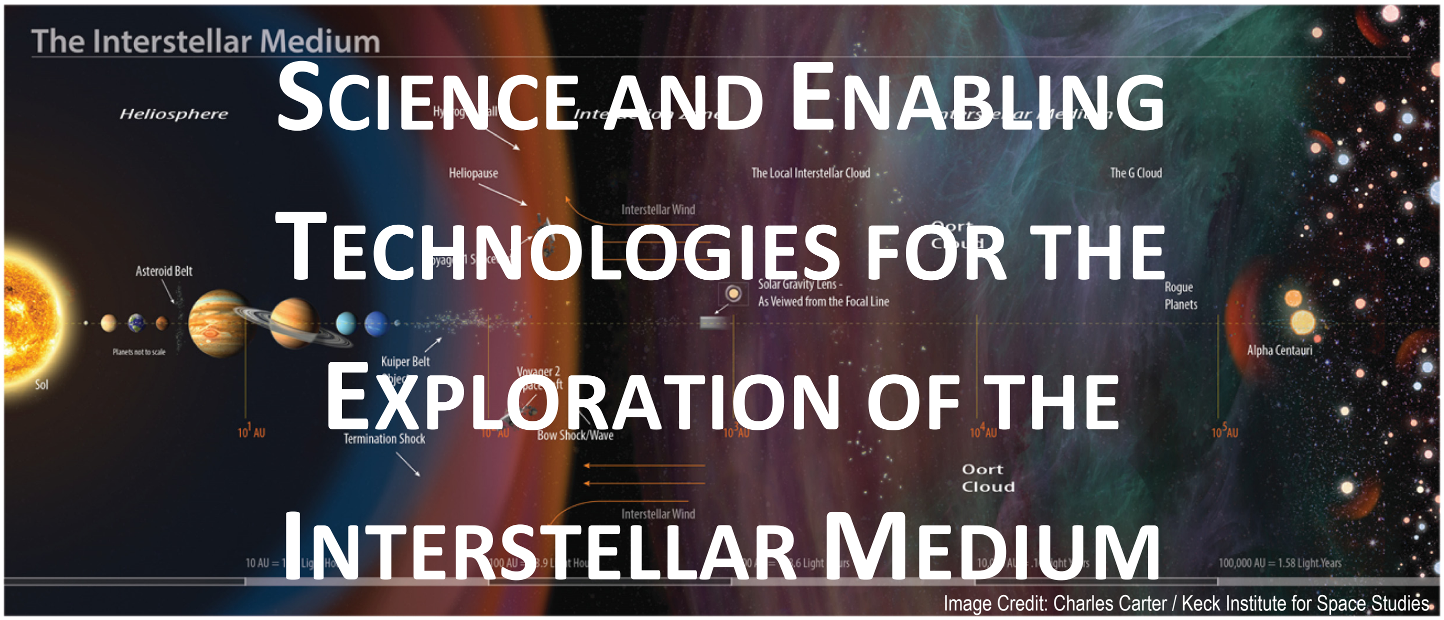
SCIENCE AND ENABLING TECHNOLOGIES FOR THE EXPLORATION OF THE INTERSTELLAR MEDIUM



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Participants in the 2nd KISS Workshop on "The Science and Enabling Technologies for the Exploration of the Interstellar Medium (ISM)" at the KISS facilities, California Institute of Technology, January 13-15, 2015. Workshop participants (some of the named participants below are not in the photo):

Nitin Arora (JPL), Manan Arya (Caltech), Nathan Barnes (L. Garde Inc.), Travis Brashears (UC Santa Barbara), Mike Brown (Caltech), Paul Wilson Cauley (Wesleyan University), Robert J. Cesarone (JPL), Freeman Dyson (Institute for Advanced Study), Darren Garber (NXTRAC), Paul Goldsmith (JPL), Mae Jemison (100 Year Starship), Les Johnson (NASA-MSFC), Paulett Liewer (JPL), Philip Lubin (UC Santa Barbara), Claudio Maccone (IAA), Jared Males (University of Arizona), Kyle McDonough (UC Santa Barbara), Ralph L. McNutt, Jr. (JHU/APL), Richard Mewaldt (Caltech), Adam Michael (Boston University), Edward Montgomery (Space and Missile Defense Command), Merav Opher (Boston University), Elena Provornikova (Catholic University of America), Jamie Rankin (Caltech), Seth Redfield (Wesleyan University), Michael Shao (JPL), Robert Shotwell (JPL), Nathan Strange (JPL), Thomas Svitek (Stellar Exploration, Inc.), Mark Swain (JPL), Slava Turyshev (JPL), Michael Werner (JPL), Gary Zank (University of Alabama).

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PART A: EXECUTIVE SUMMARY

INTRODUCTION

This report summarizes two very exciting and illuminating KISS workshops held on September 8, 2014 and January 12, 2015 entitled, "Science and Enabling Technologies for the Exploration of the Interstellar Medium (ISM)," led by Edward Stone (Caltech), Leon Alkalai (JPL), and Louis Friedman (The Planetary Society, Co-Founder and Executive Director Emeritus). The timing for these workshops aligned with two recent events related to the exploration of the ISM: in September 2013, Caltech professor and Voyager Project Scientist Edward Stone announced that the Voyager 1 spacecraft had detected the Heliopause a year earlier, in August 2012 [1]. Unrelated to this, the Kepler Space Telescope's search for exoplanets (planets around other stars) has yielded spectacular results, including the detection of Earth-like planets. Thus, the vast space between our star and those with potentially habitable planets is slowly emerging into focus. This raises the question, "*When and how will humanity bridge this divide and reach toward such destinations?*" Even more compelling is the question, "*What is a reasonable first step in that direction?*" knowing full well that reaching another star is far beyond our current technical capability. The workshops brought together over thirty scientists and engineers to address the following key questions:

- Is there compelling science to be achieved on the way to, at, and in the ISM?
- What is a reasonable first step in the long road ahead?
- What are some of the enabling technologies required to reach beyond our solar system?

The answers to these questions were formulated in terms of 1) Astrophysics and Planetary science on the way to the ISM at 5–100 AU, which would include the zodiacal background and dust measurements and flyby of one or more Kuiper Belt Objects (KBOs); 2) Heliophysics measurements to obtain a better understanding of the complex environments inside and outside the protective bubble created by our Sun as it travels through the ISM; 3) and Astrophysics from the vantage point of being in the ISM at 100–700 AU, including parallax science, gravitational measurements, and the imaging of exoplanets using gravitational lensing.

A major technological breakthrough endorsed by the team was the ability to reach the ISM in a much shorter timeframe than Voyager—approximately 10 years, compared to Voyager's 36. Equipped with the study results produced by the JPL Blue Sky (Think Tank, December 2013) and Team-X (Mission Design, December 2014), the workshop team was presented with a Design Reference Mission (DRM 1.0) that would: (a) launch on NASA's Space Launch System (SLS) in the mid-2020s; (b) perform a Jupiter gravity assist; (c) have a perihelion burn at 3–4 solar radii; (d) reach the Local ISM (LISM) within 10 years; and (e) achieve solar system escape velocities of >13 AU/year, reaching deep into the pristine ISM (>200 AU) in 20–30 years. Adding a KBO flyby could be considered in future studies.

The team also recognized that the proposed near-term capability to reach the ISM quickly (10–15 years) and leave the Heliopause at high velocities (>13 AU/year) does not scale well for missions to reach other stars. To make this leap, one would certainly require major technological breakthroughs such as beamed energy [2], electric sails [3-5], solar sails [6, 7], and others [8-10].

The team also endorsed the idea that a robotic mission to the ISM (in the mid-2020s) could span multiple scientific disciplines and be compelling to the Heliophysics, Astrophysics, and Planetary science communities. Such a mission would carry out breakthrough scientific investigations on the way to the ISM, visit a large KBO, and use the LISM as a scientific vantage point.

This endeavor would be humanity's first ever (NASA or international) mission explicitly targeting the LISM and journeying deep into the pristine ISM. It could carry an optimized science instrument suite that would be mission-enabling for humanity's first planned near-term exploration of the ISM. It would be daring and challenging and an inspiration to the public, and would be a rational first step toward reaching another star. As a bonus, it could come at the time when Voyager's historic journey nears its end, thus carrying on the work of that storied mission.

Science Rationale

With the right set of instruments, a mission to the ISM would be capable of breakthrough scientific investigations catering to the Heliophysics, Astrophysics, and Planetary Science communities.

A. Heliophysics Measurements: Breakthrough In-situ Science

Our solar system sits within a bubble called the *heliosphere*, carved out of the ISM by the supersonic solar wind and its magnetic field. The complex interaction between the solar wind and ISM—involving the solar wind and interstellar plasmas, neutrals, energetic particles and magnetic fields—is shown schematically in Figure A.1.

Recently, Voyager 1 made headlines around the world as it was confirmed that the spacecraft had left the heliosphere and entered the local ISM. Voyager 2 is still within the subsonic solar wind, the heliosheath, and is expected to cross into the ISM sometime soon. The Voyagers made a series of groundbreaking discoveries as they approached and crossed the termination shock (TS) and entered the heliosheath on their way to the heliopause, the boundary between the heliosphere and the LISM. The

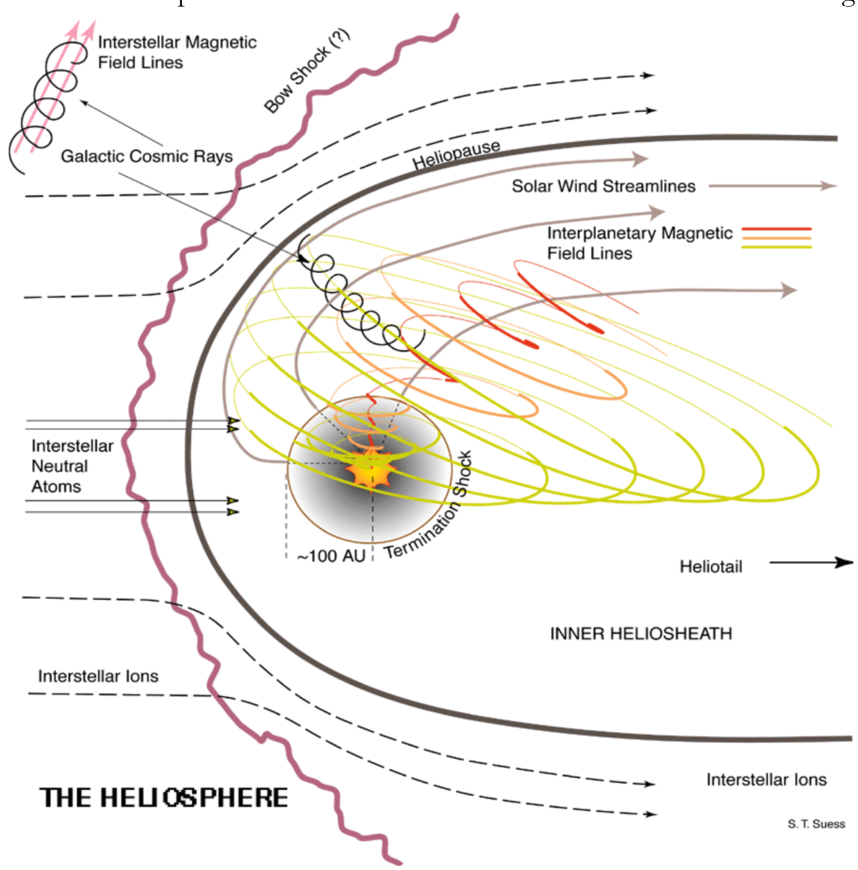


Figure A.1: Key elements of the interaction between the solar wind and the ISM, including the Termination Shock, Bow Shock, Galactic Cosmic Rays, etc.

Voyager measurements, plus remote measurements of energetic neutral atoms (ENAs) results from the Interstellar Boundary Explorer (IBEX) and Cassini/ Ion and Neutral Camera (INCA), have significantly altered our understanding of how the solar system interacts with the ISM.

Many of these discoveries have given rise to more questions, which underline the need to revisit that region with modern instrumentation:

1) One of the first discoveries is that, across the TS, 80% of the energy upstream was transferred to the suprathermal component, the pick-up ions (PUIs). This observation indicates that the heliosheath (where the solar wind is subsonic) is dominated energetically by the PUIs that are not measured by the Voyager spacecraft.
2) Another surprise was the source of anomalous cosmic rays (ACRs). The TS had long been accepted as the place where ACR acceleration occurs, but the two Voyagers found no evidence of that. In fact the ACR intensities continue to increase as the spacecraft venture deep within the heliosheath. The TS is the largest shock in the solar system and the fact that source ACRs were not seen there raises the question of particle acceleration in general, or the effectiveness of diffusive shock acceleration or alternative theories.
3) Another surprise was an unexpected quasi stagnation region where, for 10–13 AU, the solar wind flow stagnated.
4) More surprises included the different behavior of the flows on Voyagers 1 and 2, including the drop of magnetic flux along Voyager 1 the drop-outs of particles on Voyager 2. These and other surprises prompted a fierce debate that either turbulence, reconnection, or other effects might be taking place in the heliosheath.
5) Finally, with the crossing of the heliopause by Voyager 1, it became clear that that boundary is much more complex than what would be expected with reconnection (and or turbulence) taking place.

Shortcomings of Voyager's instrumentation are its inability to detect PUIs, as well as its inability to detect low fields in the heliosheath with its magnetometer.

Complementary global maps from IBEX and Cassini/INCA result from the imaging of energetic neutral-atoms (ENAs). These show an unpredicted "ribbon" (IBEX) and "belt" (Cassini) of ENA emissions from the outer heliosphere, apparently ordered by the local interstellar magnetic field (Figure A.2). How and where the ribbon (and belt) is produced is a subject of much debate. Other questions include, what is the source of the strong time-dependent variation? ENA maps of the heliosphere's tail region also show unexpected depletion areas. The dynamic role of the interstellar magnetic field in shaping the outer heliosphere is stronger than expected, prior to the recent influx of new data. Also,

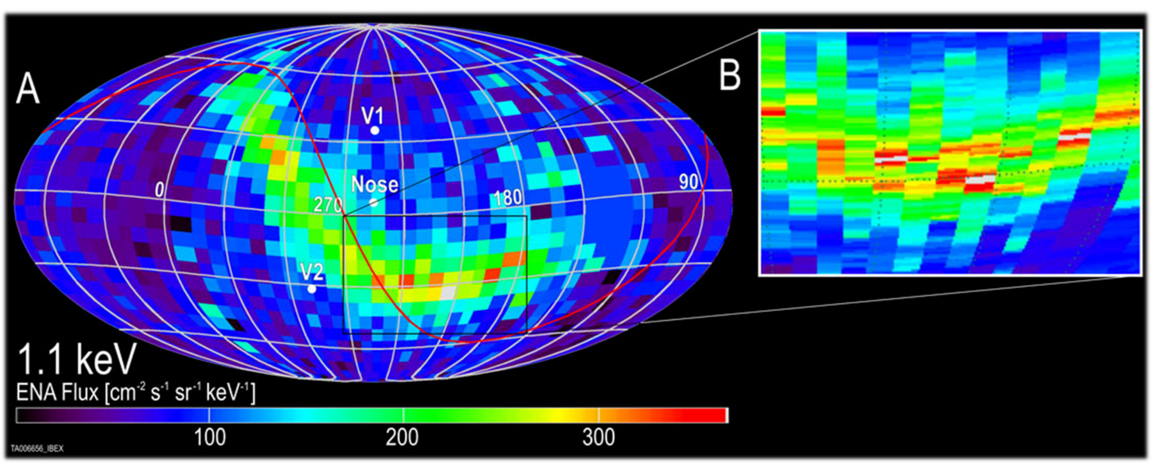


Figure A.2: IBEX ENA Ribbon. A closer look suggests that the numbers of ENAs are enhanced at the interstellar boundary. The proposed mission spacecraft intends go through this boundary as it journeys to the ISM.

the magnetic field measured by Voyager 1 in the LISM does not have the direction inferred from various remote sensing observations, including the bright "ribbon."

The most recent measurements from Voyager 1 show that the influence of solar wind extends further into the local ISM than expected, but it is not known why or how far. Furthermore, whether or not Voyager will make it to the pristine local ISM before it runs out of power in about 2020 is an open question.

The unexpected results from Voyager, IBEX, Cassini, and other observations demonstrate a very limited understanding about the interactions between stars and the interstellar environment and the need to revisit that region with modern instrumentation sensitive to the low magnetic fields in the heliosheath; to measure pick-up ions and to measure the anomalous, galactic cosmic rays (ACR/GCR). These measurements are crucial to sorting out the different scenarios and our understanding place in the galaxy.

In order to address the above science objectives, *in situ* measurements are needed of all components:

1) ISM and solar wind plasma electrons, ions, and neutrals
2) Solar and ISM magnetic fields, electromagnetic waves, and turbulence
3) Energetic particles and cosmic rays
4) Dust

Depending on the component, the energy distribution functions and/or elemental/isotopic composition need to be measured. In order to obtain non-local measurements relating to the structure and dynamics of the heliosphere and ISM, remote sensing observations such as ENA imaging and Lyman-Alpha observations are needed. The required *in situ* instruments can be loosely described as a magnetometer, cosmic ray instrument, thermal plasma instrument, suprathermal particle instrument, dust instrument, and plasma wave instrument.

B. Astrophysics Measurements

Astrophysics science for a mission to the ISM can be grouped into three topics of broad interest: (i) zodiacal dust background noise investigation, (ii) fundamental physics science, and (iii) astrometry.

1. Zodiacal Dust

Asteroids, comets, and the recently discovered KBOs, loosely referred to as planetesimals, are the source of micron-sized dust particles that make up the zodiacal dust cloud in the inner solar system and, presumably, a similar dust cloud in the Kuiper belt. Figure A.3 depicts the distribution of dust in our galactic neighborhood. A probe flying from Earth toward the outer solar system would provide an opportunity to study how the micron-sized dust diffuses outward to fill the solar system. It would also enable the investigation of dust composition as a function of radial position, and allow the comparison of the dust with what is seen in exoplanetary systems. As the probe moves outward, the scattered and reradiated sunlight produced by the dust would drop rapidly in intensity, allowing our clearest look ever at the Extragalactic Background Light (EBL) at visible and infrared wavelengths. It would also allow us to make definitive measurements of the intensity, spectrum, and spatial properties of the EBL from Reionization (R-EBL).

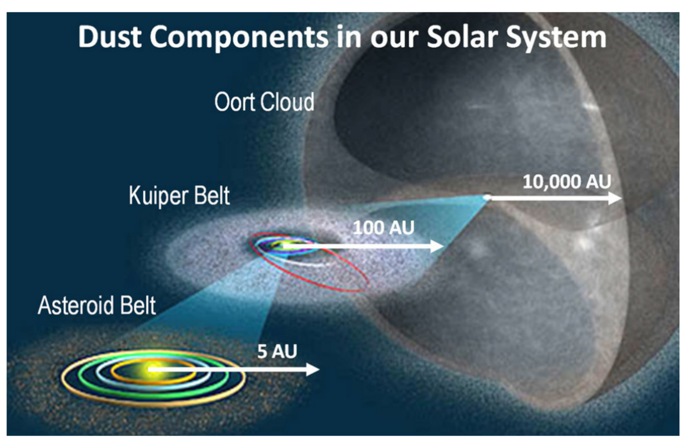


Figure A.3: Dust distribution in our solar system

2. Fundamental Physics

Highly accurate investigations of general relativity and dark matter science are possible using a probe to the ISM. Accurate ranging from Earth to the probe in the ISM can be used to test

Einstein's theory of general relativity ~100–1,000× times more precisely than the current state of the art, set by radio frequency ranging measurement on the Cassini mission. Given the radial nature of the spacecraft trajectory, such a probe could test the gravitational inverse-square law and the equivalence principle (EP) on scales never attempted before.

3. Astrometry

Astrometric investigations and data collection conducted on multiple, long Earth-to-ISM probe baselines (~100–1000× better than the Gaia space mission) may lead to major improvements in the study of galactic dynamics, binary stars mass determination, study of exoplanets, black holes, quasars, and neutron stars.

C. Kuiper Belt Object Science: Visiting a Dwarf Planet

A mission reaching the LISM presents a unique opportunity to fly by a large KBO within 10 years from launch. One potential target is Quaoar [11], a dwarf planet at ~45 AU from the Sun. Other attractive targets include Haumea [12] and MakeMake [13].

Quaoar is one of the most interesting of the KBOs as it represents a transition between the large, volatile dominated, atmosphere-bearing KBOs and the typical mid-sized volatile-poor objects. It is in the last stages of losing its methane (and likely nitrogen) atmosphere and shows evidence of methane frost patches on its surface. It is also likely to have ancient cryo-volcanic flows, making Quaoar a compelling science target to study the outer solar system and KBOs. Quaoar also has a small moon called Weywot, which has an eccentric orbit indicating the possibility of undiscovered smaller moons (Figure A.4).

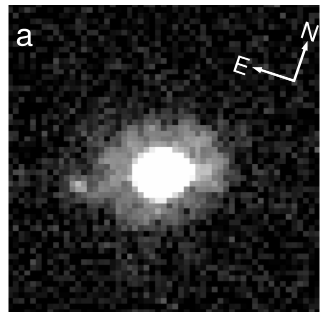


Figure A.4: Quaoar and Weywot as seen from the Hubble Space Telescope (HST)

The orbital position of Quaoar lines up with the nose of the Heliopause. This means that a spacecraft flying by Quaoar in the near future will take the shortest path out of the heliosphere and into the LISM. Furthermore, the nose of the heliopause is an attractive science target from an *in situ* science perspective. The fly-by trajectory to Quaoar would also pass very close to (possibly through) the IBEX ENA ribbon phenomenon [14]. Studying this ribbon is of high scientific value to the heliophysics science community.

One of the main challenges of doing KBO science is making these measurements while flying by at speeds in excess of 60 km/s. In comparison, the New Horizons spacecraft was travelling at ~13.7 km/s during its closest encounter with Pluto (~32 AU from the Sun). Doing the above-stated KBO measurement at such high flyby speeds has never been attempted before and will require fast imaging, as well as high-precision photometry capabilities on the spacecraft.

D. What Is a Reasonable First Step Towards Another Star?

One of the main goals of this study and the two KISS workshops was to debate this fundamental question: What is a first rational step towards exploring the ISM and one day reaching towards another star? It was widely accepted as a fact that if it takes 35 to 40 years for a robotic spacecraft to reach the ISM as a primary scientific target (it took Voyager 35 years to reach the heliopause), no national program (such as NASA), scientific decadal survey, or science community would advocate for such a mission; it would simply be impractical. However, if there were a pathway and a method to reach such a destination in 8 to 10 years, then this would indeed constitute a game changer, and the ISM could become a primary target of scientific research with perhaps multiple such missions within a reasonable length of a scientific career. Therefore, it was widely discussed that a first rational step towards reaching another star could be to better understand the environment and the interface between our own star and the interstellar medium. This could be done using a series of robotic probes or even potentially an armada of multiple smaller probes that would be deployed in many different directions.

The workshop participants considered a preliminary DRM 1.0 for a robotic probe to reach the ISM in 10 years and reach deep into the ISM in 20 years. Such a mission could be launched as early as 2025 with the launch capabilities of NASA's SLS launch vehicle. This reference mission concept is presented in detail in Section D of this report.

The DRM 1.0 is a first step – reaching deeper into the local interstellar medium. The workshop also addressed targets further in the far ISM, regions where the Sun's influence is completely negligible (roughly beyond 300 AU) and perhaps most interestingly making use of the soar gravity lens focus, which begins at 550 AU. Theoretically it might be possible to use the Sun as a lens to image a candidate habitable exoplanet to kilometer scale resolution – something not achievable in any other practical way. Presentations at the workshop showed that small spacecraft s with large solar sails might reach speeds of 20 AU/year, enabling a mission to the focus with flight times about 30 years. Further study of a possible mission there, and how it might operate is recommended.

Whereas missions like the DRM 1.0 can enable a concerted campaign of multiple robotic spacecraft to explore the ISM, it clearly does not scale as a capability to reach another star. As of today, there is no obvious, clear and compelling technology in sight to do so. Section E explores the current ensemble of technologies proposed in the literature, including beamed energy, e-sails, solar sails, nuclear propulsion, and other technologies. Whereas they all have the opportunity to scale, they all face huge technological hurdles in the foreseeable future.

All the workshop participants recognize that the topic of exploring the ISM, even if quite distinct from the futuristic topic of interstellar exploration, has a long history of prior studies. Fortunately, among the workshop attendees was also Dr. Ralph McNutt (APL) who has been an active participant in many of the relevant studies over the past few decades. In Section B, he provides a detailed overview of prior work and a historic perspective on the topic. Finally, Section F provides a hopeful outlook for the future and a call for the science communities (Heliophysics, Planetary Science, and Astrophysics) to support the exploration of the interstellar medium as the next frontier in deep-space exploration.

Part B: Overview of Previous Studies

An idea is born

The idea of a mission to interstellar space is not a new one. It is, however, convolved both with scientific and fictional speculation, and made all the more complex as the extent of space and the scope of many of the mission concepts are difficult to put into the context of human experience to date. The earliest concept dates to Goddard's "Last Migration" (1918) [15], followed by similar mention by Tsiolkovsky (1928), and the "World Ship" of Bernal (1929) [16]. With the end of the Second World War and the advent of nuclear power and practical rocketry, a series of papers explored fundamental limitations of rocket travel as imposed by physics. Nuclear propulsion was viewed as the next great step [17-19]. Shepherd discussed Ackeret's extension of the rocket equation in the relativistic regime [20, 21], and Sänger discussed the "photon rocket" as a means of reaching to the stars [22]. Other extensions of these concepts included the ideas of staging and no need for deceleration by one-way robotic spacecraft [23], the fusion of interstellar hydrogen to avoid the need for carrying propellant [24], and the use of beamed energy to the craft via high-power lasers [25]. The idea of "solar sails" for travel within the solar system first advanced in the Soviet Union by Tsander in 1924 [26] was "reintroduced" to the growing field of astronautics for this purpose in the late 1950's as well [27, 28]. At the time, the use of such light sails for enabling interstellar missions was not under consideration or study, but that would change. By the early 1960's the energy limitations on "fast" interstellar craft were well appreciated [29-32] and used in some quarters to support the idea of communication with extraterrestrial intelligence (CETI) as an alternative "practical" approach to the interstellar travel "problem" [33]. From the early 1960's forward there has been a large body of mostly engineering literature published on the subject of travel to other star systems. At the same time, speculative fiction/ science fiction from the 1920s though the same period had begun to draw on interstellar travel as a plot subject – but more typically than not with "star drives," which eliminated the problems of physics in getting from one star to another.

The first study period: Years 1950–1996

With the growing competition between the United States and the Soviet Union spreading from human to robotic interplanetary spacecraft, there was growing interest in understanding the possibilities of reaching the planets of the solar system with available or near-term rockets. Already in 1929, Oberth had noted that a powered maneuver near the Sun would result in a huge decrease of flight time to a nearer star (which he put as Regulus at 10^{15} km) [34]. The general use of planetary flybys to provide passive boosts to interplanetary speeds was considered by Lawden in 1954 [35] and further developed by Minovitch and Niehoff [36]. At the same time, Flandro recognized the existence of upcoming "grand tour" trajectories by making use of these same techniques [37]. These studies provided both the impetus and the means for carrying out the Pioneer 10 and 11 missions past the asteroid belt, and later, those of Voyager 1 and 2, the latter executing one of the "grand tour" trajectories.

During the same time period, speculation had turned to the interaction of the Sun with the local ISM. Following the initial considerations of Davis in 1955 [38] and the theoretical prediction of a supersonic solar wind [39] and its experimental confirmation by the plasma instrumentation on the Mariner 2 mission to Venus [40], Eugene Parker provided a set of models for what the large-scale interaction might be like [41]. Drawing on previous work by Axford et al. [42] in a review in 1967 Dessler coined the term "heliosphere" noting [43]:

> *The heliosphere is defined as the region of interplanetary space where the solar wind is flowing supersonically. At some heliocentric distance the solar-wind pressure is balanced by the pressure of the interstellar medium. At this distance the solar wind will undergo a shock transition to*

subsonic flow. The subsonic plasma beyond the shock forms a boundary shell. Beyond the boundary shell lies the interstellar medium.

This sketch has tended to dominate the thinking about the matter up until the passage of the termination shock first by Voyager 1 and then by Voyager 2.

With the Pioneer missions being readied for flight, and the fact that these would be the first human-made objects to leave the solar system, a series of papers was presented on this at the 17th Annual Meetings of the American Astronautical Society in Seattle, Washington from the 28th through the 30th of June 1971. As the logical "next step" of "grand tour" missions [44], dedicated missions beyond the solar system could penetrate the ISM and provide *in situ* measurements in this region [45-47]. Technological requirements were discussed including the need for radioisotope thermoelectric generators (RTGs) with extended lifetimes [48] and the requirement of large escape speeds from the solar system. In discussing the latter (for what he called an "ultraplanetary probe") Ehricke noted three approaches with chemical rockets: (1) direct departure from Earth, (2) use of a Jupiter gravity assist, and (3) use of a propulsive maneuver near the Sun (the "Oberth effect"), as well as the use of more advanced, and more exotic nuclear means [47].

The prospect of interstellar flight was raised in the massive NASA study *The Outlook for Space*, conducted during 1975 [49]. The report dismissed actual flight to another star system due to the problem of propulsion and flight times involved[1]:

A spacecraft launched by current propulsion technology would take thousands of years to reach the nearest star. It is likely that long before such a craft reached its target, our progeny here would have developed much more efficient propulsion techniques, and their craft would pass our early model enroute, making the whole mission somewhat pointless. This progeny, however, might be close at hand, perhaps the next generation. It may be that before the turn of the century we will have developed nuclear rockets capable of cutting the flight time of a probe down to less than a century instead of a few thousand years (Reference 35). This may be attractive, but it is at least conceivable to do even better.

At the same time, the report did note an objective (number 1069), "Solar System Escape Spacecraft":

Small spacecraft with particles-and-fields instrumentation launched in 1980 by Titan-Centaur plus high-performance upper stages on a trajectory-escaping solar system in general direction of solar apex. If mission launched in late 80's, electric propulsion, solar sailing, and/or Jupiter swingby could be used to reduce transit time to heliospheric boundary. Mission duration of ten years or more.

The project was estimated to cost $225M with a "high confidence level." This mission was linked to a variety of objectives including: nature of stellar explosions; where and how have elements formed?; what is the nature of cosmic rays?; what are the composition and dynamics of interstellar matter?; and corona and interplanetary matter. This entry in this comprehensive report for NASA activities for the last quarter of the 20th century is apparently the "birthplace" of what has come to be known as the "Interstellar Probe."

[1] During 1975, there were hearings on Future Space Program plans by the Congressional Subcommittee on Space Science and Applications during which NASA Administrator Fletcher briefed the Subcommittee on this effort. As part of these hearings, Dr. Robert Forward of Hughes Research Laboratory also briefed the subcommittee on a possible program for human interstellar flight [50].

It is reported both in the scientific and engineering literature that a meeting of some sort (variously identified as both a "conference" and "symposium") was held in August of 1976 at the Jet Propulsion Laboratory on "Missions beyond the Solar System"[2] which included the following discussion:

> *The idea of a "precursor" mission out beyond the planets of the solar system, but not nearly to another star, was suggested as a means of elucidating and solving the engineering problems that would be faced in an interstellar mission. At the same time, it was recognized that such a precursor mission, even if aimed primarily at engineering objectives, could also have significant scientific objectives.*

In any event, JPL staff carried out a detailed, comprehensive study, beginning in November 1975, on the mission concept. The study was completed and published as an internal JPL document in October of 1977 [51] and later in the referred literature [52]. The effort provided a comprehensive analysis of scientific goals and some of the technological hurdles [53] as well as more in-depth analyses of engineering issues to be overcome [54]. A nuclear electric propulsion (NEP) approach was baselined [55, 56]. While propulsion was flagged as a significant problem, the study led to a growing realization that mission requirement lifetime and autonomy requirements might be even more significant (C. V. Ivie, private comm.).

With the Voyagers having completed their nominal mission for flybys through the Jupiter and Saturn systems [57] attention turned to the ultimate possibilities for the Voyager 1 and 2 missions [58, 59]. Studies carried out at JPL in support of the extended Voyager mission considered (1) possibilities for the Voyagers as they headed toward interstellar space, (2) the ultimate fate of Pioneer 10 and 11, and (3) how the Voyagers were laying the ground work for an interstellar precursor mission, as discussed previously [53]. Although the Voyagers have outlived the power limitations then predicted (to ~2012 to 2013), the decay of the RTGs eventually will limit the lives of those spacecraft, with current limits now estimated as being reached in the ~2026 time-frame. These studies were important in linking the extended Voyager missions to the need for an eventual – and faster – interstellar precursor mission.

