NASA Institute for Advanced Concepts

Interstellar Explorer

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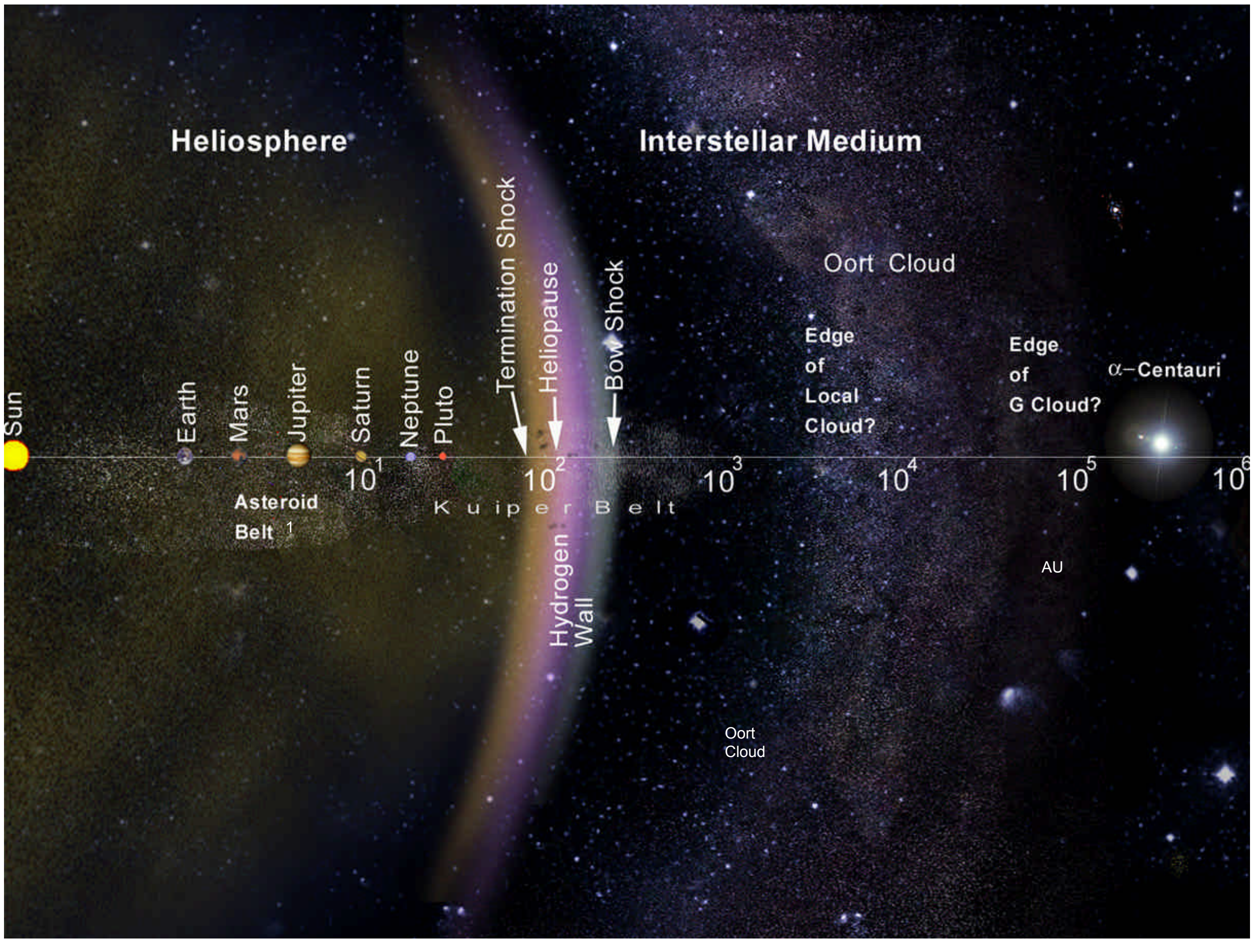
Futuristic Space Technologies

Session: Beyond 2025

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



Graphic from the Interstellar Probe Science and Technology Definition Team NASA/JPL

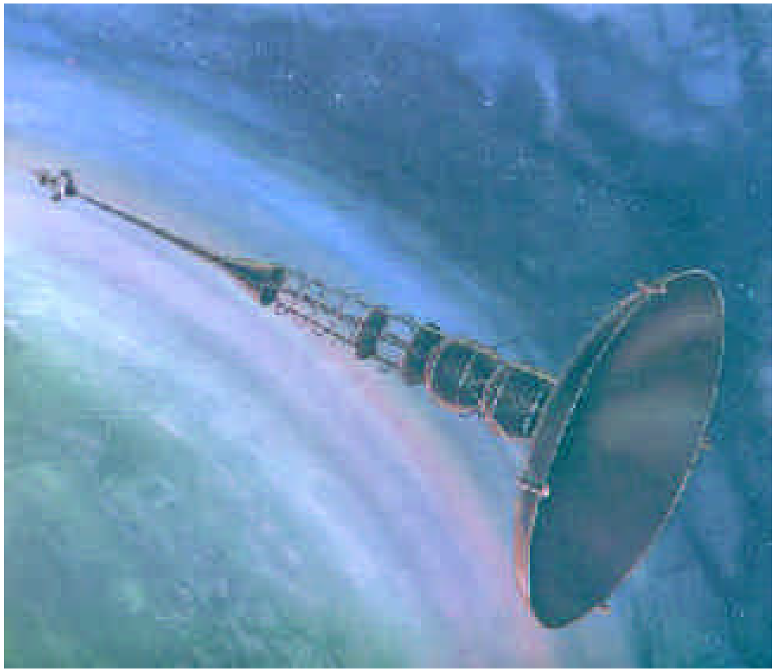
Science Goals

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

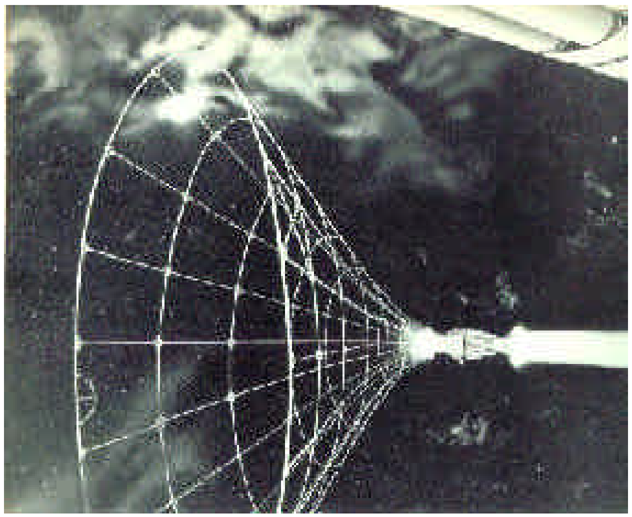
Daedalus Fusion Rocket (D-^{3}He)



