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

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Abstract. NASA's Interstellar Probe Mission, which will travel to 200-400 AU using solar sail propulsion, will be the first spacecraft specifically designed to explore the outer solar system and sample the nearby interstellar medium. During the spring of 1999, NASA's Interstellar Probe Science and Technology Definition Team[*] developed a concept for a mission to be propelled by a solar sail that would travel to >200 AU in 15 years. A 400-m diameter solar sail accelerates the spacecraft to ~15 AU/year, approximately 5 times the speed of the Voyager spacecraft. After jettisoning the sail, the spacecraft coasts to 200-400 AU, exploring the Kuiper Belt, the boundaries of the heliosphere, and the nearby interstellar medium. We discuss the scientific goals, mission concept, strawman payload, and technology requirements for this very challenging mission.

INTRODUCTION

NASA's Interstellar Probe mission will be the first spacecraft specifically designed to escape the bubble of solar wind that surrounds the solar system and begin exploring the space between the stars. As the solar wind flows out through the solar system, it pushes against the plasma, gas and fields of the interstellar medium (ISM) forming a large bubble called the heliosphere that shields our solar system from the interstellar plasma and magnetic fields, and most of the cosmic rays and dust that comprise the local galactic neighborhood (Figure 1). Outside of this bubble is a new, unexplored region about which we know very little. Voyager 1, now at 78 AU, should soon reach the first boundary in this complex structure, the solar wind termination shock, where the solar wind is expected to make a transition to subsonic flow when it can no longer hold off the pressure of the ISM. Beyond the termination shock lies the heliopause - the boundary between solar wind and interstellar plasma. Several recent estimates place the termination shock at 80 to 100 AU from the Sun, with the heliopause at 120 to 150 AU. The Interstellar Probe mission would be designed to cross the termination shock and heliopause and make a significant penetration into nearby interstellar space, with a minimum goal of reaching 200 AU and sufficient consumables to last to 400 AU. The 150 kg spacecraft includes a 25 kg scientific payload composed of a suite of advanced, low-power instruments designed to measure the detailed properties of the plasma, neutral atoms, energetic particles, magnetic fields, and dust in the outer heliosphere and nearby ISM.

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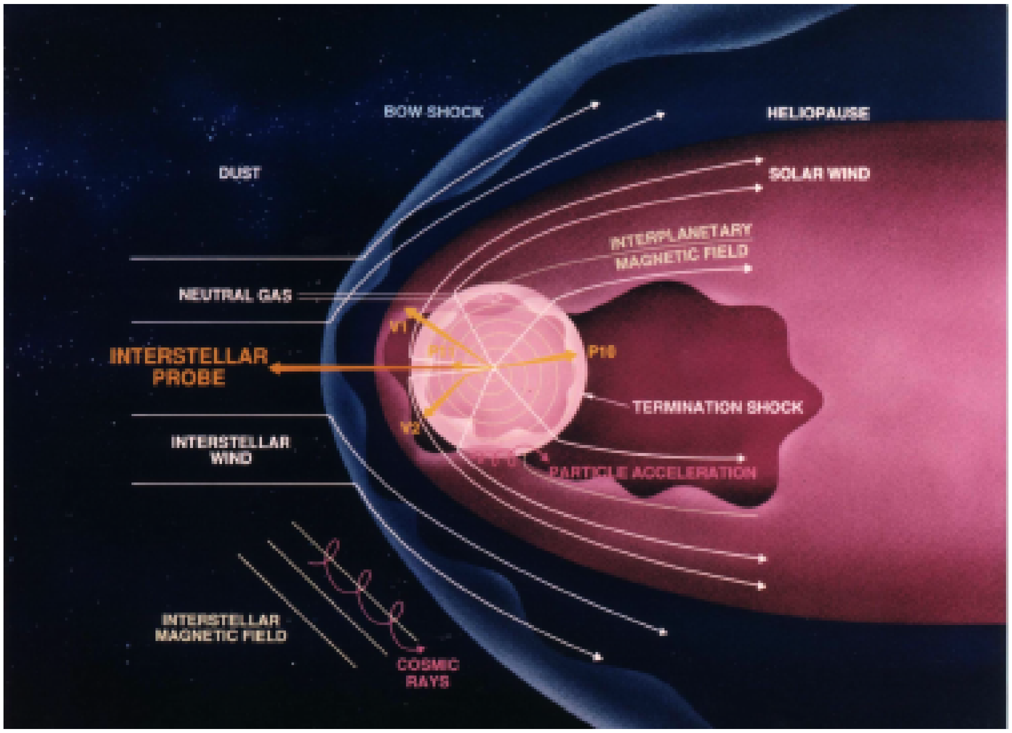

