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Interstellar Mapping and Acceleration Probe (IMAP)

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Abstract. Our piece of cosmic real estate, the heliosphere, is the domain of all human existence -- an astrophysical case history of the successful evolution of life in a habitable system. By exploring our global heliosphere and its myriad interactions, we develop key physical knowledge of the interstellar interactions that influence exoplanetary habitability as well as the distant history and destiny of our solar system and world. IBEX is the first mission to explore the global heliosphere and in concert with Voyager 1 and Voyager 2 is discovering a fundamentally new and uncharted physical domain of the outer heliosphere. In parallel, Cassini/INCA maps the global heliosphere at energies (~5-55 keV) above those measured by IBEX. The enigmatic IBEX ribbon and the INCA belt were unanticipated discoveries demonstrating that much of what we know or think we understand about the outer heliosphere needs to be revised. This paper summarizes the next quantum leap enabled by IMAP that will open new windows on the frontier of Heliophysics at a time when the space environment is rapidly evolving. IMAP with 100 times the combined resolution and sensitivity of IBEX and INCA will discover the substructure of the IBEX ribbon and will reveal, with unprecedented resolution, global maps of our heliosphere. The remarkable synergy between IMAP, Voyager 1 and Voyager 2 will remain for at least the next decade as Voyager 1 pushes further into the interstellar domain and Voyager 2 moves through the heliosheath. Voyager 2 moves outward in the same region of sky covered by a portion of the IBEX ribbon. Voyager 2's plasma measurements will create singular opportunities for discovery in the context of IMAP's global measurements. IMAP, like ACE before, will be a keystone of the Heliophysics System Observatory by providing comprehensive measurements of interstellar neutral atoms and pickup ions, the solar wind distribution, composition, and magnetic field, as well as suprathermal ion, energetic particle, and cosmic ray distributions to diagnose the changing space environment and understand the fundamental origins of particle acceleration. This paper, the first citable reference for IMAP, is similar to an unpublished whitepaper that was presented to the National Academies of Sciences, Engineering and Medicine Committee for Solar and Space Physics. We provide the IMAP objectives and instrument straw man traced from the Solar and Space Physics Decadal Survey. It is fitting that our paper is published in the volume of papers that celebrates the 80th birthday of Ed Stone.

1. Introduction

In the 2012 Heliophysics Decadal Survey [1], IMAP (Figure 1) was rated the highest priority for implementation in the Solar Terrestrial Probe (STP) mission line based on its urgency in the context of recent Voyager observations, alignment with the objectives of the Heliophysics Decadal survey, and relevancy across the Heliophysics division. IMAP is urgently needed to understand the heliosphere's direct connection to the rapidly changing space environment as solar activity subsides while Voyager 1 and Voyager 2 directly probe the inner and outer heliosheath. IMAP is ready to be implemented and explores fundamental outstanding problems in Heliophysics concerning the outer boundaries of our solar system, the physics of interstellar interactions with the solar wind, the origin and physics of the IBEX ribbon, and the fundamental origins of particle acceleration throughout the heliosphere.

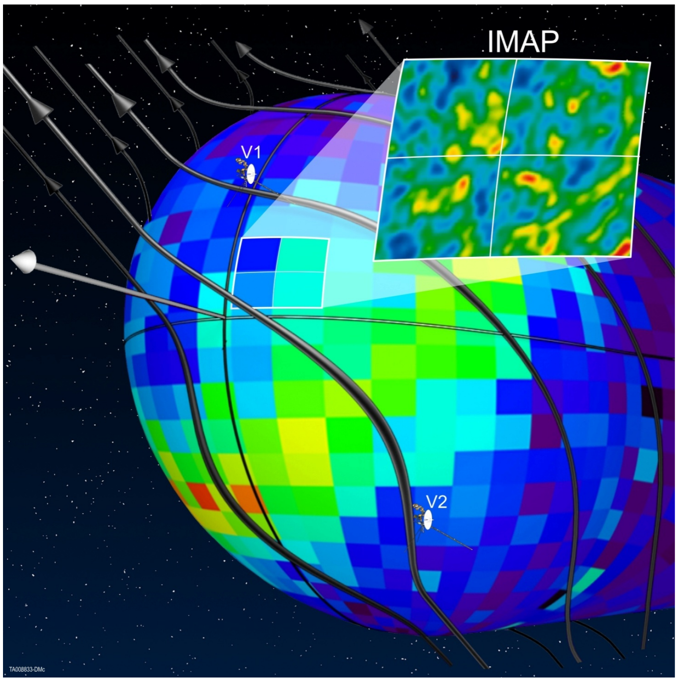

Figure 1. The Interstellar Mapping and Acceleration Probe (IMAP) will solve fundamental mysteries of our heliosphere's interaction with the interstellar medium and particle acceleration in the solar wind. Shown here projected onto the outer boundary of the solar system is the IBEX Ribbon, which was discovered by the Interstellar Boundary Explorer (IBEX) mission. The enigmatic Ribbon raises basic and profound questions related to its origin, the nature of the outer boundaries of our solar system, and the surrounding galactic medium. Most ideas involve a population of electrically charged matter existing near the boundaries of our solar system. These charged particle populations very likely originate from uncharged matter that streams out from the Sun (the neutral solar wind). Several new sources for the Ribbon have also been proposed, involving regions in the galaxy further out from the Sun. IMAP with more than twenty times the resolution of IBEX will probe the detailed source of the ribbon. Shown in the blowout is a depiction of the substructure that scientists have only so far been able to hypothesize. Image credit: D. McComas(SwRI) based on Adler Planetarium/SwRI/NASA image from [2] with mock IMAP data taken from WMAP (GSFC/Princeton/UofC/UCLA/UBC/Brown/NASA).

2. IMAP's Scientific Context and Motivation

As the Sun travels through interstellar space on its quarter billion year journey around the center of our galaxy, the solar wind—the supersonic outflow of magnetized plasma (or ionized gas) from the Sun's upper atmosphere—inflates an enormous bubble within the dilute plasma of the interstellar medium (Figure 2). Known as the heliosphere, this solar-wind-dominated cavity in the local galactic environment has been an object of speculation and study ever since its existence was first predicted in the 1950s.

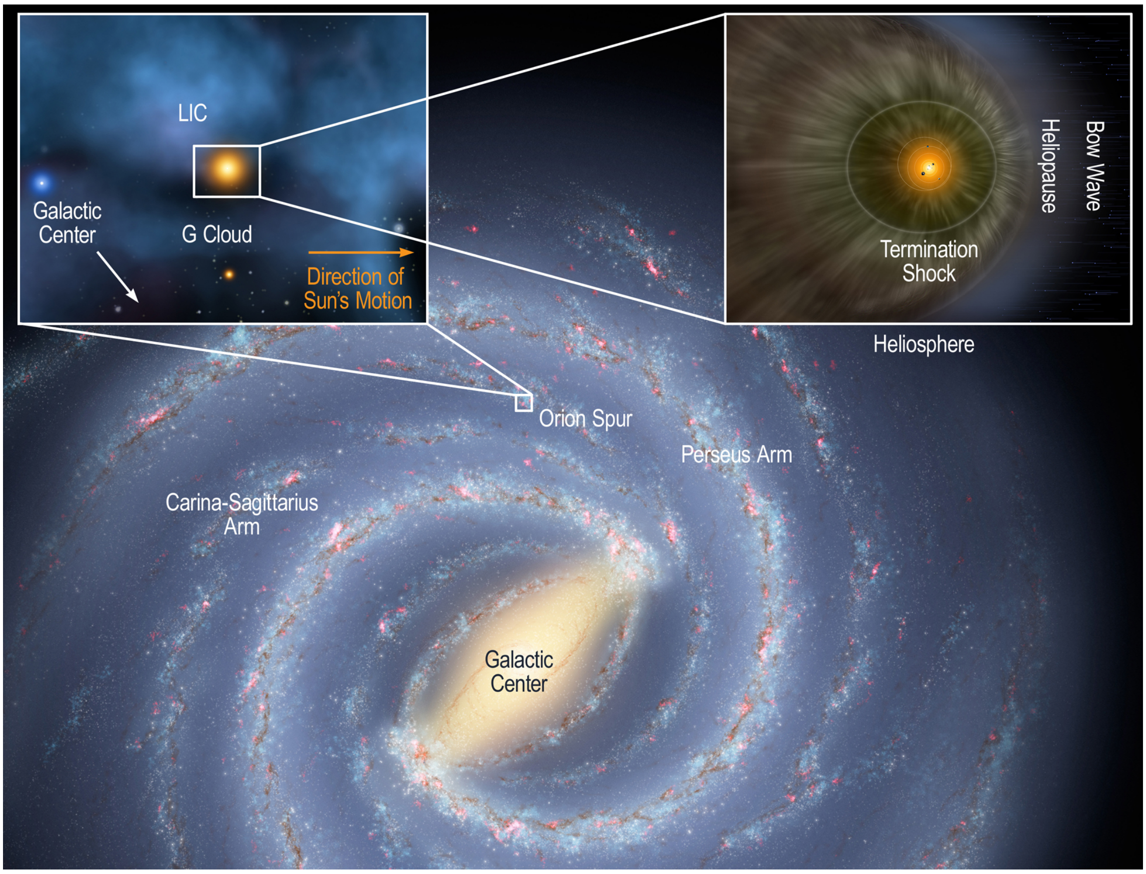

Figure 2. The galactic environment of the Sun and the heliosphere. As discussed in the text, the heliosphere is currently believed to be located near the edge of the Local Interstellar Cloud. Although it has been suggested that the heliosphere has passed into a transition region between the LIC and the G Cloud [3], IBEX measurements of interstellar helium indicate that the heliosphere remains inside the LIC, although "such a conclusion should await further refinement of analysis" [4]. Image credits: NASA/Adler/U. Chicago/Wesleyan/JPL-Caltech (Milky Way and LISM); NASA/IBEX/Adler (heliosphere)

Our heliosphere, its history and future in the Galaxy are key to understanding the conditions on our evolving planet and its habitability over time. By exploring our global heliosphere and its myriad interactions, we develop key physical knowledge of the heliospheric and interstellar interactions that influence our understanding of our home system in its current state, the distant history and destiny of our solar system, as well as the habitability of exoplanetary star systems.

