A Realistic Interstellar Explorer

Ralph L. McNutt, Jr., G. Bruce Andrews,

James V. McAdams, Robert E. Gold, Andrew G. Santo,

Douglas A. Ousler, Kenneth J. Heeres,

Martin E. Fraeman, and Bruce D. Williams

The Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20723-6099

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Other Contributors

D. R. Haley, JHU/APL
R. S. Bokulic, JHU/APL
P. E. Panneton, JHU/APL
J. I. Von Mehlem, JHU/APL
L. E. Mosher, JHU/APL
E. L. Reynolds, JHU/APL
R. W. Farquhar, JHU/APL
D. W. Sussman, JHU/APL

D. W. Dunham, JHU/APL
E. C. Roelof, JHU/APL
R. E. Jenkins, JHU/APL
R. Westgate, JHU
D. Lester, Thiokol Corp.
D. Read, Lockheed-Martin
D. Doughty, Sandia National Laboratories

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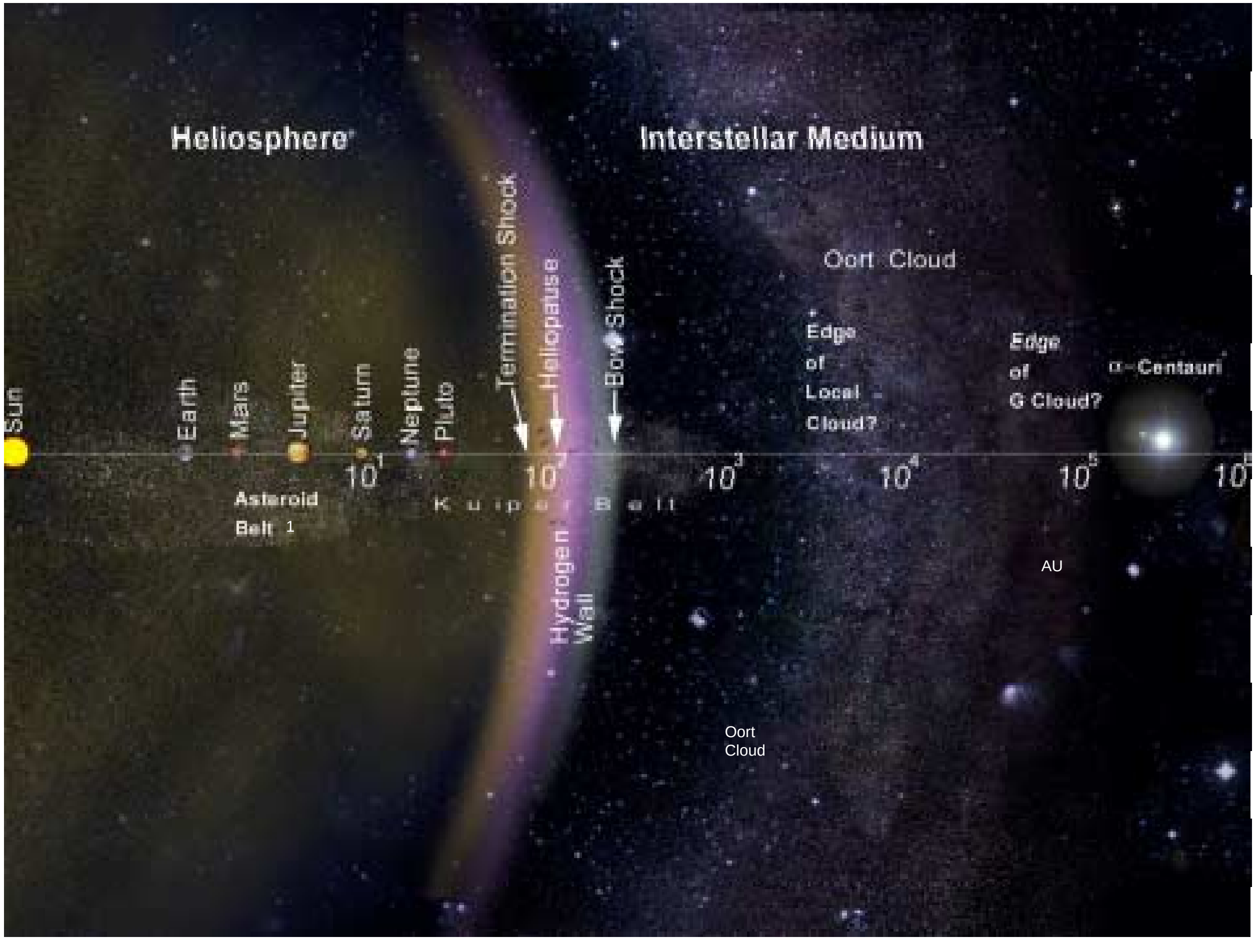
The Goals of Space Exploration Are at the Boundaries of the Heliosphere and Beyond



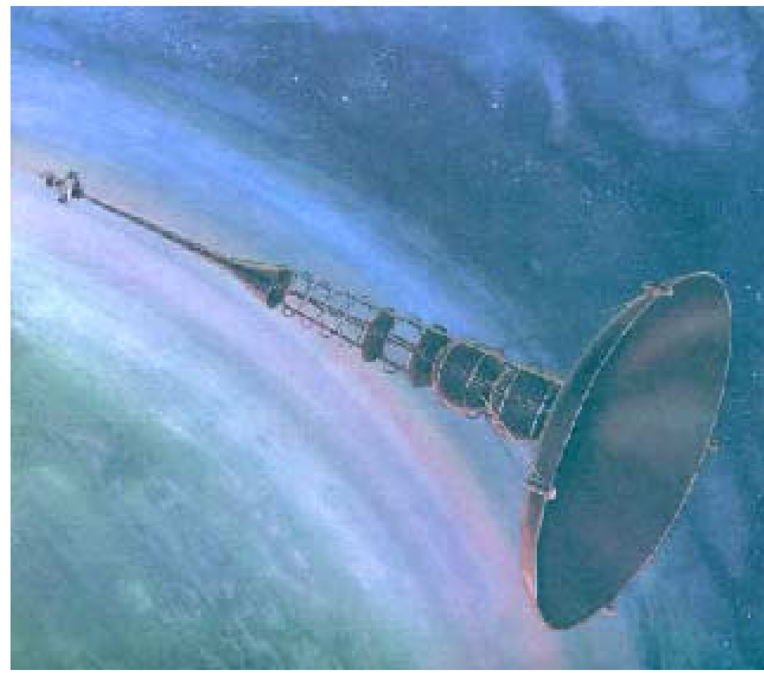
Science Goals

Travel to the stars is the stuff that dreams are made of. There is also a very scientifically compelling aspect as well. A mission past the boundary of the heliosphere would yield a rich scientific harvest.

