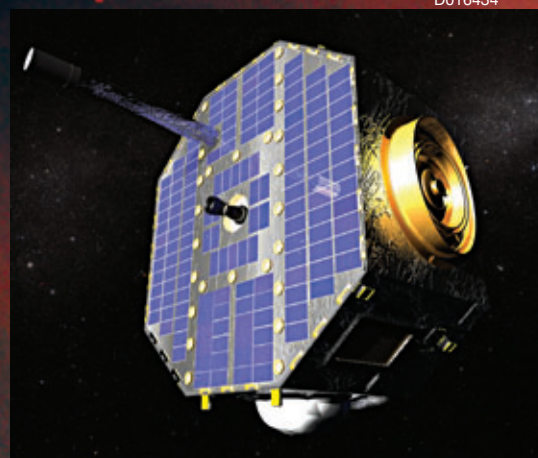


A Ribbon at the Solar System's Edge

A low-cost Earth-orbiting spacecraft developed by Southwest Research Institute discovers much more than scientists expected



The Interstellar Boundary Explorer spacecraft scans the edge of the solar system from its high-Earth orbit, completing an all-sky map approximately every six months.

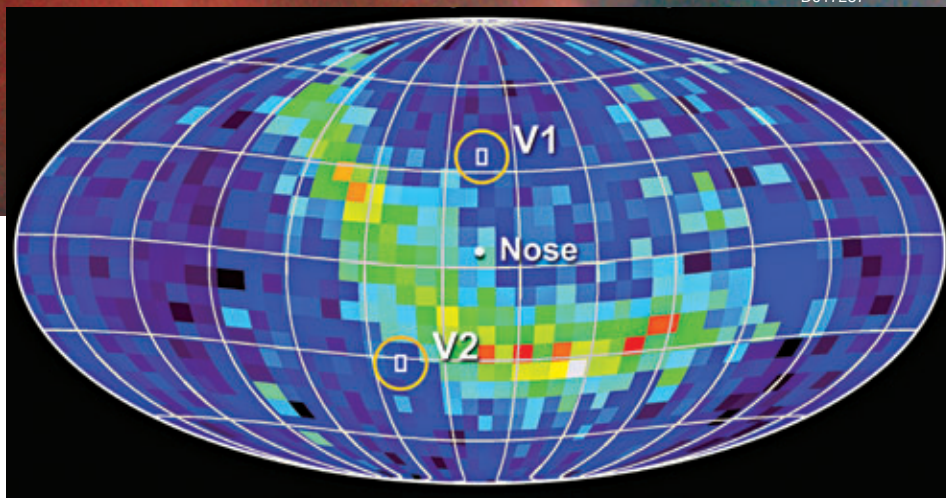
By David J. McComas, Ph.D.

Since its October 2008 launch, NASA's Interstellar Boundary Explorer (IBEX) spacecraft has mapped the invisible interactions occurring at the edge of the solar system, surpassing its mission objectives with images that reveal the invisible interactions between our home in the galaxy and interstellar space to be surprisingly structured and intense. Now, its science program has also flourished into multiple research studies extending far beyond the mission's original scope.

The maps of the never-before-seen regions at the edge of our solar system have been remarkable enough, but to see the IBEX data also being used to make other important discoveries in the space environment closer to Earth is an extremely exciting bonus for the science community and NASA.

A surprise at the solar system's edge

IBEX provides global imaging of the interstellar boundary, much the same as a weather satellite provides data about global and regional weather patterns on



IBEX simultaneously creates 14 maps of the sky at different energies. The resulting image, shown here, indicates an unexpectedly bright ribbon-like emission. Note that the ribbon passes between the paths of the Voyager 1 (V1) and Voyager 2 (V2) spacecraft.

Earth. The two pioneering, 1970s-era Voyager spacecraft made point-source measurements of interactions as each flew across the interstellar boundary some 10 billion miles from Earth. However, the Voyagers are more like individual weather stations that measure local conditions but can miss the big picture unless a storm passes directly overhead.