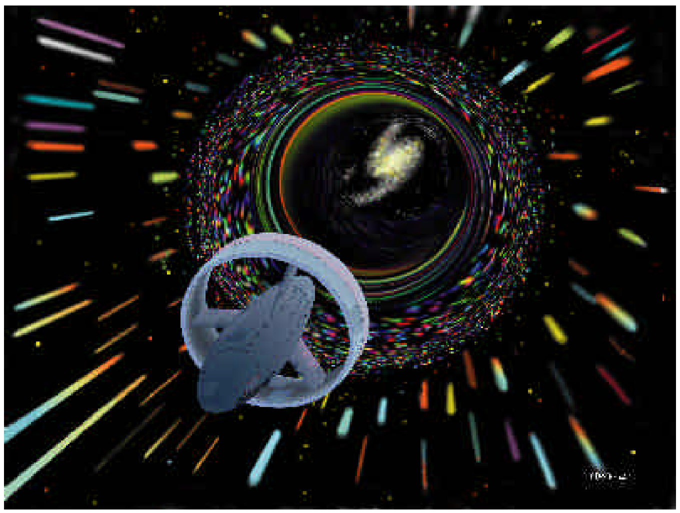
Sänger Photon Rocket

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

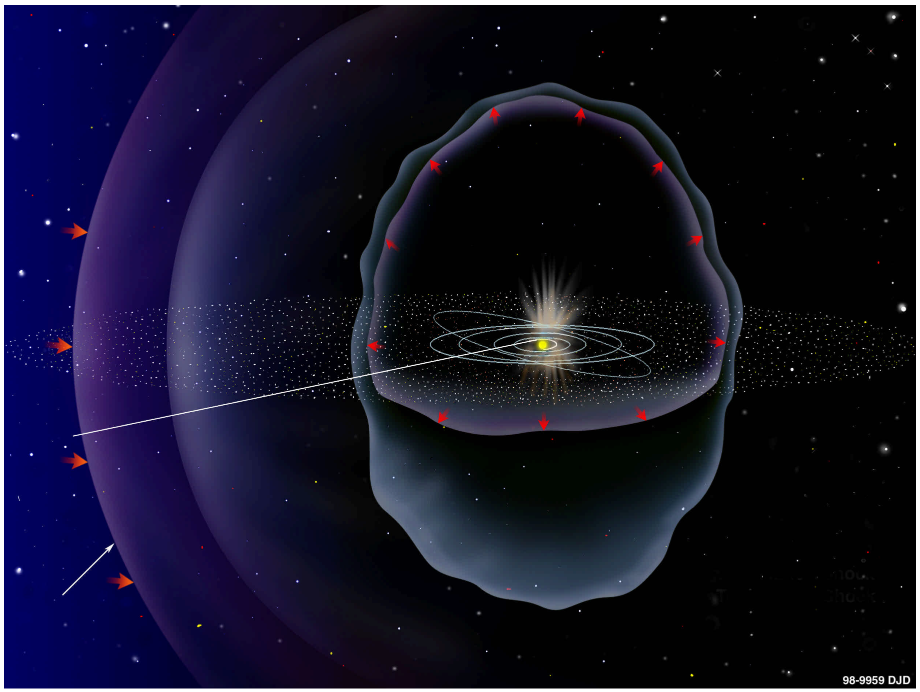


Bussard Ramjet



NASA Breakthrough Propulsion Physics Program

A Mission to the Very Local Interstellar Medium (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 DV maneuver to increase probe energy when its speed is highest to leverage rapid solar system escape

Enabling Technologies

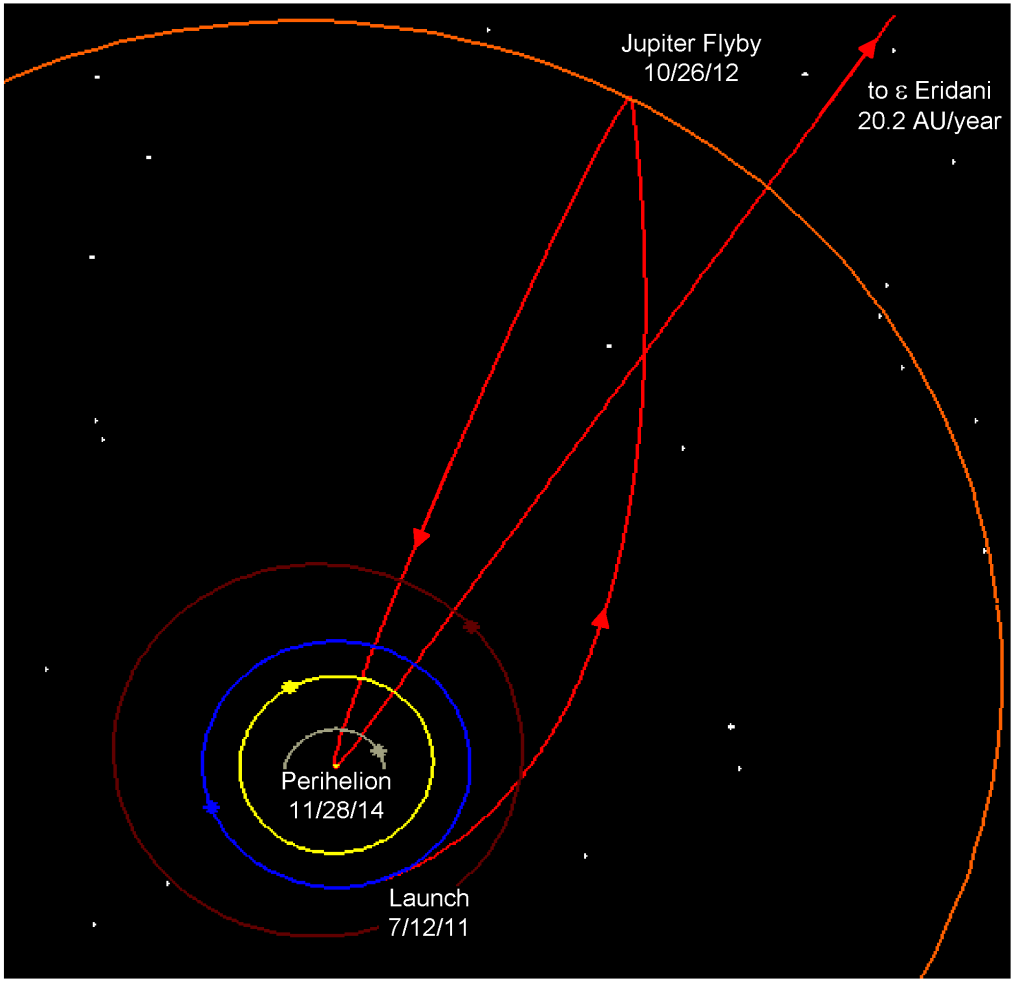
- High I_{sp}, high-thrust propulsion (for perihelion maneuver, ~15 minutes)
- Carbon-carbon thermal shield
- Long-range, low-mass telecommunications
- Efficient Radioisotope Thermoelectric Generator (RTG)
- Low-temperature (<150K), long-lived (<50 yr) electronics
- <0.1 arc second pointing for data 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