During the last half century, analytic theory and increasingly sophisticated numerical simulations led to the development and refinement of a standard model of the heliosphere as a bullet-shaped obstacle in the local interstellar flow, with a blunt nose in the upstream direction, a long comet-like heliotail downstream, and complex boundaries separating the heliosphere from the interstellar environment. In 2004, Voyager 1 crossed the innermost of these boundaries, providing the first in-situ measurements of the termination shock and the shocked solar wind beyond; Voyager 2 crossed the termination shock three years later.

Although invaluable as direct samples of the outer heliosphere and interstellar medium, the Voyagers' single-point measurements along their trajectories cannot reveal the heliosphere's global structure. Thus, as the Voyagers continued their outward journey, work was under way to develop and implement NASA's Interstellar Boundary Explorer (IBEX) mission. From the vantage point of a highly elliptical Earth orbit, IBEX would generate global images of the heliosphere and its boundaries by detecting energetic neutral atoms (ENAs) created in the solar wind's interaction with the local interstellar medium.

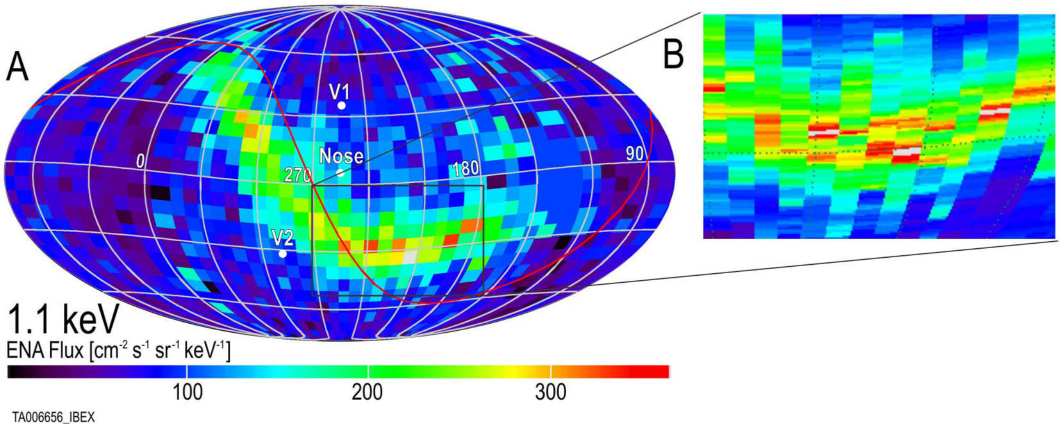

Figure 3. A. IBEX Ribbon at 1.1 keV in ecliptic coordinates using a Mollweide projection. The red line marks the galactic equator. The locations of the heliospheric nose and of the Voyager termination shock crossings are shown. B. Detail of a segment of the Ribbon showing apparent fine structure. From [2].

In October 2008, the tiny (<0.5 m^3 and ~100 kg) IBEX spacecraft, equipped with its own additional solid rocket motor, was launched from the Kwajalein Atoll on a Pegasus rocket. Two months later, IBEX began gathering ENA data for the first-ever maps of the global heliosphere. Creation of the first, energy resolved maps took six-months as the ENA cameras swept successive swaths of the sky, registering ENAs arriving from the outer boundaries of our solar system. As the data accumulated and the first detailed map emerged from the individual pixels, what the IBEX team saw was a feature fundamentally different from anything their pre-launch models of the "ENA sky" or any of the other models of the solar wind/LISM interaction had led them to expect: a bright "Ribbon" of intense emissions nearly encircling the sky and apparently aligned with the external interstellar magnetic field (Figure 3). The discovery of the Ribbon was reported in a series of papers in the November 13, 2009 issue of *Science*, which also featured the Ribbon on its cover. In the same issue of *Science,* Krimigis et al. [5] revealed the first ENA maps of the global heliosphere at energies greater than ~5 keV (above the IBEX energy range). INCA observed a belt of emissions (Figure 4) that is broader and offset from the IBEX ribbon. The white outline in Figure 5 shows the location of the IBEX ribbon. IBEX continues to complete a full scan of the sky every six months, providing better statistics and enabling the detection of time variations. The mapping by INCA also continues. However, the origin of the Ribbon and the Belt—where and how they are formed—remains a mystery and a serious challenge to the heliophysics and astrophysics communities. In addition to the surprising discovery of the Ribbon, the first in-situ sampling of the neutral interstellar H and O wind, along with He, was reported in this issue of Science [6].

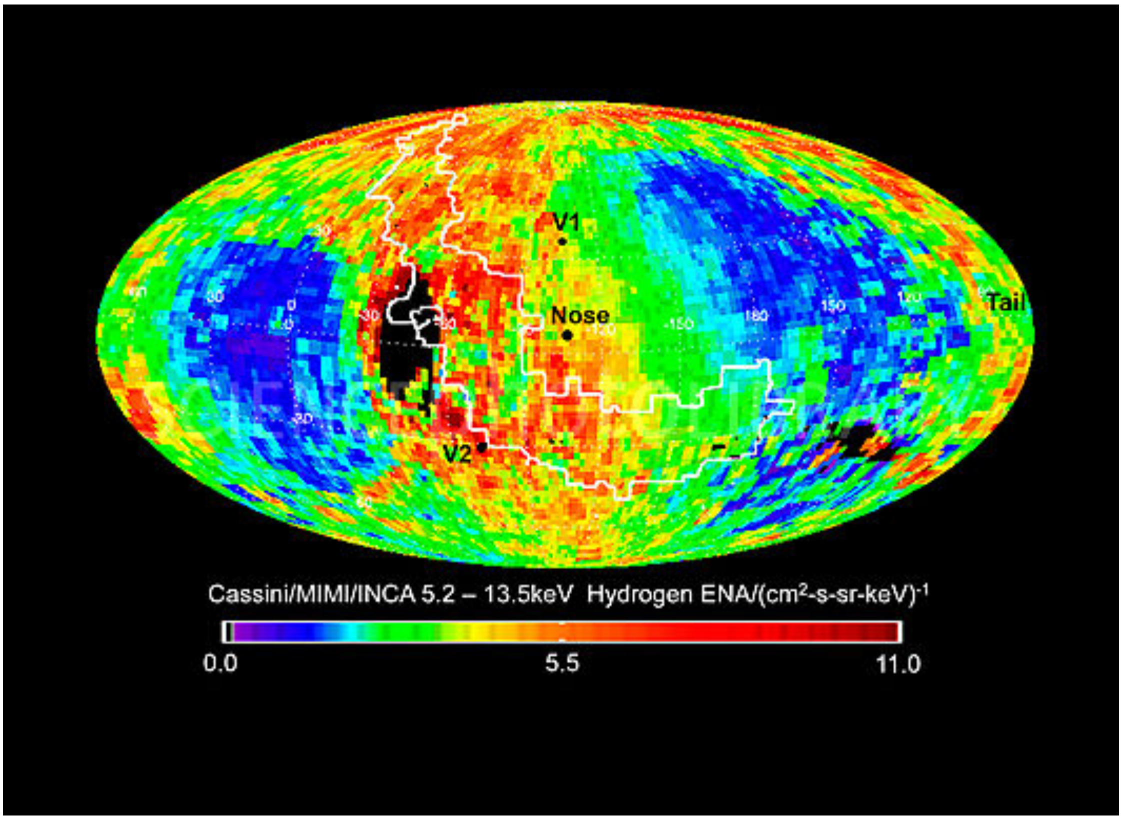

Figure 4. All-sky survey by Cassini/INCA of ENAs that map our global heliosphere. The heliosphere shape is formed as the Sun moves through the surrounding interstellar medium, with the front marked 'nose' and the rear marked 'tail'. The color-coding is by energy flux of ENAs measured by INCA. Also marked are the two Voyager space probes (V1 and V2), and the 'ribbon' of charged particles (white outline) discovered by the IBEX spacecraft. Shown here are energetic neutral atoms (ENA) in the 5.2 – 13.5 keV energy range.