This was illustrated with one of the earliest and most striking discoveries that IBEX made. Based on the Voyagers' experience, scientists had expected to see small, gradual spatial variations at the interstellar boundary. However, using

the most sensitive neutral atom detectors ever flown in space, IBEX unveiled a narrow ribbon of particles two to three times more intense than anything else in the sky. The Voyager measurements had given no indication that such a ribbon existed; therefore no theories or models had predicted it. As it turns out, the ribbon feature snakes through the sky right between the paths of the two Voyager spacecraft, and both had missed it.

The solar wind, a million-miles-per-hour stream of charged particles, emanates from the Sun in all directions. This solar wind inflates a giant bubble in



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lar interaction. ENAs propagate in from all parts of the boundary and, by detecting their directions of arrival, IBEX builds up maps of this invisible region over a broad range of energies every six months.

More time is needed to fully understand the ribbon discovered in the IBEX data; however, because the ribbon appears to be ordered by the direction of the local interstellar magnetic field outside the heliosphere, IBEX observa-

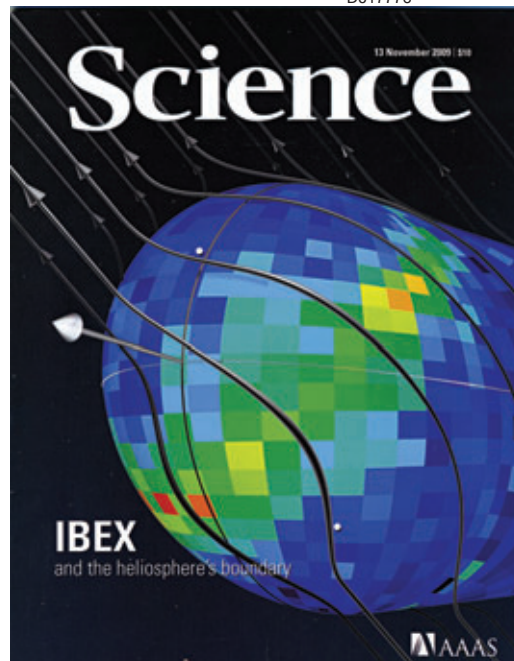
tions suggest that the interstellar environment has far more influence on the structure of the heliosphere than anyone previously believed. A closer look at segments of the ribbon shows fine structures, which suggests that ion densities may be significantly enhanced in highly localized regions at the interstellar boundary.

Untying the "knot"

Six months later, as IBEX completed its second all-sky map, it was apparent that the heliosphere's interactions with interstellar space are more dynamic than earlier had been believed. As proof, an unusual "knot" structure in the bright, narrow ribbon of neutral atoms emanating in from the boundary appeared to have "untied." The rapid evolution was reported in a paper published in the *Journal of Geophysical Research*.

Researchers believe the ribbon forms in response to interactions between interstellar space and the heliosphere, the protective bubble

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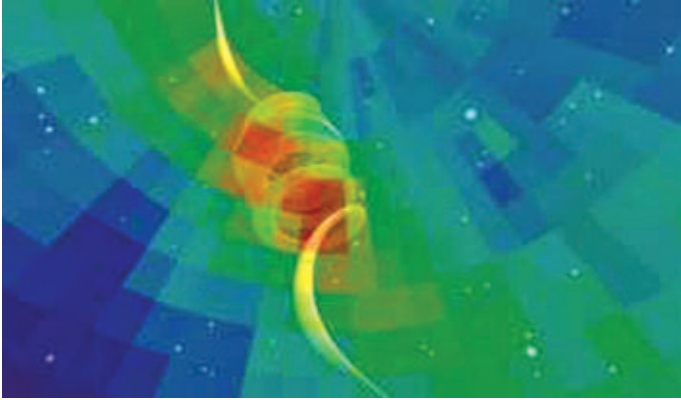
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interstellar space called the heliosphere, the region of space dominated by the Sun's influence, in which the Earth and other planets reside. Measurements of the behavior of these charged particles help researchers better understand the interstellar space environment. However, IBEX observations also help address a serious challenge facing manned exploration because the interstellar boundary shields the solar system from the majority of galactic cosmic ray radiation.