Original Study Topics

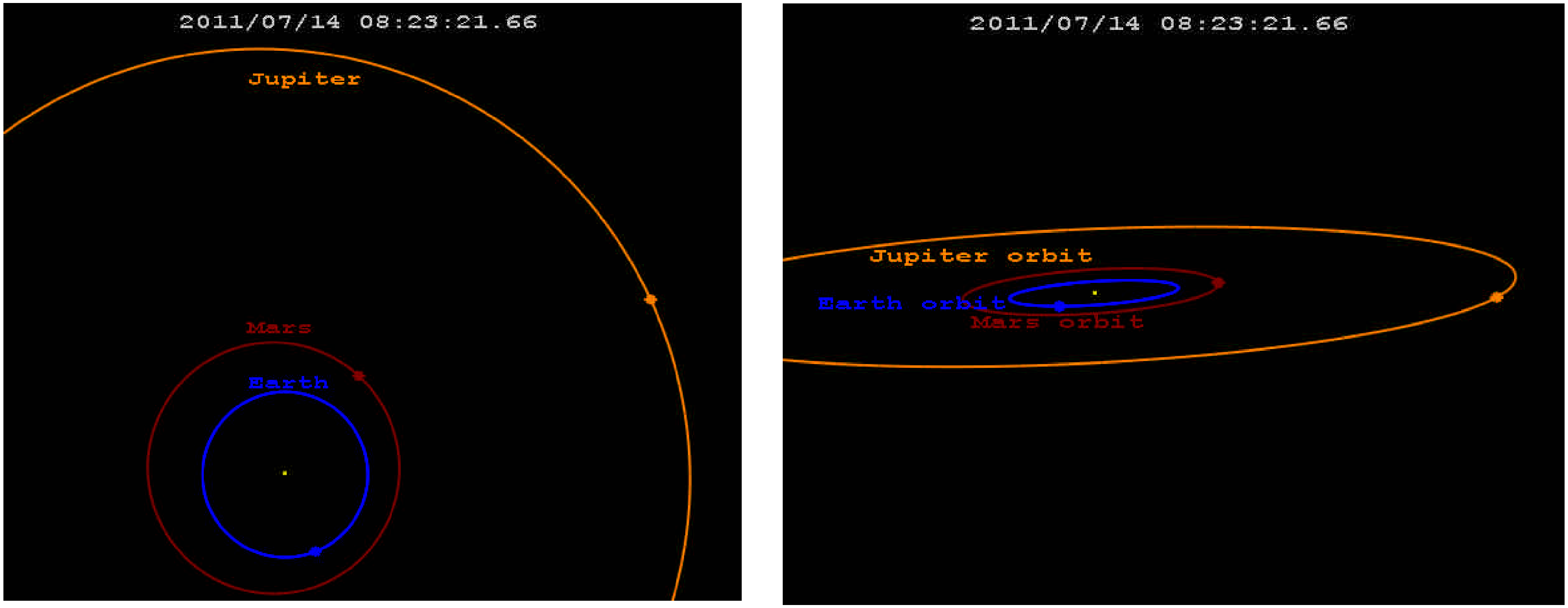
- Architectures that allow launch on a Delta III-class vehicle
- Redundancies that extend probe lifetime to >1000 years; software autonomy, safing
- Concept that links science, instruments, spacecraft engineering, and reality
- 1000 AU, 50-year mission; extension to 1,000 years (~20,000 AU)
- Optical 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.**



