Interstellar Probe

Voyager 1 and 2 observations and recent observations from the Interstellar Boundary Explorer (IBEX) and Cassini orbiter are providing significant new information about the interaction of the solar wind and surrounding interstellar space. Direct information requires *in situ* measurements to understand the global nature of our local galactic environment, which is significantly more complex than previously thought. Given the large distances involved and the limited remaining lifetimes of the Voyager spacecraft, such a mission is eminently timely. The central problem is that of providing a means of propulsion to accelerate a probe from the Solar System. Even with a low-mass spacecraft, achieving the high speeds needed has remained problematic. We consider the various promises and problems for launching such a mission during the coming decade. We conclude that such a mission is feasible with current or on-going technical developments. We discuss, in the order suggested[*], (1) the concept (approaches, spacecraft, payload), (2) implications for solar and space physics, (3) estimated cost, and (4) how this concept meets Heliophysics Decadal Survey criteria.

1 Summary of the Concept

The heliospheric boundary region, recently entered by the Voyagers, and its interaction with the interstellar medium is still one of the last frontiers of uncharted territory in heliophysics. Only an Interstellar Probe with modern instruments and measurement requirements better defined by these recent observations can provide the new information required.

1.1 Implementation Approaches

Voyager 1 is the fastest object escaping the solar system (~3.6 AU/yr) by virtue of its double gravity assists by Jupiter and Saturn. The synodic period of these two bodies is just under 20 years, but with an added constraint of the asymptotic trajectory being confined to a small range of ecliptic latitude and longitude, such mission opportunities become rarer[1]. It has typically been assumed in the scientific community that for such a dedicated effort to be worthwhile, an asymptotic speed at least double that of Voyager 1 – and preferably higher still – is a prerequisite for the mission. Hence, some form of "advanced" propulsion has always been viewed as enabling and essential.

The use of nuclear electric propulsion (NEP) was favored initially, but such systems tended to be large[2-4]. More recent work using the Project Prometheus architecture[5] came to the conclusion that the specific mass (kg/kWe) – as well as the gross mass – of that technical implementation was too large to offer the fast transit times required[6]. Such characteristics have been common for attempts to design fission systems for space[7].

Ballistic, powered, near-Sun, gravity assists[8] were recognized as offering a different potential solution, but with challenges in the high-thrust propulsion capability required[9]. More detailed studies have studied how best to supply such a capability. Specific impulses ~1000 sec at high thrust are required and solar-thermal propulsion offers a solution[10-15]. However, the approach required a very-low probe mass (~150 kg) along with a combined perihelion engine whose function was mission critical, could not be tested in the most stressing environment, and required long-term (3+ year) storage of liquid hydrogen (LH2).

Low-thrust approaches include solar sails[16-19] and RTG-powered electric propulsion[9], the latter now known as radioisotope electric propulsion (REP)[20,21]. Solar electric propulsion (SEP) has also been recently reexamined in conjunction with REP and gravity assists[22]. All of these approaches have limitations driven by materials and mass issues, but appear feasible.

[*] *Decadal Study-Request for Information (RFI) from Community* from http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_056864#White_Papers_and_Community_Input

1.2 Solar Sails and Solar Electric Propulsion

Solar sails make use of the radiation pressure exerted by sunlight. At 1 AU, the solar constant momentum flux is p_{sun} = 4.5605 μNm^{-2}. The relevant physical parameter is the "lightness number" β defined as the ratio of solar radiation pressure force on the spacecraft to the gravitational force. The decreasing effectiveness of solar sails with distance, e.g. past the orbit of Jupiter, has led to the mission-design strategy of performing so-called multiple "solar photonic assist" maneuvers that turn the trajectory into a hyperbolic one[23]. The European Space Agency (ESA) has studied this approach for the Interstellar Heliopause Probe/Heliospheric Explorer (IHP/HEX). Mission analyses suggest flyout times to 200 AU in ~20 to 30 years with launch masses of a few hundred kg could be accomplished for sail areal masses of ~5 g/m^2, areas > 10^4 m^2 with approaches to ~0.2 AU of the Sun[24,25]. Such estimates are in accord with previous calculations[18,19].

