Space Sci Rev (2009) 146: 11–33
DOI 10.1007/s11214-009-9499-4

IBEX—Interstellar Boundary Explorer

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Received: 17 November 2008 / Accepted: 23 March 2009 / Published online: 18 April 2009

Abstract The Interstellar Boundary Explorer (IBEX) is a small explorer mission that launched on 19 October 2008 with the sole, focused science objective to *discover the global interaction between the solar wind and the interstellar medium*. IBEX is designed to achieve this objective by answering four fundamental science questions: (1) What is the global strength and structure of the termination shock, (2) How are energetic protons accelerated

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at the termination shock, (3) What are the global properties of the solar wind flow beyond the termination shock and in the heliotail, and (4) How does the interstellar flow interact with the heliosphere beyond the heliopause? The answers to these questions rely on energy-resolved images of energetic neutral atoms (ENAs), which originate beyond the termination shock, in the inner heliosheath. To make these exploratory ENA observations IBEX carries two ultra-high sensitivity ENA cameras on a simple spinning spacecraft. IBEX's very high apogee Earth orbit was achieved using a new and significantly enhanced method for launching small satellites; this orbit allows viewing of the outer heliosphere from beyond the Earth's relatively bright magnetospheric ENA emissions. The combination of full-sky imaging and energy spectral measurements of ENAs over the range from ∼10 eV to 6 keV provides the critical information to allow us to achieve our science objective and understand this global interaction for the first time. The IBEX mission was developed to 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.

Keywords Interstellar boundary · Termination shock · Heliopause · Energetic Neutral Atom · ENA · LISM

1 Introduction

The galaxy is filled with the ancient debris of exploded stars (novae and supernovae) and fossil stellar winds. This interstellar medium is composed of neutral gas, ionized and magnetized plasma, and dust. The stellar winds that expand out from other stars carve out and

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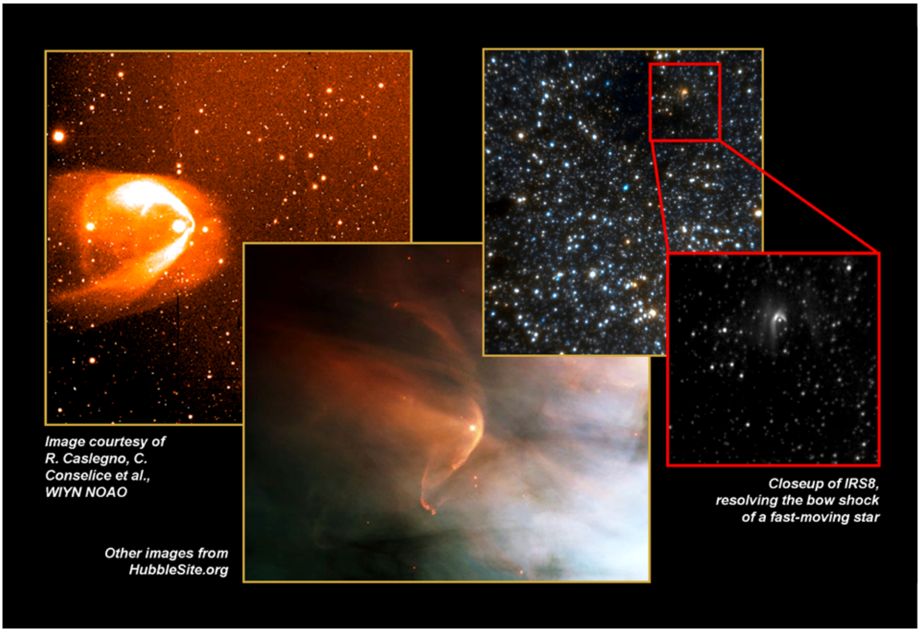

Fig. 1 Stars produce powerful stellar winds that clear out and interact with their nearby interstellar medium. This complex interaction creates the emissions seen in the images here from the Hubble telescope and WIYN NOAO observatory

interact with part of their nearby interstellar medium to form "astrospheres" (Fig. 1) around these stars. Our own astrosphere, the heliosphere, is inflated by the Sun's supersonic solar wind and its embedded Interplanetary Magnetic Field (IMF). Because the Sun moves with respect to the local interstellar medium (LISM) at $\sim$26 km s^{-1}, the interaction is highly asymmetric, being both compressed on the nose and stretched out into a long "heliotail" on the opposite side. (e.g., see recent review by Fahr et al. 2007 and references therein). Figure 2 schematically represents our heliosphere and identifies its primary boundaries.

The neutral portion of the LISM is unaffected by plasma interactions and continually drifts into the heliosphere. However, some fraction of these interstellar neutral atoms become ionized via charge-exchange with ions that pile-up ahead of the heliopause in the so-called hydrogen wall. Some of the interstellar neutrals that drift into the heliosphere become ionized, creating "pickup" ions (PUIs), which gyrate about the IMF and are swept outward from the Sun. The pickup process also endows PUIs with up to twice the solar wind speed (four times the energy per nucleon); these higher-energy ions can be preferentially accelerated at shocks, and diffusive shock acceleration at the termination shock (TS) (Pesses et al. 1981) has long been the standard model to energize these PUIs into anomalous cosmic rays (ACRs) with energies of $\sim$10–100 MeV/nuc.

In 2003, when IBEX was proposed, our limited knowledge of the interstellar interaction had been gleaned largely from a variety of indirect methods, including observations well inside the TS of interstellar neutral H and He atoms, pickup ions, ACRs, and radio waves. These observations were combined with theory and relatively simple modeling in order to try and understand the distant heliospheric interactions. (See for example the review by Zank 1999 and references therein.) Since then, the study of the outer heliosphere has burst into the forefront of Heliophysics research with the crossing of the TS by Voyager 1 on

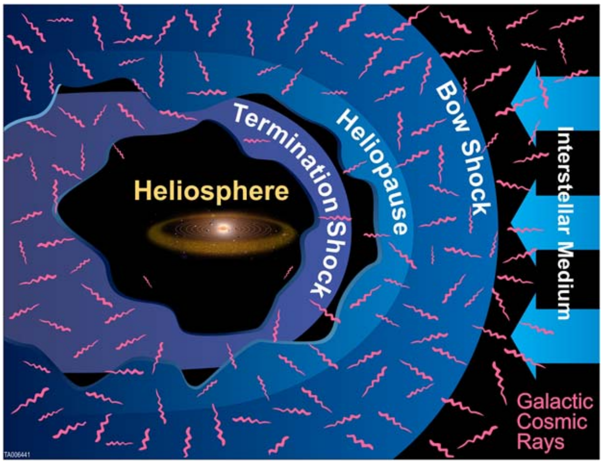

Fig. 2 Our current understanding is that the interstellar interaction creates three distinct interstellar boundaries schematically shown here. From inside out, these are: (1) the TS where the solar wind is slowed and heated and begins to divert away from the inflowing LISM, (2) the heliopause, which separates the solar wind plasma from the ionized LISM material, and, furthest out, (3) a bow shock (BS) or bow wave, which begins to divert the upstream LISM around the heliosphere. The wiggly red lines represent galactic cosmic rays, the vast majority of which are shielded out by the heliospheric interaction, particularly in the inner heliosheath, between the BS and heliopause

16 December 2004 (Stone et al. 2005; Burlaga et al. 2005; Cummings and Stone 2001; Decker et al. 2005) and then several TS crossings by Voyager 2 between 30 August and 1 September 2007 (Stone et al. 2008; Burlaga et al. 2008; Decker et al. 2008; Richardson et al. 2008). Many of the fundamental ideas that existed in 2003 about this interesting boundary have not survived the reality of the Voyagers' direct observations.

