The outer heliosphere – solar system's final frontier

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Introduction

In the summer of 2002 the twin Voyager 1 and 2 spacecraft, launched in 1977, had long since completed their primary mission to explore the giant outer planets of the solar system and were approaching the very edge of the solar system. With most of theirs instruments turned off and the spacecraft operating on a fraction of the original design power, the expectations for future science results were relatively modest. There was even talk that these two stalwarts of the NASA fleet should be retired. What happened instead was a chain of remarkable new discoveries that redefined the face of space physics for the next decade.

In 2002 Voyager 1 started to observed highly energetic ions arriving from larger heliocentric distances [*Krimigis et al.*, 2003; *McDonald et al.*, 2003]. The spacecraft had arrived in the vicinity of the inner edge of the heliospheric boundary, known as the solar wind *termination shock* (TS), whose existence had long been predicted by theoretical models [*Parker*, 1961], and was sampling the particles accelerated close to this immense plasma structure. The shock itself was crossed at the end of 2004 and in the mid-2007 by Voyager 1 and Voyager 2 respectively. While the shock was approximately where it was predicted to be, many of measurements of solar wind and energetic particles were in stark contrast with the models.

A major disagreement between theory and observations was Voyager's apparent failure to detect the source of *anomalous cosmic rays* (ACRs), which was believed to be the TS as a whole [*Pesses et al.*, 1981]. Energetic particle signatures were not consistent with steady first order Fermi acceleration at a strong collisionless shock [*Stone et al.*, 2005; *Decker et al.*, 2005]. Rather, the observed ions appeared to belong to two different populations, one (low energy) accelerated locally at the TS, and the other (high-energy ACR) accelerated elsewhere. The disagreement led to a major revision in our understanding of particle acceleration mechanisms in space plasmas (Section 3).

The termination shock itself and the region of heated shocked solar wind plasma beyond, known as the *heliosheath*, proved to be full of surprises. Far from a stationary structure, the TS was traveling with a speed of up to 100 km/s toward and away from the Sun, in response to variations of the dynamic pressure of the solar wind. Voyager 2 discovered that the TS was in a rare state known as an energetic particle-mediated shock possessing an extended upstream precursor [*Florinski et al.*, 2009]. The temperature of the bulk plasma increased by only a factor of 10 rather than ~100 that would follow from energy conservation [*Richardson et al.*, 2008]. The missing energy is evidently absorbed by *pickup ions* (PUI), former interstellar neutrals ionized in the solar wind via a process of charge transfer (Section 5).

Whereas the Voyagers are not instrumented to measure PUIs directly, their presence in the distant heliosphere is deduced via remote sensing of *energetic neutral atoms* (ENAs) produced in charge transfer collisions between ions and interstellar neutrals by the Earth-orbiting IBEX spacecraft and by Cassini in orbit around Saturn. During its first year of operation the IBEX team made a startling discovery of a ribbon of enhanced ENAs sources threading its way across the sky [*McComas et al.*, 2009]. One explanation is that the ring is composed of secondary ENAs produced from neutralized solar wind protons because it displays signatures (such as latitude variations) characteristic of the solar wind (Section 2).

Much insight was gained from observations of *galactic cosmic rays* (GCRs) in the outer heliosphere and heliosheath. These highly energetic particles are messengers from distant supernova shocks where they are believed to be accelerated. It is now revealed that GCRs spend much of their heliospheric transit time trapped in magnetic structures in the heliosheath, which plays a prominent role in modulating their intensities [*Florinski and Pogorelov*, 2009]. As the Voyagers approach the outer edge of the solar system, called the *heliopause*, the pristine interstellar spectrum of GCRs is being gradually revealed [*Webber and Higbie*, 2009]. The heliosheath is the last puzzle for a comprehensive theoretical model of GCR modulation in the heliosphere (Section 4).

