Interactions between the Sun and galactic matter

IBEX Looks at the Heliosphere's Edge

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In 2009, the heliophysics community exploded with the news that, six months after its launch, the IBEX probe yielded a completely unexpected result: instead of appearing as the anticipated smudgy blob, the full sky map revealed the heliosphere to resemble a ribbon. Then, in early 2012, IBEX revolutionized our way of thinking about the heliosphere once again

The heliosphere acts analogously to the Earth's magnetosphere, protecting the Solar System against cosmic radiation. In its journey across the Galaxy, the Sun passes through interstellar matter of variable parameters. The heliosphere's size and shape shift as the conditions in the matter surrounding it change, in turn affecting the level of cosmic radiation reaching the Earth.

The IBEX (Interstellar Boundary Explorer) project was first proposed in 2002, when astrophysicists realized how little they knew about the Sun's immediate surroundings within the Galaxy. Remedying that demanded an investment in state-of-the-art observation technologies: a pioneering imaging method using energetic neutral atoms (ENAs).

Seeing with atoms

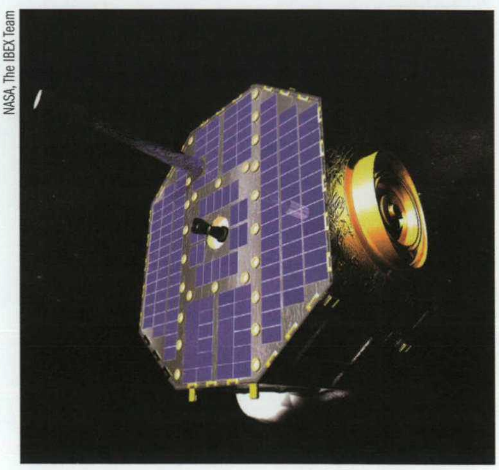
ENA images are formed as a result of a charge-exchange process between ions in a hot plasma. Since atoms are charge-neutral they are not affected by magnetic fields and are able to move freely, whereas the motion of ions carrying an uncompensated electrical charge is guided by local magnetic fields. When a fast-moving proton gets sufficiently close to a slow atom, the two particles exchange an electron. The slow atom releases an electron to the proton, rendering it insensitive to the magnetic field, while the atom - having now turned into an ion - is captured by the magnetic field. Such charge exchange processes leading to the formation of ENAs occur on the boundary between matter originating from the Sun and interstellar matter surrounding the Solar System.

ENA observations provide direct information about the boundaries of the Solar System and about the interactions between the Sun and its immediate galactic surroundings. The various types of electromagnetic radiation that are used in other fields of astrophysics cannot be applied to studying the boundaries of the Solar System, since they simply get lost among the extra-heliospheric background. ENA detectors are therefore required to study space at distances reckoned in the tens of astronomical units away from the Sun.