In a similar vein, particle acceleration in the heliosphere is a fundamental problem with implications for the future and history of life within the solar system and beyond. The acceleration of energetic particles creates a population of atoms that penetrate all forms of matter, and deposit energy in Earth's atmosphere, planetary and exoplanetary atmospheres, and materials such as tissue, organic matter, and regolith. Because of the chemical changes induced by particle radiation, it is important to forming the building blocks of life. Yet, for astronauts on potentially long flights in deep space, high-energy radiation can induce cancer and at high levels of exposure leads to radiation sickness. Particle radiation thereby presents a formidable hazard. The many significant ramifications of particle radiation make understanding particle acceleration an imperative. While particle acceleration occurs throughout the cosmos, the details of the particle acceleration process remain difficult to discern because it is so difficult to observe directly. The heliosphere presents a unique environment in which we can study the problem locally. High-energy particle acceleration occurs not only at the termination shock, which surrounds the entire solar system, but also at the plethora of shocks and disturbances the travel past Earth with the solar wind.

3. Critical Next Steps with IMAP

The recent ground-breaking all-sky images of the heliospheric boundaries from IBEX mission and the Cassini INCA instrument, in concert with dual point *in situ* observations of the inner heliosheath from both Voyager spacecraft, as well the direct IBEX measurements of interstellar neutral H, He, O and Ne flow have made outer heliospheric science one of the most exciting and fastest developing areas in Heliophysics. As a next step, substantial improvements in spatial and temporal resolution along with sensitivity gains are required to resolve the substructure of the ENA ribbon and its evolution in time.

Understanding the substructure of the ribbon is critical for establishing the physical mechanisms at work in the creation of the IBEX ribbon. With a factor of x100 combined increase in resolution and sensitivity and a broader energy range of ENA observations, IMAP will provide these capabilities and thus will, in relation to IBEX, enable a "quantum leap" forward in understanding the heliosphere.

3a. What is the Physical Origin of the Ribbon and the Belt?

The Ribbon stretches across much of the sky and its origin remains an enigma despite its persistence for over five years and after almost more than a dozen theories that attempt to explain it. While each theory that has been posed has its strengths, each one also contradicts *IBEX* observations or demonstrates significant flaws in internal consistency [see review, 7].

An example of the more than a dozen theories proposed to explain the ribbon is that it is produced by a *spatial* region [8] in the local interstellar medium where newly ionized atoms are temporarily contained through increased rates of scattering by locally generated waves in the electromagnetic fields (Figure 5). The particles in the ribbon are created predominantly from neutralized solar wind and neutralized pickup ions from inside the solar wind termination shock and inside the heliopause.

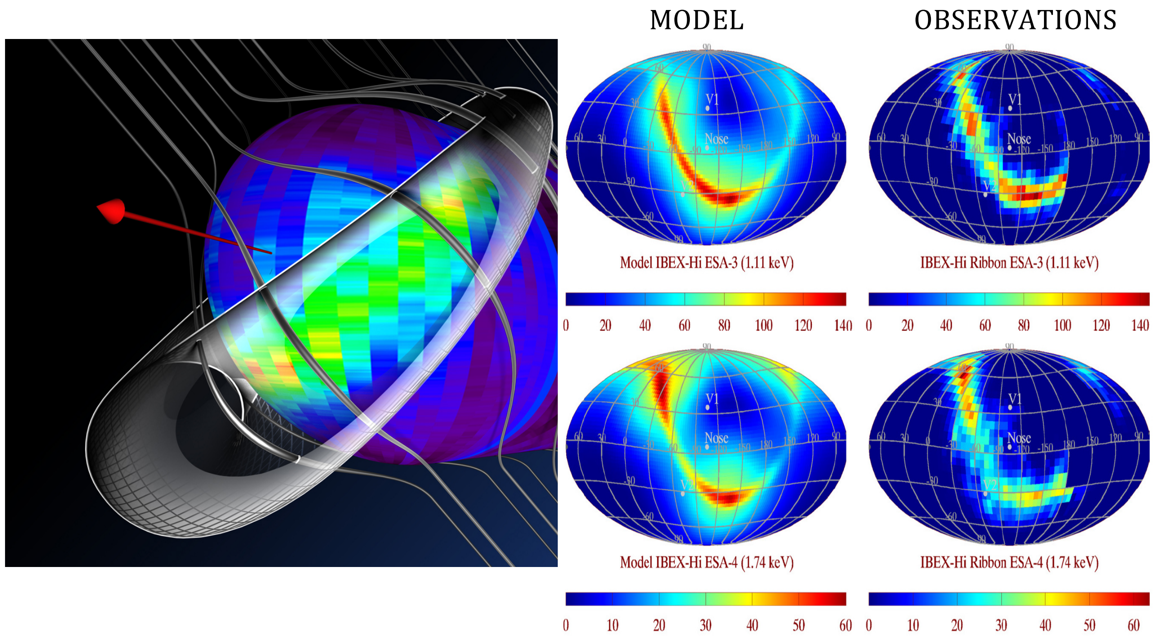

Figure 5. (Left) A new theory for the IBEX ribbon considers its source as a spatial region beyond the heliopause, which surrounds and protects the solar system from the harsh radiation environment of the local galactic medium. The heliopause is the inner surface pictured here with the IBEX ribbon ENA fluxes superimposed on the surface. The grey curves show the interstellar magnetic field lines warping around the heliopause and then stretching beyond it into the local galactic medium. The grey structure outside the heliopause that looks like an overinflated inner tube indicates the region that, according to the new theory, should hold higher concentrations of particles that form the IBEX ribbon. (Right) Left column panels show model results in comparison to observations of the ribbon on the right column Credit: NASA/IBEX/UNH.

The new theory and its competitors must be tested completely. However, the ~7° resolution of IBEX maps poses a major limitation. For example, the spatial retention concept [8] requires the existence of substructure to <1° to account for the observed fluxes of energetic neutral atoms. Until we achieve the x100 combined resolution and sensitivity observations from IMAP, the question of substructure in the ribbon will remain as a major question. Thus, the higher resolution observations of IMAP are critical to fully understanding the origin of the IBEX ribbon.

In contrast to the much narrower ribbon, the INCA belt has a width ~100° FWHM. The ribbon is inclined to the Belt in both ecliptic latitude (~25°) and longitude (~30°). The overlap in energy between Voyager ions and Cassini ENA intensities (averaged over the ENA line of sight) enables estimation of ion fluxes in the heliosheath, thus providing a continuous spectrum $5 \leq E \leq 4000$ keV. These measurements have been used to estimate the local partial pressure over this energy range (~ 0.1 pPa), suggesting the thickness of the heliosheath ~ 50 AU [9].

3b. What is the Global Structure of the Heliosphere?

IBEX measurements of energetic neutral atoms created by collisions at the solar system's boundaries have for the first time mapped out the structure of our solar systems’ tail, which is shaped like a four-leaf clover (Figure 6). While telescopes have spotted such tails around other stars, it has been difficult to see whether our own star produced one. The particles found in the tail cannot be seen with conventional instruments, and so the shape and structure of its tail remained unknown. IBEX data have shown that, very much like a comet’s tail, the heliotail is stretched out behind our solar system where the Sun’s million mile per hour solar wind flows down and ultimately escapes the heliosphere, slowly evaporating because of charge exchange.