More discoveries are in store for the upcoming decade. The Voyagers are expected to be operational until 2020, by which time both would have crossed the heliopause. Apart from the great symbolic value of first venturing outside our solar system, the heliopause itself should prove to be no less significant than the TS. The region could be the source of ACRs according to some theories, as well as a generator of turbulence via instabilities driven by charge exchange with interstellar hydrogen (Section 5). It is hardly necessary to emphasize the importance of a diverse theory program to analyze and explain past, present, and future observations. The global structure of the region, including magnetic field topology, needs to be modeled in detail based on 1 AU and in situ observations. The TS and heliosheath comprise a unique space plasma laboratory with conditions found nowhere else in the solar system, providing a broad field for theoretical investigation. An investment in an outer heliospheric theory program over the next decade will benefit multiple space-related fields from solar physics to astrophysics.

Elucidating the global structure of the heliosphere

Past achievements. The two Voyagers crossed the TS at a heliocentric distance of 94 and 84 AU, respectively, indicating a distinct North-South (and possibly East-West) asymmetry of the global heliosphere [Stone et al., 2008]. This effect has been primarily attributed to a tilt of the interstellar magnetic field relative to the velocity vector between of the solar system relative to the surrounding interstellar cloud [Opher et al., 2007, Pogorelov et al., 2007]. A second effect that plays a role is the motion of the shock toward the Sun as a result of a reduction in the solar wind dynamic pressure approaching the 2007-2009 deep solar minimum. Based on the knowledge of Voyager 1 crossing, a successful forecast of Voyager 2 crossing was made [Washimi et al., 2007]. The Voyager TS observations allowed to place theoretical constraint on the direction and magnitude of the interstellar magnetic field, one of the last unknowns of our local galactic environment (Figure 1a). Another unexpected result of the Voyager mission is the significantly faster heliosheath plasma speed measured at Voyager 2. The flow is now turning away from the radial direction as the plasma becomes deflected on approach to the heliopause. There is more deflection in the azimuthal direction than in the polar direction [Richardson et al., 2009].

Much progress has been made in explaining the origin of the IBEX ribbon and the related structure at higher ENA energies ("belt") uncovered by Cassini [Krimigis et al., 2009]. Ribbon ENAs could be produced beyond the boundaries of the heliosphere, in the interstellar space around the heliopause from PUIs of solar wind origin, or closer to the Sun, upstream of the TS from shock-reflected ions. The leading theory [McComas et al., 2009], quantified in Heerikhuisen et al. [2010] currently explains both the intensity