Mission Design



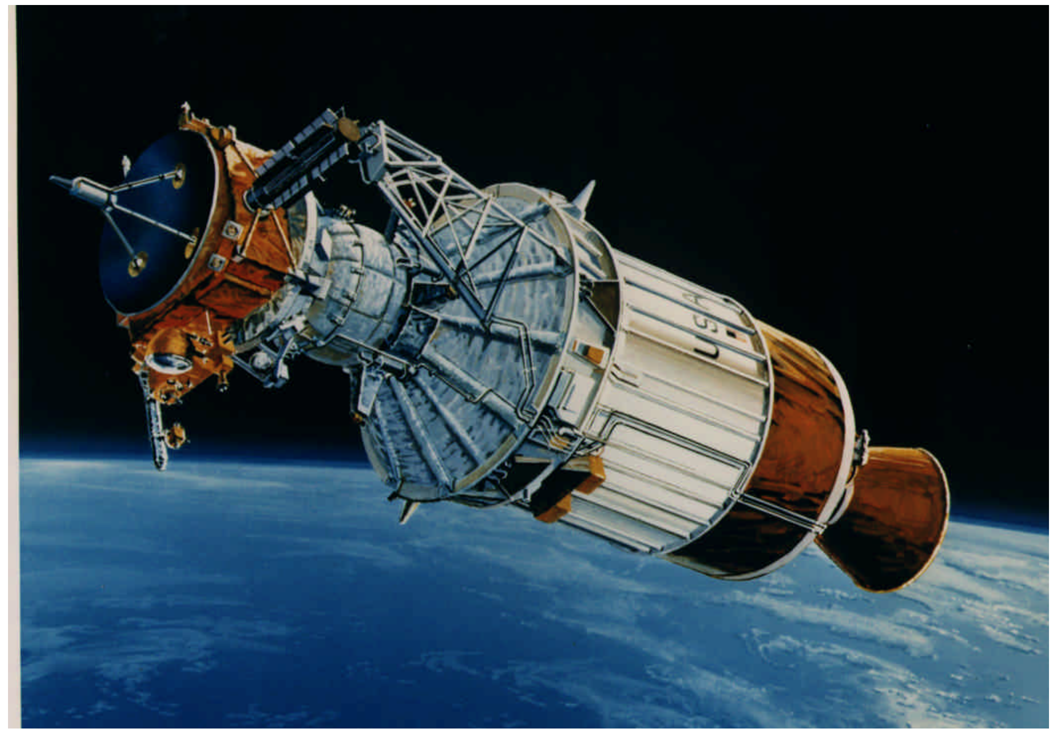
Solar System Escape Speed

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

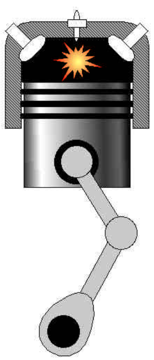
- 1 AU/yr = 4.74 km/s
- To reach ~20 AU yr $^{-1}$, the probe needs to be accelerated by ~10 to 15 km s $^{-1}$ during about 15 minutes around perihelion to minimize gravity losses
- Target stars are limited to low ecliptic declinations unless additional ΔV is provided

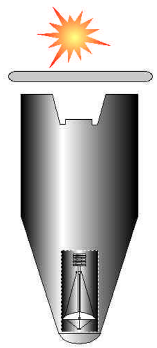
Ulysses Stack Provided 15.4 km/s

- 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 !**



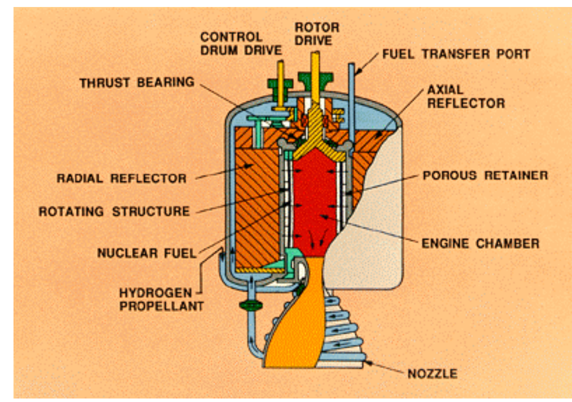
Propulsion Options

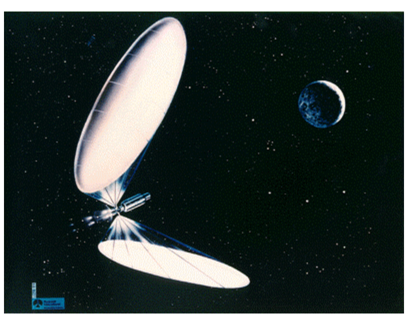




- Nuclear pulse propulsion ("Orion")
  - Does not scale to small systems - even for exotic radionuclides

- Nuclear thermal propulsion (NTP)
  - Small systems limited to solid core
  - I_{sp} limited by fuel pellet CTE and chemical reactivity





- Solar thermal propulsion (STP)
  - Use at 1 AU requires concentrators
  - Same propellant storage and transport issues as for NTP

Thermal Requirements Driven by Propulsion Requirements

- **Survive cruise mode prior to perihelion pass**
  - **Protect propellant storage system**
  - **Heat propellant for perihelion "burn"**
- **Survive high heating rates at $4R_S$ (2900 Suns)**
- **Allow perihelion burn to accelerate vehicle**
- **Deploy probe after burn**
- **Use waste heat from RTG (or equivalent) to minimize heater- power requirements**
- **Operate probe electronics at ~ 125 K**

Trade Studies

- Concentrate on STP system - results also apply to NTP
- Sufficiently large I_{sp} to provide ΔV
  - Examine LH_2, CH_4, NH_3
  - Maximize propellant temperature (up to structural failure)
  - Examine pressure vs flow rate, heating, and recombination
- Size propellant tank/cryostat for propellant requirements
  - Storage for cruise
  - Pressure and expulsion during burn

Best Performance for LH2

- At low pressure,specific impulse increases with decreasing recombination rate

Isp (s) for H_2 (Hydrogen) - Nozzle Expansion = 50:1

Temp (K)	Press (psia)	5	10	15	30	45
3500		1461.8	1400.1	1366.6	1312.5	1280.5
3400		1404.1	1346.8	1315.6	1261.7	1229.7
3300		1347.3	1294.2	1263.3	1208.7	1178.8
3200		1291.7	1239.6	1207.5	1155.9	1129.6
3100		1235.3	1181.1	1150.7	1105.4	1083.3
3000		1174.1	1122.4	1096	1058.3	1040.4

- Cryostat required for long-term LH2 storage

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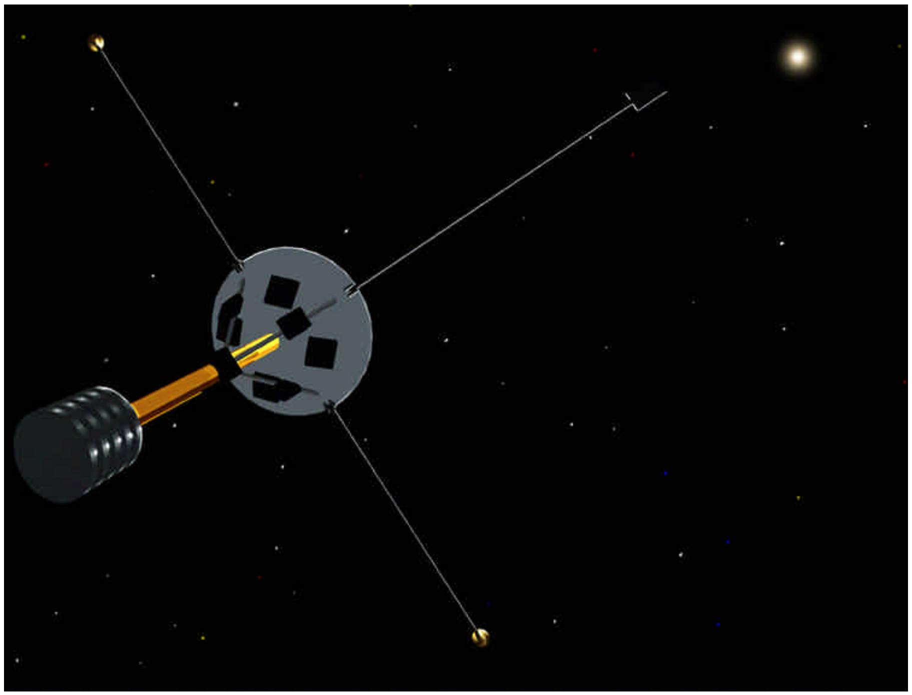
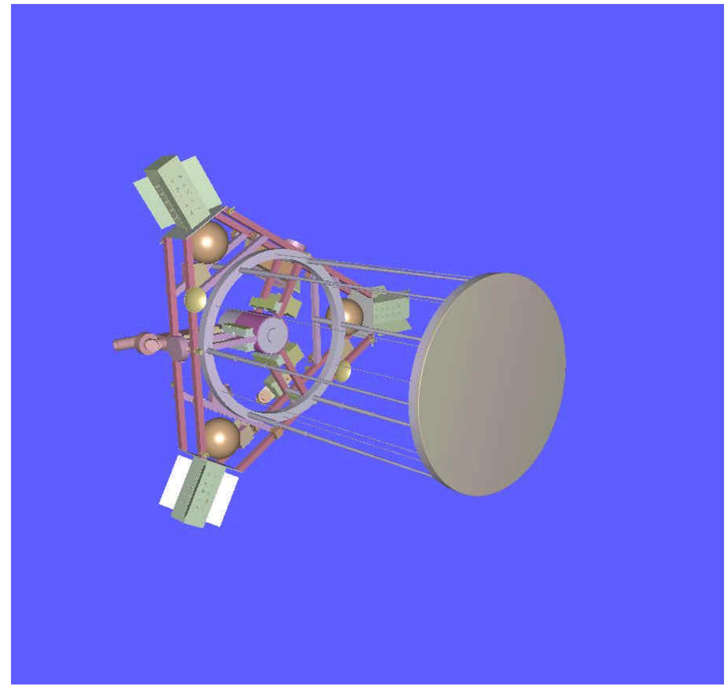
Interstellar Probe Final Flight Configuration