With the flyout speeds of the Voyagers actually less than the random proper motions of the local stars, including the Sun, flight times of the four solar-system-escaping spacecraft to other stars must take into account proper stellar motions as well. Typical close flyby times of other stars lie ~40,000 years in the future for these probes. All of these spacecraft are still gravitationally bound to the Milky Way galaxy [60, 61].

During the same time-frame, as the Voyagers were entering their extended mission Robert Forward revived the idea of using solar sails, but now pushed by the higher power levels promised by lasers, for reaching the stars [62]. He describes three missions: (1) a flyby of α Centauri in 40 years, (2) a rendezvous mission in about the same time, and (3) a human round trip mission to ε Eridani in about 51 years Earth-time and 46 years ship-time due to time dilation at the high speeds obtained. The uses of a multiple-staged system enables the second two approaches and marked a revival in solar sails and their extension to laser-propelled light sails for true interstellar travel. Forward also considered what could be done at the opposite end of the electromagnetic spectrum with microwaves and extremely small automated robotic probes, the 20-gram *Starwisp* probe, accelerated to 20% of light speed in a week with a 10 GW microwave beam [63].

The general engineering problem of interstellar travel was reviewed in a session of the 36th International Astronomical Congress held in Stockholm, Sweden in October 1985 [64]. Papers presented included an overview by Forward [65] as well specific papers including a review of Project

[2] While the published papers note the month, location, and organizer of this meeting, namely L. D. Friedman, an author of this report, neither he, nor any of the other authors of the internal JPL report who have been reached can recall such a meeting, or has any record of such a meeting been found (so far) in any JPL archives. The co-author of several of the resultant papers, Dr. C. V. Ivie has been reached and recalls the effort but no formal meeting. Unfortunately, Dr. Jaffe, previously the Project Scientist for NASA's Surveyor (lunar lander) missions is deceased and has left no other record of this gathering.

Daedalus [66]. The latter is a major concept study undertaken to consider the problems of sending an automated probe on a "fast" mission to Barnard's Star, based upon D-^{3}He fusion [67]. While such concept studies have continued, only the laser-sail approach gained traction with the parallel interstellar precursor concepts, and that a decade later under an initiative of NASA Administrator Daniel Goldin, as discussed below.

Scientific interest in the interaction of the solar wind with the ISM continued, driven, in part, by analyses of the modulation of the cosmic rays as observed by the Voyager spacecraft and the implications for the distance to the termination shock of the solar wind [68]. In addition, the detection of extremely low frequency (ELF) radiation by the plasma wave experiments on the Voyager spacecraft were also suggesting remote detection of the heliospheric boundaries [69, 70]. At this time Holzer suggested the terminology Very Local Interstellar Medium, or VLISM, to denote the region of space within 0.01 parsecs (pc) of the Sun[3]. Hence the VLISM provided a (vaguely) reachable regime by robotic spacecraft. Following advocacy in a study effort of the National Academy of Sciences [71], a subsequent study [72] was made to consider the scientific rationale, supporting instrumentation and implementation for a small probe to 200 AU. The approach considered was to use a 5 km/s Oberth maneuver near the Sun, enabled by a Jupiter gravity assist.

Advanced, in-space propulsion engineering studies during the 1980's has focused on the use of nuclear electric propulsion and science missions, which it could enable. An interstellar Probe was a natural fit for such concepts using, e.g., the SP-100 space nuclear reactor then under development [73-75]. The most ambitious such mission study was the Thousand Astronomical Unit (TAU) mission, which had the goal of reaching 1,000 AU over a period of 50 years [76, 77]. The required advanced reactor and xenon propellant for the ion engines was estimated to be over 60,000 kg for a 5,000 kg "payload."

The Holzer report [72] spawned a renewed interest in a small Interstellar Probe for heliospheric science with the an Oberth maneuver as the enabling approach [78], although the prospect of speeds of great than ~10 AU per year using "advanced propulsion systems such as solar sails" were noted [79]. More detailed considerations of the concept [80] suggested a 200-kg probe could reach ~200 AU with speeds of ~6 AU/yr to ~14 AU/yr, although no details are provided.

The discovery in 1996 of exoplanets around the stars 70 Virginis [81] and 47 Ursae Majoris [82] followed the first discovery of an exoplanet around a main sequence star 51 Pegasi in 1995 [83]. Similarly, and at about the same time, the first (post-Pluto) KBOs were discovered, beginning in 1992 with the object (15760) 1992 QB_1 [84].

The second study period: Years 1997–2010

On 3 July 1997, the strategy changed with then-NASA Administrator Dan Goldin's announcement that a robotic spacecraft, which could fly to another star in 25 years had been made a "goal" for NASA. The announcement was made at JPL the day prior to the landing on Mars of the Mars Pathfinder rover and is said to have had its origin in a meeting earlier that summer between Goldin and staff [85]. The requirement for study was set to "flight to any star within 40-light years taking less than 100 years" [86]. A variety of propulsion schemes were considered [9]. Given this more ambitious goal than just a "simple" precursor mission as had been discussed up to this point, a "beamed energy" option was selected based upon a three-month study prior to the summer of 1998. The approach was down-selected from that approach, fusion, and matter-antimatter (the "photon" rocket of Sänger) "because its solar sail, the basis for beamed energy, has a near-term technology roadmap that is relatively clear compared to the other two options" [86].

The sail approach featured predominantly in subsequent studies including internal JPL work and a Workshop held at Caltech from 28–31 July 1998 on Robotic *Interstellar Exploration in the Next Century* with support from the Advanced Concepts Office of JPL and chaired by H. Harris, D. Pieri, and R.

[3] One hundredth of a parsec is 2,062.64802 astronomical units.

Dickenson [87]. The roadmap approach tied nearer-term efforts to the NASA "40-light year in 100 years" goal and was also used in the context of meetings of the Interstellar Probe Science and Technology Definition Team (ISPTDT) convened at JPL during 1999[4]. A variety of papers were published both on this baseline mission [88-91], considerations of other propulsion options leading to the sail approach [92], and possibilities for using various nuclear electric approaches [93]. Science and concepts were discussed at a Committee for Space Research (COSPAR) Colloquium held in Potsdam, Germany 24–28 July 2000 [94].

One set of experiments were carried out to measure potential sail propulsion with a high powered laser [95]. In addition, a "breakthrough physics propulsion program" was initiated by NASA to look for anything useful in new physics which had been missed [96]. Although both of these efforts figured prominently in the initial Roadmap effort [97], which had grown from Goldin's goal of 1997, neither lasted a significant time past his tenure as head of the Space Agency[5] and became technological dead ends for the present [98, 99].

In parallel with these efforts, there were studies in Europe reexamining what could be accomplished with electric propulsion [100] and in the U.S. small spacecraft architectures for a common Solar Probe / Interstellar "bus" with the latter performing an Oberth maneuver to escape the solar system [101]. For the latter, both would approach the Sun to within 4 solar radii of its center (the design point of the then-current solar probe concept [102]). The interstellar probe would use a customized Star 20B to provide 1.56 km/s of burn at perihelion, enabling an escape from the solar system at ~7 AU/year. By using an Earth-gravity assist, the mission could be launched with existing expendable launch vehicles.

Motivated by the desire for a higher flyout speed and previous studies, proposals to the NASA Institute for Advanced Concepts (NIAC) were submitted and accepted for both Phase 1 and Phase 2 Studies. Dubbed the "Realistic Interstellar Explorer" (RISE, but sometimes, unfortunately, referred to as the "Realistic Interstellar Probe," hence RIP), the study focused on how much further one might go with the original Oberth maneuver concept in trying to approach the performance goal of the TAU mission, viz. 1000 AU in 50 years.

Again, the primary problem addressed was propulsion. To reach a flyout speed from 4 solar radii (a distance thought at the time to be "comfortable" as that was the aim point for a solar probe mission [103-105]) of about 20 AU/yr a perihelion speed change ("delta-V" or ΔV) of ~15 km/s is required for aim points near the plane of the ecliptic (e.g., the star Epsilon Eridani) and higher for targets at larger ecliptic latitudes (e.g., up to ~30 km/s for the star Alpha Centauri) [106]. At the same time, to keep the mission plan "simple" and "affordable", direct fly-out to Jupiter (for the required gravity assist to reach the Sun) and the use of existing launch vehicle capabilities placed severe mass limits on the spacecraft itself. The need for a thermal shield to deal with the proximity of the Sun at periapsis as well as the inclusion of the kick-stage for the Oberth maneuver, greatly limited the mass of the spacecraft itself (the "observatory") including power supply, telecommunications, guidance and control, avionics, structure, and, of course, the science payload.

These mass constraints mean that a chemical rocket stage would be far too heavy. The Ulysses spacecraft (~370 kg including a 55 kg science payload) was provided with a 15.4 km/s ΔV to leave low Earth orbit (LEO) where it was placed by a Space Shuttle using chemical kick-stages. However, there were three stages with a net, fueled mass of 19.97 metric tons (mt), a requirement clearly out of scope for a direct launch to Jupiter with existing vehicles. The initial approach to meet the requirement was to resurrect nuclear-pulse propulsion with small fission weapons [107-109], albeit on a small scale [110].

The Phase 2 of the NIAC study shifted to larger launch vehicle (Delta IVH or "heavy") with a solid Star 48B upper stage. Mass limitations still ruled out a chemical kick-stage and so a mission-unique, solar-thermal propulsion (STP) approach [111-113] was studied in some detail [114] including the required long-term storage of liquid hydrogen (LH2) for such an application [115]. A variety of engineering studies were carried out, e.g., optical communications with an innovative, diffractive optic

[4] Meetings were held 15 February 1999 at Caltech, 16–17 February 1999 at JPL, and a final meeting 17–19 May 1999 at JPL.
[5] Daniel S. Goldin is the longest serving NASA Administrator to date: 1 April 1992 to 7 November 2001.

[116]. The propulsion system, communications system, ultra-low power (ULP) architecture with wireless, radio-frequency, signal backplane, and low-mass, beryllium-alloy structure all pushed current fabrication, operations, and sub-micro-radian pointing [117] requirements in order to provide a realistic engineering basis for what might be accomplished with sufficient development [118, 119].

Concurrently, NASA's Glenn Research Center had been tasked with looking for newer, innovative ways of enabling deep space planetary exploration. Their answer was to consider radioisotope electric propulsion (REP), an approach that could be enabled with sub-kilowatt ion thrusters and high-specific mass radioisotope Stirling (dynamic) convertors [120, 121]. The REP idea had been initiated some years earlier by Robert Nobel at the Fermi National Accelerator Laboratory as a means of enabling deep space, robotic missions to the outer solar system, near interstellar space, and the solar gravitational lens (~550 AU). In all cases, the enabling factor is the specific mass of the propulsion system, including thrusters, power-conditioning electronics, and the radioisotope power source, all of which need to be contained within ~100 kg/kW to <200 kg/kW for a sub-kW system [122]. These concepts were nurtured by the recent successful use of ion propulsion for the primary means of propulsion on the Deep Space 1 (DS-1) mission and had led to a resurgence of interest in the U.S. in ion propulsion [123].

In 2003 NASA released a NASA Research Announcement (NRA) for "Vision Missions" to help with future strategic planning. Of the 15, one-year efforts selected for funding [124], two were for interstellar probe concepts, one building up experience from the NIAC effort noted previously, but switching to REP and elimination of the Oberth maneuver and the other reexamining the use of NEP. Both studies incorporated exercises by JPL's "Team-X," and focused on the same heliospheric scientific goals to be met by similar instrumentation with traceability back to the results of the 1999 IPSTDT effort. Both also relied on a Jupiter gravity assist and electric propulsion.

The NEP approach [125] relied upon the then on-going Project Prometheus effort[6], and, as such incorporated a comprehensive fields and particles payload augmented with remote sensing instrumentation for investigation of KBOs and the dust and neutral characteristics of the solar system and interstellar space. The payload mass is 174 kg using 176 W of power and generating 9.75 kbps of data; there are also two probes, bringing the mission module to 1500 kg, total. The overall spacecraft dry mass, "wet" mass (i.e., fueled), and power requirements were 19 mt, 36 mt, and 125 kW_e, respectively. There were issues with the design closure due to the large specific mass (the α) of the Prometheus system, confirming findings from the concurrent National Research Council (NRC) study [130][7]. The limitations of the relationship between the specific mass of the power system and the time required to reach a given ΔV is a fundamental – and long known [131], although many times forgotten [132] – one, which directly reflects the technology available.

The REP approach [133, 134] (dubbed the "Innovative Interstellar Explorer" (IIE)) incorporated a smaller payload in a much lighter payload, although the payload-to-mass ratios are similar for the two [125] ("you get what you pay for"). Here the key performance parameter is (not surprisingly) the specific power of an REP system (here ~180 kg/kW_e), including efficient production of ~1 kW_e from that system with most of it going to propulsion. Detailed design trades examined gravity-assists out to

[6] Project Prometheus was an initiative begun by NASA Administrator Sean O'Keefe who followed Dan Goldin in that role from 21 December 2001 through 13 April 2005. The project was to provide a Phase A study of a full-up NEP robotic spacecraft, which could fulfill significant science goals in the Jupiter system; the first flight would be the Jupiter Icy Moons Orbiter, a concept which grew out of the Jupiter Icy Moons Tour Study of September 2002. Following the expenditure of almost $464M and an effort of 774.5 staff years across multiple DOE and NASA facilities, the projected cost of ~$16B – not including launch vehicle(s) was considered to be prohibitive and the effort was terminated – as had been all previous NEP efforts – prior to initiation of preliminary design work [126]. Many technical issues remained unsolved, principally, the construction of an appropriate reactor to meet lifetime requirements for deep-space missions [127-129].

[7] Under "Overall Findings" the study committee notes "As shown in Chapter 2, the performance figures from NASA's studies of the Jupiter Icy Moons Orbiter (JIMO) and its parametric studies of candidate post-JIMO missions reveal a significant performance gap (in terms of, for example, transit time and launch mass) between what appears to be currently feasible and what is desirable from a scientific perspective."

the year 2050, as well as a variety of expendable-launch-vehicle/kick-stage combinations, which might increase performance. Design closure with a Delta IV H launch vehicle could be had for a trip time of just under 30 years to 200 AU [135], twice the "desirement" of the 1999 IPSTDT study and solar-sail aim point. The launch C3, the Jupiter gravity assist, and the REP system about equally provide the mission performance[8].

During this same time period work on solar sails continued on both sides of the Atlantic. In particular the European Space Agency had been conducting a long-term technology development program with an eye toward flight [139-142]. The approach was adopted for a series of studies leading to the Heliopause Explorer/Interstellar Heliopause Probe (HEX/IHP) [143-145]. The approach was used in an unsuccessful proposal to ESA for an Interstellar Heliosphere Probe/Heliospheric Boundary Explorer (IHP/HEX) Mission in response to ESA's call for mission proposals within the Cosmic Vision 2015–2025 Programme. The proposal included 91 scientists from 17 countries spread across four continents [146-148]. Turned down for flight, the reasoning for the rejection was forwarded to the proposers on 12 December 2008. While considered "extremely interesting" ESA's selection group found that

> *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. Although there would be cruise phase science beginning around 6 years after launch, the main science targets would not be reached until several decades later. The SSWG felt that this delay in the prime science return would not serve the current community well and was not necessarily in keeping, in the literal sense, with CV 2015–25. It was felt that solar system science would be somewhat on hold were this mission to be approved. In addition, results from Voyager and IBEX in the next decade or so may address some of the science goals, although the latter promises ENA imaging of target regions only.*
>
> *Concerning technical feasibility, it was felt that the proposed mission poses a number of challenges which cannot be met in the timeframe. Principal among these are the solar sail technology – a huge sail (60000 m² on 275m booms) would be needed, which poses a thermal problem, as well as assembly, deployment and AOCS (i.e., Attitude and Orbital Control System) issues. The cost of a demonstrator mission, which would be required, was not included in the proposal (although not required in the call). In addition, the transfer trajectory is very long and would require constant control, and the overall length of the mission has an impact on operations, instrument lifetime, communications and maintaining knowledge. The mission would also need very efficient RTGs. Thus the TRL of some of the technologies was judged to be too low.*
>
> …
>
> *The proposal itself made a strong case, but also honestly recognised the technical challenges. The proposing team was viewed as highly competent and broadly spread around the world. It was felt*

[8] The IIE did not incorporate optical communications, relying instead upon the lower data rates of a "conventional" Ka-band traveling wave tube amplifier (TWTA) and relatively small high-gain antenna (HGA). This was in response to a "major weakness" identified in the initial proposal evaluation, viz. "An optical downlink is baselined for communications. This is a major challenge and adds significant risk. Alternatives should be studied." The "correct" approach to deep-space communication has remained a contentious one, e.g., [136-138].

> *that the proposed mission would be of interest to a broad community of scientists in the future. It would also make a strong impact with the public.*
>
> *Overall, the SSWG felt that IHP/HEX was an innovative mission that addressed our place in the universe and which should be done at some stage, but the prime science phase in the far future and technological difficulties would make it a hard sell to science community. It was felt that the mission needed to be studied at a level below that of a candidate CV2015–25 mission. On the basis of these issues, the SSWG decided not to pursue this proposal and placed it in category C.*

By this time, NASA had begun to study what types of science might be enabled with the large Ares V launcher proposed for development as part of the Constellation system for human return to the Moon [9]. A presentation on this topic was made to an NRC panel on 21 February 2008 [149], and a subsequent workshop with 48 invited attendees was held at NASA Ames Research Center 16–17 August 2008 to investigate what science could be enabled with the notional Constellation program hardware elements. Changing the baseline launch vehicle for the notional IIE mission from a Delta IVH/Star 48 B attack to an Ares V/Centaur configuration would provide a flyout time to 200 AU at just over 23 years with a burnout speed of just under 9.8 AU/yr, ~2.7 times the current speed of Voyager 1 [150].

The third study period: Years 2011 and beyond

We are currently in the third study period. New information from the Voyagers, both now past the heliopause, at a distance only guessed at in 1967, and with a heliosheath filled with energetic particles not foreseen then of itself provides more of a scientific conundrum than before of the interaction of the solar wind with the VLISM. But this has been made even more complicated by the observations of the "ribbon" of emission of energetic neutral atoms (ENAs) observed with the Earth-orbiting Interstellar Boundary Explorer (IBEX) spacecraft along with neutrals at higher energies still observed with the INCA on the Cassini spacecraft in orbit around Saturn. If anything, these new observations have made the imperative for a new *in situ* probe of the outer heliosphere and VLISM even more pressing [151].

Although the Constellation program was cancelled, a new large launcher aimed at enabling human exploration is under active development. The Space Launch System (SLS) in its Block 1B configuration (including a liquid oxygen (LOX)/LH2 upper stage) shows similar promise to the Ares V for enabling scientific missions, which cannot otherwise be accomplished. While the earlier promises of Stirling convertor technology have failed to materialize, making REP questionable, radioisotope power systems (RPS) promise to be available for future use on deep-space systems, including an Interstellar Probe, for which RPS technology would be enabling. Preliminary calculations using multiple kick stages and an unpowered Jupiter gravity assist show promise for the SLS to enable a modest Interstellar Probe to reach 200 AU in about 27 years with a flyout speed twice that of Voyager 1 [152]. Use of the SLS in concert with an Oberth maneuver, powered Jupiter flyby, or other means, as noted later in this report, may offer even shorter flight times with near-term-available technology.

[9] The Constellation Program including the Ares I and Ares V vehicles were initiatives of Administrator Michael D. Griffin, who followed Sean O'Keefe in holding the Administrator's position from 13 April 2005 through 20 January 2009 when President Obama was sworn in.

PART C: INTERSTELLAR MEDIUM SCIENCE AND INSTRUMENTATION

An Atlas Map of the Interstellar Medium (ISM)

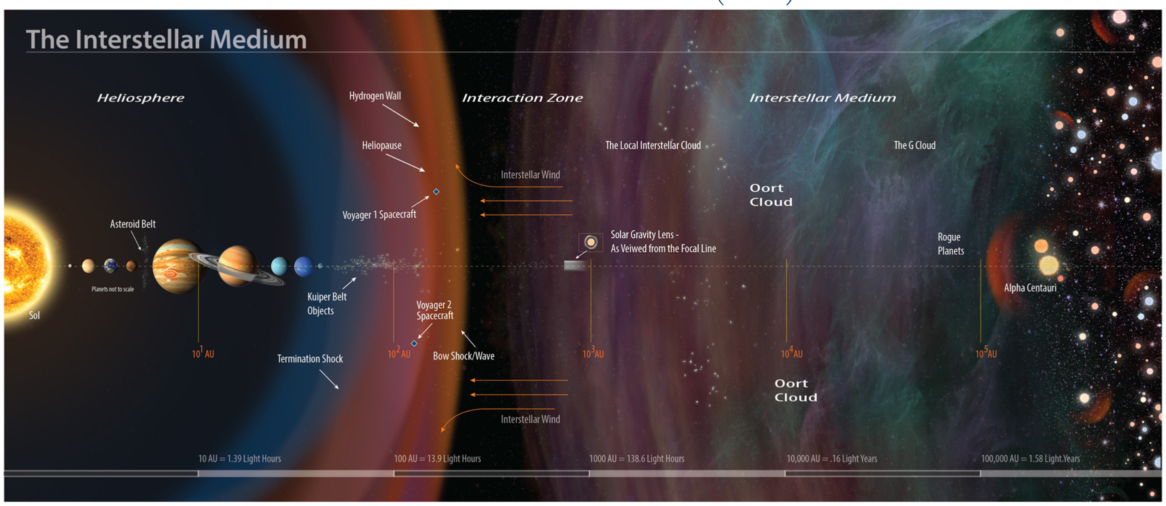


Figure C.1: The Interstellar Medium (Image Credit: Charles Carter / Keck Institute for Space Studies)

Figure C.1 (same as on cover) depicts on a logarithmic scale, the various regions of exploration that can be encountered by a spacecraft on a fast departure from our solar system. Beyond the major planets lies the Kuiper belt as well as the various structures that separate (in a fields-and-particles sense) the region of space dominated by our Sun from that dominated by the Milky Way galaxy at large. This boundary comprises the Termination Shock, Heliopause, Hydrogen Wall, and Bow Shock. Just beyond the boundary lies a region where the LISM and the Sun's Heliosphere interact. Further out lies the undisturbed pristine ISM. The distance at which the Sun's gravity can be used as a lens is also depicted on the graphic. Further out is the region of the Oort Cloud of pristine comets and possibly rogue planets. The closest star is Alpha Centauri. A scientific robotic probe to the ISM would conduct science that spans multiple astronomical regions that are traditionally addressed by different science communities and program directorates at NASA: Heliophysics, Planetary, and Astrophysics. In the following, we give a brief overview of the science in each of these three disciplines.

Chapter C.1: Science of the Outer Heliosphere and Nearby ISM

C.1.1. Structure of the Heliosphere (introduction)

As the Sun travels through the ISM it emanates plasma with supersonic speeds of 400–800 km/s called the *solar wind*. The solar wind flows well beyond the orbits of the planets and collides with the ISM. The plasma bubble-like region created by the solar wind around the Sun is called the *heliosphere*. At the heliosphere boundary interaction of the solar wind with the interstellar gas creates an interface with a complex structure shown in Figure C.1.1. The *termination shock (TS)* marks the boundary where the supersonic solar wind decelerates to slower subsonic speeds. The *heliopause (HP)* is the boundary separating the hot solar wind and the colder, denser interstellar plasma and is often considered as the boundary of the heliosphere. The region between the TS and HP with decelerated compressed hot solar wind is called the *heliosheath*. The ISM is disturbed by the interaction with the heliosphere. Depending on the properties of the local ISM a *bow shock* or *bow wave* forms in the interstellar plasma in front of the heliosphere.

There are several basic features of the very nature of heliosphere that are still not well understood. These aspects stem from the very "shape" of the heliosphere; the extent of its tail; the nature of the heliosheath; the structure of the ISM just ahead of it. Both the in situ measurements by two Voyager spacecraft and the remote energetic neutral atoms (ENA) maps from IBEX and CASSINI help us solve some of the problems but brought many more puzzles. These missions will continue to unravel more surprises and help us constrain some of the models. However only with a revisit of this region

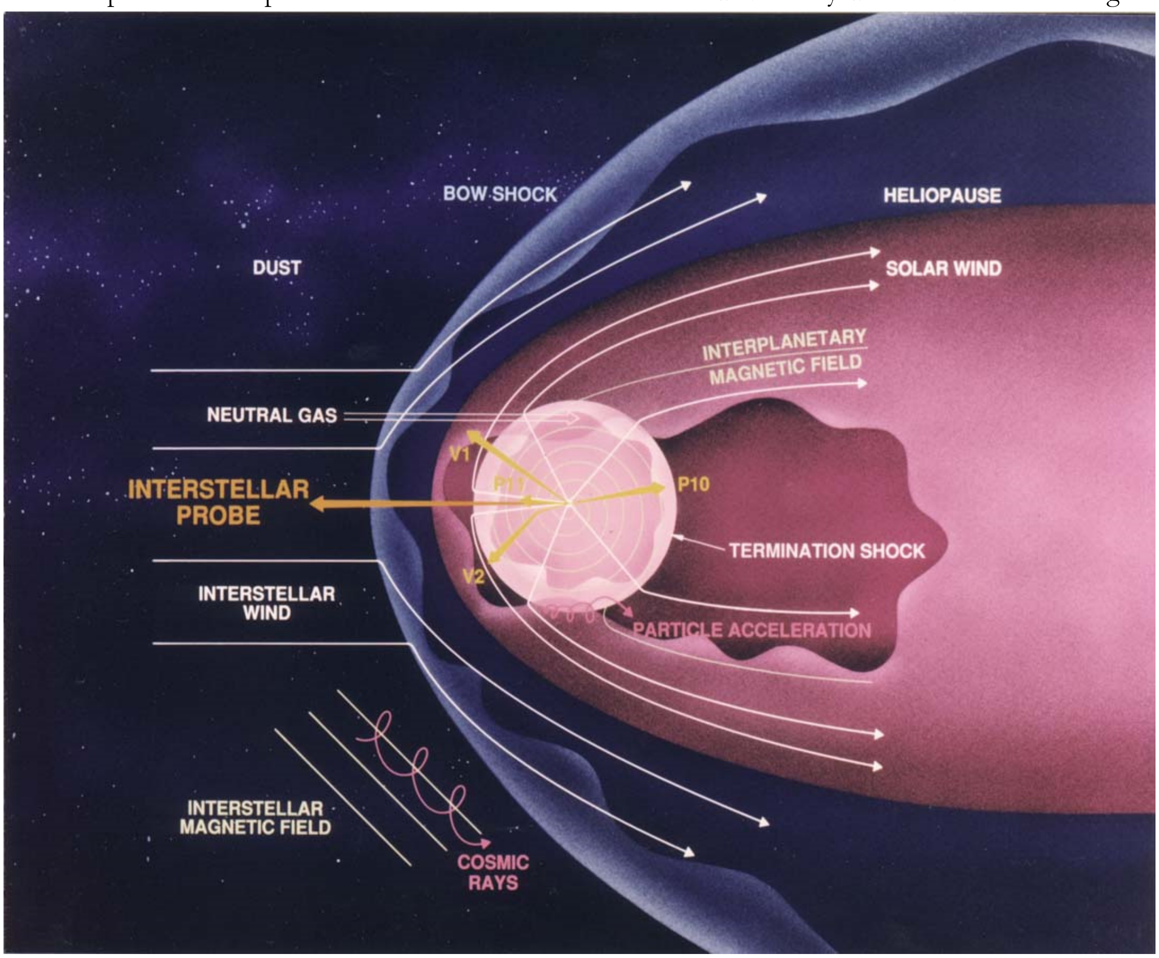


Figure C.1.1: Structure of the region where solar wind interacts with the ISM.

with a modern instrumentation; we will be able to shade light on the very fundamental aspects of our home within the galaxy, the heliosphere.

The shape of the heliosphere and the structure of the interface are determined by various physical processes. Interstellar hydrogen atoms penetrating into the heliosphere interact with the solar wind protons in a charge exchange process creating an energetic population of ions called *pick up ions* (PUIs). Early theoretical studies predicted that the charge exchange process decelerates the solar wind and pushes the heliosphere boundary toward the Sun.

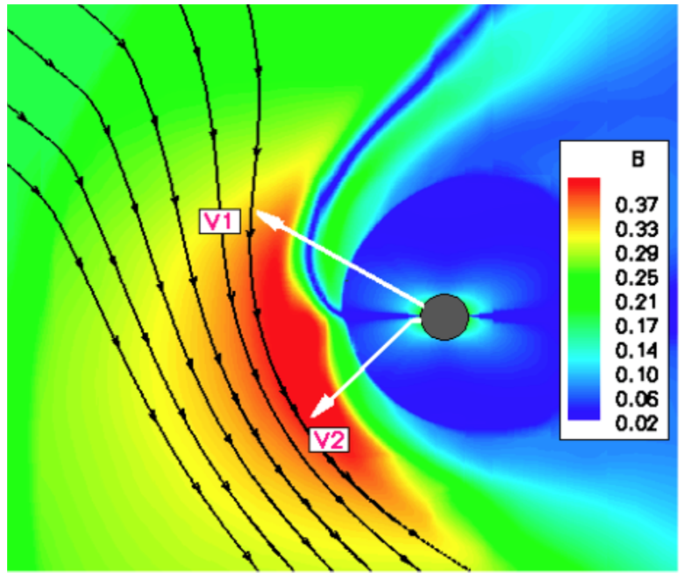


Figure C.1.2: Tilted interstellar magnetic field (black curves) creates asymmetric heliosphere. Trajectories of Voyager 1 and 2 are shown by white arrows. [153]

Both solar wind and ISM are magnetized and the magnetic field is one of the key elements determining the structure of the outer heliosphere. A tilted interstellar magnetic field distorts the shape of the heliosphere producing the asymmetry of the TS and HP (Figure C.1.2). The B_{ISM} distorts the heliosphere, pushing the southern side closer to the Sun. The heliospheric asymmetry was confirmed by the crossing of the TS by Voyager 2, 10 AU closer to the Sun than V1, although part of the asymmetry could be due to time-dependent effects (as argued by works such as Pogorelov et al. [154]).

The very nature and direction of the magnetic field ahead of the heliosphere is being debated. The observed heliospheric asymmetries seen by Voyager [155, 156] suggest a strong interstellar magnetic field with the strength of ~4 μG and north-south component producing a tilt angle ~10–20° relative to the interstellar flow direction V_{ISM} (with respect to the Sun). Another constraint on the B_{ISM} is the deflection of the H atoms with respect to the He atoms [157, 158] that constrains the plane B-V of the B_{ISM}-V_{ISM} to be in what is referred as the "Hydrogen Deflection Plane" (60° from the ecliptic plane). In 2009, the Interstellar Boundary Explorer (IBEX) revealed that the energetic neutral atoms maps produced a ribbon of higher intensity around energies ~1 keV [159]. There is an ongoing debate where the ribbon is produced and by which mechanism; although generally it seem to be organized by the direction where the radial component of B_{ISM} goes to zero (B_{ISM} * r =0). Works that try to fit the IBEX ribbon by mechanisms that produce them outside the Heliopause (e.g., [160]); use a direction where the title angle is larger ~30–40° relative to the interstellar flow direction and intensity not exceeding 3.5 μG with a B-V plane that differ from the HDP plane by 20°. This debate can only be resolved as the Voyager mission or a future one adventures farther into the ISM ahead of the Heliosphere.

Another debate is the extent with which the heliosphere influences the local ISM and how B_{ISM} drapes around the heliosphere; either as an ideal draping or mediated by another process (such as temporal instabilities; or reconnection). The expected direction of B_{ISM} implies that the interstellar magnetic field is not parallel to the solar Parker spiral magnetic field, which has an east-west direction. The models predicted the dramatic rotation of the magnetic field direction after the heliopause crossing; however, when Voyager 1 crossed the HP at the distance of ~120 AU in August 2012, observations revealed completely unexpected behavior of the magnetic field. The magnetic field magnitude increased from 1 μG in the heliosheath to ~4 μG outside the HP, but there was almost no change in the direction of the magnetic field. These data sparked a search for physical processes responsible for such behavior of the magnetic field at the heliosphere boundary. Recent work [161] suggested that the draping of the interstellar magnetic field B_{ISM} around the HP is strongly affected by the solar wind magnetic field. As it approaches the heliopause, B_{ISM} twists and acquires the east-west component. The physical reasons for such interaction of the heliospheric and interstellar magnetic fields remain to be understood. Some recent works argue that the observed direction of B_{ISM} outside the HP can be explained by draping around an ideal surface [162]. Others explain the change in direction by temporal instabilities [163, 164].