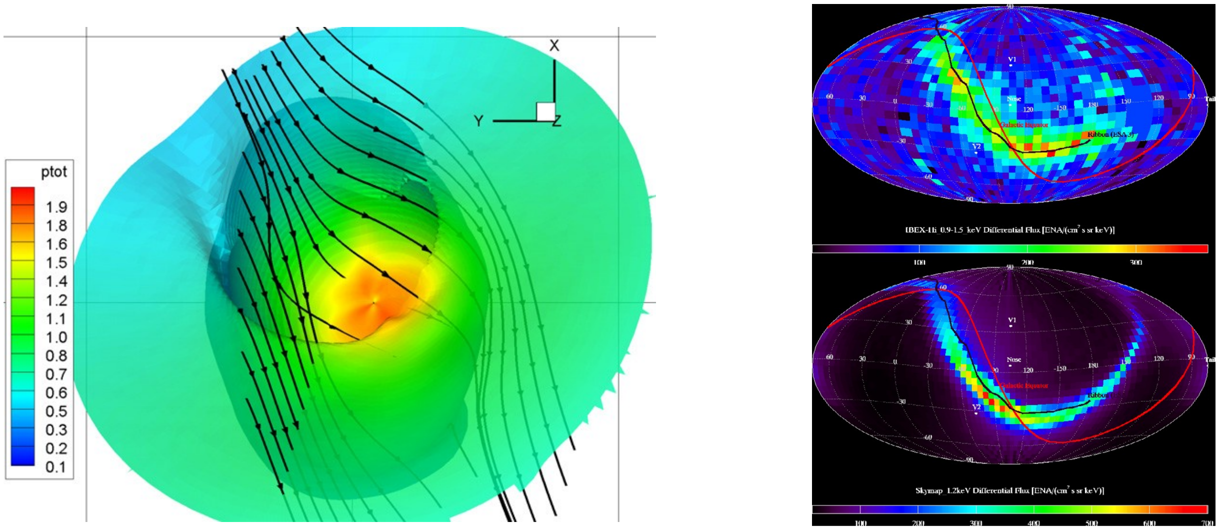

Figure 1: (a) A three-dimensional model representation of the heliospheric interface and of the interstellar magnetic field draping around the heliopause. (b) An IBEX all sky map of 1 keV ENA intensity (top) and a computer model (bottom) showing the ribbon structure [Heerikhuisen et al., 2010].

and the geometry of the ribbon (Figure 1b), although outstanding issues remain. It also provides an important clue to the direction of the magnetic field in the local interstellar space.

Case for future study. A synergy of Voyager, IBEX, and Cassini to study the remotest regions of the solar system cannot be overstated. The New Horizons space probe, currently en route to Pluto, could potentially compliment Voyager data from the direction of the heliospheric tail. We need to continue coordinated efforts to elucidate the global structure of heliospheric boundaries using both in situ and remote observations. A strong and consistently funded theory and simulation component should be an essential part of this work. Efforts to develop a complete self-consistent computer representation of the heliosphere that includes both the solar wind plasma and the interstellar neutrals, should be a priority target for funding in this field.

Much work is still needed to reconcile most of spacecraft observations with a single time-dependent global model of the heliosphere and the surrounding interstellar medium. A crucial component of this effort is the development of more accurate (kinetic) representations for interstellar and heliospheric atoms and for pickup ion populations. A more remote goal is the eventual coupling with the models of the inner heliosphere that would provide a time-dependent input of solar wind data to the models of the outer heliosphere. Computational models of the global heliosphere are in many ways still in their infancy. But in the same way that continued development of space-weather models – and terrestrial weather models in the decades prior – has greatly improved our understanding and predictive power, so too will global heliospheric models continue to improve over the next decade, provided such development continues to be supported. Due to the limited observational data, all the topics discussed in this paper rely on accurate simulations, so that continued support to develop models of the global heliosphere should be a corner stone of any outer heliospheric program.

A particle acceleration laboratory

Past achievements. The TS was traditionally considered the only source of ACRs [Jokipii, 1986]. Yet neither Voyagers collected evidence that the process was operating at the highest energies (up to 100 MeV) at the locations of their shock crossings [Stone et al., 2008]. A plethora of new theories were development in response to these puzzling results. It was recognized that the TS is an immense structure with a large degree of spatial and temporal variability. Unlike most interplanetary shocks, the TS can be both quasi-parallel and very oblique depending on latitude and longitude. Its compression ratio, speed, and magnetic field connection to other parts of the heliosphere all vary on timescales from hours to years.

If the TS is the source of ACR, then their acceleration occurs at sites not accessible to the Voyagers. The most promising locations are the flanks and the tail regions. These sites enjoy a longer magnetic field connection times to the downstream regions which allows particles to return to the shock multiple times to boost their initial energy [McComas and Schwadron, 2006; Kota, 2010]. The process is facilitated by the bluntness of the TS (Figure 2a). If ACRs are accelerated at the flanks, their Voyager-measured intensities would appear modulated, as if they were coming from larger heliocentric distances. It is also possible that time-dependent reformation of the shock caused some of the observed spectral anomalies.

Another intriguing possibility is that ACRs originate close to the heliopause, where turbulent conditions could also favor particle energization. Proposed mechanisms include stochastic acceleration and acceleration at reconnecting current sheets. The former process has been shown to produce power laws in momentum for a range of ion species similar to what is observed at Voyager 1 [Fisk and Gloeckler, 2009]. The latter is a result of a highly complex structure of the magnetic field that includes a rapidly oscillating magnetic field due to a piling up of bends in the heliospheric current sheet [Drake et al., 2010]. Reconnection leads to a formation of magnetic islands that could serve as particle acceleration sites (Figure 2b).