Three major results from the Voyager observations were especially surprising. First, the ACRs were not accelerated at the TS, at least at the times and locations where the two Voyager spacecraft crossed it. Since the Voyager 1 crossing, several possible explanations have been proposed to explain the paucity of observed ACRs. McComas and Schwadron (2006) pointed out that the asymmetric shape of the TS has critical implications for the locations where particles can be accelerated up to ACR energies. ACR acceleration should not be expected near the nose where both Voyagers crossed, but instead should occur back along the flanks and tail of the TS where the IMF has been connected to the TS for very long times ($\sim$1 year) and diffusive acceleration would have persisted long enough to accelerate PUIs to ACR energies (McComas and Schwadron 2006; Schwadron et al. 2008). Another idea is that the TS may not accelerate ACRs at all and instead they might be energized by distributed stochastic acceleration beyond the TS, out in the heliosheath (Fisk et al. 2006).

A second major surprise from the Voyagers was the huge difference in radial distance between the Voyager 1 crossing at $\sim$94 AU and Voyager 2 crossings $\sim$10 AU closer at $\sim$84 AU. While some of this difference may well be caused by a prolonged decrease in the solar wind dynamic pressure (McComas et al. 2008), some of it likely reflects a north-south asymmetry in the TS. Such an asymmetry could be caused by the interstellar magnetic field distorting the TS and heliopause (Linde et al. 1998; Lallement et al. 2005). Subsequent modeling efforts had grappled with the large asymmetry observed by the Voyagers (e.g., Opher et al. 2007; Pogorelov et al. 2007; Heerikhuisen et al. 2008; Sternal et al. 2008).

A third major surprise was not observed until Voyager 2, with its functioning plasma instrument, reached the TS (Richardson et al. 2008). These observations showed that the bulk solar wind plasma received only about a fifth of the heating available from crossing the TS. Instead, the bulk of the available energy appears to go into higher energy PUIs. Thus, these PUIs play a major role in moderating the TS physics, and detailed physical models of this region need to account for both the lower-energy solar wind and higher-energy PUI populations.

The many mysteries surrounding the Voyager observations show just how exciting and dynamic the rapidly evolving field of outer heliospheric physics is today. However, they also point to the limitations of single-point (or even dual-point) *in situ* observations in the heliosheath. Because of the size, scale, complexity, and evidently even variability of the interaction, it is extremely difficult to divine the outer heliosphere's global configuration and properties without global information from all portions of this interaction. The Interstellar Boundary Explorer (IBEX) is designed and optimized precisely to provide this global, all-sky information.

IBEX was designed to make the first all-sky observations of the heliosphere's interaction with the LISM by imaging energetic neutral atoms (ENAs) produced largely beyond the TS, in the inner heliosheath, where the solar wind and imbedded PUIs have been slowed and heated. In the heliosheath, these populations of predominantly hydrogen ions produce a significant flux of detectable inward moving ENAs via charge-exchange with local interstellar neutrals. Only one potential observation of ENAs produced from PUI populations in the heliosphere has been reported to date. Wurz et al. (2008, and references therein), reported ENAs with limited spatial and temporal coverage in the energy range from 200 eV to 80 keV. In contrast, IBEX was optimized to provide all-sky imaging of the ENA fluxes, which are spatially resolved in both latitude and longitude, and does so over the critical energy range that covers both the solar wind and much of the PUI population in the inner heliosheath.

IBEX carries two very large geometric factor ENA cameras: IBEX-Lo, which measures ENAs from $\sim$10 eV to 2 keV and IBEX-Hi, which measures them from $\sim$300 eV to 6 keV. Both sensors have angular resolutions of $\sim 6.5° \times 6.5°$, enabling well-resolved images with $\sim$1800 pixels covering the whole sky. Furthermore, IBEX-Lo has eight energy-resolved channels covering its energy range and IBEX-Hi six, thus producing images at many different energies, and even more importantly, energy spectral information for each direction in the sky. The two IBEX sensors' energy ranges also overlap from $\sim$300 eV to 2 keV to provide independent observations across the critical energy range. Thus, IBEX is optimized to globally image ENAs from the outer heliosphere for the first time. Figure 3 provides a summary of the charge-exchange process and how IBEX rotation and motion naturally generate all-sky maps of the ENAs propagating in from the inner heliosheath each six months.

IBEX is central to NASA's Heliophysics program, since 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 galactic medium. IBEX was developed to provide global, fundamental, and direct insights into the interactions at the boundary of our Sun's astrosphere, the heliosphere. These insights should also improve our understanding of the broader problem of how galaxies and stars interact and evolve. IBEX was designed to discover the global properties of energetic protons near the TS, which also allows us to explore the very important problem of how charged particles are accelerated at shocks in space plasmas more generally.

Prior to the selection of IBEX, such observations had been called for by a broad community consensus that was documented in prior Decadal Survey—*The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (*2003*); the prior

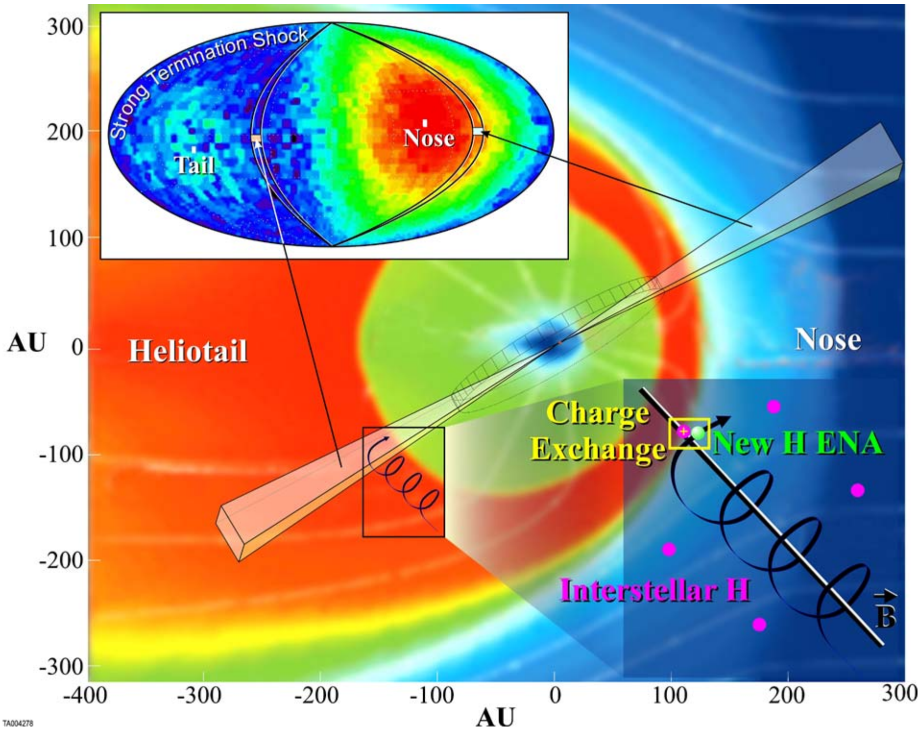

Fig. 3 Charge exchange between hot ions and cold interstellar neutrals (*lower right inset*) produce ENAs, some of which happen to be directed inward and propagate all the way into the inner heliosphere where they can be detected by the IBEX spacecraft in a very high-altitude Earth orbit. The two instantaneous ~6.5° × 6.5° fields-of-view of the IBEX-Hi and Lo sensors are depicted in the main image; these map to the two indicated pixels in the all-sky map (*top left*). As the sun-pointed IBEX spacecraft spins, the pixels viewed move repeatedly around the two indicated crescents in the sky map. Then, as IBEX repoints at the end of each orbit, the viewed crescents move across the sky producing all-sky maps each six months

Roadmap—*Sun-Earth Connection Roadmap 2003–2028: Understand how the Sun, Heliosphere, and the Planetary Environments are Connected in a Single Connected System* (*January 2003*); and even NASA's 2003 agency-wide plan—*National Aeronautics and Space Administration 2003 Strategic Plan*. In the case of the National Research Council's Decadal Survey, the Explorer Program was explicitly recommended: "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.…" The IBEX Small Explorer mission proposal responded to these urgent calls from the community for global imaging of the heliospheric interaction.

