Where do we go with Solar and Heliospheric Physics?

E. Möbius

Space Science Center and Department of Physics, University of New Hampshire, Durham, NH, USA

Abstract. After about 40 years of solar wind and heliospheric space research questions about the structure and the origin of the solar wind still await an answer. We still don't understand how the corona is heated and how the solar wind is accelerated, what are the sources for the fast and slow wind. Recent findings seem to indicate that the magnetic patterns below the sun's surface and the coronal structure are intimately connected, but quantitative connections are difficult to make. Modeling shows that the strength of the solar wind and coronal mass ejections controls the spatial and temporal response of the heliospheric boundary, while the physical state of the surrounding interstellar medium sets the boundary conditions. With a fleet of solar and heliospheric spacecraft throughout the heliosphere we have a unique situation that enables us to make substantial progress, and "Living with a Star" will add a comprehensive 3D view of the inner heliosphere. However, the fundamental questions cannot be solved without in-situ sampling to within a few solar radii, and the heliospheric boundary will not be fully understood without crossing it.

1. INTRODUCTION

Since the beginning of the space age in 1957 our satellites and probes have ventured the regions beyond the Earth's atmosphere. Our knowledge about the Earth's magnetosphere, other planets and their magnetospheres, interplanetary space and about the sun has advanced substantially. Spacecraft have visited almost every planet, they have flown by comets and asteroids. Probes have sampled the solar wind and even pickup ions, neutral atoms and dust particles of extrasolar origin, extensively in the ecliptic plane. The Ulysses spacecraft explores the high latitude regions beyond 1.5 AU, which has led to a better understanding of the 3-dimensional structure of the heliosphere. The Helios probes have extended our knowledge inward to 0.3 AU from the sun, and the Voyagers are expected to reach the first indication of the distant boundary of the heliosphere, the solar wind termination shock, within the next few years. However, we have not yet probed and understood the origin of the solar wind – the inner frontier, nor have we crossed and probed its boundary – the outer frontier, not to mention exploring the space beyond.

Concerning the origin of the solar wind, we still don't understand the physical processes that heat the corona to 1 - 2 -10⁶ K, whereas the photosphere is only at 5500 K. In layman's terms: why is the "cooking pot" hotter than the "stove"? There are still debates about the mechanisms that lead to the acceleration of the wind to supersonic speeds, about the sources of the fast and the slow wind, and where and how energetic particles are produced. Conversely, looking outward we need to understand how our galactic neighborhood interacts with the solar wind. This interaction determines the size of the heliosphere, how much of the galactic cosmic rays and interstellar dust is kept out, and how the interstellar neutral gas is filtered before it flows through our system. On a broader scheme, our heliosphere is the one example of an "atmosphere" - typical for many stars - that we can study with in-situ methods. Similarly, the local interstellar cloud (LIC) is the one sample of present day interstellar matter whose elemental and isotopic composition and physical state we can study in detail.

Why should we strive for such far-reaching goals, and will there be any tangible benefits for our society? In a nutshell there are three profound reasons:
• Firstly, it is a matter of comprehension; we need to understand our larger environment, in which the crucial Sun-Earth relationships are embedded. As we have learned over the past decade, humankind has made itself vulnerable to "space weather" [1], with continent-wide power grids that are sensitive to magnetic impulses, with application satellites whose electronics can be destroyed, and with humans in space who could be harmed by excessive radiation. Unraveling the source of the solar wind and its outer boundary is a fundamental step towards the basic understanding needed for successful "space weather" forecast, which is currently in the state of weather forecast about 100 years ago. Also, the heliosphere is the first
defensive shield of the terrestrial bio-system against high-energy galactic cosmic radiation. The inner two shields are the Earth's magnetosphere and atmosphere. 
• Secondly, it is a matter of investigation, how our universe, the sun and its planets and we ourselves evolved. Taking two disparate samples of galactic material, i.e. from the solar system, which was born 4.5 billion years ago, and from the LIC, which represents present day galactic matter, we can learn about the evolution of matter from the Big Bang to date. 
• Thirdly, sending a Solar Probe into the atmosphere of the sun, our star, and sending an Interstellar Probe into our local galactic environment, is exploration at its best. This is an indispensable aspect of cultural activity since the dawn of mankind. So far no exploratory mission has ever returned without new and unexpected findings that greatly expand our knowledge.

