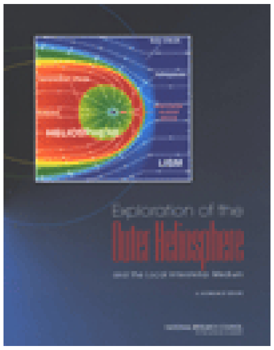

Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report

Committee on Solar and Space Physics, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Exploration of the Outer Heliosphere and the Local Interstellar Medium

A WORKSHOP REPORT

Committee on Solar and Space Physics

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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Cover: Results from a self-consistent numerical simulation of the interaction of the solar wind with the partially ionized local interstellar medium (LISM). Shown in color is the temperature distribution (plotted on a logarithmic scale) of the solar wind and interstellar plasma for the two-dimensional, steady-state, two-shock heliosphere. The plasma boundaries—termination shock, heliopause, and bow shock—are labeled. The heliosheath comprises solar wind material, both supersonic and subsonic, and extends into the heliotail (labeled). The solid lines show the stream lines of the plasma. A key feature of the interaction of the solar wind with the LISM is the ability of neutral hydrogen to enter the heliosphere, where it can then couple to the solar wind by the process of charge exchange, depicted schematically by the arrow. The distances along the *x* and *y* axes are measured in astronomical units (AU). Image courtesy of H.R. Mueller and G.P. Zank, University of California, Riverside.

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Foreword

The outward expansion of the solar wind carves out a region from the local interstellar medium (LISM) known as the heliosphere. We live in the inner part of this region, which is dominated by the Sun. Far beyond the orbit of the known planets, in the outer heliosphere, a complex interaction occurs between the solar wind and the LISM. The observation and study of this interaction region, and of the pristine interstellar medium that lies beyond, will be exploration in the truest sense, an epic journey that helps define our place in the universe.

As this report went to press in mid-2004, the Voyager spacecraft appeared to be approaching, or perhaps even encountering, the termination shock of the solar wind—the region where the supersonic flow goes subsonic. Already, the Voyagers' observations have demonstrated that the interaction region will be complex, surprising, and fascinating. Theories and models of the interaction region will have to be modified to account for the observed complexity.

Interstellar neutral gas penetrates far into the heliosphere and can be observed in its recently ionized form as pickup ions in the solar wind, in particular by Ulysses. These two missions, Voyager and Ulysses, represent our best immediate hope to increase our understanding of the properties of the LISM and its interactions with the heliosphere.

Real progress in this field, however, demands new observations and improved theories. It is possible to make far better and more insightful observations of neutral interstellar gas in the inner heliosphere, and to exploit other remote sensing techniques that may be demonstrated to provide important information on the termination shock and the interaction region beyond. Theories and models always can be improved, incorporating and explaining current and future observations.

The real journey will occur when we embark on an interstellar probe, with sufficient instrumentation and the capability to rapidly access the distant heliosphere. This journey will be one of the great explorations of humankind, when we leave the safety of our solar system and venture forth into interstellar space.

This report provides a strategy to prepare for this exploration.

Lennard A. Fisk, *Chair*
Space Studies Board

Preface

In 2003, the National Research Council (NRC) produced *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*.[1] In addition, an internal advisory committee at the National Aeronautics and Space Administration (NASA) completed a roadmap for the Office of Space Sciences' Sun-Earth Connection Theme.[2] Recognizing that exploration of the outer heliosphere was the least thoroughly developed aspect of either document and that planning and technology development for such an effort would require a long lead time, NASA requested that the NRC conduct a workshop that would further investigate the challenges and opportunities for space missions to explore this region (see Appendix A, Statement of Task).

The workshop, which was organized by the Space Studies Board's Committee on Solar and Space Physics (CSSP), took place May 6-7, 2003, at the National Academies' Beckman Center, located at the University of California at Irvine (see Appendix B for the agenda). Gary Zank, a member of the CSSP, led the committee's effort in developing the following report, which summarizes the discussions and conclusions of workshop participants.

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[1] National Research Council, 2003, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* National Academies Press, Washington, D.C.

[2] See NASA, 2003, *The Sun-Earth Connection Roadmap 2003-2028: Understand the Sun, Heliosphere and Planetary Environments as a Single Connected System*, NASA, Washington, D.C. Available at http://sec.gsfc.nasa.gov./sec_roadmap.htm.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Leonard F. Burlaga, NASA Goddard Space Flight Center,
George Gloeckler, University of Maryland,
Michael Gruntman, University of Southern California,
Les Johnson, NASA Marshall Space Flight Center,
J.R. (Randy) Jokipii, University of Arizona,
Martin Lee, University of New Hampshire,
Paulett C. Liewer, Jet Propulsion Laboratory,
David J. McComas, Southwest Research Institute, and
Ralph McNutt, Jr., Johns Hopkins University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Donald J. Williams, Johns Hopkins University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

In May 2003 the Space Studies Board's Committee on Solar and Space Physics held the Workshop on Exploration of the Outer Heliosphere to synthesize understanding of the physics of the outer heliosphere and the critical role played by the local interstellar medium (LISM)[1] and to identify directions for the further exploration of this challenging environment. What emerged was a palpable sense of excitement about the field's progress in the past 8 to 10 years.

It was only in the mid-1990s that the fundamental role of neutral interstellar hydrogen in determining the global structure of the heliosphere was elucidated and the hydrogen wall predicted. With the later discovery of the hydrogen wall, and then, the discovery of hydrogen walls about other stars in our galactic neighborhood and the associated discovery of stellar winds from solar-like stars, the field of solar and space physics underwent dramatic change.

Coupled to the theoretical advances were the increasingly exciting observations being returned by the Voyager Interstellar Mission, Ulysses, ACE (Advanced Composition Explorer), and Wind—ranging from observations of cosmic rays signaling the approach to the termination shock, to the large- and small-scale magnetic fields responsible for guiding and scattering energetic particles, to name only two types. At the workshop, the greatest excitement was generated by the suggestion that the low-energy cosmic rays showed evidence that Voyager may have crossed the termination shock—completely unexpected observations illustrating the Voyagers' promise for returning results with a capacity to surprise and baffle for years to come.

To further the exploration of the outer heliosphere four strategic directions became clear in workshop discussions:

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[1] The LISM is that region of space in the local galactic arm where the Sun is located (Thomas, 1978), the local interstellar cloud is the cloud within it in which the Sun resides, and the heliosphere is the region in space filled with solar wind material (both supersonic and subsonic flow).

- **Making use of existing assets.** ACE, SOHO (Solar and Heliospheric Observatory), Wind, Ulysses, and the Voyagers are all currently furthering understanding of the outer heliosphere. In particular, the importance of the Voyagers cannot be overstated as Voyager 1 is capable of lasting another 16 years, allowing it to reach 150 AU. The Voyager Interstellar Mission is impossible to replace at its current location in the next 20 years, making it a uniquely valuable platform. The spacecraft are reasonably well instrumented for the mission, making the Voyagers the best and only near-term hope for exploring the heliospheric boundaries and interstellar medium in situ. The other vital mission is Ulysses, since it is currently the best-situated, best-instrumented mission that directly addresses the fundamental question of how the solar wind couples to the LISM. Scientific understanding of the physics of pickup ions, their relation to interstellar atoms and anomalous cosmic rays, and their influence on the solar wind has been advanced almost entirely by Ulysses (and to a lesser extent ACE), and it is the only spacecraft to directly measure neutral interstellar material. Workshop participants agreed that continued support and a long-term vision from NASA Headquarters, and the provision of continuing data coverage of the Voyagers and Ulysses missions from the Deep Space Network, are essential.
- **Developing new outer heliosphere missions.** New missions should be developed that can use current and moderately improved in situ and remote techniques to conduct heliospheric studies from 1 to 3 AU and beyond. The possibilities include in situ studies and remote observations. For example, the ability to image the region of the termination shock and heliosheath remotely is steadily increasing, with several laboratories now working on experiments in this area. Energetic neutral atom imaging is a promising avenue, with technology outstripping theory at present. Other possibilities for remote observations involve the use of Lyman-alpha absorption and backscatter techniques; the former is possible at 1 AU with space-based spectroscopic telescopes, and the latter offers the possibility of monitoring the temporal response of interstellar gas to the solar cycle as it flows into the heliosphere. In situ studies within 1 to 4 AU will remain critical to furthering understanding of the fundamental coupling of LISM material and solar wind plasma. Such studies will require spacecraft with instrumentation that can study the inflowing neutral gas and dust, pickup ions, cosmic rays (anomalous and galactic), energetic particles, and magnetic field directly since the measurements of these variables are essential if we are to eventually probe both the LISM and the heliospheric boundaries with new spacecraft (and even remotely). Understanding of the critical microphysics will be advanced best by in situ measurements. It is now possible to build instruments that allow orders-of-magnitude more accurate measurements than those made by the instruments that currently fly on missions. Both in situ and remote measurement could be accomplished within the MIDEX (Medium-Class Explorer) program or perhaps the SMEX (Small Explorer) program. For the interim period, this approach would complement current Voyager and Ulysses activities well.
- **Continuing support of theory and modeling.** Continuing theoretical and modeling studies are essential to ensure progress in understanding the interaction of the solar wind and the LISM. Numerous questions raised by Voyager, Ulysses, and other spacecraft missions remain unanswered, and theoretical studies continue to lag observations. Optimal planning for a mission of the magnitude of Interstellar Probe requires a sufficient understanding of the physics of the remote outer heliosphere and local interstellar medium, which in turn requires far more elaborate modeling of the outer heliosphere, and incorporation of current and future in situ and remote sensing results. In particular, remote sensing techniques, because they are by nature integrated line-of-sight observations, produce results whose interpretation depends on theoretical models of the global heliosphere.
- **Preparing for Interstellar Probe.** Interstellar Probe, a mission characterized by both enormous scientific potential and technical challenge, will be one of the most exciting undertakings of NASA in the new millennium. For a mission as ambitious as Interstellar Probe, the technical requirements, the scientific payload, including instrument and communications requirements, and feasibility have to be addressed far

in advance. Developing the required propulsion technology is the primary technical challenge of this mission. At least three approaches—nuclear-electric propulsion, solar sail propulsion, and powered Sun-gravity assist—are well suited for and, in principle, capable of accelerating Interstellar Probe to the speeds needed to reach the heliopause within 15 years or less from launch.[2] However, as detailed in the text, none of these options are currently available and all present significant hurdles in their development.

Because Interstellar Probe will require only a rather straightforward trajectory with little need for precise navigation, it could be regarded as an ideal demonstration of nuclear-electric propulsion or solar sailing.

The development of a mission as scientifically and technologically far-reaching as Interstellar Probe will require considerable planning. The eventual scientific payload must be guided by current missions, Pathfinder missions, and theory. A crucial role will be played by Pathfinder missions, which may explore interstellar material such as pickup ions, neutral atoms, or anomalous cosmic rays directly, or explore the boundary regions using remote measuring techniques such as Lyman-alpha or energetic neutral atoms, or explore physical processes induced by the complex partially ionized plasma populations that make up the outer heliosphere beyond some 10 AU.

Sending a well-equipped spacecraft to the boundaries of the heliosphere to begin the exploration of our galactic neighborhood will be one of the great scientific enterprises of the new century—one that will capture the imagination of people everywhere. Significant questions about the outer heliosphere and the LISM still to be addressed include the following:

- What are the nature, structure, and temporal character of the termination shock, and is the termination shock the same in all directions?
- How do pickup ions and solar wind plasma evolve at the shock and in the heliosheath?
- What are the size and shape of the heliopause?
- Does reconnection between the solar and interstellar magnetic fields at the heliopause affect the structure and dynamics of the heliosphere?
- What are the physical state and the degree of ionization of the LISM?
- What is the elemental and isotopic composition of the LISM? What are the direction and magnitude of the interstellar magnetic field?
- Is the interstellar wind subsonic or supersonic?

These are among the most fundamental of the questions that can be addressed by space and planetary physics in the next 20+ years, and the answers will have far-reaching implications, not only revealing the nature of the heliosphere but also informing theories on the evolution of our galaxy, and, indeed, the entire universe.

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[2] Radioisotope electric propulsion is another propulsion option that should not be ruled out yet.

1

Introduction

One remarkable, and to some extent unexpected, outcome of the Voyager mission is that after the Jovian and Saturnian encounters, the science that Voyager was accomplishing became as much the science of the interstellar medium as of the solar wind. This development was further confirmed by the Ulysses mission, which began to explore the direct coupling of the interstellar medium to the solar wind through the intermediaries of pickup ions and interstellar gas. It is not widely recognized that *by mass* the interplanetary medium beyond 10 AU is in fact dominated by neutral atoms of interstellar origin rather than by solar wind protons (Gruntman, 1993). Being uncharged, however, the interstellar neutrals are not coupled directly to the solar wind. Instead, the coupling proceeds indirectly, through the ionization of the neutrals by various mechanisms (photoionization, charge-exchange, electron-impact ionization; see Zank, 1999a). Consequently, the physics of the outer heliosphere beyond 10 AU is very different from that in the inner heliosphere, which is determined by material of solar origin. Thus, exploration of the outer heliosphere offers the opportunity to learn about both the interplanetary and the interstellar medium, and the manner in which they interact.

Although considerable effort has been expended observationally and theoretically, understanding of the physics of the outer heliosphere remains limited (see Zank, 1999a, for a comprehensive review). The detailed interaction between the local interstellar medium (LISM)[1] and the solar wind is still not well understood, for reasons that range from incompletely formulated physical models to currently poor knowledge of many of the pertinent physical parameters of the LISM. For example, we do not know whether the LISM flow is super- or subfast magnetosonic or even whether it is supersonic or subsonic when galactic cosmic rays are included, which implies that we do not know the basic morphology of the heliosphere—that is, whether it is a two-shock model (bow shock plus termination shock; Baranov et al., 1971) or a one-shock model (termination shock only; Parker, 1963). See Figure 2.1 in Chapter 2.

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[1] The LISM is that region of space in the local galactic arm where the Sun is located (Thomas, 1978), the local interstellar cloud is the cloud within it in which the Sun resides, and the heliosphere is the region in space filled with solar wind material (both supersonic and subsonic flow).

The tangible manifestations of the interaction are the completely unexplored boundary regions between the solar wind and the LISM. The boundary regions are separated by the largest shocks in the solar system, of which at least one may be the site where cosmic rays are accelerated, thereby providing a link to the supernova shocks thought to accelerate galactic cosmic rays (see, for example, Blandford and Eichler, 1987). A heliopause or tangential discontinuity is another expected boundary, where the solar wind borders the interstellar plasma and the particle number density changes. An enormous inner heliosheath perhaps 50 AU wide with plasma temperatures of 10^6 K, containing a wall of amplified magnetic field and a possibly unstable current sheet (Washimi and Tanaka, 1996; Linde et al., 1998; Pogorelov et al., 2004), with perhaps very high levels of magnetic reconnection and associated particle acceleration, is bounded by the termination shock and heliopause.

The termination shock itself may act as a gigantic emitter of shocks and transients, and an outer heliosheath will most likely be present, bounded possibly by a bow shock that may be modified by the interaction of interstellar neutrals. On the side toward the Sun's motion through the LISM, the outer heliosheath will contain a region of heated, compressed, and slowed neutral hydrogen—the "hydrogen wall" (Baranov and Malama, 1993; Pauls et al., 1995). Multiple species of atoms will be present, possessing very diverse thermal properties, reflecting the complications associated with charge exchange in a highly non-equilibrated boundary region. Since neutral-atom/plasma charge-exchange mean free paths are very long compared with heliospheric length scales, simple equilibrium models of neutral hydrogen and plasma are an inadequate description for the boundary regions of our heliosphere.

