



NASA's Interstellar Probe Mission

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Abstract. NASA's Interstellar Probe will be the first spacecraft designed to explore the nearby interstellar medium and its interaction with our solar system. As envisioned by NASA's Interstellar Probe Science and Technology Definition Team, the spacecraft will be propelled by a solar sail to reach >200 AU in 15 years. Interstellar Probe will investigate how the Sun interacts with its environment and will directly measure the properties and composition of the dust, neutrals and plasma of the local interstellar material which surrounds the solar system. In the mission concept developed in the spring of 1999, a 400-m diameter solar sail accelerates the spacecraft to ~15 AU/year, roughly 5 times the speed of Voyager 1&2. The sail is used to first bring the spacecraft in to ~0.25 AU to increase the radiation pressure before heading out in the interstellar upwind direction. After jettisoning the sail at ~5 AU, the spacecraft coasts to 200-400 AU, exploring the Kuiper Belt, the boundaries of the heliosphere, and the nearby interstellar medium.

INTRODUCTION

Robotic exploration of our nearby galactic neighborhood will be one of the first great endeavors of the new millennium. NASA's Interstellar Probe mission, which will travel to 200-400 AU, will be the first spacecraft designed to travel beyond the solar system and sample the nearby interstellar medium. On its way, Interstellar Probe will explore the boundaries of the "heliosphere" -- the bubble in the interstellar medium that surrounds the Sun. The heliosphere is created by the solar wind plasma, which emanates from the corona and expands supersonically throughout and beyond the solar system. The interaction between the solar wind, flowing radially outward at 400-800 km/sec, and the local interstellar material, flowing at ~25 km/sec, creates a complex structure extending perhaps 200-300 AU in the upstream (towards the local interstellar flow) direction and thousands of AU tailward (Fig. 1). Voyager 1&2, now at approximately 76 and 60 AU respectively, should soon reach the first boundary in this complex structure, the solar wind termination shock, where the solar wind makes a transition from supersonic to subsonic flow. Beyond the termination shock lies the heliopause, which is the boundary between solar wind and interstellar plasma. The heliosphere shields the solar system from the plasma, energetic particles, small dust, and fields of the interstellar medium. To observe these directly it is necessary to go beyond the heliopause. Several recent estimates place the distance to the termination shock at ~80 to 100 AU, with the heliopause at ~120 to 150 AU. The Interstellar Probe Mission would be designed to cross the solar wind termination shock and heliopause and make a significant penetration into nearby interstellar space, with a minimum goal of reaching 200 AU, but with sufficient consumables (power, fuel) to last to 400 AU. The 150-kg spacecraft includes a 25-kg instrument payload.

The mission concept presented here was formulated by NASA's Interstellar Probe Science and Technology Definition Team (ISPSTDT) during the spring and summer of 1999 under sponsorship of the NASA Office of Space Science. 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. The resulting concept builds on a number of previous studies. In a 1990 study (Holzer et al., 1990), a 1000 kg spacecraft 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) and lighter spacecraft designs, now make it feasible to accomplish essentially the same mission using a solar sail to accelerate a 150 kg spacecraft to ~15 AU/year, allowing the mission to reach ~200 AU in ~15 years and ~400 AU in ~30 years by following the trajectory in Fig. 2.

SCIENCE OBJECTIVES AND SCIENTIFIC PAYLOAD

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, through the boundaries of the heliosphere, and on into the ISM. This will allow the mission to address key

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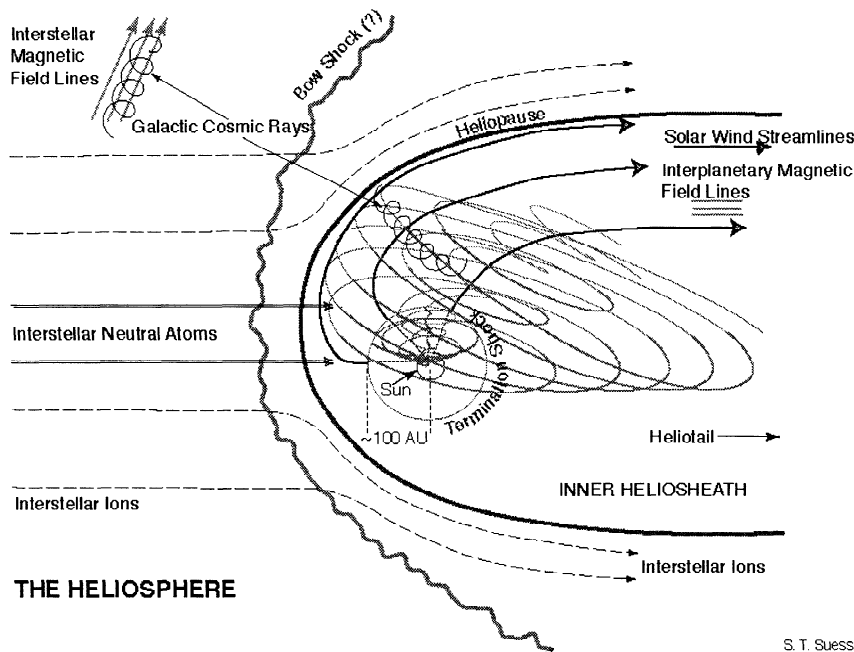