Initial Concept

Phase I Study and Phase II Proposal (2000)

Current Concept incorporates spin stability and realistic packaging

(2002)

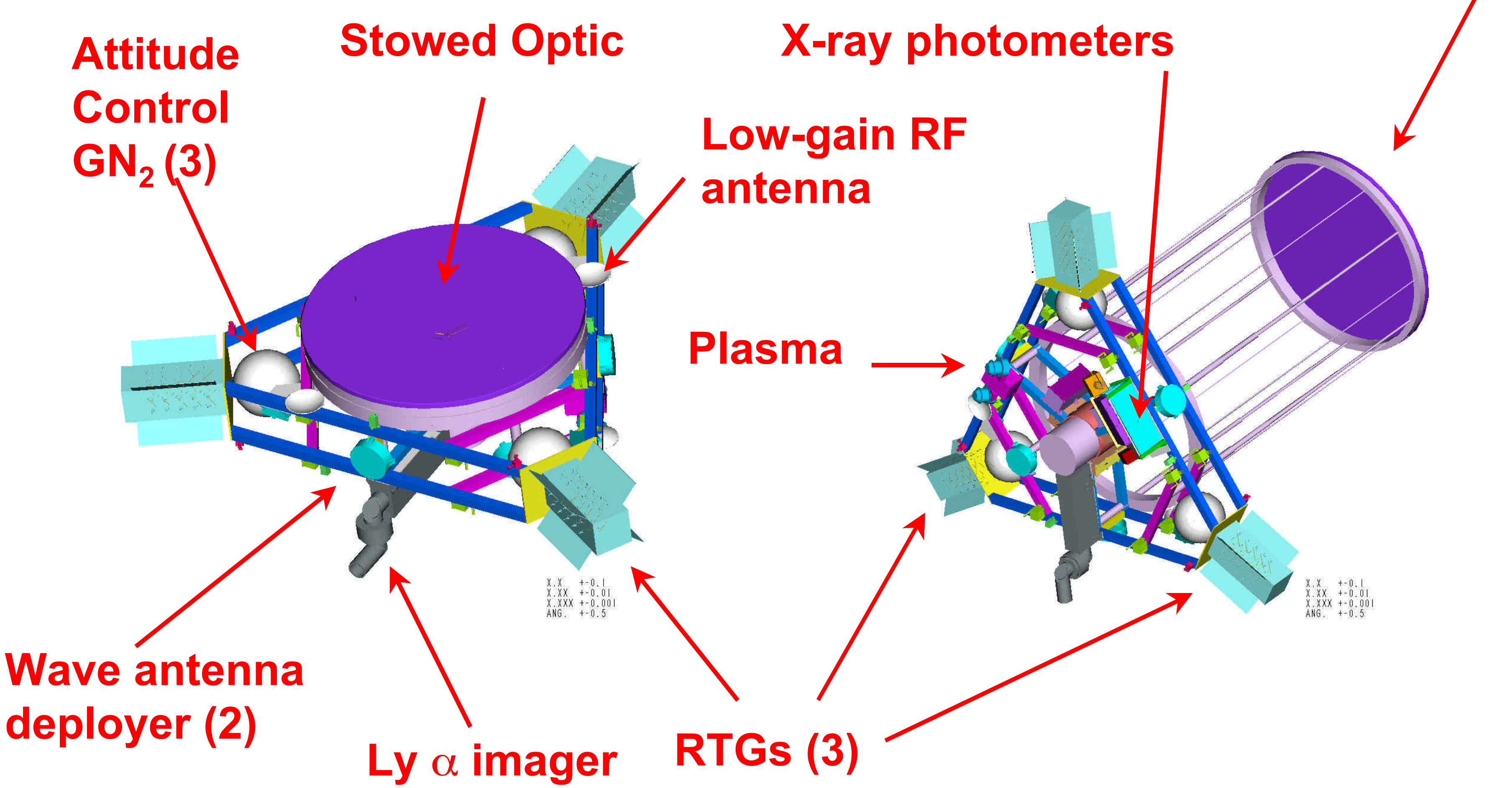
Model Science Payload

Component	Mass	Quantity	Notes	Power
Science Instruments	**12.16**		**Allocated total is 10.0 kg; power in table entries are nominal - not peak**	**1.87**
	1.89	2	Magnetometer deployment system+electronics+probe	0.18
	1.48	2	Plasma wave	0.08
	0.97	1	Plasma spectrometer	0.53
	3.43	1	Lyman alpha imager	0.13
	0.84	1	Cosmic ray spectrometer	0.16
	0.80	1	Energetic particles spectrometer	0.33
	0.70	1	Dust experiment	0.13
	2.05	1	X-ray spectrometer	0.33