Exploring this vast and complex region are two venerable spacecraft launched more than 26 years ago that constitute the Voyager Interstellar Mission.[2] Because the boundary regions (the boundaries themselves, the regions bounded by discontinuities, the hydrogen wall, the physics of the partially ionized plasma, and so forth) of our heliosphere are completely unexplored, the Voyager Interstellar Mission promises a continuing rich harvest of scientific results. Given that some 26 years passed before the Voyager 1 spacecraft reached a distance of 90 AU from the Sun, it is highly unlikely that the solar wind-LISM interaction of our heliosphere can be explored in situ by spacecraft in the next 20 years—effectively making the Voyager Interstellar Mission irreplaceable in the view of workshop participants.

Sending a well-equipped spacecraft to the boundaries of our heliosphere to begin the exploration of our galactic neighborhood will be one of the great scientific enterprises of the new century—one that will capture the imagination of people everywhere. Interstellar space is a largely unknown frontier that, along with the Sun as the source of the solar wind, determines the size, shape, and variability of the heliosphere, the first and outermost shield against the influence of high-energy cosmic rays. The interstellar medium is the cradle of the stars and planets, and its physical state and composition hold clues to understanding the evolution of matter in our galaxy and the universe. With plentiful bodies of all sizes and dust in the Edgewood-Kuiper Belt and in the Oort Cloud, the outer heliosphere is a repository of frozen and pristine material from the formation of the solar system. After the contents of our solar system, which is 4.5 billion years old, the LISM provides a second, more recent, sample of matter in our galaxy and in fact the only sample of the interstellar medium that can be studied close-up and in situ. Last but not least, the heliosphere is the only example of an astrosphere that is accessible to detailed investigation (Linsky and Wood, 1996; Gayley et al., 1997). These perspectives provide a natural bridge and synergism between in situ space physics, the astronomical search for the origins of life, and astrophysics. In general terms, the four principal science objectives of a mission to the border of our galaxy are as follows:[3]

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[2] Voyager 2 was launched on August 20, 1977, and Voyager 1 on September 5, 1977, from Cape Canaveral, Florida, aboard Titan-Centaur rockets. See the Voyager Web site at http://voyager.jpl.nasa.gov/.

[3] See Mewaldt and Liewer (2001) and http://interstellar.jpl.nasa.gov/interstellar/probe/index.html.

1. To explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our galaxy and the universe;
2. To explore the influence of the interstellar medium on the solar system, its dynamics and its evolution;
3. To explore the impact of the solar system on the interstellar medium as an example of the interaction of stellar winds with their environments; and
4. To explore the outer solar system for clues to its origin, and the nature of other planetary systems.

A spacecraft for such explorations, such as Interstellar Probe,[4] will require an advanced propulsion system as well as sophisticated communications and instrumentation, if we are to take our first halting steps to the edge of and beyond our solar system birthplace.[5]

These objectives are further elaborated in the chapters that follow.

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[4] See http://interstellar.jpl.nasa.gov/interstellar/probe/index.html.

[5] "The Earth is a cradle of the mind, but we cannot live forever in a cradle." Attributed to Konstantin E. Tsiolkovsky, the Father of Russian Astronautics, 1896. See http://vesuvius.jsc.nasa.gov/er/seh/quotes.html.

2

Science Summary: The Interaction of the Solar Wind and the Local Interstellar Medium

This chapter summarizes the community's basic understanding of the physics of the outer heliosphere, focusing on the influence exerted on the solar wind by the interstellar medium (Box 2.1). In particular, it describes several approaches that allow us to infer the properties and structure of the heliospheric boundaries. The term "boundaries" is used interchangeably in this report to refer both to specific boundaries, such as the termination shock or heliopause, and to regions enclosed by the boundaries, such as the inner and outer heliosheath, which would more properly be referred to as the heliospheric boundary regions. The context should make clear the word's meaning.

In presenting the many models and concepts that have been developed to explain different aspects of interactions between the solar wind and the local interstellar medium (LISM),[1] it should be emphasized that the underlying physics is not always well constrained. This is a consequence of only a single spacecraft mission into the outer heliosphere (Voyager) and of spacecraft whose instrumentation is not typically designed to answer questions about the outer heliosphere, with the obvious and very important exception of Ulysses (and possibly ACE). Remote sensing has placed some constraints on theoretical models, such as Lyman-alpha absorption measurements, but these are not always unique (see, for example, Florinski et al., 2003). Furthermore, data interpretation can be strongly model dependent. The only way to properly resolve the fundamental physics of the solar wind-LISM interaction will be through in situ measurements and remote sensing.

It is a trivial observation that the greatest part of the heliosphere—that beyond some 10 AU—is mostly unexplored. Less obvious, as noted above, is that the outer heliosphere beyond 10 AU consists primarily of material that is of interstellar rather than solar origin. Although the large-scale dynamics is still dominated

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[1] The LISM is that region of space in the local galactic arm where the Sun is located (Thomas, 1978), the local interstellar cloud is the cloud within it in which the Sun resides, and the heliosphere is the region in space filled with solar wind material (both supersonic and subsonic flow).

BOX 2.1 THE INTERSTELLAR MEDIUM, THE 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 (Schramm, 1998). Stars synthesize the heavier elements (Prantzos, 1998) 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 knowledge of it for several points in time will allow us to understand nucleosynthetic evolution.

Our current knowledge of the origin of the elements and their isotopes is derived mainly 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; these ratios 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.

by solar wind ram pressure, the LISM begins to introduce distinctly new physical processes that have little counterpart in the inner solar wind.

The LISM plays a fundamental role in determining the physics of the outer heliosphere. NASA recognized the importance of improving scientific understanding of this region in its 2000 Sun-Earth Connection (SEC) roadmap, which lists "understanding how the sun and galaxy interact" as one of its four top-level quests. Similarly, the 2003 SEC roadmap has the following as one of its three principal objectives: "Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments."[2] At a practical level, interest in the outer heliosphere has been strongly fostered by the Voyager Interstellar Mission (Voyagers 1 and 2). The Voyager spacecraft are the last remaining operational spacecraft in the very distant heliosphere and the only currently available platforms from which to explore the boundary regions of the heliosphere in situ. Interstellar Probe, a mission shown in the 2003 SEC roadmap as being ready for launch in 2015-2018, would require 15 years of travel to reach 200 AU (see also JPL, 1999).

The SEC roadmap objectives recognize, too, that the mutual interaction of large-scale and microscale processes is a fundamental ingredient describing the space physics of the outer heliosphere. In the context of the outer heliosphere, spacecraft such as Ulysses and ACE have provided new and important insights into the coupling between the solar wind and the LISM, revealing the importance of both macro- and microscale processes. Large-scale, sometimes termed "meso-" or "macroscale," phenomena contribute to the gross morphology of the heliosphere, in either a time-dependent or a steady-state sense. The solar

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[2] See Table 1.1 in "The Sun-Earth Connection 2003 Roadmap: Understand the Sun, Heliosphere and Planetary Environments as a Single Connected System," available at http://sec.gsfc.nasa.gov/sec_roadmap.htm.

wind, the interplanetary magnetic field (IMF), interplanetary shocks, streams and stream-interaction regions, and heliospheric boundary structures are all examples of macro-/mesoscale structures, whereas turbulence, waves, particle scattering, magnetic field line wandering, dissipation, and so forth are microscale processes. Nonetheless, the mutual feedback between these disparate scales serves to determine almost all aspects of heliospheric physics. In many respects, the complex coupling between the solar wind and the interstellar medium is the quintessential example of multiscale, regional, and disparate populations (solar wind plasma, pickup ions, anomalous and galactic cosmic rays, neutral atoms) coupling across complex boundaries. Thus, the study of the solar wind interaction with the LISM is of fundamental interest and importance to space physics. There can be little doubt that sending a spacecraft beyond the heliopause to begin the exploration of our local galactic neighborhood will yield enormous scientific advances for a wide array of astrophysical questions, such as the state and evolution of matter in our galaxy, the interaction of radiation and interstellar medium, the interaction of star systems with their neighborhood, as well as the interaction of shock waves with their environment and their role in particle acceleration.

The following sections begin with a basic overview of the structure of the heliosphere and a discussion of the fundamental role of neutral interstellar gas and then focus on several processes that are particularly promising for determining large-scale structure by probing the physical character of the boundary regions remotely.

GLOBAL STRUCTURE

Perhaps the most important lesson learned from the Voyager and Ulysses missions, complemented by theory and modeling efforts, is that the physics of the outer heliosphere is influenced profoundly by the LISM since we are embedded in the local interstellar cloud (LIC). This is because neutral hydrogen atoms flow into the heliosphere and are the dominant component, by mass, from 10 AU outward (i.e., beyond Saturn). As described below, the ionization of interstellar neutrals in the supersonic solar wind can even affect the size and structure of the global heliosphere.

The detection of anomalous cosmic ray fluxes by Garcia-Muñoz et al. (1973), Hovestadt et al. (1973), and McDonald et al. (1974) led to the construction of a remarkable chain linking interstellar neutral atoms, interstellar pickup ions (their prediction and eventual detection ~10 (He) and ~20 (H) years later; Fisk et al., 1974; Mobius et al., 1985; and Gloeckler et al., 1993), anomalous cosmic rays (ACRs) experiencing diffusive shock acceleration at a postulated termination shock (Pesses et al., 1981; Jokipii, 1986), and energetic neutral atoms created by charge exchange between ACRs and interstellar neutrals (Hsieh et al., 1992a,b). Figure 2.1 is a schematic diagram of the chain. That the various elements are linked is now well established; however, the precise details underlying the coupling are still not properly understood, and models remain incomplete. The coupling of the different elements within the chain reveals the interplay of large-scale heliospheric structure and detailed microphysics.

Major advances in understanding the physics of pickup ions resulted from Ulysses (and, subsequently, ACE) observations, demonstrating the importance of a well-instrumented mission. Ulysses, and to a lesser extent ACE, are the most vital missions for revealing the direct coupling of the interstellar medium to the solar wind plasma. Unfortunately, the observations returned by Ulysses have far outstripped theoretical understanding, leaving numerous fundamental puzzles to be resolved. The importance of similarly instrumented (but improved) missions within some 4 AU cannot be overstated, since Ulysses measurements address the absolutely fundamental question of LISM-solar wind coupling. As summarized in Figure 2.2 (also see the review by Zank, 1999a), if the LISM flows supersonically with respect to the motion of the Sun, a bow shock diverts the LISM flow about the heliosphere while a termination shock decelerates the

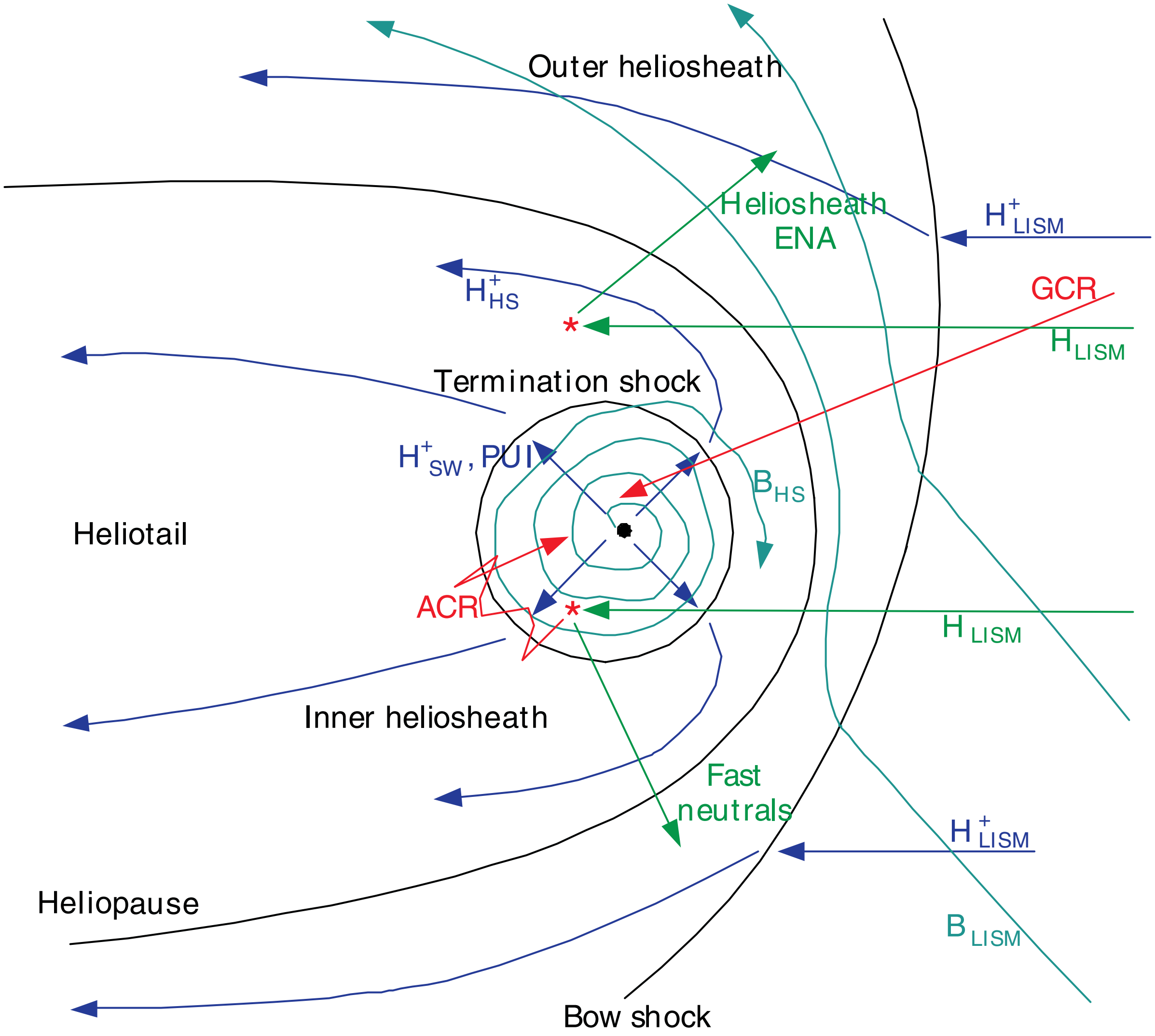

FIGURE 2.1 Overview of the heliosphere, with termination shock, heliopause, bow shock, and outer and inner heliosheath (HS). Some sample plasma (H^+), pickup ion (PU ion), and solar wind plasma (V_{HS}) trajectories are shown, as well as trajectories of neutral hydrogen (H) coming from the interstellar medium (H_{ISM}) and experiencing charge exchange (_), and galactic cosmic rays (GCRs). The solar and interstellar magnetic fields (B_{HS} and B_{ISM}) are sketched.

supersonic solar wind. The heliopause is a contact—or, in a magnetohydrodynamic (MHD) description, a tangential discontinuity (see, e.g., Washimi and Tanaka, 1996; Linde et al., 1998; and Pogorelov et al., 2004)—that separates the LISM and solar wind plasmas.