IBEX was developed on a very fast timeline, moving from selection on 26 January 2005 to the fully integrated and tested payload and spacecraft being ready to deliver to the launch vehicle at Vandenberg Air Force Base (VAFB) in mid-April 2008. Such a delivery would have supported the planned June 2008 launch. Unfortunately, launch vehicle loads problems

Table 1 Schedule of major milestones for the IBEX mission

Proposal submitted	2 May 2003
Concept Study Report	18 June 2004
Mission selected	26 January 2005
Mission PDR	17–18 January 2006
Confirmation Review	13 March 2006
Mission CDR	13–18 September 2006
Payload Delivery to Spacecraft	8 October 2007
Final Delivery to VAFB	28 July 2008
Launch	19 October 2008

forced the IBEX team to design, build, and test a "Shock Ring" in order to reduce the loads the launch vehicle would have driven into our flight system down to acceptable and previously tested-to levels. That process, led by the IBEX project, was fast-tracked and completed in about three months, far shorter than the original estimate of 9–12 months for the launch vehicle to provide a "Soft Ride" to bring the loads down. Table 1 summarizes the critical milestones for the IBEX mission.

This paper briefly summarizes the IBEX mission and serves as an overview and introduction to the other chapters in the IBEX book. The bulk of those papers provide detailed discussions of the IBEX flight hardware and other aspects of the IBEX mission; references to those chapters are provided in the appropriate sections throughout this paper. In addition, we included four chapters that summarize the state of knowledge of the LISM and outer heliospheric interaction at the time of the IBEX launch (Frisch et al. 2009, this issue; Izmodenov et al. 2009, this issue; Lee et al. 2009, this issue; Zank et al. 2009, this issue).

2 Scientific Objective, Questions, and Closure

IBEX's sole, focused science objective is to *discover the global interaction between the solar wind and interstellar medium.* IBEX is designed to achieve this 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?

Because so little was known about the heliosphere's global interaction at the time of the IBEX proposal, we developed a broadly scoped science strategy to address these questions. Now, with the Voyager observations opening new mysteries about the interstellar interaction, our broad approach is even more critical. We consider the science return in terms of three levels of study: *Discovery*, *Exploration*, and *Deep Understanding*. At the *Discovery* level, fundamental properties of the interstellar interaction can be directly gleaned from the IBEX images, energy spectra, and interstellar neutral fluxes. At the *Exploration* level, we will combine the observations with simple physics-based calculations, theory and limited 2D and 3D modeling to explore the more detailed properties of the outer heliosphere. Finally, at the

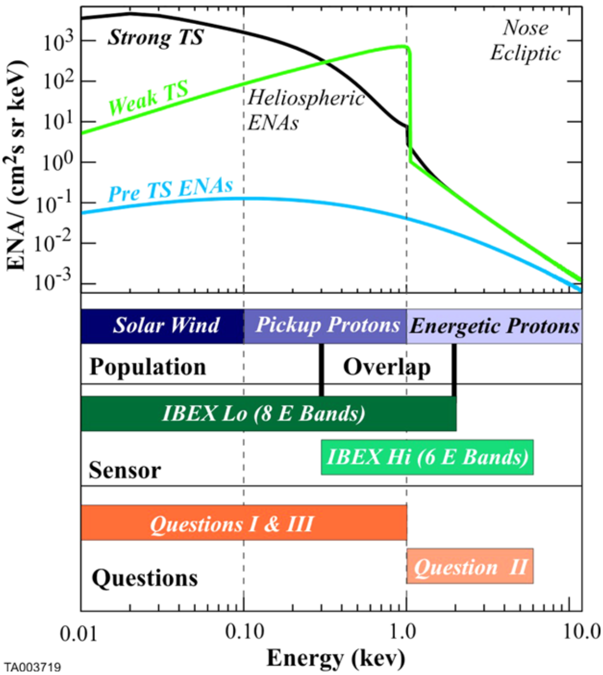

Fig. 4 The IBEX H ENA energy range is designed to provide the critical distributions needed to reveal the global properties of the proton populations of the inner heliosheath. Shown here are predicted ENA energy distributions near the nose of the heliosphere for a strong (*black curve*) and weak (*green 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 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)

Deep Understanding level, we will extract the detailed global properties of the interstellar interaction through iterative analyses using IBEX data observations in concert with detailed 3D models of the heliosphere.

At the *Exploration* and *Deep Understanding* levels, we will make increasingly extensive use of theory and modeling to gain further insight into the global properties of the interstellar interaction. Many IBEX team members have a strong background in heliospheric theory and modeling. However, in order to expand the team and pull in an even broader segment of the community, we set aside $2M from our proposal cost-cap to fund a NASA-selected Guest Investigator (GI) program that specifically targets the coordinated use of IBEX data products to iteratively refine 3D models of the heliosphere. NASA has already made a first solicitation for such proposals and we look forward to welcoming the selected scientists into the IBEX Team.

The next four subsections very briefly summarize our four science questions and how IBEX observations were designed to uniquely address them. For illustration, Fig. 4 summarizes two possible extreme shapes of the H ENA energy distribution and compares them to the energy coverage of the IBEX-Hi and Lo sensors. More detailed discussion of the four science questions and the approach that our team proposed to answer them was given in McComas et al. (2004b). Much more detail on the final, complete IBEX capabilities and our ability to make the needed measurements to answer these questions is provided in the other detailed papers throughout this volume.

2.1 Question 1: What Is the Global Strength and Structure of the TS?

When we proposed IBEX, before the Voyagers observed the TS directly, we asked: "*Is there a termination shock? If the solar wind carries most of the pressure, the TS should be a strong gas-dynamic 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.*" Now with the *in situ* observations from Voyager 1 and especially Voyager 2, we know that there is a TS, at least at times, near the nose of the heliosphere where the Voyagers crossed it. However, it is not a strong shock, and it is highly moderated by the addition of PUIs. Analysis of the combination of global images and energy-spectral information from IBEX will make it possible to derive the proton-energy distributions in the inner heliosheath and determine the shock strength as a function of position. Such 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.

As an example of the types of observations IBEX was designed to make, Fig. 5 shows simulated all-sky maps of ENA fluxes over the energy range examined by IBEX. The model (Heerikhuisen et al. 2008) includes neutrals, the suspected external magnetic field orientation in the LISM, and a realistic κ-function ion distribution (they used $\kappa = 1.63$, based on the Voyager 1 data at higher energies Decker et al. 2005). Several features stand out in these simulations, including the highest emissions from down the tail and the bright, diffuse, and apparently banded emissions from across the nose (see Heerikhuisen et al. 2008 for details). While the real heliospheric interaction is undoubtedly much more complex than this simulation, IBEX's energy-resolved maps will clearly provide the detailed all-sky observations needed to understand the global configuration.

2.2 Question 2: How Are Energetic Protons Accelerated at the Termination Shock?

The TS is a nearly perpendicular shock (shock normal perpendicular to the local magnetic field) owing to the winding up of the IMF in the outer heliosphere. This geometry leads to an "injection problem" (Lee 2000; Rice et al. 2000; Giacalone 2001) where the particles can only be efficiently accelerated at the shock if they already have very high speeds along the magnetic field. Furthermore, the TS is highly moderated by the large numbers of PUIs, suggesting that the shock acceleration is a highly non-linear process where the TS accelerates protons, and the energetic protons in turn modify the shock, thereby changing the very nature of the acceleration.

