Interstellar Boundary Explorer

Imaging the edge of our solar system and beyond --- Discovering the global interaction between the solar wind and the interstellar medium

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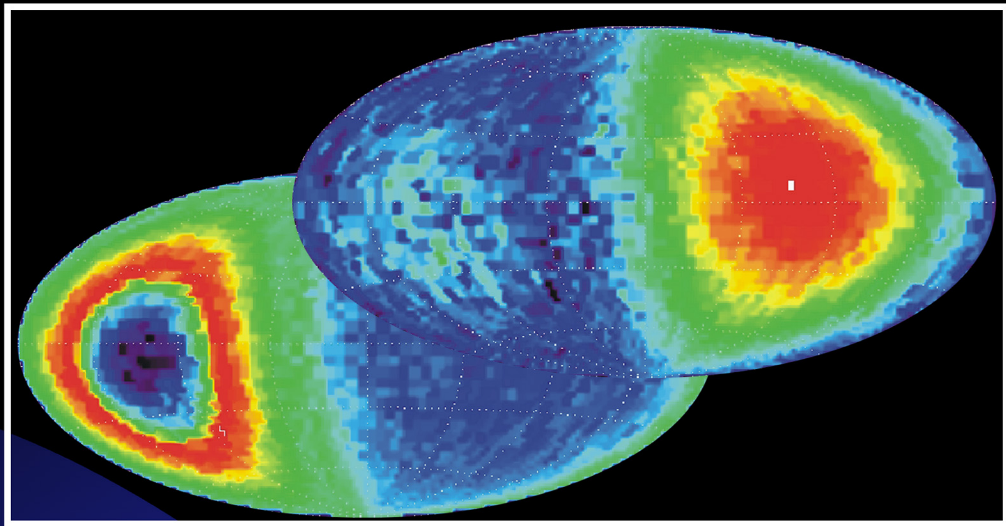
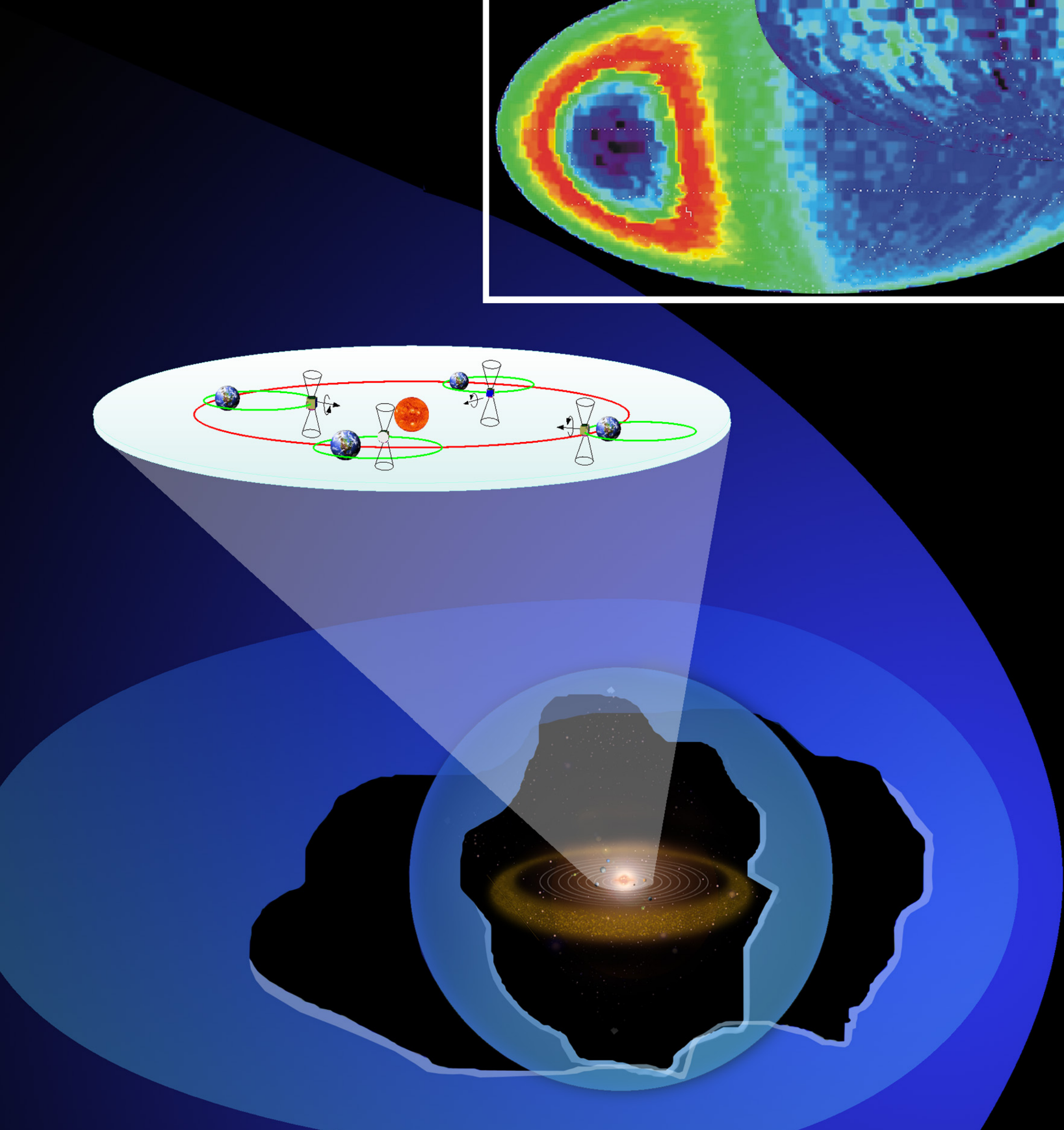




The Interstellar Boundary Explorer (IBEX) is one of five Small Explorer (SMEX) missions undergoing Phase A study for NASA's Office of Space Science. Around November 2004, NASA expects to select two of these five missions for development and flight. If selected, IBEX will provide the first global views of the Sun's interstellar boundaries; unveiling the physics of the heliosphere's interstellar interaction; providing a deeper understanding of the heliosphere and thereby astrospheres throughout the galaxy; and creating the opportunity to make even greater unanticipated discoveries.

December 1, 2003

Interstellar Boundary Explorer

Imaging the edge of our solar system and beyond - Discovering the global interaction between the solar wind and the interstellar medium

Interstellar Boundary Explorer IBEX

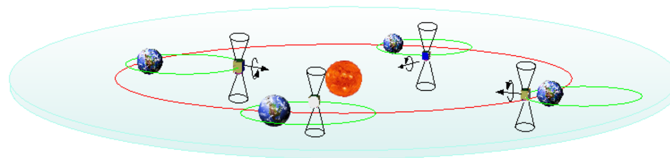
Science Objective

IBEX's sole, focused science objective is **to discover the global interaction between the solar wind and the interstellar medium. IBEX** achieves this objective by taking a set of global energetic neutral atom (ENA) images that answer four fundamental science questions:

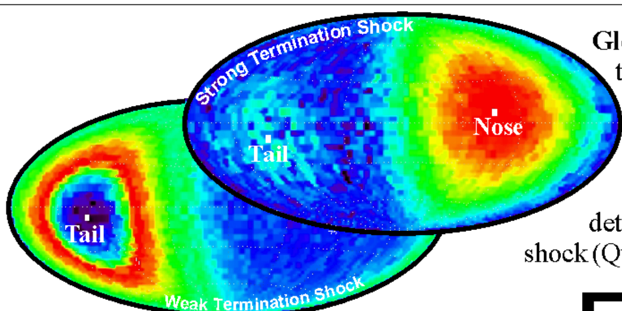
I: What is the global strength and structure of the termination shock?
II: How are energetic protons accelerated at the termination shock?
III: What are the global properties of the solar wind flow beyond the termination shock and in the heliotail?
IV: How does the interstellar flow interact with the heliosphere beyond the heliopause?