FIGURE 1. Schematic of the global heliosphere created by the supersonic solar wind diverting the interstellar flow around the Sun. The interstellar ions and neutrals flow at 25 km/s relative to the Sun. The solar wind, flowing outward at 400-800 km/s, makes a transition to subsonic flow at the termination 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 fields. There may or may not be a bow shock in the interstellar medium in front of the heliosphere. Of the four earlier spacecraft, only Voyager 1 & 2 are still operating.

Figure 2 illustrates the solar system and nearby interstellar medium on a logarithmic scale extending from <1 to 10^6 AU. Threaded through the boundaries of the heliosphere is the Kuiper Belt – the source of short period comets. The nearest edge of the low-density interstellar cloud that presently surrounds our solar system is thought to be several thousand AU away. The Oort cloud is a spherical shell of comets extending from <10,000 to ~100,000 AU that marks the edge of the our Sun's sphere of gravitational influence. The best known member of our nearest star system, Alpha-Centauri, lies considerably further away at ~300,000 AU. Interstellar Probe is to be man's first spacecraft to exit the heliosphere and begin the in-situ exploration of the nearby interstellar medium. The star Epsion Eridani at 10.5 light years from Earth is the nearest star that shows evidence for a planetary system.

The scientific importance of sending a spacecraft to the nearby interstellar medium has been recognized by a number of studies by both NASA and the National Academy of Sciences (see, e.g., Neugebauer 1995), and there have been a number of previous studies of mission concepts with related goals. More than two decades ago Jaffe et al. (1977) described an Interstellar Precursor Mission [see also Jaffe and Ivie (1979)]. A decade later JPL studied a mission concept called "TAU" that would travel to a Thousand Astronomical Units powered by a nuclear electric propulsion (Ethegaray et al., 1987, Nock 1988). A 1990 study (Holzer et al., 1990) envisioned a 1000 kg spacecraft that was to acquire data out to ~200 AU, exiting the solar system at ~10 AU/year using chemical propulsion coupled with impulsive maneuvers near the Sun. In a 1995 study of a smaller interstellar probe (Mewaldt et al., 1995), a ~200 kg spacecraft was to reach exit velocities of ~6 to 14 AU/year, depending on launch vehicle and trajectory, using chemical propulsion with planetary gravity assists or impulsive maneuvers near the Sun. Recent technological advances, notably lighter reflective sail materials (Garner et al., 1999; Garner and Leipold, 2000) and lighter spacecraft designs, now make it feasible to accomplish essentially the same mission using a solar sail to accelerate a 150 kg spacecraft.