A similar strategy can be followed with SEP. Common to both approaches is the exploitation of increased solar radiation flux and gravity by first going to the inner solar system and taking up momentum there. The SEP approach has been studied in conjunction with REP (discussed in the next section). In this case the SEP stage provides the energy otherwise provided by a large ballistic booster (see §1.3). Fast escapes still require gravity assists and significant electrical power (~50 kWe at 1 AU) with a higher initial spacecraft mass. However, in addition to a smaller required launch vehicle, a less close approach to the Sun of ~0.7 AU is required compared to ~0.2 AU in the solar sail case[22].

1.3 Radioisotope Electric Propulsion (REP)

A "small" interstellar probe requires power for the onboard electronics and instruments, which will be, at a minimum, ~150 to 200 watts of electricity (We). This requirement, in turn, is most easily fulfilled at large solar distances with a radioisotope power supply (RPS) (rather than with a nuclear fission reactor), the distances being so large as to make solar arrays totally inapplicable. By increasing the power supply one can, in principle, provide power to run ion engines, providing a constant thrust to the spacecraft.

This approach implies that a power conditioning system, ion engines, larger power supply (up to ~1 kWe), and appropriate propellant must all be supplied. Such an approach has been studied for implementation on both a Delta IV Heavy[26-28] and an Ares V launch vehicle[29]. With an Ares V and a Centaur upper stage the flyout time to ~200 AU remains ~28 years for realistic technologies. About 5 years can be trimmed off this amount by also including a gravity assist at Jupiter. For a specific target region on the sky, this also implies limiting the optimal launch windows to about every twelve years. For all of these cases, the probe moves from Earth orbit away from the Sun, so there are no increased thermal requirements as with the approaches of the previous section.

1.4 Spacecraft

The five solar-system-escaping spacecraft to date (Table I) all share the use of a high-energy "kick stage"; a large, spacecraft-fixed high-gain antenna (HGA), an RPS powered by plutonium-238 (^{238}Pu); redundant, fault-tolerant spacecraft electronics; low onboard, propulsive capability; and, single-string instruments. Similar features characterize the Innovative Interstellar Explorer (IIE) concept, with the exception of the lack of large onboard propulsion capability[28,29]. The Pioneer 10 and 11 spacecraft far outlasted their 900-day mission requirement, and the Voyagers their five-year mission requirement; New Horizons is now in its fourth year of flight in a nominal 16-year mission[30]. The IHP/HEX solar-sail spacecraft has subsystems similar to those of Ulysses[16]. These previous efforts demonstrate that an Interstellar Probe can be implemented in the near term to pass through the terminations shock, the heliopause, and into the possibly-shocked interstellar medium. Besides directly detecting the low-energy component of galactic cosmic rays, the interstellar magnetic field (ISMF), and neutral and particle composition and dynamics, the new questions in this region will also be answered (§2).

Spacecraft	Instruments		Spacecraft (dry) (kg)	Payload mass fraction
	Number	Mass (kg)		%
Voyager	10	104.32	721.90	14.45
Pioneer	11	28.98	251.79	11.51
New Horizons	6	28.43	385.00	7.38
IHP	12	25.6	517	4.95
IIE	10	35.2	516.2	6.82

Table I: Deep-space spacecraft, instruments, and their mass fractions. Voyager and New Horizons totals are from the National Space Science Data Center (NSSDC). Pioneer totals are from[31],, IHP totals are from[32] and IIE totals (option 2) are from[28]. The small mass fractions on IIE and IHP are driven by dry mass associated with the propulsion systems.

1.5 Payload

The mass limitations inherent in designing a spacecraft for fast solar-system escape imply the need for judicious selection of instrumentation. The new Voyager, IBEX, and Cassini results provide better insight into the types of instruments to fly and the magnitude of the expected signals. Prior to these results, a sample payload was worked out for IIE[28], based largely upon results for the Pioneers, Voyagers, Ulysses, and other field-and-particles robotic spacecraft. The instrument resources in the IIE payload need to be rethought, given these measurements and ongoing instrumentation developments[16,17]. For example, one would like to include neutral-atom imagers of similar sensitivity to those on IBEX[33] to follow the incoming ISM flow as it becomes increasingly pristine and to provide a tomographic view of the heliospheric boundary layers together with concurrent 1 AU observations, as well as a very sensitive plasma composition capability.