The **IBEX** objective is central to the Sun-Earth Connection (SEC) theme as demonstrated by both the 2003 SEC Roadmap and 2002 NRC's Decadal Survey and is specifically identified in the 2003 NASA-wide Strategic Plan.

Mission Overview

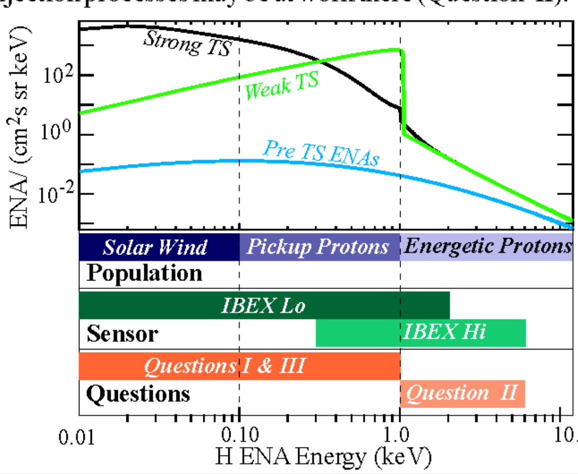


IBEX makes global observations of the interstellar boundaries by traveling outside of the Earth's magnetosphere in a highly elliptical, high altitude orbit. **IBEX** carries two very large aperture single pixel ENA cameras that look out perpendicular to the Sun-pointed spin-axis. Much like the COBE and WMAP astrophysics missions, **IBEX** uses the spacecraft motion over the year to generate its global maps. As COBE and WMAP have revolutionized our understanding of our place in the universe, **IBEX** revolutionizes our understanding of our star's interaction with the Galaxy.

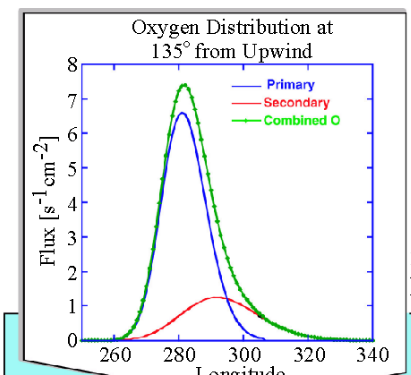


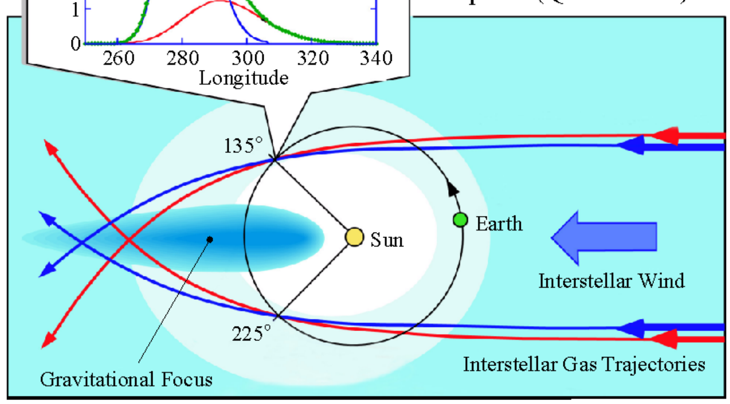
Global ENA images easily differentiate between types of interactions at the termination shock, while detailed energy spectra as a function of direction provide information about 3D configuration of the shock and energy partition of the ions at the shock (Question I). Differences between the upstream and downstream directions and more subtle asymmetries in the global images enable the determination of the solar wind flow patterns beyond the termination shock (Question III).

ENA energy spectra are direct measures of the solar wind, pickup ions, (Questions I and III) and energetic protons beyond the termination shock (Question II). Above 1 keV, these ENA energy spectra provide information about how the energetic particle pressure modifies the termination shock (TS) and what types of injection processes may be at work there (Question II).



The first direct measurements of **filtered interstellar neutral oxygen** provide information about the speed, direction, and temperature of the interstellar oxygen inside the termination shock and provide information about the interstellar interaction further out, beyond the heliopause (Question IV.)





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A. Scientific Objective and Questions

The Interstellar Boundary Explorer (IBEX) discovers the global nature of the interstellar boundaries that separate the matter and magnetic fields of our Sun from those of the nearby interstellar medium. The nearest interstellar boundary, the termination shock (TS), is thought to be ~100 AU away, making it enormously difficult to sample directly, even in a single direction. Recent observations have demonstrated, however, that it is possible to remotely image space plasmas via detection of energetic neutral atoms (ENAs), a technique now ready for imaging the interstellar interactions and interstellar boundaries at the edge of our heliosphere [Hsieh et al., 1992; Hilchenbach et al., 1998]. On IBEX, these groundbreaking ENA observations are achieved with high sensitivity measurements provided by two very large aperture ENA cameras, using heritage technologies, on a simple spinning spacecraft. IBEX's highly elliptical Earth orbit provides viewing of the outer heliosphere from beyond the relatively bright emissions of the Earth's magnetosphere. IBEX measurements enable the discovery of the global nature of the termination shock and the flow patterns of the heliosheath and the heliotail. IBEX also studies particle acceleration at the termination shock and probes the interstellar interaction beyond the heliopause. In short, the IBEX mission provides the first global views of the Sun's interstellar boundaries; unveiling the physics of the heliosphere's interstellar interaction; providing a deeper understanding of the heliosphere and thereby astrospheres throughout the galaxy; and creating the opportunity to make even greater unanticipated discoveries.

The IBEX OBJECTIVE is to discover the global interaction between the solar wind and the interstellar medium. The interstellar interaction encompasses the structures, dynamics, energetic particle acceleration and charged particle propagation in the complex region where the solar wind meets the interstellar medium -- the region that separates our solar system from the galactic environment. **IBEX provides the first global observations of the interstellar interaction – disclosing its fundamental nature and providing the observations needed for detailed modeling and in-depth understanding.**

A.1 Motivation and Context

Someday humanity may send spacecraft past the uncharted boundaries of the solar wind and into the galactic medium – a medium fed by material released from stars through novae, supernovae and stellar winds. The Sun moves at ~26 km s^{-1} with respect to the local interstellar medium (LISM), the portion of the galactic medium nearest the Sun (Fig. 1). The Sun's hot (~1-3 MK) outer atmosphere, or corona, expands supersonically to create the 300-800 km s^{-1} solar wind observed across all heliolatitudes and phases of the solar cycle [McComas et al., 1998, 2000, 2003].

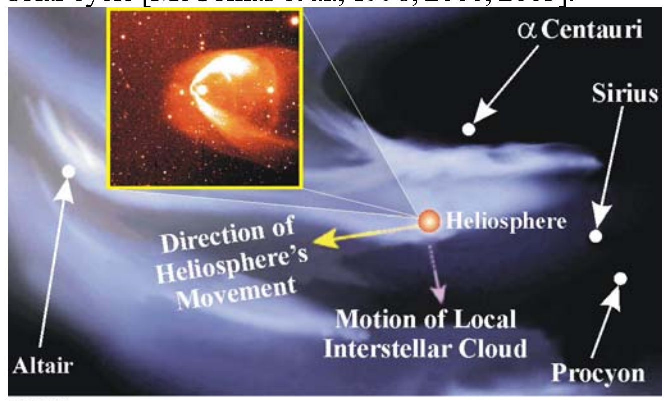

Figure 1. *IBEX images reveal global properties of the interstellar boundaries that separate our heliosphere from the local interstellar medium (Courtesy L. Huff/P. Frisch). The box shows an astrosphere at the binary star BZ Cam (courtesy R. Casalegno, C. Conselice et al., WIYN, NOAO)*

At the outer edge of our solar system, well beyond the furthest planets, the solar wind continually rams into the LISM, causing the "interstellar interaction" that is thought to result in three distinct interstellar boundaries shown on page 5: the TS where the solar wind slows from a fast supersonic to a subsonic flow; the heliopause, which separates the solar wind from the LISM flow; and, furthest out, a bow shock or bow wave beyond which the LISM flow is unperturbed by the heliosphere.