Whereas solar wind and interstellar plasmas respond to electromagnetic fields (being decelerated at the heliospheric boundary shocks, for example), interstellar neutrals flow relatively unimpeded. Plasma

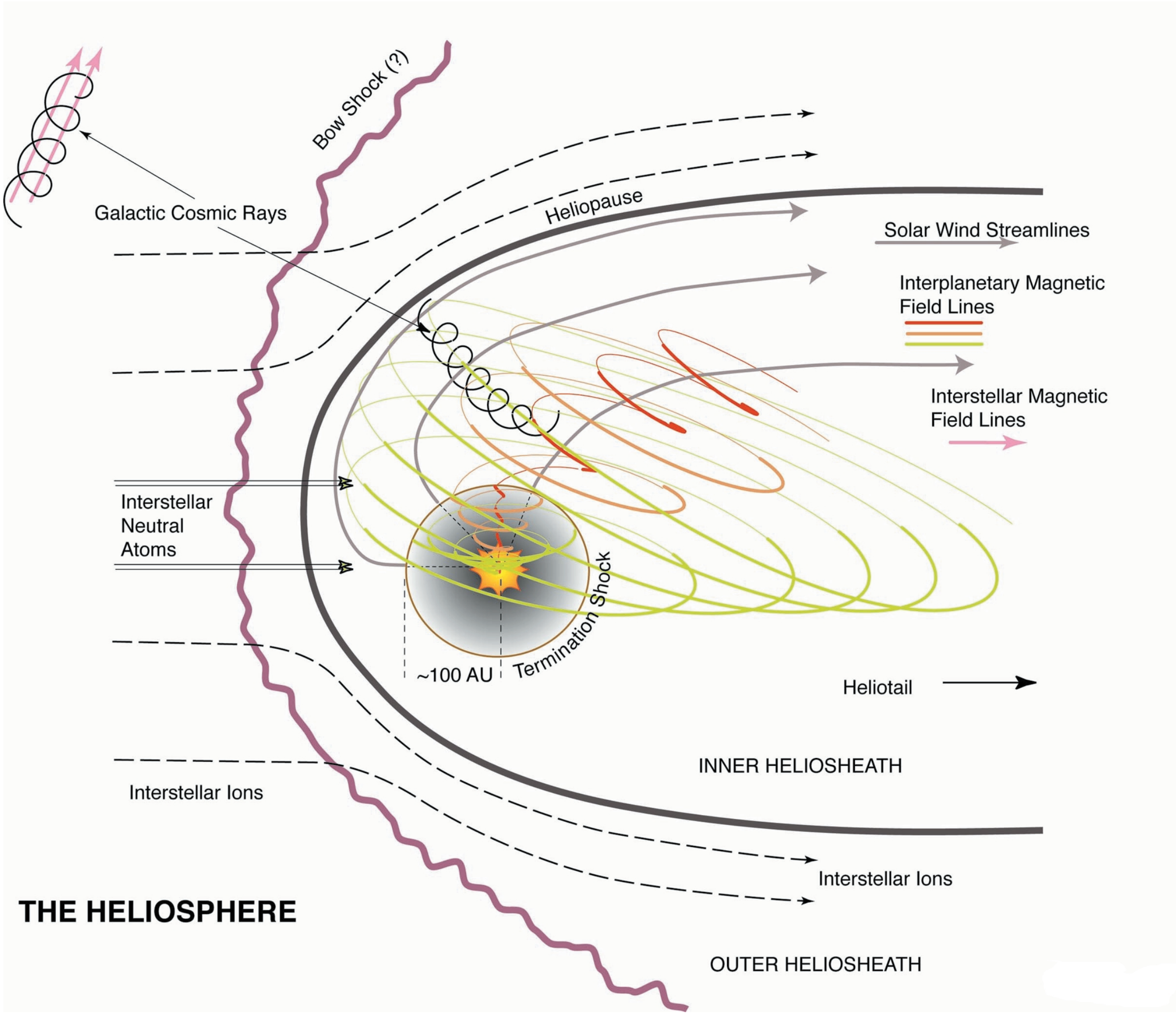

FIGURE 2.2 Schematic of the heliosphere. The global heliosphere is created by the supersonic solar wind diverting the interstellar plasma flow around the Sun. Interstellar ions and neutral atoms flow at 26 km/s relative to the Sun. The solar wind, flowing outward at 400 to 800 km/s, makes a transition to subsonic flow at the termination shock. Beyond this, the solar wind is turned toward the heliotail, carrying with it the spiraling interplanetary magnetic field. The heliopause separates solar material and magnetic fields from interstellar material and magnetic fields. Interstellar neutral atoms and higher-energy galactic cosmic rays can penetrate the heliosphere, but interstellar ions are diverted around it. Beyond the heliopause there may also be a bow shock formed in the interstellar medium. SOURCE: Jet Propulsion Laboratory (1999a), courtesy of Steven T. Suess.

and neutral atoms are coupled weakly but directly through various kinetic processes, these being charge exchange, photoionization, recombination, and electron-impact ionization, besides direct collisions between the neutral atoms and charged particles. The weak coupling of neutral interstellar hydrogen and plasma affects both interstellar hydrogen and plasma distributions in important ways. In the partially

BOX 2.2 THE NATURE OF THE HELIOSPHERIC BOUNDARY REGIONS

The Knudsen number, Kn, is the ratio λ/L, where λ is the mean free path of neutral atoms and L is a characteristic macroscopic length scale, such as the size of the solar heliosphere, ~100 AU. It is a measure of the neutral distribution relaxation distance and is >>1 inside the heliosphere and ~1 in the very local interstellar medium. Thus, within the heliosphere neutral and plasma distributions cannot equilibrate and may possess quite distinct bulk flow speeds and temperatures. Charge exchange between the coupled, nonequilibrated neutral and charged particle populations can therefore introduce distinct new populations of neutral atoms and plasma whose characteristics reflect their parent population. The subsequent interaction and assimilation of the newly created plasma and neutral populations into the existing plasma and neutral distributions may then lead to the substantial modification of the overall partially ionized plasma system. Thus, the total neutral distribution cannot relax to a single Maxwellian distribution, and either a multicomponent transport (Zank et al., 1996a) or a kinetic description for the neutral populations (Baranov and Malama, 1993; Izmodenov et al., 1999; Müller et al., 2000) is used. Furthermore, since the time for a neutral atom to enter the heliosphere and reach 1 AU is ~15 to 20 years, the local neutral atom distribution has experienced a variable charge exchange and photoionization rate, as well as a supersonic solar wind whose extent (in both latitude and longitude), velocity, and density are variable (McComas et al., 2000; Pauls and Zank, 1996, 1997). Neutral atom characteristics can therefore depend on the solar cycle, with the overall distribution being a mixture of atoms created in temporally different solar wind environments, since they cannot be lost to the system on time scales shorter than the solar cycle.

ionized LISM, the charge exchange mean free path for neutral H atoms is ~50 to 100 AU (Box 2.2; Knudsen number, Kn << 1), implying complete equilibration between neutral H atoms and LISM plasma some distance upstream of the bow shock (i.e., the charge exchange merely relabels H atoms and protons). The bow shock diverts, decelerates, and heats the LISM plasma, but neutral H is unaffected by the boundary. Between the bow shock and the heliopause (see Figure 2.1, outer heliosheath), the charge exchange mean free path is ~50 AU (Kn ~ 1), and so a large proportion of the LISM neutral H atoms experience charge exchange with slightly heated, diverted and slowed LISM protons.

This implies a related slowing, heating, and diverting of the neutral H atom distribution, and thus the formation of the hydrogen wall (Figure 2.3). This process filters neutral H as it enters the heliosphere. Although predicted theoretically using two distinct approaches (Baranov and Malama, 1993; Pauls et al., 1995; Zank et al., 1996a), the hydrogen wall was discovered serendipitously by Linsky and Wood (1996) and Gayley et al. (1997), making it the first of the heliospheric boundary structures to be detected directly. Indirect evidence for the filtration of interstellar neutral hydrogen was provided initially by the Voyager and Pioneer observations of a radial gradient in the neutral gas (Hall et al., 1993) and an apparent deceleration of the interstellar gas flow in the heliosphere (Lallement et al., 1993).

Within the heliosphere (i.e., inside the heliopause), the charge exchange mean free path increases dramatically (~1,000 AU, Kn >>1) and a simple single-fluid hydrodynamic treatment of the neutral H atoms is inadequate. Use of either a multifluid (Zank et al., 1996a) or a kinetic description (Baranov and Malama, 1993, 1996; Müller et al., 2000) of the neutral H reveals that neutrals created via charge exchange in the hot inner heliosheath (see Figure 2.1) stream into the LISM (Gruntman, 1982; Baranov and Malama, 1993; Zank et al., 1996a). These neutral atoms (“component 2”) experience secondary charge

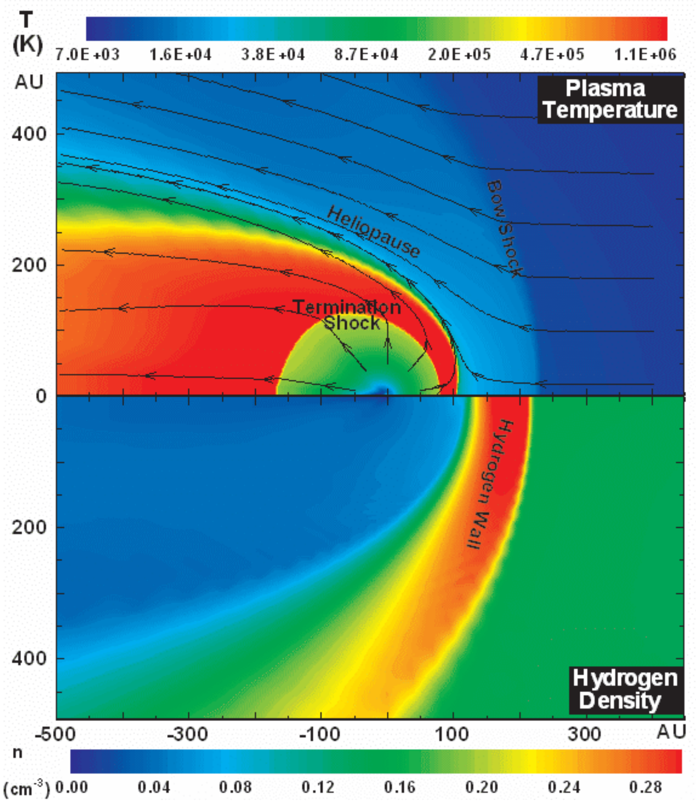

FIGURE 2.3 The two-dimensional steady-state, two-shock heliosphere showing (top plot) the temperature distribution of the solar wind and interstellar plasma and (bottom plot) the density distribution of neutral hydrogen. The plasma boundaries, termination shock, heliopause, and bow shock are labeled, and the wall of neutral hydrogen is also identified. The solid lines of the top plot show the streamlines of the plasma. The plasma temperature is plotted logarithmically and the neutral density linearly. The distances along the *x* and *y* axes are measured in astronomical units (AU).

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exchange with the LISM, thus introducing very hot (~10^6 K compared with 6,500 K) new protons into the LISM. The component 2 neutrals, although tenuous, are energetically important and transport heat anomalously from the subsonic heated solar wind plasma to the cooler interstellar medium plasma. The heating of the LISM in turn modifies the incoming neutral H distribution via charge exchange. This complex, nonlinear feedback of plasma and neutrals yields complicated neutral distributions that are different from region to region; some of these distributions are illustrated in the center row of Figure 2.4.

When neutral H atoms drifting at ~20 km/s are ionized in the supersonic solar wind (400-800 km/s), they are picked up almost instantaneously by the motional electric field, forming a ring-beam distribution. The turbulence excited by the unstable ring-beam was expected to "isotropize" the pickup ions rapidly, producing a distinct, stable suprathermal population of ions in the solar wind plasma. That neither of the latter expectations has been met fully poses challenges to existing theoretical plasma models (Zank and Cairns, 2000), and the relative scarcity of observations has so far not allowed for further refinement of

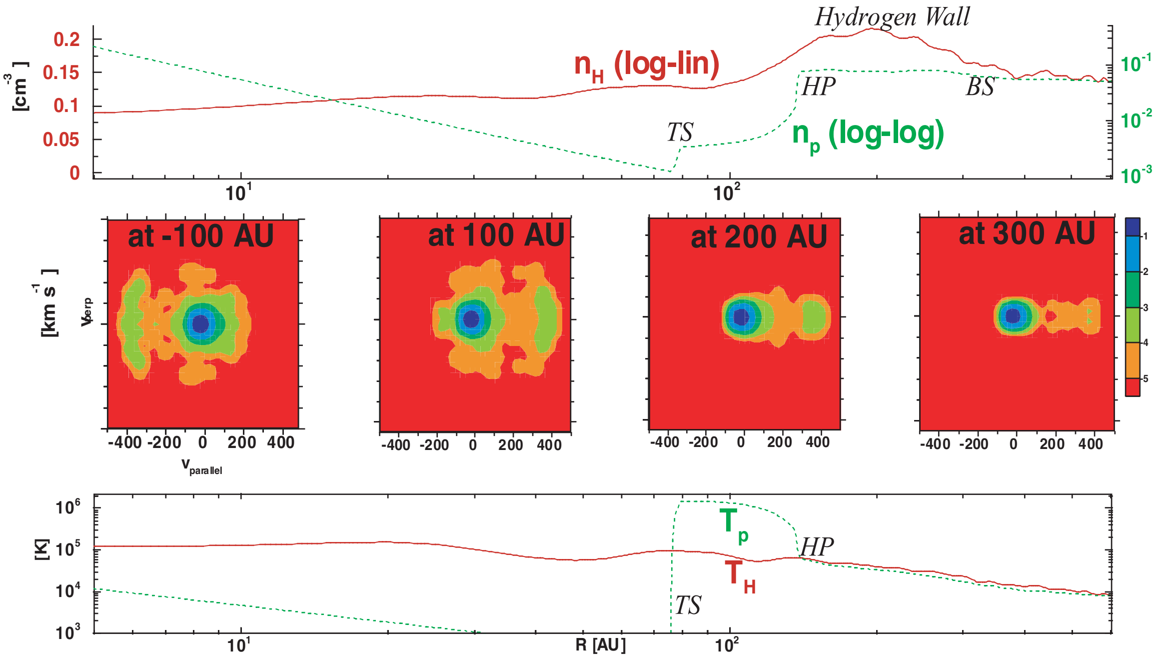

FIGURE 2.4 An example of a kinetic simulation described by Müller et al. (2000) for a two-shock model. One-dimensional profiles of plasma density n_P and plasma temperature T_P are shown as dashed lines over radial distance R from the Sun, and neutral density n_H and (averaged) temperature T_H are shown as solid lines. The profiles are obtained in the upstream direction, antiparallel to the flow of the local interstellar medium (LISM). The middle row depicts normalized two-dimensional neutral velocity distribution functions (logarithmic density scale) at various locations on that axis, with prominent H_{LISM} and H_1 26 km/s neutrals, and evidence of 100 to 300 km/s component 2 and 400 km/s component 3 neutrals. BS, bowshock; HP, heliopause; TS, termination shock.

theory. The pickup process decelerates the solar wind flow (Holzer, 1972; Wang et al., 2000) and adds considerably to the level of turbulence in the outer heliosphere (Fisk and Goldstein, 1978; Lee and Ip, 1987; Zank et al., 1996c). Pickup ions can, by virtue of their dominant pressure contribution, mediate all MHD processes in the solar wind, including small-scale structures such as shock waves and pressure-balanced structures (Burlaga et al., 1994; Whang and Burlaga, 1993; Liewer et al., 1993; Zank et al., 1996b; Zank and Pauls, 1997; Whang et al., 1999; Rice and Zank, 1999; Lu et al., 1999). Pickup ions act to weaken interplanetary shocks, even when magnetic fields (Rice and Zank, 1999) and cosmic rays (Rice and Zank, 2000) are included. This, in turn, must affect the nature of the radio emissions observed by the Voyager spacecraft (Kurth et al., 1984, 1987; Gurnett et al., 1993) and interpreted (Gurnett et al., 1993; Gurnett and Kurth, 1995; McNutt et al., 1995; Cairns and Zank, 1999, 2002) as the generation of radiation by global merged interaction-region-associated shocks interacting with the heliopause and outer heliosheath—especially in terms of the timing of the turn-on and the shock strength and speed in the heliospheric boundary regions, discussed further below.

