our published map of the heliosphere, this work has gone far to put Los Alamos in a leadership position in the heliophysics community. Indeed, we have been invited to participate in a NASA-funded DRIVE Center to develop a predictive global model for the heliosphere as a direct result of this work.

WORKFORCE DEVELOPMENT

The project PI is a strategic hire for ISR Division. This project is the foundation for success of the PI's integration into the Lab's national security programs, and has helped establish his internal and external credibility for technical and scientific leadership into the future. In addition, the project has supported the hire of a postdoc, Thomas Kim. During his work on this project, Dr. Kim wrote and has been awarded a NASA Cassini data analysis grant, demonstrating the successful outcome of our recruitment effort.

CONCLUSION

The major outcomes of this project are the successful empirical determination of the shape of the heliosphere, and the development and validation of a new IBEX ENA data set that increases the useable signal counts by a factor of three. Shortly, a new LDRD DR project will commence that will incorporate the new data set and, along with other data analysis improvements, use it to carry out a major outer heliosphere science campaign.

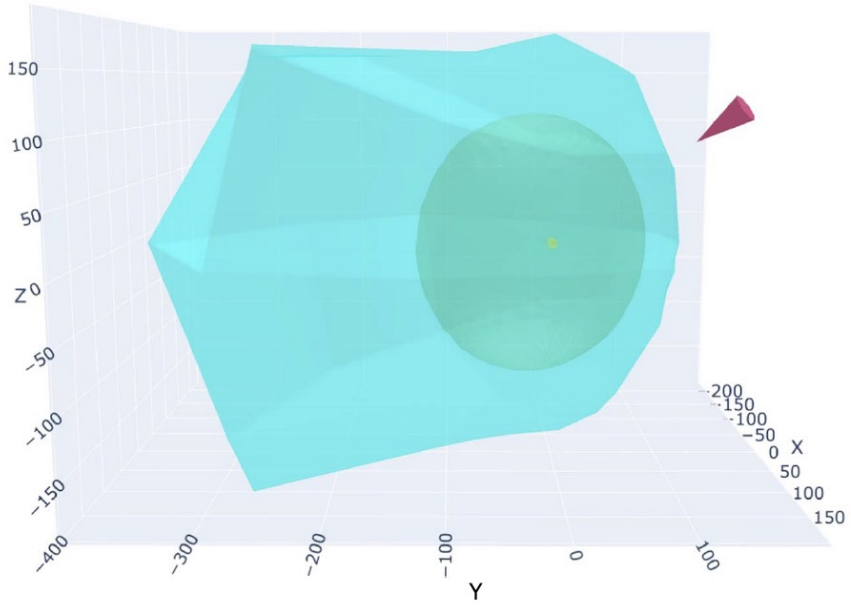

Figure 1. 3D shape of the heliosphere. The heliopause is represented in cyan, the embedded termination shock (where the solar wind transitions from super-sonic to sub-sonic speeds) is green and the Sun is represented by the yellow dot at the center of the coordinate axes. Axis units are in astronomical units. The positive y-axis points in the direction the sun is moving through the local interstellar medium, and the positive z-axis points toward the north ecliptic pole. The red cone represents the direction of far instellar magnetic field. One clearly sees the draping effect of the interstellar wind as it flows around heliosphere, creating a tail-like heliosheath on the downwind side.

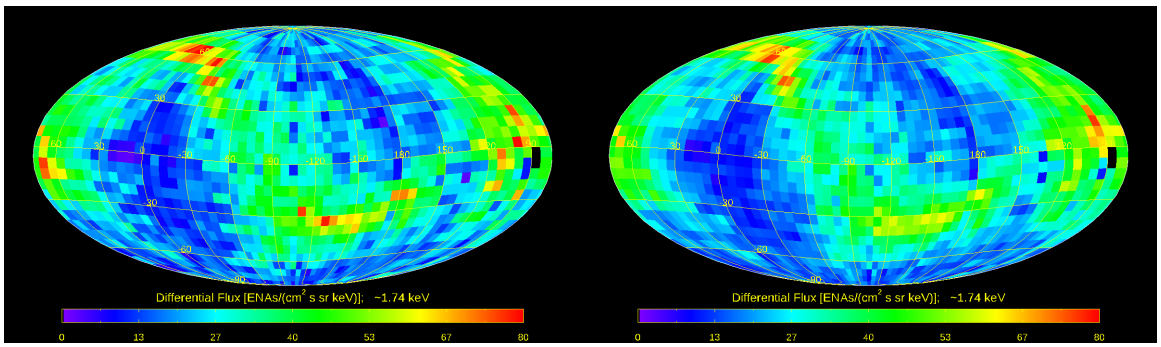

Figure 2. Comparison of a standard IBEX ENA sky map (left) and the resulting combined sky map using the new doubles data product (right). Note the relative statistical smoothness of the combined map relative to the standard map, demonstrating the large improvement in statistical accuracy with incorporation of the doubles.

ACRONYMS AND DEFINITIONS

ENA	Energetic Neutral Atom
GCR	Galactic Cosmic Ray
IBEX	Interstellar Boundary Explorer
IBEX-Hi	LANL-provided ENA imager to the IBEX mission
IMAP	Interstellar Mapping and Acceleration Probe
IMAP-Hi	LANL-provided ENA imager under development for the IMAP mission
ISM	Interstellar Medium
LDRD	Laboratory Directed Research and Development
NASA	National Aeronautics and Space Administration

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