As the solar wind travels outward, it sweeps up newly formed "pickup ions," which arise from the ionization of neutral particles drifting in from interstellar space. IBEX measures energetic neutral atoms (ENAs) traveling at speeds of roughly 500,000 miles per hour to 2.5 million miles per hour. These ENAs are produced from the solar wind and pickup ions in the boundary region between the heliosphere and the local interstellar medium.

Since its launch, IBEX has used two novel ENA cameras to image and map the heliosphere's global interaction. These energy-resolved maps provide detailed information about this interstel-

Some scientists believe the ribbon that was exposed in the first IBEX all-sky map may correspond to the galactic magnetic field, tracing the area where it is most parallel to the surface of the heliosphere, as seen in the image that appeared on the cover of the September 13, 2009, edition of the journal "Science."



The second all-sky map produced by IBEX showed that a bright feature, called the “knot” in the ribbon, appeared to have diminished, illustrating the dynamic nature of the region. This is an artist’s visualization of the feature.

in which the Earth and other planets reside. Sensitive neutral atom detectors aboard IBEX produce global maps of this region every six months.

Analyses of the first map suggested the ribbon is somehow ordered by the direction of the local interstellar magnetic field outside the heliosphere, influencing the structure of the heliosphere more than researchers had previously believed. The knot feature, seen in the northern portion of the ribbon in the first map, stood apart from the rest of the ribbon as the brightest feature at higher energies.

While the second map shows the large-scale structure of the ribbon to be generally stable within the six-month period, the polar regions of the ribbon display lower emissions and the knot diminishes by as much as a third and appears to pull apart, or “untie,” as it spreads out to both lower and higher latitudes. While the science team can’t agree on exactly what causes the knot or the ribbon, the comparison of sky maps shows that the region is changing over relatively short time periods.

Seeing hydrogen from the Sun bounce off the Moon

The IBEX spacecraft also has directly collected hydrogen and oxygen from the interstellar medium for the first time and made the first observations of very fast hydrogen atoms coming from the Moon, following decades of speculation and searching for their existence. Hydrogen from the Sun’s million-mile-per-hour solar wind becomes embedded in the Moon’s surface, so IBEX’s measurements

IBEX made the first detection of neutral atoms coming from the Moon. The spacecraft detects particles produced by reflection and neutralization of the incident solar wind protons.

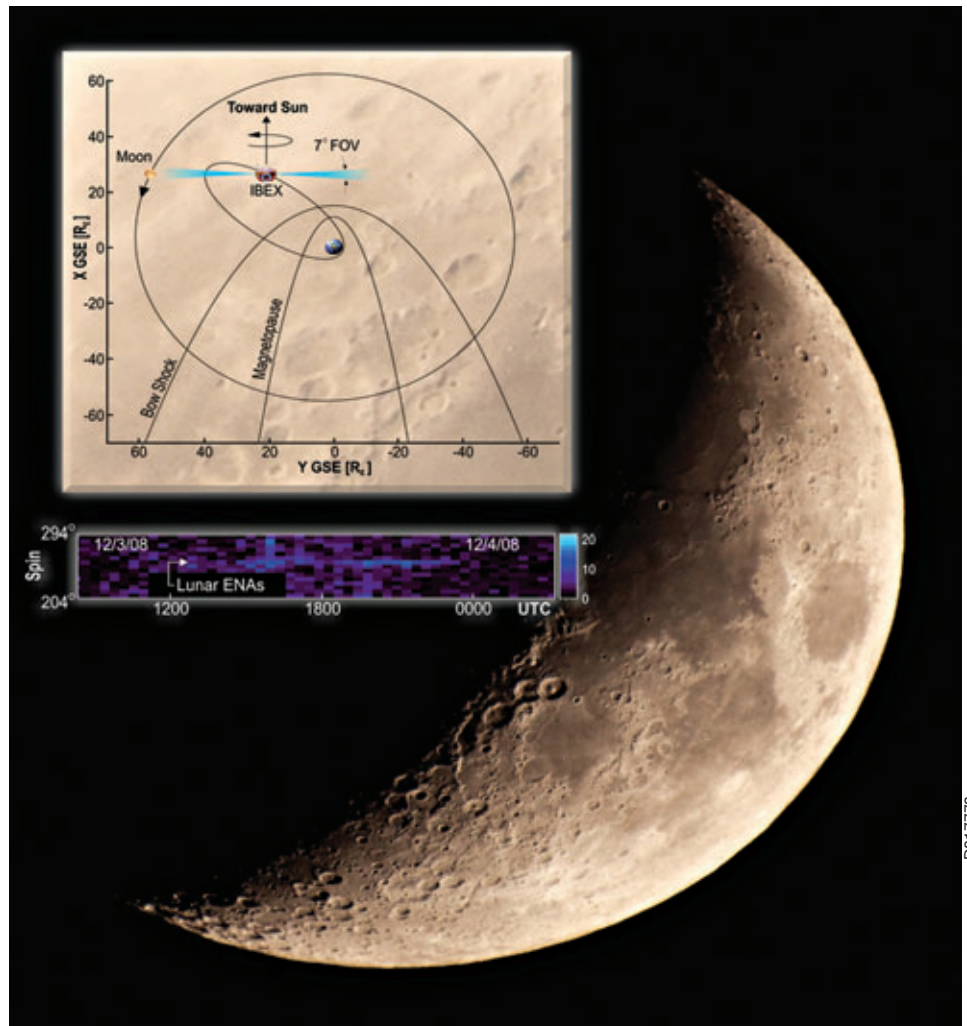
of the fraction of hydrogen atoms that bounce off the surface sheds critical light on the “recycling” processes undertaken by particles throughout the solar system and beyond.