Case for future study. The origin of ACRs remains an outstanding problem in space physics. Observations currently do not permit us to eliminate any of the theories outright. The riddle may be answered when the Voyagers approach the heliopause, which will happen within the next decade. However, we also must acknowledge a possibility that the acceleration site will not be visited by any spacecraft. For this reason it is essential to make full use of available Voyager 1 and 2 data, including spectral, spatial, and

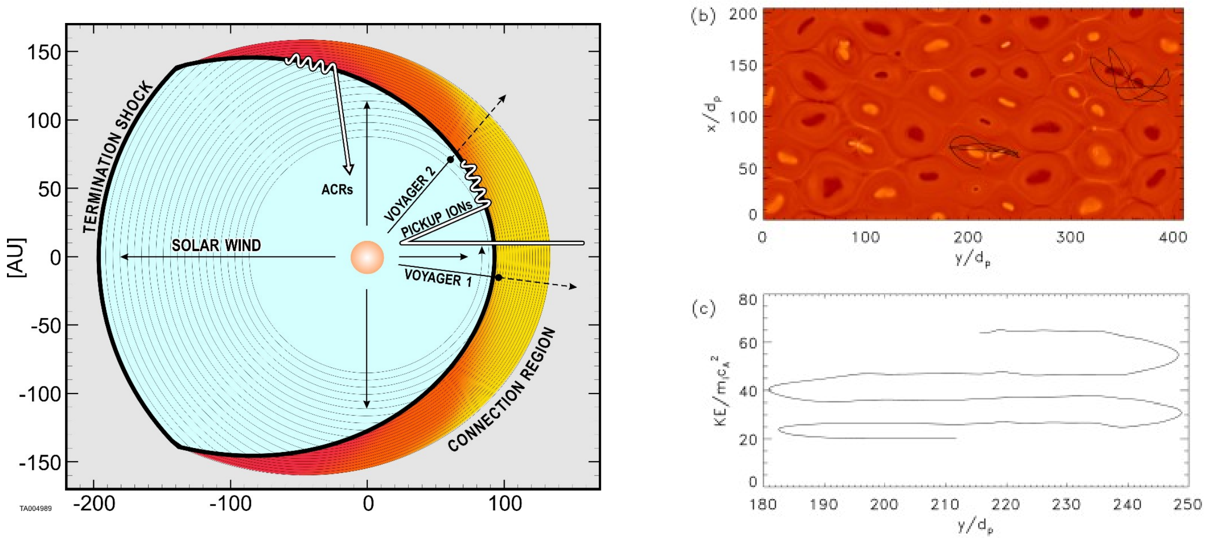

Figure 2: (a) A conceptual drawing of a blunt termination shock showing magnetic field connectivity. Acceleration is favored at the flanks (red) where the field stays connected to the shock for a long time [McComas and Scwadron, 2006]. (b) A simulation of a reconnecting current sheet leading to a formation of magnetic island that could serve as energetic particle accelerating sites [Drake et al., 2010].

temporal features, to reconstruct ACR acceleration history as accurately as possible.

Theoretical work should focus on developing working concepts of ACR acceleration capable of explaining the entire compendium of observational results. We need a realistic three-dimensional representation of the blunt TS and a model of injection of PUIs into the acceleration process at a quasi-perpendicular turbulent shock. A parallel effort should focus on elucidating the plasma and magnetic field conditions near the heliopause and on evaluating their effectiveness in accelerating charged particles to high energies. These modeling objectives tie in closely with those required to improve our understanding of the global structure. The TS and the heliosheath represent a unique particle acceleration laboratory with conditions not found anywhere else in the solar system. It is essential to make use of the opportunity to investigate the alternative acceleration mechanisms while we still have spacecraft taking in situ measurements in the region for the next decade.