- **Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in the Galaxy.**
- **Explore the structure of the heliosphere and its interaction with the interstellar medium.**
- **Explore fundamental astrophysical processes occurring in the heliosphere and the interstellar medium.**
- **Determine fundamental properties of the universe, e.g., big-bang nucleosynthesis, location of gamma-ray bursts (GRBs), gravitational waves, and a non-zero cosmological constant.**

“Realistic” Propulsion Concepts Have Intrinsically Large (100s of Tons) Dry Masses

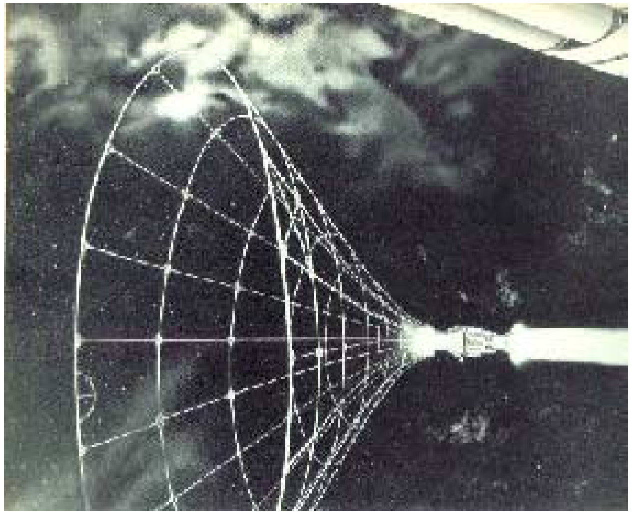
Daedalus Fusion Rocket (D-^{3}He)



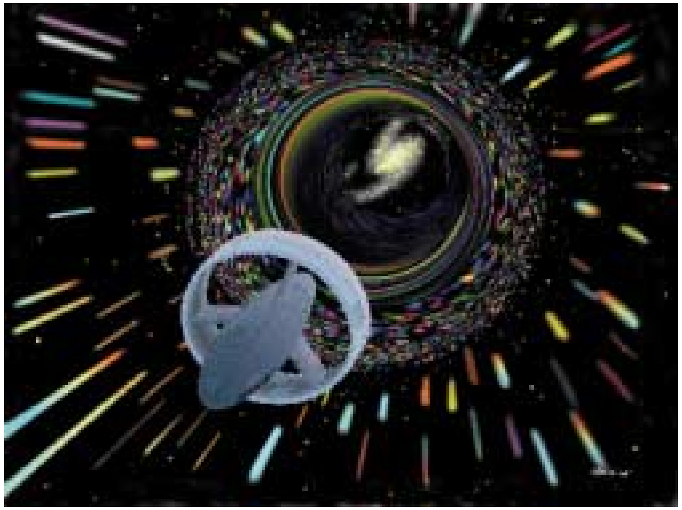
Sänger Photon Rocket

Technology Extrapolations Sound Too Good to Be True and May . . .

- **Be driven by propulsion requirements**
- **Drive costs to scale of current GDP (or beyond!) if a miracle does not occur**

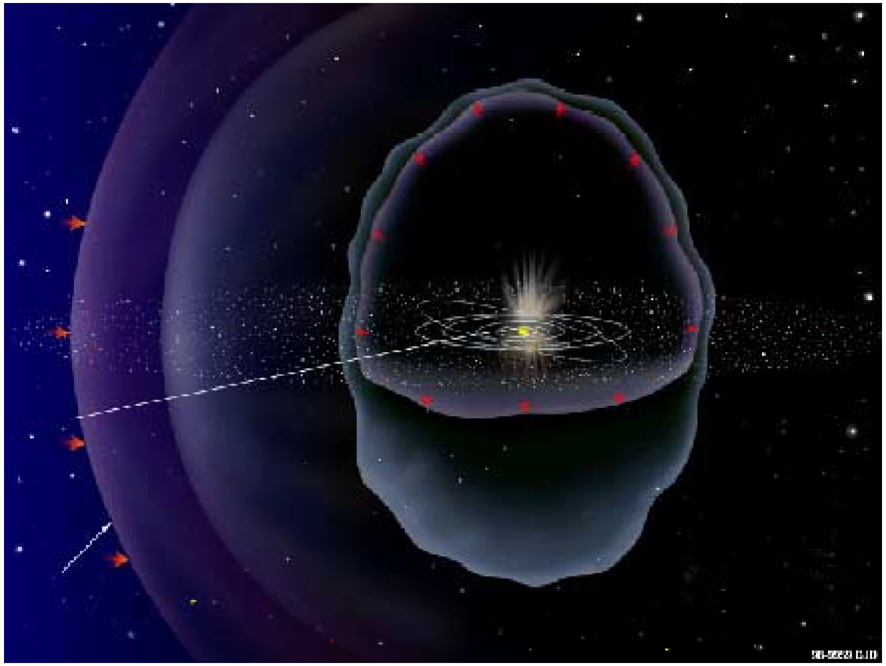


Bussard Ramjet



NASA Breakthrough Propulsion Physics Program

A Mission to the VLISM Is More Modest, but Can Be Done in the Near Term



- The external shock may be ~300 AU away
- So 1000 AU is "clear"of the influence of the Sun on its surroundings

Mission Concept

- Reach a significant penetration into the Very Local Interstellar Medium—out to ~1000 AU—within the working lifetime of the probe developers (<50 years)

- To reach high escape speed, use a solar gravity assist (due to Oberth, 1929):

  (1) Launch to Jupiter and use a retrograde trajectory to eliminate heliocentric angular momentum

  (2) Fall into 4 solar radii from the center of the Sun at perihelion

  (3) Use an advanced-propulsion system ΔV maneuver to increase probe energy when its speed is highest to leverage rapid solar system escape