Only a few key ideas of possible future directions can be presented here. A more detailed account has been given elsewhere [2]. We will explore with a few examples how progress can be made taking a three-step approach. The first step is to make the most out of our existing space assets. With ACE, SOHO, Wind, Ulysses and the Voyagers a remarkable fleet of heliospheric spacecraft is scouting simultaneously the inner, outer and 3D heliosphere. The termination shock is within reach, while continuous observations of key regions and solar variability can be compiled, provided operations continue. It should be emphasized that the sun has a 22-year cycle! In addition, we will point at innovative uses of the existing spacecraft. The second step is to close obvious gaps in our knowledge by improving existing techniques and with modest missions between 0.2 and 5 AU. The third step is to implement frontier probes to the sun and into the interstellar medium, which require a serious commitment and in the latter case substantial technology development.

2. THE INNER FRONTIER

Figure 1 shows schematically the extent of our knowledge of the sun and the inner heliosphere together with the techniques that are used. Over the past two decades great strides have been made in the in-situ sampling of the solar wind from 1 to 5 AU with detailed composition measurements on Ulysses, SOHO and ACE [3, 4] and in the understanding of the 3D structure of the wind [5]. Observations have clearly demonstrated how strongly structured the solar wind is and how sharp boundaries between adjacent regions are [6]. Regions with starkly different conditions remain separate on their way from the sun to us [7]. Modeling and optical observations with SOHO UVCS have demonstrated that temperature differences between species and flux tubes are established very close to the sun [8, 9], but the responsible processes can only be inferred. To date no in-situ measurements have been made inside 0.3 AU.

![Figure 1: Schematic view (not to scale) of the extent of our current knowledge of the sun and the inner heliosphere.](image)

With SOHO and GONG helioseismology has provided a remarkable view of the sun’s interior [10]. The radial structure and the large-scale convection pattern of the sun as well as the energy transport through its interior have been revealed. However, this technique provides no information about the last 3% of the interior below the sun’s surface. Yet it is this critical sub-surface layer, where solar activity with its complex magnetic fields is generated. Also the important high latitude regions of the sun have been barely visible to any optical observation, while it is here where the fast wind emerges during solar minimum.

2.1 Main Goals

To understand the generation and the variability of the heliosphere these are very critical gaps, which can only be closed with in-situ studies near the sun and pole-to-pole coverage. In addition, we will have to monitor the 3D heliosphere at strategic distances from the sun continuously over time scales substantially longer than the true solar cycle of 22 years. Turning this emerging knowledge into predictive power will require a continuous long term monitoring network comparable to the weather stations on Earth.

2.2 Use of Assets and Next Steps

3D Coverage and Monitoring: It can be anticipated and should be wholeheartedly supported that the substantial effort to monitor and understand the impact of solar variability on the inner heliosphere within NASA’s Living with a Star Program [11, 12] will ex-
pand our detailed knowledge of solar wind structure and composition, electric and magnetic fields, and waves, as well as the energetic particle population. High-resolution imagers in a wide wavelength range will yield more detailed pictures of the sun’s surface. However, true closure of the questions of how the solar wind is accelerated, how its distinct bi-modal structure is produced, and how the solar activity cycle is controlled, can only be reached by closing the two existing gaps in our coverage.

**The Sun’s Subsurface Layers:** Penetrating the last 3% of the sun’s interior beneath the surface will involve significant refinement of helioseismological observations in frequency and mode range together with a detailed simulation of the emerging structures and phenomena as observed on the surface. One attempt in this direction is high-resolution helioseismology of localized features, such as sunspots [13]. Such results can be tested and improved by comparing them with simulations of these upper layers of the sun’s interior [14]. To achieve enough precision with the observations higher resolution and an extension to higher frequencies is needed. Because coronal holes and fast solar wind mostly emerge from high latitude regions, it will be extremely important to extend solar oscillation observations to the full latitude range on the sun. Missions, such as Solar Probe, Solar Orbiter and/or Solar Pole Sitter can achieve this goal.