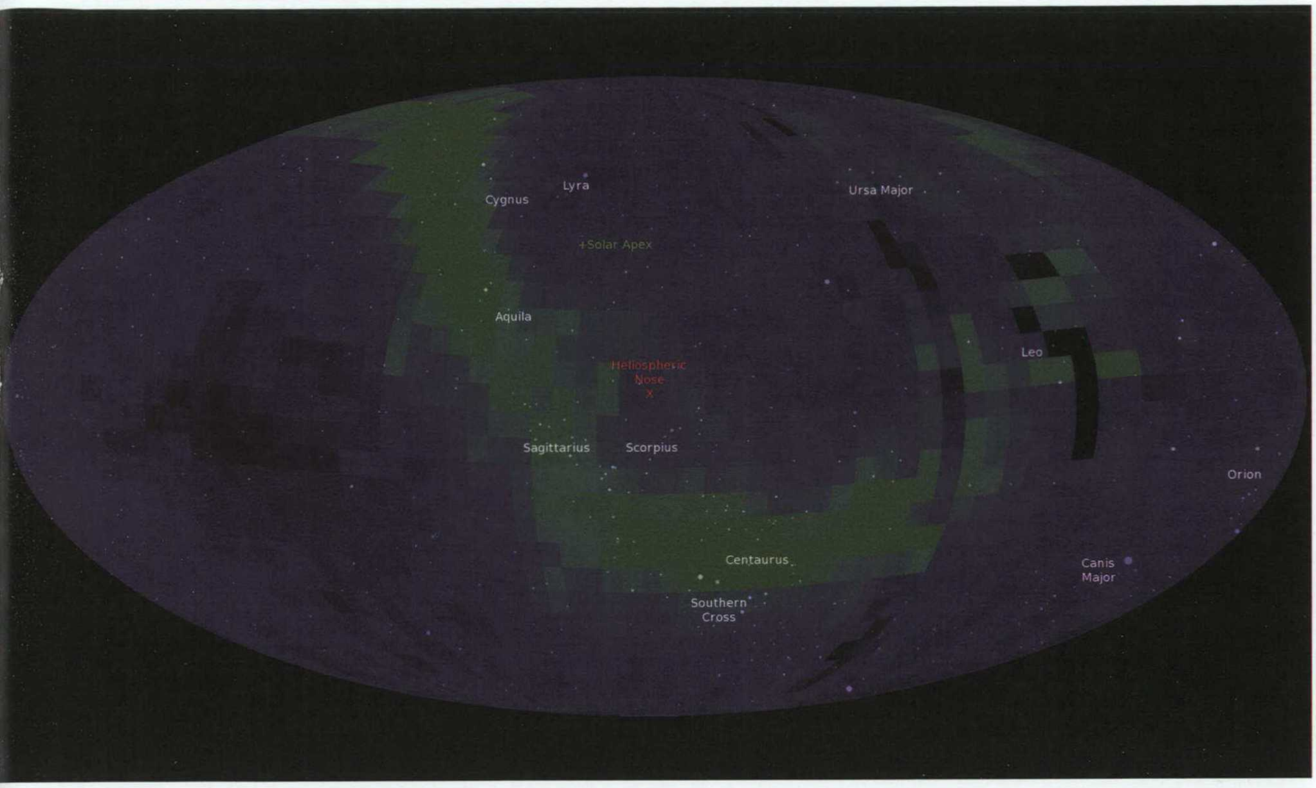
IBEX's full sky

Although ENA imaging has been used previously to observe interstellar matter, IBEX is the first instrument in history to take measurements of the ENA stream from across the whole sky. The resulting image has turned out to be rather unexpected.

NASA, The IBEX Team



Artist's impression of the IBEX probe in orbit



NASA, The IBEX Team

Image of the sky featuring IBEX against a background of summertime constellations and the Milky Way

IBEX was launched into orbit on 19 October 2008, and started taking measurements in late December of that year. There are two detectors on board, able to observe atoms with energies between 0.01-6 keV. IBEX's rotation, and its motion together with the Earth around the Sun, allow it to create a full map of the sky in six months. Initially, the mission was expected to last no longer than four years, but the satellite was recently successfully moved to a different, more stable orbit, synchronized with the Moon; as a result IBEX has sufficient fuel to last at least 15 years.

The international team working on the IBEX mission includes a group of researchers from the Solar System Physics and Astrophysics Team at the PAS Space Research Center: Dr. Maciej Bzowski, Prof. Stanisław Grzędzielski, Dr. Andrzej Czechowski, Dr. Marek Hłond, Marzena A. Kubiak, and Justyna M. Sokół.