FIGURE 1. Schematic of the global heliosphere created by the supersonic solar wind diverting the interstellar flow around the Sun. The interstellar ions and neutrals flow at 25 km/s relative to the Sun. The solar wind, flowing outward at 400-800 km/s, makes a transition to subsonic flow at the termination 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, depending on the strength of the unknown interstellar magnetic field.

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.

To achieve these broad, interdisciplinary objectives, 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. These instruments will have capabilities that are generally far superior to those of the Voyagers. The wide variety of thermal and flow regimes to be encountered by Interstellar Probe will be explored by 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. Two cosmic ray instruments are included, one for H, He, electrons and positrons, and one to measure the energy spectra and composition of heavier anomalous and galactic cosmic rays. 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. Dust will be studied with in situ measurements of the dust distribution and composition and by a remote sensing infrared photometer that will map the dust distribution via its infrared emission. The infrared detector will also detect galactic and cosmic infrared emission. A partial list of additional candidate instruments is also included in Table 1, including a small telescope to survey kilometer-size Kuiper belt

objects and additional particle instruments. The possibility of developing instrumentation to identify organic material in the outer solar system and the interstellar medium is also under study.

TABLE 1. Strawman Instrument Payload

Instruments	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	

The Interstellar Medium

Our present knowledge of the interstellar medium surrounding our heliosphere comes either from astronomical observations, measurements of sunlight resonantly scattered back towards us by interstellar H and He, or in situ measurements of the dust and neutral gas that penetrate the heliosphere. The Sun is thought to be located near the edge of a local interstellar cloud (LIC) of low density (~0.3 /cc) material blowing from the direction of star-forming regions in the constellations Scorpius and Centaurus. In situ observations of this 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 composition of interstellar dust, and of the elemental and isotopic composition of the ionized and neutral components of the interstellar gas and of low-energy particle components, including key isotopes such as ^2H , ^3He , ^{13}C , and heavier species. The local cloud is thought to be composed of younger material than that of the presolar nebula and is expected to be richer in heavier elements and neutron-rich isotopes as a result of continuing nucleosynthesis. A complete sample of the elemental and isotopic abundances of the LIC will provide a standard reference for the composition of plasma, neutrals and dust in diffuse interstellar material. Comparisons of this benchmark with the solar system abundances (representative of the presolar nebula) and with abundances from more distant galactic regions will provide important constraints on theories of galactic chemical evolution.

Measurement of the spectrum of cosmic ray nuclei and electrons, free from the influence of the heliosphere, will investigate astrophysical processes that include acceleration by supernova shock waves, interstellar radio and γ -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 under investigation.

Interaction between the Interstellar Medium and the Solar Wind

The solar wind, a continual low-density flux of charged particles, streams outward from the corona and expands supersonically throughout and beyond the solar system. The solar wind and the interstellar medium interact to create the global heliosphere, shown schematically in Fig. 1. It is primarily the balance between the solar wind ram pressure and the interstellar pressure which determines the size of the heliosphere. The ram pressure of the solar wind pushes the interstellar plasma away from the Sun, diverting the flow around it, creating an elongated "bubble" in the colder and denser ISM. The solar wind pressure decreases as the solar wind expands and, at some point (~100 AU), the solar wind pressure becomes comparable to the interstellar pressure and the solar wind makes a transition to subsonic flow at the "termination shock."

At present, there are 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, which 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 the size of the global heliosphere, 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 exploration of the structure and dynamics of the heliosphere. The Interstellar Probe Mission will answer questions relating to how the ISM influences the solar system and how the solar system influences the ISM.