Another recent debate is the very shape of the heliosphere and the extent of its tail. The long accepted view of the shape of the heliosphere is that it is a comet-like object [41, 165] with a long tail opposite to the direction in which the solar system moves through the local ISM. The solar magnetic field at a large distance from the Sun is azimuthal, forming a spiral (the so-called "Parker spiral") as a result of the rotation of the Sun. The traditional picture of the heliosphere as a comet-like structure comes from the assumption that, even though the solar wind becomes subsonic at the termination shock as it flows down the tail, it is able to stretch the solar magnetic field. Opher et al. [166] argued, based on magnetohydrodynamic (MHD) simulations, that the twisted magnetic field of the Sun confines the solar wind plasma and drives jets to the north and south very much like some astrophysical jets. Astrophysical jets around massive black holes are thought to originate from Keplerian accretion disks and are driven by centrifugal forces [167]. However, the jets in the case of the heliosphere are driven downstream of the termination shock similar to what was proposed for the Crab Nebula [168, 169]. In this region of subsonic flows, the magnetic tension (hoop) force is strong enough to collimate the wind. The tension force is also the primary driver of the outflow (Figure C.1.3, [166]).

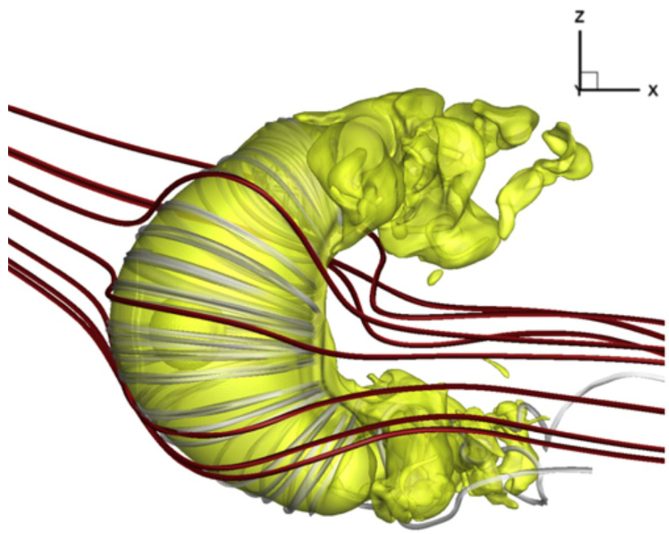


Figure C.1.3: Two-lobe structure of the heliosphere. Yellow surface shows the heliopause surface. Grey curves show the solar magnetic field lines; red curves, interstellar magnetic field lines. [166]

The overall two-lobe structure is consistent with the ENA images from IBEX that mapped the heliotail for the first time. Such images show two lobes [170] with an excess of low energy ENA (<1 keV) and a deficit at higher energy (>2 keV) around the solar equator. The ENA images from Cassini [171] revealed intensities that were comparable in the direction of the nose and tail. The observers therefore concluded that the heliosphere might be "tailless" because the emission from these high-energy ENAs is believed to come from the heliosheath. The two-lobe heliosphere is in fact almost "tailless" with the distance down the tail to the ISM between the lobes being nearly equal to the distance toward the nose.

McComas et al. [170] interpreted the ENA tail measurements as a result of a slower wind, which are due to the fact that the Sun has been sending out fast solar wind near its poles and slower wind near its equator. With additional ENA measurements through an extended solar cycle it will be possible to distinguish between the two scenarios.

In short, as described above, it is crucial to revisit the region with modern, new *in situ* observations, which would be crucial to distinguish among the existing theories and to understand the physical picture of this region.

The main Science questions:

1) How does the solar wind interact with the ISM and how does this relate to the interaction of other stars with their interstellar surroundings and formation of astrospheres?

2) How does this interaction lead to the observed complexities of the three-dimensional structure of the heliosphere?
3) What is the nature of the termination shock?
4) What is the nature of the heliosheath?
5) What are the properties of the heliopause transition region?
6) How does the heliosphere affect the properties of very local ISM and how do they relate to the pristine ISM?

Another way to probe the heliosphere is indirect measurements through measuring fluxes of energetic neutral atoms (ENAs) and backscattered Lyman-alpha emission. We describe those in section *F* and the consequence for the structure of the heliosphere.

C.1.2. Solar Wind in the Outer Heliosphere

The solar wind evolves as it moves outward from the Sun due to the solar cycle variations and interaction with the local ISM. Voyager 2 data showed that the speed is, on average, constant out to 30 AU, and then starts a slow decrease due to the PUIs. Charge exchange with interstellar neutrals reduces the speed by about 20% before the TS. The pickup ions heat the thermal plasma so that the solar wind temperature increases outside 20–30 AU. The pickup ions make up an increasingly large fraction of the solar wind with distance and are estimated to comprise about 20–30% of the solar wind at the TS. To explain the solar wind evolution with distance, the *in situ* measurements of PUIs are needed.

Solar activity over the solar cycle produces variations of the solar wind on various time and spatial scales. Interplanetary coronal mass ejections (ICMEs), often occurring during the solar maximum, move outward, expand, and interact with earlier ICMEs and merge, compressing the solar wind ahead of them to form regions of high magnetic field, often called density merged interaction regions. These regions may drive shocks with rather dramatic change of the solar wind characteristics. During the declining phase of the solar activity the solar wind is dominated by recurring large-scale structures called corotating interaction regions (CIRs) formed due to the interaction of fast and slow solar wind within the 30 degrees above and below the solar equator. These large-scale disturbances and associated shocks propagate outward and affect the TS, plasma dynamics in the heliosheath, the HP and even the ISM beyond the HP.

One of the key scientific goals for the future interstellar mission is to determine the properties of PUIs in the distant solar wind where they play a critical role in the behavior of the solar wind.

C.1.3. Termination Shock

Both Voyagers 1 and 2 (V1 and V2) are now beyond the TS, V1 most likely beyond the HP, although there are investigators that disagree that V1 is beyond the HP [172-175].

The main disagreement stems from the magnetic field measurements that indicate that the magnetic field as measured by V1 did not change direction across that boundary. We will come back to that later, when we discuss the HP. V2 is the only Voyager spacecraft carrying a working plasma instrument (although the plasma flows in the RT plane can be inferred from the particle anisotropies from V1 [176])

With the crossing of TS by V2 that carried the working plasma instrument, it has become clear that the TS was not a just a one-fluid MHD perpendicular shock as previously expected. One of the surprises was that the heliosheath plasma temperature was much colder, by an order of magnitude than expected if all the energy upstream was transferred to the plasma thermal population [177] (Figure C.1.4). The measurements downstream of the TS are consistent with 80% of the energy transferred to the suprathermal population, the pick-up ions [178, 179]. PUIs are not measured by the two Voyager spacecraft. In fact there is a *gap* in energy between the thermal plasma (at energies <1 keV) to 40 keV, the lowest energy measured by the LECP instrument. It is also possible that electrons played an important role in the energy budget stealing part of the energy downstream [180]. Again there is a gap between what the plasma instrument measures (~eV) to the lowest energies at LECP (30 keV). It is possible that hot electrons play an important role in the TS crossing and downstream in the heliosheath thermodynamics [181-183]. *This can only be resolved with a new visit to that region with proper instrumentation that bridges the gap in those energies; i.e., able to measure the suprathermal PUI population from 1 keV–40 keV and energetic electrons in the same energy.* Only then will we be able to definitively probe the structure of the TS and the thermodynamics of the HS.

C.1.4. Heliosheath

As Voyagers 1 and 2 adventured into the region where the solar wind is subsonic, the heliosheath (HS), it became clear that there are several observations that challenge our understanding of that region. While global models advanced rapidly in sophistication in the last decade, these models are still not able to predict self-consistently the flows, fields, and particles behavior in the HS. Furthermore, none of the current standard global models predict the very thin HS (~30–40 AU), implying that V1 did indeed cross the HP.

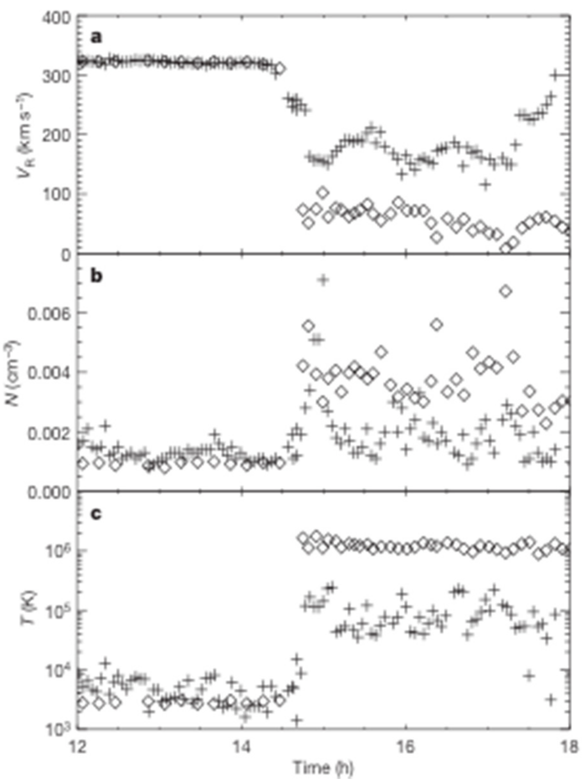


Figure C.1.4: From Richardson et al. [177]. The V2 data measured at TS (crosses), "in comparison with V2 data measured at Neptune's inbound bow shock crossing (diamonds). The solar wind parameters upstream of Neptune are normalized to those upstream of the TS; the timescales are identical. The solar wind speed (a; Neptune data divided by 1.3) at the bow shock fell by a factor of four but at the termination shock the speed decreased by a factor of only two. The density (b; Neptune data divided by five) at the bow shock increased by a factor of four, but at the termination shock by a factor of two. The major difference is in the temperature (c; Neptune data divided by two): at the bow shock it increased by a factor of 100, but at the termination shock by a factor of only ten. The differences between these two shocks are probably caused by the greater abundance of pickup ions at the TS".

There are several observations that are key challenges to the heliospheric models:

1) The flows at V1 and V2 are very different;
2) the presence of a flow stagnation region seen at V1;
3) the V1 observations suggest that the magnetic flux in the HS is not conserved;
4) the fact that the Anomalous Cosmic Ray (ACR) spectrum roll out well into the heliosheath;
5) the thin heliosheath; and
6) different behavior of energetic particles at V1 and 2; including dropouts of ~1MeV electrons and the most energetic ACRs at V2.

One of the biggest puzzles is why the flows in the heliosheath are so different at V1 and 2 (Figure C.1.5). After six years in the sheath, V2 flow magnitudes remain high, near 150 km/s, while V1 flows dropped to zero after 2010 and are sometimes negative. In fact, all the components of the speed at V1 became small in 2010 [184]. Current global models do not correctly predict the observed flows at V1 and V2 either in magnitude or direction. All current models [155, 156, 185, 186] predict that the HS flows will slowly turn to the flanks and to the poles as the Voyagers move deeper into the sheath. Instead, the V2 flows turn much more rapidly in the transverse direction than in the normal direction. Is the HP flatter than we thought or are we missing something else?

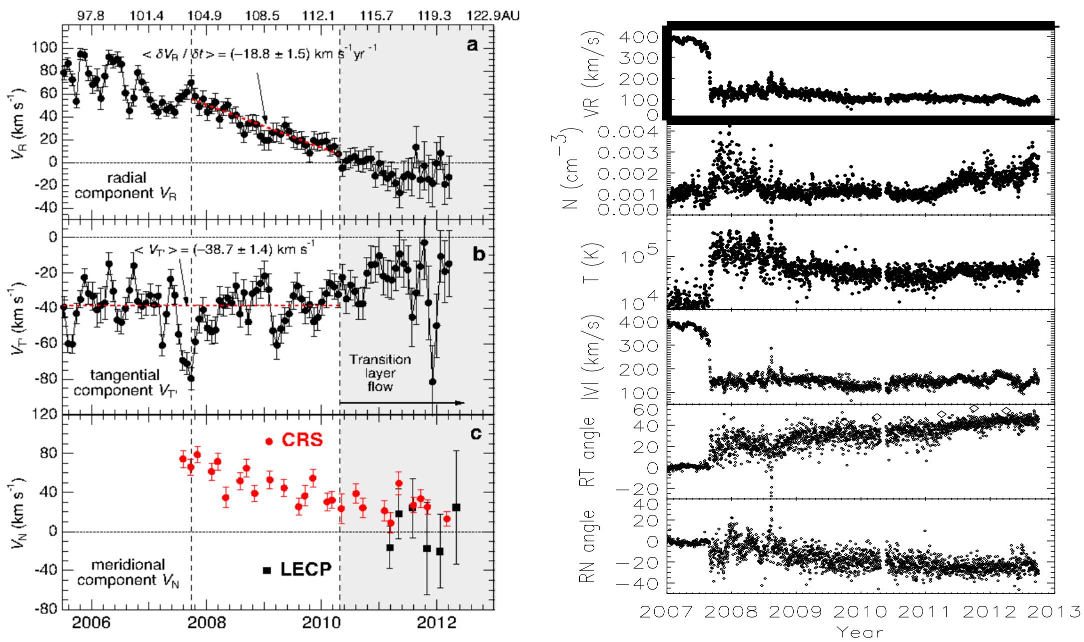


Figure C.1.5: Very different flows on board of V1 (left panel) and 2 (right panel). V1 doesn't measure directly the flows. They are inferred. The velocity components in V1 are calculated from measurements of 53–85 keV ion intensities. The components that V1 is able to extract are in the RT plane in the R-T-N heliographic polar coordinates in which the transverse (+T) direction is that of planetary motion around the Sun and +R is the radial direction relative to the Sun. Panel (b) shows the VR components as well as density N; temperature T and the RT=$\tan^{-1}(V_R/V_T)$ and RN=$\tan^{-1}(V_R/V_T)$ angles on V2.

In particular, the zero values of radial flow at V1 pose a challenge to the models, since in current models the flow rotates parallel to the HP and the radial component gradually decreases asymptotically (not abruptly) to zero, and it should become zero only at the HP itself.

There have been recent suggestions that the flows can be explained by the gradients in pressure as shown by the integrated pressure flux of PUIs [187].

Another puzzle comes from the magnetic field. We expect that from flux conservation, $B_T V_R R \sim$ const. However, when V_R decreased at V1, the magnitude of B_T did not increase as expected (Richardson et al. 2013) (Figure C.1.6). Even as V_R went to zero, B_T stayed around 0.1–0.2 nT [188]. (The exact conservation is $B_T V_\perp L \sim const.$, where $V_\perp = \sqrt{V_R^2 + V_N^2}$, and L is the separation between streamlines). The non-conservation of magnetic flux cannot be explained by solar cycle variations of the solar wind and magnetic field intensity [189].

After the crossing of the TS by V1 and then by V2, one of the first surprises was that both Voyager spacecraft found no evidence for the acceleration of the anomalous cosmic rays (ACRs) at the TS, as expected for approximately 25 years [190]. The expectation was that the ACRs were accelerated at the largest shock in the heliosphere, the TS. The ACR intensities not only did not peak at the shock, but their intensity kept increasing as the spacecraft moved deeper into the sheath [191, 192]. This finding generated several hypotheses for the ACRs acceleration mechanisms and locations: in the flanks of the shock [193]; in "hot spots" in a turbulent TS [194, 195]; deep in the sheath; by reconnection [196, 197]; or by turbulence processes also deep in the hot HS [198].

Another mystery comes from the different behavior of energetic particles at V1 and V2 (Figure C.1.7). The particles at V2 show variations of intensity of more than three orders of magnitude correlated with periods when the spacecraft was in and out of the sector region (as indicated by Wilcox data) [199], while the intensities at V1 remained steady. When V2 is in the sector region the intensities are substantially higher than when it is in the unipolar region. There is more than a three order of

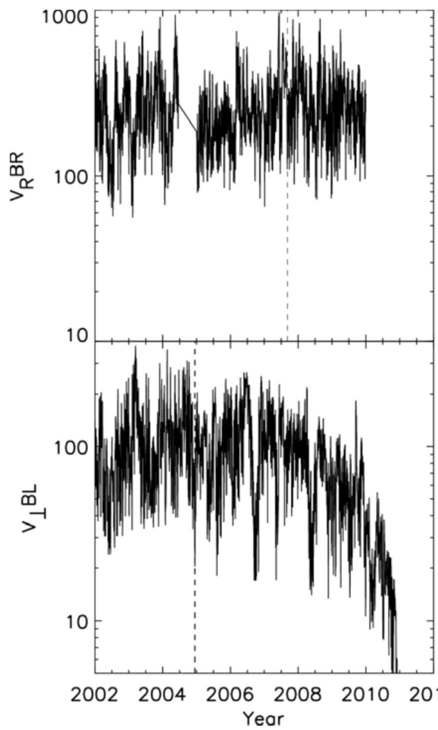


Figure C.1.6: What happened to the missing azimuthal magnetic flux at Voyager 1? The magnetic flux observed at V2 (top) and V1 (bottom). B is normalized by the values at 1 AU, V is in km/s and L is in AU. The vertical dashed lines show the TS locations (from [176]).

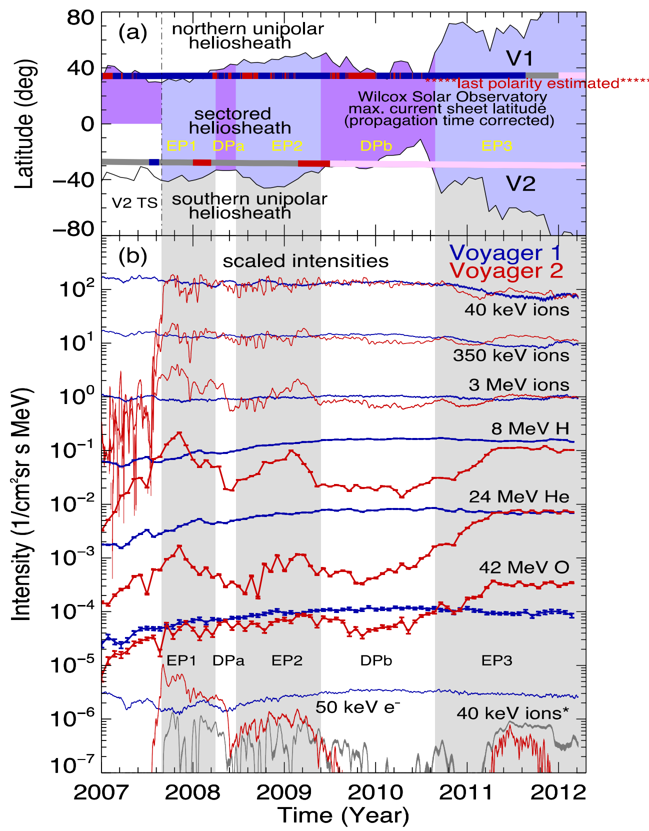


Figure C.1.7: Temporal variations of the latitudinal boundaries of the sectored HS and V1 and 2 energetic ion and electron intensities, where V2 shows a clear correspondence to the sector configuration [199].

magnitude energy range (highest energies not shown) over which ions and electrons vary coherently with the passage of the temporally varying spatial structure, the edges of the sector region.

There is also the problem of the HS thickness. Most models predict a thickness of ~50 AU even after accounting for time dependence [200, 201]. Models that include both the thermal and suprathermal components, such as PUIs (e.g., [202]) predict some reduction in the thickness. But these models still do not match the observed heliosheath thickness of 27 AU.

Which other aspects of the nature of the HS are we missing in our models that could thin the HS?

To solve these puzzles, in the last couple of years, there have been several suggestions for additional effects such as reconnection in the sector region (the region where the solar magnetic field reverses polarity) and near the HP, turbulence, and time-dependent effects.

Reconnection within the sector region (as suggested by [197, 203]) explains the ACR spectrum rolling over well into the HS by acceleration from reconnection. It can also explain the dropout of particles on V2; while particle were steady at V1 by different transport properties within a reconnected sector region – given that V2 was in and out of the sector while V1 was immersed within it throughout its trajectory [203]. Reconnection can also explain the missing azimuthal magnetic flux at V1 and potentially the flow stagnation region seen at V1 [204].

Reconnection within the sector region is a new regime of reconnection different than any other location in the heliosphere; it is where plasma β (ratio of thermal to magnetic pressure) is high (while usually reconnection occurs in regions of low plasma β) and the guide field is zero (anti-symmetric reconnection). In that regime [203, 205], the magnetic islands are very elongated and the magnetic profile is similar to the sector. *This poses a challenge to the magnetometers on Voyagers 1 and 2 that are tuned to* *strong field for the strong fields of the outer planets and not for the week fields of the heliosheath. The uncertainty on the magnetometer on V1 is 0.03 nT in each component and on V2, 0.05 nT, while the average field intensity in the HS is 0.1 nT.*

We need a way to extract energy from the HS. Is reconnection within the sector region (as suggested by [197, 203]) sufficient (Figure C.1.8)? Perhaps the HS has a strong turbulent component (as suggested by [172])? Are temporal effects such as instabilities [164, 206] or other non-ideal MHD effects important? Most likely instabilities such as Rayleigh-Taylor instability won't be present because of the stabilization effect of the interstellar magnetic field. Izmodenov et al. [207] suggests that electron thermal conduction can thin significantly the heliosheath; in the limiting case, where the thermal conduction is very effective, the heliosheath was thinned to 32 AU.

To really understand the nature of the heliosheath and help resolve the different scenarios, a new visit to that region with proper instrumentation is needed, with a high sensitivity magnetometer and an energetic particle instrument that bridges the gap in those energies; i.e., would be able to measure the suprathermal PUI population from 1–40 keV and energetic electrons in the same energy.

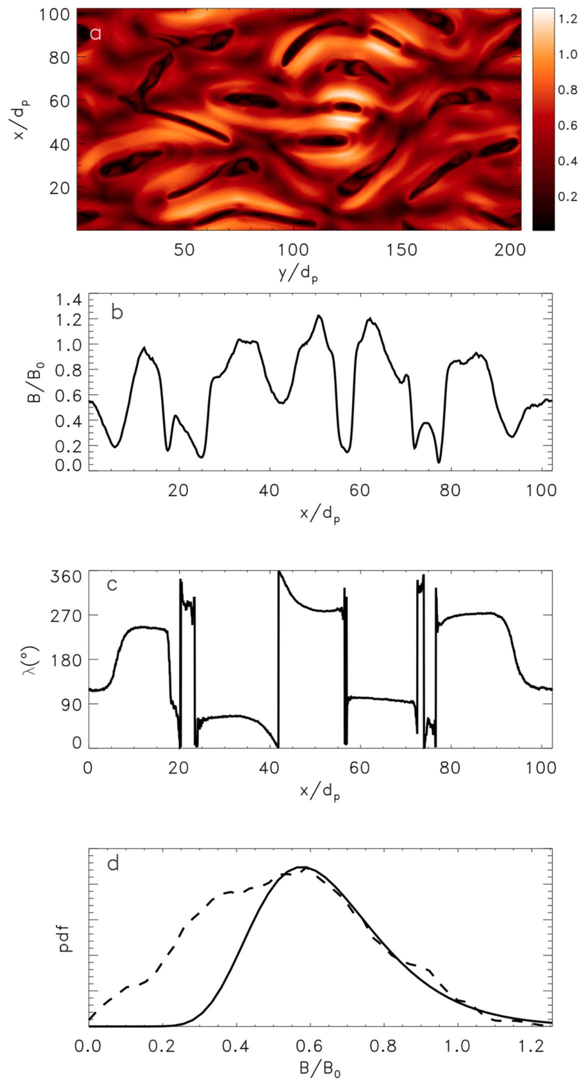


Figure C.1.8: Multicurrent system in its final stage after reconnection ceased. Elongated magnetic islands are formed with intense magnetic field at the walls. The bottom panels show the magnetic field magnitude, direction, and distribution function for a cut through the model results [203].

C.1.5. Heliopause

Between May and August 2012 there was a series of puzzling events. The cosmic ray flux increased rapidly in May. Then in August, the intensity of particles that were accelerated in the heliosphere (from ~30 keV to MeV) decreased to background levels (intensity decreases of a factor of ~1000). At the same time, the galactic cosmic rays intensity again increased, this time to the highest level ever observed. The magnetic field magnitude simultaneously increased (Figure C.1.9). This transition had been dubbed the "heliocliff." One of the expected signatures of the crossing of the HP was that the magnetic field direction would change significantly. This is expected because the solar magnetic field just inside the HP is azimuthal, or east-west, on average (called the "Parker field"), while the magnetic field in the ISM (derived from several indirect indicators) is widely believed to be inclined significantly to the east-west direction [154-156, 185]. The absence of a significant rotation in the direction of the magnetic field at the times of dropouts of energetic particles, were initially interpreted as indicating that V1 was still in the HS [163, 172, 174, 208, 209] although some models suggested the contrary [210].

However, in September of 2013 the plasma wave team announced the detection of 2–3 kHz plasma waves, so the plasma densities indicated V1 was in the ISM [211], although not all agree [172, 174].

If V1 were beyond the HP, then why is the magnetic field outside the HP still within ~20° of the Parker spiral direction [212] and thus very different from the B direction expected deeper in the ISM? Could this difference be due to the shape of the HP and magnetic draping geometry, MHD instabilities, temporal aspects, or not having really crossed HP? Opher & Drake [161] propose that, regardless of the direction in the ISM, near the HP the field twists to the Parker direction (Figure C.1.11). Not all modelers agree and this question is being hotly debated. Some argue that *ideal* draping, i.e., draping on a surface without communication between the solar and interstellar magnetic field can account for that (e.g., [213]) Do other aspects, such as reconnection or turbulence, play a role in this local rotation? The implications of understanding the behavior of the magnetic field ahead of the HP has consequences not only for what V2 will encounter as it approaches and crosses the HP, but for what V1 will see as it adventures farther away from the HP into the ISM.

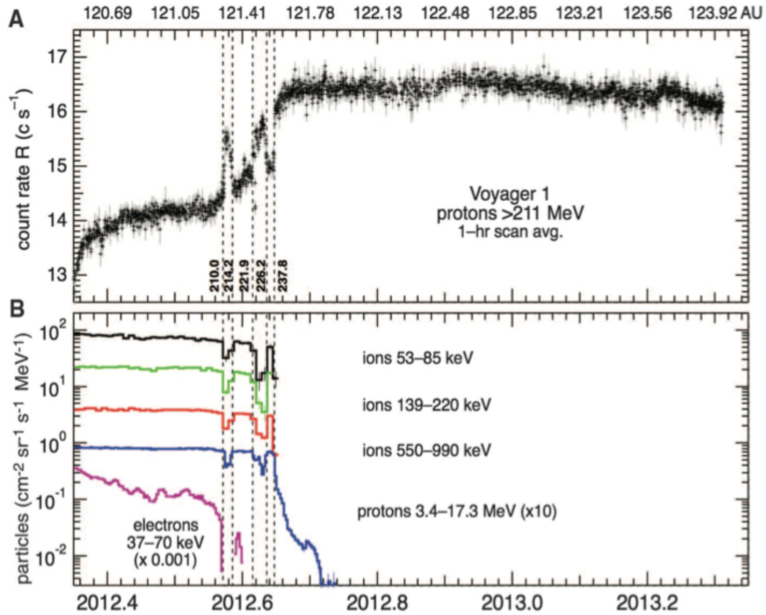


Figure C.1.9: Overview of the energetic particle observations at V1, 2012.35 to 2013.40 showing the contrary behavior of GCRs and lower-energy particles (from [163]).

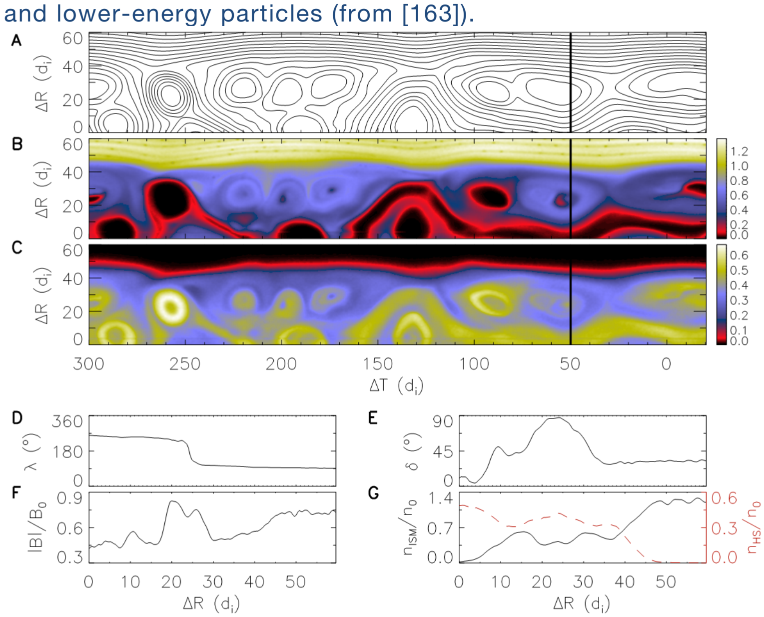


Figure C.1.10: Structure of the HP and adjacent LISM and HS at late time from the PIC simulation. In the R/T plane in (A) the magnetic field lines and in (B) and (C) the number density nLISM (nHS) of particles originally in the LISM (HS). Panels (D)–(G) are cuts along the vertical line in panels (A)–(C). In (D) λ is the angle of B in the R–T plane with respect to the R direction. In (E) δ is the angle between B and the R–T plane. In (F), the magnitude of B and, in (G), the number density nLISM (solid) and the number density nHS (dashed red) (from [210])

Swisdak et al. [210], based on particle-in-cell simulations, derived from cuts through the MHD model at V1's location, suggest that the sectored region of the HS produces large-scale magnetic islands that reconnect with the interstellar magnetic field while mixing LISM and HS plasma. Cuts across the simulation reveal multiple, anti-correlated jumps in the number densities of LISM and HS particles at magnetic separatrices where there is essentially no magnetic field rotation (Figure C.1.10). The absence of rotation at these dropouts is consistent with the V1 observations. This model [210] says that V1 had crossed the HP at the end of July 2012. Soon after this paper was published, the Voyager team reached the conclusion that V1 was in interstellar space, based on the detection of radio emissions [211].

Other works proposed that the HP dropouts could be explained by MHD reconnection predicting island structures before the crossing of the HP [215].

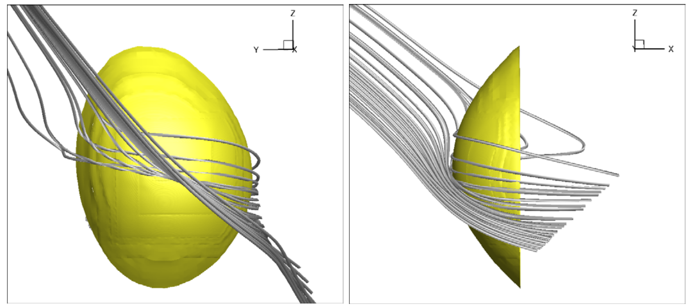


Figure C.1.11. View at the nose of the heliosphere from the ISM towards the Sun. The nose of the HP is shown in the yellow iso-surface (defined by ln T=11.9-12). The gray field lines are the B_{ISM} wrapping and twisting around the HP [214].

It is debated within the community if similar structures should be expected or will be seen when V2 crosses the HP. In any case, the plasma instrument on board V2 will only be sensitive to the thermal component. *In order to sort out the different scenarios, this region should be revisited with a sensitive magnetometer and a particle instrument covering the suprathermal populations, especially in the gap between 1 keV–40 keV.*

C.1.6. Hydrogen Wall & Bow Shock

Hydrogen wall (H-wall) is the region with high density of hydrogen atoms upstream of the nose of the heliosphere (Figure C.1.12). It is created by hydrogen atoms originated in the charge-exchange process in the region between the HP and bow shock. Interstellar plasma is decelerated and heated as it approaches the HP from outside. Hydrogen atoms coupled to the plasma also slow down and thus have a higher density compared to the pristine ISM. H-wall was predicted by the models of the outer heliosphere [165, 216, 217]. Linsky & Wood [218] have discovered H-wall absorption for the first time in the Ly-α spectra measured by the GHRS instrument onboard HST toward α-Centauri. HST/STIS measurements of absorption spectra toward another star have confirmed the presence of H wall [219]. H-wall existence has been inferred from Voyager UVS Ly-α data [220]. HST observations also yielded detections of analogous astrospheric absorption from material surrounding other observed stars. This indicates that H-wall is a common astrospheric phenomenon and our heliosphere is not unique but rather a typical example of an astrosphere forming around wind-driving stars. The astrospheric detections dramatize the importance of understanding the heliospheric interaction. However, H-wall was never observed *in situ* and the properties of the neutral component beyond the heliopause are not known: a) What is the enhancement of hydrogen density in H-wall compared to interstellar value? b) Is H-wall homogeneous or non-homogeneous? c) What is the spatial extension of H-wall? d) Is H-wall asymmetric? f) Do transients propagating from the heliosphere outside affect the dynamics of H-wall?