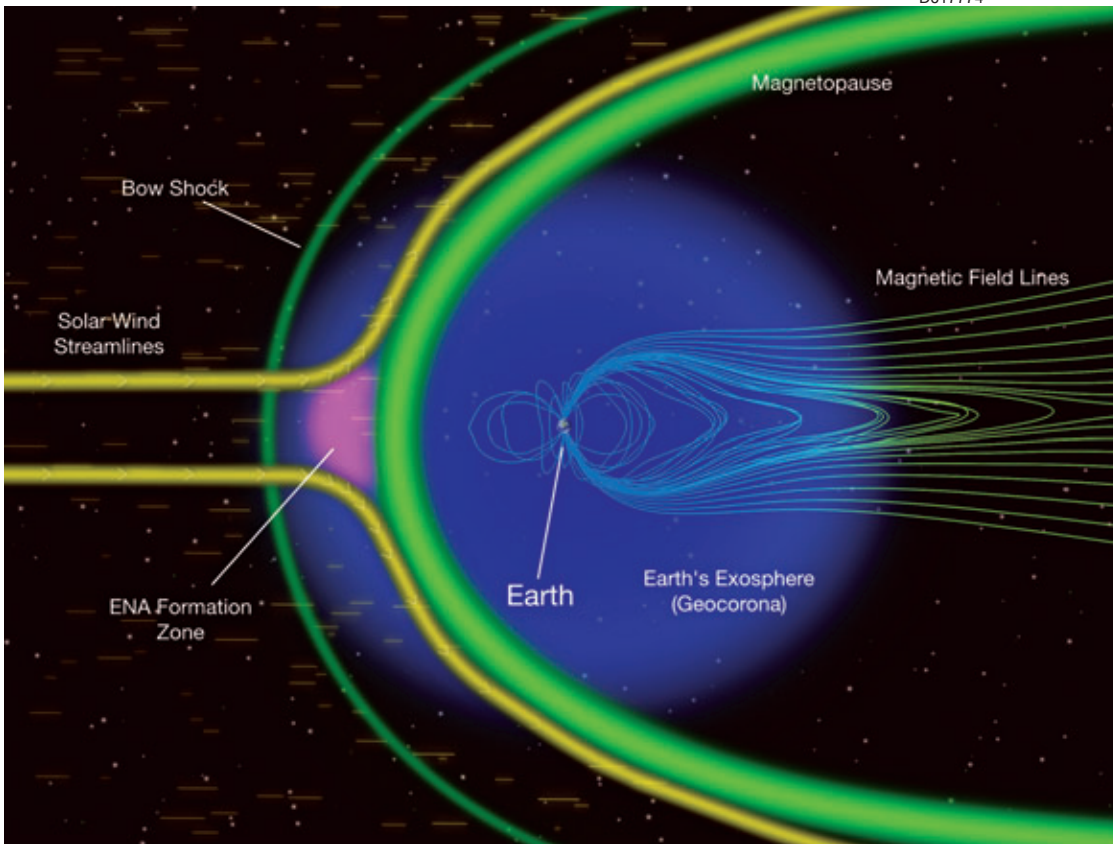
During spacecraft commissioning early in its mission, the IBEX team turned on the IBEX-Hi instrument, built primarily by SwRI and the Los Alamos National Laboratory, which measures atoms with speeds from about half a million to 2.5 million miles per hour. (Its companion sensor, IBEX-Lo, built by