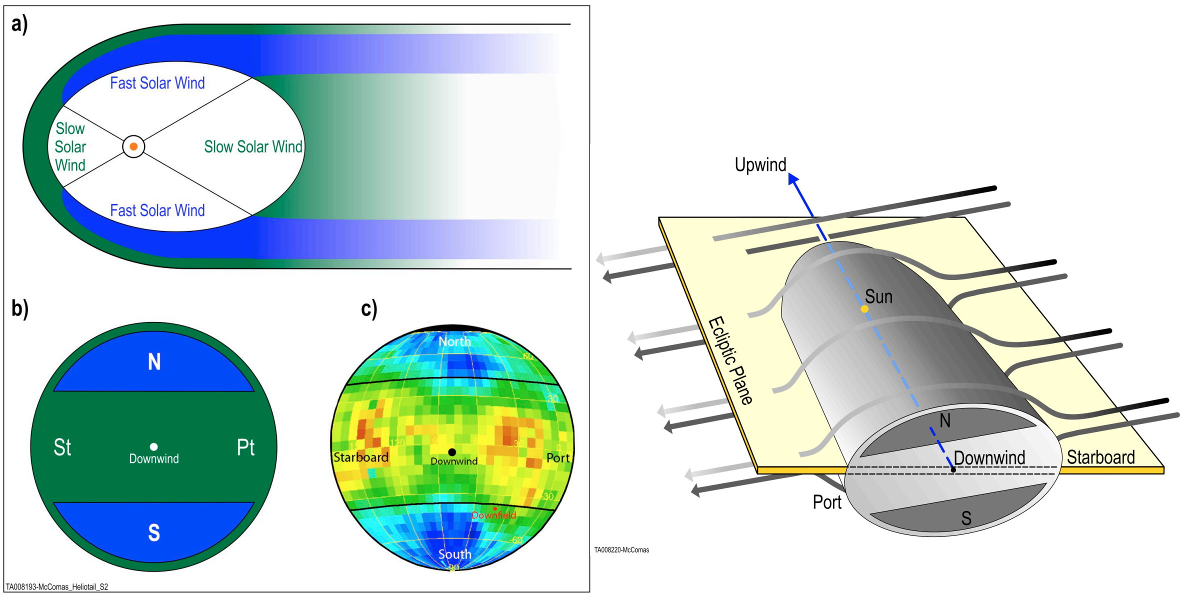

Figure 6. Data from NASA’s IBEX (panel c) shows the spectral slope of the particles looking down the solar system’s tail – the yellow and red colors represent areas of slow-moving particles, and the blue represents the fast-moving particles. Panel a) shows the latitude structure of typical solar wind, with fast wind at high latitudes and slower wind at low latitudes. Panel b) shows the corresponding solar wind structure looking down tail with faster wind in blue and slower wind in green. N & S refer to the North and South directions. St refers to the starboard direction and Pt refers to port (these are nautical terms). The panel on the right shows a cartoon of the structure of the heliotail. (Image: NASA/IBEX)

One of the fundamental quantities measured by IBEX is the line-of-sight integrated pressure of ions from the inner heliosheath (Figure 7). Determination of an absolute pressure requires some absolute distance scale, which is provided by the Voyager satellite boundary crossings of the termination shock and the heliopause. Once absolute distance scales at individual locations are established, the IBEX *global* pressure maps allow us to form a rough picture of the heliosphere (termination shock and heliopause boundary) near the ecliptic plane. The direction of the interstellar magnetic field is given by the center of the IBEX ribbon and is projected into the ecliptic plane. The draping configuration is illustrative.

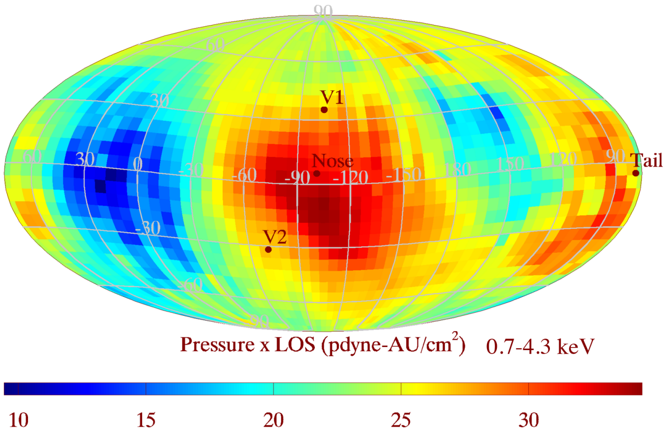

Figure 7. ENA imaging from IBEX and in the future from IMAP will resolve global line-of-sight integrated pressures, which reveal the global dynamic balance between the solar wind (the inner heliosheath plasma) and the interstellar plasma including the interstellar magnetic field. The extended energy range of IMAP compared to IBEX will allow more accurate estimation of pressure and of the line-of-sight integrations that change with energy. Shown here is the pressure of plasma protons from the inner heliosheath that form observed ENAs integrated over line-of-sight (LOS) as observed by IBEX from 0.7 to 4.3 keV.

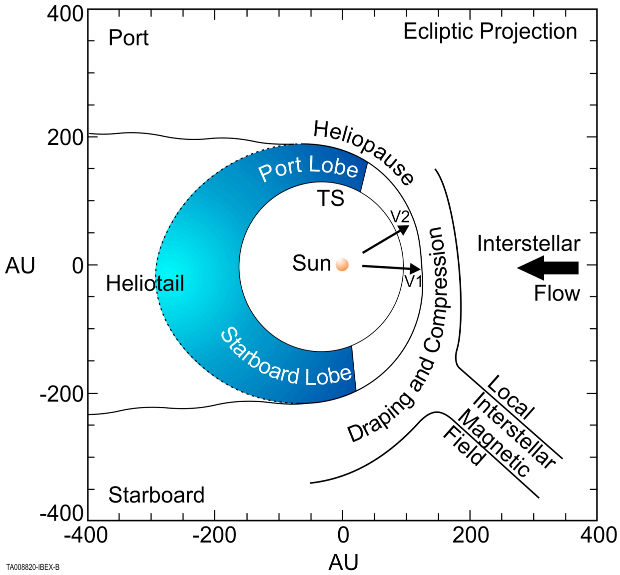

Figure 8. Analysis of IBEX data is used to form an approximate structure of the heliosphere projected into the ecliptic plane (viewed here from heliographic North). The complete energy range of distributions measured by IMAP will provide significant improvements over IBEX. In the formulation of such pictures of the global heliosphere, the distance scales provided by Voyager provide critical insight. The wavy lines extending from the lobes show regions beyond the line-of-sight sensitivity of IBEX and suggest outflow. The tail region and structure of heliosheath is asymmetric. The clearest signatures of asymmetry include the small starboard (~10°) offset of the core tail from the interstellar downwind direction, and the deeper reduction in ENA emissions from the port lobe of the heliosphere. A key question for IMAP is how these features extend down to low energies (<0.2 keV) and above 6 keV).

Figure 8 shows a rough picture of the structure of the heliosphere near the ecliptic plane. This picture is made possible only through the combined observations of IBEX and direct measurements by Voyager. Future measurements from IMAP will make fundamental use of Voyager observations to help identify distance scales, and thus, form a global picture of the heliosphere through complete energy integrations across the ENA distributions emanating from the inner heliosheath.

Sophisticated 3D MHD models (one example is shown in Figure 9) are being developed with the goal to produce ENA maps that can be compared with future observations from IMAP. The standard picture of the heliosphere is a comet-shape like structure with the tail extending for 1000's of AUs. This standard picture stems from the view that magnetic forces from the solar magnetic field are negligible and that the solar magnetic field is convected passively down the tail. Recent work [10, 11] shows that the magnetic tension of the solar magnetic field plays a crucial role on organizing the solar wind in the heliosheath (HS) into two jet-like structures. The two heliospheric jets are separated by the interstellar medium that flows between them. The heliosphere then has a "croissant"-like shape where the distance to the heliopause down tail is almost the same as towards the nose.

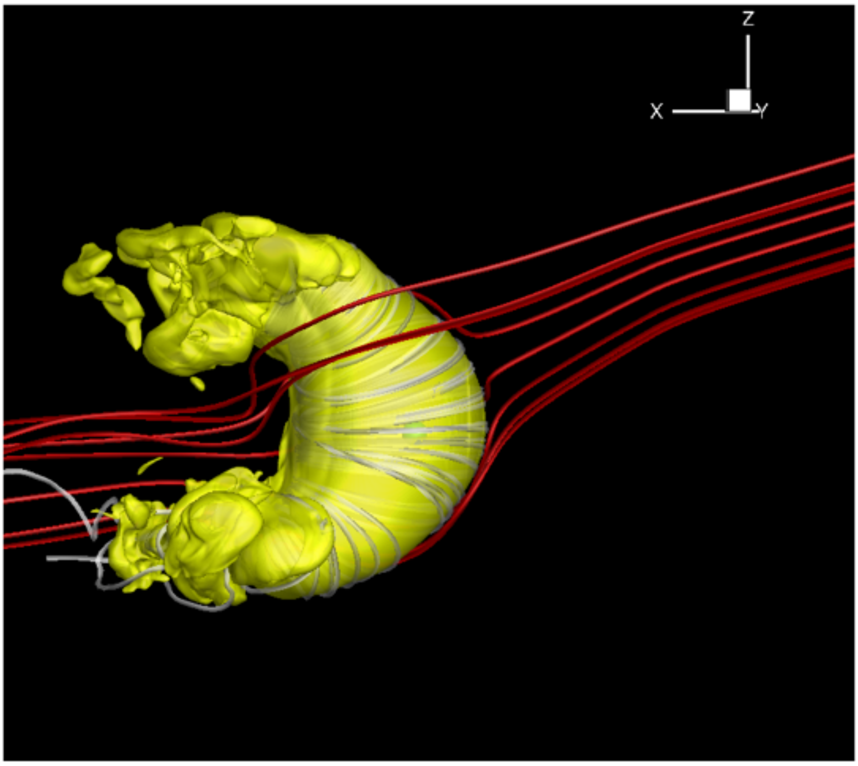

Figure 9. Croissant Heliosphere” / “Heliosphere with Jets”: Two-lobed structure of the heliosphere [10]. Yellow surface shows the heliopause surface. Grey curves are solar magnetic field lines; red curves are interstellar magnetic field lines.