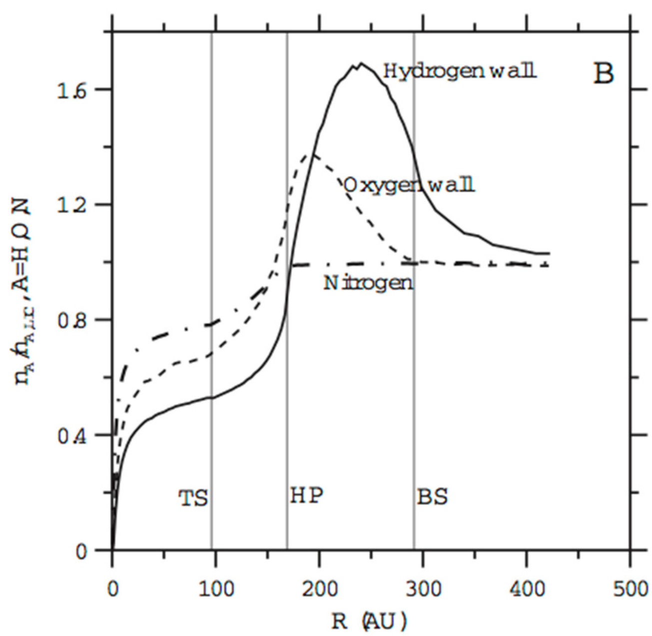


Figure C.1.12: Number density of various neutral elements along the direction from the Sun toward the nose of the heliosphere. Increase of hydrogen density between the HP and bow shock represent the Hydrogen wall. [207]

Recent analysis of IBEX data indicates that the speed of the local interstellar flow is 23.2 km/s, which is lower than previously derived from Ulysses data, 26.4 km/s [221]. Depending on the parameters of the ISM (the magnetic field strength and temperature) the interstellar flow can be super-fast-magnetosonic or sub-fast-magnetosonic [222]. Thus, the bow shock may exist or not ahead of the heliosphere. Interstellar neutrals also can mediate the bow shock structure via charge-exchange. Recent model by Zieger et al. [223] showed that with reasonable parameters of local ISM, a spatially confined quasi-parallel slow bow shock forms ahead of the heliosphere in the direction corresponding to V1's trajectory. Parameters of the local ISM inferred from IBEX data suggested that there is no bow shock [221], but rather a "bow wave" of enhanced density forms in front of the heliosphere nose with no shock transition.

Does the heliosphere possess the bow shock or not is an important question that also has consequences for the turbulence in the outer region ahead of the HP. The shock can generate turbulence that translates into locally decreased spatial diffusion of energetic particles thus contributing to a shielding against galactic cosmic rays.

C.1.7. Cosmic Rays in the Heliosphere and Nearby Interstellar Medium

Galactic cosmic ray (GCR) intensity, spectra, and composition measurements over more than half a century have shown that the 11-yr and 22-yr cosmic-ray cycles are due to cosmic-ray "modulation" processes that include convection in the solar wind, diffusion and adiabatic energy-loss in the turbulent interplanetary magnetic field (IMF), and gradient and curvature drifts in the large scale IMF [94, 224, 225]. In addition, a much longer record of cosmic-ray intensity variations based on ^{10}Be deposits in ice cores and ^{14}C in tree-rings has shown that the space era to date has occurred during the most recent of more than 20 "Grand Maxima" in solar activity that have occurred over the past 10,000 years [226]. Interspersed between these Grand Maxima have been at least 22 Grand Minima during which solar activity is low and the >100 MeV cosmic ray intensity at Earth can be as much as ~2 times greater than during the space age [227]. The most recent examples are the Maunder (1645–1715), Dalton (1790–1830), and Gleissberg (1890–1910) minima.

During 1972–1999, Pioneer, Voyager, Ulysses, and near-Earth instruments measured large-scale spatial and temporal variations in cosmic rays from ~1 to ~90 AU and out of the ecliptic (e.g., [228]). These exploratory missions demonstrated the role of various cosmic-ray modulation processes, and also found that large-scale global merged interaction regions (GMIRs) composed of coalesced ICMEs were instrumental in modulating cosmic-ray intensities. When ISP flies we are unlikely to have such a global network, but if the present grand maximum is over [226, 229], we will have a much weaker IMF, less turbulence, faster drift speeds, a smaller heliosphere, and presumably also have similar changes in the heliosheath. This will allow the ISP to explore the manner in which cosmic-ray modulation operates during more typical conditions in our heliosphere.

C.1.8. Anomalous Cosmic Rays and other Energetic Ion Sources

Anomalous Cosmic rays (ACRs) are so named because they have an anomalous composition, including those elements that are predominately neutral in the ISM (H, He, N, O, Ne, and Ar). Soon after the discovery of ACRs in the early 1970's Fisk, Ramaty and Koslovsky [190], proposed that ACRs are made from interstellar neutrals that pass freely into the heliosphere, that are then ionized by charge-exchange or solar UV. Once charged, they are picked up by the solar wind (becoming "pickup ions"), and are convected to the outer heliosphere, where (it was proposed by Pesses et al. [230]) they get accelerated to energies of 1–100 MeV/nuc at the solar wind termination shock.

However, when the Voyagers crossed the termination shock they observed acceleration to at most a few MeV/nuc [231], implying that most ACR acceleration occurs elsewhere. Current models include acceleration at the flanks or tail region of the termination shock, well away from where the Voyagers crossed [193]; acceleration by contraction of magnetic islands resulting from magnetic reconnection near the heliopause (e.g., [197]), and acceleration in the heliosheath as particles move within random compressions in the plasma [198]. There is so far insufficient evidence to choose between these or other possibilities.

With the exception of a source at the flanks or tail of the termination shock [232], the advanced payload of the Interstellar Probe may resolve this mystery with complete measurements of ACRs from pickup-ion energies to 10–100 MeV/nuc coupled with comprehensive measurements of magnetic field and plasma properties in the outer heliosphere. In addition, the ISP should be capable of resolving other sources of suprathermal ions that include non-volatile elements [233] such as the "Outer Source" of ions sputtered from dust in the Kuiper belt region [232] and ions made from charge exchange of ENAs measured by IBEX and Cassini [234].

C.1.9. ENA, SOFT X-RAY AND LYMAN-ALPHA IMAGING

Another way to probe the heliosphere is through energetic neutral atoms (ENAs). Both Interstellar Boundary Explorer (IBEX) and CASSINI/INCA instruments mapped that region in different energy ranges. IBEX is a small explorer mission that revolves around the Earth returning ENAs images in the range 0.2 keV–4.3 keV range [159]. CASSINI/INCA measures ENAs in much higher energy range (~5.4–55 keV) [171]. Both spacecraft measured unexpected features: IBEX, a so-called "ribbon" around 1 keV energies, and CASSINI/INCA a so-called "belt" around 4–13 keV. The IBEX "ribbon" seems to be organized by the interstellar magnetic field $BISM \cdot R = 0$ (or the location where the radial component of BISM is zero) and prompted a series of papers trying to explain its origin. In any case these data demonstrated as well as the Voyager heliospheric asymmetries that the heliosphere is strongly affected by the interstellar magnetic field.

All the different theories have pros and cons when compared to the data as summarized by McComas et al. [236]. Because of the ordering with $BISM \cdot R = 0$, most proposed mechanisms are outside the heliosphere in the outer heliosheath. Some proposed mechanisms make use of secondary charge exchange (e.g., [160]), magnetic mirror [237], etc. However there is an issue of scattering and stability of the PUIs in the LISM [164], so more recent mechanisms use some kind of trapping mechanism [238].

Very few works tackled the origin of the CASSINI structure that seems to organize itself in a "belt" in a location similar, but not equal to, the IBEX ribbon.

Recently, the IBEX team separated the distributed flux emission from the ribbon [170, 235]. The distributed flux emission gives a global view of the structure of the heliosphere since it is believed to be produced in the inner heliosheath. In particular, the tail emission seem to be organized by a two-lobe structure. The ENA tail observations [170] reveal two lobes at high latitudes and depletion

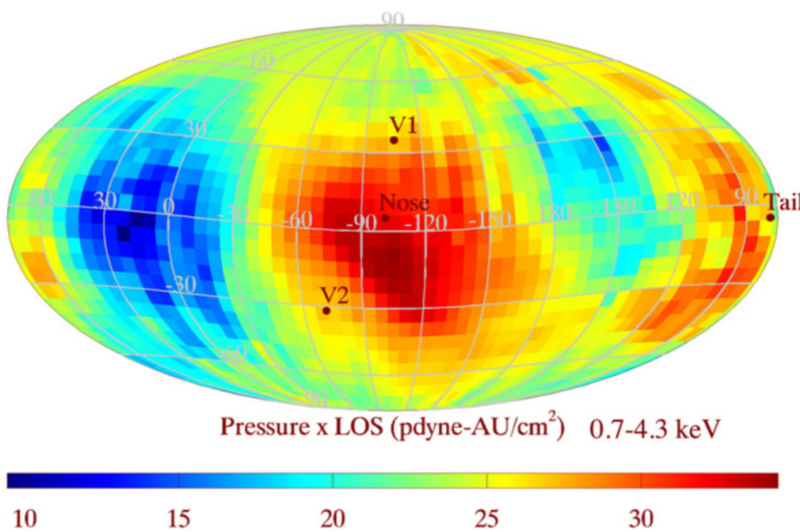


Figure C.1.13. From [235]. Pressure of plasma protons that form observed ENAs integrated over line-of-sight (LOS) as observed by *IBEX* and referenced to the inertial frame *IBEX*-Hi measurements from *IBEX*-Hi (from 0.7 to 4.3 keV) from 0.7 to 4.3 keV – perhaps image of ribbon as well.

in low latitudes of high energy ENAs (~4 keV) while, in low energies (~0.7 keV), the tail appears as two separate enhancements in low latitudes. McComas et al. suggested that these observations resulted from the spatial separation of slow and fast winds. The ENA images from Cassini [171] revealed intensities that were comparable in the direction of the nose and tail. The observers therefore concluded that the heliosphere might be "tailless" because the emission from these high-energy ENAs is believed to come from the heliosheath. The two-lobe heliosphere is almost "tailless" with the distance down the tail to the ISM between the lobes being comparable to the distance to the ISM at the nose.

Moreover, the ENA emissions show strong time variations [187] that need to be explained.

Finally an interesting complement is the low energy ENAs that are order of magnitude higher than models predict. The low energy ENAs (measured by IBEX-Lo) struggle with signal-to-noise ratio so the statistics are poor. The low energy ENAs could indicate that additional heating has to be occurring within the heliosheath [214] or that there are additional PUI populations that are important outside the HP [239].

The problem that the IBEX team faced (similar problem with CASSINI/INCA) is the sensitivity of the instruments requiring 3 years to be able, for example, to separate the tail emission from the rest, or the distributed flux. With a new mission adventuring towards the ISM having an ENA camera with a high sensitivity from energies of 0.2 keV all the way to high energies ~40–50 keV will be crucial to put in perspective the measurements with a global view of the heliosphere.

First measurements of the solar Lyman-alpha emission backscattered by the interstellar hydrogen atoms penetrating into the interplanetary medium were reported in early 70s [240, 241]. Spectral properties of the backscattered solar Lyman-alpha radiation essentially depend on the distribution of hydrogen atoms inside the heliosphere [242]. Hydrogen distribution in the heliosphere is strongly affected by the interface between the heliosphere and local ISM since atoms are coupled with the plasma through the charge exchange process and have large mean free path. Thus the data on the Lyman-alpha radiation carry important information about the properties of hydrogen atoms modified by the heliosphere interface. Several spacecraft perform observations of the backscattered Lyman-alpha radiation in the inner heliosphere (SOHO, HST, Cassini, Ulysses). Voyager 1 and 2 Ultraviolet Spectrometers (UVS) made the unprecedented measurements of the Lyman-alpha radiation in the outer heliosphere.

Lallement et al. [157] measured the Doppler shifts of the solar Lyman-alpha radiation observed on SWAN/SOHO and discovered that the hydrogen flow in the heliosphere is deflected relative to the He flow. Unlike hydrogen, neutral He experiences much less charge exchange when it enters the heliosphere and retains its properties of the local ISM. Meanwhile hydrogen atoms in the heliosphere carry the characteristics of interstellar plasma. Observed deflection is caused by the distortion of the heliosphere by the ambient interstellar magnetic field. This study provided constraints for the direction of the magnetic field in the LISM. Also, measurements of the Lyman-alpha radiation on the SWAN/SOHO provide the large-scale time and latitudinal structure of the solar wind at 1 AU [158].

Quémerais et al. [243] reported that the excess upwind Lyman-alpha intensity observed by UVS on Voyager 1 and 2 can be explained as an emission backscattered by the decelerated hydrogen atoms of the hydrogen wall. The shape and extent of the excess emission gives information about the hydrogen wall hydrogen population. Lyman-alpha photons backscattered by the hydrogen wall are visible from a much further distance than the normal interplanetary Lyman-alpha glow (which is mainly generated within 10 AU). As Voyager leaves the heliosphere, contribution of the interplanetary hydrogen glow decreases, making it possible to detect Lyman-alpha diffuse emission from our Galaxy [244]. Future measurements of Lyman-alpha at large distances of the order of several 100s AU, along with existing sophisticated models of the heliosphere – ISM transition region and radiation transfer models, will provide new information on the behavior of hydrogen gas in the ISM and galaxy.

Chapter C.2: Science of the Pristine ISM

C.2.1. Introduction

The interstellar medium (ISM) surrounding the Sun is the closest example of cosmic *terra incognita*. The places in the universe which we have explored have essentially all been limited to the solar system and the interplanetary medium dominated by phenomena originating from our Sun. The gas and dust drifting among the stars, the ISM, is found throughout our Galaxy and is an integral part of the ecology of all galaxies. It is the repository of the raw materials which are used to form new stars, and which is replenished by stars at the end of their evolutionary cycles when they redeposit large quantities of material as supernovae or planetary nebulae.

The local interstellar medium (LISM), the material in the immediate vicinity of the Sun, is the outer boundary condition that dictates the interaction of the Galaxy with the Sun, which produces the heliosphere (see [245] for a recent review of the LISM). Given the relatively small variability in solar emission and the relatively large variability in ISM properties (e.g., density), the ISM dominate the general structure of the heliosphere. It is therefore of critical importance to fully characterize its properties (e.g., [246, 247]). In particular, we must sample the ISM that has yet to be perturbed by the interaction with the Sun. This pristine ISM is located beyond the Bow Wave/Shock, at a distance of >500 AU. The heliosphere acts as a filter, and there are components of the ISM that make it into the inner solar system (e.g., neutral helium [248, 249]); however, most of the material that makes up the ISM can only be sampled in its pristine form beyond the heliosphere.

In this volume of space, beyond the heliosphere, where we find the pristine ISM, we also find the closest stars and planetary systems. Even in our most immediate cosmic neighborhood (see Figure C.2.1), perhaps a sphere of 10 pc (only 0.00001% of the volume of our Milky Way Galaxy), we find a complex morphology of ISM clouds [250], hundreds of stars [251], dozens of known exoplanets[10], and a handful of astrospheres (structures analogous to the heliosphere, where the LISM is interacting with the winds of other stars [252]). Given that stars with winds, orbited by planets, and adrift in the ISM are ubiquitous, the study of our own heliosphere and its interaction with the Galaxy will be the gold standard by with all analogous structures will be understood.

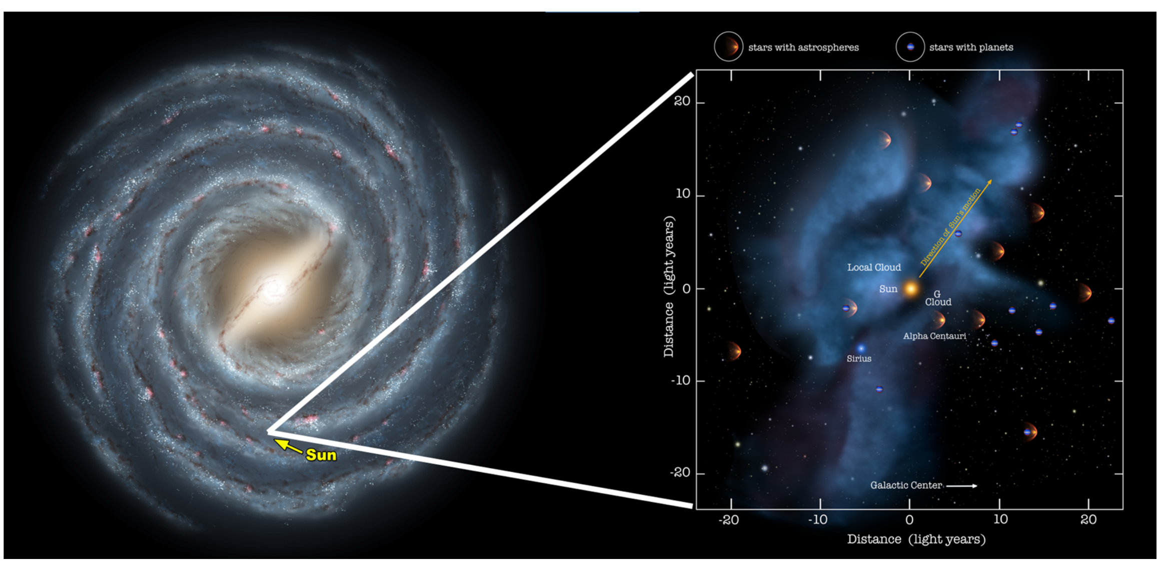


Figure C.2.1: Accurate representations of the Milky Way Galaxy and the collection of ISM clouds, stars, planets, and astrospheres in our cosmic neighborhood.

[10] www.exoplanets.org

C.2.2. Science Objectives

Our current understanding of the pristine ISM is limited to line-of-sight averages measured across astronomical distances (many parsecs). Therefore, *in situ* observations will provide access to measurements completely available to such techniques and will be critical to evaluating degeneracies or uncertainties in the long sight line average.

C.2.3. Direct *in situ* Measurements of the LISM

1. A Comprehensive Inventory of the Composition of Interstellar Matter

Using both *in situ* and line-of-sight averages, our inventory of matter in the ISM is incomplete. The *in situ* data to date have been within the heliospheric structure which alters and filters the material passing into the solar system, and the line-of-sight measurements primarily rely on electronic atomic transitions which gives a selective view of only the most prominent transitions/ions and largely misses the dust entirely. We do have a complete inventory of the composition of the Sun, but the birth material of the Sun could be very different from the ISM that surrounds it now (e.g., [255]). An independent comprehensive inventory of the LISM would be extremely valuable to understand chemical evolution and mixing of matter within galaxies. There are several components that make up the matter in the ISM (e.g., neutrals, ions, isotopes, molecules, dust; see Figure C.2.2) and each need to be sampled in order to get the fundamental elemental abundances. The line-of-sight observation suffer from limited observational capability for some elements given the lack of specific transitions and from degeneracies between the ionization structure and the depletion of an element from the gas phase onto dust [256], and therefore *in situ* measurements are vital. Further, evaluating the spatial variations of the admixture of all these components will identify interesting phenomena (e.g., isotopic ratios, ionization ratios, dust-to-gas ratios, and organic molecular fractions). Instruments are currently available that can measure the composition of solar wind plasma up through Fe (including H, He, C, N, O, Ne, Mg, Si, and Fe), and these same instruments can be used to obtain a comprehensive inventory of the diverse distribution of elemental abundances in the ISM.

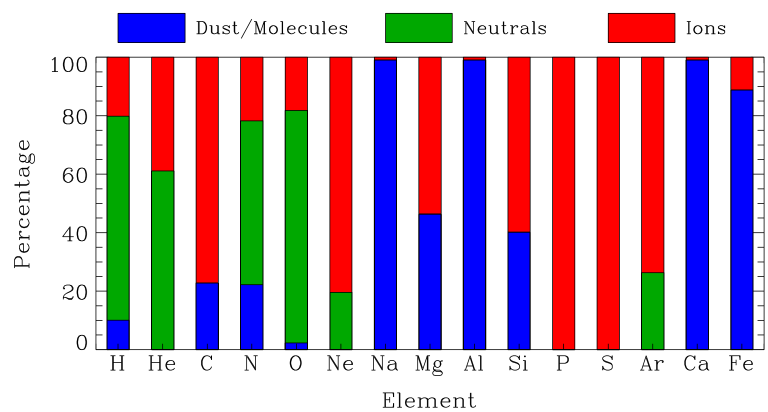


Figure C.2.2: Estimates of the distribution of elements in the various phases of matter in the LISM. Note that large uncertainties exist, particularly for dust content, and rely heavily on few observations or theoretical arguments. Ionization structure is taken from Slavin & Frisch [253] and dust content from Jenkins [254].

2. Interstellar Magnetic Field

The magnetic field threading through the LISM has a profound influence on the structure of our heliosphere and the distribution of many particles (e.g., ENAs, dust, cosmic rays). The magnetic field structure through the heliosphere is also complex and not fully understood. A first direct measurement of the pristine ISM magnetic field would be critical to understanding our heliosphere, as well as interpreting the line-of-sight averaged measurements of indirect magnetic field measurements (i.e., polarization of light due to alignment of dust grains). The critical measurements are the magnetic field orientation, strength, and variability/turbulence in the field.

3. Dust

Dust grains, which come in a wide range of sizes (from 10^{-3} to 1 micron), are a ubiquitous component of the ISM and play an important role in interstellar chemistry, which results in the formation of the most abundance molecule (H_2), and a rich collection of complex organic molecules (e.g., PAHs). Dust is also important in the heating and cooling of the ISM [257]. While pervasive, dust is notoriously difficult to measure directly (the most common astronomical technique is to assess the "missing" elements from the gas phase by assuming a known cosmic abundance standard, typically the Sun, even though it is known that the Sun and ISM could have very different elemental abundances). A complete understanding of nearby dust is important in a broad range of astrophysical areas, as it is a foreground contaminant of more distant signals, such as evaluation of the Big Bang through the Cosmic Microwave Background (CMB) requires an accurate removal of foreground dust [258]. The critical measurements are composition, kinematics, and grain size distribution, with particular emphasis on the complex organic molecules. These measurements have an important astrobiological connection as well. They can be used to evaluate the formation and survivability of dust, and thereby illuminate the sites of chemical reactions that lead to the complex organic molecules that we find in the ISM.

4. Density

The density of the LISM, together with the kinematics, is a critical parameter in understanding the heliosphere. It is also a very difficult measurement to make from astronomical observations, where instead the density integrated along the entire line of sight is measured. A direct measurement of the volume density, and its small-scale structure will be necessary to interpret the astronomical data and understand the variability on the size of the heliosphere.

5. Temperature/Turbulence and Small Scale Structure

Together with the magnetic field strength, measurements of the fundamental properties of the gas, such as temperature and turbulent structure [259], are needed to evaluate the pressure balance in the LISM. Knowledge of how pressure is balanced is necessary to understand the origins (i.e., lifetime) and evolution of the ISM. It is a long-standing mystery for all of ISM science (e.g., [260]), and really requires *in situ* measurements to fully characterize the small-scale variations, at the source of the pressure drivers.

C.2.4. Measurements of the ISM Enabled by Observations Beyond the Heliosphere

1. Galactic Cosmic Rays

Modulated by the solar magnetic field, Galactic Cosmic Rays (GCRs) can only be directly measured beyond the heliosphere. These energetic particles are critical to ISM chemistry and those that make it into the solar system have an important influence on planetary atmospheres. Voyager is presently making the first measurements of the interstellar energy spectra of galactic cosmic rays [209]. These one-of-a-kind measurements provide our best determination yet of the interstellar spectra of cosmic-ray ions and electrons. It is interesting that the first reported Voyager 1 measurements of interstellar cosmic-ray spectra appear to be a factor of ≥10 lower than required to account for the ionization rate of H_2 in diffuse interstellar clouds [261, 262], which is believed to be due to galactic cosmic rays. In order to address this discrepancy, it is important to extend direct measurements of interstellar ions and electrons, especially to lower energies, but also to higher energies. Extension to lower energies is easily accomplished with modern instrumentation. Interstellar measurements of radioactive isotopes in cosmic rays are important to distinguish cosmic-ray acceleration and transport models, including measurements of the cosmic-ray lifetime in the Galaxy, and of the average density of material in the cosmic-ray storage region [263]. Also important are interstellar measurements of cosmic-ray positrons [264], which arise from a variety of astrophysical sources including supernovae and pulsars.

2. Short Path Length Emissions: Lyman-α, ENA, and soft X-ray imaging

Each of these emission sources have very short path lengths, from 10s of AU to 1 parsec. As a result, current observations from the inner solar system are dominated by heliospheric signals. However, observations beyond the heliosphere would enable direct measurements of these sources in the pristine ISM. For example, Lyman-α measurements would provide the number density of hydrogen [242], and an ENA imager would identify the location of detected ENA sources throughout the heliosphere, and possibly find new sources of ENAs from suprathermal ions in the ISM, and a soft X-ray imager would provide a diagnostic of the neutral hydrogen and detect the hot interstitial gas that pervades the Local Bubble region and presumably resides between all the warm LISM clouds, such as the LIC [265].

C.2.5. Conclusion

The measurements detailed above require instruments that will likely be used throughout the mission to observe similar phenomena in various components of the heliosphere. However, getting to the pristine ISM is truly the next frontier in terms of unexplored territory. No other spacecraft will have been in this region and making these kind of measurements. Therefore, the scientific return is expected to be tremendous and transformative for ISM science.

Chapter C.3: Science of the Outer Solar System: Zodiacal Background, Dust, and Kuiper Belt Object Science

C.3.1. Zodiacal / Kuiper Belt Dust – Structure and Composition

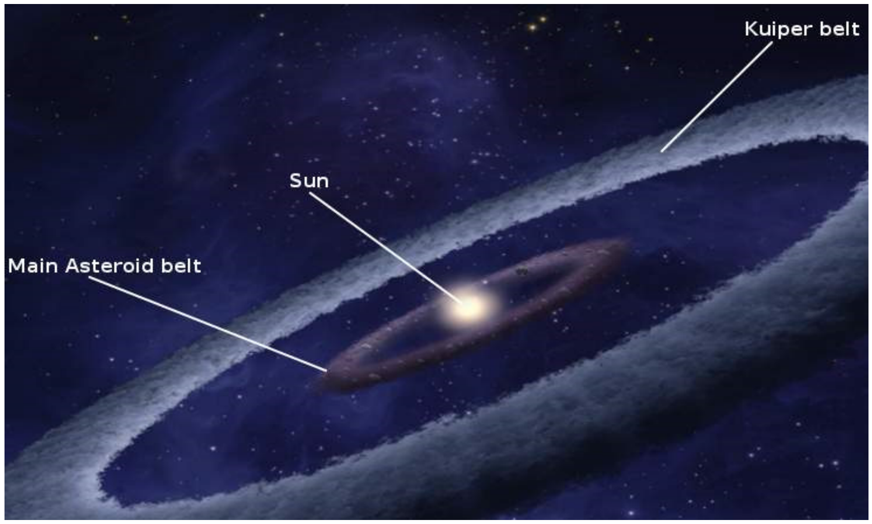


Figure C.3.1: Oblique view of the asteroid and Kuiper belts, with associated dust clouds

The Sun and planets are not alone in the solar system. They are joined by asteroids and comets, and in the region beyond Neptune, by the recently discovered KBOs. These bodies, loosely referred to as planetesimals, are the source of yet another solar system component, the micron-sized dust particles which make up the zodiacal dust cloud in the inner solar system and, presumably, a similar dust cloud associated with the Kuiper belt. Either the continual collisional cascade, which converts larger bodies into smaller ones, or the evaporation of cometary material, fills interplanetary space with these dust clouds. Particles smaller than a few microns are ejected from the solar system by radiation pressure, while larger ones may spiral sunward under the action of the Poynting-Robertson effect. Thus, these dust populations are continually replenished by a rumble of activity, which goes on over time scales of millions of years.

The vantage point of the outer solar system provides an unprecedented opportunity to measure the interplanetary dust (IPD) cloud. Figure C.3.1 depicts the asteroid belt lying between the orbits of Mars and Jupiter, and the Kuiper belt, lying beyond the orbit of Neptune. These belts, with the cometary contributions as well, are the main sources of the zodiacal dust, which fills the inner solar system, and the presumed Kuiper belt dust as well. An instrument, flying from Earth towards the outer solar system, would provide a unique opportunity to study:

- How the dust created by these planetesimals diffuses outward to fill the solar system,
- What the dust density and composition is as a function of radial position, and
- How these dust populations compare with what is seen in exoplanetary systems.

Such an instrument could measure the radial distribution of the IPD, and map resonant enhancements and band structures in the zodiacal dust influenced by planetary bodies. It would study the compositional distribution of dust and determine if it arises from comets, asteroids, or both, from the inner to the outer solar system. A notional, and previously proposed, version of such an instrument is called ZEBRA, for **Z**odiacal dust, **E**xtragalactic **B**ackground and **R**eionization **A**pparatus.

The study of interplanetary dust is of broader scientific interest because of its connection with extra-solar planetary systems (called exo-systems below), which are now known to exist around well over half of the stars in the solar neighborhood [266, 267]. Dust belts produced by the processes described above are also commonly found around nearby stars, tracing planetesimals in the exo-systems just as they do in our solar system. In some cases, the architecture of the exoplanetary system is remarkably similar to that of the solar system, with inner and outer planetesimal belts analogous to the asteroid and Kuiper belts, and a relatively dust-free region between, occupied by one or more planets, just as Jupiter, Saturn, Uranus, and Neptune lie between the asteroid and Kuiper belts. Clearly what we learn from studies of the IPD in the solar system will enhance our understanding of the exo-systems and indicate whether our own planetary system is an outlier in some important way. In this connection, it is very important that an outer solar system probe could detect and map for the first time dust originating from the Kuiper belt, the belt of small bodies beyond the orbit of Neptune. This is the best-studied component of the exo-systems. We infer that there must be dust associated with the Kuiper belt as its planetesimals grind down collisionally, but this dust cannot readily be seen from the Earth's vantage point because of the bright foreground emission of the zodiacal dust cloud. Kuiper belt dust levels comparable to or even an order of magnitude fainter than those seen frequently around nearby stars would be readily detectable by the instrumentation envisioned here. Figure C.3.2 is another view of the Kuiper belt, highlighting the extent of its dust cloud.

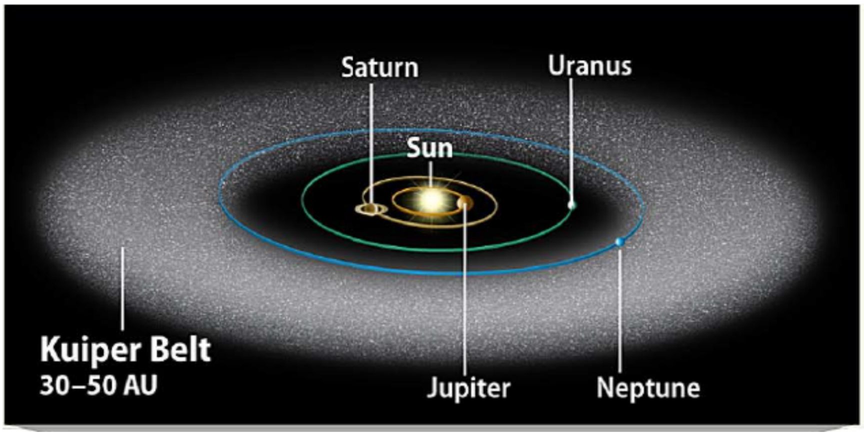


Figure C.3.2: Oblique view of the solar system depicting the extent of the Kuiper belt dust cloud

Figure C.3.3 is a model of the infrared surface brightness of the outer solar system [268] including the effects of dust grain collisions. Evident in this image is a prominent Kuiper belt structure, caused by trapping of particles in mean motion resonances with Neptune, as well as asymmetric clumps along the orbit of Neptune, and a clearing of dust at Neptune's location. The proposed instrument and experiment will map these dust structures in the outer solar system for the first time.

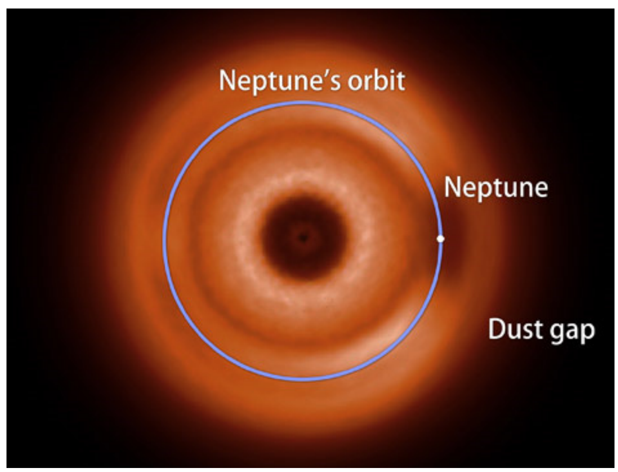


Figure C.3.3: Face-on view depicting structure within the Kuiper belt

Figure C.3.4 depicts the estimated brightness of the zodiacal light at the ecliptic pole from 1 AU to 10 AU shown in cyan, fitted to measurements out to 3 AU [269, 270]. Shaded areas indicate the uncertainty in projecting to 10 AU. Other components are also illustrated on the figure. The Diffuse Galactic Light (DGL; green) arises from starlight scattered by interstellar dust and emission from the ISM. The large reduction in zodiacal brightness enables a precise measurement of the Extragalactic Background Light (EBL; red curve) and a deep search for the photons from reionization, (R-EBL; shown by the violet shaded region). Note that the R-EBL is constrained to have the *minimum* level required in order to initiate and sustain reionization. All of the components illustrated here are within the grasp of the instrumentation described in this report.