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Enabling Technologies

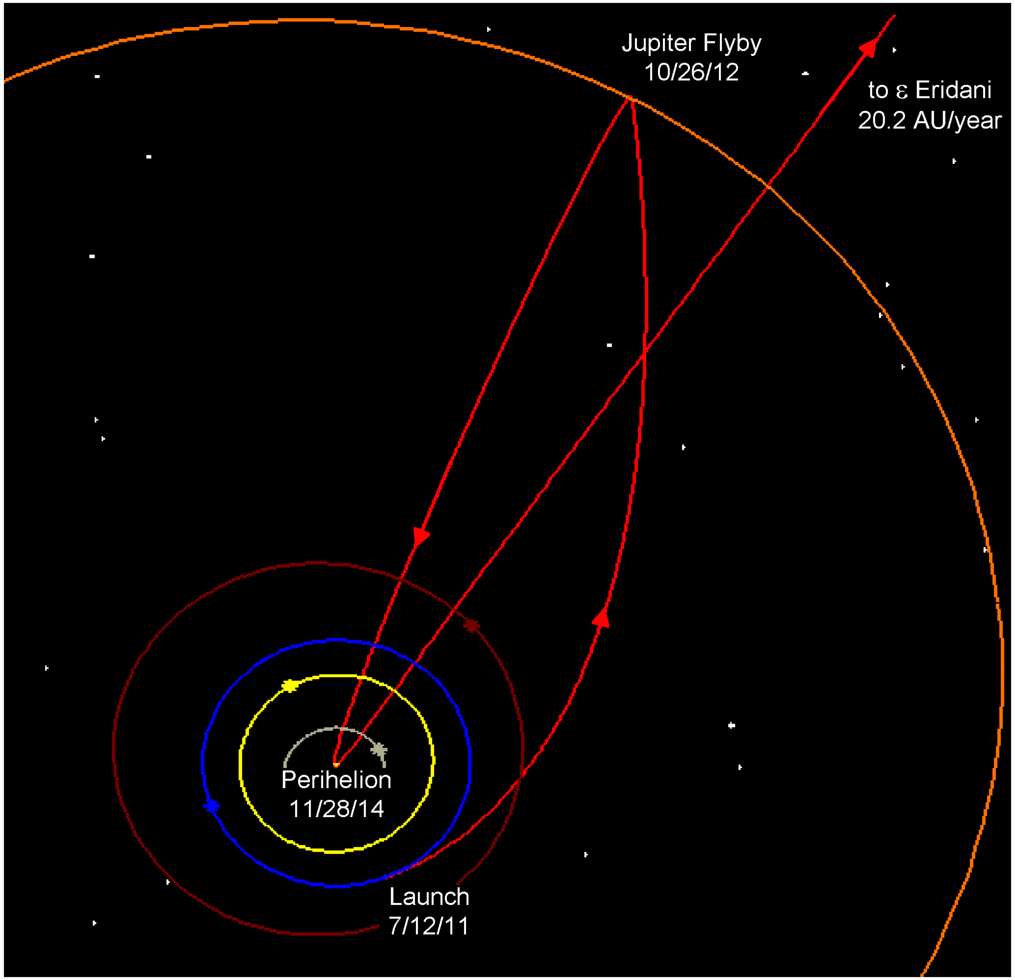
- High I_{sp}, high-thrust propulsion (for perihelion maneuver, ~15 minutes)
- Carbon-carbon thermal shield
- Long-range, low-mass telecommunications
- Efficient Radioisotope Thermoelectric Generator (RTG)
- Low-temperature (<150K), long-lived (<50 yr) electronics
- <0.1 arc second pointing for data downlink
- Open loop control
- Fully autonomous operational capability with onboard fault detection and correction
- Possible extension to multi-century flight times while maintaining data taking and downlink operations

Study Topics

- Architectures that allow launch on a Delta III-class vehicle
- Redundancies that extend probe lifetime to >1000 years; software autonomy, safing
- Concept that links science, instruments, spacecraft engineering, and reality
- 1000 AU, 50-year mission; extension to 1,000 years (~20,000 AU)
- Optical downlink: data/attitude requirements
- Propulsion concepts: solar thermal, nuclear pulse, nuclear thermal—search for higher speed

Trajectory Toward ε Eridani

- **Launching toward a star enables comparison of local properties of the interstellar medium with integrated properties determined by detailed measurements of the target-star spectrum.**
- **Additional planetary flybys over-constrain the trajectory design.**



Target Trajectory

- Target the Sun-similar star ε Eridani, a K2V dwarf main sequence star 10.7 light years from Earth.
- A 2011 launch to Jupiter with a launch energy $C_3 = 117.1$ km^2/s^2, and two years later, a 15.4 km/s perihelion burn near the Sun sends the spacecraft at 20.2 AU/year.
- Launching toward a star enables comparison with locally measured properties of the interstellar medium with integrated properties determined by detailed measurements of the target-star spectrum.
- This low-ecliptic latitude target minimizes the required perihelion burn for a given asymptotic escape speed.
- The details of Jupiter’s orbit cause the launch energy requirements to return to an optimum roughly once every 80 years for a launch toward ε Eridani.

Solar System Escape Speed

- Varies as the inverse fourth root of the perihelion distance
- Varies as the square root of the perihelion ?V

$$v_{escape} = (\Delta V)^{1/2} \frac{35.147}{r_p^{1/4}}$$

- 1 AU/yr = 4.74 km/s
- A "now-technology" Interstellar Probe could supply a ?V of 1.56 km s^{-1} at perihelion, about one-tenth of what is desirable. Perihelion distance = 3 RS => ~7.0 AU yr^{-1}.
- To reach ~20 AU yr^{-1}, the probe needs to be accelerated by ~10 to 15 km s^{-1} during about 15 minutes around perihelion to minimize gravity losses.

Target Stars are Limited to Low Ecliptic Declinations Unless Additional ΔV Is Provided

Star	Distance (Light Years)	Spectral class	Habitable planet probability
Alpha Centauri A	4.3	G4	0.054
Alpha Centauri B	4.3	K1	0.057
Epsilon Eridani	10.8	K2	0.033
Tau Ceti	11.8	G8	0.036
70 Ophiuchi A	16.4	K1	0.057
Eta Cassiopeiae A	18.0	K9	0.057
Sigma Draconis	18.2	G9	0.036
36 Ophiuchi A	18.2	K2	0.023
36 Ophiuchi B	18.2	K1	0.020
Delta Pavonis	19.2	G7	0.057
82 Eridani	20.9	G5	0.057
Beta Hydri	21.3	G1	0.037
Data is from Dole [1964]			
Designations A and B refer to components in multiple (bound) star systems; the effect of multiple systems on the formation of stable planetary orbits remains unknown			