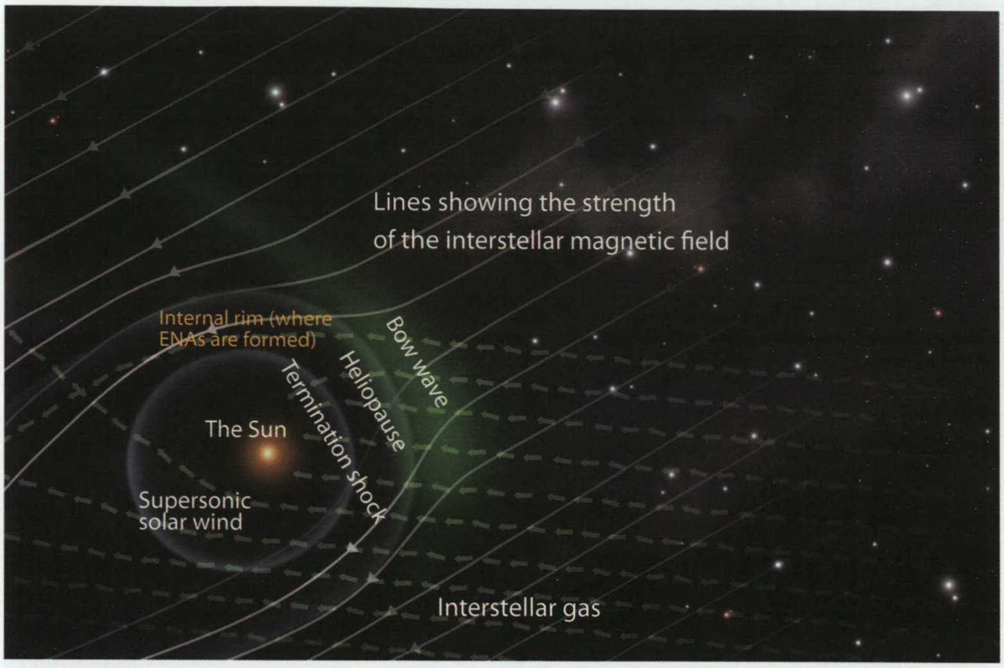
Wind and matter

The Sun's corona is constantly emitting streams of plasma (ions and electrons), spreading out into interplanetary space for tens of astronomical units, becoming increasingly sparser and colder the further they are from the star. These streams of matter are known as solar wind; they cannot be studied directly from the Earth's surface, since we are protected from them by our own planet's magnetosphere.

Interstellar space around the Sun is filled with matter largely consisting of debris left behind by supernova explosions. The matter is permeated with a magnetic field, and comprises neutral gases, plasma, and dust. The wind escaping the star interacts with matter around it, and creates a solar-wind bubble or astrosphere. IBEX is designed to study these interactions.

The Sun's solar-wind bubble, known as the heliosphere, is filled with supersonic solar wind. Its boundary is marked by a balance of pressures between solar wind and the surrounding interstellar matter. Since the Sun moves at a velocity of over 20 km/s with respect to the local interstellar medium, the heliosphere is strongly asymmetric, with a nose flattened towards the direction of motion and a tail stretched out in the opposite direction.

The boundary area between the solar wind and intergalactic matter comprises several surfaces. According to what was the standard thinking, there are three such surfaces: a termination wave of solar wind impact, an outer surface separating the solar wind from interstellar matter (known as the heliopause), and the bow impact wave



PAS Space Research Center. Graphics: M.A. Kubiak, M. Frołow, Tentaris

Heliosphere with its boundary area (artist's impression)

formed where interstellar matter starts to surround the heliosphere.

Yet two groups modeling the boundaries of the heliosphere have independently found that recent data obtained by IBEX shows no physical basis for the formation of a bow impact wave in front of the heliosphere. In fact, it is likely that what is formed is not dissimilar to the wave in front of a slowly-moving boat. This means that the phenomena observed on the boundaries of the heliosphere are governed by different laws than previously thought.

IBEX studies streams of hydrogen ENAs (H ENAs) formed outside the termination shock, in the inner surface of the heliosphere's boundary. But due to losses resulting from ionization processes affecting particles on their way through the Solar System, the statistical distribution of particles observed in Earth's orbit differs from the distribution at the source. The Warsaw team therefore models the factors responsible for ionizing ENAs, and calculates the probability of survival of atoms from the source to the detector in order to make corrections to the observed stream and create a map of locations where H ENAs are formed.

Which cloud?

As well as creating full maps of the heliosphere's boundaries, IBEX is also registering particles originating from outside the heliosphere, from the local interstellar medium. To deduce the conditions present within it, the direction, speed, and temperature of the inflowing gas need to be recorded. IBEX has taken a new set of such measurements, and the speed turns out to have been lower than previously thought. The results are seemingly very similar to those obtained previously, but the adjustments have led to a major revision of scholarly views on the layered structure of the boundaries of the heliosphere.

The lower speed of the inflowing gas means that the pressure exerted by galactic matter on the heliosphere is lower. Since the size of the heliosphere is a result of the balance between the pressure exerted by solar wind and the external pressure exerted by the local interstellar medium, it follows that the size and shape of the heliosphere may be different than previously thought.