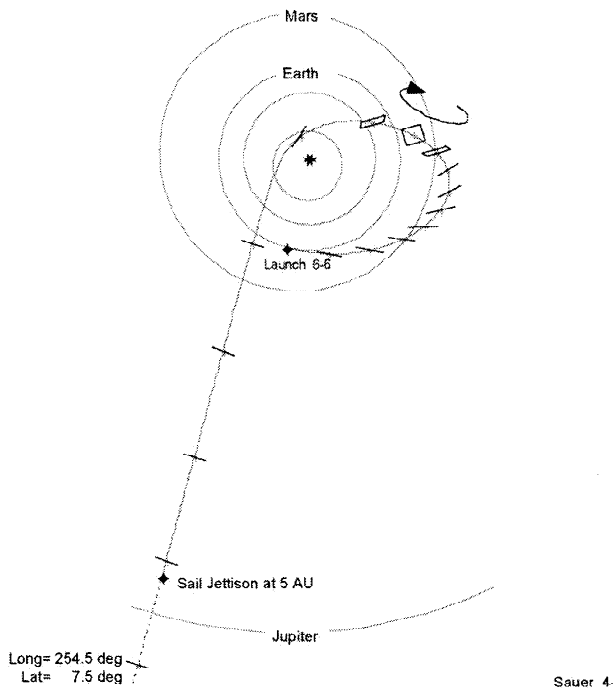


FIGURE 2. Interstellar Probe trajectory using a solar sail to reach a final velocity of 15 AU/year. The trajectory is towards the nose of the heliosphere, the shortest route to the interstellar medium. The orientation of the sail to achieve the proper thrust vector is also shown. The sail is jettisoned at 5 AU when further acceleration is negligible to avoid possible interference with some of the instruments.

heliosphere nose, referred to as the "hydrogen wall." Interstellar Probe will explore the structure of this wall with in-situ and remote-sensing observations, and relate its properties to observations of similar structures and winds observed in neighboring star systems. In general, the study of the structure and dynamics of our heliosphere will serve as an example of how a star interacts with its environment.

The Outer Solar System

Our Solar system is thought to be the end product of a common astrophysical process of stellar system formation from protoplanetary disk nebulae. Collisions play a central role in the formation and evolution of planetary systems, either increasing or eroding the mass of the bodies. The present interplanetary dust population is a result of collisional processes occurring in the solar system. Interstellar Probe will provide the opportunity for in situ and remote sensing of both interplanetary and interstellar dust in the heliosphere and the ISM. It will determine the composition and the mass and orbital distributions of dust in the outer solar system, study its creation and destruction mechanisms, and also search for dust structures associated with planets, asteroids, comets, and the Kuiper Belt. These studies will constrain theories of the collisional dynamics of the solar system and help us understand the origin and nature of our solar system and other planetary systems as well. Interstellar Probe can uniquely address the fundamental question of the radial extent of the primordial solar nebula, or, more precisely, the extent of the primordial planetesimal disk. This can be accomplished most directly by measuring the variation with heliocentric radius of the population of small bodies in the Kuiper Belt, or, less directly, by measuring the density

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. The heliopause is the boundary between the heated solar wind in the heliosheath and the interstellar plasma. 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. The interstellar neutrals which penetrate the heliosphere can charge exchange with the supersonic solar wind ions, creating energetic "interstellar pickup ions" which heat the solar wind. 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.

The termination shock is known to accelerate particles from keV to GeV energies, and in situ studies of shock structure, plasma heating, and acceleration processes at the termination shock will serve as a model for other astrophysical shocks. Energetic ions created by charge exchange in the heliosheath can be imaged to provide information on 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

distribution of dust grains derived from Kuiper Belt objects. Moreover, the Kuiper Belt is an analog for circumstellar disks around other stars and improved understanding of its properties will aid the interpretation of astronomical observations of planet-forming or planet-harboring disks in other stellar systems.

Organic material is found in both our solar system (in asteroids, comets, meteorites and dust) as well as the interstellar medium. It is not known if these non-terrestrial organic materials have a similar origin. 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. A suitable instrument on the Interstellar Probe would 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.

The cosmic infrared background (CIRB) is the integrated light from all stars and galaxies that cannot be resolved into individual objects. Observations of the CIRB can determine how much energy was converted into photons during the evolution of galaxies, back to their formation. As a result, fundamental measurements about galaxy formation can be made even though individual protogalaxies cannot be seen. The CIRB spectrum provides information on how the first stars formed and how early the elements were formed by nucleosynthesis. The Cosmic Background Explorer (COBE) satellite detected the CIRB at wavelengths longer than 140 microns and established limits on the energy released by all stars since the beginning of time. COBE results at shorter wavelengths were not possible because of the very bright foreground emission from zodiacal light. The zodiacal dust is known to decrease in density with radius. ISP will map the radial distribution of zodiacal emission and beyond ~ 10 AU, it will be able to detect or limit the CIRB at wavelengths below 140 microns as the zodiacal background decreases.