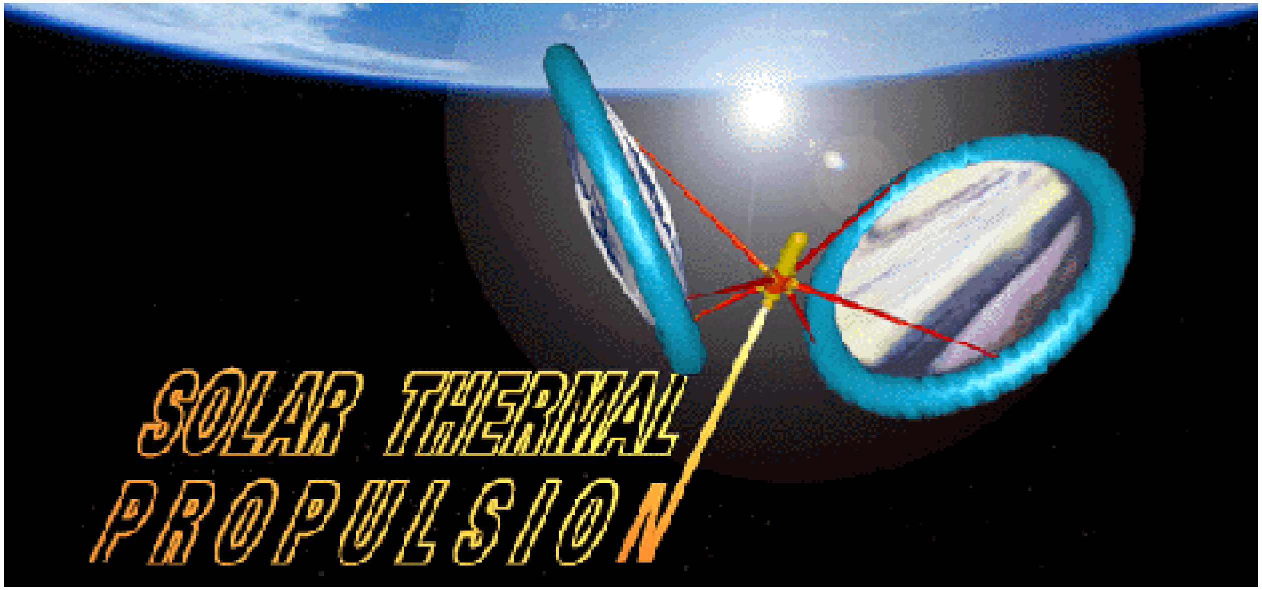
Star	Spectral Class	a Right Ascension (deg)	d Declination (deg)
Epsilon Eridani	K2	48.29	-27.76
Tau Ceti	G8	17.66	-24.77
Wolf 28	DG	13.28	0.19
Procyon	F5	115.87	-16.00
191408	K3	297.06	-15.68
131977 A	K5	228.26	-4.31
36 Ophiuchi	K1	259.96	-3.54

Ulysses Launch Configuration

Ulysses Stack Provided 15.4 km/s

- **Chemical production of such high-speed changes in deep space is not possible.**
- **Ulysses spacecraft and propulsion module were released into Earth orbit from the Shuttle.**
- **Ulysses launch mass = 371 kg with 55 kg of science payload.**
- **Total stack (mass 2-stage IUS + PAM-S upper stage) = 19.97 metric tons.**
- **15.4 km/s over 5.8 minutes burn time BUT we need this applied at 4 R_S !**

Solar Thermal Propulsion Concept

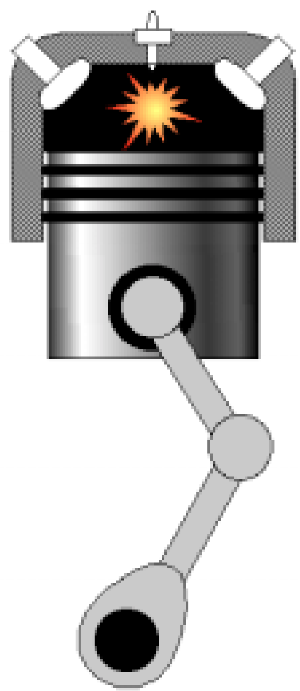


- Being studied for high-I_{sp}, low-thrust orbital transfer vehicles
- Possible implementation for perihelion maneuver with I_{sp} ~1000 s at high thrust

Solar Thermal Propulsion

- **Solar thermal propulsion uses energy from the Sun to heat a low-molecular-weight working fluid to a high temperature (~2400K) and expel the propellant mass from the system.**
- **An "obvious" choice for a working fluid is liquid hydrogen (LH_2); however, realistic cryostats carry a substantial mass penalty for long-term LH_2 storage for use as a working fuel at perihelion.**
- **The use of ammonia enables standard pressurized titanium tank technology, but dissociation of the ammonia requires higher temperatures and so the specific impulse is lower.**
- **A bottleneck, in addition to mass, is providing sufficiently rapid heat transfer to the fuel in the near-Sun environment.**

Nuclear Pulse Propulsion

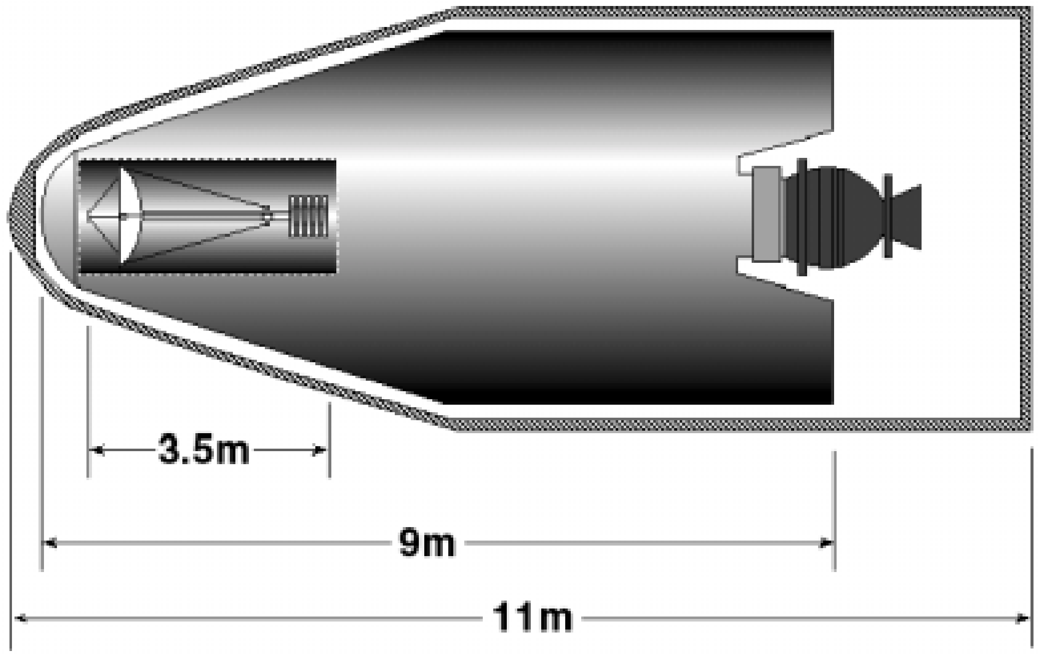


Scalability to low-mass systems is problematic due to critical mass of fission assemblies. Nuclear Thermal Propulsion may be the real answer.