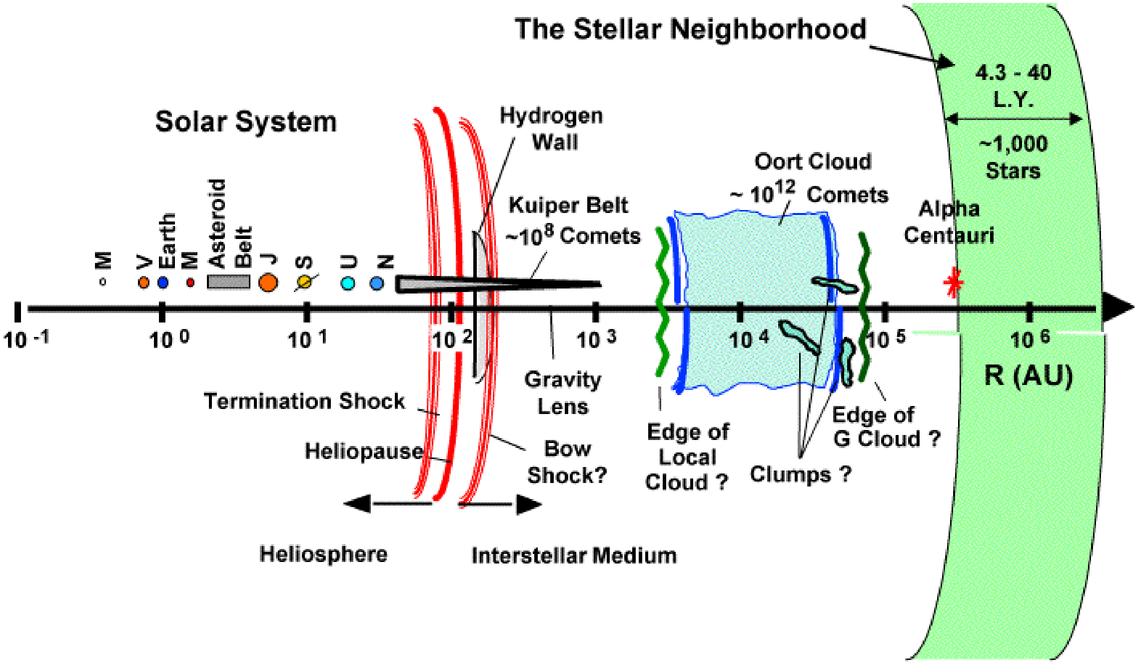

FIGURE 2. The local interstellar neighborhood, shown on a logarithmic scale from the Sun to 10^6 AU.

Given the recognized scientific importance of a mission to the nearby interstellar medium, one can ask why none of these concepts has moved forward into development. There are probably two principal reasons. First, our understanding of how far it is necessary to go to escape the heliosphere and enter interstellar space has, until recently, been reasonably uncertain, making it difficult to specify the requirements for propulsion, communications, and mission lifetime. To a large extent this uncertainty has been removed during the last decade, and a variety of approaches now generally agree that the distance to the termination shock is between 80 and 100 AU (see, e.g., the summary by Stone and Cummings, 2000), with the heliopause approximately 40 to 50 AU beyond. A more fundamental problem is that this mission will clearly take a long time to complete using currently available propulsion technology. For example, a mission duration of ~20 to 40 years is required with currently available rockets fueled by chemical propulsion, even when combined with planetary and/or solar gravity assists (see, e.g., Mewaldt et al. 1995). As a result, Interstellar Probe is dependent on advanced propulsion technology.

The mission concept presented here was formulated by NASA's Interstellar Probe Science and Technology Definition Team (ISPSTDT) under sponsorship of the NASA Office of Space Science (OSS). The primary goal of this team was to develop a mission concept for the Sun-Earth-Connection Roadmap (http://www.lmsal.com/sec), as part of NASA's strategic planning activities. As a result of these activities an interstellar probe mission is now included in the NASA's new Space Science Enterprise Strategic Plan scheduled for release in September 2000. A summary of the science goals and mission concept can be found at http://interstellar.jpl.nasa.gov.

SCIENCE OBJECTIVES

Interstellar Probe's unique voyage from Earth to beyond 200 AU will enable the first comprehensive measurements of plasma, neutrals, dust, magnetic fields, energetic particles, cosmic rays, and infrared emission from the outer solar system, though the boundaries of the heliosphere, and on into the ISM. This will allow the mission to address key questions about the distribution of matter in the outer solar system, the processes by which the Sun interacts with the galaxy, and the nature and properties of the nearby galactic medium.

The principal scientific objectives of the Interstellar Probe mission would be to:

- Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our Galaxy and the Universe;
- Explore the influence of the interstellar medium on the solar system, its dynamics, and its evolution;
- Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment;
- Explore the outer solar system in search of clues to its origin, and to the nature of other planetary systems.

We describe below examples of the scientific issues that could be addressed.