NEUTRAL INTERSTELLAR ATOMS AND PICKUP IONS

Perhaps the most crucial factor for determining global heliospheric structure and the properties of the boundary regions is also the most unconstrained. The structure and extent of the heliosphere depend critically on the state of the LISM (electron and neutral hydrogen density, temperature, velocity, magnetic field strength and orientation, ionization state, and so on). As is discussed below, only two of these, temperature and velocity, are now known within reasonable error bounds and the rest are very uncertain.

Evidence for the presence of interstellar hydrogen and helium in the heliosphere was provided initially by the measurement of resonantly scattered solar ultraviolet light (Bertaux and Blamont, 1971; Thomas and Krassa, 1971). From subsequent measurements solar physicists have tried to infer the density, temperature, and (relative) velocities of hydrogen and helium (Adams and Frisch, 1977; Bertaux et al., 1985; Ajello et al., 1987). Analyses have concentrated on the strongest resonance lines, H 1216 Å (Lyman-alpha) and He 584 Å. As solar photons travel outward they scatter resonantly from heliospheric H and He atoms. These scattered photons are detected by the Voyager, Pioneer 10, and the SOHO Solar Wind Anisotropies (SWAN) ultraviolet instruments as well as by the Hubble Space Telescope, and intensities vary with heliocentric distance, pointing direction, and the illuminating solar flux (Hall, 1992). H 1216-Å photons are expected to travel on the order of 10 AU before scattering, and He 584-Å photons scatter after traversing on the order of 100 AU. Most H 1216-Å measurements have been obtained by spacecraft within 5 AU of the Sun, where the lines are dominated by scattering from within 10 to 20 AU. The Voyager and Pioneer 10 spacecraft observed resonance lines beyond 5 AU. Finally, it was suggested by M. Gruntman, at this workshop, that the heliopause might possibly be mapped by measuring backscattered solar light at wavelengths 30.4 nm and 83.4 nm, since doing so directly probes interstellar plasma at the heliopause and beyond. This technique is in its infancy, however.

With the launch of Ulysses and ACE, several novel instruments now provide direct measurements for the physical parameters of the interstellar gas in the heliosphere:

- Close to the Sun (within ~5 AU), the local distribution of interstellar neutral helium has been measured using an impact-ionization method by the Ulysses Interstellar Neutral Gas Experiment (GAS) (Witte et al., 1992). These measurements provide the velocity and direction of the flow of interstellar He as well as its temperature and density.
- The densities and velocity distribution functions of the pickup ions H^+, $^4He^+$, $^3He^+$, N^+, O^+, and Ne^+ have been determined by the Ulysses Solar Wind Ionic Composition Spectrometer (SWICS) experiment (Gloeckler et al., 1993; Geiss et al., 1994; Gloeckler and Geiss, 1996). If a model is assumed for the transport of interstellar neutrals within the heliosphere—for example, the hot model (Thomas, 1978; Rucinski and Bzowski, 1995)—the pickup ion data can then be used to infer the neutral parameters at the heliospheric termination shock or possibly even beyond, depending on the importance of filtration. Similarly, the ACE SWICS and Solar Wind Ion Mass Spectrometer (SWIMS) instruments also measure interstellar Ne, He, and O at 1 AU (Gloeckler, 1996; Gloeckler and Geiss, 2004).

Table 2.1 shows the hydrogen and helium parameters and their method of determination.[3] As can be seen, there is disagreement about the inferred number density of neutral hydrogen in the LISM. This is a result of H filtration at the heliospheric boundaries, which makes it very difficult to relate heliospheric

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[3] The latest determination of the direction of the He flow, based on a combination of neutral gas, pickup ion, and ultraviolet measurements, is 74.7 ± –0.6 degrees ecliptic longitude; –5.3 ± 0.3 degrees ecliptic latitude (Möbius et al., 2004).

TABLE 2.1 Hydrogen and Helium Parameters Derived from Various Experiments

Method	Velocity (km/s)	Density (10^{-2} cm^{-3})	Temperature (K)	Observation
Interstellar Helium				
Pickup He^{+} [a]	23-30	0.9-1.2	4,800-7,200	AMPTE (Active Magnetospheric Particle Tracer Explorer)
Pickup He^{+} [b]		1.5 ± 0.15		Ulysses/SWICS (Solar Wind Ionic Composition Spectrometer)
Pickup He^{++} [b]		1.5		Ulysses/SWICS
Direct[c]	26.3 ± 0.4	1.5 ± 0.3	6,300 ± 340	Ulysses/GAS (Energetic Particle and Interstellar Neutral Gas Experiment)
UV[d]	19-24	0.5-1.4	8,000	Prognoz, V1, V2
Heliospheric Hydrogen				
Pickup H^{+} [b]		11.5-5		Ulysses/SWICS
UV[e]	18-20		8,000	HST (Hubble Space Telescope)
UV[f]	19-21		8,000	Prognoz
UV[g]			<20,000	Copernicus
UV[h]	18-0		30,000	HST (downstream)

NOTE: Primary references only. See, for example, Lallement et al. (1996) for a review.

[a] Möbius (1996).
[b] Gloeckler (1996), Gloeckler and Geiss (2004).
[c] Witte et al. (1996), Witte et al. (2004).
[d] Chassefière et al. (1988).
[e] Lallement (1996).
[f] Bertaux et al. (1985).
[g] Adams and Frisch (1977).
[h] Clarke et al. (1995).

pickup ion data directly to the LISM H. Secondly, there is some disagreement about the temperature of neutral hydrogen in the interplanetary medium. However, the interstellar helium temperature now appears to be well constrained and, by implication, the temperature of the interstellar H as well.

The results presented in Table 2.1 provide a baseline against which to begin to constrain global heliospheric models, but a crucial goal of future missions will be the determination of the state of the LISM.

HELIOSPHERIC LYMAN-ALPHA ABSORPTION TOWARD NEARBY STARS

Rather serendipitously, the first of the heliospheric boundaries to be discovered, the hydrogen wall, was found by measuring the absorption of Lyman-alpha light toward our nearest stellar neighbor α-Centauri (Linsky and Wood, 1996; Gayley et al., 1997). This technique has since evolved into a very promising approach both for investigating the structure of our heliosphere and for discovering stellar winds and hydrogen walls associated with neighboring solarlike stars (Box 2.3).

The effectiveness of the Lyman-alpha absorption technique for investigating the outer heliosheath resides in its ability to probe local density and temperature enhancements. The Lyman-alpha absorption

BOX 2.3 ASTROSPHERES

The heliosphere is not unique, but it is the one astrosphere that can be studied in detail with in situ observations. Astrospheres around other stars should certainly exist. Because many stars with a magnetic field and a stellar wind are surrounded by a partially ionized interstellar medium like that surrounding our heliosphere, much of the physics that we are learning locally about neutral atoms, pickup ions, anomolous cosmic rays, and so forth will carry over to the astrospheres of other stars.

The deceleration and accumulation of neutral hydrogen on the upwind side of the heliosphere and other astrospheres have already led to the identification of hydrogen walls in both our own solar system and at several nearby star systems, using typical absorption features in the Lyman-alpha profile (Linsky, 1996; Wood et al., 2000a,b). In situ studies of the outer reaches of our home system will sharpen these tools, allowing us to understand the surroundings of many star systems and thus providing a direct link to astrophysics.

seen in high-resolution stellar ultraviolet spectra obtained by the Hubble Space Telescope can be explained only in part by the ubiquitous interstellar absorption observed toward nearby stars (see, for example, Linsky and Wood, 1996; Gayley et al., 1997; Wood et al., 2000b). Since the assumed stellar Lyman-alpha profile as well as the intervening interstellar absorption is rather well constrained through analysis of the corresponding absorption line of deuterium, one requires the existence of a further hydrogen absorption component. There is strong evidence for excess absorption in various spatial directions, including toward 36 Oph, α Cen, and Sirius, for example (Wood et al., 2000a). This excess absorption has been linked convincingly to heliospheric neutrals, since heliospheric models predict that neutral hydrogen in the heliosphere should be hot, with temperatures on the order of 20,000 to 40,000 K. This high-temperature gas produces neutral H Lyman-alpha absorption broad enough to be separable from the interstellar absorption. In upwind directions, such as that toward α Cen (Gayley et al., 1997) and 36 Oph (Wood et al., 2000a), the heliospheric H I column density is dominated by compressed, heated, and decelerated material in the hydrogen wall. For downwind lines of sight (e.g., toward ε Eri), the H I density is much lower than in the hydrogen wall, but the sightline through the heated heliospheric H is longer, potentially allowing heliospheric Lyman-alpha absorption to be observed also in downwind directions.

There have already been successful attempts to match observations with heliospheric models through parameter studies that vary key LISM parameters (Gayley et al., 1997; Wood et al., 2000b) (see Figure 2.5), which underscores the value of this approach for constraining LISM parameters and the global heliospheric structure. While successful in predicting observed Lyman-alpha profiles, the models are not necessarily constrained uniquely by the observations (Florinski et al., 2003).

PARTICLE ACCELERATION IN THE HELIOSPHERE AND AT THE TERMINATION SHOCK

The termination shock is likely to provide our first opportunity to study in situ the acceleration of anomalous cosmic rays, providing us with a tangible glimpse into how galactic cosmic rays are thought to be accelerated by shock waves associated with supernova remnants. The development of diffusive shock acceleration theory as an explanation for the universal form of the cosmic ray spectrum over many decades in energy space has made it one of the most important and widely used results in astrophysics today. Investigating the origin of anomalous cosmic rays within and at the heliospheric boundaries will therefore

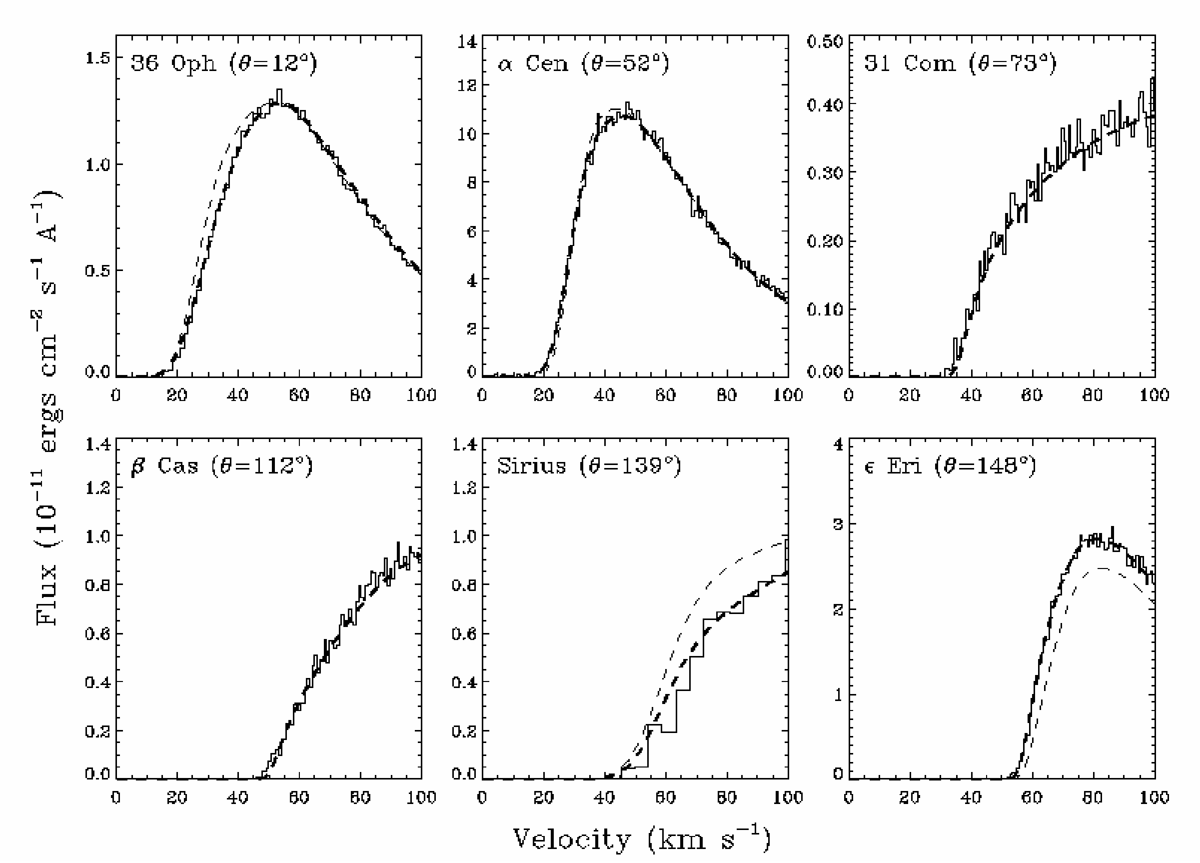

FIGURE 2.5 Lyman-alpha profiles on the red side for six sightlines toward neighboring stars. The solid lines show observations made using the Space Telescope Imaging Spectrograph instrument (see http://www.stsci.edu/instruments/stis/) and the dashed lines are theoretical predictions from a self-consistent model of the global heliosphere. SOURCE: Wood et al. (2000b).

embed much of the theory firmly in observations, allowing the termination shock to be viewed as an example of an astrophysical shock (see Box 2.2). However, as is discussed below, the termination shock is also distinguished by the presence of pickup ions, by its comparatively weak strength (due to pickup ion momentum loading), and by its largely quasi-perpendicular character.

The origin of anomalous cosmic rays is intimately related to the interaction of the LISM with the solar wind. It is generally accepted that ACRs are formed when a fraction of the interstellar pickup ion population[4] is injected into the diffusive shock acceleration process at the solar wind termination shock (Fisk et

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[4] There is a possibility that, besides the interstellar source, there is another source of ACRs in the outer heliosphere. This "'outer source' is thought to consist of atoms that are sputtered from small grains of material from the Kuiper Belt. These atoms are subsequently ionized, picked up by the solar wind, and transported to the termination shock, where they are accelerated by the same processes that act on the interstellar pickup ions." See Schwadron et al. (2002).

al., 1974; Pesses et al., 1981). However, without direct observations of the termination shock structure and the injection and acceleration process, sufficient constraints are not available to form a detailed understanding of this process, and competing theories have been developed. Preliminary observations should be returned by Voyager 2, but these will be limited by the absence of a working plasma instrument and pickup ion instrumentation.

