The Quest for Interstellar Exploration

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Abstract. NASA strategic planning includes the objective for a set of missions that would begin exploration beyond our solar system. These missions would determine the nature of the interface between our solar system and the local interstellar medium, as well as directly sample the properties of the interstellar medium as an initial step in exploring the nearby Galaxy. Preliminary planning envisions four missions making up this initial quest for exploration. Each of the mission concepts is described in terms of science objectives, mission characteristics, and technology needs. The four missions are: 1) Interstellar Probe (reaching 200 AU in < 15 years via solar sail to explore the heliospheric boundaries and the interstellar medium); 2) Heliosphere Imager & Galactic Gas Sampler (delivery to a low inclination, 1 by 4 AU ecliptic orbit to establish the 3-D structure of the heliosphere and boundaries and sample Galactic material injected into the heliosphere); 3) Outer Heliosphere Radio Imager (16 subsatellites with mother spacecraft delivered to 20 to 30 AU via solar sail to radio-image the boundaries of the heliosphere); and 4) Interstellar Trailblazer (reach 2000 AU in ~ 30 years via advanced solar sail to explore the local interstellar cloud). Technology needs for these missions include solar sail propulsion, advanced instrumentation, autonomous spacecraft operations, advanced power, advanced telecommunication, and long life systems.

INTRODUCTION

NASA's Office of Space Science has recently completed a set of comprehensive strategic planning roadmaps for its four themes (Sun-Earth Connection, Exploration of the Solar System, Astronomical Search for Origins, and Structure and Evolution of the Universe). In the Sun-Earth Connection (SEC) Roadmap (NASA, 1999) a set of four missions is called out to answer the question of how the Sun and Galaxy interact. The four missions seek to take significant steps in three scientific endeavors:

1. Explore the structure and dynamics of the heliospheric boundaries
2. Determine the properties and composition of the interstellar medium
3. Explore the local galactic neighborhood

Each mission will address the above in both an evolutionary manner as well as with different investigative modes.

Figure 1 illustrates the scale of the missions in the sense of distances reached and the focus for their investigations. Although the entire region shown in Figure 1 is of interest, the focus for the four missions is on the interface between our solar system and the Galaxy/local interstellar medium. Two of the four missions penetrate the interface and carry out explorations into interstellar space. Interstellar Probe (ISP) will explore the heliospheric boundaries and the nearby interstellar medium in addition to preliminary investigations at the edge of our solar system. Interstellar Trailblazer (ITB) is expected to follow with an order of magnitude further exploration into the Galaxy. Heliosphere Imager & Galactic Gas Sampler (HIGGS), operating from well within the heliosphere, will sample material traveling to the inner solar system from interstellar space. Outer Heliosphere Radio Imager (OHRI) will travel to the region of the far outer planets to image the structure of the solar system-Galaxy interface. The overall strategy of these four missions is to significantly address how the Sun and our Galaxy interact via exploration of the heliospheric boundary and nearby galactic environment.

Three of the missions are enabled by application of solar sail propulsion. With recent technology advances in materials, solar sail technology has changed the concept of delivering, in reasonable flight times, scientifically significant payloads to the solar system-Galaxy interface and beyond, from conjecture into one of possibility (Garner, 1999) and (Sauer, 1999). The trajectory optimization process for the three solar sail-enabled missions was carried out by Carl Sauer in a similar manner to that in (Sauer, 1999).