Nuclear Pulse Propulsion ("Orion")

- Fission may provide the key element for the perihelion propulsion, but only in a pulsed mode with low fission yields per pulse; we need the fission energy of ~1.3 g of uranium–a total of about 13 tons of TNT equivalent.
- The problem is the coupling of the momentum into the ship over short time scales, ~10^{-8}s. Transferring this impulse over such short times typically causes stress to exceed the yield strengths of all known materials.
- The Orion concept requires large masses for dealing with the release of ~1 to 10 kT explosions; however, the spacecraft masses tend to be large due to the power plant overhead.
- Ideally, a pulsed-mode autocatalytic reaction similar to the operation of a pulse jet, e.g., the German V-1, is preferred. This type of rocket would represent the next step past a gas core nuclear engine.

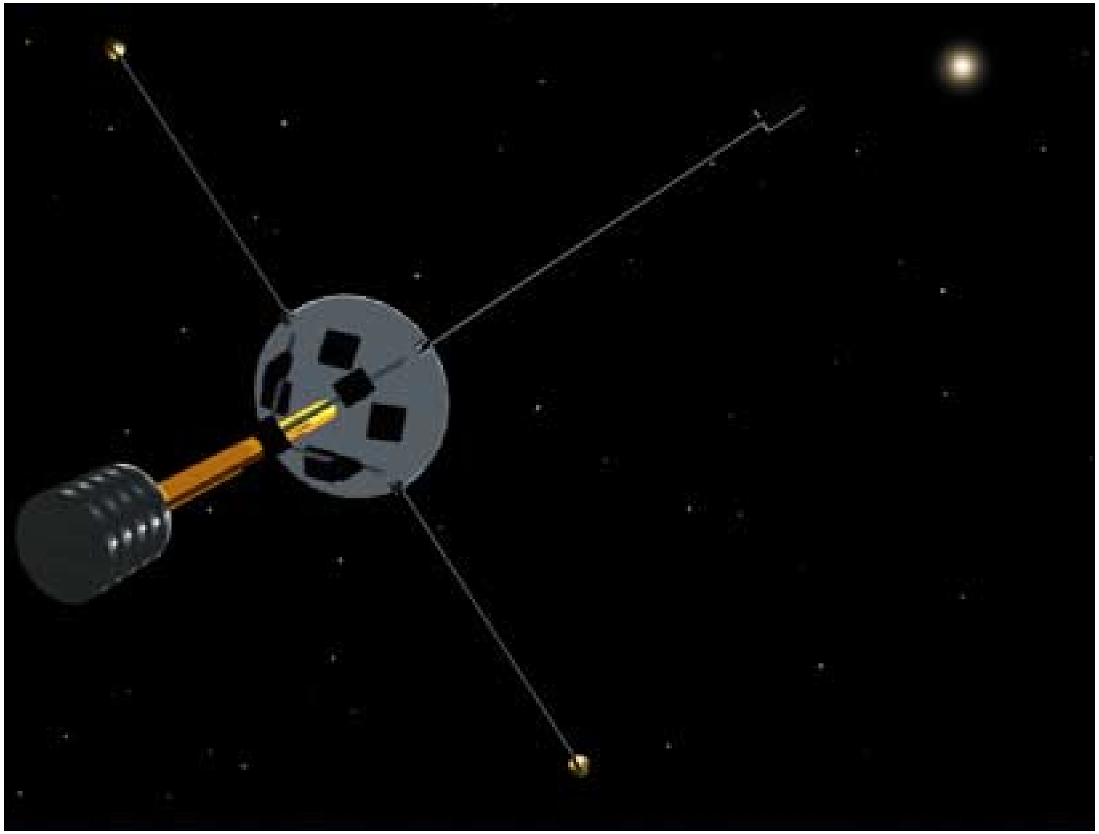
Interstellar Probe in Delta III Shroud



Probe Configuration After Trans-Jupiter Injection

- The probe, thermal shield, and perihelion propulsion stage are sized to fit within a Delta II shroud.
- The cocoon-like structure carries the probe past Jupiter and into its perihelion maneuver at the Sun.
- The probe itself is small; most of the volume is occupied by the thermal shield and perihelion propulsion system.
- Following the perihelion burn, the probe is mechanically jettisoned from the cocoon structure to begin its 50-year prime science mission.

Interstellar Probe Final Flight Configuration



Probe Architecture

- Following the perihelion burn, the probe mechanical design consists of three main mechanical elements –a Radioisotope Power Source (RPS) assembly, a central support mast, and an optical dish.
- The RPS is placed at one end of the mast in order to minimize the radiation dose to other spacecraft components.
- At the other end of the mast is the large optical dish, which faces away from the direction of travel and back toward the solar system.