Observations of energized pickup ions in the inner heliosphere have presented challenges to theory. Observations of co-rotating interaction regions (CIRs), for example, suggest that pickup ions created close to the Sun (the 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 (Möbius et al., 2002). However, Gloeckler (1999) has found strong suprathermal tail distributions in the solar wind and pickup ion distributions that appear to strengthen with distance from the Sun. This observation suggests that a preacceleration mechanism that becomes increasingly effective with heliocentric distance may be at work, thereby enabling particles to be more easily accelerated at the termination shock.

To study such behavior quantitatively and to draw inferences about acceleration processes in the outer heliosphere, pickup ion, suprathermal, and energetic particle populations need to be observed at 1 to 5 AU with elemental and ionic charge resolution and a collection power comparable to those of the energetic particle instruments on ACE. By following the acceleration of particles in CIRs and coronal mass ejections at increasing distances from the Sun, it will be possible to delineate the injection and preacceleration processes necessary to understand particle acceleration at the termination shock. In combination with quantitative modeling and simulations, this will allow reasonable extrapolation to the outer heliosphere. These objectives can be achieved with state-of-the-art instrumentation similar to that flown on ACE,[5] but on a 1 to 5 AU orbit, and will allow us to achieve the first quantitative understanding for the origin of cosmic rays throughout the universe.

GALACTIC COSMIC RAYS: ENTRY INTO THE HELIOSPHERE

Like interstellar neutrals, galactic cosmic rays allow us to probe the interstellar medium, with the distinction being that their origin is not necessarily local. However, unlike interstellar neutrals, galactic cosmic rays, being charged, respond to the (electro)magnetic structure of the heliosphere-LISM interaction region. Observations (McDonald et al., 2000) and models are beginning to use galactic cosmic rays flowing into the heliosphere to infer the structure of the boundary regions. Such studies can be accomplished only by spacecraft placed far out in the heliosphere since diffusion effectively washes out any signature or imprint of the heliospheric boundaries on the cosmic ray flux observed within 40 to 50 AU (Florinski et al., 2003).

The global heliospheric transport of galactic cosmic rays (GCRs) has tended to focus on the region inside the termination shock. However, it has become increasingly apparent that we need to address GCR interaction with the complex three-dimensional structure of the heliosphere (Jokipii, 1989; Jokipii et al., 1993; McDonald et al., 2001; Florinski et al., 2003). Most importantly, the heliospheric interface is very inhomogeneous, containing regions with vastly different flow patterns and magnetic fields, resulting in very different patterns of cosmic ray propagation. As GCRs approach the heliopause they encounter the modulation or magnetic wall (Figure 2.6), a region with a strongly amplified magnetic field. At least half of

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[5] A description of instruments on ACE is available at http://www.srl.caltech.edu/ACE/.

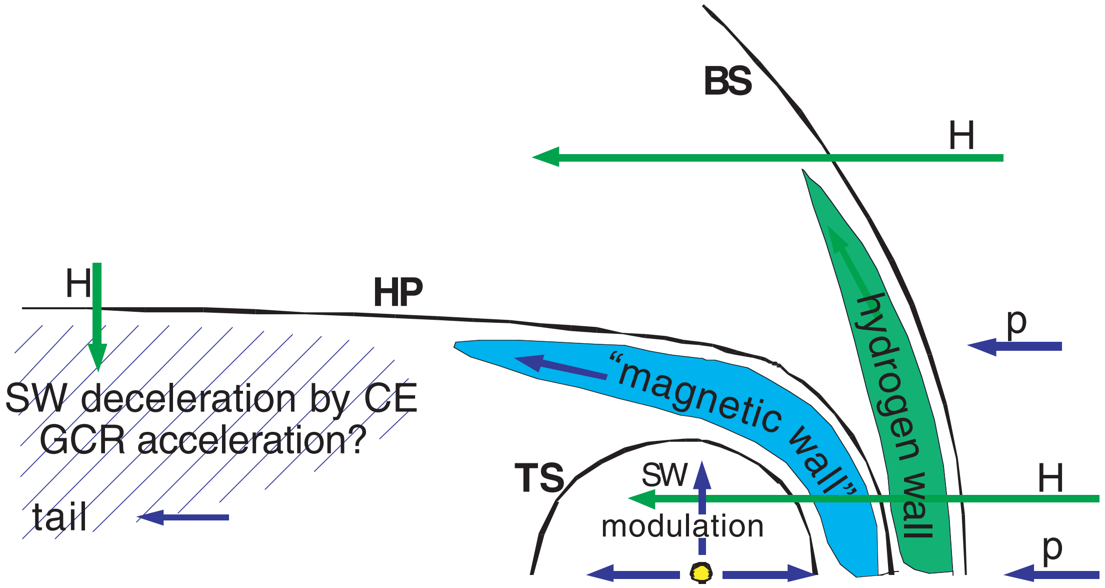

FIGURE 2.6 Schematic showing the overall structure of the heliosphere and its expected effect on the modulation of galactic cosmic rays.

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the particles with energies below 1 GeV are filtered by the magnetic wall. The second obstacle is the inner heliosheath itself, a highly asymmetric region around the termination shock. As the heliosphere extends in the tailward direction, the solar wind flow is decelerated by the process of charge exchange with neutral interstellar atoms; that is, charge exchange in the heliotail decelerates and cools the shocked plasma flow, creating a convergent flow structure. GCRs propagating with the convergent flow experience re-acceleration through large-scale compression (Figure 2.7). The final region that GCRs must traverse before reaching Earth is the supersonic solar wind upstream of the termination shock. During solar minima, transport in this region is strongly dominated by polar diffusion and drift, effectively erasing the asymmetry present in the GCR distribution in the heliosheath. This necessitates in situ detection methods, preferably outside the termination shock region. Although the picture described so far is already quite complex, it is still not complete. In addition to the above regions, the outer heliosheath may play an important role in GCR modulation if the heliopause is unstable to a charge exchange instability (Zank et al., 1996a; Liewer et al., 1996; Florinski et al., 2004). The evolution of the turbulence in the solar wind and LISM has yet to be modeled.

By enabling measuring of the level of modulation that occurs in the inner heliosheath compared with that in the supersonic wind, GCRs may provide a mechanism for probing the large-scale magnetic structure of the heliospheric boundary region. This will require that the observations be made in the very distant heliosphere. It is conceivable, too, that the LISM magnetic field can be probed indirectly via cosmic rays, again provided that the spacecraft is sufficiently deep within the boundary region.

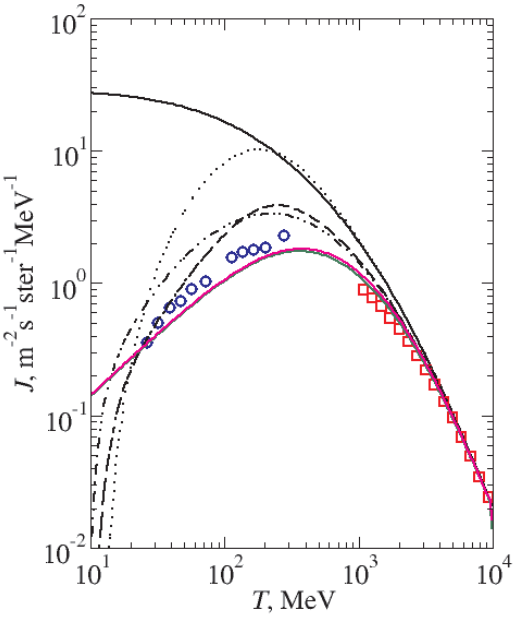

FIGURE 2.7 Galactic cosmic ray spectra based on a self-consistent heliospheric model that includes H atoms explicitly. The lines identify the theoretical cosmic ray differential flux at various heliospheric locations. LISM (solid); 1.1 r_s 0° (dashed), nose region; 1.1 r_s 90° (dash-double-dotted), polar region; 800 AU 180° (dotted), heliotail; 10 AU 0° (green). An example of the spectrum at 10 AU when no H atoms (red) are included in the self-consistent model. The effect of the modulation cavity reduction due to neutrals is not significant (~5 percent) at small heliocentric distances. SOURCE: Florinski et al. (2003).

RADIO EMISSIONS FROM THE OUTER HELIOSPHERE

Another avenue for investigating the heliospheric boundaries remotely is through radio emissions of the kind observed by Voyager. Approximately every 11 years (solar cycle), the Voyager spacecraft detect bursts of radio waves at frequencies of 2 to 3 kHz in the outer regions of our solar system (Kurth et al., 1984, 1987; McNutt, 1988, 1989; Gurnett et al., 1993). The radiation is from the strongest radio source in our solar system but does not come from the Sun or planets (Gurnett and Kurth, 1994; Cairns, 1995). Instead it appears to be generated when shock waves caused by solar activity reach the vicinity of the heliopause (Gurnett et al., 1993; Kurth and Gurnett, 1995; Gurnett et al., 2003; McNutt et al., 1995; Cairns and Zank, 1999). This radiation provides an opportunity to probe the outer boundaries and plasma characteristics of the solar system remotely, including the heliopause region where the solar wind plasma and LISM plasma interact (as distinct from the interstellar neutral atoms and the solar wind plasma).

Gurnett et al. (1993) and Gurnett and Kurth (1995) argue persuasively that the radiation is generated when certain global merged interaction regions (GMIRs) and associated shocks reach the vicinity of the heliopause and move into the outer heliosheath. The main arguments are based on the observation of GMIRs and shock waves for each major outburst of radiation, the existence of almost identical time lags 415 ± 5 days between when the GMIRs originate at the Sun and when the radiation starts, very similar GMIR propagation speeds, and estimates based on these speeds and time lags that the source is at distances $R \sim 115$ to 180 AU, comparable to those predicted for the heliopause. Another argument is that the emission frequency is approximately equal to the electron plasma frequency, $f_p = 8.98(n_e/m^{-3})^{1/2}$ Hz, predicted for the outer heliosheath and the LISM, based on the number densities of pickup ions observed in the inner heliosphere and associated modeling (Gloeckler et al., 1993) and the average plasma number density inferred from the column densities to nearby stars (e.g., Zank, 1999a). The emission frequencies are larger by factors of ≥ 8 and ≥ 4 than the values of f_p predicted for the solar wind near the termination shock and in the inner heliosheath, respectively. It is worth emphasizing that the radiation is only a few decibels above the noise levels of the Voyager radio receivers, despite being the most powerful known radio source in our solar system (Gurnett et al., 1993). This means that other weaker radio events or components of the observed emissions may exist and be observable closer to the source, as suggested by Cairns and Zank (1999, 2002).

ENERGETIC NEUTRAL ATOMS IN THE HELIOSPHERE

Like energetic neutral atoms used to image Earth's magnetosphere (Burch et al., 2001), energetic neutral atoms (ENAs) born in the inner heliosheath can be used to image the heliospheric boundaries and to infer plasma properties. ENA imaging can be done within a few astronomical units of the Sun as well as by outer heliospheric missions.

Neutral hydrogen detected close to the Sun (within ~5 AU) with an energy above about 10 eV is unlikely to be of interstellar origin. Instead, the spectrum of energetic neutral H in the range from 10 eV to 1 keV is dominated by ENAs of heliospheric origin (Hsieh, 1992a; Gruntman, 1992), born through charge exchange with the hot plasma (10^6 K) of the inner heliosheath (between the termination shock and the heliopause)—that is, component 2 neutrals. At those temperatures, the ions have large thermal velocities in mainly random directions. During charge exchange, the initial ion velocity is preserved, but the now energetic neutral decouples from the plasma and is no longer affected by magnetic fields. The sunward component of such a heliospheric ENA distribution can reach spacecraft detectors in the vicinity of the Sun traveling in almost direct trajectories from the site of charge exchange. The distribution is depleted only by ionization events on this path and can therefore serve to probe the ion distribution in the heliosheath. The energy range above 1 keV is dominated by ENAs that are born through charge exchange of anomalous cosmic rays with LISM neutrals (Hsieh et al., 1992b).

Efforts to use <1 keV ENAs as a tool for mapping the global structure of the heliosphere and the associated ion distributions have begun (Gruntman, 1992, 1997; Gruntman et al., 2001). Analysis of the dependence of ENA fluxes on observation direction (e.g., by SOHO; Hilchenbach et al., 1998) will provide a measure of heliospheric asymmetry. Asymmetry is suggested by numerical studies that incorporate a non-parallel interstellar magnetic field (Ratkiewicz et al., 1998; Linde et al., 1998; Pogorelov et al., 2004), or heliolatitude-dependent solar wind parameters (Pauls and Zank, 1996, 1997), or both (McNutt et al., 1998, 1999a,b). The asymmetry that can be expected from the inclusion of both the interplanetary and interstellar magnetic fields is illustrated in Figure 2.8, where a very complex topology for the LISM streamlines and the magnetic field lines is shown.

Considerable interest has been expressed in using ENA imaging, which has been successfully employed on the IMAGE mission, to image the termination shock and regions beyond. High-sensitivity ENA observations will help constrain global models of the heliosphere and will advance our theoretical understanding of the nature of the termination shock and the pickup ion population in the heliosheath. At least three spacecraft missions employing ENA imaging have been proposed: two Interstellar Pathfinder missions (e.g., McComas et al., 2003) and the Interstellar Boundary Explorer (IBEX) (McComas et al., 2004), which is currently in Phase A study. Both the imaging and the designs demonstrating the required instrumentation for such interstellar missions are well documented in the refereed literature. The application of this technique to imaging the termination shock will greatly benefit from determining the degree of interference from background ENAs inside the heliosphere. This ENA background is produced from strong, time-variable suprathermal ion tails that are observed between 1 and 5 AU by ACE and Ulysses. Both current theoretical and experimental studies can be used to characterize this background population.