Neutral atoms from the interstellar medium continually stream into the heliosphere (page 5). A significant portion of these interstellar atoms become ionized by charge-exchange with ions that pile-up at the so-called hydrogen wall. This pile-up occurs because the interstellar flow is slowed, heated and deflected around the heliopause. The remaining interstellar neutrals drift into the heliosphere where, at solar distances of typically ~1-4 AU, they become ionized by solar UV or charge exchange with the solar wind. These newly created ions, called pickup ions, gyrate about the interplanetary magnetic field (IMF) that is frozen into the solar wind. In this process, newly formed ions are picked up and swept outward from the Sun. The pickup process also endows pickup ions with up to 4x the solar wind energy (per nucleon), allowing them to be preferentially accelerated at shocks. Diffusive shock acceleration at the TS [Pesses et al., 1981] transforms pickup ions into anomalous cosmic rays (ACRs) with energies of 10-100 MeV/nuc.

Our limited knowledge of the interstellar interaction has been gleaned over the last several decades through clever use of a broad range of indirect observations (page 5) of interstellar neutral H and He atoms, pickup ions, ACRs, and radio emissions from the outer heliosphere, combined with modeling.

ENA Observations - ENA imaging on several precursor missions and now on IMAGE is revealing the global dynamics of Earth's magnetosphere and providing rudimentary measurements of heliospheric neutral atoms. By carrying much more sensitive ENA cameras beyond the intense magnetospheric emissions and backgrounds, IBEX globally images ENAs from the outer heliosphere for the first time.

In the outer heliosphere, Hydrogen (H) ENAs are produced from multiple populations including solar wind, pickup, and energetic protons. Heliospheric ENAs are generated predominantly beyond the TS, in the inner heliosheath, where the previously supersonic solar wind with outward moving protons is abruptly slowed and heated, causing these protons to move in all directions. In this region of slower, hotter solar wind, a large flux of detectable inward moving ENAs is produced from protons that charge-exchange with interstellar neutrals. Thus, the ENAs imaged by IBEX illuminate the inner heliosheath.

ENA imaging is now a mature technology ready to take on the challenge of resolving the heliosphere's interstellar interaction. Through global ENA imaging, IBEX achieves its objective of discovering the global interaction of the solar wind with the interstellar medium.

A.2 Relationship of IBEX to NASA & NRC Plans

The objective of IBEX is central to the NASA Sun-Earth Connection (SEC) program, for it aims to discover the ultimate fate of the flow of energy and matter from the Sun, and more fundamentally, how the Sun and solar wind interact with the galaxy. IBEX provides global, fundamental, and direct insights into the interactions at the boundary of our Sun's astrosphere, the heliosphere. These insights improve our understanding of the broader problem of how galaxies and stars interact and evolve. IBEX discovers the global properties of energetic protons near the termination shock, and thereby explores the general problem of how charged particles are accelerated at perpendicular shocks in space plasmas.

The box below provides specific quotations from the most recent NASA roadmap, the NASA strategic plan, and the NRC survey that demonstrate how IBEX science is woven through these documents. In particular, the just released (2003) NASA-wide Strategic Plan specifically identifies remote sensing of the interstellar gas that enters the solar system.

While IBEX science is central to the SEC's goals, its program does not have a mission to make these observations within the next decade. In the case of the NRC's Decadal Survey this was clearly intentional as they stated: "Such a mission is gauged to be feasible within the resource limits of the Explorer program and so is not prioritized specifically in this report." *It falls to the Explorer program in general, and IBEX in particular, to make these critical observations.*

The Sun to the Earth – and Beyond: A Decadal Research Strategy in Solar and Space Physics (2002)
Challenge 2: Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium. "The boundary between the solar wind and the local interstellar medium (LISM) is one of the last unexplored regions of the heliosphere. Very little is currently known about this boundary or the nature of the LISM that lies beyond it. … certain aspects of these regions can be studied by a combination of remote sensing and in situ sampling techniques. This investigation could be accomplished by a mission … to obtain energetic neutral atom images… of the heliospheric boundary. Such a mission is gauged to be feasible within the resource limits of the Explorer program …"

Sun-Earth Connection Roadmap 2003-2028: Understand how the Sun, Heliosphere, and the Planetary Environments are Connected in a Single System (January 2003)
"An entirely new level of information on the interface between the heliosphere and the LISM is required. …Imaging of the outer boundaries ~100 AU away can also be done from orbits near 1AU. …Remote-sensing techniques such as energetic neutral atom (ENA) imaging of energetic protons…near the termination shock and in the heliosheath should provide additional diagnostics of the interfaces with the galaxy."

National Aeronautics and Space Administration 2003 Strategic Plan
Objective 5.13: Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments. "We also will show how the outer layers of the solar atmosphere are energized, and we will track the causes of terrestrial disturbances…Even the interstellar gas that enters the solar system can be analyzed using remote sensing."

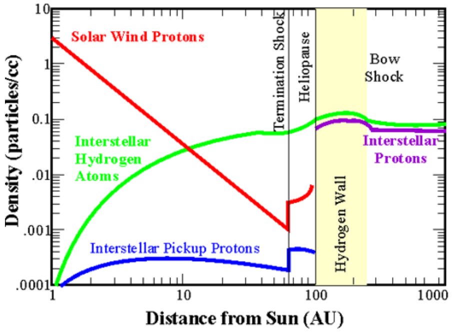

Figure 3. Density of heliospheric particle populations.

Anomalous Cosmic Rays (ACRs) have energies 10-100 MeV/nuc and are formed from pickup ions (~1 keV/nuc) that are carried out by the solar wind to the TS where they are somehow injected into diffusive shock acceleration.

ACRs Observed: Above the injection energy (traditionally thought to be ~1 MeV), the shock acceleration process produces an energy spectrum with a power-law that can be directly related to the shock strength of the TS [Cummings and Stone, 1996]. Spacecraft such as Voyager, Ulysses, ACE, and Wind measure ACRs.

Observed Radio Emissions from the outer heliosphere occur in sporadic outbursts [Kurth et al. 1984, 1987] and are thought to be produced when large interplanetary shocks reach the vicinity of the heliopause [Gurnett et al., 1993]. The emissions come in two components: a 'transient' part lasting about half a year that drifts in frequency, and a 2 kHz component, which persists for ~ 2 years. One interpretation is that the emissions are generated at the electron plasma frequency and twice this frequency due to a coupling between electrostatic Langmuir waves and plasma instabilities [Ginzburg and Zheleznyakov, 1959]. Detailed calculations based on this concept have been used to explain how the 2 kHz component can arise from beyond the heliopause, but cannot explain the durations of the transient emissions [Cairns and Zank, 1999].