**Tracing Structures from the Sun to 1 AU:** The lack of in-situ observations at <0.3 AU includes particle distributions and composition, with the need to extrapolate from a distance. It is even more glaring for magnetic fields, on which virtually no information is available outside the near sun corona. Before we look towards Solar Probe in this respect, let us present an example of what can be done with existing spacecraft and then is enhanced with a logical extension of current techniques - by taking steps 1 and 2 first. One important question is how to trace any magnetic field or particle information back to a specific location on the sun’s surface. This would give us a better handle to infer processes on and below the sun’s surface. It may also lead to better predictions of how solar events translate into effects at Earth.

For decades interplanetary space was thought to have a quasi-static pattern of interplanetary magnetic fields that rotate with sun, and particles generally were expected to disperse via diffusion. However, more recently a quite different picture has emerged. Motivated by Ulysses observations of structures extending to high latitudes in interplanetary space, Fisk [15] suggested that the differential rotation of the sun leads to large-scale latitudinal transport of field lines. A model emerged that can explain the reconfiguration of the solar magnetic field over the solar cycle through field line transport across the sun’s surface via successive reconnection [16]. On the smaller scale it is consistent with SOHO observations that supergranules typically reconfigure through emerging magnetic flux in ≈1.5 days [17]. The model even offers an intriguing explanation for the energy source that may drive the solar wind. Interesting in connection with our discussion is a) that this model can be tested and b) that it can lead the way to more accurate tracing of phenomena from the sun’s surface into space.

Contrary to the earlier naïve expectation that such a complex and small scale mixing of magnetic flux tubes on their way out from the sun might lead to enhanced mixing of particle populations equivalent to efficient diffusion, regions of solar wind with different composition [6] and different energetic particle populations [18] are found to remain separate on a very small scale. It is the latter that may be instrumental in probing the variable surface structures and their transport away from the sun. Mazur et al. [18] observed distinct dropouts in the clear time-dispersive structure of energy-time diagrams of energetic ions from compact impulsive solar events. Giacalone et al. [19] explained them in terms of a quickly changing flux tube topology through the combination of emerging flux, reconnection and convection with the solar wind.

In other words, particles from a localized source are spread (yet in discrete flux tubes) over an extended volume that expands with distance from the sun. The typical size of such a region can be estimated from the size of supergranules and radial expansion to reach a few million km at 1 AU. A mini-cluster of satellites, equipped with high collecting power energetic particle spectrometers, solar wind sensors and a magnetometer can be used to map individual supergranules with energetic particles and to determine the flux tube transport through interplanetary space. Existing spacecraft at and near L1, like ACE, SOHO and Wind, can serve as a pathfinder configuration.

**2.3 The Challenge: Solar Probe**

In spite of all progress, models of solar wind acceleration, coronal heating, particle acceleration in flares and at coronal shocks, as well as the role of magnetic fields, waves and instabilities in these processes can only be tested with in-situ observations. A Solar Probe with comprehensive particles and fields instrumentation is indispensable. In addition to its unique capability to close this glaring observational gap in solar and inner heliosphere physics, Solar Probe has the fabu-
lous potential to be an inspiring mission of exploration, as it will be the first close-up visit of a star.

To unravel the particle-fields interaction that lead to heating, solar wind and energetic particle acceleration the payload must provide detailed particle velocity distributions, at least separate for key elements and isotopes, such as H, $^3$He, $^4$He, C, O, and Fe. In addition, magnetic and electric fields must be resolved in the key frequency range that covers important plasma waves, such as ion cyclotron, hybrid, whistler and Alfvén waves. The fast passage of the perihelion, as dictated by orbital dynamics, requires high time resolution to within seconds, for key wave features and the bulk of ions possibly also with sub-second resolution.