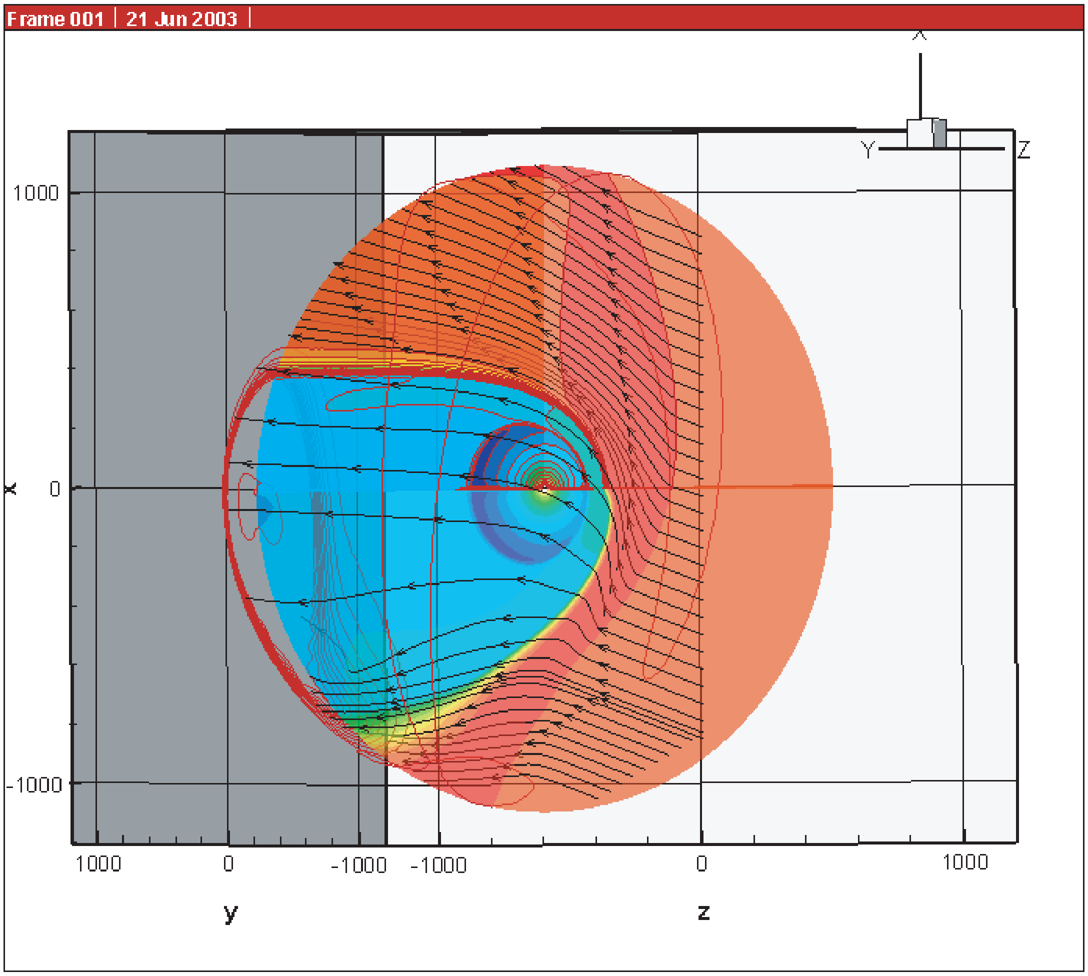

FIGURE 2.8 Projection of a three-dimensional magnetohydrodynamic-only simulation (i.e., excluding interstellar H atoms) in the presence of an interplanetary and an interstellar magnetic field. The interstellar magnetic field is oriented 20° from the interstellar flow direction and the interstellar magnetic field strength is assumed to be 1.6 μG. Density isolines are plotted in the meridional plane, together with three-dimensional steamlines starting in this plane. SOURCE: Pogorelov et al. (2004).

3

The Next Logical Steps

A mission to the edge of the heliosphere will take at least two decades (if we count the time for a probe to reach that distance). However, progress can be made in exploring the outer heliosphere using current state-of-the-art technology and relatively small space missions. Such missions will both complement the Voyager and Ulysses discoveries and serve as valuable and necessary precursors to Interstellar Probe. This chapter summarizes possible experimental directions that can be undertaken relatively inexpensively.

First, it notes the crucial importance of the pervasive interstellar wind of neutral atoms that blows through the solar system and carries gas to within 3 AU of Earth (see, e.g., Möbius et al., 2001). Securing rides on missions that are focused on and optimized for other objectives has enabled great advances in determining the physical parameters and composition of interstellar gas through ultraviolet glow (see, e.g., Bertaux and Blamont, 1971; Lallement, 1996), pickup ions (Möbius et al., 1985; Gloeckler and Geiss, 1998), and neutral He atoms (Witte et al., 1996). Dedicated efforts with instruments optimized for interstellar gas studies in the inner heliosphere will substantially advance knowledge of the local interstellar medium (LISM)-solar wind interaction. As discussed above, suprathermal and energetic ion populations generated at the heliospheric termination shock produce energetic neutral atoms (ENAs) through charge exchange with the interstellar neutral gas and can be used to provide a full-sky image of this region (see, e.g., Gruntman, 1997; Gruntman et al., 2001). Likewise, remote sensing in the extreme ultraviolet (EUV) of singly charged ions should provide extremely valuable information through a full-sky image of the heliopause (Gruntman and Fahr, 2000; Gruntman, 2001a,b), providing that the instrumentation can achieve the necessary sensitivities and spectral resolution and that the inherent background from heliospheric ENAs is small. Such studies are extremely timely, as the Voyagers' approach to the termination shock and heliopause will provide essential constraints to the imaging techniques, such as limits on intensities and spectral shapes of ENAs and the distance to the boundary regions.

In situ studies within 1 to 4 AU will remain critical to furthering our understanding of the fundamental coupling of LISM material and solar wind plasma. Interstellar pickup ions and energetic particle acceleration processes at shocks and other interaction regions can be studied in detail within the inner heliosphere. Focusing especially on radial variation, composition, charge states, injection, and sources will yield new and valuable information, which can be extrapolated to the heliospheric boundary. This will require spacecraft with instrumentation that can study the inflowing neutral gas and dust, pickup ions, and cosmic rays (anomalous and galactic), energetic particles, and magnetic field directly, since these are essential if we are eventually to probe both the LISM and the heliospheric boundaries with new spacecraft (and even remotely). Our understanding of the critical microphysics will be revealed best by in situ measurements.

PROBING THE LOCAL INTERSTELLAR MEDIUM IN THE INNER HELIOSPHERE

With a renewed emphasis on dedicated observations within the inner heliosphere substantial steps can be taken to address the first, second, and fourth science objectives listed in Chapter 1.

Studying nucleosynthesis or the evolution of matter in our galaxy requires extensive modeling of the production of elements and isotopes in stars and their dissemination into the interstellar medium. Constraints on the models require precise composition observations of samples from different ages of the galaxy. While the solar system is a sample from 4.5 billion years ago, the local interstellar cloud (LIC) provides material of today's galaxy and is thus much more evolved.

The necessary composition measurements can be achieved through pickup ion observations (Gloeckler and Geiss, 1998). To make substantial progress requires a pickup ion mass spectrometer with good resolution and a large geometric factor. Such an instrument can be built today, based on time-of-flight instruments used on board the Ulysses and ACE spacecraft (Gloeckler et al., 1998; Mason et al., 1998). Mass resolution, energy range and geometric factor (up to 500×) must be tailored specifically to the pickup ion investigation, because past and current instruments were designed for other purposes. The composition of elements and isotopes with high ionization potential, such as H, He, N, O, Ne, and Ar, can be studied from the neutral gas entering the inner heliosphere. Key isotopic ratios, such as $^{3}\mathrm{He}/^{4}\mathrm{He}$, $^{14}\mathrm{N}/^{15}\mathrm{N}$, $^{18}\mathrm{O}/^{16}\mathrm{O}$, and $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$, can be observed without any significant alteration through heliospheric interface processes. Elemental ratios may require corrections for selective filtration at the interface, another important topic that can be understood more thoroughly through observations in the inner heliosphere.

Progress in constraining the physical parameters of the LIC and the interaction with the heliosphere has been made recently through a coordinated analysis of interstellar He using three complementary techniques: direct neutral gas measurements, pickup ion measurements, and ultraviolet backscattering observations. A benchmark set of physical He parameters has been derived that yields consistent results for all three techniques (Gloeckler and Geiss, 2004; Lallement et al., 2004; Witte et al., 2004) if the ionization environment and the solar illumination are taken into account correctly. A lesson learned from this analysis is the recognition that direct observations of the neutral gas provide the most accurate and complete information on the arriving neutral distribution. The key to these observations is the use of the Sun as a gigantic gravitational lens for the inflow of interstellar gas, as depicted in Figure 3.1. The controlled deflection of interstellar trajectories on Keplerian orbits leads to a distinctive pattern for the gas distribution in the inner heliosphere and to a unique dependence of the flow direction on the location of the observer (Fahr, 1968; see, e.g., Zank, 1999a). It is the latter characteristic that is utilized in the form of an image of the neutral gas flow in the sky.

Unlike He, which is not affected by heliospheric interface filtration, the distributions of H and O experience substantial depletion, deceleration, and heating entering the heliosphere when compared with their pristine state in the LIC (see, e.g., Izmodenov et al., 1999a; Müller et al., 2000). As depletion, deceleration, and heating are intimately coupled to interface processes, deviations in the flow pattern and temperature of the H and O distributions compared with that of He will allow us to evaluate the filtration and original LIC distribution from interplanetary neutral gas observations. Such studies will rely on well-developed models. The analysis of neutral He observations (Witte et al., 1996, 2004) has shown that highly accurate LISM parameters can be derived, provided the angular resolution and precision of the observa-

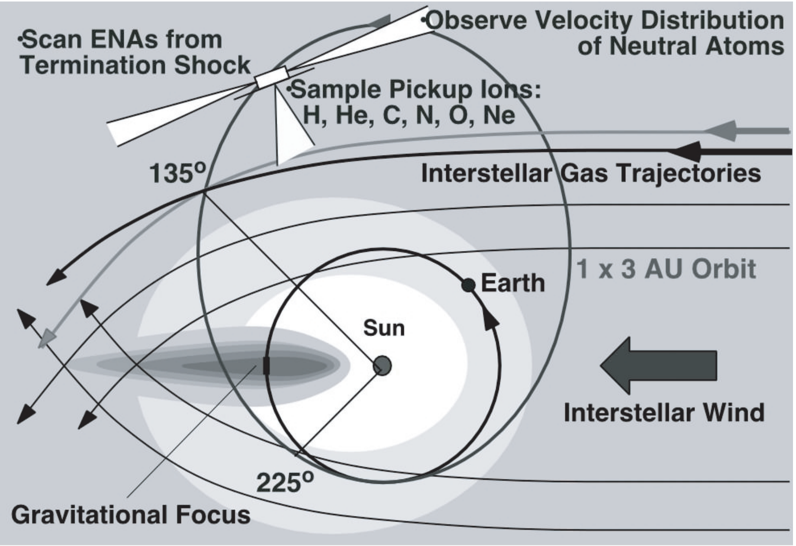

FIGURE 3.1 Typical orbit, main objectives, and viewing of projected Interstellar Pathfinder with trajectories of the interstellar gas flow and a qualitative distribution of interstellar gas.

tions are commensurate with each other. The logical next step is to use a neutral imaging instrument, similar to the one flown on Ulysses but now with the ability to distinguish H and O (Möbius et al., 2001). Concepts to increase angular resolution and geometric factor have been developed (Livi et al., 2003). A sensor with front-end, surface conversion of neutrals into negative ions, and subsequent time-of-flight analysis similar to the LENA (Low-Energy Neutral Atom) instrument on the IMAGE (Imager for Magnetosphere to Aurora Global Exploration) spacecraft (Burch, 2000), can extend the neutral gas observations to O and possibly H (see, e.g., Wurz et al., 1995).

The gravitational deflection of the interstellar flow by the Sun used by a 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, at 1 AU, inner source pickup O ions—that is, ions created from dust close to the Sun—dominate the interstellar O population. Only beyond 1.4 AU can we distinguish unambiguously between inner source and interstellar pickup ions (Geiss et al., 1995). The farther away from the Sun, the more the interstellar pickup ion distribution becomes visible without contamination by the inner source. To measure both inner source and interstellar pickup ions, an elliptical orbit in the ecliptic plane into the side-wind direction relative to the interstellar gas flow would be an ideal compromise (see Figure 3.1) and would also cut through the gravitational focusing cone of He.

REMOTE SENSING OF THE HELIOSPHERIC BOUNDARY REGIONS

Interaction processes in the nose direction[1] can be deduced from the interstellar gas flow, but only remote-sensing techniques with full-sky imaging allow us to investigate the characteristics and the three-dimensional topology of the heliospheric termination shock.

The heliosphere is an essentially asymmetric three-dimensional object on a scale of several hundred AU, which calls for remote techniques to study its boundary. Only remote observations (complemented by the Voyager and the proposed Interstellar Probe "ground truth" in situ measurements) can provide a global view of the time-varying heliosphere and its boundary on a continuous basis. Two remote-sensing experimental techniques, using fluxes of ENAs (Gruntman, 1997; Gruntman et al., 2001) and EUV photons (Gruntman and Fahr, 2000; Gruntman, 2001a,b) with different degrees of maturity, promise significant advances in imaging the heliospheric boundaries.

Energetic Neutral Atom Imaging

The inner heliosheath, between the termination shock and the heliopause, contains shocked solar wind plasma and pickup ions. Energetic protons charge exchange with interstellar hydrogen to produce ENAs, some of which reach 1 AU, where they can be reliably detected by instrumentation based on well-tested technology. Provided that the background from heliospheric ENAs is sufficiently small compared with ENA fluxes from the termination shock and beyond, ENA imaging of the heliosphere could establish the nature of the termination shock and its directional dependence and could also determine the asymmetry of the interstellar magnetic field.

The experimental concept and the instrumentation to carry out these observations are mature and ready for implementation. For example, an ENA imager that is optimized for the energy distribution of H neutrals from the termination shock with energies that range from a few hundred eV to several keV could be derived from instruments on Cassini, IMAGE, and TWINS[2] (Two Wide-Angle Imaging Neutral-Atom Spectrometers) (Funsten et al., 2001). As mentioned above, three spacecraft missions to image the heliospheric boundaries through ENA observations have already been proposed—two Interstellar Pathfinder (e.g., McComas et al., 2003) missions and the IBEX (McComas et al., 2004), which is currently in Phase A study. Clearly, ENA imaging has reached a level of maturity that the EUV and x-ray imaging techniques discussed below have yet to attain.

Extreme Ultraviolet Imaging

As a complementary technique, heliospheric imaging in the EUV with high sensitivity and spectral resolution will significantly advance our knowledge of the physical processes at and beyond the heliopause—that is, in the region where the expanding solar wind meets the galactic medium. The

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[1] The direction of the nose is 180 degrees opposite to the direction of the flow and is therefore approximately 254 degrees ecliptic longitude and +5.6 degrees ecliptic latitude (Geiss and Witte, 1996). The most recent data puts the nose at 254.7 ± 0.6 degrees ecliptic longitude and +5.3 ± 0.3 degrees ecliptic latitude (Möbius et al., 2004; Witte et al., 2004). The direction to the nose is, of course, a key consideration in selection of a flight path for Interstellar Probe.

[2] Scheduled for launch in 2005, the TWINS mission will provide a new capability for stereoscopically imaging the magnetosphere. By imaging the charge exchange neutral atoms over a broad energy range (~1 to 100 keV) using two identical instruments on two widely spaced, high-altitude, high-inclination spacecraft, TWINS will enable the three-dimensional visualization and the resolution of large-scale structures and dynamics within the magnetosphere for the first time. See the TWINS home page at http://nis-www.lanl.gov/nis-projects/twins/.

interstellar plasma beyond the heliopause reflects line emissions of the Sun in the EUV range, thus providing information on the distance to the heliopause and on interstellar plasma properties. Observations in the He^+ 30.4-nm line are most promising. Mapping of the heliopause at 30.4 nm could allow us to establish the shape of the heliopause, determine the ionization degree of interstellar helium, and reveal the asymmetry of the interstellar magnetic field. It may also tell us whether there is a heliospheric bow shock. This measurement requires the development of a new generation of extremely sensitive diffuse EUV spectrometers with high spectral resolution. The experimental concepts have been formulated, and a feasibility study of the proposed instrumentation is being conducted. In addition, full-sky images of the heliosphere at 30.4 nm with high spectral resolution will allow us to establish remotely, from 1 AU, the time-varying flow properties (velocity and number density) of the solar wind plasma flow in all directions, including over the Sun's poles and on its far side (Gruntman, 2001b).