The Nearby Interstellar Medium

Our Sun is thought to be located near the edge of a low-density interstellar cloud (~0.3 $cm\text{-}^{3}$), often referred to as the local interstellar cloud (LIC), that is made up of material blowing from the direction of star-forming regions in Scorpius and Centaurus. Present knowledge of the ISM is based on astronomical observations that average over long lines of site, measurements of sunlight resonantly scattered back by interstellar H and He, and on *in situ* measurements of neutral gas and dust that penetrate the heliosphere. Direct observations of our local cloud by Interstellar Probe will provide a unique opportunity to derive the physical properties of a sample of interstellar material, free from uncertainties that plague the interpretation of data acquired over astronomical lines-of-sight, and from uncertainties arising from the exclusion of plasma, small dust particles and low energy cosmic rays from the heliosphere. Direct measurements would be made of the elemental and isotopic composition of the ionized and neutral components of the interstellar gas and of low-energy particle components, and of the composition and size distribution of interstellar dust. These measurements would provide a benchmark for comparison with solar system abundances (representative of the presolar nebula) and with abundances from more distant galactic regions, thereby providing important constraints on theories of galactic chemical evolution.

Interstellar Probe will also of measure cosmic ray nuclei and electrons, free from the influence of the heliosphere, and investigate astrophysical processes that include acceleration by supernova shock waves, interstellar radio and x-ray emission, recent nucleosynthesis, and the heating and dynamics of the interstellar medium. Little is known about the properties of magnetic field in the local cloud or in the region beyond the termination shock. Interstellar Probe will make the first in situ measurements of interstellar magnetic fields and of the density, temperature, and ionization state of the interstellar gas, including studies of their variations over a variety of spatial scales. The possibility of identifying organic matter in the outer solar system and ISM is also an exciting possibility that is under investigation.

The Interaction between the Interstellar Medium and the Solar Wind

The solar wind and the interstellar medium interact to create the global heliosphere, shown schematically in Fig. 1. The size of the heliosphere is determined by the balance between the solar wind ram and the interstellar pressure. There are presently no direct measurements of the size and structure of the heliosphere and our present understanding is based on theory and modeling, constrained by a few key measurements. The Voyager spacecraft have detected radio emissions that are thought to be caused by interplanetary shock waves hitting the denser interstellar plasma. Voyager 1 should soon reach the termination shock, providing a first direct test of our current understanding of heliospheric structure, although some of the Voyager instruments were not designed to explore the boundaries of the heliosphere and interstellar medium. Interstellar Probe’s enhanced capabilities and lifetime will greatly extend Voyager’s exploratory studies, answering answer questions relating to how the ISM influences the solar system and how the solar system influences the ISM.

The termination shock is a powerful accelerator that accelerates particles to energies as high as 1 GeV. *In situ* studies of shock structure, plasma heating, and acceleration processes at the termination shock will serve as a model for other astrophysical shocks. Past the termination shock, in the region called the heliosheath, the solar wind flow is turned to match the flow of the diverted interstellar plasma, as illustrated Fig. 1. The spiraling solar magnetic field, frozen into the solar wind, is swept back with this flow. Depending on the unknown interstellar magnetic field strength, there may or may not be a bow shock created in the interstellar medium ahead of the nose of the heliosphere. Energetic ions created by charge exchange in the heliosheath can be used to provide an image of the 3D structure of the heliosphere. Charge-exchange collisions lead to a weak coupling between the neutral and ionized hydrogen in the interstellar medium causing a pile-up 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 of the dust, plasma, fields and flows to answer questions regarding the size, structure and dynamics of the heliosphere and the processes occurring at the boundaries. Our heliosphere will serve as an example of how a star interacts with its environment.

The Outer Solar System

Some 4.6 billion years ago our solar system condensed out of the interstellar medium as the end product of a common astrophysical process of stellar system formation from a protoplanetary disk nebula. Collisions play a central role in the formation and evolution of planetary systems, and the present interplanetary dust population is a result of collisional processes occurring in the solar system. Interstellar Probe will provide in situ and remote sensing surveys of both interplanetary and interstellar dust in the heliosphere and the ISM, determining the mass and orbital distributions as well as composition. These studies will help us understand the origin and nature of our solar system as well as other planetary systems. Interstellar Probe can address the key question of the radial extent of the primordial solar nebula. This can be accomplished by measuring the variation with heliocentric radius of the number of small bodies in the Kuiper Belt, or, less directly, by measuring the distribution of dust grains derived from Kuiper Belt objects. Understanding the properties of the Kuiper Belt will aid the interpretation of planet-forming or planet-harboring disks in other stellar systems.