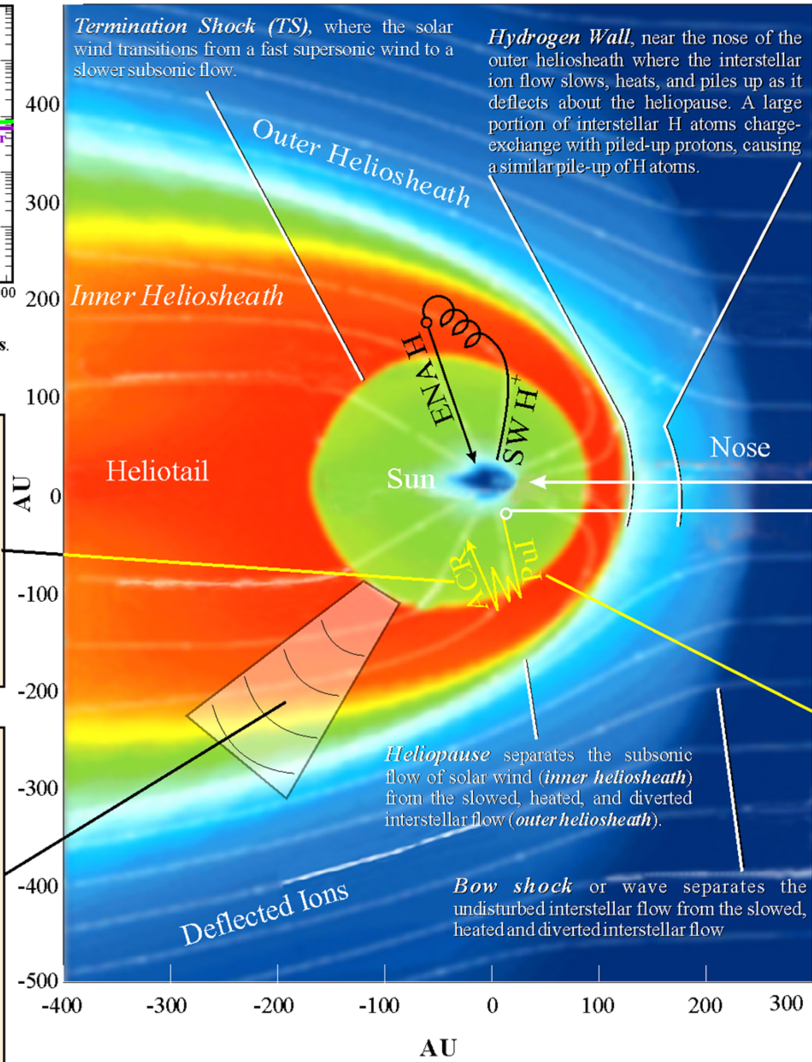

Figure 2. The heliosphere IBEX measures Hydrogen ENAs generated predominantly in the inner heliosheath from solar wind protons, pickup protons, and energetic protons.

Interstellar Neutral Atoms flow continually into the heliosphere, unimpeded by heliospheric magnetic fields. Some of these neutrals charge-exchange with H^+ at the hydrogen wall, starting the ***filtration*** process that depletes the ***primary population*** of neutrals that flows in from the interstellar medium. Filtration also produces a ***secondary population*** of neutrals from interstellar ions that charge-exchange with H atoms at the hydrogen wall. The secondary neutrals are hotter and slower than the primary neutrals since their properties reflect the heated and slowed interstellar ions of the outer heliosheath. Secondary H and O neutrals are numerous since H and O atoms charge-exchange readily with H^+. In contrast, the secondary He neutrals are few since the charge-exchange cross-section for He with H^+ is small. Therefore, the interstellar neutral He population inside the heliopause is mostly the cooler primary population streaming in directly from the interstellar medium.

Interstellar Neutral Atoms Observed: The differences between the neutral interstellar H and He have been observed. The properties of the interstellar H inside the heliopause have been derived from the observation of back-scattered Ly-α, which is generated by resonant scattering of solar Ly-α photons on interstellar H atoms [Quémerais et al., 1999]. The H bulk speed (22-23 km/s) is slower and temperature (11,000 K) hotter than the He bulk speed (26 km/s) and temperature (6300 K) using direct observations of inflowing He atoms by Ulysses/GAS [Witte et al., 1996]. While these He parameters agree well with those obtained through UV absorption in the LISM [Bertin et al., 1993], the lower bulk speed and higher temperature of H are signatures of the filtration process caused by charge-exchange coupling between cooler interstellar atoms and the warmer, slower interstellar protons at the hydrogen wall.

Interstellar Pickup Ions are created when interstellar neutral atoms become ionized through charge-exchange and/or photoionization. Newly created ions begin to gyrate about the magnetic field lines frozen into the solar wind. Gyration and scattering by magnetic inhomogeneities moving with the solar wind causes pickup ions to be carried out with the solar wind. The pickup process endows pickup ions with substantial random energy (~1 keV/nuc) allowing them to be more efficiently accelerated at shocks and through wave-particle interactions. The pickup process also causes "mass-loading," a slowing of the solar wind as it picks up and carries out numerous pickup ions [Szego et al, 2000].

Interstellar Pickup Ions Observed: Interstellar hydrogen parameters, most notably the hydrogen density after filtration, can be derived from pickup ions [Gloeckler et al., 1995; Izmodenov et al., 1999]. Thus far, the properties of interstellar pickup ions have been observed only inside of 5 AU by Ulysses and near 1 AU by ACE, Wind, SOHO and AMPTE. Interstellar pickup ion observations have also been used to derive abundances in the LISM [Gloeckler and Geiss, 1998].

Table 1: The IBEX approach and measurement requirements

The sole IBEX objective to discover the global interaction between the solar wind and the interstellar medium is achieved by answering four fundamental science questions

Levels \ Fundamental Science Questions	I: *TS Strength/ Structure*	II: *Energetic Protons Near TS*	III: *Solar Wind Flow Patterns of Inner Heliosheath*	IV: *Interstellar Flow and Interaction*
Discover (Straightforward interpretation of IBEX data products)	All-sky survey: strong vs. weak TS	Intensity and spectra of energetic protons near TS	Nose/tail asymmetries	First direct measurement of filtered interstellar neutral, O
Explore (Interpretation based on simple physics-based calculations and limited modeling)	All-sky map of shock strength	Modification of TS dynamics due to energetic particle pressure	Solar wind flow direction beyond TS vs. angle from the nose	Bulk speed, direction, and temperature of interstellar O inside TS
Understand (use data products to iteratively define, revise, and refine 3D models of the heliosphere)	-3D TS configuration incl. distance scale and strength -Energy partition of solar wind, pickup protons, and energetic protons	Bound injection processes at TS	-3D solar wind flow patterns beyond TS -LISM B	-Filtration -Ionized fraction of O in the LISM -Interstellar flow patterns beyond heliopause -Bow shock existence

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A.3 IBEX Fundamental Science Questions

IBEX achieves its sole objective by answering four fundamental science questions:

- **Question I:** What is the global strength and structure of the termination shock?
- **Question II:** How are energetic protons accelerated at the termination shock?
- **Question III**: What are the global properties of the solar wind flow beyond the termination shock and in the heliotail?
- **Question IV:** How does the interstellar flow interact with the heliosphere beyond the heliopause?

The current lack of information concerning the interstellar interaction also dictates a broadly scoped science strategy. We consider the science return in terms of three levels of study (Table 1):

Discovery Level: Discover global, fundamental properties of the interstellar interaction directly from the IBEX data products (the distribution of ENAs as a function of energy and direction and the fluxes and flow directions vs. time-of-year of low energy neutral O that flows into the heliosphere from the LISM).

Exploration Level: Explore global fundamental properties of the interstellar interaction using IBEX data products, simple physics-based calculations, theory and limited 2D and 3D modeling.

Understanding Level: Understand in depth global properties of the interstellar interaction through an iterative analysis using IBEX data products to define and refine 3D models of the heliosphere.

At the exploration level and particularly at the understanding level, IBEX utilizes theory and modeling to gain further insight into the global properties of the interstellar interaction. Many members of the team have a strong background in heliospheric theory and modeling. Additionally, IBEX sets aside $2M for a NASA-selected guest investigator program that specifically targets the coordinated use of IBEX data products to iteratively refine 3D models of the heliosphere. NASA-selected guest investigators will participate as full members of the IBEX Team.

A.4 Fundamental Science Questions and IBEX Measurement Strategy

I: What is the global strength and structure of the TS?

Is there a termination shock? If the solar wind carries most of the pressure, the TS should be a strong gasdynamic shock producing a large, abrupt speed decrease. The presence of pickup and energetic protons, however, provides additional pressure that weakens the shock, or possibly, in an extreme case, causes the shock to dissolve into a wave. Global observations are the only way to answer the fundamental questions of the existence and strength of the TS in all directions of the sky.