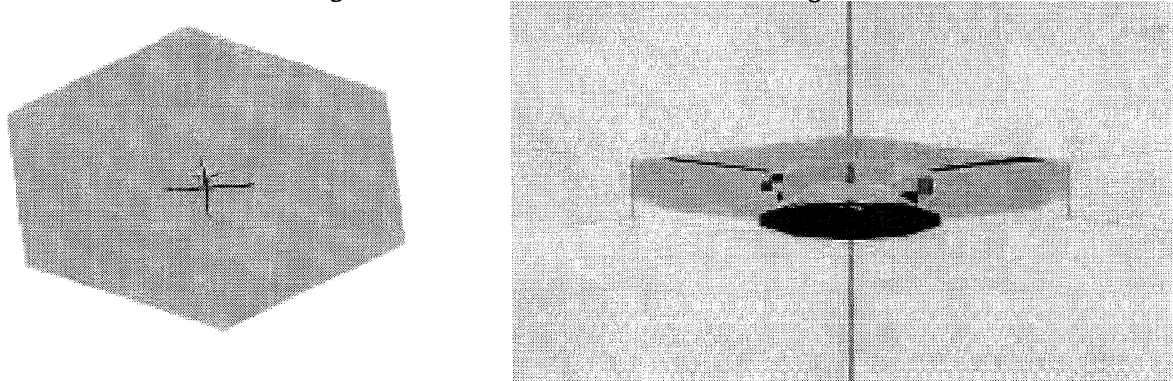


FIGURE 3. Left: The hexagonal ~ 400 m diameter solar sail with the spin up booms still attached. Right: The spacecraft, whose 2.7 m dish antenna serves as the main support structure, is supported by three struts in an 11-m hole in the center of the solar sail. Sail control is achieved by moving the spacecraft with respect to the center of mass of the sail. The instruments are attached near the rim of the antenna. The sail is spin-stabilized during sailing.

MISSION CONCEPT

Interstellar Probe mission requirements were defined by the ISPSTDT. To accomplish its science objectives, the probe should acquire data out to a distance of at least 200 AU, with a goal of ~ 400 AU. The trajectory should aim for the nose of the heliosphere, the shortest route to the interstellar medium. The average science data rate at 200 AU would be 25 bps; a lower data rate is acceptable at 400 AU. The instrument payload requires ~ 25 kg and ~ 20 watts of power. The spacecraft should spin to enable the in situ instruments to scan the particle, plasma, and magnetic field distributions and to permit the remote-sensing instruments to scan the sky.

JPL's mission design team developed mission and spacecraft concepts which met all requirements. The resulting spacecraft design is shown in Fig. 3 (right) in sailing configuration. The spacecraft is suspended inside an 11-m hole in the hexagonal sail. The instruments are placed around the rim of a 2.7-m dish antenna, which also functions as the main support structure. The spacecraft is designed for a mission to 200 AU with consumables to last to 400 AU (~ 30 year mission). Science and engineering data are gathered at an average rate of 30 bps. The telecommunications system uses Ka band to communicate with the Deep Space Network; data is stored and dumped using approximately 1 pass/week. The antenna is limited to 2.7 m to fit in the shroud of the Delta II launch vehicle. A downlink data rate of 350 kbps at 200 AU is achieved using a transmitter requiring 220 W. Power is provided by three next-generation advanced radioisotope power source (ARPS) units.

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 gm/m² 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 sail is jettisoned at ~5 AU when the further acceleration from radiation pressure becomes negligible, thereby avoiding potential interference with the instruments. Fig. 2 shows the orientation of the sail relative to the Sun to obtain the proper thrust vector for the trajectory shown. The total ΔV achieved is 70 km/s. In the sailing configuration, shown in Fig. 3 (right), the spacecraft is supported within a hole in the center of the sail by 3 struts. Sail control is achieved by offsetting the spacecraft with respect to the center-of-mass of the sail. 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. Figure 3 (left) shows the sail after deployment, but with the spin-up booms still attached.

CONCLUSIONS

Although most of the instruments required for this mission have considerable flight heritage and could be built today, all of them would benefit from new technology in order to optimize the scientific return within the very restrictive weight and power resources. In addition, there are several exciting instrument concepts such as the molecular analyzer and the Kuiper Belt Imager that 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. Many of these developments are also being counted on for other future NASA missions.

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 (Wright, 1992), they have never flown in space (although a large ~20 m sail 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. These developments will have to be tested in one or more flight demonstrations before a 400-m sail with an areal density of ~1 g/m² 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. 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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