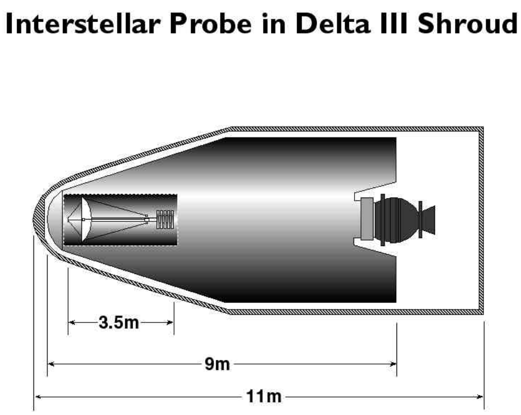
Mass and Power of Probe

Component	Mass	Notes	Power
Science Instruments	12.16	Allocated total is 10.0 kg; power in table entries are nominal - not peak	1.87
IEM/IES: C&DH, G&C	1.44		1.38
Power System	45.60		2.12
Telecommunications	16.17		11.28
Structure	18.32		0.00
Attitude Control	5.40		1.69
Thermal	0.00	All thermal input is via waste heat from RTGs; no thermal insulation or active control	0.00
Propulsion	41.49	Propulsion components for cold-gas N2 system for attitude control; peak power is 56W if two thrusters are firing simultaneously; also hydrazine system for trim prior to perihelion	0.16
Dry Mass Total / Power Total	140.58	Total dry mass before harness	18.50
	147.15	Total including harness	18.87
	0.00	Reserve of 5% in power	0.94
	147.15	Total for probe including reserve	19.81

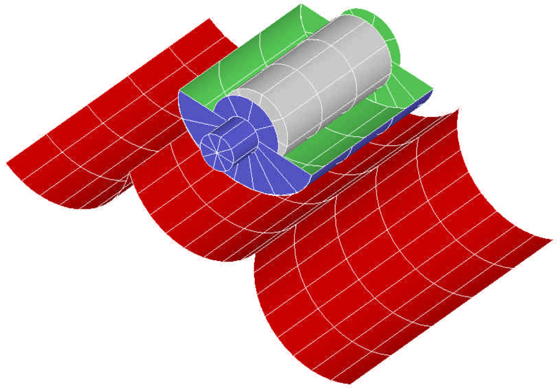
Probe in Cruise Configuration



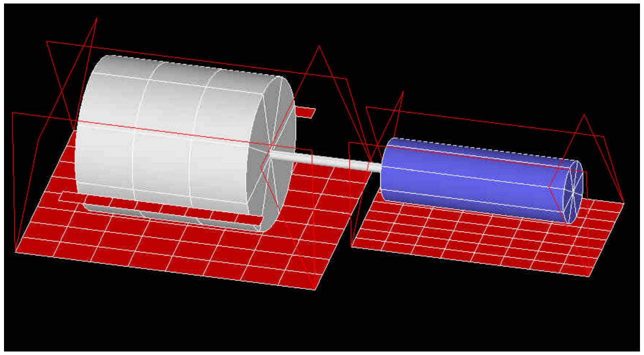
"Carrier" Configuration Driven by LH_2 Volume



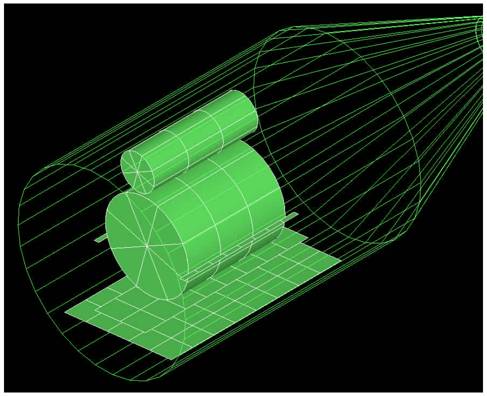
(1) Initial Concept



(2) Maximize volume for Delta III



(3) Size diven by 250 kg (dry) cryostat

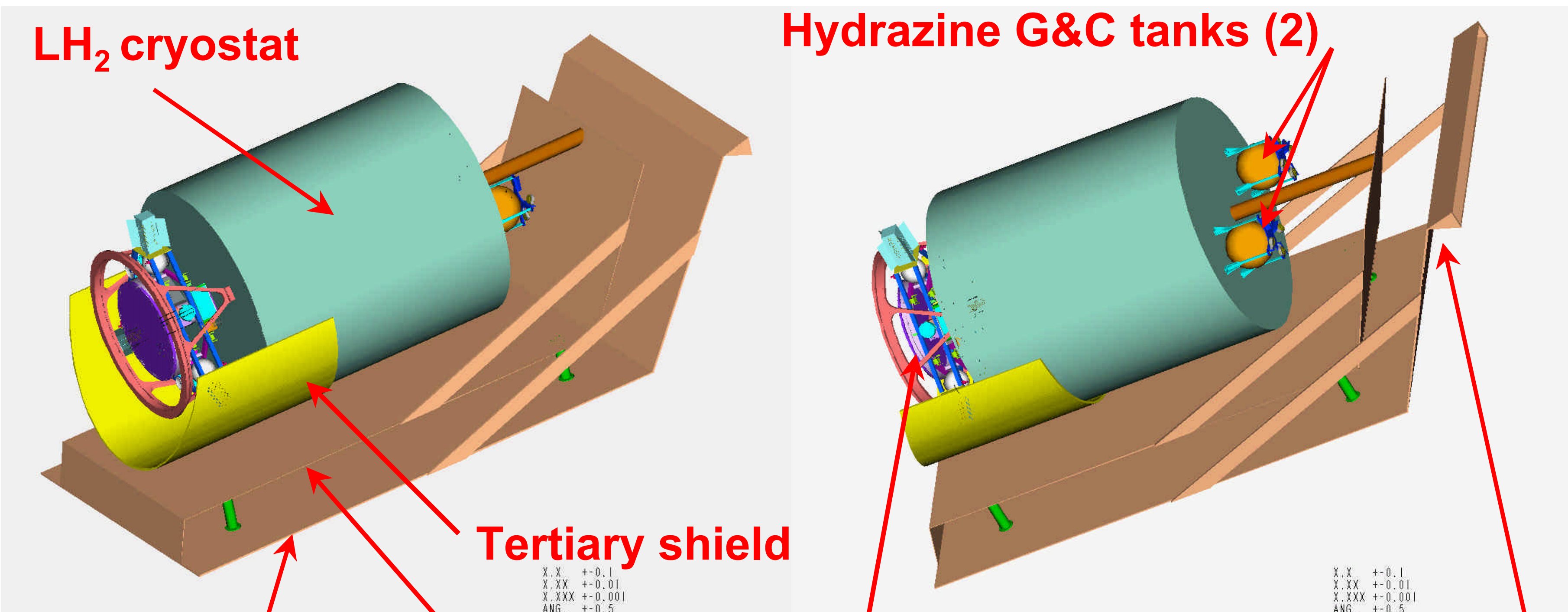


(4) Stack probe and cryostat shield in 5-m shroud

Trades for Propellants and Launch Vehicles

Probe in Pre-perihelion Configuration

(some structure deleted for clarity)