IBEX will infer the properties of accelerated protons near the TS by measuring their energy distributions via the H ENAs produced from these accelerated protons up to 6 keV. While these protons are much lower energy than ACRs or even the injected particles, they feed these higher energy protons. By measuring the intensity and energy dependence at lower energies, IBEX will infer the injection and acceleration of protons at higher energies. In addition, IBEX's energy spectral measurements from all directions in the sky are designed to enable the exploration of the variability of the TS, further informing the complicated, iterative mechanisms of shock physics. IBEX will directly observe the intensity of ENAs from accelerated protons relative to the solar wind and pickup protons below 1 keV. These observations, in concert with modeling to deconvolve the line-of-sight (LOS) integration and to extrapolate the measurements over an energy range needed to estimate the energetic proton pressure, should make it possible to determine how the TS is moderated at various locations. Finally, more advanced models of shock acceleration in the future will ultimately have to tally with all of the detailed IBEX spectral observations.

2.3 Question 3: What Are the Global Properties of the Solar Wind Flow beyond the Termination Shock and in the Heliotail?

After crossing the TS, the solar wind and PUIs become swept back in the inner heliosheath by the interaction with the LISM. Ultimately, nearly all this material must flow back and

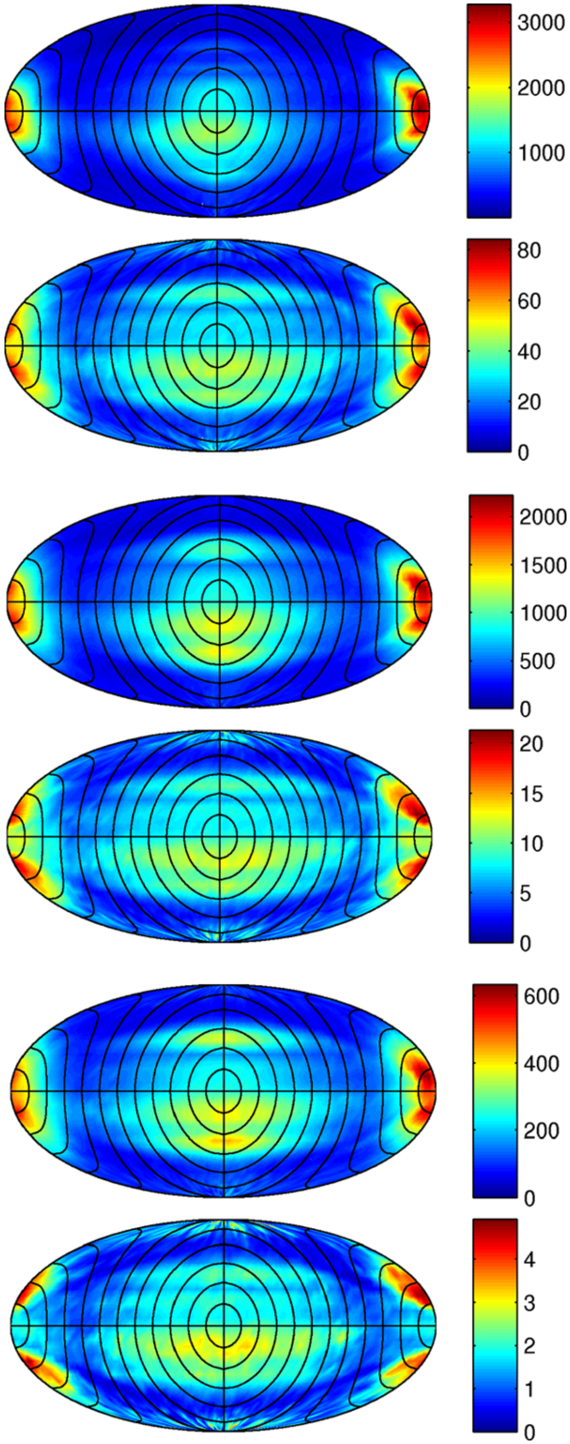

Fig. 5 Simulated all-sky maps of ENAs at various energies taken from Heerikhuisen et al. (2008). The maps plot color-coded ENA fluxes in units of $\mathrm{cm}^2\,\mathrm{s\,sr\,keV}^{-1}$ for energy bands of 8–12 eV, 40–60 eV, 180–220 eV, 900–1100 eV, 2200–2600 eV and 5600–6400 eV, respectively from *top* to *bottom*. In each panel, the nose of the heliosphere is in the center with the poles at the *top* and *bottom* and tail on the *far left* and *right sides*

down the heliotail. Various models predict the flow patterns in the heliosheath and heliotail (e.g., Baranov and Malama 1993, 1996; Zank et al. 1996; Linde 1998; Linde et al. 1998; Müller et al. 2000) with differences that depend critically on the model approach and assumptions about both the solar wind and LISM.

Global ENA observations from IBEX should provide extremely sensitive measures of the asymmetries in the properties of the ions in the inner heliosheath as well as the thickness of this region. By making all-sky observations over the full energy range of the bulk populations, IBEX will measure the thermalization and energy partition of the solar wind and PUIs and the global flow patterns of the solar wind beyond the TS.

As a simple example, Fig. 4 compares model energy spectra for a strong gas-dynamic shock (black) with no contribution from PUIs and a shock weakened by PUIs (green). Differences in the source ion energy distributions generate significant differences in the ENA emissions even in this one energy band. The combination multiple images across the broad range covered by IBEX will very strongly constrain the properties and flow patterns in the inner heliosheath.

2.4 Question 4: How Does the Interstellar Flow Interact with the Heliosphere beyond the Heliopause?

Because hydrogen and oxygen ions and atoms readily charge-exchange with each other, the filtration process that modifies the inflowing interstellar neutral H similarly modifies the interstellar neutral O. Thus, interstellar O measured by IBEX comprises two populations: an unmodified or "primary" population that reflects the undisturbed properties of the LISM and a "secondary" population, which generally reflects the ion population in the outer heliosheath. IBEX is designed to provide the first direct measurement of filtered interstellar neutrals (see Fig. 6). This is possible because the Sun's gravity focuses the inflowing interstellar O atoms in the direction opposite to the interstellar flow. Careful measurements of the detailed distribution of the incoming neutrals' directions by IBEX will allow differentiation between and separate quantification of the primary and secondary populations. Measurements of the primary population should provide additional direct information about the LISM, while measurements of the secondary population should allow us to measure the heating, deceleration and depletion associated with the interstellar interaction near the heliopause at the hydrogen wall. Detailed discussion of this topic is provided by Möbius et al. (2009, this issue).

2.5 Scientific Closure

The process we followed to define the IBEX capabilities and requirements flowed naturally from deciding what was needed to answer the above four science questions. As summarized in Table 2, for each question, we identified answers that could be provided at each of the three levels of examination: *Discovery*, *Exploration*, and *Deep Understanding*. Then we specifically identified what measurement requirements would allow us to fully answer these questions with sufficient margin to span unanticipated discovery science because of the extremely limited knowledge at the start of the IBEX mission of the structure and dynamics of the interaction region. As examples, the required angular and energy resolutions and ranges are shown at the bottom of Table 2. These and many other requirements went into our baseline mission requirements, which drove the entire design and development of the IBEX mission. In addition to baseline requirements, we also developed minimum mission requirements that would still provide acceptable science return for the mission if we