Measurement strategy. Extremes of TS formation for strong shock conditions (top panel) and for weak shock conditions (bottom panel) are shown in Fig. 4. In the case of a strong shock, the solar wind population is most evident, resulting in a more intense and beamlike ENA energy distribution concentrated near the nose of the heliosphere. In the case of a weak shock, pickup ions and energetic ions are more intense, resulting in a much broader energy distribution peaked in the tailward direction. The cases in Fig. 4 represent extremes, and it is likely that the TS is quite variable globally, stronger in places and weaker elsewhere. We emphasize that the differences between strong and weak shocks are readily apparent using IBEX global

ENA images. Thus, at the discovery level, the IBEX data are used to reveal the fundamental global properties of the TS. The precise quantification of the shock strength and derivation of the detailed energy partition in each look direction are accomplished at the exploration and understanding levels first using physics-based calculations, then using detailed 2D and 3D heliospheric models (discussed below). We emphasize that until the basic nature of the interaction can be determined from the direct observations, the process for deeper investigation is open ended.

At the understanding level, observed IBEX ENA energy distributions (Fig. 5) in each look direction are used to derive the proton energy distribution in the inner heliosheath. Modeling is used to deconvolve the line-of-sight (LOS) integration. Proton distributions in the inner heliosheath are a function of TS distance since pickup ions increase the random thermal energy of the solar wind and are more abundant for larger TS distances. Thus, the 3D TS structure and the energy partition of the proton populations are derived through a coordinated analysis using observed ENA energy distributions to iteratively refine heliospheric models. It is important to note, first, that pre-TS ENAs (blue curve, Fig. 5) generated from accelerated protons inside the TS (e.g., at co-rotating interaction regions - CIRs) are not a significant background; and, second, that loss of ENAs by charge-exchange or photoionization is not a significant issue as 80% of the 1 keV H ENAs make it in from the TS to 1 AU; a reduced fraction makes it in at lower energies (down to 15% at 10 eV) [Gruntman et al., 2001].

II: How are energetic protons accelerated at the termination shock?

Particle acceleration is a fundamental problem in space physics as well as astrophysics. The TS shock is believed to create ACRs (10-100 MeV/nuc) through diffusive shock acceleration of interstellar pickup ions (~1 keV/nuc) [Fisk et al., 1974, Pesses et al., 1981]. In this context, the TS is thought to be the heliospheric analog for particle acceleration of cosmic rays at supernovae shocks. Because the IMF is tightly wrapped in the outer heliosphere, the TS is nearly a perpendicular shock (shock normal perpendicular to the local magnetic field). The difficulty with such shocks for particle acceleration is that for ions to move back upstream across the TS, and be efficiently accelerated through multiple energy-gaining crossings, they must have very large speeds along the magnetic field. This difficulty is referred to as the "injection problem" [Lee, 2000; Rice et al., 2000; Giacalone, 2001]. There are two possible solutions:

- Pre-acceleration inside the TS, which is observed in the inner heliosphere [e.g., Gloeckler et al., 1994, 2000; Schwadron et al., 1996], might provide sufficient speeds for direct injection at the TS. This pre-acceleration may be caused by statistical acceleration due to wave-particle interactions [Bogdan et al., 1991; Schwadron et al., 1996; Le Roux and Ptuskin, 1998] and/or acceleration at inner heliospheric shocks that bound CIRs. Also, there may be systematic [Schwadron and McComas, 2003a,b] and random deviations of the magnetic field from the tightly wrapped spiral at certain locations along the TS where the required injection speed would be greatly reduced.
- Highly efficient injection mechanisms may operate at the TS. Some theoretical suggestions include multiple ion reflections [Zank, 1996a; Lee et al., 1996] and cross-field diffusion [Jokipii, 1987].

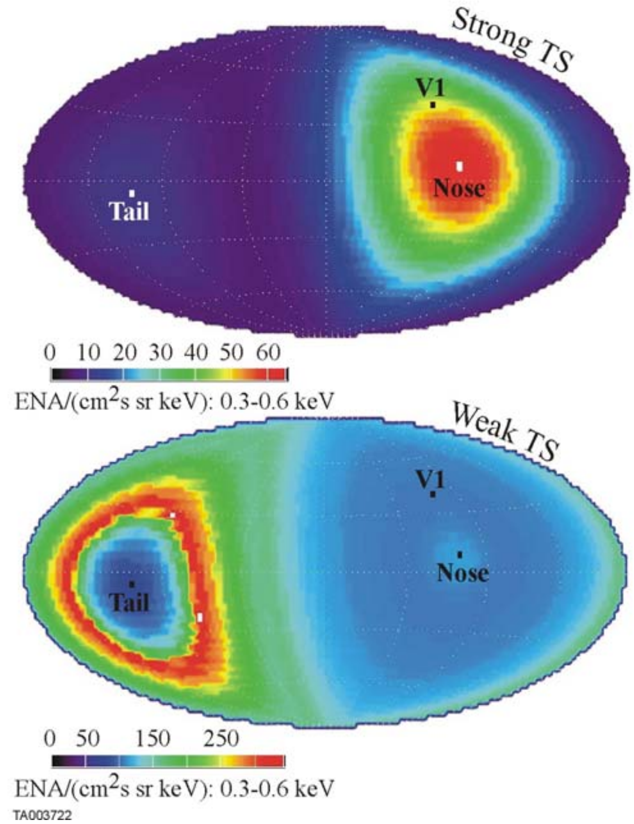

Figure 4. *Global ENA images observed by IBEX reveal the global strength of the TS. Shown here are two extremes of predicted ENA emissions: (Top) a strong gas-dynamical TS; (Bottom) a TS weakened by a large pickup ion pressure [Gruntman et al., 2001]. Colors correspond to differential ENA fluxes from 0.3-0.6 keV, which are imaged by both IBEX sensors. The data are plotted as a function of solar ecliptic coordinates with the center of the figure at 0° latitude and 180° longitude. Also indicated are the positions of the heliospheric nose, tail, and Voyager 1.*

IBEX infers the properties of accelerated protons near the TS. Protons are the most abundant species of interstellar pickup ions and ACRs [Gloeckler, 1996;

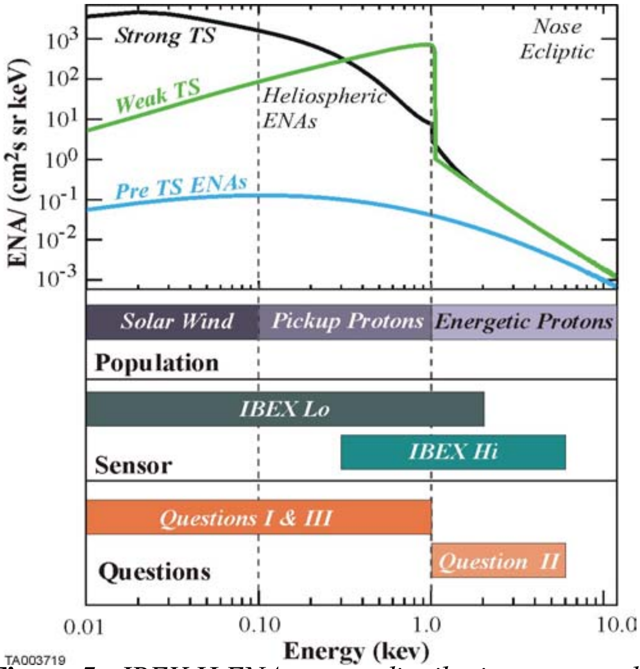

Figure 5. *IBEX H ENA energy distributions are used to discover the global properties of the proton populations of the inner heliosheath. Shown here are predicted ENA energy distributions near the nose of the heliosphere for a strong (black curve) and weak (green curve) TS [Gruntman et al., 2001]. These curves are for a nominal, slow (1 keV) solar wind. The blue curve shows the predicted ENA flux due to energetic protons inside the TS. Energetic ENA distributions >1 keV (black and green curves) are the accelerated energetic protons of the inner heliosheath, also based on observed distributions that have been projected out beyond the TS.*

Cummings and Stone, 1996]. Due to their high abundance, it is very possible that energetic protons carry sufficient pressure to significantly modify the dynamics of the TS. If this is the case, the acceleration of energetic protons at the TS is a highly non-linear process where the TS accelerates protons, which in turn modify the shock, and thereby change the very nature of the acceleration. In addition, it is generally thought that pickup ions are accelerated at the TS, whereas the solar wind ions are not since they are very strongly cooled in transit to the TS. This is supported by observations showing that ACRs, like pickup ions, are singly charged [Adams et al., 1991] whereas solar wind heavy ions are highly charged. However, it is possible that solar wind ions are also accelerated at the TS, and that the highly charged ACRs have more difficulty propagating into the inner heliosphere (due to their high charge-to-mass ratio) where they can be detected. By inferring the relative acceleration efficiencies of solar wind and pickup protons at the TS, IBEX directly addresses the issues of the seed populations, pre-acceleration, and TS acceleration of energetic protons.