While travelling out to Saturn's orbit and beyond, the proposed instrument can monitor the zodiacal light continually, testing the model shown here and looking for resonant structures and other features reflecting the processes which shape the cloud and may be important in exo-systems. Moreover, as the probe moves outward, the scattered and reradiated sunlight produced by the planetesimals will drop in intensity, allowing our clearest look ever at the brightness of the extragalactic sky at visible and infrared wavelengths (Figure C.3.4).

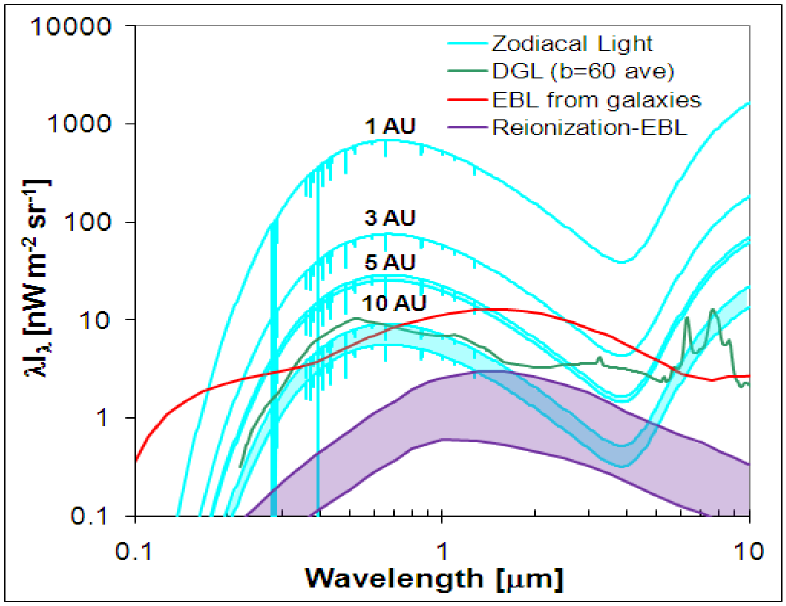


Figure C.3.4: Estimated brightness of the Zodiacal light & other components

C.3.2. Kuiper Belt Object science

The Kuiper belt is a disc-shaped region beyond the orbit of Neptune, extending all the way to 50 AU. As of August 2015, more than 100,000 KBOs over 50 km in radius are believed to exist. A mission reaching the LISM presents a unique opportunity to fly by a large KBO, some of which are called dwarf planets, within 10 years from launch. Various KBO candidates were studied for a near term mission to the ISM. The KBO's MakeMake, Haumea, and Quaoar were determined to be of high science value. Out of these three, Quaoar was studied in more detail.

Quaoar is one of the most interesting of the Kuiper belt objects as a transition between the large, volatile-dominated, atmosphere-bearing KBOs and the typical mid-sized volatile-poor object. Quaoar had a methane atmosphere (and likely N_2, as well) for most of its history, and is now in the last stages of losing that atmosphere. The surface is likely patchy in methane frost – perhaps the methane is mostly cold-trapped near the poles (depending on the [thoroughly unknown] obliquity) or in craters. Atmospheric loss is a very uncertain process in the outer solar system, so Quaoar is an interesting case in seeing the process in its late stages. Based on its size, Quaoar is also likely to have ancient cryovolcanic flows on the surface (where it is not obscured by methane). Both of these processes will be interesting to investigate with full global imaging in broadband colors, but it will be even more interesting to use the broadband colors to make specific spectroscopic identifications. This would require at least 3 narrow-band filters in the 2 micron range. One would be ~2.0 microns, in the water ice absorption, one would be ~2.3, in the methane absorption, and one would be ~2.2 (an educated guess) in the continuum.

The orbital position of Quaoar lines up with the nose of the heliopause. This means that a spacecraft flying by Quaoar in the near future will take the shortest path out of the heliosphere and into the LISM. Furthermore, the nose of Heliopause is an attractive science target from an *in situ* science perspective.

The direction of travel when flying by Quaoar also passes very close to (possibly through) the IBEX ENA ribbon. Studying this ribbon has high scientific importance in the Heliophysics community.

Key science questions for mission to Quaoar are likely cover are:

- Studying fraction of cryovolanic coverage, and (based on craters) time of last activity
- Measuring depth/coverage of methane,
- Determining crater-count ages of frosty surfaces
- Studying spatial distribution of volatiles
- Determination the mass ratio of Quaoar/Weywot
- Radial velocity search for additional moons
- Determination of Quaoar's interior by precise measurements of Weywot's orbit

- Understanding vertical and horizontal structure of Quaoar's atmosphere via occultation science

Finally there is also a possibility of studying study Quaoar's interior using a KBO impactor. Imaging the crater would be an interesting probe into surface conditions. Plume spectroscopy could explore subsurface composition.

Many of the above stated question could also apply if studying the other two KBOs, Haumea and MakeMake. Further work is needed to understand the nature and the instruments needed to carry out these scientific investigations before incorporating them into a mission to the ISM.

Chapter C.4: Cosmic Background, Solar Wind and Perihelion Science

C.4.1. Cosmic Background & Epoch of Re-ionization

From its vantage point in the outer solar system and beyond, the proposed ZEBRA instrument – as an example – can study fundamental questions in astrophysics and cosmology. It will address the NASA 2010 Science Plan question, "How did the Universe originate and evolve to produce the galaxies, stars, and planets we see today?" by measuring the Extragalactic Background Light (EBL), the integrated brightness from all photon sources since the Big Bang. The EBL is a cornerstone measurement for addressing the Astro2010 Decadal science investigation for understanding "the fossil record of galaxy assembly from the first stars to the present day." We will make the first precise measurements of the optical to near-infrared EBL, at wavelengths where emitted stellar radiation peaks. We will combine the low zodiacal foreground brightness viewed from the outer solar system with arc second resolution and multi-band spectral information, to remove to a great extent the galactic and zodiacal foregrounds that have limited previous EBL measurements from Earth's orbit at 1 AU from the Sun. An extensive review of the challenges and complexity of such measurements is given by Hauser & Dwek [271], and the scientific background is also reviewed by Primack et al. [272].

ZEBRA will be able to make definitive measurements of the intensity, spectrum, and spatial properties of the Extragalactic Background Light from Reionization (R-EBL). These precise EBL measurements also address the Astro2010 Decadal science investigation of "what were the first objects to light up the Universe, and when they did they do it?" The first generation of stars, formed out of primordial gas gravitationally collected in dark matter halos, produces the first UV photons that reionized the intergalactic medium (IGM). Information encoded in the R-EBL is one of the few experimental measures of the Epoch of Reionization, and can probe the energetics and formation history of first sources beyond what is possible with planned deep galaxy surveys, 21-cm mapping, or CMB polarization studies. The experiment can reach the theoretical minimum R-EBL levels needed to produce and sustain reionization, and uses multiple experimental methods to ensure a robust measurement.

The need for doing this type of study from beyond the orbit of Saturn, and the impossibility of doing it from 1 AU, are illustrated in the pie charts in Figure C.4.1. The top pie illustrates the situation pertaining to the darkest field observed by the DIRBE experiment on the Cosmic Background Explorer [COBE] at 2.2 μm with 0.7° resolution from 1 AU. Contributions to the total observed intensity from zodiacal light, stars, DGL, and the estimated EBL are depicted. Clearly, zodiacal light is the dominant factor in current EBL measurements from 1 AU. The bottom pie shows the same field observed by the proposed ZEBRA instrument with arc-second resolution from 10 AU. By undertaking these observations from outside the zodiacal dust cloud, and with sufficient resolution to identify individual stars, we will strongly suppress these foregrounds.

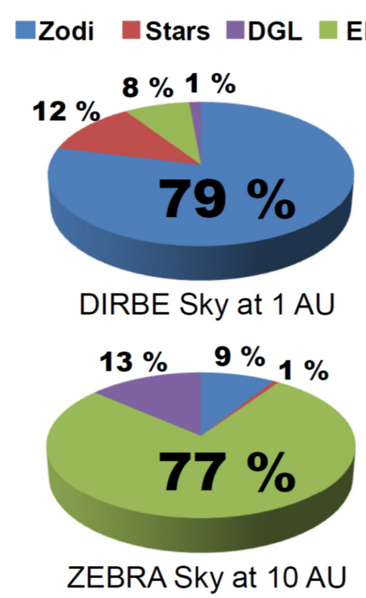


Figure C.4.1: Estimated sky brightness measurements with DIRBE (COBE) at 1 AU and with ZEBRA at 10 AU

C.4.2. Solar wind Evolution and Perihelion science

The voyage to the ISM provides an exciting opportunity to explore the evolution of the solar wind – from its source at the Sun to its contact with the ISM – using *in situ* instruments that greatly exceed the capabilities of those on Voyagers 1 and 2.

1. Evolution of the Solar Wind

As discussed in Chapter 4, much has been learned from the Voyagers and other missions about the evolution of the solar wind with distance from the Sun. In the inner heliosphere, the solar wind has distinct large-scale structures: fast and slow solar wind streams and coronal mass ejections of various sizes. However, as the wind propagates out, these individual structures, moving at various velocities with various kinetic pressures, strongly interact. The streams of fast and slow wind merged together as the fast wind pushes on the slow, created large co-rotating interactions regions (CIRs). At times of high solar activity, coronal mass ejections (CMEs) of various speeds can also merged together. The outer heliosphere is dominated by large Merged Interaction Regions (MIRs) formed from these interactions [273] In some cases, when multiple CMEs and shocks are interacting with the wind streams, very large Global Merged Interaction Regions (GMIRs) form, which may completely encircle the Sun at large distances [274]. These GMIRs lead to a modulation of the Galactic Cosmic Ray intensity at Earth, as discussed in Chapter 4. It is thought that it is large GMIRs or their shocks, propagating into the denser ISM, which give rise to the plasma wave radio emissions detected by Voyager [211, 275]. It was these plasma wave observations that led to the conclusion that Voyager 1 has reached the ISM.

The opportunities for new science of the solar wind in the outer heliosphere, as well as the structure of the heliosphere, has been described in Chapter 4. But some of these objectives are also relevant to the evolution from Earth to the outer heliosphere. As the wind propagates out, the role of the interstellar neutral atoms that penetrate into the heliosphere increases; their role becomes very important to the evolution of the solar wind. These neutrals charge exchange with the solar wind ions, slowing and heating the solar wind and creating PUIs. These ions have a non-thermal distribution that drives turbulence. A properly instrumented spacecraft can address issue relating to the thermalization of these PUIs and their role in particle acceleration in the outer heliosphere.

2. Perihelion Science

Should the interstellar mission pass to within 10 solar radii from the Sun at perihelion, the spacecraft will explore a region never before visited, thus potentially enabling new science: sampling the solar wind and solar energetic particles closer to their source. However, due to the extreme criticality of spacecraft maneuvers at perihelion, science operations may not be possible there for mission safety considerations. Solar Probe Plus (SPP), to launch in 2018, is a mission designed to fly near the Sun to study the origin of the solar wind, but will go only to about 10 solar radii on its closest pass. SPP's orbit and instrumentation are tailored specifically to study the origin and acceleration of the solar wind. But the interstellar mission's *in situ* fields and particles instrument can make valuable measurements complementary to SPP's more extensive measurements because the wind and energetic particles would be measured closer to their solar source and thus less effected by interaction and transport. In addition, the interstellar mission may carry an instrument that can measure the ionic and isotopic composition of the wind; such an instrument is lacking on SPP. Indeed, the SPP mission is likely to give rise to new questions about the origin of the solar wind that can only be answered by a mission going even closer to the Sun.

Two SPP science objectives that would be complemented by measurements closer to the Sun are as follows:

Objective 1: Trace the flow of energy that heats and accelerates the solar corona and solar wind.

- How is energy from the lower solar atmosphere transferred to, and dissipated in, the corona and solar wind?
- What processes shape the non-equilibrium velocity distribution observed throughout the heliosphere?
- How do the processes in the corona affect the properties of the solar wind in the heliosphere?

Objective 2: Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.

- What are the sources of slow solar wind?
- Are the sources of the solar wind steady or intermittent?
- How are energetic particles injected into the solar wind?

Regarding these objectives, we know solar wind electron and velocity distributions are non-thermal, even at 1 AU. SPP will measure these non-equilibrium distribution functions closer to the Sun in an attempt to understand what shapes them and how this leads to the heating and acceleration of the solar wind. Presumably waves and turbulence play a role in both creating and dissipating the non-equilibrium distributions. But it may be that the important processes occur closer to the Sun than 10 solar radii. An interstellar mission's measurements of the particle distributions and the waves and turbulence even closer to the solar sources might be needed to understand the processes. Similarly, we know that the slow wind is highly variable in space and time on small scales, but it is more difficult to determine the sources because of interactions between the Sun and the observation point. Is the variability due to different sources or the same source varying in time? Measurements closer to the Sun than SPP's orbit may be needed to pin down the location and nature of the sources. Likewise, solar energetic particles are scattered as they propagated from the Sun; measurements closer to their sources will help understand how they are injected into the solar wind.

Chapter C.5: Astrophysics Science

C.5.1. Solar Gravity Lens Focus

1. Direct Multi-pixel Images of Exoplanets with Solar Gravity Lens

Recent reports from Voyager 1 and Kepler missions have brought our attention to two important facts. Voyager 1 is the first spacecraft that reached the ISM and is capable of gathering and transmitting data from heliocentric distances beyond 130 AU. The Kepler telescope demonstrated that planets are ubiquitous in the Universe by detecting a plethora of Earth-like exoplanets [276]. These results frame the context for further intellectual curiosity, scientific questions, and exploration goals that will define objectives for innovative and far-reaching space exploration missions heading out of the solar system and someday reaching towards the stars. We are rapidly approaching the day when a major newspaper [277] will open with a headline: "*The first habitable Earth-like exoplanet is discovered!*" What do we do the next day? How are we going to explore this alien world? Can we do anything today to prepare ourselves for this extraordinary event?

Nature itself has presented us with a very powerful "instrument" that we have yet to explore and learn how to design, build, and operate engineering structures around it. This powerful instrument is the Solar Gravitational Lens (SGL). According to the general theory of relativity, rays of light passing in the vicinity of a massive object are deflected from their initial direction by the amount of $\theta = 4GM/c^2b$, where G is the gravitational constant, M is the mass of the object, c is the speed of light, and b is the ray's impact parameter. Therefore, a massive object acts as a lens causing two rays passing from two sides of the object to converge at a focus.

Gravitational lensing is a well-known effect and has been observed over cosmological distances where relatively nearby galaxies, or even clusters of galaxies, act as gravitational lenses for background galaxies, and in our Galaxy where micro-lensing of stars in the Galactic bulge or in the Magellanic clouds are caused by intervening (sub-)stellar bodies. In the solar system, the effect was originally observed by Eddington in 1919 and now is routinely accounted for in astronomy and deep space navigation [278]. Astrometric micro-lensing is used to determine masses of stellar objects [279]. The effect is well understood and now is the time to start using it for the practical purposes of interstellar astronomy.

Of the solar system bodies, only the Sun is massive enough that the focus of its gravitational deflection is within the range of a realistic mission. Depending on the impact parameter, the focus of the SGL starts at ~547 AU, going beyond 2,500 AU [280, 281]. By naturally focusing light from distant sources, the SGL provides a major brightness amplification $\sim 2GM/(c^2\lambda)$, where λ is the observing wavelength (yielding a gain of ~110 dB at 1 μm), extreme angular resolution (~10^{-9} arcsec) in a narrow FOV [282, 283]. In particular, a 1-m telescope placed on the optical axis of the SGL (line connecting the source and the Sun), has a collecting area equivalent to that of a ~40-km-diameter telescope in space, providing the SGL with its enormous magnifying power. Astronomical facilities that could use the enormous magnifying power of the SGL together with its naturally high angular resolution will greatly benefit humanity in many ways, one of which is the direct observations of an exoplanet.

The Sun's gravitational field acts as a lens formed in the shape of a narrow annulus around the Sun, magnifying the intensity of light from a distant source along a semi-infinite focal line that begins at ~550 AU. A spacecraft anywhere on that line could observe and communicate using equipment typically employed for interplanetary distances. No one to date has yet determined how to instrument a spacecraft for such a purpose [284]; our KISS effort was the first serious examination of this idea.

Trajectories of light rays from an object will be bent by solar gravity. As seen from a telescope at one of the foci, the light from a planet fills an annulus around the Sun (Figure C.5.1). This light, while magnified greatly, is still dimmer than the Sun. A modest coronagraph would be used to block the solar light, so that the exoplanet's light could be detected at the telescope.

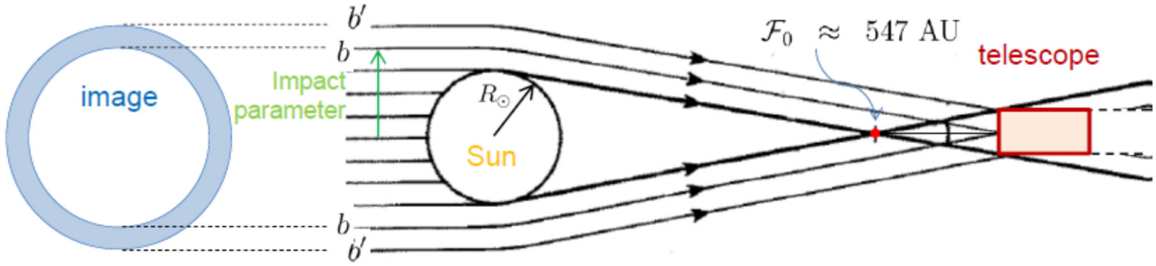


Figure C.5.1. Imaging of an exo-Earth with solar gravitational Lens. The exo-Earth occupies (1 km × 1 km) area at the image plane. Using a 1m telescope as a 1 pixel detector provides a (1000 × 1000) pixel image.

At 550 AU the Sun subtends ~3.5". At a wavelength of 1 μm, the diffraction limited size of a telescope is comparable to the size of the solar disk: a 1m telescope has a beam size of ~0.1". Light in this narrow annulus would come from a ~(3 km × 3 km) spot on the exoplanet's surface. However, light from outside the annulus would come from other parts of the exoplanet. This light will also be blocked by the coronagraph. In fact, because of the very high resolution of the SGL, the image of the exo-Earth at 30 pc would extend ~1.1 km at the location of the spacecraft 550 AU from the Sun. The spacecraft would have to scan this (1.1 km × 1.1 km) area one pixel at a time to develop multi-pixel image of an exo-Earth with resolution of (1000 × 1000) pixels (Figure C.5.2). Clearly, effects of the radial/azimuthal plasma density of the solar corona [281] on the structure of the lensing caustic must be taken into account, including analysis of the second-order effects and possible chromatic structure of the caustic.

Figure C.5.2. Possible image of an exo-Earth 30 pc from the Sun with resolution of (1000×1000) pixels as a 1 pixel detector provides a (1000×1000) pixel image.

Prior studies had looked at the SGL as an amplifier; the SGL was viewed as an addition to one-pixel detectors at the focus of a parabolic receiver dish [285-289]. What mattered there was the antenna gain. However, there is great potential for using the SGL as an imaging telescope, as the imaging properties of the SGL are important.

The SGL may provide us with the first direct *multi-pixel* high-resolution images and spectroscopy of a potentially habitable Earth-like exoplanet 30 parsec away with resolution of ($10^3 \times 10^3$) pixels. It is a good time to investigate the details of the process of image formation at the caustic formed by the SGL with solar plasma on the background. It is also a good time to explore a mission architecture for a Solar Gravitational Lens Focus Mission (SGLFM) designed for high-resolution imaging science and to evaluate technologies needed to implement an SGLFM.

2. Why this is exciting? What benefits it would enable?

Kepler has detected a plethora of potential Earth-like exoplanets, making exoplanets a household name. Although it will be difficult to follow-up on Kepler with any other exoplanet characterization, already the next steps in the remote exploration of exoplanets are scheduled, including TESS (2017) [290] that will further identify targets, the James Webb Space Telescope (JWST; 2018) [291] that will perform some validation and others. TESS will find some nearby exoplanets suitable for further characterization. JWST will likely spend months of observing time to try to evaluate atmospheric properties (possibly biomarkers) on just a single target–and we may still be left with a marginal detection [292]; the same may be true with the 30-m ground-based telescopes. Even not counting the Kepler detections, ~62% of known exoplanets are within 100 pc, and almost all (~80%) of the Earth-like (i.e., Super-Earths) planets. Therefore, there is already a nice sample. Given that the small planets are ubiquitous [293] in the coming decade, we expect to learn about Earth-like exoplanets with atmospheres, free oxygen, water, etc. Therefore, we will have a fairly lengthy list of truly Earth-sized planets in the habitable zone to choose from.

Natural questions that the public and science community will ask are: What do we do next? When can we send robotic probes towards Earth-like destinations? Whereas sending robotic missions to explore exoplanets *in situ* is technologically beyond the scope of the proposed study, it is timely to begin to understand the first steps in the long path forward. One such step is a telescope placed on the optical axis of the SGL beyond 550 AU to observe a promising exoplanet, representing a logical advance to the intriguing goal of robotic interstellar missions.

Every exoplanet-imaging mission concept currently envisioned by NASA detects the light of the planet as a single pixel. The major problem has been contamination from the parent star that is 0.1" from the planet. A 1-m telescope at the SGL would collect the light from a ~(3 km × 3 km) spot on the surface of the planet, bringing this light to one 1-m size pixel in the image plane of the SGL. Because of the high angular resolution of the SGL, the parent star will be completely resolved from the planet with its light being amplified many AU away from the optical axis provided by the direction to the planet, thus removing the contamination issue.

The high-resolution imaging and spectroscopy of alien worlds are two of the most exciting benefits of this unique instrument [281]. What is most exciting is that using unique capabilities of the Lens, we can build an image of a life-supporting exoplanet. In fact, the SGL could be used to image an exo-Earth around a star 30 pc from the Sun with a pixel resolution of ~(3 km × 3 km) on its surface – which is not feasible with any other potentially conceivable approach. Given the enormous amplification of the SGL, one could easily consider doing spectroscopic research of the exoplanet, even spectropolarimetry. It will not just be an image, but potentially a spectrally resolved image over a broad range of wavelengths, providing a powerful diagnostic for the atmosphere, surface material characterization (mineralogy), and biological processes. As such, an SGLFM could be used to determine seasonal changes, oceans, continents, surface topography, and life signatures on an exo-Earth.

3. Towards a realistic mission to the Solar Gravity Lens

A mission to the SGL may provide a major motivation for us to consider a series of interstellar precursor missions to heliocentric distances of 500–1000 AU. However, before any quantitative analysis on the mission design could begin, we will study the physical properties of the SGL. This will help us to understand the process of image formation in the context of a realistic space mission that is capable of operating beyond 550 AU and will lead to formulation of the key mission and instrument requirements. There are efforts under way to analyze image formation processes and to derive realistic mission requirements with relevant architecture trades.

The results obtained in these efforts would enable an evaluation of measurements principles, design of the instrument, the coronagraph, and methods of extracting the planetary signal. For instance, a coronagraph operating at the SGL focus may be the only technologically feasible approach to image an exoplanet directly. At 1 μm, the gain of the SGL is ~110 dB (27.5 mag), so an exoplanet that is a 32.4 mag object will become a ~4.9 mag object. When averaged over a 1 m telescope (the gain is ~2×10^9), it would be 9.2 mag, which is sufficiently bright (even on the solar background). To derive an image with the SGL, including contributions from the Sun, parent star (which will be resolved at the anticipated resolution), and zodiacal light, one would have to rely on a coronagraph in a shape of a thin annulus.

Mission deign for an SGLFM would present a set of interesting challenges. The instrument (or the spacecraft itself) must be able to sample various spots on the image plane while travelling at a large velocity, because for 1-m class telescope one pointing is equal to only one (3 km × 3 km) pixel on the surface of the exoplanet. As one pixel is ~3 km, to cover (1000 × 1000) pixels, we would need to be able to wander from the principal optical axis at 550 AU by ~1.1 km. We would have to consider various error sources contributing to the instrument pointing as it will depend on various factors including the proper motion of the parent star, orbital motion of the planet around it, spacecraft logistics in sampling the image plane, wave front sensing, etc. We will evaluate contributions of these error sources on the imaging with the SGLFM.

Conceptually, many studies were made to investigate the science objectives and the technological feasibility of missions to deep space beyond the solar system [76, 77, 294], including several NIAC studies [295, 296], and most recently [284, 297]. Our work will benefit from these earlier studies by allowing us to focus on the SGLM-specific challenges.

Distances beyond 500 AU can be achieved in practical flight times with solar sails flying toward the Sun with a perihelion of 0.1–0.2 AU. Spacecraft area to mass ratios are required larger than the current state of the art, but the requirements are consistent with those studied and considered in prior NASA and ESA studies [298]. Other propulsion technologies may be relevant – an Oberth maneuver in particular was considered in the KISS 2014 study [297], and electric propulsion – but solar (or possibly electric) sails appear to be both of greatest performance potential and of nearest term readiness. A number of technologies that, when combined into mission architectures, enable a meaningful step to venture significantly beyond our solar system, were identified in the KISS study and in a companion JPL study [284]. Voyager 1 took 36 years to travel 126 AU from the Sun and is currently moving at heliocentric velocity of ~17 km/s. An order of magnitude increase in this speed may be possible with near-term technologies. Large area to mass ratios for the solar sail require consideration of small spacecraft (e.g., nanosats) – a promising enabling technology. Instrument capabilities for small spacecraft will be considered. In addition to solar sails and spacecraft requirements, key technologies of communications and power will be analyzed. The work on the technologies enabling reaching and communicating from large heliocentric distances is ongoing. There are realistic mission concepts capable of reaching 250+ AU available [297].

A number of technologies will be combined into conceptual mission architecture, to show at least one approach to a mission design to achieve 550–1000 AU on the solar gravity lens focal line in a practical mission times of 25–35 years. These include: (i) optical communications with low mass, volume, and power, operating at large distances; (ii) small spacecraft with large solar sails; (iii) use of small radioisotope power generators (some of which have been studied in previous NIAC studies); (iv) use of advanced materials to enable closer flybys of the Sun with a solar sail and potentially of electric sails; and (v) Reliable, long-life missions to the SGL will require major advances in autonomy, control, and the design of adaptive systems, with much more to be developed in the future. A small spacecraft architecture permitting a number of diverse missions to multiple extra-solar planet image targets will be considered.

One would also need to consider the tradeoffs between a traditional telescope versus a microsat system which opens up the possibility of sending multiple spacecraft. In fact, we could devise an instrument that would rely on a swarm of small spacecraft, perhaps even launched together but each moving at a slightly different trajectory parallel to the principle optical axis. Such an instrument would rely on the light collection capabilities enabled by a formation flying architecture.

4. The a priori properties of the target

Evaluating what we may already know about the proposed exoplanet (e.g., rotation period, prevalence of clouds) will be important for estimating mission requirements. Optimizing the reconstruction of a spatially resolved image will be critical for planning the proposed mission as well as motivating precursor projects.

The occurrence rate of Earth-sized terrestrial planets in the habitable zones (HZs) of Sun-like (FGK) stars remains a much-debated quantity. Only a handful of such planets have been discovered (e.g., [276]). Current estimates range from 2% [299] to 22% [300, 301]. The Simbad database lists 8589 F stars, 5309 G stars, and 1688 K stars within 30 pc. Taking even the lowest estimates, we can expect to detect at least one terrestrial planet in the HZ of a star within 30 pc in the near future. Once such a planet is discovered significant observational resources will be devoted to characterizing it.

Most likely, we will want to image Earth 2.0 around a G star which is not transiting. The SGLFM could follow a "big TPF" that observes an exo-Earth around a G star and measures its spectra. We should be very confident that the selected target is habitable. A spacecraft at the SGL would be the next major step – possibly the biggest step in the 21st century for exoplanet exploration. (The next step after that would be to send a probe to 30 pc.) If the planetary atmosphere contains oxygen and possibly signs of life, the next step would be to launch the SGLFM to image this planet at 1000×1000 pixels. The planet's orbit would have to be measured in 3D, using either astrometry and/or radial velocity measurements combined with direct imaging (to measure inclination). If we are lucky, it will be inclined so that it transits, providing a radius. These measurements would allow us to obtain the information as to where to send and point the spacecraft.

Once we know of a terrestrial HZ planet so close to our own, we posit that significant resources will be devoted to characterizing the planet and its system using the above techniques. The knowledge we gain from this will include: (i) orbital ephemeris, to at least milli-arcsecond accuracy and precision; (ii) detailed knowledge of the atmosphere, including temperature, structure, chemical composition, and albedo, all inferred from non-spatially-resolved spectroscopy; (iii) estimates of rotation rate, gained from temporal monitoring of the spectroscopy; and (iv) some understanding of cloud and surface properties from Doppler imaging [302].

C.5.2. Parallax Science

Astrometric investigations conducted on several Earth-to-spacecraft baselines may lead to major improvements in the study of galactic dynamics. They will be critical for measuring stellar diameters, will allow for research with pulsar timing, and will help investigations of quasars and dynamical processes in our galaxy. Precise astrometric data may also be used to determine masses of binary stars, look for and study planets, and will be critical for investigations in astrophysics of black holes and neutron stars. These unique data will allow for development of a highly precise galactic reference frame and initiation of precise mapping of our galaxy. In conjunction with post-Gaia astrometric catalogues, these data will provide unique information about our galactic neighborhood, its structure, chemical composition, astrophysical properties, kinematics, history, and evolution – all of which are primary data needed for future space explorers.

Because it will take a number of years to get to a distance of 500 AU from the sun, we also make the assumption that similar capability telescopes exist in the inner solar system. These two telescopes, making astrometric measurements to a precision of ~1–10 microarcseconds (μas) would enable parallax distance measurements ~500–5000 times better than GAIA, at the end of its 5-year mission (i.e., ~4.8 years from now).

GAIA is projected to have a parallax accuracy of <10 μas. An improvement by a factor of ~500–5000 would imply a parallax precision to ~2–20 nano-arcseconds (nas). Note that this improvement in parallax precision is due to the 500-AU baseline rather than a dramatic increase in astrometric accuracy. (This improvement in parallax distance accuracy does not apply to astrometric detection of exo-Earths.)

However, 20 nas parallax would enable 10% distance measurement of objects to a distance of ~5 megaparsec, basically the local group of galaxies. At 2 nas, the distance would extend to 50 Megaparsec, to the Virgo cluster, well into the regime where the motion of galaxies is dominated by Hubble flow.

As we look at objects far away, their intrinsic brightness means we will need very long integration times. Fortunately, there are some intrinsically very bright objects. Individual stars in the local group of galaxies can be bright enough (−10 absolute mag) for a small telescope to measure its position to a few μas in a few months' integration. For objects beyond the local group, the "point" sources that are bright enough are "transient" sources like novae and supernovae. Fortunately, supernova occur approximately once per year per galaxy, and they last several months. Large ground based surveys like Panstarrs, ZTF, and in the future, LSST, will be constantly scanning the sky for these transients.

The deviation from uniform Hubble flow discovered in the last part of the 20th century led to a paradigm change in cosmology that gave rise to the concept of Dark Energy. Dark Energy represents ~70% of the energy of the Universe, and causes the expansion of the Universe to accelerate with time. There are many approaches to measuring Dark Energy, but the most direct one is to measure the change in the Hubble constant with age. The universe is expanding, as evidenced by the Doppler shift of the spectral lines. Galaxies are moving away from each other. In the mid-20th century, Edwin Hubble discovered that the velocity with which galaxies are moving away from us seemed to be proportional to their distance from us. The proportionality constant is called the Hubble constant. In the late 1990s astronomers, using type 1 supernovae, found that rate of expansion is increasing with time; that led to the concept of Dark Energy. While it is straightforward to measure the Doppler shift of spectral lines, the distance is much more difficult to measure. All measurements that form the basis for the discovery of Dark Energy are indirect. We assume that Type 1A supernova all have the same absolute luminosity so their brightness is an accurate measure of distance. The brightness measurement is made in the IR where interstellar dust and intergalactic dust have less attenuation than in the visible and where we can more easily calibrate the effect of dust, and so forth. A direct trigonometric distance measurement to supernovae at cosmological distances would cement all these measurements.