X-ray Imaging

Recently also the diffuse x-ray background has received attention as a potentially powerful diagnostic technique for the interstellar gas/solar wind interaction (see, e.g., Cravens, 2000; Robertson et al., 2001). This radiation is produced through the excitation of heavy solar wind ions when they collide with interstellar gas atoms. The serendipitous observation of x-rays from comets (Dennerl et al., 1997; Cravens, 1997) paved the way for this promising new tool. When fully developed, it could provide a full-sky image of the solar wind/interstellar gas interaction and provide an independent account of the spatial distribution of interstellar gas.

4

An Interstellar Probe to the Boundaries of the Heliosphere and Nearby Interstellar Space

During the next few years the Voyagers are expected to cross the termination shock, if Voyager 1 has not yet already done so (Krimigis et al., 2003), and make fundamental discoveries about the size of the heliosphere and the nature of its boundaries. Precisely when this occurs may depend on the motion of the shock itself, which may be moving outward owing to solar cycle changes in ram pressure, on both 11-year and shorter time scales. It should be realized, however, that the Voyagers carry in situ instrumentation that was designed 30 years ago with the primary objective of exploring planetary magnetospheres. Beyond this initial reconnaissance work, a new mission—an interstellar probe—carrying modern instrumentation is needed if we are to make detailed measurements in the outer solar system and at the heliospheric boundaries and to then exit the heliosphere and begin the in situ exploration of the space between the stars. To relate the particles and fields measured along the spacecraft trajectory to models of the global heliosphere, it is important that Interstellar Probe carry a complementary package of both in situ and remote-sensing instruments.

A voyage by an interstellar probe from Earth to beyond 200 AU could enable the comprehensive measurements of plasma, neutral atoms, magnetic fields, dust, energetic particles, cosmic rays, and infrared emission from the outer solar system, through the boundaries of the heliosphere, and on into the interstellar medium. Such an exploratory journey could address key questions about the distribution of matter in the outer solar system, the processes by which the Sun interacts with our galaxy, and the nature and properties of the nearby galactic medium. An interstellar probe could also directly gather the data that are necessary to address the four principal science objectives (see Chapter 1) of a mission to the border of our galaxy:

1. *To explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our galaxy and the universe*. Interstellar space is a largely unknown frontier that holds many keys to understanding our place in the Galaxy. The nearby interstellar medium includes species that are predominantly ionized (e.g., C, S, and Si), those that are mostly neutral (H, He, N, O, Ne, and Ar), and others that are mainly locked up in grains (e.g., Al, Ca, and Fe) (Slavin and Frisch, 2002). Although pickup

ions and anomalous cosmic rays provide information on neutral species, we currently have no information on the elemental and isotopic composition of ionized species, nor do we know to what extent refractory elements have condensed into grains. In addition, we have almost no knowledge of the direction and strength of the interstellar magnetic field, or of the intensity and composition of low-energy cosmic rays outside the heliosphere. Direct sampling of the composition of interstellar matter would provide a benchmark for comparison with solar-system abundances and provide constraints on galactic chemical evolution. Abundance measurements of isotopes such as ^{2}H, ^{3}He, ^{13}C, ^{18}O, ^{22}Ne, ^{26}Mg, and ^{30}Si would constrain cosmological and nucleosynthesis models and provide a more accurate picture of the evolution of the solar system, the Galaxy, and the universe.

2. *To explore the influence of the interstellar medium on the solar system, its dynamics, and its evolution*. The heliosphere and its boundaries provide a unique laboratory for studying plasma processes and the interaction of a star with its environment. The termination shock is thought to be a powerful accelerator, with particle energies reaching more than 1 GeV. In situ studies of shock structure, plasma heating, and acceleration processes will serve as a model for other astrophysical shocks. Beyond the termination shock, in the heliosheath, the solar wind flow turns to match the flow of the diverted interstellar plasma. At the boundary between the solar wind and interstellar plasmas, there could be magnetic reconnection between interplanetary and interstellar magnetic field. A bow shock might be created in the interstellar medium ahead of the nose of the heliosphere, depending on the unknown interstellar magnetic field strength. Energetic neutrals created by charge exchange in the heliosheath can be used to image the three-dimensional structure of the heliosphere. Charge-exchange collisions cause a pileup of neutral hydrogen at the heliosphere nose, referred to as the "hydrogen wall." Interstellar Probe will pass through these boundary regions and make in situ measurements to answer questions about the size, structure, and dynamics of the heliosphere and processes occurring at the boundaries. As the solar wind pressure varies over the solar cycle, the termination shock and heliopause are expected to move by ~10 to 20 AU (Zank and Mueller, 2003). Over the course of the Sun's journey through the Galaxy, these boundaries were undoubtedly much closer in during times when the heliosphere encountered more dense interstellar regions.

3. *To explore the impact of the solar system on the interstellar medium as an example of the interaction of stellar winds with their environments*. Models show that the interstellar medium experiences considerable heating by charge exchange of fast, hot neutrals created in the inner heliosheath. These neutrals transport heat anomalously across the heliopause, and via a secondary charge exchange they heat the very local interstellar medium. It has also been suggested that the newly created pickup ions in the local interstellar medium (LISM) act to heat electrons (Cairns and Zank, 2002), making this region more likely to produce radio emissions when global merged interaction region shocks of solar origin sweep through. The plasma physics of the LISM is therefore likely to be affected by solar wind neutrals, as well as by anomalous cosmic rays diffusing out. By observing the plasma state of the LISM, Interstellar Probe will directly address this question.

4. *To explore the outer solar system for clues to its origin and the nature of other planetary systems*. By carrying a small charge-coupled device (CCD) camera, Interstellar Probe could survey the population of Kuiper Belt objects >1 km in size and determine the radial extent of the Kuiper Belt and the primordial solar nebula. Interstellar Probe could also survey the composition and distribution of dust due to collisions of Kuiper Belt objects and could possibly investigate the nature and evolution of organic material in the outer solar system.

NASA's last four Sun-Earth Connection roadmaps (2000-2003) have included a mission to explore the boundaries of the heliosphere and nearby interstellar space, and interstellar probe became part of the

NASA Strategic Plan in 2000.[1] The recently published NRC decadal research strategy in solar and space physics recognized the scientific importance of an interstellar probe mission but listed it as a "deferred high-priority flight mission" because of its requirement for advanced propulsion (NRC, 2003). Specifically, the report included the following recommendation: "NASA should assign high priority to the development of advanced propulsion and power technologies required for the exploration of the outer planets, the inner and outer heliosphere, and the local interstellar medium" (pp. 10-11).

To be sure of crossing the heliopause and making a significant penetration into interstellar space, Interstellar Probe should reach at least 200 AU within a reasonable time frame (e.g., 10 to 20 years), requiring an escape velocity of 10 to 20 AU/year. This requires propulsion technology well beyond that of Voyager 1, which is on an escape trajectory with an average velocity of ~3.6 AU/year.[2]

Over the past decade, three approaches have emerged that, following some development, could achieve the required spacecraft velocities carrying an advanced scientific payload. The first of these, which has been studied at various times in the past, makes use of a Jupiter flyby, followed by a powered solar flyby passing within 4 solar radii of the center of the Sun. By performing a rocket burn deep in the Sun's gravitational well, the resulting change in velocity can be translated to escape velocities well in excess of those normally achieved with chemical propulsion and planetary gravity assists (Mewaldt et al., 1995; Ehricke, 1972). This approach and related technology issues have recently undergone additional study through funding by NASA's Institute for Advanced Concepts program, resulting in a mission concept that might achieve escape velocities of 12 to 15 AU/year (McNutt et al., 2001, 2003a,b). Of course, before this trajectory is attempted with an interstellar probe it will be necessary to successfully demonstrate the heat shield and other technologies required for a close solar flyby by carrying out a successful solar probe mission.

The other two propulsion technologies that hold promise for an interstellar probe are nuclear-electric propulsion (NEP) and solar sail propulsion (see Gavit et al., 2001). Solar sail propulsion is more efficient closer to the Sun, where the radiation pressure is greater. In the mission concept adopted in a 1999 study (JPL, 1999b),[3] a 200-m-radius sail with an areal density of 1 g/m^2 (sail material plus support structure) would be used to maneuver the spacecraft for a swing-by at 0.25 AU, where the increased radiation pressure could accelerate the spacecraft at escape velocities of ~14 AU/year. Because almost all of the propulsion takes place within the first few AU, it is possible to jettison the sail at ~5 AU, thereby avoiding possible effects that a large, conducting sail might have on in situ particles and fields measurements as well as on other instruments.

Although solar sail propulsion holds great promise for a number of new missions (see, e.g., *The Sun-Earth Connection Roadmap 2003-2028,* NASA, 2003; and *The Sun to Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* NRC, 2003), a solar-sail-propelled spacecraft has never been tested in space. However, funding for solar sail development has increased significantly during the past few years, largely owing to NASA's OSS-funded In-Space Propulsion Program and technology development within the New Millennium Program.[4] Even before a NASA-funded test flight could occur, solar-sail

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[1] On page 21 of the 2000 NASA Strategic Plan, in the section "Long Term Plans 2012-2025," is the statement, "Obtain x-ray images and composition of chemical elements created in supernovas, and directly measure the composition of the gas outside our solar system with an interstellar probe." See the 2000 NASA Strategic Plan at http://www.hq.nasa.gov/office/codez/plans/pl2000.pdf.

[2] According to the Voyager Web site, the escape speeds are 3.3 AU/yr for Voyager 2 and 3.6 AU/yr for Voyager 1. See http://voyager.jpl.nasa.gov/mission/interstellar.html.

[3] See also Liewer et al. (2001) and NASA's Interstellar Probe Web site at http://interstellar.jpl.nasa.gov/interstellar/probe/index.html.

[4] Solar sail technology development at NASA is summarized at http://solarsails.jpl.nasa.gov/index.html. Information about the New Millennium Program is available at http://nmp.jpl.nasa.gov/program/program.html.

demonstration flights are planned for 2004 by the Planetary Society[5] and for 2005 by a private consortium named Team Encounter.[6] A realistic roadmap for solar sail propulsion will most likely require at least one flight of a somewhat less ambitious mission like Solar Polar Imager or PASO (Particle Acceleration Solar Orbiter), for which the requirements on sail size and areal density are more easily achieved.[7] However, it should be recognized that large technical differences may exist between near- and long-term solar sail propulsion systems, and it is possible that evolving the technology from a smaller to a larger sail may not be straightforward.

With the announcement of NASA's 2003 budget, a new era in spacecraft propulsion began when NASA and the Department of Energy (DOE) embarked on a bold, new initiative named Project Prometheus, which will develop nuclear-powered propulsion capabilities that promise to revolutionize our ability to explore the solar system. Over the next decade it is expected that Project Prometheus will invest several billion dollars in the development of nuclear-electric propulsion (in which a nuclear reactor is used to power ion-drive engines), and it will also develop advanced radioisotope power systems that are needed for a number of deep-space missions. The first mission slated to use this new propulsion capability is the Jupiter Icy Moons Orbiter (JIMO), which will search for evidence of global subsurface oceans on Jupiter's three icy moons: Europa, Ganymede, and Callisto.[8] In addition to providing abundant electrical power for in-space propulsion, these new nuclear systems would provide revolutionary capabilities for powering instruments and for returning data. The science working team that is studying JIMO is also charged with identifying other mission concepts that could make use of this new capability.

Nuclear-electric propulsion is also potentially suited for accelerating Interstellar Probe to the required speeds, as illustrated in Figure 4.1, which compares the solar sail and NEP trajectories for two mission concepts studied in 1999 (JPL, 1999). NEP has been studied in the context of an interstellar probe mission at many times in the past due to its potential for this type of mission.[9] Note that while the solar sail achieves essentially all of its acceleration within the first few AU of the Sun, the NEP approach involves slow, continuous acceleration that can, in principle, eventually reach even greater speeds. Because the environment surrounding a nuclear reactor will likely interfere with some in situ measurements (plasma, magnetic fields, low-energy charged particles, and so on), it may be desirable to shut down the reactor periodically, to deploy a small, tethered instrument package, or to jettison the reactor once the required terminal velocity has been achieved (e.g., at 80 to 100 AU). At that point an advanced radioisotope power system could provide power for the spacecraft.[10]

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[5] The Planetary Society is developing and conducting a privately funded solar sail project with the Cosmos Studios. The spacecraft is being built in Russia by the Babakin Space Center under a contract to the society. It will also be launched and operated from Russia. See description of the project at http://www.planetary.org/solarsail/missions/planetary_solar_sai.html.

[6] See description at http://www.teamencounter.com/faq/about_us.asp#anchor1.

[7] PASO and Solar Polar Imager are discussed in the 2003 SEC Roadmap at http://sec.gsfc.nasa.gov/sec_roadmap.htm.

[8] JIMO is currently planned for a launch no earlier than 2012. See the NASA mission Web site at http://www.jpl.nasa.gov/jimo/.

[9] See Jaffe and Ivie (1979), Jaffe and Norton (1980), Jaffe et al. (1980), Jones and Sauer (1984), and Pawlik and Phillips (1977). See also Nock (1987).

[10] A fourth, low-thrust concept, not as well studied to date as the others, is radioisotope electric propulsion (Noble, 1999; Oleson et al., 2001). Ion thrusters are used as with NEP, but the power supply is based on radioisotope power systems, so that the mass is at a premium as with solar sailing and the ballistic approach.

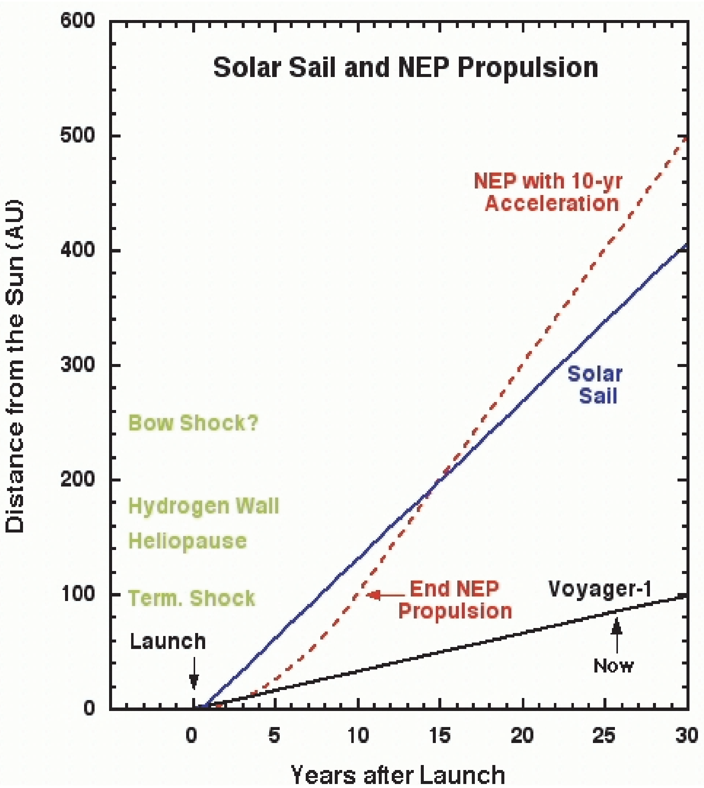

FIGURE 4.1 Possible Interstellar Probe trajectories based on nuclear-electric propulsion (NEP) and solar sail propulsion are compared with that of Voyager 1. It was assumed that NEP was terminated after 10 years. The estimated location of various heliospheric boundaries is also indicated. See *The Interstellar Probe Mission Architecture and Technology Report,* JPL-D-18410, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., October 1999, or http://interstellar.jpl.nasa.gov/interstellar/probe/index.html.