Primary shield/STP exchanger

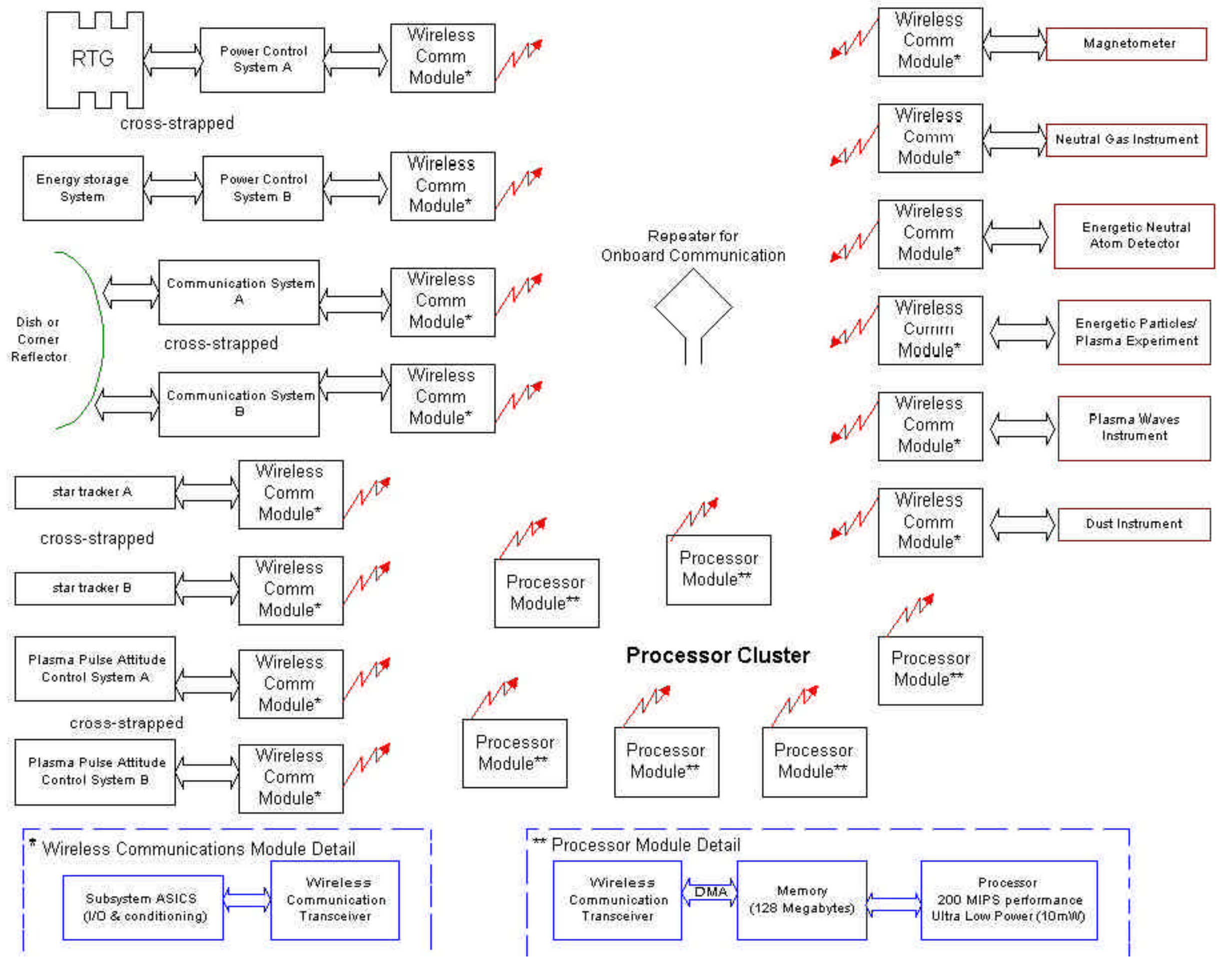
Secondary shield/STP exchanger

Stowed Probe (within adapter)

2D STP propulsion nozzle

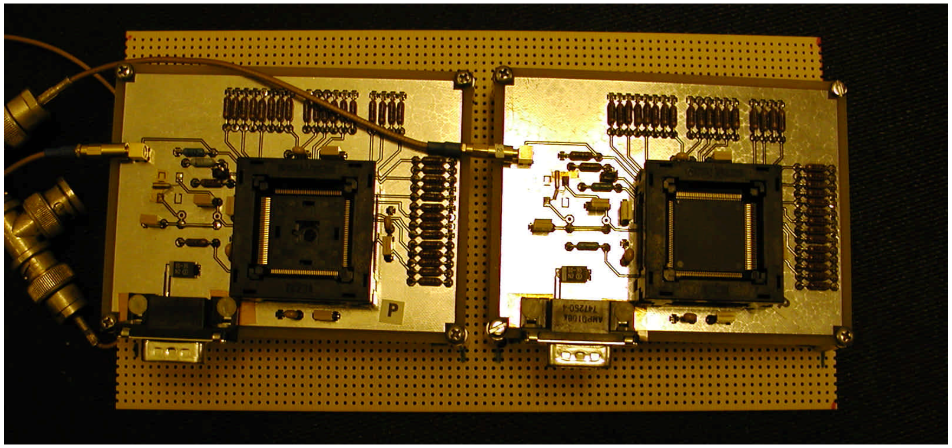
Probe Block Diagram

Perihelion propulsion module is not shown



Architecture Breadboard

- Breadboard test unit ("tabletop spacecraft") will consist of eight ultra low power processors, each configured with two wireless communication transceivers
  - One transceiver communicates with the spacecraft subsystems
  - The other transceiver is used for inter-processor communication
  - This cluster of processors will control and collect or send data to eight spacecraft subsystems
  - Each subsystem has one transceiver
- The number of processors and subsystems is completely arbitrary on an actual interstellar probe
- Photo shows processor test fixture