Measurement strategy. IBEX measures H ENAs produced from accelerated protons up to 6 keV. While these protons have much less energy than ACR protons (10-100 MeV) and less energy than that required for injection (~1 MeV at a perpendicular TS), they are interesting because they feed higher energy protons. By measuring the intensity and energy dependence at low-energies, IBEX infers the injection and acceleration of protons at higher energies.

Fig. 5 shows predicted energy distributions of H ENAs >1 keV, produced from energetic protons in the inner heliosheath near the nose of the heliosphere (green and black curves) and from energetic protons inside the TS (blue curve). These distributions are predicted from observed energetic proton tails [Gloeckler et al., 1994, 2000; Schwadron et al., 1996] assuming that the intensity of the tails scale with the intensity of interstellar pickup protons [Vasyliunas and Siscoe, 1976].

At the level of discovery, IBEX observes the global properties of energetic protons (1-6 keV). Several features will be immediately evident: 1) the intensity of the accelerated protons relative to the solar wind and pickup protons below 1 keV, and 2) the global correlation between the energetic proton intensity and the shock strength and structure. At the level of exploration, we determine whether accelerated protons have sufficient pressure to modify the TS strength and dynamics. To address this issue, we first estimate the pressure of the energetic particles in the energy range from 1-6 keV and then use modeling to deconvolve line-of-sight (LOS) integration and to extrapolate the measurements over an energy range needed to estimate the energetic proton pressure. Finally, at the level of understanding, we undertake a coordinated analysis of IBEX data with iteratively refined models of the heliosphere that incorporate energetic particle acceleration and propagation. Solar wind and pickup proton distributions provide seed populations for energetic protons. Highly efficient acceleration mechanisms at the TS (e.g., multiple ion reflections or strong cross-field diffusion) result in more energetic distributions that transition smoothly beyond pickup ion energies. In contrast, mechanisms involving pre-acceleration well inside the TS result in less energetic distributions with an abrupt transition near the pickup proton energies.

III: What are the global properties of the solar wind flow beyond the termination shock and in the heliotail?

Large-scale models of the heliosphere (Fig. 6) predict the flow patterns in the heliosheath and heliotail [e.g., Baranov and Malama, 1993, 1996; Zank, et al., 1996b; Linde, 1998; Linde et al., 1998; Müller et al., 2000]. The models all show that the solar wind flow stagnates near the nose of the inner heliosheath, is deflected near the flanks, and moves in the same sense as the interstellar flow in the tail. The details of the models, however, depend critically on the assumptions and approach. In particular, the conditions of the LISM are not well known. High LISM temperatures cause subsonic flow. Accordingly, the bow shock is weakened into a wave and the large external pressure compresses the heliosphere (Fig. 6, lower right panel). The orientation and strength of the magnetic field in the LISM also influences the large-scale pressure and electric currents in the heliosheath. Fig. 6 (upper panel) exemplifies the asymmetries caused by the orientation of the LISM magnetic field, which in this simulation is nearly perpendicular to the LISM flow (see Linde, 1998 for details). The vastly different density and temperature structures shown in Fig. 6, are created by the different simulated solar wind flow patterns of the inner heliosheath. Thus, the solar wind flow patterns in the inner heliosheath are critical for understanding the interstellar interaction as a whole.

Measurement strategy. Fig. 4 shows global ENA images over the energy range 0.3-0.6 keV for a strong gasdynamic shock with no contribution from pickup ions (top) and a shock weakened by pickup ions that are not thermalized in the inner heliosheath (bottom). In both cases the assumed flow properties are the same, but significant differences arise because the ENA emissions are highly sensitive to the source ion energy distributions. By imaging the heliosheath at different energies, various features are revealed. At low energies (~0.05 keV), particles that produce ENAs are very sensitive to the solar wind flow; in the nose the flow stagnates and emissions are more intense because more particles have sufficient random speeds to produce ENAs that radiate inward. At higher energies (>0.4 keV), the distribution of particles becomes more isotropic, leading to ENA emissions in all directions. In this case, the most intense fluxes come from the tail where the LOS integrations are largest.

The power of IBEX in this context is that it can image ENAs in different energy bands, and thereby derive the global flow patterns of the solar wind beyond the TS. At the discovery level, nearly raw IBEX all-sky maps at various energies enable the discovery of basic global features of the solar wind flow pattern in the inner heliosheath. At the levels of exploration and understanding, inclusion of physics-based calculations and iteratively refined 3D heliospheric models uncover increasingly detailed and asymmetric 3D flow patterns of the solar wind.

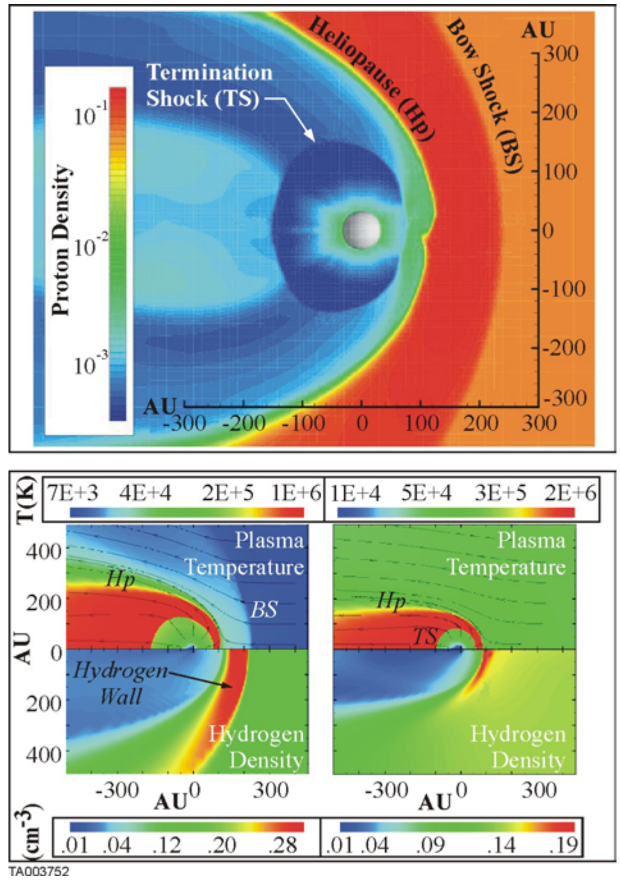

Figure 6. *IBEX discovers solar wind flow properties of the inner heliosheath that depend critically on the overall interstellar interaction. (top) The orientation of the field in the LISM strongly influences the global density structure and solar wind flow patterns of the inner heliosheath (Linde, 1998); (bottom) Influence of the LISM temperature on heliospheric structure (Müller et al., 2000): (bottom left) relatively cool LISM, well-defined bow shock; (bottom right) hot LISM, no bow shock.*

IV: How does the interstellar flow interact with the heliosphere beyond the heliopause?

O atoms readily charge-exchange with protons since H and O have similar first ionization potentials. Thus, filtration processes that modify inflowing H also modify inflowing interstellar O. As in the case of interstellar H, there are two interstellar O populations: the primary population (~75-80% of detectable interstellar O) that has not interacted at the hydrogen wall and therefore reflects the undisturbed properties of the LISM; the secondary population (~20-25%) that is slowed and heated due to interaction at the hydrogen wall near the heliopause. Note that interstellar H is very difficult to directly detect due to its low energy (mass). Once inside the TS, interstellar atoms are focused by the Sun's gravity and lost through ionization. These collective effects have been studied in great detail and allow interstellar neutral measurements to be used to accurately determine filtration [Izmodenov et al., 1999; Müller et al., 2000]. Hence, through the first direct measurement of filtered interstellar neutrals, oxygen, we derive the signatures of heating, deceleration and depletion associated with the interstellar interaction near the heliopause at the hydrogen wall.