C.5.3. Astrometric investigations of the solar system and beyond

The GAIA mission, launched in December 2013, will survey millions of asteroids in the solar system, with astrometry precision at the 10s of μas accuracy and obtain accurate orbits for these millions of objects. A mission flying ~10–20 years later with similar 10s μas accuracy, could survey these same objects and measure the change in their orbits. A large change in orbital parameters would occur if two asteroids came close enough to each other to gravitationally perturb their orbit. Astrometry of solar system objects at the 10s μas level 10 years after GAIA could result in detecting 100s to 1000s of orbit-changing encounters. With 50-μas astrometry, a position change of 1 km is detectable. Said another way, a change in an orbital parameter, such as semi-major axis, of 1×10^{-8} is detectable. Tracking the orbits before the encounter by GAIA and after a close encounter by this mission lets us derive the masses of both asteroids, and the date and location of the encounter.

There are several types of astrometric science possible with a 500 AU mission. One makes use of the long baseline of 500 AU for trigonometric parallax measurements discussed earlier. Another is due to ~10 μas-level astrometry of objects, as the spacecraft moves through the solar system.

To assess the latter opportunity, we make the following assumptions on the telescope available to do astrometry. This telescope would be also be used for optical communication with the Earth. In addition, pointing of the laser beam to Earth will require some level of astrometric accuracy. However, for most accurate astrometry, several types of calibration would be needed prior to launch.

We further assume that the telescope has a ~30 cm aperture but we can scale to larger apertures. Our European colleagues are proposing a 1-m telescope with properly calibrated focal plane as well as optical field distortion calibration to achieve 1-μas astrometry in ~1 hr. For exoplanet astrometry of nearby stars, the photon-limited accuracy is from the reference stars. However, the goal is control of systematic errors to enable centroiding to 1×10^{-5}.

As expected, the probe will be placed on a highly energetic hyperbolic escape trajectory taking it through the extreme gravitational environments in the solar system including the very close proximity to the Sun and the regions very distant from its gravity. This unique trajectory, in combination with radio tracking and high-precision optical navigation techniques together with on-board accelerometers and clocks, will allow for a number of very accurate tests of Einstein's general theory of relativity. It will provide conditions necessary to investigate the sun and the solar system, as well as to study the vast region of space that extends beyond.

C.5.4. Radio Science investigations on the way out from the solar system

The list of possible science objectives significantly extends the radio science investigations of general relativity currently conducted with interplanetary spacecraft. In particular, as the spacecraft moves alone, its trajectory in the solar system major improvements are expected.

Thus, with its path in a nearly radial direction away from the Sun, a mission could test the gravitational inverse-square law on scales never before attempted by humanity. Such a test, conducted at the extreme distances beyond 200 AU, would place stringent limits on the presence of dark matter in the solar system and in its local environment.

With its multiple solar conjunctions, the probe may test for the presence of a new physical interaction by measuring the Eddington parameter *gamma* with a precision better than the current Cassini result of 2.3×10^{-5}. As the communication instrument will be able to point at the Sun (or within 1–2 solar radii) and ranging through the solar corona, improvements of up to 2–4 orders of magnitude are possible.

The likely presence of an atomic clock on board the spacecraft could enable a highly precise test of the local position invariance (LPI). This test would drastically improve the current bounds by also verifying LPI on vast heliocentric distances. There is a unique possibility to conduct tests of spatial and temporal dependencies in the gravitational and fine structure constants that are predicted by a number of viable theories of gravitation. Precision optical ranging during conjunction to stable clocks on board may be used to test the one-way speed of light. This test could be conducted from several points along the spacecraft's highly dynamic trajectory and may be used to verify the theoretical foundation of relativistic reference frames.

The mission may be able to conduct a galactic test of the Equivalence Principle using the spacecraft and the Sun as two bodies freely falling towards the Galaxy – a unique test, never before attempted. A probe would be an excellent platform for testing the modern gravitational theories via analysis of radio-metric and optical tracking and a set of on-board sensors including precision clocks and accelerometer. Many tests of a number of modern theories of gravity, especially those proposed to explain Dark Energy, are possible. Taking advantage of the mission's trajectory that will take the spacecraft from the solar system deep into the ISM, and relying on the tracking data and optical very-long baseline interferometry (VLBI) capabilities, the interstellar probe may be used to search for and to study gravitational waves from a variety of sources.

Chapter C.6: Science Instrumentation for Exploration of the ISM

One of the major recommendations from the two KISS workshops is to investigate and develop a science-driven, integrated instrument suite capable of making required Astrophysics and Heliophysics measurements, doing KBO science, and high-data-rate laser communications for a mission to the ISM.

This integrated science measurement suite is needed to address the compelling science of an unprecedented mission to the ISM. It should include both the *in situ* instruments (Heliophysics) and the remote sensing instruments (Heliophysics, Astrophysics, KBO imaging). The main purpose of a highly integrated instrument suite is to significantly reduce the overall mass, volume, and power requirements compared to a set of individual instruments. Because of the uniqueness of a mission to the ISM, any kg, watt, or cc (volume) saved translates directly into increased energy to reach the ISM faster and to travel into the ISM further. For example, by saving, say, 20–30 watts on the instruments, one may be able to reduce the nuclear power source from 2 MMRTGs to 1 MMRTG, which further reduces the mass of the spacecraft by 80 kg or more. Infusion of new instrument technologies and capabilities not only impacts a mission to the ISM but all future deep space missions.

C.6.1. Science Definition and Requirements For the Dessign Refeerence Mission

Before we can design an instrument suite for exploration of the ISM, one of the first tasks is to understand the mission science traceability requirements. Understanding key science questions (defined during the two KISS workshops) and study of the interplay between various science goals from a systems perspective is a primary recommendation of the workshop attendees. To enable an optimized instrument suite, mapping of various science objectives to Astrophysics, Heliophysics, Planetary, and KBO science measurements is required. Given the mass-constrained nature of a mission to the ISM, performing science value vs. implementation complexity trades to maximize science return for given mass, power, and cost constraints is also needed to optimize the science payload.

Key Objectives and Goals

Heliophysics

1) Structure of the Heliosphere and the Solar Wind, Inner & Outer heliosheath, Termination Shock, Heliopause, Bow shock or wave.
2) Origin and structure of the interstellar magnetic field.
3) Origin and Composition of solar wind and ISM Plasma, neutrals and dust.
4) Wave-particle interactions, Particle-neutral-dust coupling, particle acceleration and transport in the LISM
5) Composition and evolution of our solar system and the ISM.

Zodiacal and Astrophysics

1) Extragalactic background light (EBL) brightness and spectrum.
2) Reionization background light (REBL) brightness, spectrum, and anisotropy.
3) Interplanetary dust structure and composition (Zodiacal to the Kuiper Belt).
4) Search for Earth-like planets: Measure parallax of micro-lensing events.
5) Astrometric investigations for studying galactic dynamics.
6) Tests for General Theory of Relativity.

KBO Science

1) Detect, track, characterize, and catalogue KBOs.
2) Determine the nature KBO's of the atmosphere, exterior, and interior of KBOs.
3) Search for moons around the KBO and study its 3D topography.

C.6.2. Instrument Concepts

Based on the major science requirements, the instrument suite can be divided into two parts:

Multi-Purpose Astrophysics, KBO imaging and Optical communication instrument

One of primary enablers for exploration of the ISM will be a new multi-purpose optical instrument. The instrument will be capable of: (1) making key Astrophysics measurements (Zodiacal background, Zodiacal and Kuiper belt dust); (2) taking critically sampled images for precision astrometry, parallax science, spectrometry and gravitational science; (3) imaging and study Quaoar (a dwarf planet in the Kuiper belt) during the high speed flyby; and (4) serving as a high-data-rate optical communications terminal for data intensive phases of the mission (e.g., during Zodiacal Background, Dust measurements, and KBO science).

At heliocentric distances of 100 AU, the solar light is 10,000 times fainter than at Earth's orbit. If the total dust column looking out at 100 AU is the same as that at 1 AU, the Kuiper belt background will be lowered significantly (by a factor of 10–25×). This will be a big win for studying the Zodiacal Background and for making Zodiacal/Kuiper belt dust measurements. For background-limited observations, similar to those conducted for the Hubble ultra-deep field images, the proposed instrument will enjoy a nice increase in sensitivity. On the other hand, to image a KBO during a fast flyby, we would need a very fast detector. Traditionally these two types of science observations call for two different types of cameras. The New Horizons mission, in fact, has two telescopes and two different focal plane arrays, LORRI [303] and RALPH [304]. Furthermore, a multi-purpose optical instrument can also be used as a high data rate optical terminal.

The feasibility of such a multi-purpose optical instrument hinges on recent progress in many relevant technology areas, such as flight electronics, lasers, and low read noise cameras, and has provided crucial components to realize such an ambitious goal. More work in needed to address the unique challenge of miniaturizing several modern technologies, while extending their capabilities and integrating them in a single flight instrument, capable of operating at extreme heliocentric distances (1–200 AU).

Heliophysics instruments

To understand the physical processes in the outer heliosphere and LISM, the Interstellar Probe (ISP) payload needs to sample and analyze each of the many diverse components: thermal and energetic ions, electrons and neutrals, cosmic rays, dust, and steady and fluctuating electromagnetic fields. The vast range of energies and densities makes designing instruments challenging. Figure C.6.1 (from [305] provides the ion and ENA spectra compiled from IBEX, Cassini, and Voyager measurements that the ISP will improve as it moves all along its journey. In addition to these *in situ* measurements, remote sensing of ENAs and Lyman-alpha backscatter provide information on the structure of the heliosphere.

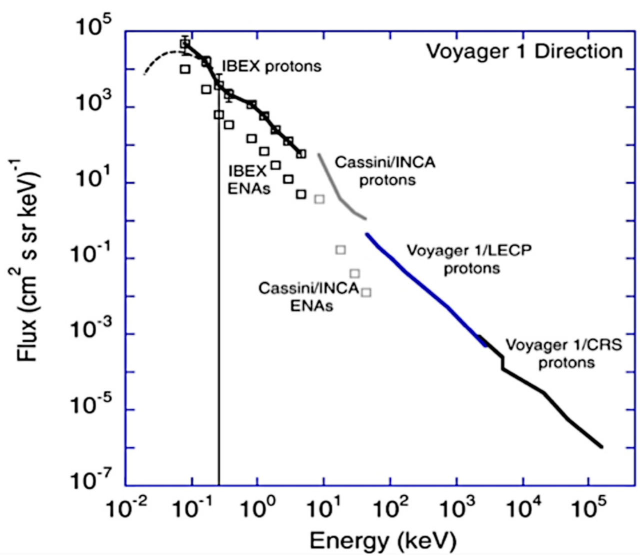


Figure C.6.1: Ion and ENA spectrum from the Voyager 1 direction in the sky, taken from [305].

Designing a prioritized *in situ* science instrument package with technical development work on the most critical instruments was identified as the most prudent way of designing a Heliophysics instrument package. The proposal will focus on technical development (improving current prototype designs, or conceptual design of a new instrument) and trade studies of four *in situ* instruments (ENA imager, plasma + suprathermal particles instrument, cosmic ray instrument, and magnetometer) to answer the most scientifically important Heliophysics questions.

The required Heliophysics instruments can be loosely described as a magnetometer, cosmic ray instrument, thermal plasma instrument, suprathermal particle instrument, dust instrument, and plasma wave instrument. In order to obtain non-local measurements relating to the structure and dynamics of the heliosphere and ISM, remote sensing observations, such as ENA imaging and Lyman-Alpha observations, are also needed.

Apart from these two main science suites, the idea of having an impactor to boost KBO science was also discussed during the two workshops. A low-cost, CubeSat-sized KBO impactor like Deep Impact (which impacted the comet Tempel 1). The impactor would provide an unprecedented opportunity to study and characterize the interior of a dwarf planet.

Part D: Reaching the Local Interstellar Medium

Chapter D.1: A Mission to the Local ISM

D.1.1. Reaching the Local Interstellar Medium (ISM)

Voyager 1 has traveled a distance of 126 AU from the Sun in 36 years since its launch and is currently travelling at a speed of ~17 km/s relative to the Sun. It recently entered the ISM and is humanity's first interstellar spacecraft. As Voyager's historic journey in the ISM nears its end (see Figure D.1.1), a planned, sustainable exploration program of the ISM is a necessary first step in our efforts to reach for the stars. The main enabling aspect of such an exploration strategy would be the need to travel fast

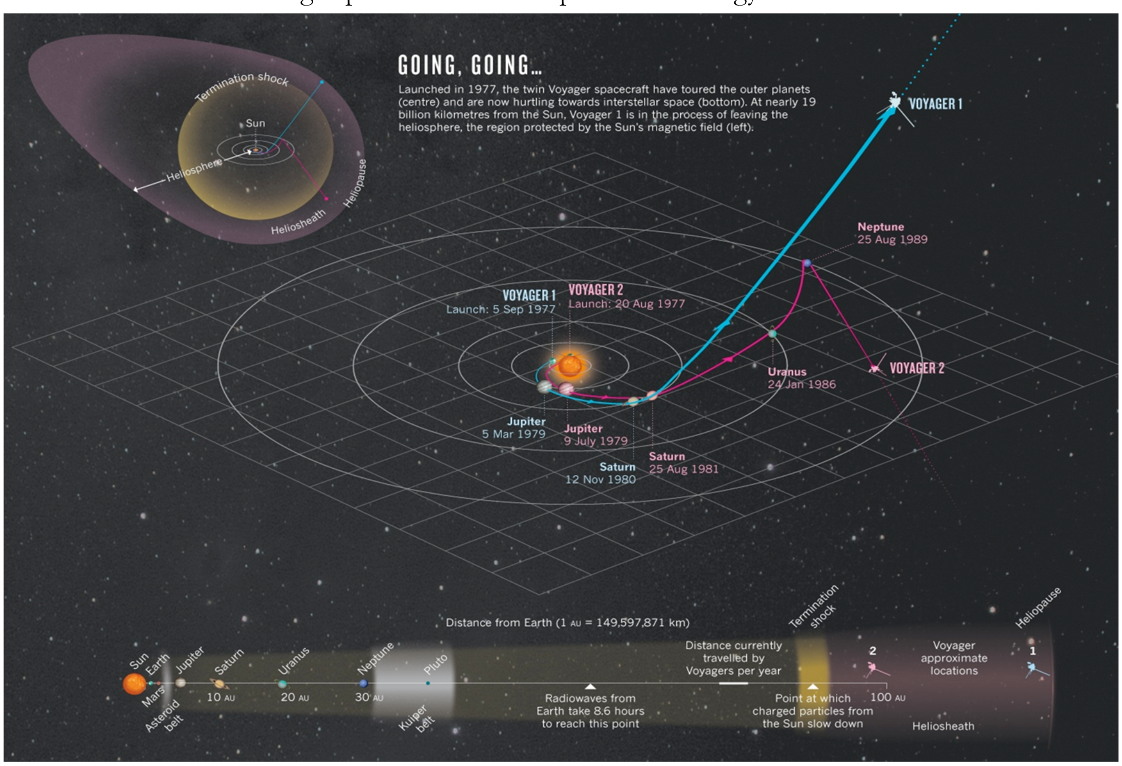


Figure D.1.1: Voyager 1 and 2 trajectories [306] and survive longer. Whereas current technology is not able to take us to another star any time soon (within a reasonable time frame), we are poised today to target the ISM as an explicit destination for robotic exploration and science investigations.

During the KISS workshop, the motivation for this reference mission study was to demonstrate the feasibility of a near-term mission that would target the ISM as a destination for *in situ* science, as well as unique science from its vantage point inside the ISM. In particular, it was identified that a near-term compelling mission to the ISM would need to achieve the following goals: (a) Launch on NASA's Space Launch System (SLS) in mid 2020s; (b) perform a Jupiter gravity assist; (c) perihelion burn at 3–4 solar radii; (d) reach the LISM within 10 years; and (e) achieve solar system escape velocities of 13–19 AU/year and reach deep into the pristine ISM (>200 AU) in 20–30 years. Adding a KBO flyby was not considered during the KISS workshop, but has been investigated since by Arora et al. [307].

Furthermore, given the current uncertain budgetary scenario it is imperative that such a mission rely on near-term technology and be cost effective. Such a mission, if feasible, would be truly revolutionary for the combined fields of planetary science, heliophysics, and astrophysics. Moreover, it would be a technological revolution and remembered for many generations to come.

The team recognized that the proposed near-term capability to reach the ISM quickly (10–15 years) and leave the Heliopause at high velocities (13–19 AU/year) does not scale well for missions to reach another star. To make this leap, one would certainly require major technological breakthroughs such as beamed energy [2], electric sails [3-5], solar sails [6, 7], and others [8-10].

This chapter gives an overview of the proposed Design Reference Mission (DRM) 1.0 to explore the ISM. The proposed mission would be humanity's first to explicitly target the LISM and journey deep into the pristine ISM. The mission would be daring, challenging, inspirational to the public, and would be a rational first step towards attempting to reach another star.

We start with a brief description of the reference science payload allocation, which is followed by a discussion on mission design and spacecraft architecture. Various spacecraft subsystems requirements are identified and the chosen subsystems hardware is discussed. Finally, results from the cost analysis are summarized and key mission risks are identified.

D.1.2. Science and Payload

The science instrument suite is selected based on previous studies (summarized in part B of this report) and answers a subset of the various science questions identified in part C of this report. The main purpose of the current science payload allocation is to define instrument mass, volume, power, and data rate requirements, which are necessary for DRM 1.0 and sizing of the spacecraft flight system. There is no optical instrument as part of this payload, as that would require an instrument technology development effort, which is expected to be part of a follow-on effort to the KISS workshop.

The science payload mass and power allocations for the reference mission are given in Table D.1.1. The current best estimate (CBE) mass of the science payload is ~35 kg. For reference, the total science payload mass on Voyager 1 is ~75 kg.

Table D.1.1: Science Payload Allocation

Instrument	CBE Mass (kg)	CBE Power (W)
Lyman-Alpha Detector	0.3	0.3
Energetic Neutral Atom (ENA) Imager (0.2-10 keV)	2.5	4
Neutral Atom Detector	2.5	4
Magnetometer with Boom (MAG)	8.8	5.3
Plasma Wave Instrument with Antenna (PWS)	10	1.6
Main Plasma Instrument (PLS)	2	2.3
Cosmic Rays (GCR/ACR) Instrument	3.5	3.5
Proton Electron Telescope (LoZCR)	2.3	2
Cosmic Dust Collector (CDC)	1.8	5
Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI)	1.5	3.0
Total	**35.2**	**31**

Note that the above-stated science payload is not sufficient to answer many of the science questions brought up during the two KISS workshops. An instrument technology development effort combining multiple science measurements would result in a mass/power optimized solution for the science instrument suite. Such an instrument suite would not only enable a lighter spacecraft (and hence faster escape velocities) but will also enable exciting new science, not possible with current off-the-shelf technology. Furthermore, having a multipurpose optical instrument would enable a new class of science investigations and capabilities (Zodiacal dust, astrometry, KBO science, precision navigation gravitational, solar gravity lens, etc.) and could also serve as a high-data-rate optical communications terminal during data-intensive phases of the mission.

D.1.3. Mission Design

One of the key challenges for this reference mission is to explore innovative mission design techniques that would enable the interstellar probe (ISP) to both reach the ISM in a short time (~10 years) and achieve high escape velocities (~17–20 AU/year).

Over the past two decades there have been many articles extolling the merits of different ways for propelling robotic spacecraft as well as human spaceships towards the stars. These schemes span electric propulsion, nuclear fission, nuclear fusion, solar sail, laser sail, electric sail, microwave sail, magnetic sail, anti-matter, and even concepts as wild as warp drive and zero-point energy. Whereas we acknowledge the merits of maturing these efforts over the coming years and decades, they are not readily applicable to a near-term mission (2025) that will enable rapid (10 years) access to the ISM.

Changing the orbital velocity of a spacecraft requires a change in its kinetic energy, which can be accomplished by performing gravity assists or by various propulsion technologies such as chemical propulsion (impulsive), electric propulsion (low thrust), or solar/electric-sails. Reaching 200 AU in ~20 years from launch, even with a Voyager-like planetary alignment (which will not happen until 2145) is not trivial and requires the spacecraft to travel at a solar system escape velocity of >13 AU/year (~4× Voyager 1). Most of the previously studied ISP mission concepts [51, 80, 110, 118, 135, 150, 308-310] have a high launch energy (C3) in excess of 100 km^2/s^2, rely on a Jupiter gravity assist, and can be grouped into two main categories: 1) trajectories flying close to the Sun taking advantage of a large solar sail or a perihelion maneuver; or 2) trajectories utilizing Jupiter gravity assist and electric propulsion (nuclear powered) to achieve high escape velocities (~9.5 AU/year). However, high launch C3 requirement results in a lower launch mass, thereby limiting onboard propulsive capabilities by the probe after launch.

An enabling technique to achieve high solar-system escape velocity employed in the DRM 1.0 and described here (Figure D.1.2) utilizes a Jupiter gravity-assist followed by a large maneuver at perihelion (closest point on the trajectory from the Sun).

To understand the effect of the perihelion maneuver, Figure D.1.3 shows solar system escape velocity (V_∞^{SUN}) contours (in AU/yr) for parametrically varying values of perihelion distance (x-axis) and ΔV executed at perihelion (y-axis). For this plot, the solar approach

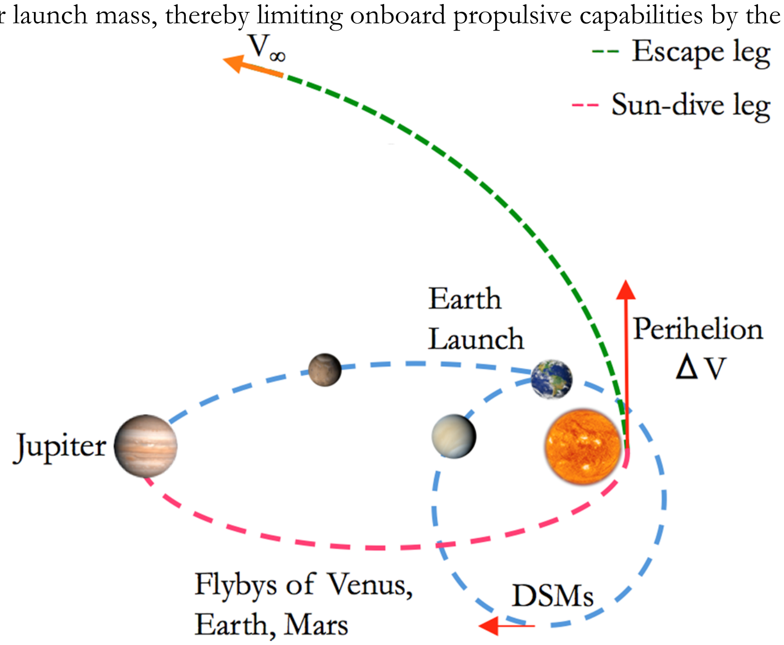


Figure D.1.2. Mission Design overview utilizing Earth, Jupiter gravity-assist and a perihelion maneuver

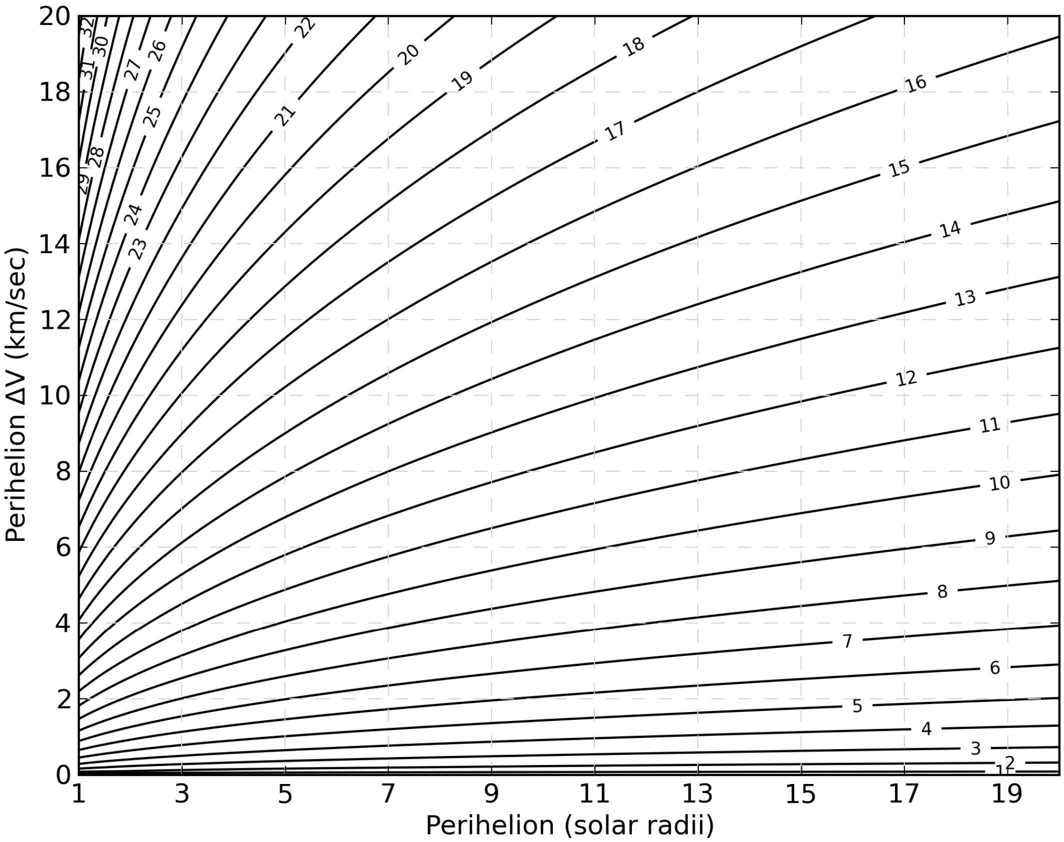


Figure D.1.3. Escape velocity contours (in AU/yr) for a parabolic solar approach trajectory

trajectory is assumed to be parabolic. As expected, the solar system escape velocity increases substantially as the perihelion distance goes down and as the ΔV of the maneuver goes up (Figure D.1.3). As an example, a 5 km/sec ΔV at a 4 solar radii would result in a V_∞^{SUN} of ~11 AU/yr, a little over 3 times that of Voyager-1. Going as close as 2 solar radii would result in resulting V_∞^{SUN} of ~15 AU/yr, almost four times that of Voyager-1. This large gain in speed by a small propulsive maneuver is due to the Oberth effect [311], which states that the efficiency of a propulsive maneuver is proportional to the speed of the spacecraft (which is highest at the perihelion). See [307] for more details.

To achieve the stated mission goals with near-term technology we propose a mission design (Figure D.1.2) that: (i) launches on the SLS Block 1-b launch vehicle; (ii) performs a 400 m/s deep space maneuver (DSM; also known as a leveraging maneuver); followed by (iii) an Earth flyby, to significantly lower the launch C3 requirements from ~115 km²/s² to 47.3 km²/s²; (iv) does a Jupiter gravity assist to put the spacecraft on a near retrograde sun-dive trajectory with perihelion very close to the sun (~3 solar radii); and (v) performs a large impulsive maneuver of 5.55 km/s at the perihelion to achieve a solar system escape velocity (V_∞) of ~13 AU/year.

Assuming we launch on the NASA new Space Launch System (SLS) Block-1B launch vehicle (expected to be ready for use in early 2020s), a reduction in launch C3 from ~115 km²/s² to 47.3 km²/s² increases our maximum injected mass (maximum possible spacecraft mass) capacity from 7.3 tons to 16.8 tons. This in turn allows us to carry more fuel near the Sun, enabling us to achieve the required ΔV of 5.55 km/s. Other trajectories with even lower launch C3s (and utilizing multiple gravity assists of Earth, Venus and Mars) and higher escape velocities are possible and will be part of follow-on studies.

The spacecraft on the current mission trajectory exits the solar system close to the nose of the Heliopause and near the large KBO Quaoar, which has been identified as one of the exciting KBO

Table D.1.2: Mission Timeline

Mission Events	Date	Stage	Characteristics	Main Propulsion
Launch	19 Feb 2027	SLS	C3 = 47.3 km^2/s^2	Launch vehicle
DSM	27 Dec 2028	DSM	Maneuver = 0.4 km/s	Bi-prop
Earth	12 Jan 2030	DSM	Gravity assist	None
Jupiter	15 July 2031	DSM	Gravity assist	None
Solar Perihelion ΔV	22 June 2033	Perihelion Kick	Maneuver = 5.55 km/s	Solid Rocket Motor (SRM)
200 AU	~25 July 2047	ISM Probe	V_∞ = ~13 AU/year	None

targets for a mission to the ISM. For trajectory options with a KBO flyby see [307]. The required planetary alignment for the above trajectory occurs in 2027, and the mission time line is given in Table D.1.2. The probe reaches 200 AU in ~21.5 years from launch.

Launch: The mission is designed to be launched on NASA's SLS Block-1B launch vehicle with a C3 of 47.3 km^2/s^2 and a total spacecraft launch mass of ~16.75 tons. Figure D.1.4 shows the spacecraft inside the 8.4-m launch fairing (scaled to actual dimensions).

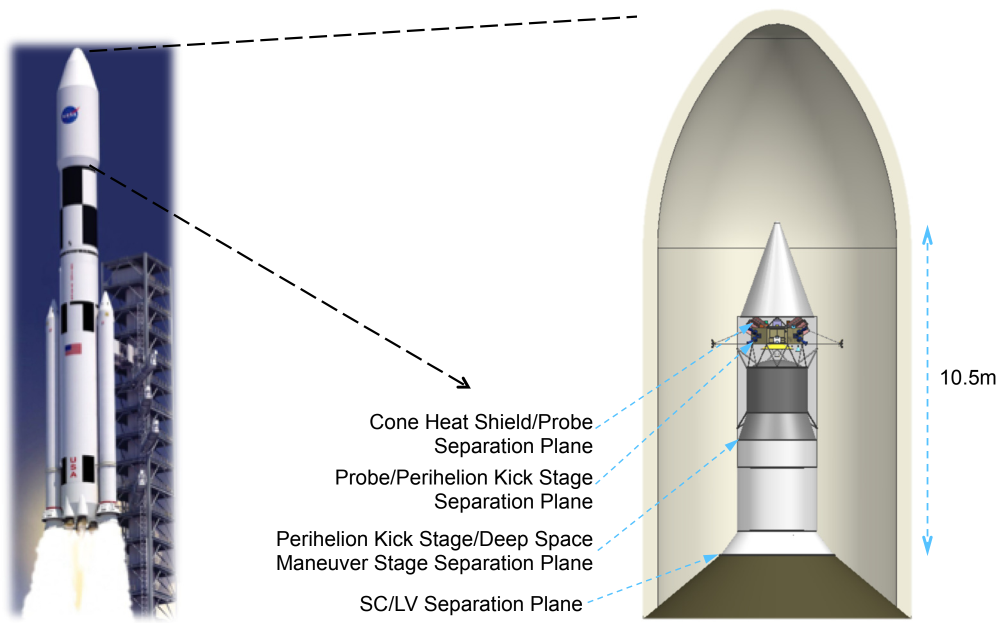


Figure D.1.4: Spacecraft on SLS Block-1B

Deep Space Maneuver: The spacecraft performs a deep space maneuver of 400 m/s using a bi-propellant engine, which puts it back on an Earth approach trajectory. This maneuver is also knows as a V_∞ leveraging maneuver [312, 313].

Earth Flyby: The spacecraft performs a "pump up" Earth flyby (flyby altitude of 300 km), putting it on a Jupiter-bound trajectory.

Jupiter Flyby: The spacecraft then approaches Jupiter at a Jupiter-relative velocity of ~12 km/s and performs a Jupiter Gravity Assist (JGA) maneuver (flyby altitude of 621,781 km). The JGA greatly reduces the "tangential" component of spacecraft velocity, bending the spacecraft trajectory towards the Sun on a near parabolic approach, also called to as the Sun-dive arc. This phase of the mission is accomplished by the DSM stage.

Perihelion Burn: At a distance of ~0.15 AU from the Sun, the spacecraft jettisons the DSM stage and starts warming up the (enlarged Star-75) Solid Rocket Motor (SRM). The DSM stage can be jettisoned earlier if needed. Jettisoning the DSM stage makes the spacecraft lighter and increases the maximum achievable ΔV from the SRM. The spacecraft takes approximately two years (from Jupiter) to reach its closes approach of 2.8 solar radii from the center of the Sun. At its closest approach to the Sun, the spacecraft is travelling at a speed of ~375 km/s. Leveraging the Oberth effect, the spacecraft performs a solid rocket burn using the SRM to achieve a ΔV of 5.55 km/s. The SRM is then jettisoned after imparting the required change in velocity.