Several observational consequences of this new view are being explored. The heliospheric jets are very turbulent with large-scale turbulence ~ 100AU and with a turnover of years. One should expect that this turbulence will cascade to smaller scales and shorter time scales. These turbulent jets are the largest turbulent structures in the heliosphere. Furthermore we do expect that the heliospheric jets will vary in their structure and intensity with solar cycle. These signatures may manifest in ENA maps, particularly over large timescales. Initially signatures in variability should exist over mid-scale ENA energies (0.7-4keV) and some suggestions have been made that this variability may extend to higher energies (>10 keV) that will be measured by IMAP. Both IBEX as well as CASSINI/INCA show time variability, although IBEX measurements indicate very little variability in the region of the heliotail. The current baseline over which variability could be detected is half of a solar cycle, and a much larger timescale (more than a decade) is needed with IMAP, IBEX and INCA to test for the existence turbulent evolution of the heliotail. IMAP measurements should pin down the following questions: a) Why the ENA images on IBEX (0.7-4keV) of the tail reveal two lobes? Is it only related to the bimodal distribution of the solar wind (slow vs. fast wind) and will disappear as the cycle progresses, or is it a permanent feature of the tail associated with the heliospheric jets? (b) Why the ENA images on CASSINI of the tail reveal such strong time variability? Is this variability a solar cycle effect or is it related with the turbulent jets? IMAP ENA mapping will have high sensitivity and be able to detect temporal and spatial variations due to the turbulence generated by the heliospheric jets and their associated variations over the solar cycle.

3c. What are the Conditions of the Interstellar Medium?

After initial sampling of the neutral He ISN flow with Ulysses GAS [12, 13], observations of the interstellar neutral (ISN) flow with IBEX have provided the first direct multi-species measurements of the ISN flow parameters, with a strong indication that the local interstellar cloud (LIC) conditions around the heliosphere are largely isothermal [4,12]. The local determination of the LIC temperatures from the neutral gas velocity distribution for several species provides the most detailed independent measurement of this key quantity, with a handle on differential heating and cooling processes for the different interstellar species, provided that also the distributions of the minor species (O and Ne) can be obtained with excellent counting statistics and angular resolution. IBEX has also provided the first measurements of the ISN H velocity distribution and the effect of the Sun's radiation pressure, based on direct neutral gas observations [15].

Differences in radiation pressure have also enabled the first local detection of ISN D [16]. The interstellar D/H is a powerful probe of big bang nucleosynthesis and the chemical evolution of the Milky Way galaxy [e.g. 17, 18], yet observations in the interstellar medium are scarce and line-of-sight integrated [19]. IMAP will take advantage of the differential deflection of these flow distributions by radiation pressure [20], in combination with the varying angular aberration along the 1 AU orbit, to separate the D signal from the He ISN flow distribution. As with other ISN flow related observations IMAP provides the critically needed capability to track the ISN flow distributions in the sky along the orbit around the Sun. The remaining improvement provided by IMAP to obtain a D/H ratio with statistical uncertainties <10%, is achieved with a combined collecting power and observation time increase for D by >10x.

With IBEX ISN observations, the flow vector and temperature of ISN He have been constrained within a narrow tube in the 4-dimensional parameter space (ISN inflow longitude, latitude and speed, as well as temperature), where the latter three can be expressed as a function of inflow longitude [21-23], but with a larger uncertainty along the parameter tube. The allowable parameter region has recently been constrained further [24 – 28], and the ISN flow vector is now largely consistent with that obtained with Ulysses GAS [29, 30], but with a LIC temperature that is substantially higher than in previous determinations [13, 31].

The speed and direction of the ISN flow have profound implications for the LIC-heliosphere interaction, i.e. whether it is largely super- or sub-sonic [23] and, in conjunction with the determination of the interstellar magnetic field direction based on ENA ribbon observations [32, 33], the Voyager termination shock passages [34-36], and interstellar H flow direction [37, 38], the shape and structure of the heliosphere relative to the $V_{ISM} – B_{ISM}$ symmetry plane can be determined. In fact, rather small differences in the ISN flow direction have substantial leverage on the $V_{ISM} – B_{ISM}$ plane [21, 39] and thus on the large-scale heliosphere structure. Furthermore, the small original difference in the best fitting inflow longitude [21, 22] compared with previous observations [13, 31] had initiated the intriguing discussion whether we could potentially witness variations in the ISN flow vector over a few decades [40-42]. While the differences in the flow vector have been largely reconciled, some recent work has focused on the possibility of variations of the local ISN flow vector due to turbulence in the ISM over a large range of scales [42]. Previous studies recognized the changes of the global flow vector due to variations in individual interstellar clouds along the line-of-sight used in integrating across absorption spectra [43]. This line-of-sight integration poses issues in comparing local determinations from measurements of interstellar neutral atoms with remote line-of-sight integrated observations.

All the aforementioned topics require a precision determination of the ISN flow vector, preferably with contiguous data sets over decades. Imaging of the ISN flow and the evaluation of the speed cut-off of interstellar pickup ion distributions [44] provide highly complementary methods, which can independently validate each other, if performed over a range of ecliptic longitudes. ISN bulk flow and pickup ion distributions over a large portion of the orbit around the Sun are needed to obtain such precision measurements of the H, He, O, and Ne ISN flow vector. IMAP provides the needed next step by enabling tracking of the ISN flow, along with a pointing accuracy that is as good or better than IBEX and continuous observations of He, O, D and Ne (Figure 10) pickup ion distributions.

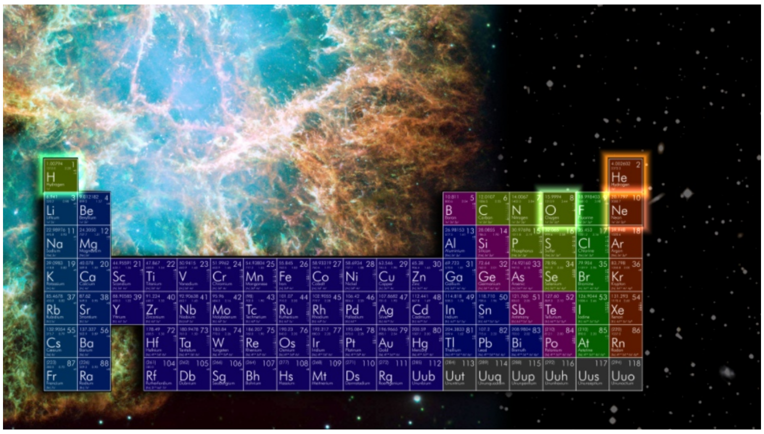

Figure 10. Most elements on Earth are produced by supernova explosions. About thirty elements in the periodic chart have been detected in the interstellar medium. Supernovae, such as the Crab, have produced the interstellar oxygen and neon that is observable by IMAP. In addition, IMAP will resolve Deuterium (D), which has major implications for big bang cosmology.

IMAP will also measure in detail the secondary components of the interstellar neutrals as pioneered with the IBEX-Lo maps for O [6, 45] and extracted as a secondary component from the He flow distributions [46, 47]. Definitive measurements of secondaries by IMAP provide powerful complementary tools to probe the LIC-heliosphere interaction. In combination with the ribbon and the precise ISN flow direction, these observations will put multiple strong constraints on heliospheric structure and the interstellar magnetic field. IMAP provides both images of these distributions over most of the orbit around the Sun and substantially improves collecting power for the heavy neutrals, such as O, over IBEX. In addition, for the H ISN flow distribution, IMAP observations over large fractions of a 1 AU orbit and over dramatically varying radiation pressure with solar activity will provide a tool to obtain more complete ISN H distributions and to clearly separate the primary ISN flow and the secondary neutrals, which for H are typically only observed as a combined distribution. With the superior neutral atom collecting power and its continuous coverage of the sky for low flux distributions, IMAP will be able to seriously test, whether the observed distributions have additional non-thermal components and, if so, will characterize them and connect them to physical processes in the ISM and the heliospheric boundary.

3d. What is the Direction and Strength of the Interstellar Magnetic Field?

Determining the direction of the local interstellar magnetic field (LISMF) is important for understanding the heliosphere's global structure, the properties of the interstellar medium, and the propagation of cosmic rays in the local galactic medium. Measurements of interstellar neutral atoms by Ulysses for He and by SOHO/SWAN for H provided some of the first observational insights into the LISMF direction. Because secondary neutral H is partially deflected by the interstellar flow in the outer heliosheath and this deflection is influenced by the LISMF, the relative deflection of H versus He provides a plane - the so-called B-V plane in which the LISMF direction should lie. IBEX subsequently discovered a ribbon, the center of which is conjectured to be the LISMF direction. The most recent He velocity measurements from IBEX and those from Ulysses yield a B-V plane (Figure 11) with uncertainty limits that contain the centers of the IBEX ribbon at 0.7-2.7 keV.