Mass and Power of Probe

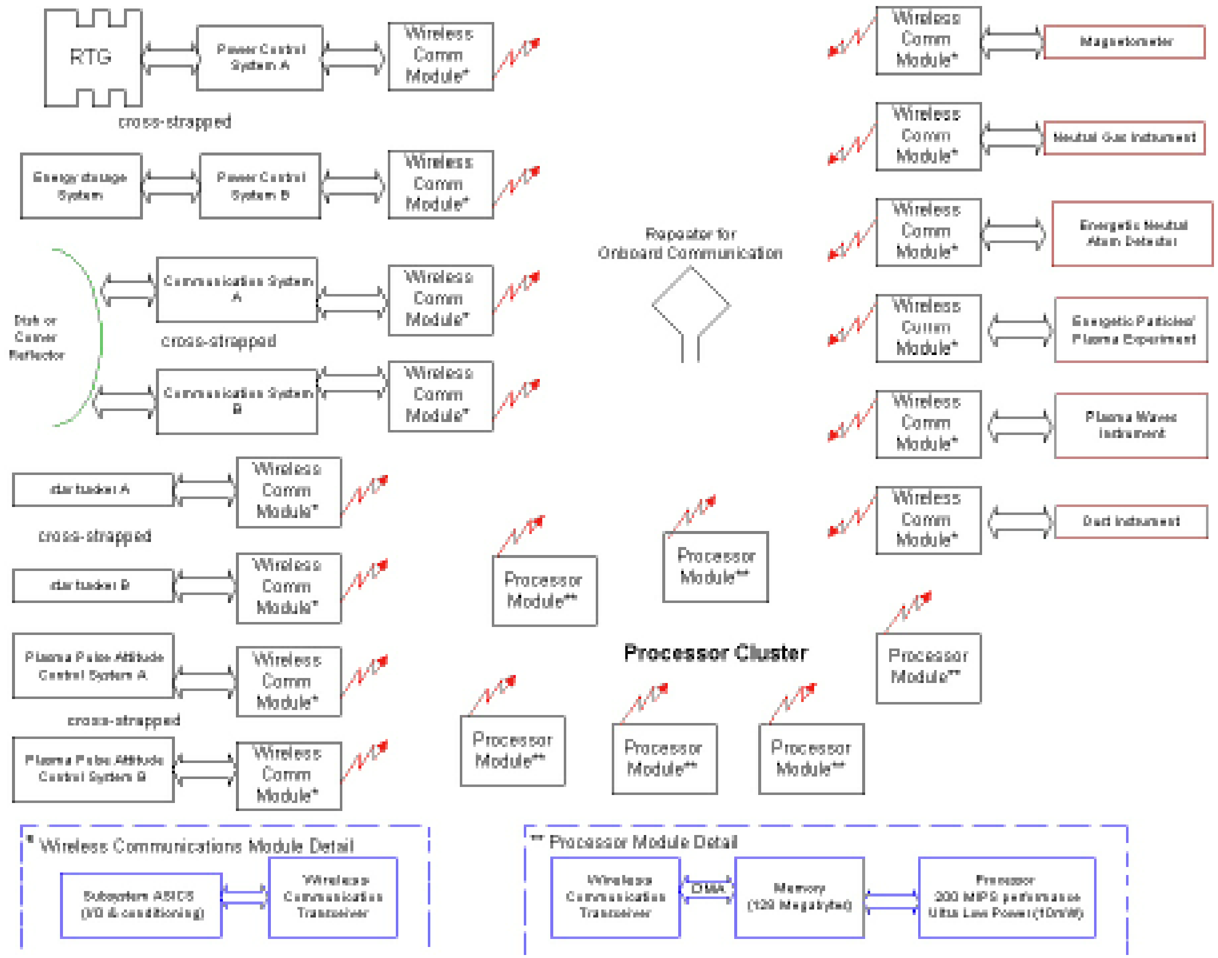
Interstellar Probe	Mass (kg)	Power (Watts)
Power System	10	—
Instruments	10	10
Structure	15	—
Communications	10	Intermittent, uses energy storage system
S/C Electronics	5	5
Totals	50	15

Probe Structural Configuration

- Instruments and spacecraft electronics boxes are placed on the back of the optical dish and along the mast.
- Four booms, used for field measurements, are mounted orthogonally to one another at the perimeter of the optical dish.
- The spacecraft secondary battery and power control system are placed inside of the mast roughly at its midsection.
- The communication system laser is also placed inside the mast and points out the end of the mast, through a small hole in the 1-m optical dish, toward the hyperboloid reflector.

Probe Block Diagram

Perihelion propulsion module is not shown



Command and Data Handling

- The probe does not have a subsystem onboard that can be strictly identified as a "command and data handling system."
- Modules perform command and data handling functions but are not aligned or connected to any particular subsystem or task.
  All processing is distributed and all tasks are only loosely coupled with specific hardware.
- All the identical processor modules exceed 200 MIPS so that any processor is capable of handling all the tasks onboard single-handedly if necessary.
- Each module contains a central CPU, memory, and a wireless communication submodule.
- If a processor fails, its task shifts to an unused processor. If no spare processors are available, then some of the remaining processors handle more than one task. In the worst case scenario, when only one processor is still working, it alone handles all tasks.

Mass and Power of Science Payload

Instrument	Identifier	Mass (kg)	Power (W)
Plasma waves/dust detection	PWD	1.5	2.5
Plasma/particles/cosmic rays composition and spectra	PPC	1.0	1.5
Magnetometer (w/boom)	MAG	3.0	0.5
Lyman- α imager	LYA	1.0	2.0
Infrared imager	IRI	1.5	1.5
Neutral atoms composition, density, speed, temperature	NAC	2.0	2.0
Totals	—	10.0	10.0

Prime Science Period

- Once two-way communication is lost, the Interstellar Probe enters an autonomous mode with only infrequent downlinks.
- This is the prime science portion of the mission in which

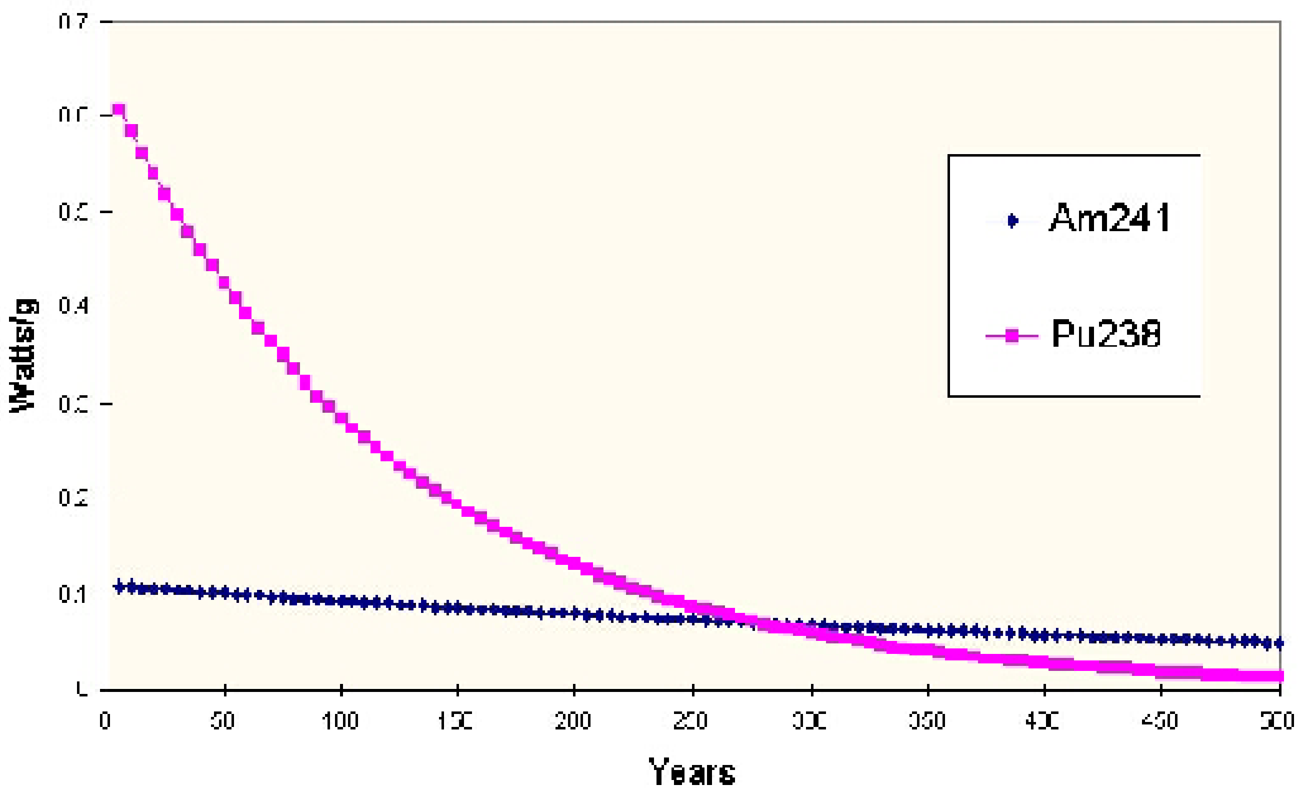
(1) The probe maintains a slow spin with the spin axis pointing back at the Sun. The spinning spacecraft allows the science instruments to see the entire sky.