Solar System Escape: Post perihelion burn, the spacecraft orbit eccentricity goes from 0.995 (elliptical orbit) to 1.056 (hyperbolic orbit), resulting in a solar system escape velocity of ~62 km/s or ~13 AU/year. After passing 1 AU, the spacecraft jettisons its heat shields. The ISM probe uses its Attitude Control System (ACS) thrusters to spin up (at ~2 rpm) and continues to travel on a hyperbolic escape trajectory away from the Sun. It powers up the instruments for the science data collection phase of the mission, carrying out multiple scientific investigations on its way to the LISM.

D.1.4. Flight System Overview

Based on the mission trajectory the spacecraft consists of four main elements. A propulsion system element to perform the (400 km/s) deep space maneuver, a heat shield for surviving a close encounter with Sun, solid rocket motor based propulsion system to perform the required 5.55 km/s ΔV at the perihelion, and the ISM probe (also called as interstellar probe (ISP) in some literature). Figure D.1.5 shows the CAD of the complete spacecraft flight system with its components at launch. The spacecraft uses a bi-propellant rocket engine for performing the DSM and an enhanced Star 75 Solid Rocket Motor (SRM) for performing the perihelion ΔV. The spacecraft thermal protection system consists of two heat shields (front and side). The ISM probe with the science payload and two RTG-based power sources is sandwiched between the SRM and the front heat shield.

ISM Probe Overview:

The ISM probe is a 544 kg (with margin and contingency), spin-stabilized spacecraft powered by two eMMRTGs (enhanced version of the radioisotope power source used on MSL). It has dual cold case redundant electronics (for long life) and utilizes a 1-m solid reflector for communications. It achieves a data rate of ~250 bps from 100 AU. The dual cold-case cross-strapped system is critical for achieving long lifetime. The study did not look at optimizing the spacecraft subsystems for low, power autonomous operations, which will be part of a future in-depth effort. The probe also has a very capable ACS system required for precise pointing and control during various phases of the mission. The mass of the ISM probe is dominated by the two eMMRTGs and the mechanical structure, which goes along with them.

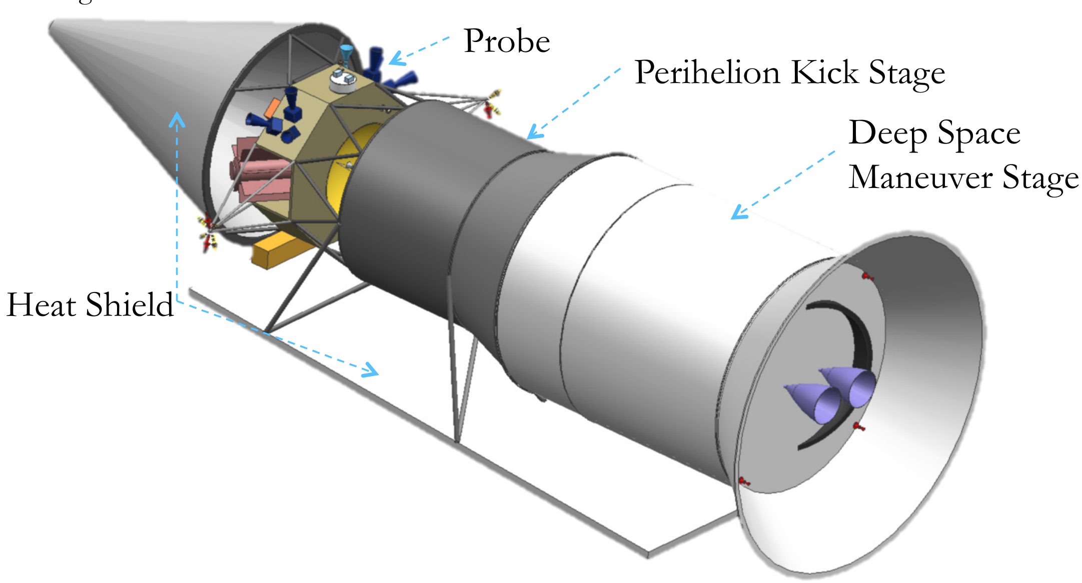


Figure D.1.5: Spacecraft overview showing major flight system elements

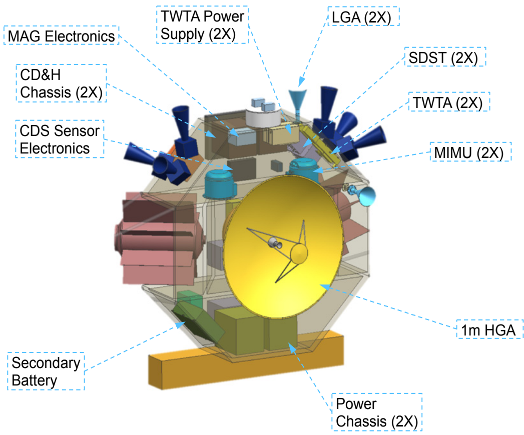


Figure D.1.6: ISM probe with major subsystem components (without ACS thrusters)

Table D.1.3: ISM Probe Subsystem Masses

Subsystem	MEV (kg)
Power (2x eMMRTG)	145
Propulsion	17
Telecom	24
Mechanical	160
Thermal	28
Attitude & Control	30
C&DH	14
Payload	40
Propellant (mono-prop)	13
Additional System Margin	73
Total	544

Table D.1.3 gives overview of the subsystem masses for the ISM probe. Figure D.1.6 gives a front view (without the main ACS thrusters) of the spacecraft with major subsystems components.

All three phases of the mission rely on the ISM probe for power and attitude control. Furthermore, the waste heat from the eMMRTGs is also used to keep the probe warm during cold phases of the mission.

Perihelion KICK

The proposed mission uses ~10 tons of propellant to achieve the required 5.55 km/s ΔV. Hence, the mission requires an enlarged graphite case Star 75 solid rocket motor (Figure D.1.7). Furthermore, as the perihelion kick stage is 3-axis stabilized, the motor requires a vectorized nozzle to achieve the required control. Finally, the Star 75 motor will also use a deployable gas nozzle extension to achieve an ISP of 312 seconds. The total time required for the perihelion burn is ~3–5 minutes. Note that the Star 75 motor is already flight qualified and most of the above-stated technologies have already been tested on other smaller Star motors (e.g., Star 48BV).

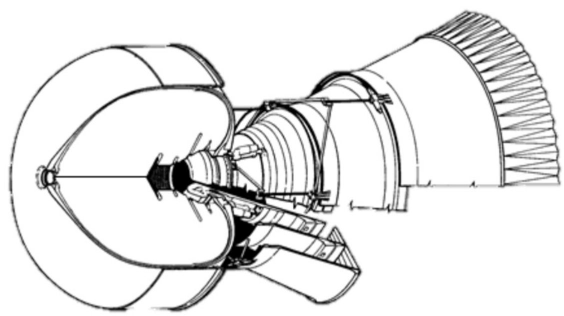


Figure D.1.7: Star 75 with enlarged nozzle

Heat Shield Design

The heat shield for the spacecraft relies on heritage from the original Solar Probe mission study, relying on a large front conical heat shield for providing most of the protection. A side flat heat shield is also used to help the spacecraft survive during the SRM burn, which lasts for about 30 minutes. The side heat shield comprises a thin layer of Carbon-Carbon along with a thick layer of aerogel. The shields are connected to the main structure via Carbon-Carbon struts. The heat shields have been designed such that the maximum temperature on the side facing the spacecraft does not exceed 500°C. The CBE mass for the front and side heat shields are 183 kg and 107 kg respectively.

Figure D.1.8 gives an overview of the concept of operation during the perihelion pass of the Sun. After dropping the DSM stage, the spacecraft keeps on slewing to point the front shield at the Sun. Approximately 15 minutes before the perihelion burn, the spacecraft slews sideways to orient itself into the burn position and orients itself back after performing the perihelion maneuver.

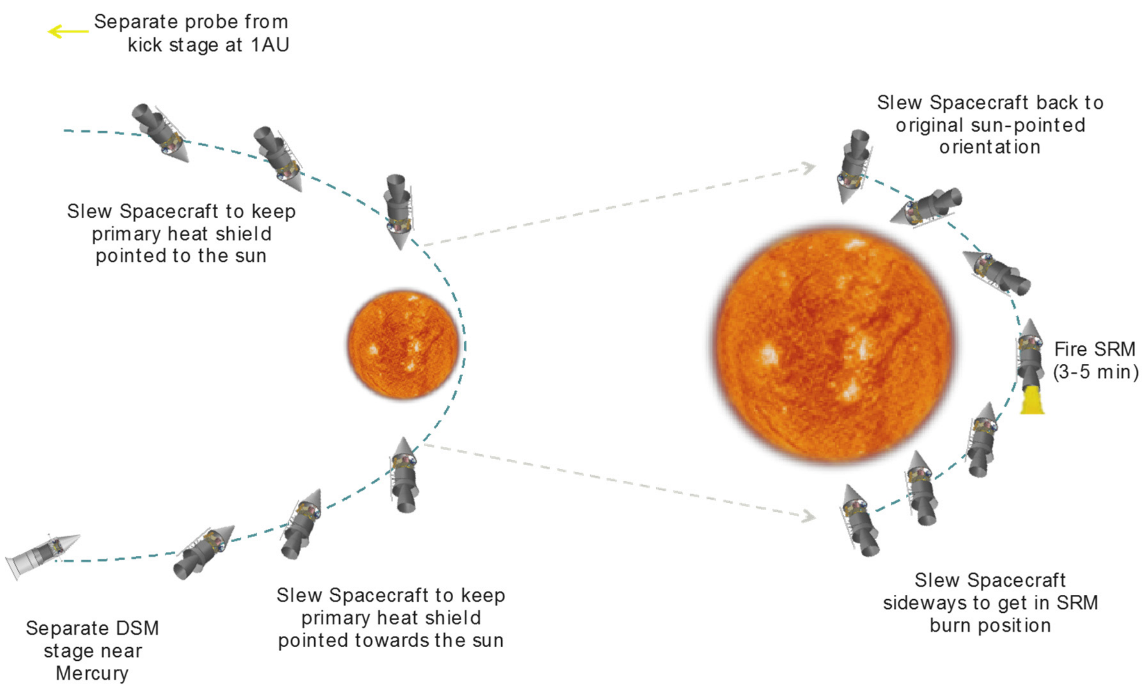


Figure D.1.8: Perihelion pass Con-Ops; the critical maneuver phase is shown on the right

DSM Stage

Given that the solid motors are not restartable, the DSM (400 m/s) is achieved by having two bi-propellant engines attached axially to the Star 75 motor (as shown in Figure D.1.5). This simplifies the structural design of the spacecraft and utilizes the load-bearing capacity of the Star motor to reduce launch mass. The same bi-propellant engines are also used performing trajectory correction maneuvers (~100 m/s) before the perihelion burn. To achieve the required ΔV of 500 m/s, the DSM stage tanks carry ~3.5 tonnes of propellant. The DSM stage also uses a large amount of RHUs to keep the spacecraft warm (especially during Jupiter flyby).

D.1.5. Key Technologies and Risks Associated with the Reference Mission

The current reference mission architecture requires two eMMRTGs, each weighing ~65 kg in structure mass. They are one of the main drivers of the probe spacecraft mass. If it were possible to design lightweight integrated instrumentation to reduce mass and power requirements, the mission could answer all key science questions without sacrificing performance. A new spacecraft flight system with reduced mass and power requirements will also have a trickle-down effect on all the spacecraft sub-systems. Furthermore, low power spacecraft operations would also enable longer life.

The second key technology for this mission is the heat shield design. Surviving close to the Sun is one of the key enablers and key risks of this mission and, thus, warrants detailed study. There is also some risk and uncertainty associated with SLS performance at this stage. This has a direct effect on how much fuel we can carry close to the Sun and hence affects mission performance.

Finally, given the unconventional design of the spacecraft, the structural estimates used during the Team-X design study also have some degree of uncertainty.

D.1.6. Conclusions and Future Work

In this work we have established feasibility of a DRM 1.0 which is capable of satisfying majority of the mission goals outlined during the two KISS workshops. Nevertheless, the work presented here has just scratched the surface of a rich technology/mission design space. Straight forward additions to the

DRM 1.0 would include adding onboard propulsion (e.g. solar sail, electric sails, or electric propulsion) after perihelion maneuver; exploiting targeting a Kuiper Belt Object (KBO) flyby post perihelion maneuver and adding multiple gravity-assists to further reduce mission launch C3 requirements. Some of this have been addressed in [307]. Impact of new and upcoming thermal, propulsion, telecommunications, instrumentation etc., technology on mission capability and risk, could also be studied.

Each of these additions (both to technology and the mission design) could result in a significant change in the flight system which would also need to be studied. Hence, given the coupled nature of this mission future studies will look into determining various flight system architectures for different classes of trajectories.

Instead of a single large ISM probe, an architecture with swarm of probes (e.g., multiple small-sats), each travelling in different directions could also be analyzed.

Chapter D.2: On-Board Probe-Propulsion Trades for a Near Term Missions to the ISM

The Pioneer 10 and 11 missions illustrate the gains to be realized for high-speed escape from the solar system by using close encounters with Jupiter. Similarly, the Voyager 1 and 2 missions demonstrate the even greater gains that can be realized by multiple, outer-planet gravity assists. For a selected target region, the trade is speed versus launch opportunities. The more planets required, the greater the span of time between opportunities. In studying outer-planet gravity assists, both with and without augmentation with radioisotope electric propulsion (REP; discussed in more depth below), it became clear that if gravity assist is used, the greatest advantage is at Jupiter alone [135]. Already, such an approach limits launch windows to a ~12-year cycle, Jupiter's orbital period. An additional assist at Saturn does not significantly improve performance and greatly limits opportunities (the next is in 2038 and the following one ~60 years later).

The near circularity of Earth's and Jupiter's orbits (eccentricities of 0.0167 and 0.0489, respectively), as well as their near co-planarity (Jupiter's orbital plane is inclined only 1.304° with respect to that of Earth [314], enables simple but fairly accurate rapid estimates of the advantage that can be applied by Jupiter gravity assists to maximizing solar system escape speed. The finite non-zero eccentricities, launch opportunities and windows, and orbital inclination of Jupiter, as well as the exact aim point on the sky, will all, of course, require small corrections to the results of a simple analysis.

All chemical / ballistic approaches can be assembled into various families. Increased flyout speed typically involves more complexity and, hence, more risk – or at least the perception thereof. Variants include: (1) direct flyout from Earth [34], (2) direct flight to Jupiter with an unpowered, prograde, optimized flyby, (3) direct flight to Jupiter with an optimized, prograde, powered flyby, and (4) direct flight to Jupiter with an unpowered, optimized, retrograde flyby, followed by a near-Sun, powered flyby ("Oberth maneuver") [34]. There are other schemes utilizing retrograde orbits leading to gravity assists [47, 315] not considered here. Launches of larger payloads can be accomplished at a smaller launch energy per unit mass (C3) by making use of combinations of Earth and/or Venus gravity assists in the inner solar system. While these are unpowered, they do require a substantial (~100s of meters per second) deep-space maneuver (DSM) in order to set up the flyby approach trajectory. Such maneuvers require more time in the inner solar system, and this trades against the increased payload capability, along with an appropriate propulsion system to provide the DSM.

The baseline mission (DRM 1.0) discussed in the previous chapter makes use of a single Earth gravity assist followed by a retrograde Jupiter flyby and a large Oberth maneuver near the Sun. Here we consider trades using only direct flight to Jupiter, as such an Earth gravity assist and DSM may be applied to any of these examples in order to decrease the required launch C3 for a given mission-design approach; this in turn would result in increased perihelion ΔV and hence, higher escape speeds.

Augmentation of the baseline, all-chemical, SLS(1b)-based mission concepts with an onboard spacecraft Advanced Propulsion System (APS) system was considered to reduce trip time to the ISM. Three types of onboard APS were considered: REP, Solar Sail Propulsion, and Electric Sail Propulsion.

Note that this study was carried out before the reference mission design outlined in the previous chapter; nonetheless, the relative comparison between the three APSs holds true.

D.2.1. Radioisotope Electric Propulsion

REP uses the electricity generated by the spacecraft's onboard radioisotope power system to ionize and accelerate propellant (typically xenon) to produce thrust. Similar in operation to Solar Electric Propulsion (SEP), REP systems operate at much lower power but are unconstrained in performance by proximity to the Sun, making them an attractive option for a deep space mission to the ISM.

D.2.2. Solar Sail Propulsion

Solar sail propulsion uses sunlight to propel vehicles through space by reflecting solar photons from a large mirror-like sail made of a lightweight, highly reflective material. The continuous photonic pressure provides propellant-less thrust. Since the Sun supplies the necessary propulsive energy, solar sails require no onboard propellant, thereby significantly increasing useful payload mass. Current sail technology is constrained by material properties to be operable from no closer to the Sun than ~0.25 AU (due to the heating of materials) to not much farther from the sun than 5 AU (because of thrust losses due to the inverse square law). Carbon-carbon and pure metallic sails may in the future permit closer solar approaches.

D.2.3. Electric Sail Propulsion

An Electric Sail propulsion system consists of 10–100 electrically conducting wire strands, each many kilometers in length. Strands are deployed from the main spacecraft bus and the spacecraft rotates to keep the strands taut. An electron gun is used to keep the spacecraft and the strands in a high positive potential. The gun of course will require significant power. The electric field of the strands extends into the solar wind plasma. The field repulses positive ions in the solar wind and thrust is generated. The technology appears promising because it can operate deep into the outer solar system, much farther than is possible with a solar sail, but its TRL is low (only theoretical studies have been done), making it a higher-risk option for a near term mission to the ISM.

To compare these APSs in an apples-to-apples fashion we used a consistent set of mission-specific ground rules and assumptions (Table D.2.1) in a high-level systems study considering various mission trajectories into the ISM. Actual comparison of these systems should also be done for concepts beyond the Design Reference Mission which need further study – specifically the use of small spacecraft for multiple probes.

Table D.2.1. GR&A for assessment of alternate on-board APS options.

Item	Description
Mission Performance	100+ AU in ~10 years
Launch Window	2025 – 2035
Launch Vehicle	SLS Block 1B + EUS + 8.4-m fairing
Spacecraft Mass*	380 kg (838 lb_m)
Spacecraft Heat Shield Mass†	300 kg (661 lb_m)
Spacecraft Power	450 W

* Mass includes all components except onboard low-thrust propulsion system.
† Mass scaled from that of Solar Probe Plus heat shield.

The total spacecraft mass was assumed to be 380 kg, which included all components except for the onboard low-thrust propulsion system. It was assumed that 450 W of power would be available onboard the spacecraft supplied by an Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) because this technology was considered to be potentially available within the project development timeline. It was assumed that a protective heat shield would be attached to the spacecraft, particularly for an impulsive Oberth maneuver performed very close to the Sun, approximately 11 solar radii or 0.05 AU above the surface. (Note: this is considerably farther away from the Sun than assumed in the baseline mission concept but should not impact the outcome of the assessment of onboard propulsion options. We are concerned about the relative performance of the various propulsion system options to determine which, if any, should be considered, not their absolute performance.) The heat shield mass was derived by scaling the heat shield currently being designed for NASA's Solar Probe Plus mission by the Johns Hopkins University Applied Physics Laboratory (APL) to a size adequate for this mission.

Several low-thrust onboard propulsion system technologies were traded for each of the trajectory profiles considered, including a MaSMi Hall thruster, solar sails, and an E-Sail propulsion system. In addition to the spacecraft having some kind of onboard low-thrust propulsion system, the required quantity and size of aft-attached, series-burn SRM kick stages for various impulsive maneuvers were also assessed. The MaSMi Hall thruster would be powered by the onboard eMMRTG outputting 450 W of power assumed to be capable of 50,000 hours maximum and exerting 19 mN (0.004 lbf) of thrust with an I_{SP} of 1,870 seconds. The solar sail and E-Sail propulsion systems GR&A are outlined below in Tables D.2.2 and D.2.3, respectively.

Table D.2.2 Solar sail propulsion system GR&A.

Item	Description	
Reflectivity	0.91	
Minimum Thickness	2.0 μm	
Maximum Size (per side)	200 m (656 ft)	
Sail Material	CP1	
Areal Density *	3 g/m^2	10 g/m^2
Characteristic Acceleration	0.426 mm/s^2	0.664 mm/s^2
System Mass	120 kg (265 lb_m)	400 kg (882 lb_m)

* Assumes an advancement in technology. Current technology is approximately 25 G/m^2.

Table D.2.3. Electric Sail (E-Sail) propulsion system GR&A.

Item	Description	
System Mass	120 kg (265 lb_m)	
Wire Material (Density)	Aluminum (2,800 kg/m^3)	
Wire Diameter (Gauge)	0.127 mm (36 gauge)	
Characteristic Acceleration	1 mm/s^2	2 mm/s^2
Tether Quantity	10	20
Individual Tether Length	20 km (12.4 mi)	20 km (12.4 mi)

Two trajectory profiles were considered for this assessment: (1) an escape trajectory using a JGA maneuver (E-Ju) and (2) an escape trajectory first performing a JGA maneuver followed by a Sun dive via an impulsive Oberth maneuver and Saturn gravity assist maneuver (E-Ju-Su-Sa). Both trajectory profiles are depicted in Figure D.2.1 and are separated based on the type of low-thrust onboard propulsion system employed.

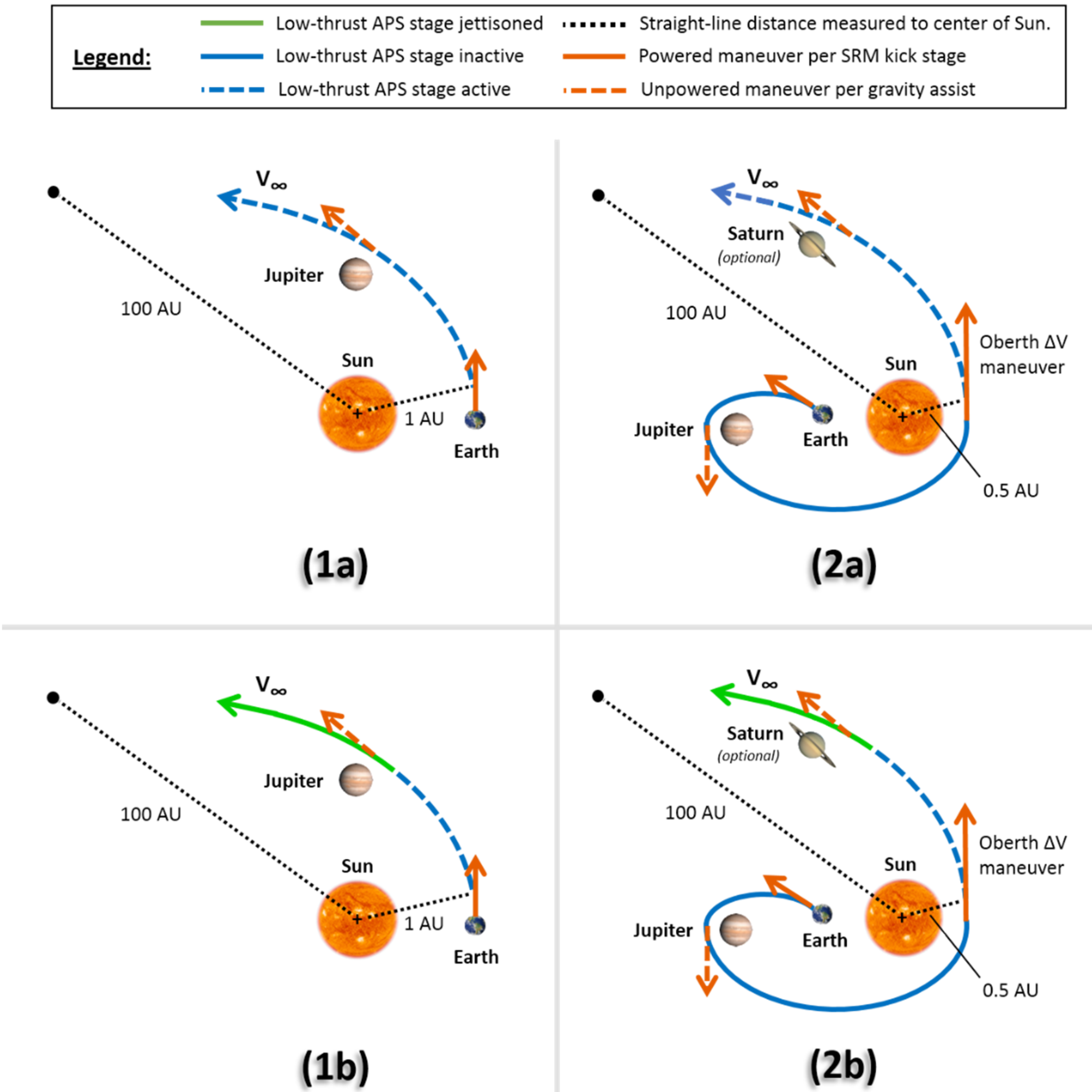


Figure D.2.1. Mission trajectory profile options: (a) trajectories apply to MaSMi Hall thruster and E-Sail systems and (b) trajectories apply to solar sail system.

As the spacecraft approaches Jupiter, it performs a gravity assist with a minimum flyby distance of 4.89 Jupiter radii. For this analysis, the orbit of Jupiter is assumed to be circular at 5.203 AU. Figures D.2.2 and D.2.3 illustrate the effect of each low-thrust APS type on the total trip time to the termination shock and heliopause at 100 AU. Two E-Sail data points are plotted in Figure D.2.2 denoted by , which corresponds to an E-Sail characteristic acceleration of 2 mm/s^2, and , which corresponds to a 1 mm/s^2 characteristic acceleration.

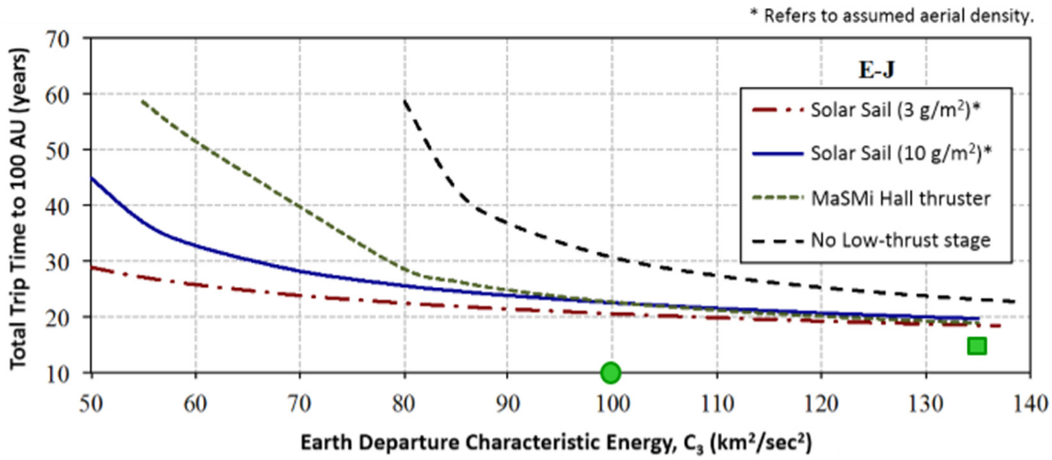


Figure D.2.2. Low-thrust APS analysis for E-Ju trajectory profile

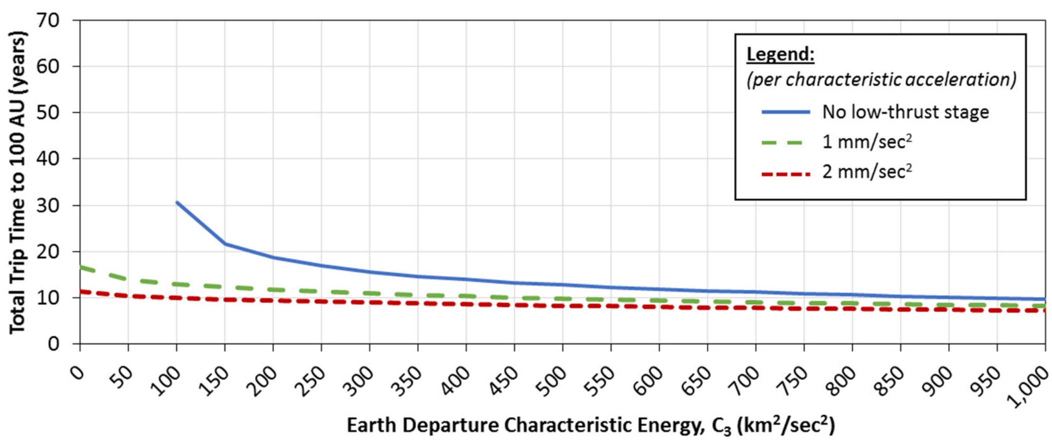


Figure D.2.3. E-Sail propulsion system analysis for E-Ju trajectory profile.

Similar to the first trajectory option, the second trajectory begins with an Earth-departure performed by the SLS and an additional SRM kick stage. With the low-thrust APS yet to be activated, the spacecraft performs a Jupiter flyby, which occurs at a minimum passage distance of 18.72 Jupiter radii, to reduce its heliocentric speed such that the resulting perihelion is 11 solar radii (~0.05 AU). At perihelion, about 2.97 years into the mission, another SRM kick stage performs the final high-thrust maneuver. The heat shield, along with the SRM, is jettisoned when the radial distance from the sun is 0.5 AU. This is also where the low-thrust APS is initiated. Similar to the first trajectory option, the MaSMi Hall thruster operates for 50,000 hours, the solar sail is dropped just prior to the next planetary flyby (in this case Saturn), and the E-Sail option is employed until the thrust has a negligible effect. At Saturn, which in this study is assumed to have a circular orbit at 9.583 AU, a final gravity assist is performed with a minimal flyby distance of 2.67 planetary radii. Table D.2.4 describes the SRM kick stages chosen for this particular study for various low-thrust APS masses. Again, note that the perihelion distance is farther and SRM stages are lower performing than those on the baseline mission.

Table D.2.4. SRM kick stages chosen for the E-Ju-Su-Sa trajectory option

Low-thrust APS Stage Mass	Impulsive Burn 1 (Earth departure)	Impulsive Burn 2 (Perihelion)	Notes
0 kg (0 lb_m)	Star 63D	Star 48V	Star 63D – 20% of propellant offloaded.
120 kg (265 lb_m)	Star 63F	Star 48V	Star 48V – 5% of propellant offloaded.
400 kg (882 lb_m)	Star 63F	Star 48V	Star 48V – 20% of propellant offloaded.
700 kg (1,543 lb_m)	Star 63D	Star 48V	No propellant offloaded for either SRM.

Figure D.2.4 below describes how the performance capability of the SRM kick stage chosen for the Oberth impulsive ΔV maneuver affects the total trip time to 100 AU. Figure D.2.4 also provides additional insight into the target trajectory for Option 2 shown in Figure D.2.1, where the point corresponds to an E-Sail characteristic acceleration of 1 mm/s². Lastly, Figure D.2.5 shows that the mission goal of reaching the ISM within approximately 10 years of launch can be achieved using only an onboard Electric Sail APS and two SRM kick stages, without the need of an Oberth Maneuver near the sun.

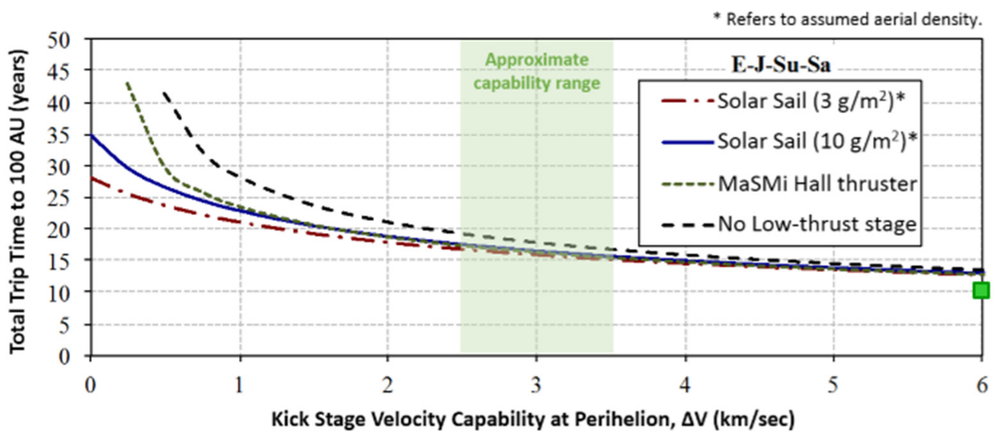


Figure D.2.4 Kick stage analysis for E-Ju-Su-Sa trajectory profile.