In order to relate the time series of in-situ observations to coronal structures simultaneous context observations are paramount. This is partly satisfied with a near quadrature of the probe orbit, which allows a complete view of the orbital plane with coronagraphs from Earth. For tomographic viewing and to locate the in-situ findings in the corona a coronagraph with forward viewing is highly desirable on Solar Probe.

With its anticipated polar pass Solar Probe may also provide a unique platform to gather a first pole-to-pole helioseismological map of the important high latitude regions. It could also take close-up images in the visible and X-ray band to study solar surface structures beneath its path. The proximity to the sun could provide advantages in spatial resolution for these observations. A description of such a Solar Probe spacecraft, payload and baseline mission may be found in the Solar Probe Definition Report [20].

At this point Solar Probe has been pushed back in its schedule due to the recent cancellation of the instrument selection. Substantial support from the scientific community is needed to move the process forward. As shown in the report Solar Probe is technically feasible and sound, yet the resources to accommodate the full payload are extremely tight. In this possibly over-constrained situation benefit may be gained from the simultaneous effort towards a Solar Orbiter by the European Space Agency, with a perihelion of 20 solar radii and the attempt to reach high latitudes during an extended mission [21]. With a full complement of in-situ and remote sensing instruments Solar Orbiter will be complementary to Solar Probe, cover different regions and longer periods. Remote sensing instruments could benefit even from being on Solar Orbiter and not on Solar Probe because of the slower relative motion and long cadence of observations. If resources are the ultimate issue towards implementation of Solar Probe, a decision to take advantage of the complementarity of the two missions and to concentrate remote sensing on Solar Orbiter may help to get Solar Probe on the way. “Ceterum Censeo”, to close the in-situ observation gap close to the sun Solar Probe is absolutely indispensable and must be pursued.

3. THE OUTER FRONTIER

Let us now turn towards the edge of the heliosphere and into our galactic neighborhood. Here several fundamental questions may be summarized as follows: 1) What is the nature of the interstellar medium and the implications for the origin and evolution of matter? 2) How does the interstellar medium influence the heliosphere, its size, interior conditions and variations? 3) What is the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment?

The broad nature of these questions gives them fundamental significance in several fields. In particular, the combination of in-situ observations and the astrophysical nature of the questions suggest a cross-disciplinary approach of space physics and astrophysics. They address objectives of all four NASA themes. "Sun-Earth-Connections", studying the influence of the sun and the surrounding space on Earth and other bodies in the solar system is addressed in all three questions. "Origins", which is geared towards formation and evolution of stars, planetary systems and life can relate to 1) and 2). "Structure and Evolution of the Universe" is addressed in 1), and "Planetary Exploration" topics are found in 2). Therefore, the outer frontier of "Sun-Earth Connections" can become a focus for all science disciplines.

3.1 Main Objectives

Cradle of the Stars: The interstellar medium is the cradle of the stars and provides the raw material for all bodies in stellar systems, including those of our own. This material has undergone continuous evolution from the Big Bang until today. The Big Bang produced only light nuclei, such as H, He, their isotopes $^3$He and D, and some $^7$Li [22]. Stars synthesize the heavier elements [23]. and high-energy galactic cosmic rays contribute very rare elements, such as Be and B. Consequently, the abundance of elements and isotopes changes over time, and its knowledge for several points in time will provide the input to understand nucleosynthetic evolution.
Our current knowledge of the origin of the elements and their isotopes is mainly derived from composition measurements in the solar system. The relative abundance of nearly 300 nuclear species has been derived for the proto-solar nebula, which represents a sample of galactic matter from 4.5 billion years ago. Meteorites also provide some isotopic ratios in stellar grains, which represent very specific information about certain stellar sources, such as supernovae. Finally, spectroscopic data on elemental abundances (rarely on isotopes) are available for a variety of astrophysical objects. Missing is a sample of the present-day galaxy with reliable observations of a number of important elemental and isotopic abundance ratios. In situ measurements of interstellar material inside and just outside the heliosphere, combined with remote absorption spectroscopy, will fill this gap.