Fields and particles instruments from various flight missions are listed in Table II along with notional IIE and IHP payloads. These need re-examination in light of the recent science results.

Spacecraft → / Instrument ↓	IIE	IHP	Helios	Pioneer	Voyager	New Horizons	Ulysses	IBEX	STEREO
Vector helium magnetometer	8.81	1.5	4.40	2.7	5.6		2.332		
Fluxgate magnetometer			4.75	0.3			2.4		0.27
Plasma wave sensor	10.0	5.8	NA		9.1		7.4		13.23
Plasma	2.00	2	15.696	5.5	9.9	3.3	6.7		2.37
Plasma composition		1.5					5.584		11.4
Energetic particle spectrometer	1.50	3.0	3.50	3.3	7.5	1.5	5.8		1.63
Cosmic-ray spectrometer: anomalous and galactic cosmic rays	3.50	3.5		3.2	7.5		14.6		1.92
Cosmic-ray spectrometer: electrons/positrons, protons, helium	2.30	1.5	7.15	1.7					1.98
Geiger tube telescope				1.6					
Meteoroid detector			8.93	3.2					
Cosmic dust detector	1.75	1.1		1.6		1.6	3.8		
Solar X-rays and gamma-ray bursts							2.0		
Neutral atom detector	2.50							12.1	
Energetic neutral atom detector	2.50	4.5					4.3	7.7	
Lyman-alpha detector / UV measurements	0.30	1.2		0.7	4.5	4.4			
Infrared measurements				2.0	19.5				
Imaging photopolarimeter				4.3	2.6	8.6			
Imaging system			8.93		38.2	10.5			48.1
Common electronics, harness, boom, etc.								5.4	19.1
Totals	35.2	25.6	72.2	30.1	104.4	29.9	54.9	25.2	100.0

Table II. Instrument masses on deep-space, robotic spacecraft.

Notes: Instrument names are from IIE (Table 2 of [28].). Equivalences to payload elements on other spacecraft are notional and sometimes very divergent with respect to capabilities; they provide a rough guide only. Pioneer instrument masses are from [31], Voyager masses from the NSSDC, New Horizons masses from [34], Ulysses masses from *Astron. Astrophys. Suppl. Series*, 92, 207 *et seq.*, 1992; IBEX masses from [33]; STEREO masses from *Space Sci. Rev.* 136 (1-4) 2008; Helios masses from *Raumfahrtforschung*, Band 19, Heft 5, September/Oktober 1975 (not all are available; marked "NA"); and, IHP masses from [32].

2 Advancing Solar and Space Physics

Davis[35] first called attention to the possible modification of the local interstellar medium by solar activity prior to the postulation[36] and confirmation[37] of the near-constant supersonic solar wind. The effects of this action on the nature of near-Sun space has been a subject of scientific speculation ever since[38,39].

All five spacecraft with speeds sufficiently high to escape the solar system are planetary missions but include instrumentation capable of making *in situ* particle and/or field measurements relevant to probing the nature of the Sun's interaction with the very local interstellar medium (VLISM)[§]. The earlier two spacecraft, Pioneer 10 and 11, launched 2 March 1972 and 5 April 1973, fell silent on 23 January 2003 and 30 September 1995, respectively[41], while both were still inside the termination shock. Voyager 1 and 2, launched 5 September and 22 August 1977, continue to return data, now from the heliosheath, having crossed the termination shock of the solar wind at 94.0 AU on 16 December 2004[42] and at 83.7 AU on 30 August 2007[43], respectively. Both should continue to return data until at least ~2020[44]. Voyager 1 is the fastest (~3.6 AU/yeart) and most distant of the five. The New Horizons spacecraft launched to Pluto on 19 January 2006, remains on course for that object and a Kuiper Belt Object (KBO) beyond at roughly the same heliographic longitude as Voyager 2, but near the plane of the ecliptic[45].[¶]