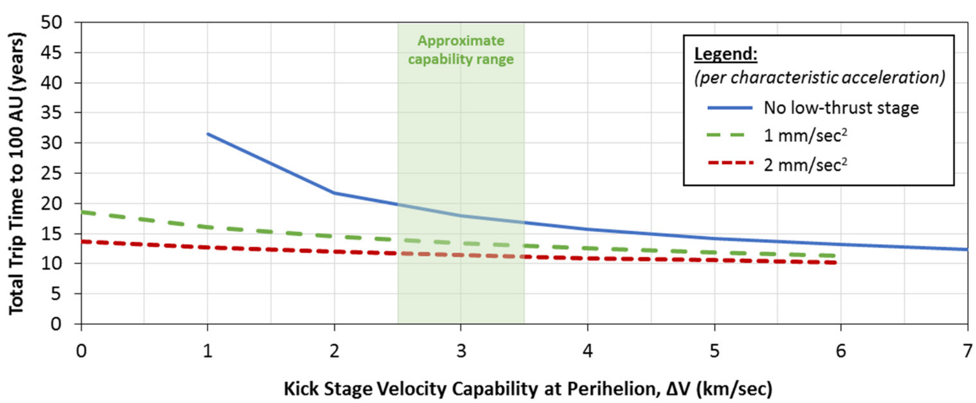


Figure D.2.5 Kick stage analysis for E-Ju-Su-Sa trajectory profile (E-Sail only).

D.2.4. Discussion

A spacecraft can reach the ISM within a somewhat shorter amount of time compared to the baseline when employing low-thrust APS stages. In fact, applying an E-Sail low-thrust APS stage results in the lowest total trip time of approximately 11 years for the E-Ju-Su-Sa trajectory option. There is also an additional potential mass and, thus, time savings if an SLS Block 1B 5.0-m PLF is employed rather than the 8.4-m PLF since there appears to be adequate room to do so. With that said, all low-thrust APS technologies for either trajectory option provide modest total trip time improvements.

The addition of an onboard APS using technologies that can be developed within the next ten years generally does not significantly decrease the trip time to the ISM beyond the baseline SLS all-propulsive Oberth Maneuver approach. However, one APS technology, Electric Sails, has the potential to allow meeting the desired trip time without the need for any sort of Oberth Maneuver. The performance of Electric Sails is still uncertain at this time and should be revisited to determine its actual potential performance.

PART E: JOURNEY TOWARDS ANOTHER STAR

CHAPTER E.1: ENABLING NEW TECHNOLOGIES

We have shown a possible mission design to take the first step beyond Voyager – faster and farther into the ISM. This mission uses current technology with a propulsive maneuver from a conventional rocket firing on a sun-diving trajectory – albeit with a large and new heat shield. This is described in Part D of this report. However, the mission design architecture based on the low perihelion Oberth maneuver is limited and does not naturally lead to farther or faster steps on the interstellar path. The current mission approach reaches 200 AU in 20 years (a factor of three improvement over Voyager); we seek another factor of three improvement in spacecraft architecture that leads to reach at least 600 AU in 20 years and advance the technologies that may lead to the first interstellar flight in the next century. This might enable a Solar Gravity Lens Mission [286], from ~700–1000 AU to be the next step beyond the reference mission or, upon further study, to provide an alternate approach to meet the reference mission goals.

The three major propulsion technologies that were considered in this study are: Solar sails, Laser Sails, and Electric Sails. The team acknowledge, discussed a plethora of other technologies, e.g. nuclear pulsed propulsion, nuclear thermal propulsion, nuclear electric propulsion, fusion drivers etc., but given the time constrained nature of this study, technologies with the lowest perceived risk were studied in detail.

E.1.1. SOLAR SAIL PROPULSION

The KISS ISM study considered space sails to achieve higher velocity missions to exit the solar system. Space sails include solar sails, electric sails, and laser sails. A parametric study of solar sail performance shows that very large sail area to spacecraft mass ratios will be required, along with approaches to the Sun as close as 0.1 AU. Figure E.1.1 shows exit velocity vs. area-to-mass ratio for different trajectories. The best case depicted is still less than 20 AU/year for A/m ~ 500 m^2/kg. To reach 30 AU/year would require A/m ~ 1000 m^2/kg. Current solar sails (LightSail, Lunar Flashlight, and NEA Scout) have A/m approximately 7–8 m^2/kg, two orders of magnitude less than we seek! Previous JPL studies of the Halley Comet Rendezvous and of the "Near-ISM Mission" had designs with A/m > 700 m^2/kg, suggesting that such large values might be credibly considered – even if their development is not yet feasible. A study of conventional solar sails (metallic reflectors on plastic substrates) also led to the conclusion that approaching the Sun as close as 0.1 AU was not currently feasible due to sail material thermal limits.

However, several key technology developments may enable solar sails to be considered for interstellar precursor missions. Here, we outline three possible developments.

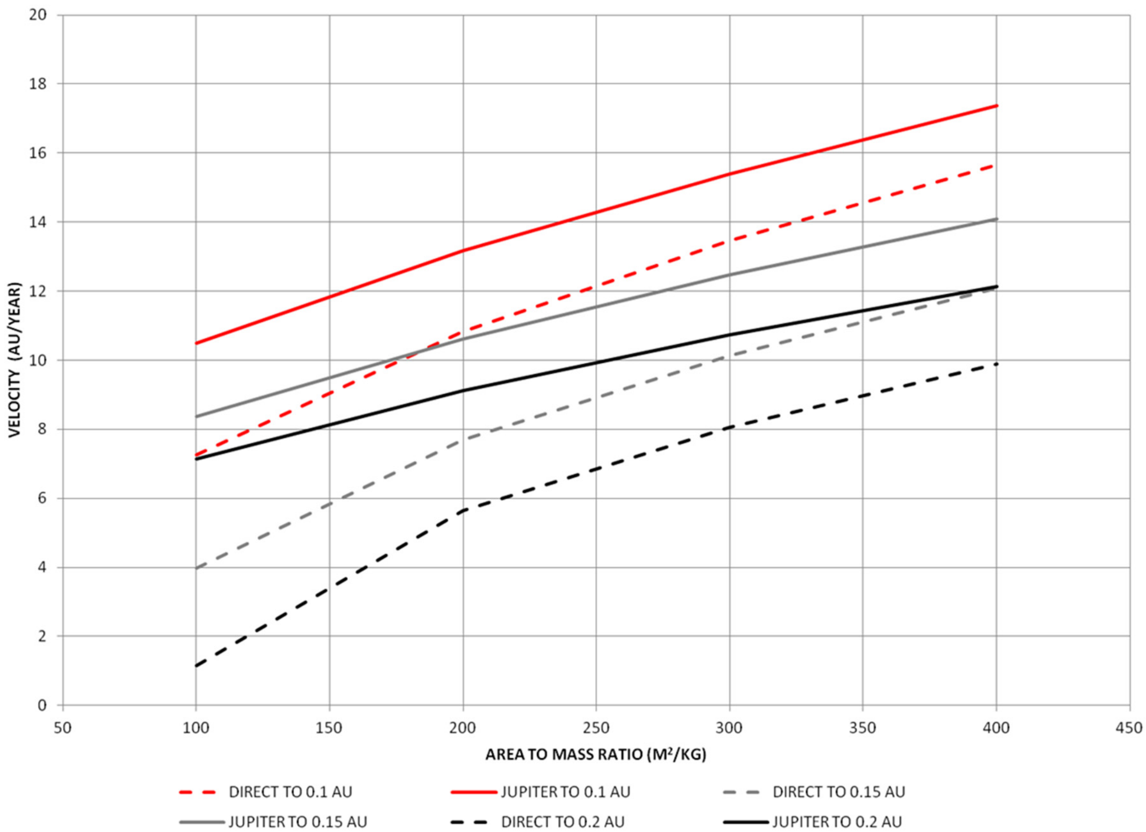


Figure E.1.1: Exit Velocity vs. Sail Area/Mass

1. Nanosats with Solar Sails

Sails might be deployed on nanosats, i.e., spacecraft with total mass less than 10 kg. This follows on a current development trend of nanosats (and specifically Interplanetary CubeSats) and of the Nanosail-D, LightSail, Lunar Flashlight, NEA Scout series of solar sail missions. If a long-life nanosat spacecraft can be developed with advanced technology instrumentation, then a solar sail of 10,000 square meters (e.g., 100 × 100 m sail) might achieve 30 AU/year exiting the solar system.

Novel sail packaging, deployment, and rigging techniques may allow for larger sails to be used with nanosats. Recent efforts in membrane compaction have reported sail packaging efficiencies of up to 70%. Novel solar sail architectures without deployable booms that use spinning and centrifugal forces to tension the sail may achieve A/m ratios of 50–200 m²/kg. A particular architecture of a spinning nanosat solar sail is shown in Figure E.1.2. The sail is packaged into 3U of a 6U CubeSat. (A 1U volume is a cube with 100 mm sides.) The remaining three 1U CubeSats (each of which may contain spacecraft components, e.g., on-board computers, attitude determination, etc., or a science payload) are deployed to be the tip masses that tension the sail by spinning. This sail rigging technique requires no booms, and can achieve A/m ratios of ~65 m²/kg in the near term using available 2.5 μm-thick sail material. In the medium term, with thinner materials (1 μm thickness), A/m ratios of 200 m²/kg may be achievable.

Power and communications on nanosat spacecraft remains to be determined – but low power devices, use of lightweight nuclear batteries, and printing of batteries, photovoltaics, electronics, and antenna components on the large solar sail may lead to the feasibility of such small spacecraft for long-range flight. Alternatively, the sail may be deployed to a parabolic profile and used as a photovoltaic concentrator. For example, at ~70% optical concentrating efficiency and ~25% photovoltaic efficiency, a 50 × 50 m sail acting as a concentrator will produce ~15 W at 200 AU. This is sufficient

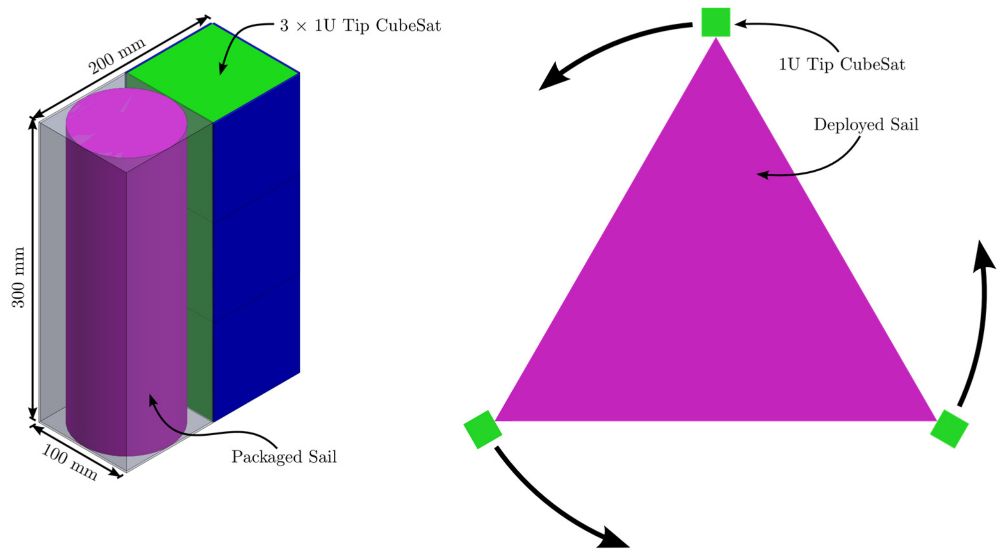


Figure E.1.2. A concept for a spinning nanosat solar sail with 62 m^2/kg. Packaged with 80% efficiency, the 2.5 μm-thick sail fits into a cylinder with 100 mm diameter and 300 mm height. Deployed, the sail has an area of 750 m^2, and a side length of 42 m. The ~12 kg spacecraft is spun, and the sail is tensioned by the centrifugal forces applied by three tip 1U CubeSats.

to drive the low-power systems used in nanosats. The sail may be used as a communications antenna as well, either by having a sail with a parabolic profile, or by using a flat sail as a reflect-array antenna.

Nanosat lifetime remains an issue and small spacecraft, e.g., CubeSats, have yet to be used outside low Earth orbit. Several upcoming missions (e.g., INSPIRE, NEAScout, and Lunar Flashlight) will demonstrate CubeSat functionality in deep space and address concerns about nanosat longevity. Flight times to 200 AU for this class of small satellite missions are expected to be at least ~30 years; hibernation strategies must be employed for this class of missions.

Nanosats may also enable a multi-spacecraft "swarm" architecture, which is far more desirable for exploring the ISM. The vast distances and topography of the Medium would ideally be explored at a number of places in the three-dimensional space. So, too, the many KBOs and the many (likely) candidate exoplanets that will be targets of interest, if use of the Solar Gravity Lens Focus (SGLF) for their imaging turns out to be feasible. A nanosat swarm architecture will also enable broad participation in the development of Interstellar Precursors and for exploring the ISM. Lower-cost entry missions may come from other countries besides the major space-faring nations, and even from private or educational organizations.

Finally, nanosats allow for low cost space technology demonstrations and rapid design iteration.

2. Novel solar sail materials

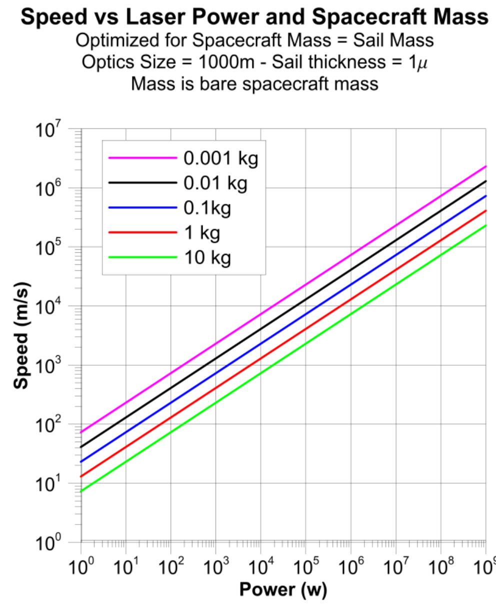
Sail designs employing carbon-carbon and other non-metallic films are also under study. Vacuum deposition in space may negate the need for a deployable structure and other reflective material support. Such lightweight sails may enable the feasibility of nanosat sail spacecraft and more importantly may permit closer approaches to the Sun, and hence higher exit velocities through and from the solar system.

E.1.2. Laser Sails (Beamed energy propulsion)

Solar sails are obviously ultimately limited by their dependence on the Sun; hence the need for attendant power and communications technologies to work on such spacecraft.

To overcome some of the limits to interstellar flight, a candidate technology is to beam energy to the spacecraft – either over interstellar distances or with enough power to produce interstellar flight speeds (a noticeable fraction of relativistic speeds) while exiting the solar system. The laser systems to accomplish that are truly prodigious, but theoretically possible, i.e., they are only an engineering problem. For example: "…a laser power of 70 GW, a 100 kg craft can be propelled a distance of 1 AU in approximately 3 days achieving a speed of 0.4% the speed of light (250 AU/year), and a 10,000 kg craft in approximately 30 days" [2]. Laser (or microwave) sailing over interstellar distances is at least a century away (some say even longer). We studied the possibility of intermediate steps with beamed energy, to assist the missions under study in their exploration of the ISM. Figures E.1.3 and E.1.4 illustrate the difficulty: to achieve a velocity increment of 10 AU/year (approx. 50 km/s) requires lower mass and higher power than available in the foreseeable future. This limitation may be overcome by reducing the size of the spacecraft.

At least two NIAC studies have examined laser propulsion for an interstellar roadmap. [2, 316-319], and a laboratory demonstration of a laser propelling a CubeSat has been done [Louis Friedman (louisfriedman@gmail.com), private communication, October 2015]. A small team has spun-off from this KISS Study to assess (with support from KISS and from a private donor) the laser technology for a demonstration of laser propulsion in space (see Sec. E.2)



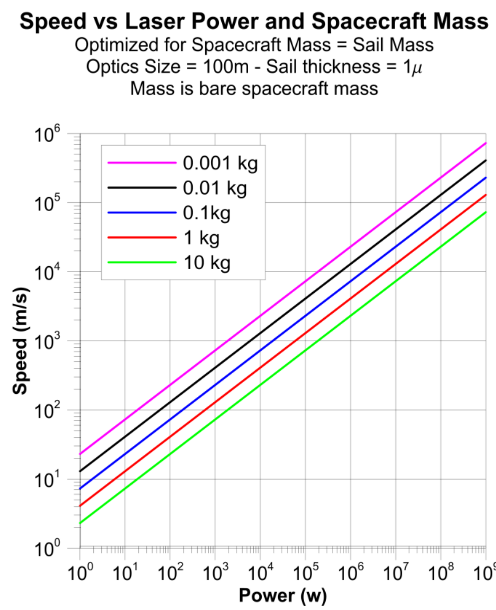


Figure E.1.3, E.1.4: Laser Sail performance for two different optics.

E.1.3. Electric Sail Propulsion

Also considered was a relatively new, hence low TRL, technology: Electric Sail Propulsion. While not scalable to true interstellar flight, electric sails do have the potential to enable rapid exploration of the near ISM to distances as great at ~1000 AU. An Electric Sail propulsion system consists of 10–100 electrically conducting wire strands, each many kilometers in length. Strands are deployed from the main spacecraft bus and the spacecraft rotates to keep the strands taut. Powered by an onboard radioisotope electric power system, the electric field of the strands extends into the solar wind plasma, where the field repulses positive ions in the solar wind, and thrust is generated. Unlike solar sails, the thrust generated drops at a ratio of −7/6 instead of −2 (for solar sails), allowing them to produce significant thrust much farther from the Sun into deep space. If they prove out, and can be scaled to a reasonable size spacecraft, they may be the only near- to mid-term option that can meet the 100 AU within the 10-year goal without the very close perihelion Oberth maneuver, or close solar flyby required of the solar sail

Electric Sails are a low TRL technology and there is significant uncertainty in their ultimate performance and applicability. Given their tremendous theoretical performance capability, further study and development of the technology is warranted.

E.1.4. Technology Development Recommendations

Based on the considerations above we recommend the following technology development concepts for further study:

a) Electric sails

i) An analysis of the key electric sail subsystems finds that many of them are relatively mature. However, wire deployment and system guidance, navigation, and control are areas where the system-level implementation of the technology are immature and would benefit from research and development.

b) Solar sails

i) Solar sail technology for near-interplanetary missions is mature and being implemented. Scaling the technology from current 100 m² capabilities to the 10,000 m² sails required for exploring the ISM is needed. Advanced small spacecraft may allow achievement of high area to mass ratios with smaller sails. Advances in materials to allow near-sun sail deployment, lightweight structures and deployment techniques for unfurling large sails, and novel packing approaches are all required.

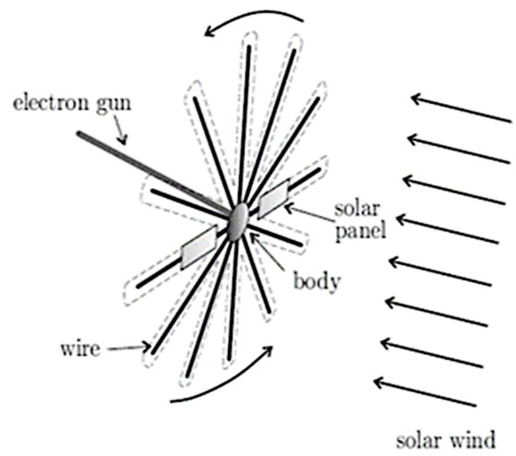


Figure E.1.5. An Electric Sail consists of several conducting positively charged wires, each of multi-kilometer length. An electron gun is used to keep the spacecraft and wires at a positive potential so that solar wind ions are repulsed by the field, providing net thrust.

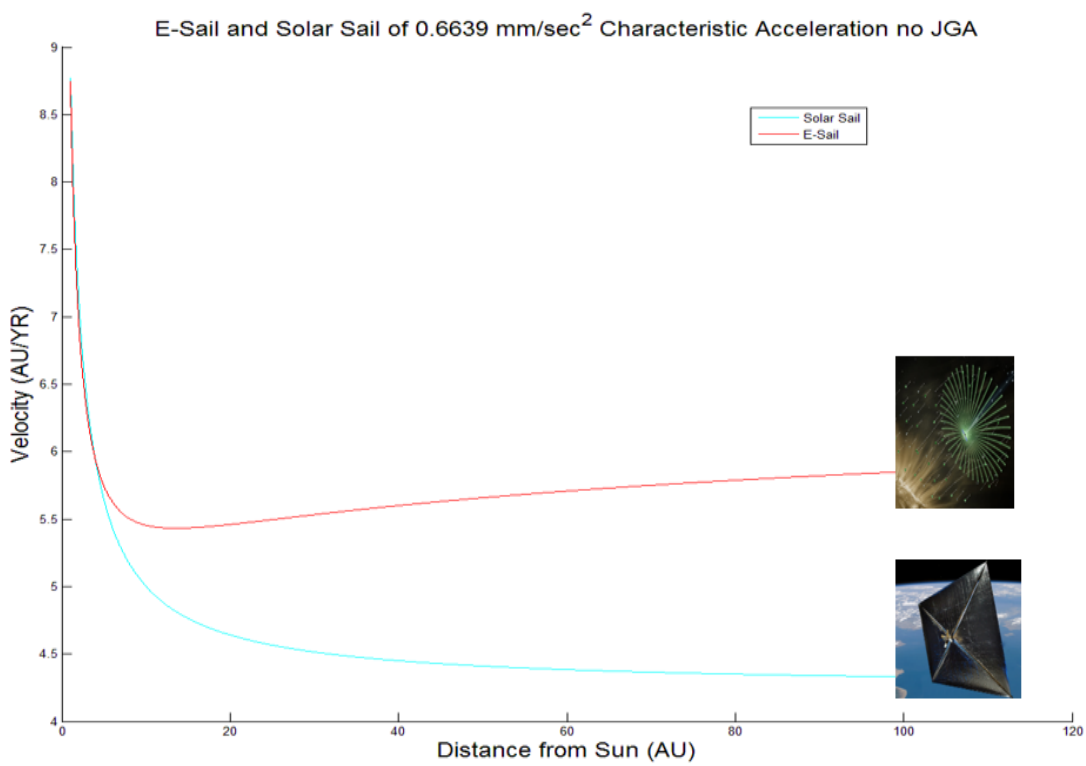


Figure E.1.6. Electric sail velocities are ~25% greater than solar sails because of the rate of acceleration decline ($1/r^{7/6}$) vs. solar sail acceleration decline ($1/r^2$)

ii) Enabling missions beyond the near ISM will require a new generation of solar sail technologies that may not be directly scalable from those that precede them. Development that will be required include in-space fabrication, which would allow extremely low areal-density sails (avoiding the stresses of fabrication in one gravity and those induced during launch), and advanced materials such as graphene, which would further reduce system mass and decrease the minimal operable distance from the sun to increase system-level performance.

c) Laser sails

More work is needed to understand power generation and material requirements on the laser sail. This technology has the highest risk but also has the potential of highest payoff and maybe one day allow us to reach speeds reaching significant fraction of speed of light. The laser propulsion demonstration being consider as an outgrowth of this study may be the first significant step in the true interstellar propulsion roadmap.

Chapter E.2: Near-Term Technology Demonstration Missions

E.2.1. Laser Sailing Demonstration

Laser propulsion in space has never been demonstrated (although space based lasers at lower power levels are now being used for optical communication). It is currently the only known means for interstellar propulsion, and some new and innovative suggestions are also being made for applications to ultra-light (e.g., wafer, chipsat, or picosat) spacecraft experiments and possibly for planetary defense. The physics is understood and does not need to be verified. But spacecraft implementation (attitude control, guidance, navigation, pointing, sensors, etc.) does need to be demonstrated and developed. Thus, we studied (in a technology assessment activity previously mentioned) a possibility of a near-term laser sailing demonstration mission. We specifically considered small, low-cost approaches, using CubeSats, in order to take a cost effective, step-by-step approach. This led to consideration of the following three-phase demonstration program:

1) A. ground-based laser (and possibly microwave) illumination of a CubeSat solar sail in low Earth orbit;
2) A space based laser in a CubeSat (or other nanosat) used to accelerate a wafer or other very light objects; and
3) A space-based laser used to accelerate a nanosat sail spacecraft.

Acceleration on the spacecraft can be measured from ground based tracking, but we recommend consideration of nano-accelerometers in the payload that can sense less than one micro-g. Even if the beamed energy acceleration is less than drag or solar illumination, we can extract its sense from the data. We can also measure such acceleration at night and with the sail flying aerodynamically, edge-on, in the atmosphere. Magnitude of acceleration is depicted in the adjacent parametric plot (Figure E.2.1).

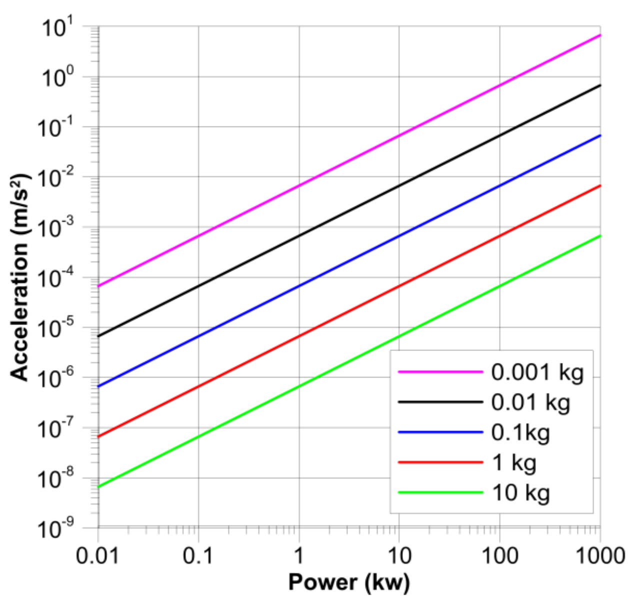


Figure E.2.1: Achieved acceleration vs. power for different spacecraft mass

A mobile Army laser platform could provide the ground-based laser for the first step. The platform houses a 10-kW system, but this is expected to go to 60 kW by the end of 2015. The space sail could be LightSail, The Planetary society's solar sail. Notice in Figure E.2.1 that the acceleration on the nanosat will be measurable. We recommend that this concept be studied further to determine mission requirements and to provide a preliminary cost estimate. If the latter is low enough, some possibilities for private funding can also be explored. In any case, the overall program is of likely interest to NASA and DoD so funding a moderate program is a reasonable goal. The space-based laser requirement, using two CubeSats – one with a laser and one with a sail, for the second step can be included in this first phase study.

We also recommend using the nanosat (at least in step 2 above, if not in step 1) for test of new technologies for nanosat sails, such as with deployment and packaging of sails, perhaps an electric sail demonstration, use of the sail as an antenna or with printed electronics and other devices related to using nanosats for deep-space exploration. A small sail, sized for laser illumination, may be ideal for such first tests. How much can be included in these steps will be part of our recommended first phase requirements study.

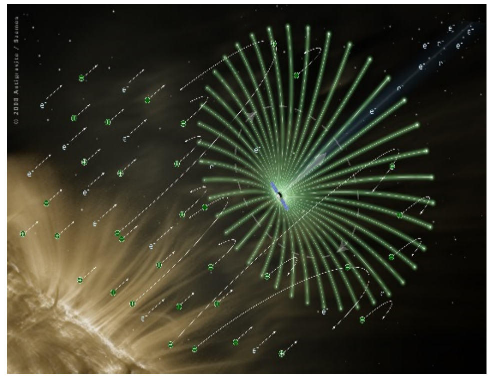


Figure E.2.2: Electric Sailing (artist concept)

E.2.2. Electric Sailing Demonstration

A low-cost electric sail (Figure E.2.2) technology demonstration mission could be fielded within the next few years using the deep-space CubeSat technology being developed by the NASA MSFC Near Earth Asteroid Scout and JPL Lunar Flashlight Projects. These low-cost spacecraft are based on the CubeSat architecture and are scheduled to fly in interplanetary space onboard the first flight of the Space Launch System.

The Electric Sail would consist of ten 5-km long conducting tethers deployed radially from 6U (10 cm × 20 cm × 30 cm) CubeSat spacecraft. To minimize current collection and resulting power requirements, it is desirable to use as small a wire as technically feasible. The wires will nominally consist of 44 gauge Copper Bonding wire (50 µm diameter) with a total wire tether mass of ~877 g.

In order to keep the tethers oriented perpendicular to the solar wind velocity, it will be necessary to set the CubeSat in rotation so that the centrifugal forces on the tether overcome the solar wind force by a factor of about 5. Figure E.2.2 shows the equilibrium configuration of the tether under influence of a solar wind force and a once-per-hour rotation. The maximum tether tension for this case is 9 mN, well within the tensile capabilities of 50 µ copper wires.

Although the required rotation rate is quite slow, the long tether lengths involved result in a substantial total angular momentum. As a result, a simple deployment scheme involving first spinning up the satellite and relying purely upon centrifugal forces to deploy the tether is not practical, as the required initial rotation rate would be too large to be feasible. Thrusting by the tether deployer-endmass modules, as shown in Figure E.2.3 is an approach that may provide enough rotation to ensure the wires remains taut as they are deployed. A concept definition study for the proposed demonstration mission is recommended.

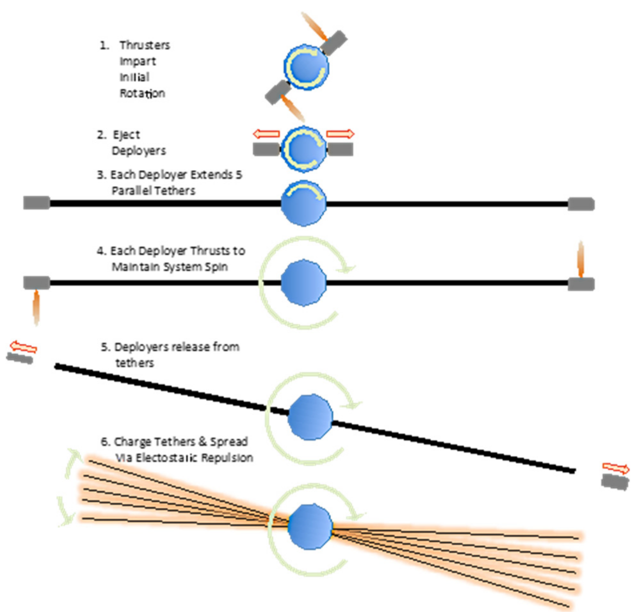


Figure E.2.3: Concept for deploying / spinning the wires.

PART F: THE PATH FORWARD

The KISS workshop on the "Science and Enabling Technologies for the Exploration of the Interstellar Medium (ISM)" provided a very insightful perspective on three questions:

1. Is there compelling science on the way to, at, and from the vantage point of the ISM?
2. What is the rational near-term first step forward?
3. What are some of the enabling technologies towards reaching another star?

It is clear that a near-term mission (2025) to reach the ISM in ~10 years from launch is feasible and could enable a series of scientific probes to explore the interface between the bubble created by our sun and the ISM. This, in itself, is a significant result. It is also recognized that this kind of a mission that uses a perihelion Oberth maneuver to swing from deep in the solar gravity well towards the ISM, is not scalable towards reaching another star. To do so, one would have to develop and demonstrate new technologies of which a few were identified and reviewed such as: beamed energy, e-sails, solar sails, and various forms of nuclear-based propulsion systems. It was also widely discussed that one of the key features of venturing deep into the ISM is reaching the specific vantage point called the solar gravity lens focus at 500–700 AU. From this vantage point, a robotic probe that carries an optical telescope could be used to image one or more exoplanets at unprecedented resolutions that are simply impossible to do from Earth or from Earth's orbit. It is quite possible that, with additional future engineering studies, an observatory mission to the solar gravity focal point could become a major initiative to provide detailed images of an Earth-like exoplanet.

The workshop participants also discussed some of the programmatic obstacles facing the establishment of a mission or a program of missions to explore the ISM or beyond. Currently, the structure of NASA's (or other government agencies) programmatic landscape is not conducive to such a program. That is, a mission to the ISM would span multiple scientific disciplines including Heliophysics, Planetary Science, and Astrophysics, but would not likely be owned by any one of them to the point of providing dedicated funding. One possible solution is for one (NASA) program directorate, say Heliophysics, to initiate such a scientific mission, and then solicit from the other two (Planetary Science and Astrophysics) directorates to provide their fair share of funding for such a mission or program, as they too would have a clear scientific motivation to do so. The workshop participants also identified the regular (NASA and ESA) decadal survey process (Heliophysics, Planetary Science, and Astrophysics) as opportunities to provide such feedback to the space agency planners and mission formulators.

Long-range vision of interstellar flight and someday visiting (or even high-resolution seeing) a habitable exo-planet is compelling and popular. Private initiatives and a number of interstellar technical interest groups may lead to public-private ventures that advance the technologies discussed here. NASA leadership in innovation and adventure is needed.

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