Influence of the LIC on the Heliosphere: The state of the LIC controls the boundary of the heliosphere and, together with the solar wind, determines its size and inner state. With its (current) large size, its magnetic structure and its dynamics the heliosphere is the first shield of three that keep high-energy cosmic rays away from the Earth. With its journey through the galactic environment, which contains interstellar clouds with widely varying densities, the heliosphere must have varied substantially in size, most likely changing terrestrial conditions over time [24].

The interplay of the partially ionized LIC and the heliosphere leads to a complex boundary region that is controlled by the plasma flow around this obstacle and charge exchange with the neutral gas, which normally is not affected by the magnetic nature of the heliosphere. Depending on species this leads to stronger or weaker slowdown, accumulation at the boundary, heating and filtered penetration into the solar system. The main interstellar component, hydrogen, is among the species most affected and forms a so-called H-wall [25, 26]. To understand the physical processes and to quantitatively determine the elemental composition outside, these effects must be understood.

Further inside, at the solar wind termination shock, products of the LIC-heliosphere interaction, i.e., interstellar atoms, which are ionized in the inner heliosphere and subsequently transported outward with the solar wind, are accelerated to form the anomalous component of cosmic rays (ACRs) [e.g. 27]. These energetic particles that fill the solar system with a unique composition of mostly singly charged ions with high ionization potential must also be messengers of our heliosphere into the galactic neighborhood. Although there is a rather good understanding of the main source [28], the key acceleration process, and the modulation inside the heliosphere [e.g, 29], their injection into the acceleration process is still unclear [30], and the recent detection of minor contributions of species with low ionization potential [31] so far escapes an explanation.

Example for Astrospheres: The heliosphere cannot be unique. It is just an example – in fact, the only example that can be studied in detail with in-situ observations – of “astrospheres” around other stars. Any star with a magnetic field and a stellar wind must be surrounded by a similar sphere of influence and send messengers into its neighborhood, such as ACRs and fast neutral atoms that stem from charge exchange with the charged stellar wind.

The deceleration and accumulation of neutral hydrogen on the upwind side of the heliosphere and other astrospheres has already led to the identification of such H-walls in our own system and at several nearby star systems, through typical absorption features in the Ly\[ profile [32, 33]. In-situ studies of the outer reaches of our home system will sharpen these tools to understand the surroundings of many star systems and thus provide a direct link to astrophysics.

3.2 Future Pilot Missions

It is self-evident that an advance into the LIC proper requires extraordinary effort and probably is many years away. Yet, it should be emphasized that there is still much to do short of an Interstellar Probe.

First, it should be noted that two probes are on their way out of the heliosphere, Voyager 1 and 2, which have just surpassed their 25th anniversary. Although not optimized for the study of the interstellar environment, they will provide us with the first genuine in-situ information about the space beyond the termination shock and with a solid scale for the heliosphere. Because of this unique capability and because any variations happen on a scale of the solar cycle these probes, along with their inner heliosphere cousins, must be kept operational as long as technically feasible.

Second, energetic particles generated by the heliosphere, such as the ACRs and their sources can be studied in detail within the inner heliosphere, and it is the radial variation of composition and charge state that will yield new and valuable information on the sources and related acceleration processes. In addition, the suprathermal and energetic ion populations at the heliospheric boundary produce energetic neutral atoms (ENAs) through charge exchange with the interstellar neutral gas and can be used to provide a full sky image these regions [34].
Last, but not least, an interstellar wind blows through our system and carries neutral gas inside 3 AU. Hitching a ride on missions that are focused on other objectives, the sun or the Earth’s magnetosphere, and often using instruments that are optimized for different problems, great strides have been made by investigating the UV glow [35, 36], pickup ions [37, 3], and neutral He atoms [38] of the interstellar gas. What is needed is a dedicated effort on a 1 by 3 AU orbit with instruments optimized for interstellar gas studies to effectively harness this information.