Following the Pioneer 10 and 11 Jupiter flybys, there was an initiative for flying a dedicated "interstellar precursor mission"[2,8,46-48]. Subsequently, the scientific rationale for such a mission has been repeated in a number of NASA and National Academy of Sciences documents (see §4.2 below). However, the ongoing *in situ* measurements by the Voyagers in the heliosheath (the Voyager Interstellar Mission (VIM), coupled with remote measurements of energetic neutral atoms (ENAs) from the interaction region (from the Interstellar Boundary Explorer (IBEX)[49-54] and Cassini missions[55-57]) have shown that the scientific need for new measurements with modern instruments from the remote reaches of the heliosphere are even more compelling than had been thought. Indeed these recent and ongoing observations have revealed that the interaction of the heliosphere with the VLISM is much more complex than heretofore assumed by our present-day concepts. These puzzling discoveries also call for a major re-examination of the strategy for the Interstellar Probe mission.

The *in situ* instruments on Voyager 1 and Voyager 2 continue to reveal significant fluxes of energetic particles in the heliosheath, including a well-defined suprathermal ion "tail" in which the differential intensities fall off ~$E^{-1.5}$ above ~30 keV[58]. At even higher energies (~100 MeV), there is no "unfolding" of the energy spectrum of the anomalous cosmic rays (ACRs), thus pointing to a more remote location for the modulation region and source[59]. The plasma flow in the heliosheath is peculiar; at Voyager 1, some 20 AU into the heliosheath, the radial-flow velocity component (V_r) is trending towards zero. Most strikingly, direct measurements of the shocked, solar-wind flow speed obtained from Voyager 2 revealed that the core flow remains supersonic in the heliosheath beyond the termination shock[60], contrary to previous thought. All of these particle observations at both Voyagers, taken together, unambiguously imply that the bulk of the energy density in the plasma resides in a non-thermal component that extends to very high energies. Strong implications, both quantitative and qualitative, follow from this fact for the overall heliosheath structure. We have never encountered a large-scale plasma regime in which the non-thermal ion pressure dominates the thermal pressure and overwhelms the magnetic field stresses. The closest parallel regime lies in localized regions of planetary magnetospheres during extremely disturbed conditions, but in the heliosheath these conditions always exist everywhere. This means that no simple distribution function (neither maxwellian nor "kappa" distribution) is adequate to describe the essential physics. This is why even sophisticated MHD models failed to predict anything like the striking new features that have just been observed in the last two years.

Then, in 2009, remote sensing of the heliosheath proton population by IBEX and the Ion and Neutral Camera (INCA) on Cassini revealed stunningly unexpected structures on a variety of scales[52,57]. In addition to the general "glow" of the sky in ENAs, IBEX data show a relatively

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[§] Generally taken as 0.01 parsecs (pc) or 2,063 astronomical units (AU) so as to be outside the limit of influence of the Sun[40].

[¶] Unfortunately, the available, but old, ^{238}Pu used in the power supply on that mission will likely limit the mission life to sometime before 2040 at a heliocentric distance of less than 100 AU.

narrow "ribbon" of atomic hydrogen emission from ~200 eV to ~6 keV, roughly circular, but asymmetric in intensity, suggesting that it is ordered by the interstellar magnetic field (ISMF). It passes through, rather than being centered on, the direction towards the "nose" where the interstellar plasma flow around the heliosphere stagnates, suggesting that the flow is not the primary driver of the system as has been thought, but rather it is the pressure of the interstellar field that configures the heliosheath. The hydrogen ENAs from both the glow and ribbon are also characterized by non-thermal distribution functions. INCA on Cassini sees at higher energies (10s of keV) a "belt" of emission in ENAs, broader than the ribbon, and tilting significantly away from it, and exhibiting a much steeper energy spectrum than observed in the IBEX energy range[56]. Further, an estimate of total plasma pressure in the heliosheath, combining the Voyager *in situ* and the ENA remote measurements[56] suggests an ISMF strength < 0.6 nT, higher than the previously estimated values of ~ 0. 25 nT.