With a suitable instrument on Interstellar Probe, it would be possible to search for organic material in the outer solar system, as well as the nearby ISM, in order to address questions about the nature and chemical evolution of this material. Organic material can be found in our solar system (in asteroids, comets, meteorites and dust) as well as in the interstellar medium. Amino acids have been found in meteorites, but it is not known if they exist in the ISM. Organic material from both small bodies and the interstellar medium are known to reach Earth, but their possible role in the emergence of life on our planet is uncertain. The development of instrumentation to make such measurements is one of the challenges for the ISP payload.

The cosmic infrared background (CIRB) spectrum provides information on how the first stars formed and how early the elements were formed by nucleosynthesis. The CIRB is the integrated light from all stars and galaxies that cannot be resolved into individual objects. COBE, the Cosmic Background Explorer, established limits on the energy released by all stars since the beginning of time by measuring the CIRB at wavelengths longer than 140 microns, but it could not observe at shorter wavelengths because of the very bright foreground emission from zodiacal light. The zodiacal dust decreases in density with heliocentric radius and beyond 10 AU or so Interstellar Probe may be able to detect the CIRB at wavelengths below 140 microns.

MISSION REQUIREMENTS

The mission requirements for Interstellar Probe were defined by the ISPSTDT after considerable discussion. It was decided that a necessary requirement for meeting the science goals is to cross the heliopause and make a significant penetration into the interstellar medium. Taking into account current knowledge of the size of the heliosphere, the probe should be capable of acquiring data out to a minimum distance of 200 AU, with a goal of eventually reaching ~400 AU. The ISPSTDT further decided that the spacecraft should reach 200 AU within 15 years or less, which requires spacecraft velocities several times that of the Voyagers. The trajectory should aim for the nose of the heliosphere, a direction that provides the shortest route to the interstellar medium and that also benefits studies of the in-flowing interstellar plasma and neutral particle populations. The spacecraft should spin about an axis parallel to the direction of flight to allow the in situ instruments to sample particle, plasma, and magnetic field distributions and to allow the remote-sensing instruments to scan the sky. A total of 25 kg and 20 W are allocated for the scientific payload. Science and engineering data are to be collected continuously at an average bit rate of 30 bps out to at least 200 AU.

MISSION CONCEPT

By far the biggest challenge presented by the Mission Requirements is the requirement to reach 200 AU within 15 years. Among the variety of propulsion options considered by the

ISPSTDT, only solar sails and nuclear electric propulsion appeared to be capable of meeting this requirement. Solar Sail propulsion was selected because: a) it was more compatible the requirement to make continuous measurements of particles and fields in the outer heliosphere (the a solar sail can be jettisoned, but a nuclear electric system must continue for many years); b) the size and cost of sail systems were judged to be more in keeping with cost guidelines for the SEC road-mapping activity; and c) there is considerable interest in solar sails for other possible future missions (see, e.g., Mulligan et al. 2000, this proceedings).