**Particle Transport and Acceleration:** As outlined above ACRs constitute a major source of energetic ions that emerges from the heliosphere and fills its interior. It is widely accepted that interstellar pickup ions with their highly suprathermal velocity distribution have a significant advantage for injection into shock acceleration [e.g. 39]. This can explain the prevalence of interstellar pickup ions as the source of ACRs. Based on this paradigm it was suggested [40, 41] that the minor ions with low ionization potential in ACRs could be explained by pickup ions from the so-called inner source [40, 42]. However, recent findings in co-rotating interaction regions (CIR) suggest that inner source pickup ions are not effectively accelerated at 1 AU. In CIRs energetic heavy ions exhibit a charge state compatible with that of the solar wind with only a small contribution of Ne⁺, while He⁺ - clearly of interstellar origin - is effectively accelerated [43].

Because pickup ions are effectively cooled during radial transport with the solar wind and contrary to the interstellar source no ions of the inner source are added outside 1 AU, the ability to accelerate inner source ions should decrease rather than increase with distance from the sun. However, Gloeckler [44] has found strong suprathermal tail distributions in the solar wind and in pickup ion distributions, which even appear to be strengthened with distance from the sun. This observation suggests that an increasing pre-acceleration may be at work, which can propel particles into the acceleration at the termination shock.

To study this behavior quantitatively pickup ion, suprathermal and energetic particle populations need to be observed at 1 - 5 AU with elemental and ionic charge resolution and a collection power comparable to the instruments on ACE. By following the acceleration in CIRs and coronal mass ejections at increasing distances from the sun, it will be possible to delineate the injection and preacceleration processes. These objectives can be achieved with an ACE-like mission on a 1 by 5 AU orbit using current instrumentation, within the scope of a Solar-Terrestrial Probe.

**Probing the LIC inside the Heliosphere:** Another mission that concentrates on studies of the LIC and its interaction with the heliosphere with accessible messengers has been coined Interstellar Pathfinder, with the following key scientific questions:

- What is the nucleosynthetic status of a present-day sample of the galaxy, and what are the implications for Big Bang cosmology, galactic evolution, and stellar nucleosynthesis?
- What is the physical state of the LIC and the nature of its interaction with the heliosphere?
- What are the characteristics and the 3D topology of the heliospheric termination shock?

Composition measurements require a pickup ion mass spectrometer with good resolution and a large geometric factor, which can be built, based on flight-proven time-of-flight instruments on Ulysses and ACE [3]. Mass resolution, energy range and geometric factor (up to a factor of 500 higher) must be tailored specifically to the pickup ion investigation, as past and current instruments were designed for other purposes. A neutral gas instrument that measures the interstellar He velocity distribution has been successfully flown on Ulysses [38]. Concepts to increase angular resolution and geometric factor have been developed [45]. A sensor with similar front end, surface conversion of neutrals into negative ions and subsequent time-of-flight analysis, similar to LENA on IMAGE, can extend the neutral gas observations to O and possibly H [e.g. 46]. An energetic neutral atom imager that is optimized for the energy distribution of H neutrals from the termination shock with energies that range from a few 100 eV to several keV is derived from instruments on Cassini, IMAGE and TWINS [34].

In order to survey the interstellar gas and pickup ions effectively an orbit between 1 and 3 AU is needed. The gravitational deflection of the interstellar flow by the sun that is used by the neutral gas instrument to infer the flow velocity from the direction of the incoming neutrals is most pronounced very close to the sun. Conversely, interstellar pickup ions other than He can only be observed effectively at distances > 2 AU. For example, it should be pointed out that for O at 1 AU the inner source pickup ions become the most prominent component. Only beyond 1.4 AU can we distinguish unambiguously between the inner source and interstellar pickup ions. The farther away from the sun, the more of the interstellar pickup ion distribution becomes visible without interference from the inner source. To cover both, inner source and interstellar particles, an elliptical orbit in the ecliptic plane into the side-wind direction relative to the interstellar gas flow represents the ideal compromise (Fig. 2). This orbit will also cut through the gravitational focusing...
cone of He. With an aphelion of 3.16 AU the orbital period is exactly 3 years, thus providing for the oppor-
tunity of an Earth flyby after one orbit, which could be used to moderately change the orbital plane for a
different cut through the gravitational focusing cone.