Measurement Strategy. Inflowing interstellar O atoms are focused downstream from the Sun (with respect to the interstellar flow) due to solar gravitation. Gravitational focusing is very sensitive to the bulk velocity and temperature of the neutral species and acts very differently on O and He because O contains a secondary component with reduced velocity and increased temperature whereas He contains only the unmodified primary component from the LISM. Fig. 7 shows the LISM flow pattern in the inner heliosphere along with two simulated distributions as a function of velocity angles of O atoms. Current models find a contribution from the secondary component of 20-25% [Izmodenov et al., 1999], which leads to a 2° angular shift between the O and He when Earth moves into the interstellar flow (~225° Fig. 7), and an angular shift of 7° when Earth moves with the interstellar flow (~135° Fig. 7). While the majority of the neutral O becomes ionized as it approaches the Sun, 1-2% survive in to 1 AU (the surviving fraction [Wu and Judge, 1979] of O atoms is ~$\exp(-\beta r_1/v_0)$ where β~$7.75\mathrm{x}10^{-7}$ s^{-1} [Rucinski et al., 1996], is the ionization rate, r_1 is 1 AU, and v_0~26 km/s is the speed of inflowing neutrals). Calculations show that the surviving fraction of interstellar O can be measured by IBEX with high statistical accuracy.

At the discovery level, IBEX makes the first direct measurements of a filtered interstellar neutral, oxygen (0.01-0.5 keV). At the level of exploration, IBEX measures the interstellar O flux during optimum times in each year to infer the properties of the secondary O population. These O flux observations are then used with filtration models to derive the bulk speed, direction and temperature of interstellar O atoms inside the TS.

As discussed above, the properties of the TS, energetic protons, and the solar wind flow of the inner heliosheath are inter-related components of the larger system. Clearly, the components of the LISM and the outer heliosheath are also pivotal. Understanding level interpretation about the existence of the bow shock, the interstellar flow properties of the outer heliosheath, and the conditions of the LISM require full integration of IBEX data with iteratively refined simulations of the 3D heliosphere.

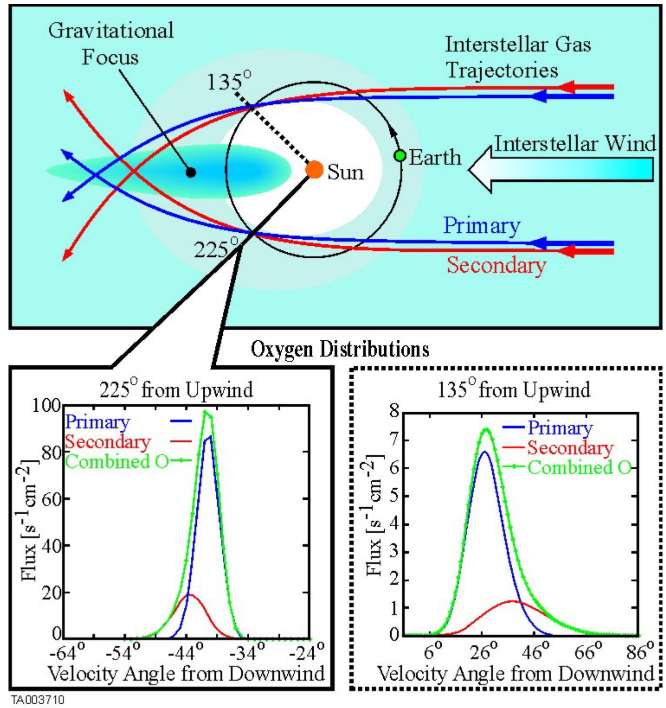

Figure 7. *By measuring the populations of O atoms from the LISM that are gravitationally focused by the Sun, IBEX explores how the interstellar flow interacts with the heliosphere. During optimum times in each year, IBEX accumulates the neutral O flux as a function of O velocity angle (x-axes on cutouts). The secondary population is slower, hotter and more strongly deflected than the primary population.*

A.5 Relationship to Past, Current and Planned Missions

Voyager 1 (V1) is approaching the TS. Although still controversial, V1 has detected anomalies in energetic particles that suggest it may have crossed the termination shock during a recent ~6 month period, and then passed back into the supersonic solar wind [Krimigis et al., 2003]. This interpretation is challenged by V1 magnetic field measurements and anomalous cosmic ray measurements showing contrary evidence [McDonald et al., 2003; Burlaga et al., 2003]. Despite these controversies, it is clear that V1 measurements will continue to challenge many preconceptions about the nature of the termination shock. The V1 *in situ* energetic particle spectra and the magnetic field strength (if it is large enough) are known at one specific location as a function of time. Because IBEX provides *global* maps of the interstellar interaction, IBEX observations are complimentary to, and synergistic with, the detailed single direction measurements that may be provided by Voyager 1.

IMAGE observations are relevant to IBEX in two ways. First, HENA has set an upper bound on higher energy ENAs (10-16 keV). Second, LENA observations (at much lower sensitivity than IBEX will achieve), suggest the surprising possibility of ENA emissions from a location 10°-40° from the heliospheric nose [Collier et al., 2003]. While these results are controversial, they do emphasize how critical IBEX's high sensitivity/high resolution ENA observations are for determining the global interaction.

Many NASA missions including Voyager 1&2, Pioneer 10&11, AMPTE, ACE, Ulysses, Wind, and SOHO, have provided valuable information related to the interstellar interaction. IBEX provides important input for ongoing and future pickup ion measurements while observations of H ENAs from accelerated protons near the TS provide context for measurements of particle acceleration in the heliosphere and facilitate a deeper understanding of the observations of ACRs.

Oxygen is a key metallicity indicator in the Milky Way Galaxy, and ISM dust grains harbor an uncertain amount of O. Spectroscopic data from HST and FUSE show interstellar O abundances towards distant stars, which typically sample lower density material [Andre et al., 2002], that are larger than abundances towards nearby stars, which typically sample denser ISM [Sofia et al., 2001]. Although errors are large, observations of nearby stars and radiative transfer models indicate that LISM abundances appear to be comparable to the lower density ISM [e.g., Wood et al., 2002]. IBEX observations will constrain the O filtration factor and the LISM interstellar oxygen abundance.

Interstellar Probe is a notional future mission to fly beyond the confines of the solar system and explore the LISM directly. The mission is costly and extremely technically challenging. Additionally, because so little is now known about the outer heliosphere, remote sensing of the outer boundaries will provide critical information for the design of an Interstellar Probe. Thus, IBEX is the critical first stepping-stone for our voyage into the interstellar medium.

A.6 Need and Timing for the Investigation

IBEX fills a void in our understanding of the global nature of the interstellar interaction and heliospheric boundaries. IBEX also offers great opportunity for unanticipated discovery. Over many years of study, the frontiers of space science have pushed toward the outer heliosphere. Currently however, we have very little direct knowledge of the interstellar interaction. Arguably, our most advanced understanding of the outer heliosphere comes from results of numerical models, but the parameters and very nature of the coupling are not well defined due to a current lack of direct or remote observations. As mentioned above, it appears Voyager 1 may soon pass beyond the TS at one location, if it hasn't already; however, global information concerning the interstellar interaction will remain a critical need – a need remedied by the IBEX mission. Discovery of both the global heliospheric interaction by IBEX and single direction *in situ* observations by Voyager 1 in the same solar cycle would be optimum.