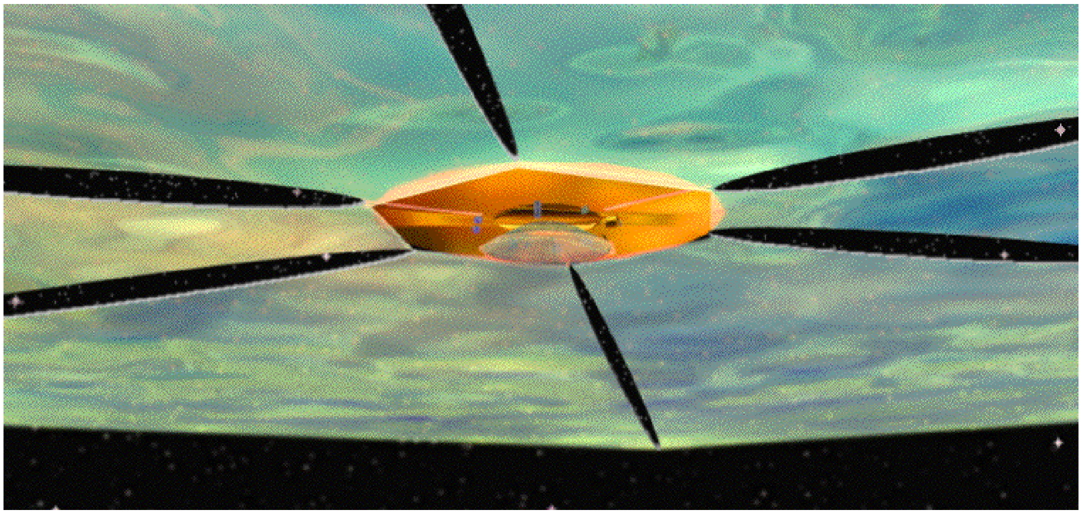

FIGURE 3. Spacecraft in sailing configuration. The spacecraft is supported by three struts in an 11-m hole in the center of the solar sail. A gold sun-shield covers the hole. Sail control is achieved by moving the spacecraft with respect to the center of mass of the sail by changing the length of the three struts. The gold is a sun-shield covering the hole.

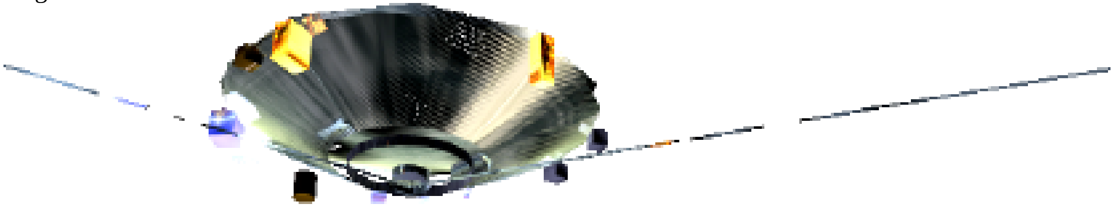

FIGURE 4. The spacecraft. The 2.7-m dish antenna serves as the main support structure. The instruments are attached near the rim of the antenna structure. The magnetometer boom and a dipole antenna for the plasma wave instrument are also visible

The mission and spacecraft concept developed by the mission design team at JPL developed met the requirements outlined above. The resulting spacecraft in sailing configuration is shown in Figure 3; the spacecraft is attached inside an 11-m hole in a 400-m diameter hexagonal solar sail. Sail control is achieved by offsetting the spacecraft with respect to the center-of-mass of the sail by varying the length of the 3 struts supporting the spacecraft. The instruments are placed around the rim of a 2.7-m dish antenna, which also functions as the main support structure for the spacecraft (Figure 4). The sail is deployed and stabilized by rotation; a number of mechanisms used to provide the initial spin up and deployment of the sail are jettisoned after sail deployment to reduce the accelerated mass.

The spacecraft is designed to reach 200 AU in ~15 years with enough consumables (power, fuel) to last to 400 AU (~30 years). Science and engineering data are gathered at an average rate of 30 bps. The telecom system uses Ka band to communicate with the Deep Space Network; data is stored and dumped using ~1 pass per week. The antenna is limited to 2.7 m to fit in the shroud of a Delta II launch vehicle. A downlink data rate of 350 bps at 200 AU is achieved with a 220 W transmitter.