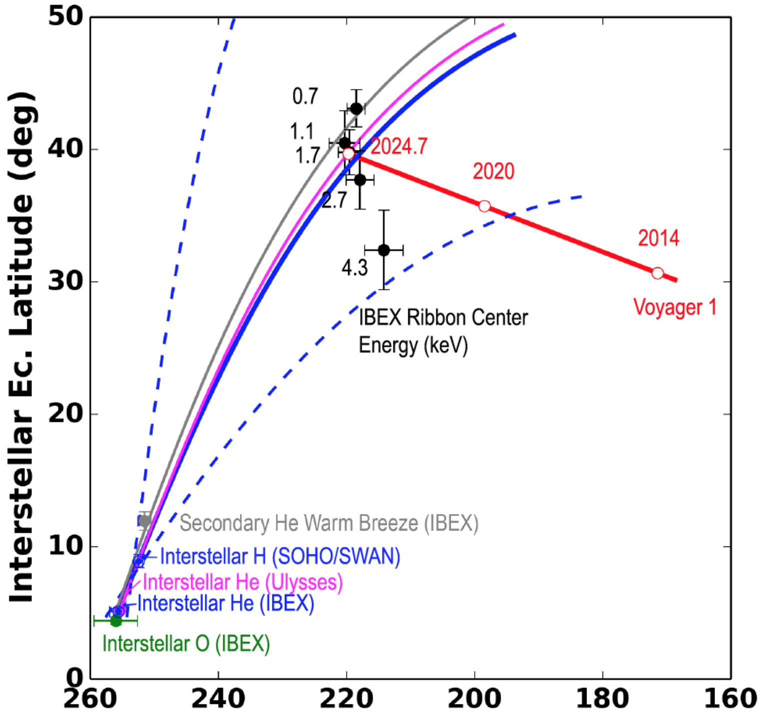

Figure 11. We combine seven different sets of observations to determine the direction of the interstellar magnetic field. The red line shows the linear fit to Voyager 1 observations of the interstellar magnetic field [50]. This linear fit is projected forward in time (the red circles surrounding a "V" show discrete points in time along the Voyager trajectory). The H flow direction from SOHO/SWAN [37, 49] is shown with the He flow direction derived by Schwadron et al. [28] in blue. The H inflow is more strongly deflected by secondary interactions in the heliosheath than the He inflow. Therefore, the BISM-VISM plane contains the deflection of H relative to He [37]. The region bounded by the dark blue dashed curves shows the limits of the BISM-VISM plane, which contains the orientation of the IBEX ribbon [32] from 0.7-2.7 keV. The purple closed circle shows the He inflow direction based on the most recent analysis of Ulysses ISN flow observations [30]. The purple line shows the corresponding B-V plane connecting the Ulysses He and SOHO/SWAN H observations. The center (closed black circles) of the IBEX ribbon is shown at separate energy steps observed by the Hi sensor on IBEX. The projected interstellar field direction from Voyager 1 converges with the 1.7 keV IBEX ribbon center on the date of 2024.7. The grey curve is the B-V provided by fitting secondary He in addition to H and primary He [47]. Also shown in green is the direction of interstellar O based on a recent determination from IBEX data [51].

Immediately outside and beyond the heliopause lies interstellar space, where Voyager 1 is currently making ground-breaking observations. The possibility that Voyager 1 has moved into the outer heliosheath now suggests that Voyager 1's direct observations provide another independent determination of the LISMF. The LISMF direction measured by Voyager 1 is > 40° off from the IBEX ribbon center and the B-V plane (Figure 11). However, taking into account the temporal gradient of the field direction measured by Voyager 1, we extrapolate to a field direction that passes directly through the IBEX ribbon center (0.7-2.7 keV) and the B-V plane (Figure 11), allowing us to triangulate the LISMF direction and estimate the gradient scale size of the magnetic field [50, 30]. The linear projection of the Voyager 1 data suggests that it could observe a field direction at the IBEX ribbon center by 2025 when the spacecraft is at 165 AU from the Sun. This also indicates a draping region of ~ 45 AU in radial extent near Voyager 1.

Because Voyager 1 is at a single location, it is difficult to develop a complete global picture from its measurements. Recently, Schwadron et al. [48] used near-Earth IBEX ENA data from the past five years in conjunction with observations of highly energetic cosmic ray particles with 99% the speed of light streaming in from elsewhere in the Milky Way galaxy to shed new light on our cosmic neighborhood, and propose an explanation for a decades-old mystery – why we measure more incoming high-energy cosmic rays on one side of the heliosphere than on the other. The IBEX ribbon appears to be ordered by the direction of the interstellar magnetic field direction that drapes around the heliosphere. The direction of the interstellar magnetic field revealed by the IBEX ENA ribbon observations is nearly perpendicular to the motion of our solar system through the galaxy. This information was then used to predict the distribution of high-energy (~10 TeV) cosmic rays that penetrate into the heliosphere. These predictions are shown on the right in Figure 12. The blue regions represent a lower intensity of cosmic rays whereas the red regions signify a higher intensity of cosmic rays. This uneven distribution looks similar to what is actually observed, shown on the left of Figure 12, thus supporting IBEX's findings.

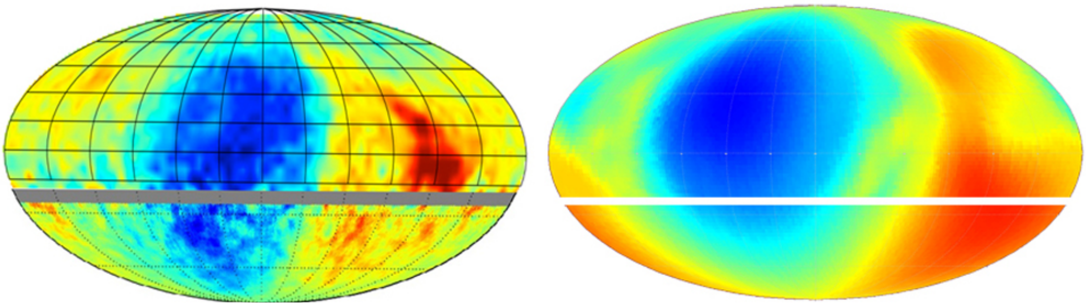

Figure 12. The magnetic fields in interstellar space inferred from IBEX lead to a prediction for the global anisotropies of TeV cosmic rays as shown on the right. Regions in blue have a decrease in the intensity of cosmic rays, while regions in red represent an increase in cosmic ray intensity. This looks similar to what is actually observed, shown on the left, thus supporting IBEX's findings. These global maps of TeV cosmic ray anisotropies are shown in Mollweide projection and in standard J2000 equatorial coordinates.

How does the ribbon change over ~10 year timescales? Stability of the ribbon over these timescales would support the idea that the ribbon is ordered by the interstellar magnetic field. However, if the ribbon changes significantly on these timescales and IMAP detects a very different structure than observed by IBEX, this would call into question not only the leading ideas to explain the ribbon, but also the concept that it is ordered by the interstellar magnetic field. Thus, IMAP is positioned to answer a critical question about the stability of the ribbon with major implications not only for the interstellar magnetic field, but also for the interstellar interactions with the magnetic field and the global structure of our heliosphere. Ultimately, these questions must be answered to understand how precisely our interplanetary plasma environment changes with time and how cosmic rays are controlled by the structure of the heliosphere.

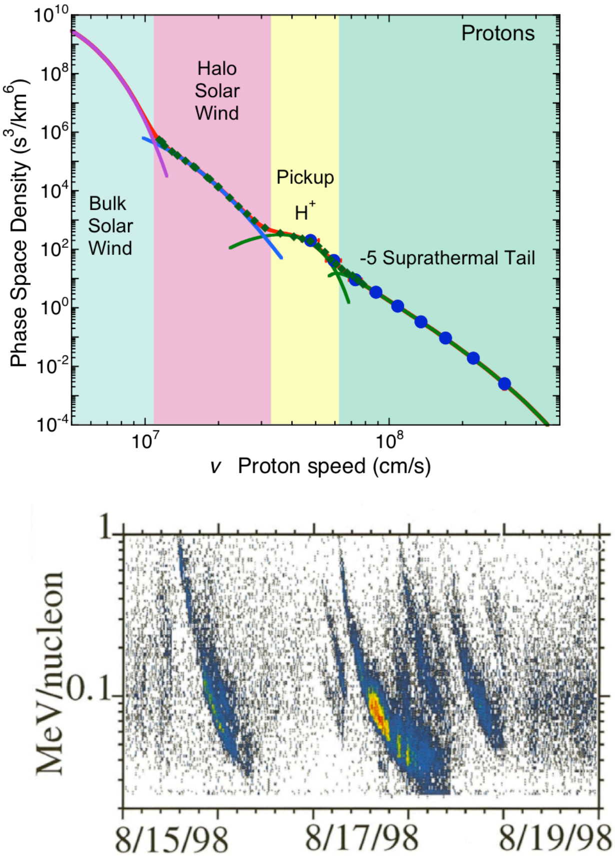

Figure 13. (Upper panel) Ion velocity distribution measured in the solar wind frame. Four components are clearly distinguishable: 1) Bulk solar wind studied since the beginning of the space age (red), 2) much hotter halo solar wind (blue), 3) interstellar pickup H^+, observable at 1 AU during the deep solar minimum (green), and 4) suprathermal tail (ST), just above the pickup ions. The ST spectrum is well approximated by a power law, with a gradual exponential rollover at ~$2.5 \cdot 10^8$ cm/s.