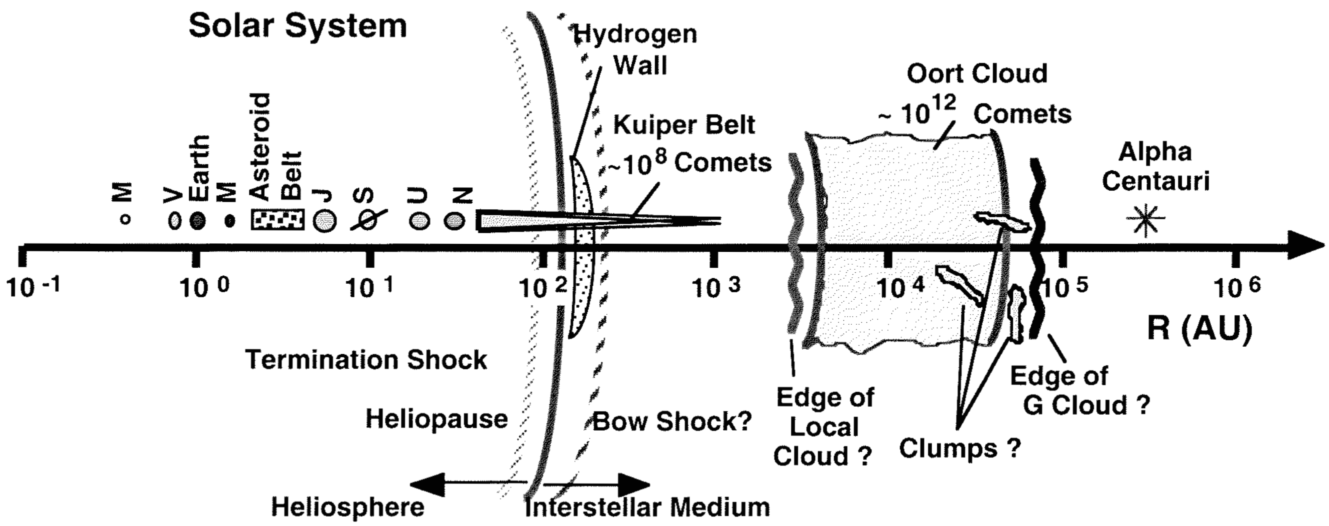

FIGURE 1. Scale of the Interstellar Medium (Mewaldt, 1998).

During the summer of 1999 the authors assembled a small team of JPL experts in space science mission and system design. After working intensively with this team during a two to three week period, a number of deep space mission concepts evolved and were defined that met science requirements in the then-developing new SEC strategic planning Roadmap. This paper describes a subset of the missions addressed, the four mission concepts defined for exploring the heliospheric boundary and the nearby galactic environment in the Roadmap's Quest III. Each of the four mission concepts is described in terms of science objectives, mission characteristics, and technology needs. The mission designs described, in most cases, are considered starting points for subsequent performance and technology trade studies. Where possible, preliminary trade study results are included.

INTERSTELLAR PROBE

Interstellar Probe will be the first mission to cross the heliosphere and begin exploring the interstellar medium. The mission concept has a long history of interest as a precursor to eventual travel to the stars (Wallace, 1999). The conceptual basis for the current design was laid out in 1990 (Holzer, 1990) when preliminary science objectives and a strawman science payload were described. Of the four mission concepts described in this paper the Interstellar Probe design is the most mature due to having science definition, mission/system design, and technology development teams dedicated to it.

Science objectives and mission concept description with key technology requirements for the Interstellar Probe are provided below. In addition the results of mission performance trades with sail technology capability are discussed.

Science Objectives & Mission Requirements

The Interstellar Probe science objectives listed below are taken from the SEC Roadmap (NASA, 1999):

- Explore interstellar medium and determine properties of plasma, neutral atoms, dust, magnetic fields, and cosmic rays;
- Determine structure and dynamics of heliosphere as an example of the interaction of a star with its environment;
- Study, in-situ, structure of solar wind termination shock and acceleration of pickup ions and other species;
- Investigate the origin and distribution of solar system matter beyond the orbit of Neptune.
- Measure in-situ, properties and composition of interstellar plasma, neutrals, dust, and low-energy cosmic rays;
- Determine heliospheric structure and dynamics by in situ measurements and global imaging;
- Map zodiacal dust cloud IR emissions; measure distribution of interplanetary dust & small Kuiper Belt Objects

The mission goal developed for the science objectives is relatively straightforward and evolved from analyses performed with inputs from the Interstellar Probe-dedicated science definition, mission/system design, and technology development teams: deliver a scientific payload of 25 kg to 200 AU in < 15 years.

Mission and Sail Technology Performance Trade

A baseline mission concept for the Interstellar Probe mission was developed for the application of solar sail technology that would be available for integration into a mission system launching in the 2010 time period (Garner, 1999). Other propulsion system candidates continue to be considered as options to this baseline.