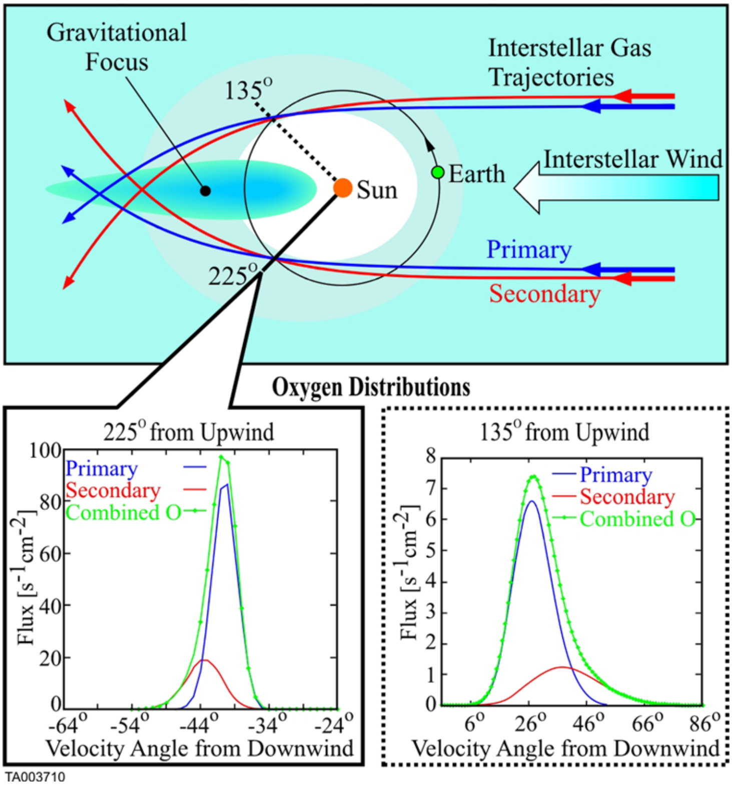

Fig. 6 Schematic diagram of neutral O trajectories along hyperbolic orbits and locations in the IBEX orbit when it will be able to make direct measurements of the inflowing interstellar oxygen (*top*). The *bottom panels* show model fluxes as a function of velocity angle measured during the two optimum times of the year. The filtered secondary population is slower, hotter and more strongly deflected than the primary population

were unable to fully meet the baseline requirements in some area. We are delighted to report that the IBEX mission as built and flown meets, and in most areas exceeds, our full baseline requirements.

3 IBEX Flight System

The IBEX flight system comprises all the mission components that launched into space on board the Pegasus launch vehicle. These include the IBEX payload, which consists of two science sensors and a combined electronics box; the IBEX spacecraft bus, which carries the payload; and a solid rocket motor (SRM) and adapter cone, which are used to help boost the spacecraft into a highly elliptical, high-altitude Earth orbit.

3.1 The IBEX Payload

The IBEX payload was designed to meet or exceed all baseline requirements and answer all four science questions described in the previous section. Because technical resources in general and mass in particular, were very limited, we needed to develop the most efficient

Table 2 IBEX science questions, levels of study, and derived top-level measurement requirements

	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				
	Fundamental Science Questions / **Levels**	**I:** *TS Strength/ Structure*	**II:** *Energetic Protons Near TS*	**III:** *Solar Wind Flow Patterns of Inner Heliosheath*	**IV:** *Interstellar Flow and Interaction*
Raw Images	**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
Detailed Models	**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
	Measurements Requirements				
	Global heliospheric ENA imaging	$7^{\circ}\times7^{\circ}$ pixels	$21^{\circ}\times21^{\circ}$ pixels	$7^{\circ}\times7^{\circ}$ pixels	Determine O Direction to 2.0° FWHM
	H energy spectra: Solar wind through energetic particle ENAs	0.01-1 keV in 7 energy bands	1-6 keV in 4 energy bands	0.01-1 keV in 7 energy bands	
	O fluxes and velocity direction vs. time of year				0.01-0.5 keV in 6 energy bands

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science payload possible, making full use of all of the heritage experience and expertise from across the IBEX team. This process led to an optimized payload consisting of two very large aperture single pixel ENA cameras: IBEX-Lo (Fuselier et al. 2009, this issue), which measures ENAs with energies from ∼10 eV up to 2 keV, and IBEX-Hi (Funsten et al. 2009, this issue), which measures ENAs with energies from ∼300 eV up to 6 keV. Both sensors are served by a single combined electronics unit (CEU). Critical parameters for IBEX-Hi, Lo and the CEU are summarized in Table 3.

Both the IBEX-Hi and Lo sensor designs are based on the same physical principles, but each is tailored to optimize ENA measurements for their respective energy ranges. Figure 7 shows schematic diagrams of the two sensors. Each is comprised of the same four subsystems: an entrance system, a charge-conversion system, an electrostatic analyzer (ESA), and a detection system.

ENAs enter the IBEX sensors through entrance systems, which are comprised of a sun shield, electron rejection ring, pre-collimator, and collimator. A slanted sunshade shields the rest of the entrance system components from any direct solar illumination during normal operations. The electron rejection ring imposes a negative potential across the aperture without any grids or other structures that could generate neutral particles. This potential excludes all except the highest-energy electrons (>600 eV) from reaching the aperture.

The pre-collimators and collimator set the intrinsic angular resolution of our measurements to ∼6.5° FWHM in both sensors. In addition, IBEX-Lo has a higher angular resolution quadrant (∼3.2° FWHM) that is used for direct detection of the low-energy interstellar oxygen (science question 4 above). The entire collimator is biased to +10 kV, which rejects positive ions from the surrounding space environment with energies <10 keV/q. UV light, which can be a significant source of background for these measurements, passes unaffected through the collimators as do the ENAs.

Table 3 Key IBEX payload parameters and resources

	IBEX-Hi	IBEX-Lo	CEU
Energy Range	300 eV–6.0 keV	10 eV–2 keV	N/A
Energy resolution ($\Delta E_{FWHM}/E$)	0.47–0.66	0.8	N/A
Number of Energy Steps	6	8	N/A
FOV (FWHM)	6.5° × 6.5°	6.5° × 6.5° 3.2° × 3.2°	N/A
Geometric Factor for H near 1 keV (double coincidence)	3×10^{-3} cm^2 sr eV/eV at 1.1 keV	8.1×10^{-4} cm^2 sr eV/eV at 0.78 keV	N/A
Geometric Factor for H near 1 keV (triple coincidence)	7.3×10^{-4} cm^2 sr eV/eV at 1.1 keV	2.9×10^{-4} cm^2 sr eV/eV at 0.78 keV	N/A
Mass	7.70 kg	12.09 kg	5.42 kg
Volume	43.94 cm Dia × 23.75 cm	40 cm Dia × 31.45 cm	43.82 cm × 27.9 cm × 9.5 cm
Power	0.7 W	3.5 W	11.2 W
Telemetry	102.6 bps	122.8 bps	11.8 bps

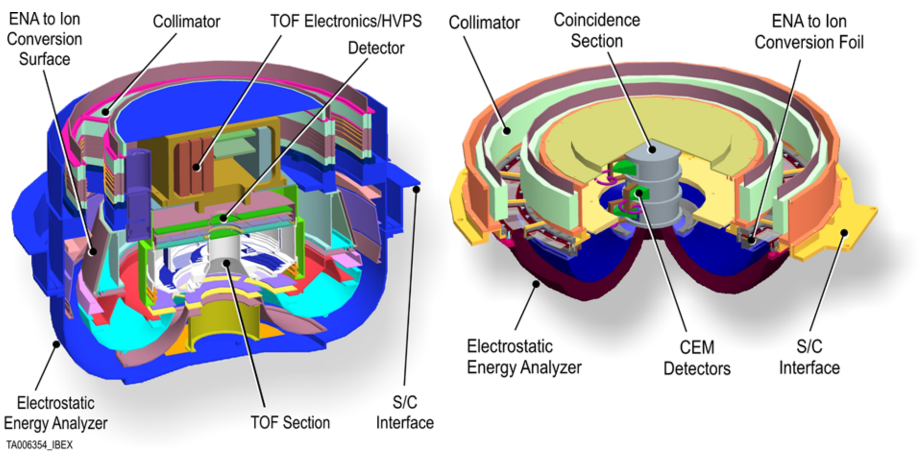

Fig. 7 Schematic diagrams of the IBEX-Lo (*left*) and IBEX-Hi (*right*) sensors. Both are based on large "bundt pan" type ESAs, which focus huge aperture areas onto their central detector sections. While optimized differently for the higher and lower energy ranges, both are comprised of the same four basic subsystems