Attempts to explain consistently all the afore-mentioned fascinating observations exhibit no clear trend towards a consensus. All the diverse *in situ* and remote observations obtained to date only serve to emphasize the need for a new generation of the more comprehensive measurements that will be required to understand the global nature of our Sun's interaction with the local galactic environment. Only an Interstellar Probe with modern instruments and measurement requirements better defined by these recent observations can provide the critical information required. We now know that we are dealing with a strongly non-thermal plasma, and that the complex large and small scale structures in the heliosheath are produced by physical processes yet to be adequately described by theory or simulation.

3 Estimating the Cost

An Interstellar Probe mission pushes on the technical limits of the three enablers for any deep space mission traveling away from the Sun: a highly capable, yet "affordable" launch vehicle, electric power from a low-specific-mass RPS, and reliable, sensitive, deep-space communications at Ka-band. All three elements of this robotic-mission-infrastructure triad are necessary for such a mission to take place; they also can be available in the coming decade.

Launch vehicle prices must be negotiated for any given mission. For the REP approach, a large vehicle with an energetic upper stage is required. Delta IV H costs have likely not decreased from their reported level of $254M in late 2004[61]. While Star 48A motors are available, the type of custom stack required for this application would require design work. The overall stack could likely be produced for less than $400M, including the National Environmental Protection Act (NEPA) costs associated with use of an RPS for spacecraft power. An appropriate launch vehicle for the IHP/HEX-solar-sail approach would likely be in the ~$150M or less category, including NEPA, provided that current mass and initial launch energy (C3 ~ 0) requirements hold.

From past usage of RPSs, we estimate a price of ~$30M per unit (cf. Discovery 2010 Announcement of Opportunity, Amendment I, §5.9.3) with 6 required for the REP approach and 2 for a solar-sail spacecraft. Key to this and other deep-space robotic missions is restarting the production of Pu-238[62]. Estimated power costs are then ~$180M and ~$60M, respectively.

The aperture fee for use of NASA's Deep Space Network (DSN) can be estimated using a variety of NASA resource tools. For three 8-hr tracks/week with the 34-m, high-efficiency (HEF) antennas following a Jupiter flyby some five years after launch (with more frequent tracks earlier in the mission), we estimate 30-year tracking costs (FY2025$) of ~$70M (Waldherr, private comm., 28 Oct 2010)[§§]. Mission-operations-and-data-analysis (MO&DA) costs of ~$5M to $10M per year compare well with recent costs for Ulysses and VIM.

For 12 instruments at an average cost of $15 M each and $500 M for the spacecraft bus, the basic unit for either propulsion approach should be buildable for ~$950M, including a 40%

[§§] S. Waldherr, DSN Commitments Engineer, DSN Mission Commitments Office.

reserve. For a solar-sail implementation, we might guess that a ~$150M precursor mission with an additional ~$50M in development may be needed to prove out the required technology.

Tallying these hypothetical costs for the two approaches suggests the Delta IV H/Star 48/REP mission could be built for ~$1.1 B (spacecraft + instruments + 6 RPS + reserve) and launched for another $500M, a total of ~$1.6B. A solar-sail unit (spacecraft + instruments + 2 RPS + reserve) could be built for $1.0B, qualified for ~$200M and launched for another ~$100M, a total of $1.3B, if the technology works out. Running and tracking either mission for the first 10 years could total ~$25M for the Deep Space Network (DSN) and ~$50M to $100M for ten years of operations in fixed year costs[¶].