Galactic cosmic rays in the heliosheath

Over the past decade Voyager observations have shown just how important the role of the heliosheath is in protecting the inner heliosphere from the ionizing cosmic radiation in the form of GCRs. This barrier effect is very significant at moderate GCR energies (below a few hundred MeV). Intensities in the heliosheath during the 2007-2009 extended solar minimum were about 50% lower than the model interstellar values. At the same time radial cosmic-ray gradients were small indicating that a stronger barrier effect at even larger distances, most likely close to the heliopause [Stone et al., 2008].

Much was learned from computer simulations about the pattern of GCR transport in the turbulent heliosheath. Figure 3a illustrates the very complex topology of magnetic field in the outer heliosphere and heliosheath. The oscillating neutral sheet is folded very tightly in the heliosheath and segments of the opposite polarity, corresponding to different solar cycles, are simultaneously present on the leeward (tail) side. We now have the capability to simulate a range of cosmic-ray trajectories in this very complex field using Monte Carlo simulations. A time history of galactic protons is illustrated in Figure 3b. Clearly these particles spend 3 to 5 times longer in the heliosheath than they do in the solar wind. The heliosheath thus serves as a long term storage for GCRs.

Case for future study. The next decade will finally reveal the unmodulated spectrum of GCRs at the edge of interstellar space. This is crucial for the models of GCR production and transport throughout the

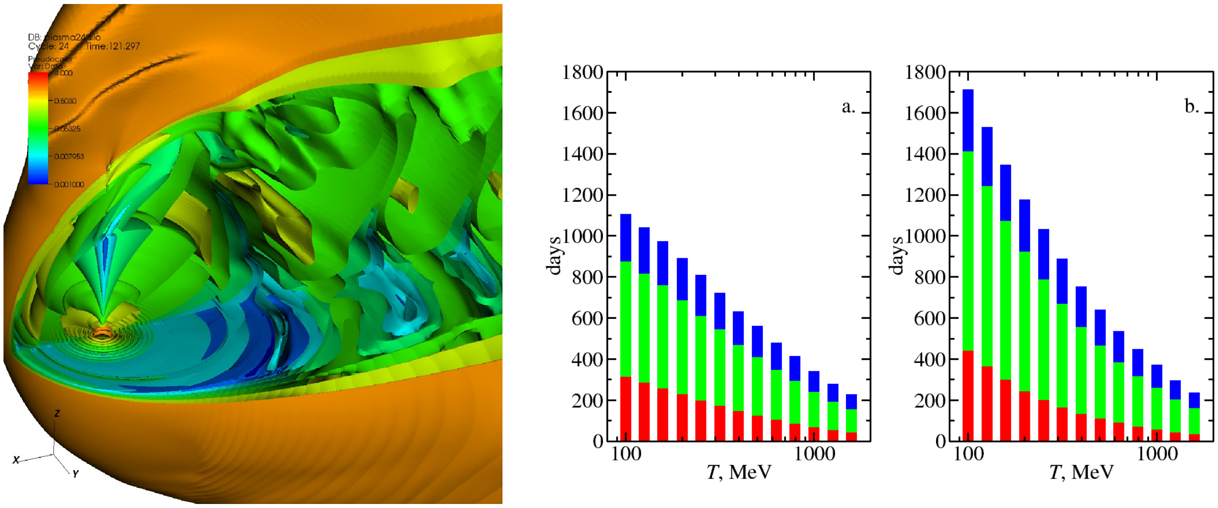

Figure 3: (a) A three-dimensional topology of magnetic field in the solar wind heliosheath. Notice regions with changing polarity of magnetic field corresponding to positive and negative solar cycles. (b) Time spent by cosmic ray protons in the solar wind (red), the heliosheath (green) and the heliotail (blue) regions [Florinski and Pogorelov, 2009].