![Figure 2: Typical orbit, main objectives and viewing of an Interstellar Pathfinder with trajectories of the interstellar gas flow and a qualitative distribution of interstellar gas.](image)

**3.3 The Grand Challenge**

Substantial new information on the LIC and its in-
teraction with the heliosphere can be gathered with moderate missions in the inner heliosphere. However, rich the harvest of such missions will be, they cannot supplant an ultimate mission into the LIC proper, yet they serve as extremely valuable precursor missions.

**Objectives that must be studied outside:** The LIC is a partially ionized environment with ionization fractions that are thus far only inferred [47]. Neutral gas can enter the heliosphere relatively unimpeded, but plasma is completely excluded and only the largest dust grains come through. This limits our study of isotopic and elemental abundances to H, N, O and the noble gases. Cosmic radiation with energies less than 100 MeV/nucleon is heavily shielded and modulated by the heliosphere, and probably the major fraction of this radiation has escaped our detection. Finally, the surrounding magnetic field is completely undetectable from inside and can only be inferred. Access to these components of our galactic neighborhood requires an Interstellar Probe. Direct observation of the interface layers in the heliospheric boundary region is much superior to inference from afar. In addition, infrared and radio observations of cosmic sources can be pushed to much lower intensities and frequencies. Close-up observations of Kuiper Belt objects may come into reach. Last but not least, the outer frontier is the final frontier of our heliosphere and thus awaits its exploration.

**Interstellar Probe Implementation:** Currently, two functioning spacecraft are on their way to leave the heliosphere, Voyager 1 and 2. These spacecraft were launched in 1977 and are now at ≈83.5 and ≈ 67.2 AU from the sun, respectively. They will probably pass the termination shock within the coming few years [48]. However, to reach, for example, the heliopause will need another 15-20 years, and may never happen while enough energy is available. Beyond this the payload was never designed for the interstellar medium, so useful measurements will not be possible.

Needed is a craft that can carry a full particles and fields payload, optimized for plasma, neutral gas, cosmic rays, magnetic and electric fields in the LIC. According to a recent study this will require a payload of at least 25 - 30 kg. It should reach a minimum distance of 200 AU within ≈ 15 - 20 years (together with the preparation the time span of a researcher’s fruitful work) and should be able to return data from out to 400 AU [49]. This requires a final speed of 10 - 15 AU per year, which cannot be achieved with conventional rockets and swingby techniques. Two options have been studied, nuclear electric propulsion and a combination of a near sun passage with solar sailing. Under current circumstances the solar sail appears to be the most viable concept, based on the sizing of an interstellar probe, on the versatility of this technology, and on the acceptance in the wider community. While studies of the basic technologies are underway, solar sailing lacks the effort for a reasonably sized demonstration mission in the inner solar system. Clearly, before Interstellar Probe can be implemented, substantial effort has to go into propulsion. In addition, sensor and spacecraft system technology with emphasis on miniaturization and autonomy must be developed.

Solar sail technology not only has the potential to enable many long duration and low maintenance flights to a variety of targets within the solar system and just outside the heliosphere, it may serve as one of the few viable paths to sending probes deeper into interstellar space. Coupled with large-scale laser arrays as a fixed home-based energy source, light sails may be the only known way to propel a spacecraft without the need to carry all the necessary fuel, a requirement that hampers rocket technology. This has been described in a technically correct and brilliant way in the (truly) science fiction novel “Rocheworld” [50].

**ACKNOWLEDGMENTS**

Support by NASA under NAS5-32626 and NAG 5-6912 and valuable discussions with T. Forbes, P.A. Isenberg and M.A. Lee are gratefully acknowledged.
REFERENCES