4 Meeting Heliophysics Decadal Survey Criteria

4.1 Identification as a high priority or requirement in previous studies or roadmaps

In the U.S. the scientific case for an interstellar precursor mission continues to be made in reports by both NASA (National Aeronautics and Space Administration) and the NRC acting under the National Academy of Sciences (NAS). The latter have included:

1. Physics through the 1990's - Panel on Gravitation, Cosmology, and Cosmic Rays (D. T. Wilkinson, chair), 1986 NRC report
2. Solar and Space Physics Task Group Report (F. Scarf, chair), 1988 NRC study Space Science in the 21st Century - Imperatives for the Decade 1995-2015
3. Astronomy and Astrophysics Task Group Report (B. Burke, chair), 1988 NRC study Space Science in the 21st Century - Imperatives for the Decade 1995-2015
4. The Decade of Discovery in Astronomy and Astrophysics (John N. Bahcall, chair)
5. The Committee on Cosmic Ray Physics of the NRC Board on Physics and Astronomy (T. K. Gaisser, chair), 1995 report Opportunities in Cosmic Ray Physics
6. A Science Strategy for Space Physics, Space Studies Board, NRC, National Academy Press, 1995 (M. Neugebauer, chair)
7. The Sun to the Earth - and Beyond: A Decadal Research Strategy in Solar and Space Physics, 2003
8. Exploration of the Outer Heliosphere and the Local Interstellar Medium, 2004
9. Priorities in Space Science Enabled by Nuclear Power and Propulsion, 2006

Past NASA documents and reports include:

1. Outlook for Space, 1976
2. An Implementation Plan for Solar System Space Physics, S. M. Krimigis, chair, 1985
3. Space Physics Strategy-Implementation Study: The NASA Space Physics Program for 1995-2010
4. Sun-Earth Connection Technology Roadmap, 1997
5. Space Science Strategic Plan, The Space Science Enterprise, 2000
6. Sun-Earth Connection Roadmaps, 1997, 2000, 2003
7. NASA 2003 Strategic Plan
8. The New Science of the Sun - Solar System: Recommended Roadmap for Science and Technology 2005 - 2035, 2006

The most recent NAS/NRC document advocating the mission[63] recommended "NASA should conduct further study of the following mission concepts, which have the most potential to demonstrate the scientific opportunities provided by the Constellation System: …, Interstellar Probe, …."

The explanatory note[*] to the proposal team in the Cosmic Vision 2015 – 2025 competition explaining the rejection of the proposed solar-sail version of the mission (which included a substantial proposed NASA collaboration) noted that this is "…an innovative mission that addressed our place in the universe and which should be done at some stage…." This mission was endorsed in NASA's Heliophysics Roadmap[65] as a potential mission for an international

[¶] N.B. the launch plus power plus DSN costs are dependent upon NASA infrastructure.

[*] "The [reviewers] considered the concept of a mission to the outer heliosphere to be extremely interesting…. The main issues are with the timeliness of the main science return from the mission, the technical feasibility of some of the elements and the need to preserve technical information across several generations of scientists/engineers." Technical feasibility concerns primarily centered on the 60,000 m^2 solar sail and what was seen as a required demonstrator mission to prove the concept and implementation. A secondary concern was the need for "very efficient" RPSs, which would be a NASA contribution. Efficient RPSs remain a recognized issue, but that problem is being addressed[62] and the mission flyout time to a given distance is contemplated as being faster than that of the Voyagers, but it will still be long. On the other hand, other missions including those of the Voyagers, Ulysses, and the Solar and Heliospheric Observatory (SOHO) have demonstrated that the appropriate maintenance of corporate knowledge across multiple decades is a manageable problem[64].

partnership[†].

4.2 Makes a significant contribution to more than one of the Panel themes

Interstellar probe is primarily a solar and heliophysics mission/investigation. To the extent that it can uncover more information about the conditions in the very local interstellar medium (VLISM) and how these are modified in the interaction region, it *may* provide more information on the spectra of galactic cosmic rays and how they evolve in reaching human-occupied space and planetary magnetospheres. Any contribution will be indirect, but could be significant.

4.3 Contributions to important scientific questions facing solar and space physics today

The exact formulation of the science questions has varied with particular studies. The formulation used with the NASA Vision Mission study (IIE) is:

1. What is the nature of the nearby interstellar medium?
2. How do the Sun and galaxy affect the dynamics of the heliosphere?
3. What is the structure of the heliosphere?
4. How did matter in the solar system and interstellar medium originate and evolve?