Galaxy. The unmodulated intensity will provide the absolute upper limit on the intensity of ionizing galactic radiation in near Earth and interplanetary space with important implications for the future of manned space missions to other planets. We will learn, through Voyager measurements and theoretical modeling, just how effective is the heliosheath as a cosmic-ray shield for the inner solar system during different phases of the solar cycle. The role of the TS and the heliotail region in re-accelerating GCRs [Florinski et al., 2003] also needs to be evaluated.

Despite much progress, a number of observations remain puzzling. For example, the intensity of low-energy electrons has recently risen at Voyager 1, hinting that the heliosheath could be more “porous” than previously thought. It is possible that this observation means Voyager 1 is near the heliopause and is detecting a galactic electron component. We still do not have a good understanding of turbulence in the heliosheath, which controls scattering and diffusion of cosmic rays. This needs to be one of the theory focus areas for the next decade.

The termination shock, the heliosheath, and the heliopause

Voyager 2 discovered the TS to be in a highly unusual state known as an “energetic particle mediated shock” [Richardson et al., 2008; Florinski et al., 2009]. The plasma flow is slowed down upstream of the shock,in the region called the shock precursor, by the back-pressure of the shock-accelerated ions. Such shocks were only observed a handful of times in interplanetary space and the fact that the largest shock in the solar system is of this type is a boon to the science of mediated shocks in space and astrophysics. For example, supernova remnant shocks, believed to be sources of GCRs, could be themselves mediated by cosmic ray particles [Berezhko, 2001]. The TS may be regarded as a reference case for these distant astrophysical objects, an important cross-discipline connection.

Another landmark Voyager discovery was a lack of heating of solar wind ions as they crossed the TS [Richardson et al., 2008]. The missing energy is believed to be transferred to PUIs through efficient reflection from the shock potential [Lee et al., 1996; Zank et al., 1996]. An effort is currently underway to reconstruct the spectrum of low-energy PUIs using IBEX measurements of heliosheath ENAs. Figure 4a shows a comparison between IBEX-derived fluxes below 6 keV and higher-energy in situ Voyager proton data [Gloeckler and Fisk, 2010]. This comparison provides important clues as to how PUIs are heated and accelerated to eventually become anomalous cosmic rays.

The character and nature of turbulent fluctuations in the heliosheath has proven to be entirely different

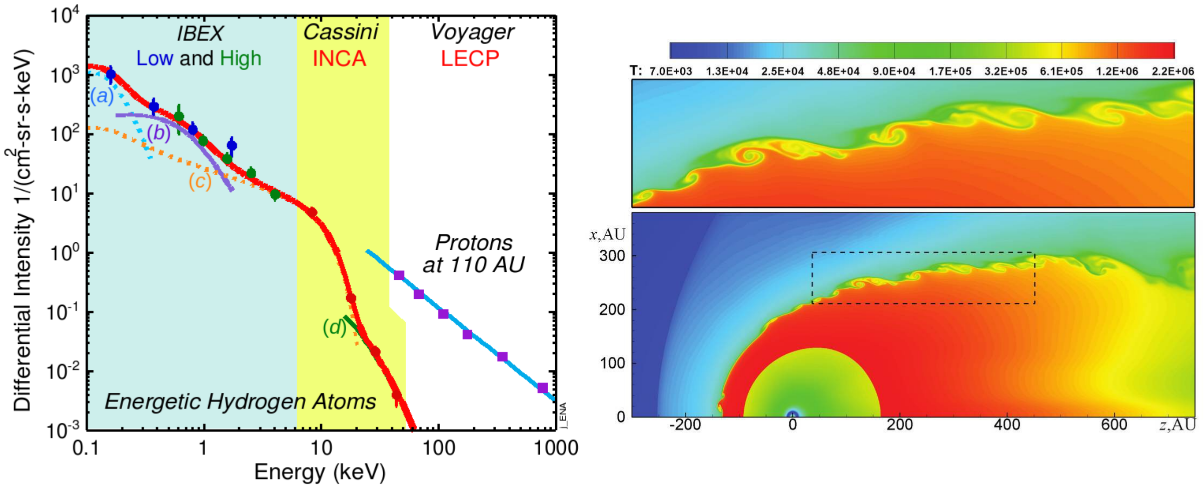

Figure 4: (a) Spectra of energetic protons and ENAs in the heliosheath from a model compared with Voyager, IBEX, and Cassini [Gloeckler and Fisk, 2010]. (b) A computer simulation showing vortices forming on the surface of the heliopause as a result of instability driven by charge exchange [Borovikov et al., 2008].