The Sun and the Solar System are moving through a set of debris remaining after a series of supernova explosions several million years ago, known as the Local Bubble. This matter is hot and ionized, although it also contains cooler clouds of not fully-ionized matter. The properties of the matter the Sun is currently passing through have an impact on the shape of the heliosphere. Spectroscopic measurements suggest that the Sun could be located within one of the two nearby clouds, albeit close to its boundary. The relative velocity of the cloud and the Sun has been estimated to be 25 km/s. The neighboring cloud, known as the G-Cloud, moves slightly faster relative to the Sun. It is also possible that the Sun is moving through the boundary of these two clouds, or that they together even form a single swirling cloud. However, results obtained by IBEX indicate that the Local Cloud is moving more slowly than previously thought, and although the Sun does appear to be near the cloud's boundary, the cloud is distinct from its neighbor and the matter within it seems to be surprisingly uniform.

Ribbon

Prior to obtaining the first image of the sky, researchers expected the ENA emissions to be more powerful from the nose of the heliosphere, and weaker from the direction of the tail. However, IBEX has shown the distribution to be rather different: the background of a roughly bipolar distribution of the signal across the sky is dominated by an emission resembling an arcing ribbon. It is visible in all of IBEX's energy ranges, and its structure has been evolving over time. So far it has remained undetermined what phenomenon is responsible for this bizarre formation, although two hypotheses stand out as the most likely. Prof. Stanisław Grzędzielski from the PAS Space Research Center has put forward a theory stipulating that the ribbon is formed on the boundary between two clouds in the vicinity of the Solar System. The competing theory suggests that the ribbon is formed as a result of the magnetic field immediately beyond the termination shock and multiple charge exchanges between atoms and ions in the heliosphere's boundary region. Unfortunately, both hypotheses have some major weaknesses.

So what are the interactions between the Sun and intergalactic matter really like? The only answer we have so far is: "Not quite what we imagined." Resolving that will take time, more observations, new modeling techniques, and of course patience. IBEX's extraordinary discoveries have posed many intriguing questions, leaving researchers still struggling to find clear-cut answers - which just goes to demonstrate that humankind has a long way to go in terms of understanding the objects and space even in the close vicinity of our own Solar System. ■

Further reading:

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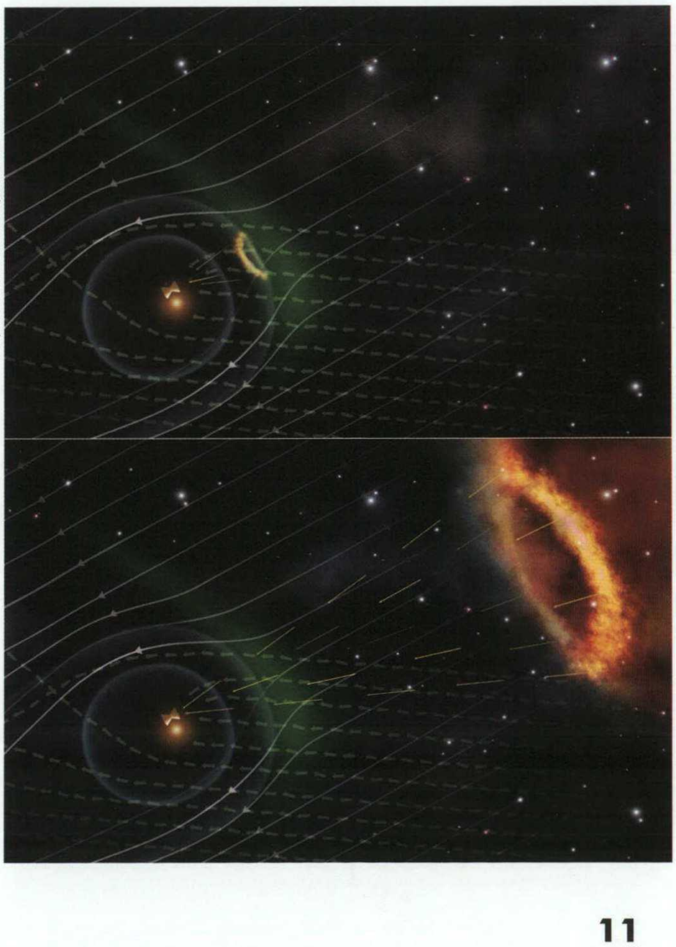

PAS Space Research Center. Graphics: M.A. Kubiak, M. Frołow, Tentaris

There are two competing hypotheses on the origins of the ribbon discovered by IBEX: it is either formed locally on the boundary of the heliosphere itself (top panel), or on the boundary between two neighboring interstellar clouds (lower panel)