(2) The instruments collect and process their own data.

(3) At regular intervals, the probe points accurately toward a Hubble-class receiving station, which is orbiting the Earth, and then transmits the science data.

(4) Onboard processors continually monitor the health of the probe and take corrective action(s) as required.

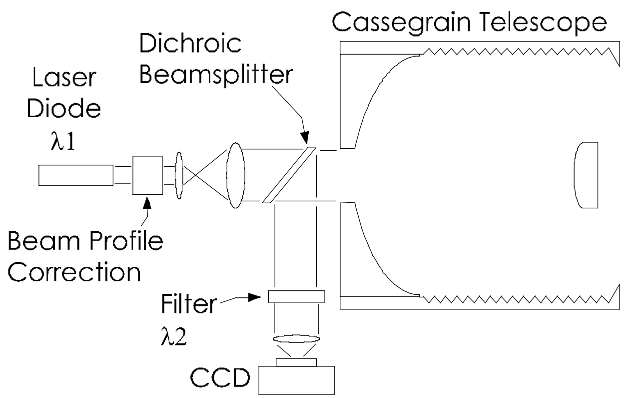
An RPS Provides Centuries of Power for Very Long Missions



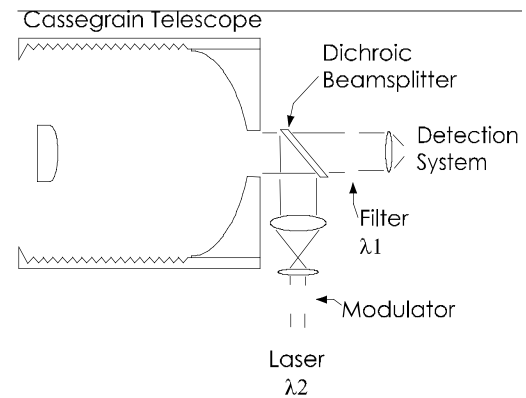
Power System

- The power source for a deep-space interstellar mission must be a Radioactive Power Source (RPS).
- For "closer" missions Pu-238 will suffice: one 15-W Pu-238 ARPS satisfies steady-state power requirements and weighs 4 kg.
- For "further" missions, Am-241 has a longer half-life, but a lower operational temperature is problematic.
- Communication and attitude systems operate intermittently and require significant peak power; they utilize an energy storage system (capacitor bank), which is trickle charged by the RPS.

Optical Communication System Concept



Interstellar Probe optics



Optics at the Earth terminal

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Communications Requirements

- **At a range of 100 AU, electromagnetic waves take 13.9 hours to travel from the spacecraft to Earth. Interactive control of the spacecraft becomes nearly impossible at these distances necessitating a highly autonomous craft and one-way communications to Earth.**

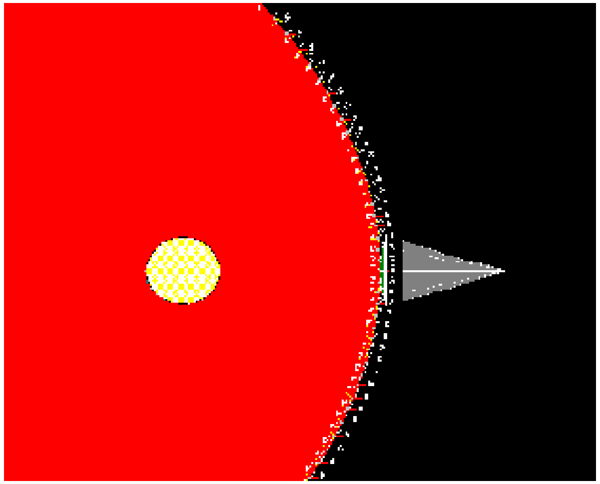
System Requirements

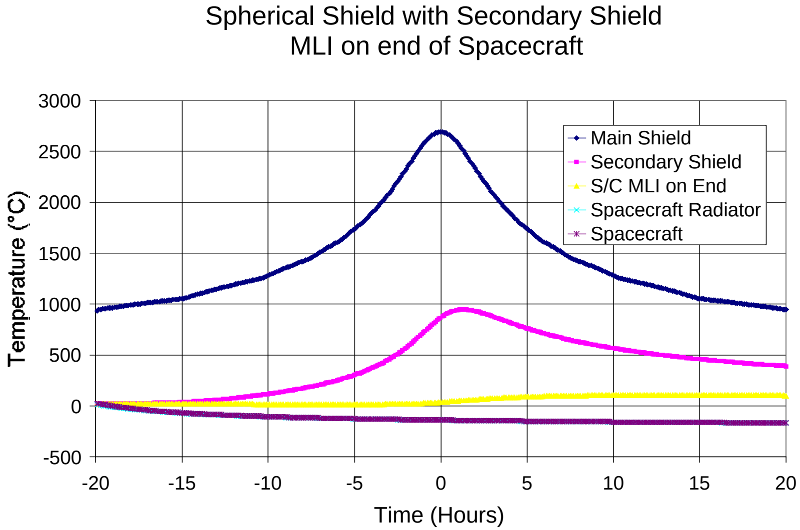
Requirement	Value
Data rate	500 bps
Bit error rate	10^{9} (encoding dependent)
Range (probe)	100 to 1000 AU
Range (Earth terminal)	High Earth orbit
Probe tracking	Sun tracker and star camera
Pointing accuracy	0.15 arcsec (0.72 μ rad)
Electrical power load	10 W (continuous)
Mass	10 kg
Lifetime	>50 yr
Reliability	95%
Transmission redundancy	Probe highly autonomous; transmissions labeled with header and repeated X times at predetermined intervals