(Lower panel) Suprathermal particles injected at the Sun and in interplanetary shock events stay relatively close to their field lines, providing seed populations that vary by orders of magnitude in space and time. [52].

3e. What are the Suprathermal Seed Populations for Particle Acceleration in the Heliosphere?

Observations from many spacecraft in the Heliophysics System Observatory have contributed dramatically to our understanding of solar energetic particle events, the importance of suprathermal particles in interplanetary space for their effective acceleration, the source and evolution of solar wind, solar wind and energetic particle inputs into geospace, and the evolution of the coupled solar and heliospheric magnetic field. It is abundantly clear that a myriad of complex physical effects, variable with time and location, contribute to the properties of the solar wind, the heliospheric magnetic field, suprathermal and energetic particle populations at 1 AU (Figure 13), that are still poorly understood. With its combination of highly sensitive pickup and suprathermal ion sensors, IMAP will provide the species and spectral coverage as well as the temporal resolution to associate emerging suprathermal tails with interplanetary structures and physical processes.

IMAP, like ACE before it, will be a keystone of the Heliophysics System Observatory by providing comprehensive solar wind observations, measurements to diagnose the source and evolution of solar wind and suprathermal ions, provide solar wind and energetic particle inputs into the geospace environment, and track the evolution of cosmic rays and of the coupled solar and heliospheric magnetic field. IMAP’s comprehensive interplanetary monitoring suite is critical to support on going geospace interaction studies and space weather observations at the ideal location of the Lagrangian point L1. The high societal relevance of comprehensive solar wind, suprathermal, magnetic field and cosmic ray observations from L1 makes the IMAP mission an imperative as a successor to ACE.

4. IMAP's Urgency in a New Paradigm of the Evolving Space Environment

The space environment is a complex system regulated by the solar wind's interaction with the Local Galactic Environment. Our local interstellar boundaries separate the solar wind plasma from the Local Interstellar Medium (LISM), which is composed of the galactic matter (neutral atoms, ionized matter, and dust) and galactic magnetic fields left over from supernovae, stellar winds, ultimately as a relic of the primordial field. The distant interstellar plasma boundaries surrounding our heliosphere and the outflowing solar wind partially protect our solar system by regulating the intensity of GCRs that enters our solar system. GCRs are charged particles with relativistic energies and they permeate our galaxy; because they are charged, their motions are governed by the magnetic fields they encounter. GCRs present one of the greatest hazards for long-term space exploration since these high energy (~GeV) particles are so difficult to shield against deep in interplanetary space, that is, at altitudes well above Earth's strong internal magnetic field. The most energetic GCRs penetrate even the powerful magnetic fields closest to Earth ultimately colliding with and producing complex interactions with Earth's massive atmosphere; the effects of GCRs on the Earth system, including the biosphere either directly or indirectly, remain poorly understood and oftentimes highly controversial [53]. Recent compilation of paleontological data into estimates of global diversity suggest there is a significant ~62 million year cycle to biodiversity that as of yet has no agreed upon cause and is possibly driven by extraplanetary processes [54].

GCRs not only present a hazard to life through the breakdown of DNA, but also may help to stimulate evolution by increasing the rate of cell mutation [57]. In other words, the radiation environment of the Earth and planets, which is largely defined by the intensity and composition of GCRs in the solar system, may play a fundamental role in the formation and evolution of life. Similarly, as we begin our search for life elsewhere in the cosmos, particularly on planets surrounding other stars, we must also investigate the interstellar boundaries surrounding these stellar systems, and the effects these interstellar boundaries have on the cosmic rays within these systems. GCRs may also affect life in indirect ways through climate variability [53], although this relationship remains highly controversial.

The deep solar minimum between cycles 23 and 24 and the activity in cycle 24 differed significantly from those of the prior cycle. During this period, the fast wind was slightly slower, was significantly less dense and cooler, had lower mass and momentum fluxes, and weaker heliospheric magnetic fields compared to earlier cycles [58]. During the rise of activity in cycle 24 the mass flux of solar wind remained low and the magnetic flux of the heliosphere remained at significantly lower levels than observed at previous solar maxima in the space age. Cycle 24 is the weakest solar maximum of the space age, which continues the highly anomalous trends observed in the deep cycle 23-24 minimum. Conditions during the cycle 23-24 minimum appear to be similar to conditions at the beginning of the 1800's at the start of the Dalton Minimum [59]. Taken together, these recent changes suggest that the next solar minimum may continue to show declining sunspot numbers, associated with declining values of magnetic flux and further reductions in solar wind particle flux.

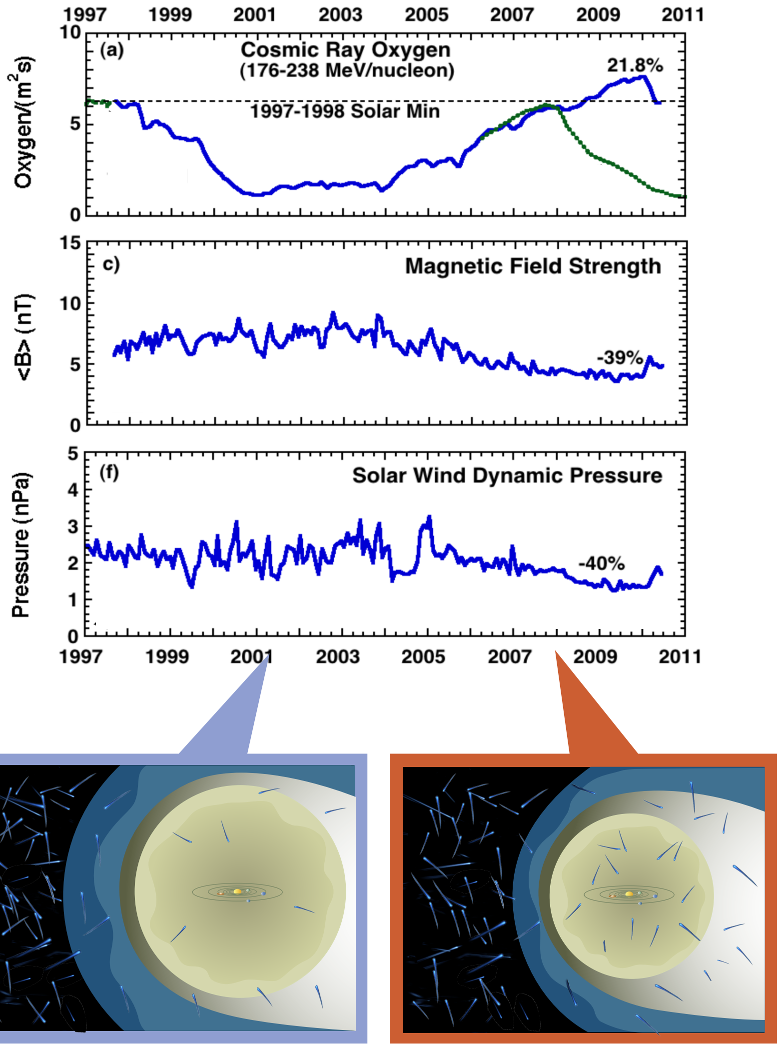

Figure 14. (Top Panels from 53) The recent anomalous rise in GCR flux (a) is associated with both a drop in the interplanetary magnetic field (b), solar wind ram pressure (c), and in the size of the heliospheric boundaries (bottom) where as much as 90% of low-energy GCRs (shown as blue streaks) are deflected in the strong magnetic field of the heliosheath [56].

The anomalously weak heliospheric magnetic field and low solar wind flux during the last solar minimum (Figure 14) have resulted in GCRs achieving the highest flux levels of the space age [55, 60], and fluxes continue to be unusually elevated through the cycle 24 maximum. It is unknown if the recent anomalous deep solar minimum is a harbinger of larger changes in the near future, or if the unusual changes in GCR fluxes and conditions on the Sun have an impact on Earth's atmosphere. These compelling questions provide fundamental motivation for IMAP.

The changes in the space radiation are strongly controlled by the changes in the global heliosphere. Understanding the interplay between changing solar conditions, the resulting changes in the global heliosphere, and the resulting changes in the radiation environment throughout the solar system remains a fundamental challenge. IBEX and INCA have opened a new window on the interaction between the Interstellar Medium and the Heliosphere. IMAP extends and expands this domain of discovery through:

- Improved resolution (higher sensitivity and suppression of background) of interstellar boundaries. While gross features of the interstellar boundaries such as the nose, tail and lobes have been identified by IBEX, these features have required years of observation and subsequently averaged over a changing medium.

- Improved time resolution of observations of interstellar boundaries to identify the connection between changes in the solar wind including and motion of interstellar boundaries

- Increased resolution of structures in both time and angular coverage allowing significant improvement in the connection between detailed observations of Voyager 1 and Voyager 2 and IMAP.