from the more familiar turbulence in the solar wind sampled by ACE, Wind, and Ulysses at 1-5 AU. Little is known about the physical processes that govern the intricate multi-scale interactions. The heliosheath region features unusual nonlinear structures, such as magnetic hole and humps. Another intriguing observation is that the magnetic field distribution is log-normal in supersonic solar wind, but Gaussian in subsonic heliosheath, with marked differences between the regions sampled by Voyager 1 and by Voyager 2 [Burlaga et al 2009].

The heliopause is now believed to be in a turbulent state as well. This boundary of the solar system may be unstable owing to a different degree of drag from plasma-neutral interaction on the solar and the interstellar sides. This process could lead to a formation of vortices shown in Figure 4b [Zank, 1999; Borovikov et al., 2008]. A mixing between the interstellar and heliosheath plasmas could lead to a production of X-rays that opens an intriguing possibility of observing astrospheres around other stars.

Case for future study. A realistic modeling of the heliosheath plasma, one that includes a self-consistent treatment of the PUIs, is critically important and essential to our understanding of the highly variable heliosheath plasma. This calls for theoretical and modeling development of the magnetic structures and turbulent interactions in the presence of PUIs in mutli-scale subsonic heliosheath plasma. More realistic models of heliosheath plasma taking into account its essentially non-thermal (non-Maxwellian) nature need to be developed over the coming decade.

Work continues on deducing the low-energy heliosheath PUI component, invisible to the Voyagers, from IBEX and Cassini ENA observations. Future IBEX measurements will reveal the differences in the suprathermal components in the fast and slow solar wind and in the upwind vs. heliotail directions. Research should also focus on elucidating the conditions near the heliopause, including the possible plasma depletion layer, magnetic reconnection sites, and instability due to charge exchange.

Summary

The next decade will be an exciting time for the outer heliospheric physicist. It is hard to overestimate the importance of the Voyager interstellar mission in being our only chance to study directly the very edge of the solar system and, for the first time, the interstellar space itself. In this paper we presented a list of discoveries made in the outer heliosphere over the past decade and discussed their significance in other areas of space physics and astrophysics. New discoveries of this magnitude are still out there, and call for a focused and reliably funded supporting theory and modeling program concentrating on the outer heliosphere. At present, the field is a relatively minor component of the Heliophysics program element at

NASA. While in principle, the outer heliosphere is included in this component, funding has traditionally been redirected to disciplines perceived to be more "mainstream" (solar physics and space weather).

The following is of what we believe would be an appropriate range of focus areas in the outer heliospheric research for the next decade.

- Large-scale structure of the heliospheric interface, heliosheath flow geometry,
- Conditions in the very local interstellar medium (magnetic field, galactic cosmic ray specra),
- Interstellar and heliospheric neutral atoms, composition,
- Suprathermal plasma component, pickup ion evolution in the heliosheath,
- Deducing acceleration sites and mechanisms of anomalous cosmic rays,
- Physics of the termination shock, ion reflection and energization, role of turbulence and shock variability,
- Understanding galactic cosmic ray filtration by the "heliospheric shield",
- Properties of turbulent fluctuations and nonlinear structures in the heliosheath, their effects on energetic particles,
- Physics of the heliopause, magnetic reconnection, instabilities of the heliopause.

To sustain the current outer heliospheric theoretical science community a modest level of funding is required. We estimate support is needed for an equivalent of 20 full time researcher positions per year at $200,000/year, which comes to a total of $40M over ten years. Funding could be delivered via dedicated theory or guest investigator program as 7 or more three-year awards of $500,000-$600,000 each per year.

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