A trade study was performed based on defining sail technology in terms of three parameters: sail size, sail areal density (the ratio of sail material and structure mass to sail area), and closest approach to the Sun. These parameters relate to a number of key solar sail technology developments and describe the capability of a particular sail quite well for early concept design studies:

- sail size: deployment, control, fabrication, packaging, structure
- areal density: materials, deployment, fabrication, packaging, structure
- solar closest approach: thermal management, materials, structure

Figure 2 illustrates a trade in solar closest approach, driving selection of materials and system configuration to withstand thermal input. To achieve low flight times it is necessary for the spacecraft to first travel inward towards the Sun (Sauer, 1999); the closer the pass, the faster the flight time (see Figure 2).

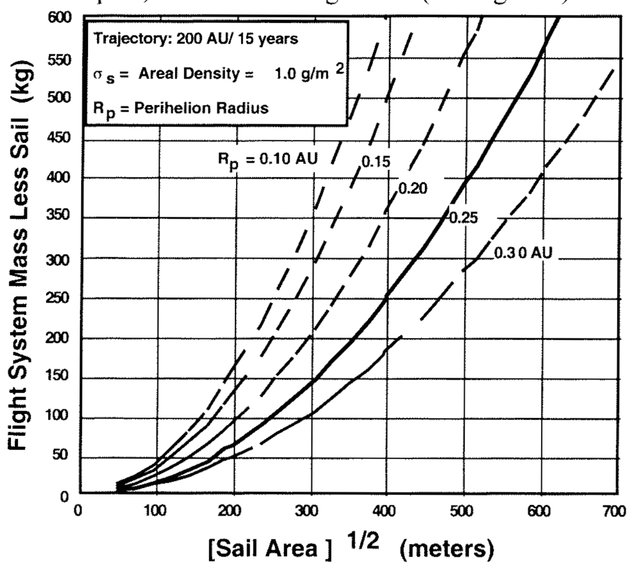

FIGURE 2. Sail Performance Trades: Radius of Perihelion Tradespace with Areal Density.

Trades similar to Figure 2 are possible varying areal density. Using such trades and estimating the level of sail technology development over the next 10 years, we have arrived at a summary chart for the performance of a sail that would allow trades in flight time and delivery mass. Figure 3 illustrates this trade for a circular sail of 200-m radius.

Preliminary system analyses indicates that spacecraft delivery mass will need to be in the range of 150 to 250 kg to support the required 25-kg science payload at 200 AU. This range of delivered spacecraft mass drives the sail size to circular areas with radii of from about 100 to 300 m (see Figure 2).

Mission Concept Selection & Key Technology Requirements

Sail definition parameters were varied with system design, and a 200-m radius sail with areal density of 1 g/m^2 was selected which could withstand a solar closest approach of 0.25 AU. The resulting spacecraft delivered to 200 AU is about 200 kg carrying a scientific payload of 25 kg and returning 25 bits per second (bps) of data from 200 AU.

A solar sail of 200-m radius, areal density of 1 g/m^2, and able to withstand a close solar approach of 0.25 AU is the key technology of the Interstellar Probe mission concept. An advanced Ka-band phased array system allowing 25 bps data return and spacecraft power system that can provide 275 W from 200 AU are the other two key technology developments needed for the baseline Interstellar Probe concept. Technology development in low mass/power instruments is a further need.

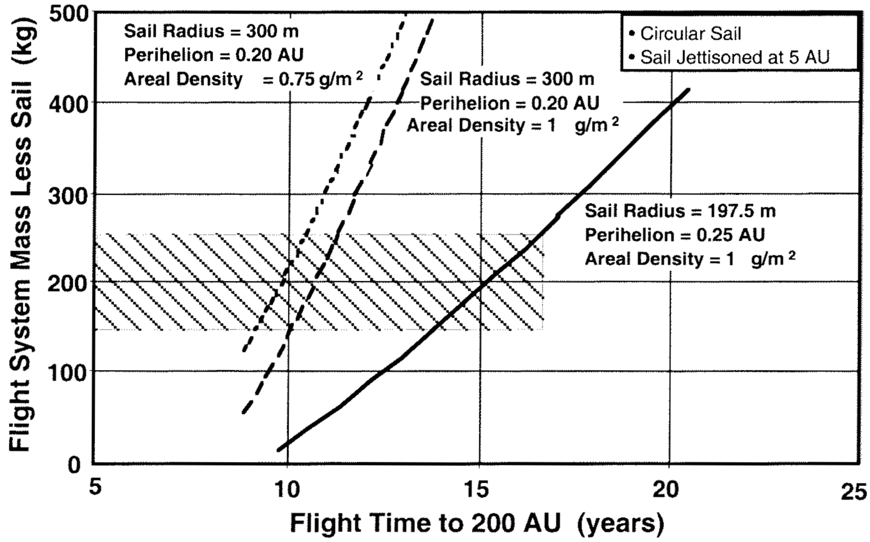

FIGURE 3. Mission Performance Trades: Flight Time to 200 AU Mission Trade Space.