5

Strategic Directions

It was only in the mid-1990s that the fundamental role of neutral interstellar hydrogen in determining the global structure of the heliosphere was elucidated, and with it the prediction of the hydrogen wall—a completely new and somewhat unexpected result. With serendipitous discovery only a few years later (using a technique new to space physics as well) of the hydrogen wall and then, only a few more years after that, using the same Lyman-alpha absorption technique, the discovery of hydrogen walls about other stars in our galactic neighborhood and the associated discovery of stellar winds from solar-like stars, the field underwent dramatic change.

Coupled to the theoretical advances were the increasingly exciting observations being returned by the Voyager Interstellar Mission, Ulysses, ACE, and Wind—ranging from observations of cosmic rays signaling the approach to the termination shock, the remarkable radio emissions, the deceleration of the solar wind, and the important dynamical contribution of pickup ions to shock waves and pressure-balanced-structures, to the large- and small-scale magnetic fields responsible for guiding and scattering energetic particles, to name only a few. At the workshop, the greatest excitement was generated by the suggestion that the low-energy cosmic rays showed evidence that Voyager may have crossed the termination shock. Whether it indeed did is still under debate,[1] but the completely unexpected observations illustrate Voyager's capacity to surprise (Krimigis et al., 2003; McDonald et al., 2003; Burlaga et al., 2003). There is no doubt that the Voyagers will be returning results with a capacity to surprise and baffle for years to come as they explore the unknown.

To further the exploration of the outer heliosphere and to take advantage of the Voyagers, four strategic directions became clear as a result of the workshop discussions:

1. *Making use of existing assets*. The highest importance must be given to preserving current missions. The Voyager spacecraft, while clearly not designed to optimize the exploration of the heliospheric bound-

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[1] For a summary of the debate accessible to the general public, see http://www.sciencenews.org/articles/20040103/bob8.asp.

aries, nonetheless offer a once-in-a-lifetime opportunity to investigate in situ the most remote and inaccessible region of the heliosphere. This should be viewed as a 25+ year investment of NASA (and national) resources that could not be replicated for at least 20 years (assuming optimistically that development and launch of an interstellar probe could occur within 10 years and that the spacecraft would take only 10 years to travel ~100 AU). Instruments on Ulysses measure neutral interstellar material (He and dust[2]), provide an essential basis for understanding the three-dimensional structure of the global heliosphere, and, like ACE, measure interstellar pickup ions, cosmic rays, and the magnetic fields that enable transport of energetic particles. Other spacecraft, such as ACE, SOHO, and Wind, are needed as 1-AU monitors to explore the solar influence on the outer heliosphere boundaries, and to provide insights into interstellar composition.

2. *Continuing support of theory and modeling.* Although great progress has been made and key insights achieved, current theoretical understanding of the interaction of the solar wind with the LISM remains limited. The heliospheric boundary region is characterized by non-equilibrated distributions of neutral atoms over a large energy range. The mutual interaction and feedback of plasma and neutral interstellar and heliospheric atom populations, and the coupling of neutral atoms, pickup ions, solar and LISM plasma, solar and LISM magnetic fields, anomalous and galactic cosmic rays, and so on, make for an extraordinarily complex region to model theoretically. Further progress demands the development of more sophisticated models to capture the appropriate physics together with the development of three-dimensional, temporal numerical solutions to the models using realistic parameters.

To refine theoretical models will require both observational input and observational testing of theoretical predictions. Since only the Voyagers are providing (limited) in situ data in the vicinity of the solar wind boundaries, modelers need to explore alternative approaches to either constrain or validate their models. For example, greater use of remote sensing measurements (see, e.g., Gayley et al., 1997; Mueller et al., 2000; Wood et al., 2002b; Gruntman, 2001a,b) such as Lyman-alpha absorption and backscatter techniques, imaging with energetic neutral atoms, x-ray measurements, and extreme ultraviolet mapping of the heliopause, should be explored. Workshop participants noted the vital role of theoretical studies in making the best use of past, current, and near-future measurements from existing spacecraft, in developing scientific directions that would allow smaller SMEX and MIDEX[3] missions to be conceived and developed, and in providing the best scientific knowledge for optimizing an ambitious Interstellar Probe mission.

3. *Developing new outer heliosphere missions.* New missions that use current and moderately improved in situ techniques to conduct heliospheric studies from 1 to 3 AU and beyond should be developed. The possibilities include in situ studies (neutrals, pickup ions, anomalous and galactic cosmic rays) and remote observations. For example, technology for imaging the region of the termination shock and heliosheath remotely is steadily improving, with several laboratories now working on detector systems in this area. Imaging with energetic neutral atoms is another promising approach. Technology is available for making these measurements, but other issues, such as heliospheric background contributions, need to be addressed soon. Remote detection missions by spacecraft located within 1 to 3 AU could be accomplished within the MIDEX program (e.g., Interstellar Pathfinder; McComas et al., 2003) or the SMEX program (e.g., the Interstellar Boundary Explorer). For the interim period, this would complement current Voyager activities well. Other possibilities for remote observation involve the use of Lyman-alpha absorption and back-

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[2] The Cosmic Dust Analyser that is on board the Cassini spacecraft is also currently making dust measurements. Cassini is approaching Saturn and will be inserted into orbit around that planet on July 1, 2004.

[3] Information on NASA's Small Explorer and Medium-Class Explorer programs is available at http://explorers.gsfc.nasa.gov.

scatter techniques and extreme ultraviolet mapping of the heliopause; the first is possible at 1 AU with space-based spectroscopic telescopes. Cosmic rays (anomalous and galactic) and pickup ions continue to offer opportunities to probe both the LISM and the heliospheric boundaries.

4. *Preparing for Interstellar Probe.* Interstellar Probe will be a mission that captures the imagination of the public as it takes humanity's first steps into interstellar space. Scientifically, it will be breathtaking in scope; technologically, the mission will be extremely demanding, requiring very advanced propulsion systems and advanced data acquisition, processing, autonomy, and communication capabilities. Developing the required propulsion technology remains the primary technical challenge. At least three approaches—nuclear-electric propulsion, solar sail propulsion, and powered Sun-gravity assist—are well suited for and, in principle, capable of accelerating Interstellar Probe to the speeds needed to reach the heliopause within 15 years or less from launch.[4] However, as detailed in the text, none of these options are currently available and all present significant hurdles in their development. Because Interstellar Probe will require only a rather straightforward trajectory with little need for precise navigation, it could be regarded as an ideal demonstration of nuclear-electric propulsion or solar sailing. The optimal approach requires further study and involves trade-offs among science requirements, launch vehicles, technology development, and system runout cost.

Interstellar Probe will be one of the great NASA missions of the new millennium. Exploration of the vast new outer heliospheric frontier promises a rich dividend of scientific results and discoveries that will illuminate the way in which the Sun and the stars interact with our galaxy. With Interstellar Probe, we will ". . . slip the surly bonds of Earth,"[5] leave our local neighborhood, and begin the exploration of interstellar space.

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[4] Radioisotope electric propulsion is another propulsion option that should not be ruled out yet.

[5] From the poem "High Flight" by John Gillespie Magee, Jr. (killed in the Battle of Britain, age 19).

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Appendixes

A

Statement of Task

Background The NRC Solar and Space Physics Survey Committee has just published, "The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics." In addition, a NASA internal advisory committee has just completed a "Roadmap" for the Sun-Earth Connection, which is planning space missions as part of its Living With A Star and Solar-Terrestrial Probes programs. Richard Fisher, Director of NASA's Sun-Earth Connection program, and prominent members of the solar and space physics community (e.g., Dr. Lennard Fisk, Professor and former NASA Associate Administrator for Space Science) are concerned that exploration of the outer heliosphere is the least thoroughly developed aspect of either strategy.

The NASA Roadmap and NRC Decadal Survey emphasize that the baseline mission to explore the outer heliosphere—"Interstellar Probe" —is very exciting; however, its success requires significant technical developments, especially in the propulsion area. The recent NASA/OMB decision to seek funding for nuclear propulsion does not change the timetable for Interstellar Probe, but does indicate a higher probability that such a mission can be accomplished. In view of the long lead time to develop needed mission technologies, NASA is seeking a sampling of the current state of research in this field and the likely notable scientific questions that are likely to emerge over the next few years. Currently, the only NASA probes in the vicinity of this region are the Voyager spacecraft.

Plan The Space Studies Board Committee on Solar and Space Physics will organize a workshop to explore issues related to NASA's exploration of the outer heliosphere. Four areas will be targeted for special emphasis:

1. *The role of NASA's Voyager 1 and 2 spacecraft*. These missions should probably last another 15 years with V-1 reaching 140 astronomical units (AU). The magnetometer experiment should return to complete coverage after the spacecraft crosses the termination shock. One can regard the Voyagers as reasonably well instrumented for this portion of the mission. However, there are concerns regarding support from NASA Headquarters and the availability of continuing data coverage from the Deep Space Network of receivers.

2. *Imaging the region of the termination shock and heliosheath*. This capability is steadily increasing with several laboratories now working on experiments in this area. Imaging of energetic neutral atoms is a very promising area, with the technology probably outstripping theory at present. Such a mission could probably be accomplished within NASA's MIDEX Program. For the interim period this might complement on-going Voyager activities well. Other remote observation possibilities include Lyman-alpha absorption and backscatter.

3. *Theoretical and modeling studies*. Continuing studies are still needed in this area as illustrated by the numerous unsolved problems that Voyager and Ulysses continue to present. As in 2), above, theoretical studies lag observations substantially.

4. *Interstellar Probe*. Mission technical requirements, payload, feasibility, etc., with a focus on propulsion issues/nuclear electric power.

These areas will be explored in a 1.5-day workshop that would coincide with a regularly scheduled meeting of the committee. The results of the workshop will be published in a summary report that will be written by the committee; the report will *not* include recommendations.

Schedule The committee will hold a 1.5 day workshop in late Spring/early Summer 2003. Writing and editing of the workshop report will be completed by December 31, 2003.

B

Workshop Agenda and Participants

AGENDA

Tuesday, May 6, 2003

8:15 a.m. Introductory Remarks
Gary Zank, University of California, Riverside

Session 1: The Role of the Voyager Interstellar Missions—Convener, Edward Stone

8:30 Overview of the Voyager Spacecraft
Edward Stone, California Institute of Technology

9:00 Plasma Instrument: Voyager
Edward Stone, California Institute of Technology

9:30 Magnetic Field: Voyager
Norman Ness, Bartol Research Institute

10:00 Low Energy Charged Particles: Voyager
Tom Krimigis, Johns Hopkins University

10:30 Break

10:45 Cosmic Rays: Voyager
Alan Cummings, University of Hull

11:15 Plasma/Radio Waves: Voyager
Donald Gurnett, University of Iowa

Session 2: The Role of Theory—Conveners, Gary Zank and Frank McDonald

11:45 Overview: Theory
Gary Zank, University of California, Riverside

12:15 p.m. Lunch

1:15 Cosmic Rays: Theory
J. Randy Jokipii, University of Arizona

1:45 Particle Injection and Acceleration at the TS: Theory
Jakobus le Roux, University of California, Riverside

2:15 ISM: Theory
Priscilla C. Frisch, University of Chicago

2:45 Break

3:00 Neutral Atoms, Heavy Ions: Theory
Hans-Reinhard Müller, Bartol Research Institute

3:30 Magnetic Structure in the Heliosheath: Theory
Paulett Liewer, NASA Jet Propulsion Laboratory

Session 3: Imaging of Heliospheric Boundaries—Conveners, Len Fisk and Thomas Zurbuchen

4:00 Microstructure of the Termination Shock: Theory
Joe Giacalone, University of Arizona

4:30 Non-Standard Models of the Heliospheric Interface
Vladimir Florinski, University of California, Riverside

5:00 Break

5:30 Reception

Wednesday, May 7, 2003

Session 3: Imaging of Heliospheric Boundaries—Conveners, Len Fisk and Thomas Zurbuchen (Cont'd)

8:30 a.m. PUIs + Superthermal Ions
Len Fisk, University of Michigan

9:00 Low Energy Neutral Atoms + Superthermal Ions
Eberhard Moebius, University of New Hampshire

9:30	EUV Backscatter Observations *John Vallerga, University of California, Berkeley*
10:00	Break
10:15	X-ray Imaging *Tom Cravens, University of Kansas*
10:45	Lyman-alpha Absorption *Brian Wood, Joint Institute for Laboratory Astrophysics*
11:15	3D Solar Wind Mapping in EUV *Michael Gruntman, University of Southern California*
11:45	HENA/IMAGE Emission from the TS *Michael Gruntman, University of Southern California*
12:00 noon	Lunch

Session 4: Interstellar Probe—Conveners, Richard Mewaldt and Herb Funsten

1:00 p.m.	Science Objectives: Outer Heliospheric Missions *Richard Mewaldt, California Institute of Technology*
1:30	Outer Solar System Science *Renu Malhotra, University of Arizona*
1:50	Mission Design Issues *Juan Ayon, NASA Jet Propulsion Laboratory*
2:10	Nuclear-Electric Propulsion *Garry Burdick, NASA Jet Propulsion Laboratory*
2:30	The Solar Probe Approach to ISP *Ralph McNutt, Johns Hopkins University*
2:50	Break
3:10	NASA and the Exploration of the Outer Heliosphere and the Local ISM *Eric Christian, NASA Headquarters*
3:30	Solar Sail Propulsion *Juan Ayon, NASA Jet Propulsion Laboratory*
5:00	Adjourn

PARTICIPANTS

Juan Ayon, NASA Jet Propulsion Laboratory
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Peter Chi, University of California, Los Angeles
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C

Acronyms and Abbreviations

ACE	Advanced Composition Explorer
ACR	anomalous cosmic ray
AU	astronomical unit—mean distance of Earth from the Sun
CCD	charge-coupled device
CIR	co-rotating interaction region
DOE	Department of Energy
ENA	energetic neutral atom
EUV	extreme ultraviolet
GAS	Ulysses Interstellar Neutral Gas Experiment
GCR	galactic cosmic ray
GMIR	global merged interaction region
HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
IMAGE	Imager for Magnetosphere to Aurora Global Exploration
IMF	interplanetary magnetic field
JIMO	Jupiter Icy Moons Orbiter
LENA	Low-Energy Neutral Atom
LIC	local interstellar cloud
LISM	local interstellar medium
MHD	magnetohydrodynamic
MIDEX	Medium-Class Explorer
NASA	National Aeronautics and Space Administration
NEP	nuclear-electric propulsion

NRC	National Research Council
OSS	Office of Space Science
PASO	Particle Acceleration Solar Orbiter
SEC	Sun-Earth Connection
SMEX	Small Explorer
SOHO	Solar and Heliospheric Observatory
SWAN	Solar Wind Anisotropies
SWICS	Solar Wind Ionic Composition Spectrometer
SWIMS	Solar Wind Ion Mass Spectrometer
TWINS	Two Wide-Angle Imaging Neutral-Atom Spectrometers