The next step in detecting the ENAs is to convert them back into charged particles. ENAs are detected in the IBEX sensors using the same process that produced them in the outer heliosphere—charge exchange. In the case of IBEX-Hi some fraction of the neutrals are converted to positive ions as they pass through a set of ultra-thin carbon foils, which are only $\sim$0.5 μg cm^{-2}, or $\sim$50–100 atoms thick (see McComas et al. 2004a and references therein). At even lower energies, the ENAs can't make it through even these very thin foils. Instead, in IBEX-Lo, conversion produces negative ions, as they reflect off of special CVD diamond surfaces (Gruntman 1997 and references therein). The efficiency for both of these processes is low: $\sim$one percent to a few tens of percent, so one of the biggest drivers for the sensor design was to find a way to maximize the aperture area.

The aperture areas of both IBEX-Lo and Hi were maximized by using "Bundt pan" shaped ESAs (Moestue 1973). With this design, truly immense open areas can be arrayed around the perimeters of the sensors, and ions produced by the incident ENAs are bent around into reasonable sized, central detector sections. Thus, in addition to removing the UV that enters the sensors and setting a voltage-dependant energy pass band as all ESAs do, the IBEX ESAs also concentrate the particles from a very large aperture onto a small, central detector in a way that greatly increases both sensors' signals and signal-to-noise ratios.

The final stage of measuring the heliospheric ENAs is the detection process. In both detector subsystems, the converted incident ions pass through a pair of ultra-thin carbon foils, which then emit secondary electrons. In IBEX-Lo, both the primary particle and the secondary electrons are detected on a microchannel plate (MCP) detector, and the time-of-flight (TOF) of the primary is measured, allowing determination of its species (e.g., H, He, or O). In the case of IBEX-Hi, the ionized ENA transits three stacked detection chambers separated by the two foils, and secondary electrons generated in each chamber are detected by the channel electron multiplier (CEM) in that chamber. Both sensors have both double and triple coincidence data products, with the triple coincidence ones having exceptionally low background (false positive) rates. Both of these designs are optimized to suppress the intrinsic detector section backgrounds. The backgrounds of both sensors and the overall mission noise and background have been carefully studied and painstakingly minimized (Wurz et al. 2009, this issue).

Finally, both IBEX sensors have small additional components that support their science observations. For IBEX-Lo, a small star sensor has been added that allows extremely precise knowledge of this sensor's pointing. These measurements greatly increase the precision with which the interstellar neutrals can be measured and the primary and secondary populations can be separated (Möebius et al. 2009, this issue). In IBEX-Hi, we added a small background monitor to provide independent measurements of the local energetic ion environment (Allegrini et al. 2009, this issue). These observations enhance our ability to identify and remove times when the local plasma environment could be contaminating the ENA observations.

Both sensors are served by the CEU. This box provides the single spacecraft interface, data processing, low-voltage power supplies, and high-voltage power supplies for both sensors. As part of the spacecraft interface, the CEU accepts, parses and routes commands and stores and plays back spacecraft and science telemetry. The command and data handling is based on a 8051 core processor. As the CEU steps the various sensor high voltages, it gathers, bins, and processes the raw science data. A two-gigabit solid state recorder makes it possible to store multiple orbits' worth of science data and spacecraft telemetry.

The CEU's low-voltage power supplies create and distribute separate custom low voltages for the two sensors and provide monitoring as well as solid-state relay switching for all of these outputs. The high-voltage system comprises four independent high-voltage supplies, which have a resonant (at $\sim$100 kHz) fly-back-type topology and contain collimator supplies and combined bulk supplies separately for each sensor. Other than one additional high-voltage supply located inside IBEX-Lo, the CEU supplies all 16 sensor high-voltage outputs on coaxial high-voltage cables.

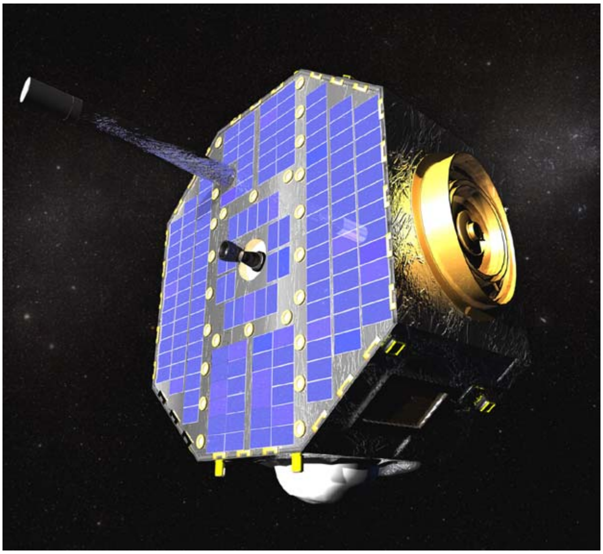

Fig. 8 The IBEX spacecraft is just under 1 m across and approximately 0.5 m tall. The sun-pointed surface is covered with solar cells; IBEX spins around an axis perpendicular to this plane. The white protrusion on the bottom is a blanket that covers one of the two symmetric hydrazine tanks; the gold-plated instrument on the right is IBEX-Lo

3.2 The IBEX Spacecraft

The IBEX spacecraft (Fig. 8) was designed and built by Orbital Sciences Corporation, based on their earlier "MicroStar" line flown on the 35 ORBCOMM spacecraft launched between 1995 and 1999. Although single string, the MicroStar bus has proven to be reliable in its previous missions; it was also part of NASA's Rapid Spacecraft Development Office catalog that we reviewed at the time of the IBEX proposal.

For IBEX, the largely unchanged MicroStar avionics were put into a new thrust-tube-based mechanical design structure. These electronics feature a distributed Motorola 68302 microprocessor-based architecture, with the Command and Data Handling (C&DH) system, Attitude Control System (ACS), and Electrical Power Subsystem (EPS) each controlled by a dedicated processor. The Flight Computer is the spacecraft controller; the Attitude Control Electronics interface to the ACS components and hosts the ACS software; and the Battery Charge Regulator provides power for all spacecraft loads and performs ancillary functions including heater control, SRM fire, and separation-system actuation. The Mission Interface Unit (MIU) provides the interface between the spacecraft and the payload CEU. (The CEU, briefly described above, stores all mission data, including spacecraft housekeeping telemetry.) The MIU also provides the interface to the S-band transceiver to receive uplinked commands and downlink telemetry and science data. On-board propulsion for perigee raising, spin down, and orbital maneuvers is provided by the hydrazine propulsion system (HPS). The spacecraft block diagram is shown in Fig. 9. More details about the CEU, spacecraft, and mission design are provided by Scherrer et al. (2009, this issue).

The IBEX flight system and spacecraft key parameters are summarized in Table 4. The IBEX flight system was the heaviest object ever launched by Pegasus with a total mass of ∼458 kg. Of that, the fueled (wet) spacecraft was only ∼105 kg, less than a quarter of the total launch mass. The remainder of the mass was used for our SRM, adapter cone, and associated separation systems and harnessing. By developing and flying these additional components, the IBEX team was able to lift our spacecraft from its low Earth orbit provided by Pegasus to a very high-altitude orbit required for our science mission; this process is described in Sect. 4.