This set of questions (from the 3rd Interstellar Probe Science and Technology Definition Team Meeting, 17-19 May 1999) feeds into objectives and questions articulated in NASA's IPSTDT Report and was used to establish a Traceability Matrix for the mission[28]. In the recent NASA Roadmap[65], the science context flows from Research Focus Areas (RFAs) under each of the three broad science objectives in that report, all of which couple to the priority investigations of determining:

1. What is the composition of matter fundamental to the formation of habitable planets and life?
2. How do the heliosphere and the interstellar medium interact?
3. What is the magnetic structure of the Sun-heliosphere system?

as well as to Decadal Survey Challenge 2: "Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium."

Along with the Voyager Interstellar Mission (VIM), comprised of Voyagers 1 and 2 launched in 1977, the Advanced Composition Explorer (ACE) mission launched in 1997, and the Interstellar Boundary Explorer (IBEX), launched in 2008, and now providing paradigm-shifting results [49,50,52-54,57], the Interstellar Probe is called out as fundamental to addressing these questions.

Similarly, the IHP/HEX mission has had the announced science goals of [16,17,64]

1. How do solar wind and interstellar medium interact to form the heliosphere and how does this relate to the universal phenomenon of the formation of astrospheres?
2. What are the properties of the very local interstellar medium and how do they relate to the typical ISM?
3. How do plasma, neutral gas, dust, waves, particles, fields, and radiation interact in extremely rarefied, turbulent, and incompletely ionized plasmas?
4. What is the cause of the Pioneer Anomaly?[66] (a potential "bonus" science goal).

While emphasizing different features and levels of detail, all of these formulations point to the science of our local neighborhood in the galaxy with an emphasis on what it, and the Sun's interaction with it can tell us about ourselves, our solar system, and the what lies beyond.

4.4 Contributions to applications and/or policy making

There are no direct contributions to societal applications or imminent policy decisions.

[†] "The nature of composition and dynamics of the interstellar medium are among the highest ranked science questions in heliophysics. No international partnership opportunity to explore the interstellar boundary is known at this time. Were it to materialize, a spacecraft directly sampling the environment outside the heliosphere could address these questions.

"The next logical step in exploration would be to directly sample the medium that lies beyond the extended solar atmosphere. The solar wind and magnetic field keep the unique plasma of the interstellar medium outside the heliosphere. A partnership mission to interstellar space would allow us to sample its unique dynamics and composition and to access the regime of low-energy cosmic rays that helps us understand cosmic particle acceleration processes for the first time." Indeed, "the [Roadmap] team identified one high-priority science target for a potential international partnership, interstellar mission…." (p.64 of [65]).

4.5 Complementing other observational systems or programs available

An interstellar probe will complement the entire set of heliospheric spacecraft by providing the "outer boundary condition" for the heliosphere. Launch during the operational lifetime of the Voyagers or a New Horizons extended mission, i.e., within the end of the decade under consideration, would, of course, provide an even tighter complementarily with fields and particles observations from those platforms.

4.6 Cost-benefit

The spacecraft and instrument hardware are not the primary drivers, except indirectly in terms of mission lifetime requirements. Development through launch will not cost less than New Horizons but probably not more than Cassini (§3). The question of what the mission would really cost requires further study.

4.7 Degree of readiness (technical, resources, people)

An Interstellar probe has consistently been rated as technically ready using near-term instrumentation. The issue is that of propulsion. Recent work has indicated that neither ballistic nor NEP approaches are credible. Further full-up study is required to determine credible flyout times for REP alone, REP in conjunction with SEP, and solar sail approaches; initial studies suggest they are all feasible (see §1 and included references).

4.8 Fit with other national and international plans and activities

A European-led international team proposed the similar IHP/HEX mission under the Cosmic Vision 2015 – 2025 competition as noted in §4.1.

5 The International Interstellar Probe Team

The International Interstellar Probe Team is an open group of 92 scientists and engineers from 16 countries on 5 continents dedicated to reaching the beginnings of interstellar space[††].

[††] Signatories to this white paper follow:

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