Lockheed Martin, the University of New Hampshire, NASA Goddard Space Flight Center and the University of Bern in Switzerland, measures atoms with speeds from about one hundred thousand to 1.5 million mph.)

Just after scientists turned the IBEX-Hi instrument on, the Moon happened to pass through its field of view, and the instrument lit up with a clear signal of the neutral atoms being detected as they backscattered from the Moon.

The Earth’s strong magnetic field shields our planet from the solar wind. The Moon has no such protection, causing the solar wind to slam onto the





IBEX found that ENAs are coming from a region just outside Earth's magnetopause, where nearly stationary protons from the solar wind interact with the tenuous cloud of hydrogen atoms in Earth's exosphere.

boundary between the Earth's magnetosphere and interplanetary space, giving important new details about the processes

moon's sunward side. From its vantage point in space, IBEX sees about half of the Moon — one quarter of it is dark and faces the nightside (away from the Sun), while the other quarter faces the dayside (toward the Sun). Solar wind particles impact only the dayside, where most of them are embedded in the lunar surface, while some scatter off in different directions. The scattered ones mostly become neutral atoms in this reflection process by picking up electrons from the lunar surface.

The IBEX team estimates that about 10 percent of the solar wind ions reflect off the sunward side of the moon as neutral atoms, while the remaining 90 percent are embedded in the lunar surface. Characteristics of the lunar surface, such as dust, craters and rocks, play a role in determining the percentage of particles that become embedded and the percentage of neutral particles, as well as their direction of travel, that scatter.

The IBEX results also shed light on the "recycling" process undertaken by particles throughout the solar system and beyond. The solar wind and other charged particles impact dust and larger objects as they travel through space, where they backscatter and are reprocessed as neutral atoms. These atoms can travel long distances before they are stripped of their

electrons and become ions and the complicated process begins again.

The combined scattering and neutralization processes now observed at the Moon have implications for interactions with objects across the solar system, such as asteroids, Kuiper Belt objects and other moons. The plasma-surface interactions occurring within protostellar nebula, the region of space that forms around planets and stars — as well as exoplanets, planets around other stars — also can be inferred.

Earth's magnetic bubble, and what it means

Most recently, IBEX data have been extended to observe the Earth's magnetosphere from the outside. The magnetic bubble that surrounds the Earth and interacts with the solar wind flowing out from the Sun has been studied extensively with various instruments and spacecraft from within, but IBEX has enabled the first direct observations from the outside.

Just as the interstellar boundary shields the solar system from the majority of galactic cosmic ray radiation, so does the Earth's own magnetosphere protect it from solar particle radiation. IBEX data show the pileup of the solar wind in front of the magnetopause, the

that protect Earth's atmosphere. A number of other studies on the magnetosphere are in progress, including studies of the "night side," the plasma sheet, the tail and other magnetospheric structures.

Science is often a process of getting new observations, admitting that scientists don't know nearly as much as they thought they did, and building up new understanding from there. The fun begins when the science community is faced with new observations and is forced to debate new theories and ideas. It will take a while before the community comes to a consensus about what the IBEX data really mean, yet much more already has been learned about our place in the solar system.

IBEX is the latest in NASA's series of low-cost, rapidly developed Small Explorers space missions. SwRI leads and developed the mission with a team of national and international partners. NASA's Goddard Space Flight Center in Greenbelt, Md., manages the Explorers Program for NASA's Science Mission Directorate in Washington. ❖

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