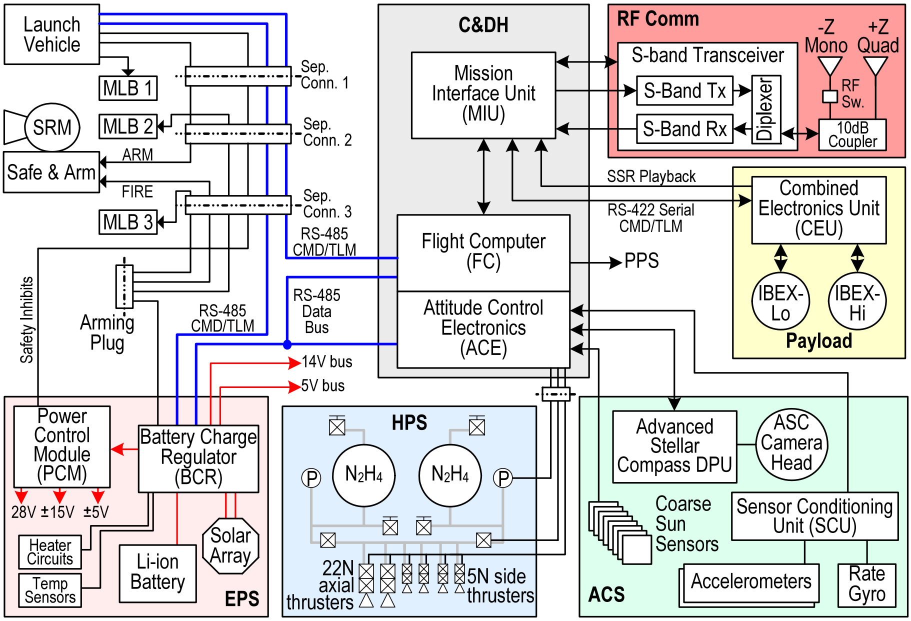

Fig. 9 Block diagram of the IBEX flight system

Table 4 Key parameters for IBEX Spacecraft and Flight System

Resource	Value
Dry Mass (Spacecraft)	78.6 kg
Wet Mass (Spacecraft)	104.9 kg
Wet Mass (Flight System)	457.7 kg
Volume (Spacecraft)	95 × 89 × 49 cm (124 cm with antennas)
Volume (Flight System)	95 × 89 × 166 cm (221 cm with antennas)
Energy Consumption (Nominal Ops)	14.0 kW-Hr
Solar Array Generation (Nominal Ops)	15.9 kW-Hr
Data Generation (Per Orbit)	257.9 Mbits
Data Storage Capacity	1074 Mbits
Science Spin Rate	4 RPM (23 for maneuvers, 60 at launch)
Pointing Knowledge	0.12°
Pointing Control	1.7°
Command Protocol	S-Band
Telemetry Downlink Rate	2, 40, 64, 160 or 320 kbps
Command Rate	2 kbps

4 A New Launch Capability and Mission Design

One of the most challenging aspects of the IBEX mission was to develop a totally new way to achieve a very high-altitude Earth orbit starting from a Pegasus rocket launch. The Pegasus

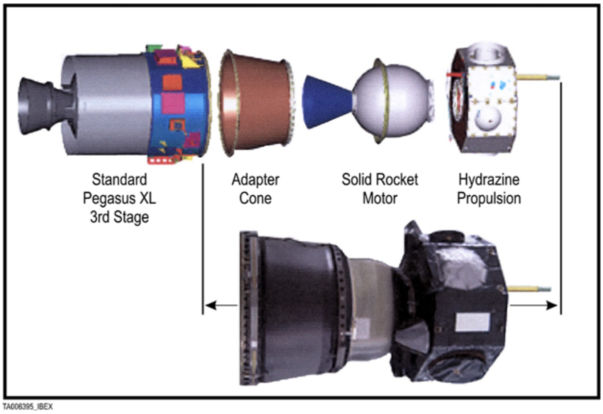

Fig. 10 Picture of IBEX flight system (*bottom*) and exploded view (*top*) along with the Pegasus third stage. The addition of our own SRM and HPS allowed IBEX to use a Pegasus launch to low Earth orbit as a starting point to boost our spacecraft into a very high-altitude ($\sim$50 R_E) orbit

is an airplane-launched rocket. It is also the smallest and cheapest launch vehicle available in NASA's arsenal. Pegasus was designed to deliver small spacecraft (up to $\sim$400 kg) to low Earth orbits of a few hundred km altitude. Because IBEX needs to be well outside the Earth's magnetosphere in order to observe the tenuous heliospheric ENA emissions, we needed to add significant additional propulsion on top of the Pegasus rocket supplied by NASA.

After considerable study and optimization, we developed a new approach that combines the addition of another disposable SRM and a highly capable HPS on the IBEX spacecraft. Our SRM was an Alliant Techsystems (ATK) STAR 27 motor optimized with a STAR 30C nozzle (McComas et al. 2006). We also added a well-balanced adapter cone to connect our SRM to the Pegasus and replaced the usual Pegasus separation band with three lighter-weight Motorized Light Band (MLB) separation rings, one between the Pegasus and our adapter cone, one between the adapter cone and our SRM, and finally one to separate the SRM from the spacecraft after burnout. Figure 10 shows this configuration, which we call the full IBEX flight system.

After completion of its third stage burn out, Pegasus pointed the IBEX flight system along the track of its trajectory, spun the flight system up to $\sim$60 RPM, and sent the release pulse that initiated its separation from the bottom of the adapter cone. This separation, which occurred at $\sim$200 km altitude, marked the end of the Pegasus launch and initiated the timer that ran the rest of IBEX's internal launch sequence. Within the next 5 minutes, we ejected the adapter cone, ignited the SRM, performed active nutation control during the SRM burn, and released the burned out SRM. This sequence put IBEX into a high-altitude orbit with apogee at $\sim 35 R_E$ and perigee still at $\sim$200 km.

Over the following several weeks we spun the spacecraft down to $\sim$23 RPM, raised both apogee and perigee with a series of hydrazine burns, and finally spun down to $\sim$4 RPM and repointed the spacecraft toward the Sun. This orbit-raising activity was followed by commissioning of the spacecraft and then the science payload. Finally, in early December 2008, IBEX entered its science phase and began routinely collecting IBEX-Hi and Lo observations of heliospheric ENAs.

Once we moved past the admittedly new and challenging way of getting IBEX into its high-altitude orbit, the remainder of the mission design is extremely simple. Science observations are taken throughout the orbit whenever the spacecraft is above $\sim$10 R_E. Below that altitude, on each orbit, we reduce and safe the instrument high voltages, downlink the data from the just-completed orbit, and repoint the spacecraft spin axis from $\sim 4°$ east of the Sun to $\sim 4°$ west of the Sun; this must be done because the Earth moves $\sim 1°$ per day in its orbit about the Sun (360° in 365 days), so over IBEX's ∼8-day orbit, the Sun has an apparent motion of ∼8° with respect to the inertially fixed spin axis. As IBEX passes perigee and rises past ∼10 R_E, the high voltages are ramped back up and science observations begin again. IBEX spends over 7 out of each ∼7.6 day orbit at high altitude in science data collection mode, and each orbit provides excellent viewing of a single swath of the sky. As IBEX repoints repeatedly over each six months, those swaths move across the sky allowing the generation of two all-sky maps per year (see Fig. 3); of course, the swaths will also be combined to produce a single all-sky map with even better angular resolution and statistics.

5 Science Operations

Science operations are carried out through the IBEX Science Operations Center (ISOC) (Schwadron et al. 2009, this issue). The ISOC is responsible for supporting analysis of IBEX data, generating special payload command procedures, delivering the IBEX data products and building the global heliospheric ENA maps in collaboration with the IBEX team. The software provides considerable flexibility in the building of the global flux maps. This flexibility is essential since the global properties of the interstellar interaction are virtually unknown. As the data analysis proceeds and we discover the physical properties associated with heliospheric ENA production, the ISOC will iteratively improve its software and data products.