HELIOSPHERE IMAGER & GALACTIC GAS SAMPLER

Heliosphere Imager & Galactic Gas Sampler (HIGGS) measures the elemental and isotopic composition of interstellar neutral atoms leaking deep into the heliosphere, allowing a determination of the size and shape of the heliosphere. These chemical messengers from interstellar space penetrate to within 3 to 4 AU of the Sun and provide us a direct sample of present-day galactic matter. This mission will take measurements from a relatively nearby orbit, making payload delivery/placement simplest of the four missions. The HIGGS mission concept is based on preliminary design; trade studies are a next step.

Science Objectives & Mission Requirements

The HIGGS science objectives listed below are taken from the SEC Roadmap (NASA, 1999):

- Establish 3-D structure of the interaction region between heliosphere and local galactic environment
- Determine elemental and isotopic composition of neutral atoms in a present-day galactic sample and explore implications for Big Bang cosmology, galactic evolution, stellar nucleosynthesis, and birthplace of the Sun
- Determine the shape of the heliosphere
- Measure precisely the cosmologically important abundances of ^{2}H and ^{3}He in local interstellar material
- Map the location and establish the characteristics of the extended inner source of neutral atoms in the heliosphere

An elliptical heliocentric orbit of 1 AU by 4 AU was selected for scientific observations. This orbit can be reached via chemical propulsion with Venus and Earth-return gravity assists with the required scientific payload mass after a flight time of one year. Delivery mass is driven by the specification of a science payload of 8 advanced space physics instruments with a total mass of 65 kg.

System Concept and Key Technologies

The system design includes solar power, chemical propulsion, one-day of data return per month at X-band at 100 bps, and 5-years of orbit observations. The total spacecraft mass delivered to the measurement orbit is 300 kg (including instruments and dry propulsion system); launch is via Delta II launch vehicle.

Advanced instrument developments will be required for this mission. Lower mass sensor structure and better sensitivity than current state of the art will be required. In particular, for two key instruments:

- EUV Spectrometer/Imager: low noise to < 1 micro-Rayleigh
- Pickup Ion Spectrometer: 100 times increased sensitivity

OUTER HELIOSPHER RADIO IMAGER

Outer Heliosphere Radio Imager (OHRI) measures radio emissions from the interaction of strong interplanetary shocks with the outer regions of the heliosphere. This mission will provide a way to sample the large-scale structure of the heliospheric boundary and measure its response to solar wind variations and disturbances.

Science Objectives & Mission Requirements

The OHRI science objectives listed below are taken from the SEC Roadmap (NASA, 1999):

- Determine the large scale structure of the heliospheric boundary
- Map 2-D shape of heliospheric boundary, including dynamic response to solar disturbances and to the solar cycle

A mother spacecraft with 16 subspacecraft are delivered to 20 AU via a trajectory similar to that of Interstellar Probe (initial perihelion of 0.25 AU). After about a two-year flight to 20 AU, the 16 subspacecraft are dispersed into an interferometric array. Each subspacecraft carries baseline orientation measurement equipment, as well as radio wave instruments, totaling about 7 kg. The total system mass delivered, including mother spacecraft and 16 subspacecraft, is about 650 kg. A further requirement is that the interferometric system of subspacecraft and its mother continue at about the same speed, 10 AU per year towards the nose of the heliosphere. A measurement operations objective is 5 years of observations after deployment of the subspacecraft, with a goal of as much as 11 years.

System Concept and Key Technologies

Our OHRI baseline design depends on solar sail technology application. The sail design must deliver a relatively large payload (650 kg) to orbit in a short period of time (20 AU in 2 years) and continue through regions of interest at this high rate of speed. The trajectory design is similar to that of Interstellar Probe with a close solar approach of 0.25 AU and high solar system departure speed. A sail design that meets the mission requirements has a sail radius of 300 m and areal density of 0.25 g/m^2. In addition to advanced solar sail technology, two other key developments are in space power (~ 25 W for each of the 16 subspacecraft) and in capability to place and keep the subspacecraft in positions for continued interferometric measurements (an interferometer multi-baseline acquisition and measurement system).