Example System Properties

Property	Description
Probe light source	Quantum cascade (QC) laser
Wavelength $\lambda 1$	~890 nm - near IR
Probe optical aperture	1 m (Gaussian beam angle is 1.13 μrad
Earth terminal aperture	4 m
Modulation (probe to Earth)	External binary phase shift modulation - BPSK
Modulation (Earth to probe)	Amplitude modulation - binary
Earth terminal detection	Coherent - homodyne
Probe terminal detection	Incoherent - direct detection

Thermal Characteristics of Spherical Thermal Shield



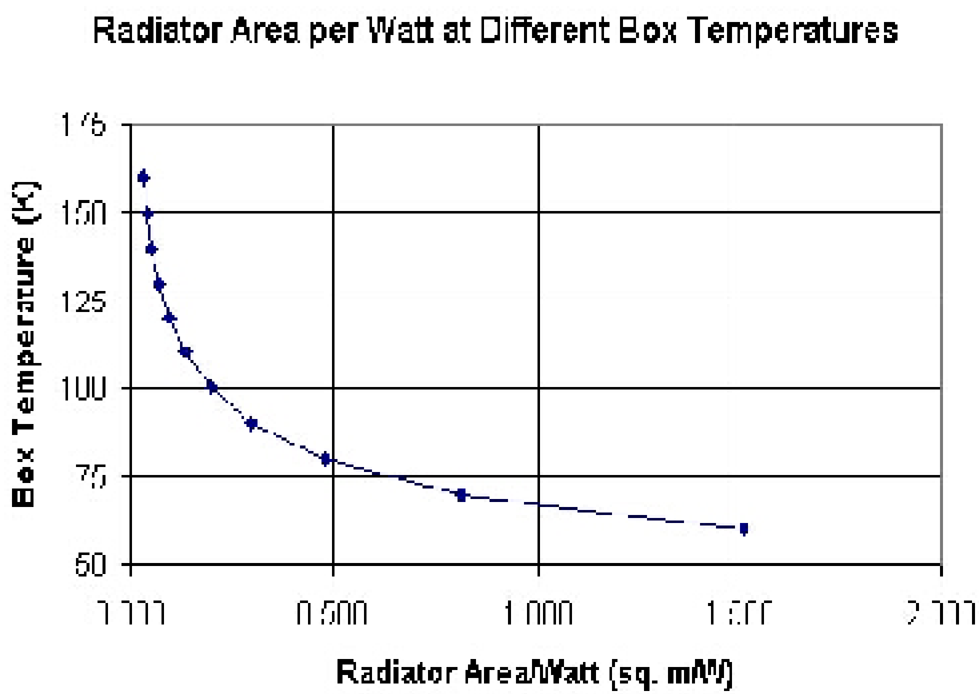


Perihelion Thermal Shield

- A carbon-carbon spherical shield protects the vehicle from the Sun. The conical shape shown represents the available volume for the probe and the propulsion model.
- A secondary shield further reduces the thermal soak back, and a standard MLI blanket is used to protect the spacecraft from the backside of the secondary shield.
- Although the shield temperature approaches 2700°C, the spacecraft is protected.
- The thermal shield also must be incorporated into the general mechanical design that must both accommodate the propulsion system and allow for the spacecraft to work under Orion-type or solar-thermal propulsion conditions.

Thermal Issues

- **Ultra Low Power (ULP) electronics work best at low temperatures. They use passive radiators to dump heat generated by RPS and electronics. The goal is to operate at 125–150K. No blankets are required.**



Probe Thermal Design for Cruise

- **The goal of the thermal design for the mirror and its attached hardware is to operate between 75 and 12K.**
- **The thermal analysis assumes that the RPS generates 100 W of thermal energy, with 15 W going out as electrical power to the instruments. The 85 W of heat are rejected at the RPS locally. The ARPS is assumed to have a surface temperature of 200°C.**

Programmatics

- A 65-year technology development and flight program can be done for ~$1000 M, exclusive of a DOE-cost shared $800 M NTP development effort (if required).
- At an average cost of ~$15 M/year out of the NASA Technology budget and with multiple commonalities in technology requirements for other NASA missions, such a development program:
  - Makes sense as a science initiative and a technology focus.
  - Provides a low-cost means of reaching for the stars.

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Schedule

2000-2002	Advanced Technology Development study(ies)
2000-2002	Continued definition studies of the solar sail concept for IP at JPL
2002-2003	Update of OSS strategic plan with study for a "New Millennium" -like mission
2003-2007	Focused technology development for small probe technologies
2004-2007	Development of sail demonstration mission
2004-2007	Development of Solar Probe mission (test for perihelion propulsion)
2006-2007	Hardware tests for radioisotope sail feasibility
2006-2007	Hardware tests for antimatter implementation in propulsion schemes
2006-2007	Monitor DoD STP effort and conduct NASA-specific hardware tests
2002-2007	Development of space-qualified nuclear thermal reactor
2007-2010	Focused technology development for an Interstellar Probe
2009-2012	Design and launch of first-generation solar-sail probe
2010	Test of Solar Probe performance in the perihelion pass of October 2010
2012-2015	Design and launch second-generation probe 1000 AU goal in 50 years
2015-2065	Data return from out to 1000 AU

Current Status

- **Phase II funding authorized 17April 2000**
- **Subcontracts in process for mini-studies of:**
  - **Advanced star tracker architectures**
  - **Solar thermal propulsion to apply at perihelion**
  - **Advanced LH_2 storage for long-term, deep-space propulsion**

Presentations and Papers

- **“Low-Cost Interstellar Probe” talk presented 4 May 2000 at Fourth IAA International Conference on Low-Cost Planetary Missions (Technical Session VI-Part 2: Outer Planets Missions) Laurel, MD**
- **Corresponding MS submitted to proceedings as Paper IAA-L-0608 (for publication in *Acta Astronautica*)**
- **Solicited presentation on Interstellar Probe concepts at next meeting of the Sun-Earth Connections Advisory Subcommittee (SECAS), NASA HQ, June 13–15, 2000.**
- **Abstract submitted to COSPAR Colloquium on The Outer Heliosphere: New Frontiers, Potsdam, Germany, July 24–28, 2000.**

This Step

- 50-kg probe is difficult but doable. Many new technologies support this effort (ultra-low power CMOS, Explorer Advanced Technology and PIDDP funding, optical and wireless developments in commercial sector, etc.)
- Novel propulsion system is key. Three-stage Delta III with 50-kg probe leaves only 250 kg for perihelion-burn propulsion system.

The Next Step

- What is needed next is another factor of 10 in speed, to

  200 AU yr-1, at which the first targeted interstellar crossing to Alpha Centauri will take ~1400 years, the time that buildings have been maintained, e.g., Hagia Sophia in Istanbul (Constantinople) and the Pantheon in Rome

Though not ideal, the stars would be within our reach.

Ad Astra!