IBEX analysis can be viewed as a processing pipeline connecting the principle science data products. This pipeline is a part of a larger framework for receiving telemetry, trending the payload, delivering Science Tasking Files when needed, archiving data, and distributing data to the scientific community and public (Fig. 11). Because the raw telemetry (Level 0 data) may contain corrupted, garbled communications, data dropouts or repeats, the first stage of the processing produces a "clean copy" of the science data (Level 0.5) as it was stored in the solid state recorder on orbit. If necessary, commands can be sent to the spacecraft to resend portions of the recorded data until it has all been received on the ground. The CEU flight algorithm encodes the data rather compactly, and for subsequent processing expanded forms of this data (Level 1.0 data products) are needed. The most significant change is the correlation of event times (or spin phase) with the corresponding IBEX attitude to determine the arrival direction of each event.

At this point in the processing pipeline, with a magnetospheric model and knowledge of background sources, we remove obvious non-heliospheric signal events and perform data quality checking (magnetospheric ENA data are culled and assembled into a separate data set for use by that community). With the resulting data, we construct ENA count maps or simple spectral estimates for various regions of the sky (Level 2.0 data products). A "toolbox" of methods for the selection and display of data along with some degree of human interaction is used at this processing level. At the next level, we include sensor calibration data and produce estimations of the true ENA flux into the sensor from the direct-event counts. Because these calculations require the inclusion of detailed instrument models, the maps and spectra of ENA flux are higher-level (3.0) products.

Level 3 maps include both the incident maps of ENA flux onto the sensors near 1 AU and heliospheric maps of ENA flux from the outer heliosphere. (The ENA flux from an arbitrary outer boundary at 100 AU is used in existing software, but can be easily modified to any closed surface in the outer heliosphere.) An important component in the generation of the heliospheric ENA maps is understanding the transmission of ENAs from their points of origin to observation at the IBEX spacecraft (Bzowski 2008;

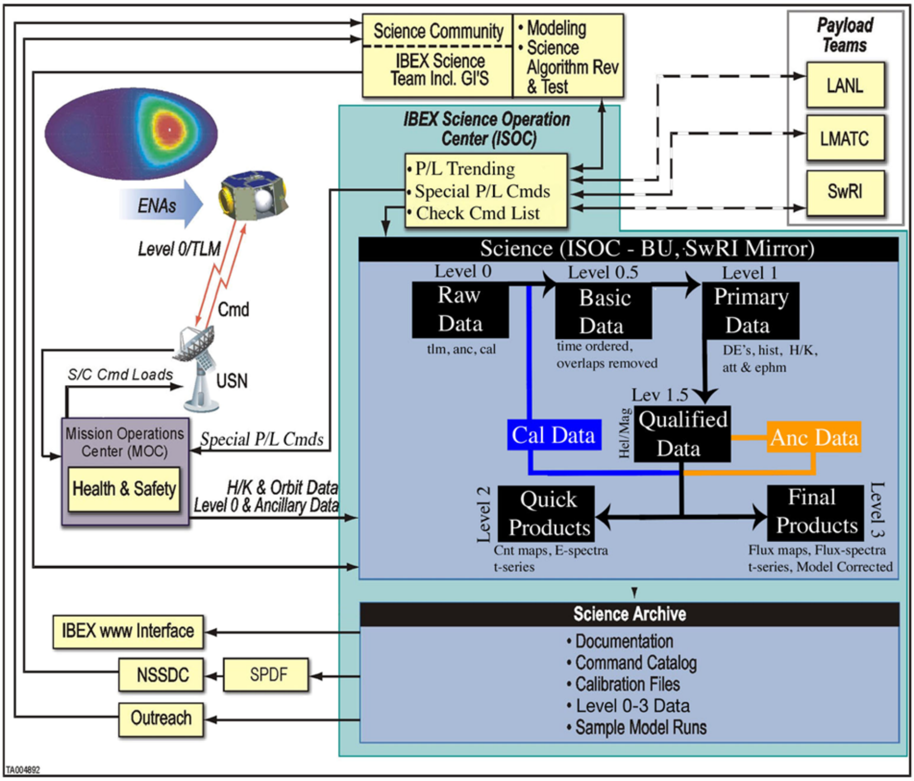

Fig. 11 IBEX data flow from the spacecraft and through the ISOC. The IBEX raw telemetry data and ancillary data are received and processed into high-level data products, archived and distributed to the scientific community

Roelof and Bzowski 2009, this issue). To solve for the ENA transmission, we take into account loss by ionization (predominantly photo-ionization and charge-exchange) and the effects of gravitation and radiation pressure. The final destination of IBEX data products is the SPDF (Space Physics Data Facility) at the National Space Science Data Center in a form suitable for use by the community.

6 Conclusions

The IBEX mission's sole focused science objective is to discover the global interaction between the solar wind and the interstellar medium. This interaction encompasses the structures, dynamics, energetic particle acceleration and charged particle propagation in the complex region where the solar wind meets the interstellar medium. IBEX was designed to provide the first global observations of the interstellar interaction—disclosing its fundamental nature and providing the observations needed for detailed modeling and in-depth understanding.

In order to make heliospheric ENA observations from high above the contamination of Earth's magnetosphere, we developed a new method for launching small satellites to extremely high-altitude orbits, starting from the low Earth orbit achieved by the NASA-supplied Pegasus rocket. In order to achieve this we included our own SRM and highly capable HPS on the IBEX spacecraft. Using this newly developed scheme, future missions could also use a Pegasus rocket as the starting point for propelling other small satellites, up to ∼100 kg, to high Earth orbit, the Moon, the L1 point between the Earth and Sun, or even further out in the solar system or to other planets (McComas et al. 2006).

The IBEX-Hi and Lo sensors collectively measure ENAs from ∼10 eV up to 6 keV, with redundant, overlapping measurements from 300 eV to 2 keV. These two sensors were optimized to maximize the open aperture area while simultaneously providing exceptionally low background rates from triple coincidence detector sections. The result is extremely high sensitivity and low background observations of the heliospheric ENAs, coming predominantly from the inner heliosheath. In addition, because of IBEX's viewing, throughout much of the year, IBEX will also make the highest sensitivity observations of ENAs coming from various regions of the magnetosphere ever made. While not a formal part of IBEX science, these data are culled from the heliospheric observations and used for additional magnetospheric studies by both members of the IBEX team and the broader magnetospheric community.

Another important part of the IBEX mission is our Education and Public Outreach (EPO) program (Bartolone et al. 2009, this issue). This ambitious and comprehensive program develops exciting EPO themes from Astronomy and Heliophysics and includes substantial formal and informal education components as well as a diverse array of public outreach approaches. The program is implemented by the Adler Planetarium & Astronomy Museum and includes a nationally distributed planetarium show about IBEX with accompanying informal education materials that are also accessible to individuals with special needs. The IBEX EPO program also helped develop a national Space Science Core Curriculum program for grades 6-8 in collaboration with other NASA missions; a professional development program for teachers; and workshops that engage Hispanic and Native American students. Materials are made available for download or for order via our website (www.ibex.swri.edu).

IBEX is a remarkable mission of exploration and discovery. With a launch on 19 October 2008 and the highly successful subsequent orbit-raising and commissioning activities, IBEX is now on station, collecting unique and first-ever observations of the global interaction at the edge of our heliosphere—the region that separates our solar system from the galactic environment.

Acknowledgements We are deeply indebted to all the outstanding men and women who made the IBEX mission a reality. This work was funded by the National Aeronautics and Space Administration as a part of its Explorer program.

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