5. Overview of IMAP Scientific Objectives

IMAP builds on the highly successful first heliospheric ENA mapping mission, with its concurrent capability to provide in-situ observations of the interstellar gas flow for a variety of species, and on a broad array of in-situ pickup-ion (PUI) observations, to enable the discovery of the detailed processes and interaction between the heliosphere and the local interstellar medium (LISM). IMAP answers these fundamental questions:

1) What is the spatio-temporal evolution of heliospheric boundary interactions?
2) What is the nature of the heliopause and the interaction of the solar and interstellar magnetic fields?
3) What are the composition and physical properties of the surrounding interstellar medium?
4) How are particles injected into acceleration and what mechanisms energize them throughout the heliosphere and heliosheath?
5) What is the time-varying magnetic field, plasma, energetic particle, and galactic cosmic ray input at L1 into the Earth system and inner solar system?

The IBEX ribbon and the INCA belt provide fundamental motivation for IMAP. Since the first observations of the ribbon, the prospect of the existence of fine structure has remained a significant potential finding that strongly limits possible Ribbon mechanisms. However, the existence of this fine structure remains at the observing limit of IBEX both in terms of angular temporal resolution. IMAP's enhanced sensitivity and improved background suppression will allow a factor of almost 100 improvement in resolution compared to IBEX.

The mission's focus on understanding heliospheric boundaries makes it important to try to simultaneously take IMAP observations while also making direct *in situ* measurements via the two Voyager spacecraft in the heliospheric boundary region. IMAP will also enable observation of suprathermal ions of solar wind, interstellar, and inner-heliospheric origin with unprecedented collection power and time resolution. These measurements are essential for understanding particle acceleration. IMAP instruments will provide the environmental monitoring that is critical for effective background evaluation and removal in the ENA images and the interpretation of the pickup ion distributions. In addition, these instruments will serve as a comprehensive interplanetary monitoring suite in support of geospace interaction studies and space weather observations at the ideal location of the Lagrangian point L1.

Answering the questions motivating IMAP requires substantially advanced observations:

- High-resolution mapping and time evolution of heliospheric boundaries;
- Properties of interstellar neutral gas flow and its composition for H (including isotopes), He, O, and Ne (to also address Big Bang Cosmology with the first in situ D/H observations), and properties of the outer heliosheath;
- Pickup Ion Composition (implications for big bang cosmology and nucleosynthesis with a dedicated PUI instrument: He^3/He^4 and Ne^{22}/Ne^{20} with better than 5% accuracy);
- Seed populations of energetic particles with high time resolution (several minutes);

- Underlying time variations of ubiquitous suprathermal ions;
- Solar Energetic Particle composition, injection and acceleration;
- Suprathermal and energetic particle transport;
- ACR/GCR modulation and evolution with time; and
- L1 environmental monitoring and solar wind input for magnetospheric and ITM science

6. IMAP Mission and Instrument Implementation

The IMAP goals can be achieved with a mission concept that is largely drawn from ACE, with greatly-improved ENA imaging aspect infused from IBEX and INCA, with the first dedicated pickup ion instrument, and with a high-collecting power suprathermal ion sensor. IMAP is conceptualized as a Sun-pointed spinner, with re-adjustment of the spin axis every few days to provide all-sky maps every 6 months. To escape the ENA background environment of the magnetosphere and to allow continuous interplanetary observations, the spacecraft will be placed at L1. The mission goals can be achieved with a 2-year baseline mission, including the transit to L1, with extensions to a longer operation possible. To provide the necessary observations IMAP combines the following state-of-the-art measurement capabilities, for which no further development effort is required because the improvements over previous missions are based on experience with the instruments during calibration, testing, and operation.

High-Resolution ENA Maps: Two ENA cameras will produce critical new observations of ENAs from the heliospheric boundary region over an extended energy range and with significantly improved sensitivity, and spatial and energy resolution, compared to prior observations. They will cover the energy range 0.3-20 keV and 3-200 keV with 10x the angular resolution and ≈100x the combined sensitivity/duty cycle of the IBEX-Hi and CASSINI INCA sensors. With the sensitivity gain, these sensors will take advantage of oversampling the polar regions with high time resolution of a few days.

High-Resolution & Sensitivity ISN Flow Collection: An **Interstellar Neutral Atom Camera** and the first dedicated **Pickup Ion Sensor** will take coordinated high sensitivity observations of the interstellar gas flow through the inner solar system. The ISM Neutral camera will provide ISM flow observations of H, D, He, O, and Ne at 5-1000 eV with a pointing knowledge of 0.05^{o} and >10x the combined sensitivity/duty cycle of IBEX-Lo, also extending the ENA maps below 0.3 keV. The pickup ion sensor provides pickup ion distributions of interstellar H, ^{3}He, ^{4}He, N, O, ^{20}Ne, ^{22}Ne, and Ar as well as inner source C, O, Mg, and Si over the energy range 100 eV – 100 keV/e with a combined sensitivity/duty cycle 100x that of SWICS, also providing SW heavy ion composition.

High-Cadence Suprathermal Ion Observations: Overlapping with the pickup ion sensor, a suprathermal ion sensor will provide composition (0.03-5 MeV/nuc) and charge state (0.03-1 MeV/e) for H through ultra-heavy ions (5 min cadence for H and He).

Solar Wind and Interplanetary Monitoring Suite will serve to understand and mitigate backgrounds from the local environment for high-sensitivity ENA observations and can also provide societally important real-time solar wind and cosmic ray monitoring. This suite measures SW ions (0.1-20 keV/e) and electrons (0.005-2 keV) every 15 s, the IMF to ≤1nT at 16 Hz, and SEP, ACR, and GCR electrons and ions (H-Fe) over 2-200 MeV/nuc.

7. Conclusion and Outlook

Our piece of cosmic real-estate, the heliosphere, is the domain of all human existence. Its history and future in our galaxy is key to understanding the conditions on our evolving planet and future expansion across the solar system. As we ask about the habitability of other planets surrounding other stars, we grapple with understanding the complex environments and interactions in the local parts of the galaxy where these stars exist. Our own heliosphere is an astrophysical case-history of the successful evolution of life in a habitable system. By exploring our global heliosphere and its myriad interactions, we develop key physical knowledge of the interstellar interactions that influence exoplanetary habitability as well as the distant history and destiny of our solar system and world. The interactions in the solar wind and the heliosphere produce highly energetic particles and help shield much of the galactic cosmic radiation that penetrates the heliosphere from the interstellar medium. Thus, the heliosphere presents a fundamental opportunity to study the basic processes that control particle radiation.

IBEX was the first mission to explore the global heliosphere and in concert with Voyager 1 and Voyager 2 is discovering a fundamentally new and uncharted physical domain of the outer heliosphere. The enigmatic ribbon is an unanticipated discovery demonstrating that much of what we know or think we understand about the outer heliosphere needs to be revised. The next quantum leap enabled by IMAP will open new windows on the frontier of Heliophysics at a time when the space environment is rapidly evolving and becoming increasingly hazardous due to rising levels of galactic cosmic ray fluxes.

The remarkable synergy between IMAP, Voyager 1 and Voyager 2 will remain for at least the next decade as Voyager 1 pushes further into the interstellar domain and Voyager 2 moves through the heliosheath. In fact, Voyager 2 moves outward in the direction of part of the ribbon and Voyager 2's plasma measurements will create singular opportunities for discovery in the context of IMAP's global measurements.

IMAP, like ACE before it, will be a keystone of the Heliophysics System Observatory by providing comprehensive solar wind observations, measurements to diagnose the source and evolution of solar wind and suprathermal ions, provide solar wind and energetic particle inputs into the geospace environment, evolution of cosmic rays and the evolution of the coupled solar and heliospheric magnetic field. IMAP's comprehensive interplanetary monitoring suite is critical to support on going geospace interaction studies and space weather observations at the ideal location of the Lagrangian point L1. *The high societal relevance of comprehensive solar wind, suprathermal, magnetic field and cosmic ray observations from L1 makes the IMAP mission an imperative as a successor to ACE.*

This paper is similar to an unpublished whitepaper that was presented to the National Academies of Sciences, Engineering and Medicine Committee for Solar and Space Physics (CSSP). The author list is identical to that of the white paper, and all authors were heavily involved in the IMAP deliberations as a part of the Solar and Space Physics (SSP) Decadal Survey. This paper provides a citable reference for IMAP objectives and the instrument straw man traceable to the SSP Decadal Survey. It is fitting that our paper appears in the volume that celebrates the 80^{th} birthday of Ed Stone as part of the AIAC.

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Authors wish to thank and acknowledge the many dedicated individuals that have made possible the Voyager missions, the IBEX mission, the Cassini/INCA project, the ACE mission, the individuals that have contributed SSP Decadal Survey, and the CSSP. We would like thank Ed Stone for his work in space science over many decades, which has lead to the remarkable successes of the ACE mission, the Voyagers, and countless other projects. Lastly, we would like to thank Gary Zank and Adele Corona, the organizers of AIAC, and the editors of this volume. The meeting and the volume of papers that has resulted is a great benefit to the field of Heliophysics and Heliospheric Physics.

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