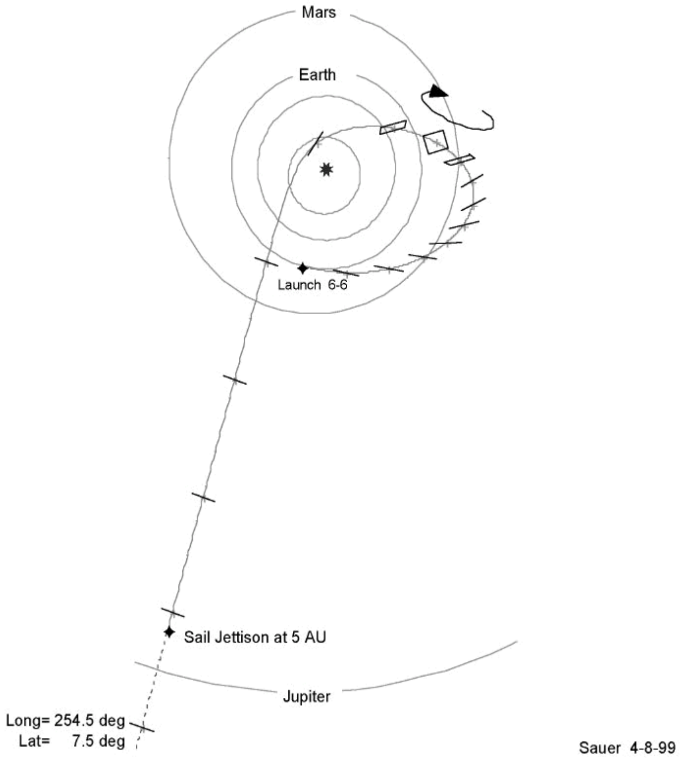

FIGURE 5. Interstellar Probe trajectory using a solar sail to reach a final velocity of 15 AU/year. The trajectory is towards the nose of the heliosphere, the shortest route to the interstellar medium. The orientation of the sail to achieve the proper thrust vector is also shown.

The total spacecraft mass (excluding sail) is ~150 kg including the instruments (Table 1). To achieve the 15 AU/year exit velocity, a solar sail with 1 g/m^2 areal density (sail material plus support structure) and a radius of ~200 m is needed. The total accelerated mass (spacecraft plus sail system) is ~246 kg. The spacecraft initially goes in to 0.25 AU to obtain increased radiation pressure before heading out towards the nose of the heliosphere; the trajectory is shown in Fig. 5. The sail is jettisoned at ~5 AU when the further acceleration from radiation pressure becomes negligible, thereby avoiding potential interference with the instruments. Fig. 5 also shows the orientation of the sail relative to the Sun to obtain the proper thrust vector. The total ΔV achieved is 70 km/s.

SCIENTIFIC PAYLOAD

To achieve the broad scientific objectives of this mission, the strawman scientific payload (Table 1) includes an advanced set of miniaturized, low-power instruments specifically designed to make comprehensive, in situ studies of the plasma, energetic particles, fields, and dust in the outer heliosphere and nearby ISM. They include a comprehensive suite of neutral and charged particle instruments, including a solar wind and interstellar ion and electron detector, a spectrometer to measure the elemental and isotopic composition of pickup and interstellar ions, an interstellar neutral atom spectrometer, and a detector for suprathermal ions and electrons. There is one cosmic ray instrument for H, He, electrons and positrons, and one to measure the elemental and isotopic composition of heavier anomalous and galactic cosmic rays up through the iron group. The magnetometer will make the first direct measurements of the magnetic fields in the ISM, and the plasma and radio wave detector will measure fluctuations in the electric and magnetic fields created by plasma processes and by interactions and instabilities in the heliospheric boundaries and beyond. As the spacecraft transits the inner solar system to the ISM the energetic neutral atom (ENA) imager will map the 3D structure of the termination shock and the UV photometer will probe the structure of the hydrogen wall, a localized region of increased neutral hydrogen density just beyond the heliopause. Interplanetary and interstellar dust will be studied with in situ measurements of the dust distribution and composition and by a remote sensing infrared photometer. The infrared detector will also detect galactic and cosmic infrared emission. These instruments will have capabilities that are generally far superior to those of the Voyagers.