INTERSTELLAR TRAILBLAZER

The science rationale for the Interstellar Trailblazer mission that follows is taken from the SEC Roadmap (NASA, 1999). The solar system traverses a wide range of environments as it moves through the Galaxy. The Sun is presently located at the border of a great void in nearby interstellar matter known as the "Local Bubble", where we are embedded in a low-density cloud (our Local Interstellar Cloud, or LIC). We do not know the scale of density variations within our LIC, but it appears that the edge of the LIC in the direction of the Sun's travel is < 6000 AU away, possibly much less. Upon exiting the LIC the Sun may enter the hot, low-density Local Bubble, or it could enter a neighboring cloud. MHD simulations show that if the local interstellar density increased to that of a typical diffuse cloud (~10 cm^{-3}) the dimensions of the heliosphere would shrink by nearly an order of magnitude, which would undoubtedly have significant effects on the interplanetary environment at 1 AU. By targeting the Interstellar Trailblazer in the direction upstream of the Sun's motion, it will effectively blaze a trail through the future environment of the solar system over the coming centuries, scouting out the scale of density and other variations. Conversely, a downwind probe could explore our past.

Mission/System Concept and Key Technologies

The mission goal developed for the science objectives is relatively straightforward: deliver an advanced scientific payload of about 50 kg to 2000 AU in ~ 30 years, and communicate back to the Earth from 2000 AU at 25 bps. Figure 4 illustrates a trade in spacecraft mass as a function of sail size. An advanced sail of areal density equal to 0.1 g/m^2 and able to withstand a solar closest approach of 0.1 AU was selected for the baseline design. A net spacecraft system mass of about 225 kg (including 50 kg of instruments) resulted from our preliminary analysis. A circular sail of radius 600 m will be required to deliver this mass to 2000 AU in 30 years (see Figure 4).

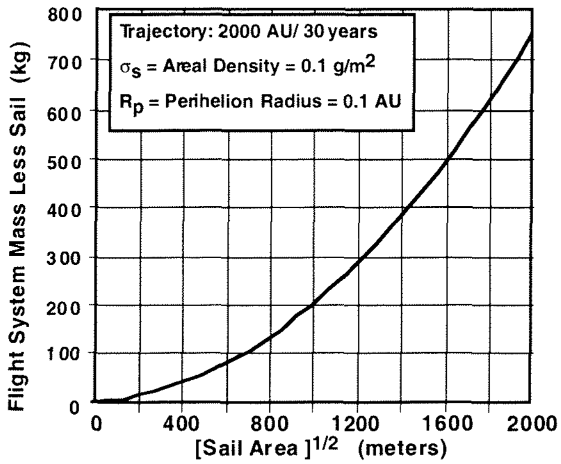

FIGURE 4. Interstellar Trailblazer Mission Performance Trade.

The key technologies and performance requirements for the above preliminary design are listed below:

- Solar Sail: Effective Sail Area of~ 10^6 m^2 (circular sail radius of 600 m); Areal Density 0.1 g/m^2
- Telecommunications/Power: 25 bps at 2000 AU/ ~ 1 kW DC at 2000 AU
- Thermal Management: Survive Solar Closest Approach of 0.1 AU

SUMMARY

The quest for interstellar exploration has begun with a step by step outline of the objectives for a suite of four mission-based set of science investigations (NASA, 1999). Baseline mission designs have been defined in this paper for each of the four mission concepts, with mission requirements, mission/system designs, and technology needs.

ACKNOWLEDGMENTS

During the summer of 1999 the authors assembled a small team of JPL experts in space science mission and system design to assist us in defining a number of mission concepts suggested by the NASA SEC Roadmap Development Team. Those on the JPL team significantly aided in defining the four missions described in this paper: C. Budney, R. Oberto, K. Roust, G. Sprague, and T. Sweetser, all from Jet Propulsion Laboratory/California Institute of Technology. Science requirements integration into mission requirements were greatly assisted by R.A. Mewaldt, SEC Roadmap Team Quest III Leader, (California Institute of Technology) and P.C. Liewer from Jet Propulsion Laboratory/California Institute of Technology), JPL SEC Program Scientist.

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