Selection of IBEX in this SMEX round also provides good timing in the solar cycle as it will fly around solar minimum, when the Sun is relatively calm and the 3D heliosphere is in a quasi-static configuration [McComas et al., 1998, 2000]. Ideally, the baseline mission would occur nearer solar minimum, and Phase F nearer maximum. This goal would be accomplished with a launch in the 2007-2008 timeframe, achieving the baseline measurements by 2010, and extended measurements in the timeframe of increased activity, 2010-2012. Thus, selection of the IBEX mission in this round of Small Explorers provides excellent timing both within the solar cycle and because Voyager 1 will likely encounter the TS, if it hasn't already, during this solar cycle.

A.7 Mission Overview

IBEX is designed to provide global viewing of the interstellar boundaries. The IBEX spacecraft is a Sun-pointed-spinner with two narrow-angle field-of-view (FOV) sensors that view perpendicular to the spin-axis. Panel **B** of Fig. 8 shows the total sampling time in each pixel, excluding pixels that intercept the magnetosphere, over two years of observations. The IBEX-Lo sensor has an energy range of 0.01 - 2keV that images low energy ENAs and measures neutral interstellar O with very high resolution. IBEX-Hi has an energy range from 0.3-6 keV that measures both pickup ion ENAs and energetic ENAs produced from the seed population of ACRs. The overlap between the Hi and Lo sensors (0.3-2 keV) was chosen to maximize the statistics, allow for in-flight cross-calibration, and provide imaging via two completely independent sensors across the most critical energy range for achieving the IBEX science objective.

B. Observations and Data Required to Achieve IBEX Objective

The IBEX objective is achieved by obtaining well-resolved global images and energy spectra of ENAs from the heliosheath, and by measuring the interstellar O temperature and flow direction with high accuracy. Below we describe an example of the observations and data required to answer one of our four fundamental science questions.

Example for Question I: What is the global strength and structure of the termination shock?

Fig. 8 demonstrates the sensitivity of IBEX for imaging the ENA emissions and resolving the TS structure in one of our energy bands. Panel **A** simply replots simulated ENA fluxes for strong and weak TS shown in Fig. 4 [Gruntman et al., 2001]. Panel **B** shows the hours of sampling time (summed over both sensors) in each pixel over the 2 year IBEX mission.

Panel **C** provides the counts/pixel, determined by multiplying the predicted ENA spectra (**A**) by energy, geometric factor, sampling time (**B**), and dutycycle. Finally, in Panel **D** we added background and statistical noise based on the counts in each pixel and rederived the flux. Comparison of Panels **A** and **D** of Fig. 8 clearly shows that the count rates are sufficiently high to obtain extremely accurate images that will easily differentiate between various types of TS structure. Thus, IBEX provides statistically significant, energy-resolved global images of the interstellar interaction at the TS. The images reveal the shock strength, which, with modeling, allows us to infer the energy partition of the solar wind, pickup ions and energetic particles at the TS, as well as the full 3D configuration of this innermost boundary.

C. IBEX Science Team

The IBEX Scince team includes PI Dave McComas; Co-Is Peter Bochsler, Maciej Bzowski, Horst Fichtner, Priscilla Frisch, Herb Funsten, Steve Fuselier, Mike Gruntman, Vlad Izmodenov, Paul Knappenberger, Marty Lee, Don Mitchell, Eberhard Moebius, Tom Moore, Ed Roelof, Nathan Schwadron, Peter Wurz, Gary Zank; and Collaborators Frederic Allegrini, Mike Collier, Dan Reisenfeld, Martin Wieser, and Manfred Witte.

D. IBEX has Science Opportunities for Everyone

In addition to the science team, everyone is invited to join and participate in the IBEX mission, and contribute to its science return. If IBEX is selected:

- All IBEX science team meetings will be open to everyone interested in participating;
- All IBEX science data will be made available to the public as soon after it is taken and is practical;
- A $2M IBEX-funded, but NASA peer reviewed and selected Guest Investigator program will be implemented to support outside researchers;
- Very high sensitivity magnetospheric ENA observations, while not a formal part of IBEX science, will also be provided to the community;
- Astrophysical-heliospheric cross-disciplinary research enabled by IBEX will explore synergies in the heliosphere-astrosphere connection.

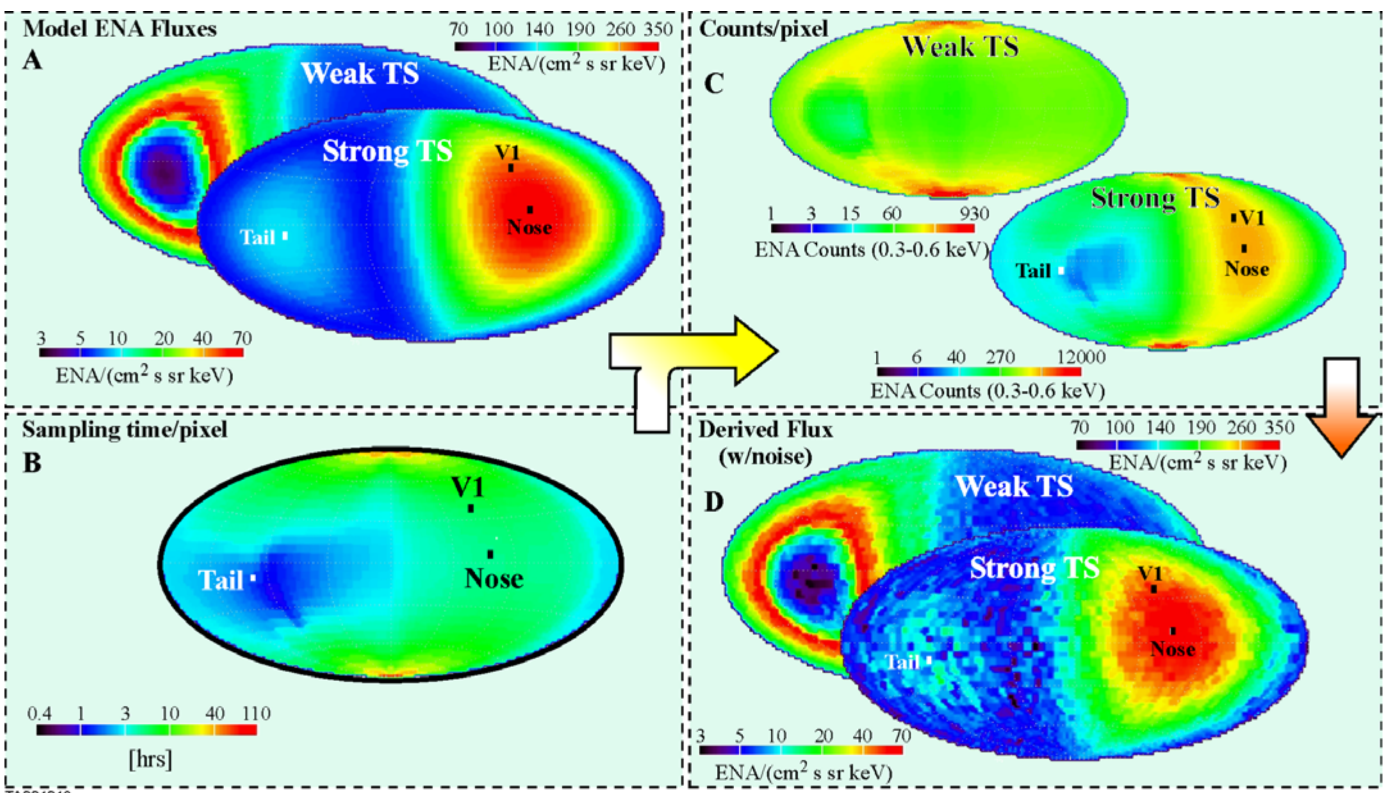

Figure 8. IBEX resolves high quality images of the global heliosphere. Shown here are (A) the simulated H ENA differential fluxes for the extreme cases of a strong and weak TS (Fig. 4), (B) the sample time per pixel over the first two years of observation (excludes views through the magnetosphere), (C) predicted H ENA (0.3-0.6 keV) counts per pixel determined by multiplying ENA fluxes time energy, sample time, geometric factor and dutycycle, (D) H ENA differential fluxes with random noise based on predicted counts.

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