TABLE 1. Strawman Instrument Payload

Instrument	**Additional Candidates**
Magnetometer	Kuiper Belt Imager
Plasma and Radio Waves	New Concept Molecular Analyzer
Solar Wind/Interstellar Plasma/Electrons	Suprathermal Ion Charge-States
Pickup and Interstellar Ion Composition	Cosmic Ray Antiprotons
Interstellar Neutral Atoms	
Suprathermal Ions/Electrons	
Cosmic Ray H, He, Electrons, Positrons	**Resource Requirements**
Anomalous & Galactic Cosmic Ray Composition	• Mass: 25 kg
Dust Composition	• Bit Rate: 25 bps
Infrared Instrument	• Power 20 W
Energetic Neutral Atom (ENA) Imaging	
UV Photometer	

A partial list of additional candidate instruments in Table 1 includes a small CCD telescope to survey kilometer-size Kuiper belt objects, which would be expected to detect as many as 10^4 to 10^5 new objects in the region from ~40 to ~200 AU. The cosmic ray antiproton instrument would search for low-energy antiprotons that may originate in primordial black holes, or in the annihilation of weakly interacting massive particles (WIMPs) that may comprise the unobserved dark matter in our Galaxy. Measurements of the charge states of suprathermal ions are key to identifying the source of material that is accelerated at the solar wind termination shock. The possibility of developing instrumentation to identify organic material in the outer solar system and the interstellar medium is also under study.

TECHNOLOGY DEVELOPMENT

Although most of the instruments required for this mission have considerable flight heritage and could be built today, all would benefit from new technology in order to optimize the scientific return within the very restrictive weight and power resources. In addition, exciting instrument concepts such as the molecular analyzer will require considerable development.

The mission concept presented here also assumes a number of developments in spacecraft systems, including low-power avionics, advanced power systems, and phased-array Ka-band telecommunications. Other future NASA missions also rely on these technology developments. The baseline spacecraft concept described here uses three 8.5 kG Advanced Radioisotope Power System (ARPS) units with Alkali Metal Thermal-to-Electric Converters (AMTEC) (see e.g. Shock et al., 1999). Each initially delivers 106 W, but degrades at approximates 1 W/year, yielding 228 W after 30 years. The AMTEC ARPS is under development by NASA and DOE and is expected to be available by 2003, but additional time may be necessary to project a 30 year lifetime with confidence. The Stirling cycle ARPS (Or et al., 1999), another ARPS under development that is baselined for the Europa Orbiter mission, is not suitable for the current ISP mission concept for two reasons. (a) The Stirling cycle ARPS is too heavy for the ISP solar sail mission concept (at least twice the mass per kilogram), and (b) this ARPS uses a reciprocating dynamic engine with a permanent magnet linear alternator, which may interfere with the magnetometer and plasma wave instruments.

The most critical technology needed to carry out the mission described here is, of course, solar sail propulsion. Although solar sails have been studied extensively, (e.g., Wright 1992), they have never flown in space (although a large ~20 m sail with ~22 g/m^2 areal density was deployed on MIR). Indeed, spacecraft velocities of the kind envisioned here will require rather advanced sails, necessitating new, light-weight reflective material and developments in sail packaging, deployment and control.

Recently, major advances have been made in sail material, packaging and deployment. In December 1999, a 20m by 20m aluminized plastic sail was deployed in a ground demonstration technology test at DLR in Cologne, Germany (see http://solarsystem.dlr.de/MT/solarsail/new.shtml). The 4-quadrant sail of approximately 12 g/m^2 was supported by carbon trusses. Advances in sail materials include the development of a new porous carbon microtruss fabrics by Energy Science Laboratories Inc. (ELSI). The fabrics, made of 10 micron carbon fibers, are stiff and easily handled for coating. Reflective coatings have been applied to carbon microtruss fabrics of less than 10 g/m^2; ELSI had made fabrics with areal densities down to 1 g/m^2 (Garner and Leipold, 2000).

The developments in solar sail technology will have to be tested in one or more flight demonstrations before a 400-m sail with an areal density of ~1 g/m^2 will be ready for flight, requiring an aggressive solar-sail development program (see, e.g., Wallace, 1999). Fortunately, there are also a large number of other missions that could benefit from solar-sail propulsion (see, e.g., Mulligan et al., these proceedings). If this program is successful, launch could be as early as 2010, and Interstellar Probe can serve as the first step in a more ambitious program to explore the outer solar system and nearby galactic neighborhood.

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