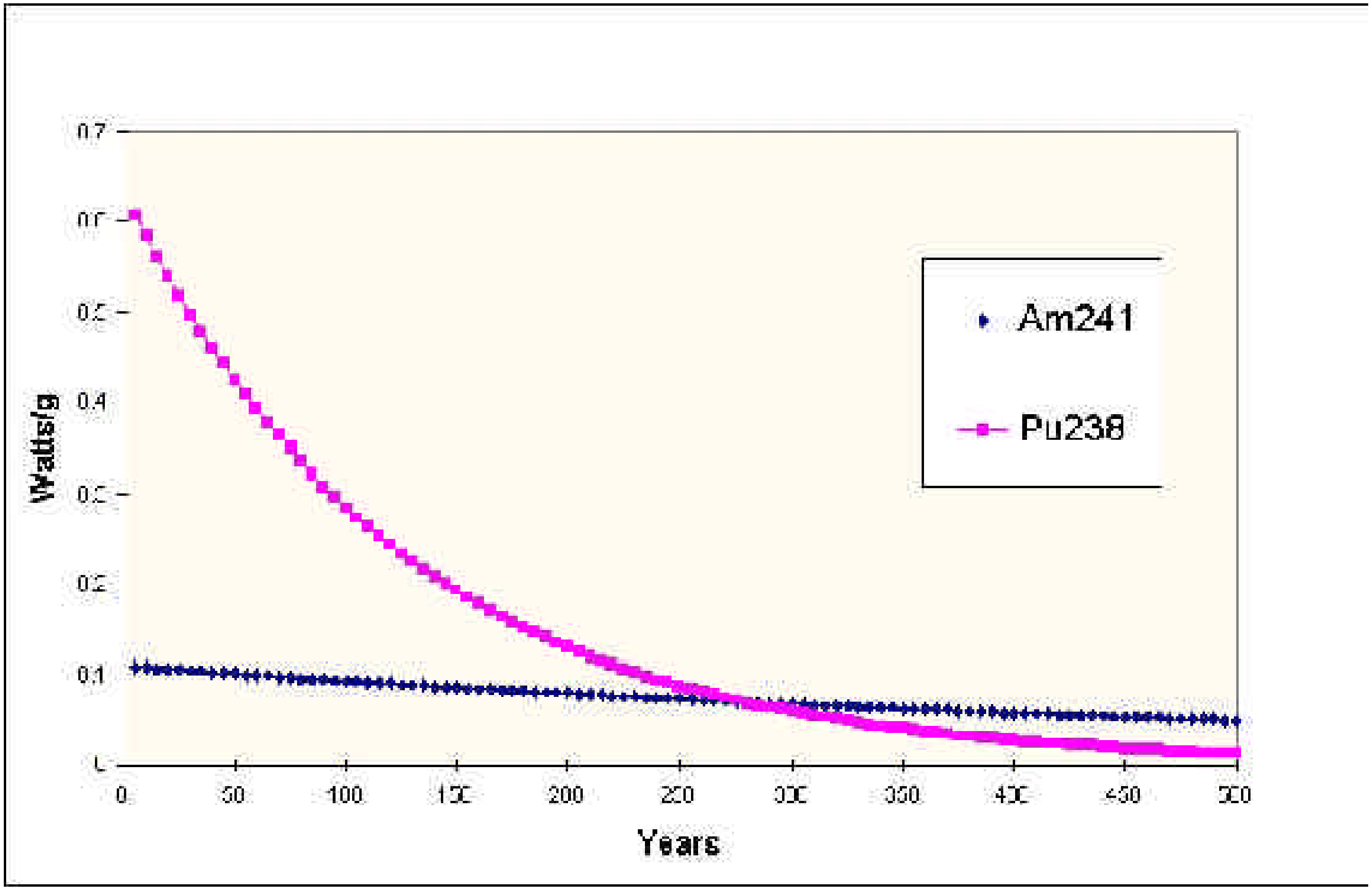
Power System

- Communication and attitude systems operate intermittently and require significant peak power; utilize trickle-charged storage system (capacitor ban)
- RTG based upon multicouples with 4 General Purpose Heat Sources and direct voltage
  - 1 Pu-238 RTG (at 55W after 9.5 years)
  - 2 Am-241 RTGs (at 7.867W each or 15.733 W total)
- Total power after 9.5 years is 70.7 W
- Estimated half life of Pu including multicouples of ~70 yr and ~350 yr for Am
- Power remaining after 50 years is 51.3W and ~6.27W after 500 years (all three RTGs)

Radioisotopes with > 50 yr Half Life

	Isotope	Atomic weight	Alpha energy (MeV)	Half life (years)	P/ρ (Watt/gram)	Notes
1	U-232	232	5.3	72	0.6729	Large gamma-ray background
2	Pu-238	238	5.5	87.74	0.5586	Decays to U-234; long halflife
3	Gd-148	148	3.1828	93	0.4904	Decays to Sm-144 (stable); NO gammas
4	Po-209	209	4.88	102	0.4855	Decays to Pb-205; long halflife
5	Am-242	242	5.2	152	0.2998	Isomeric transition to short-lived state
6	Cf-249	249	5.8	351	0.1407	Decays to Cm-245
7	Am-241	241	5.4	432	0.1100	Decays to Np-237; long halflife
8	Cf-251	251	5.8	900	0.0545	Decays to Cm-247; long halflife
9	Si-32	32	0.21	280	0.0497	beta emitter; decay to P-32 to S-32 (stable)
10	Bk-247	247	5.7	1400	0.0350	Decays to Am-243
11	Ra-226	226	4.78	1600	0.0280	Large gamma-ray background
12	Cm-246	246	5.3	4730	0.0097	Decays to Pu-242; long halflife
13	Pu-240	240	5.1	6537	0.0069	Decays to U-236; long halflife
14	Th-229	229	4.8	7340	0.0061	Decays to Ra-225; chain of short-lived nuclides
15	Am-243	243	5.2	7380	0.0061	Decay product of Bk-247
16	Cm-245	245	5.3	8500	0.0054	Decay product of Cf-249

An RPS Can Provide Centuries of Power for Very Long Missions



Communications Requirements

- **Burst mode of 500 bps from 1000 AU (over 5 light-days) is system requirement**
  - **At 100 AU, electromagnetic waves take 13.9 hours to travel from the spacecraft to Earth**

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 μrad)
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

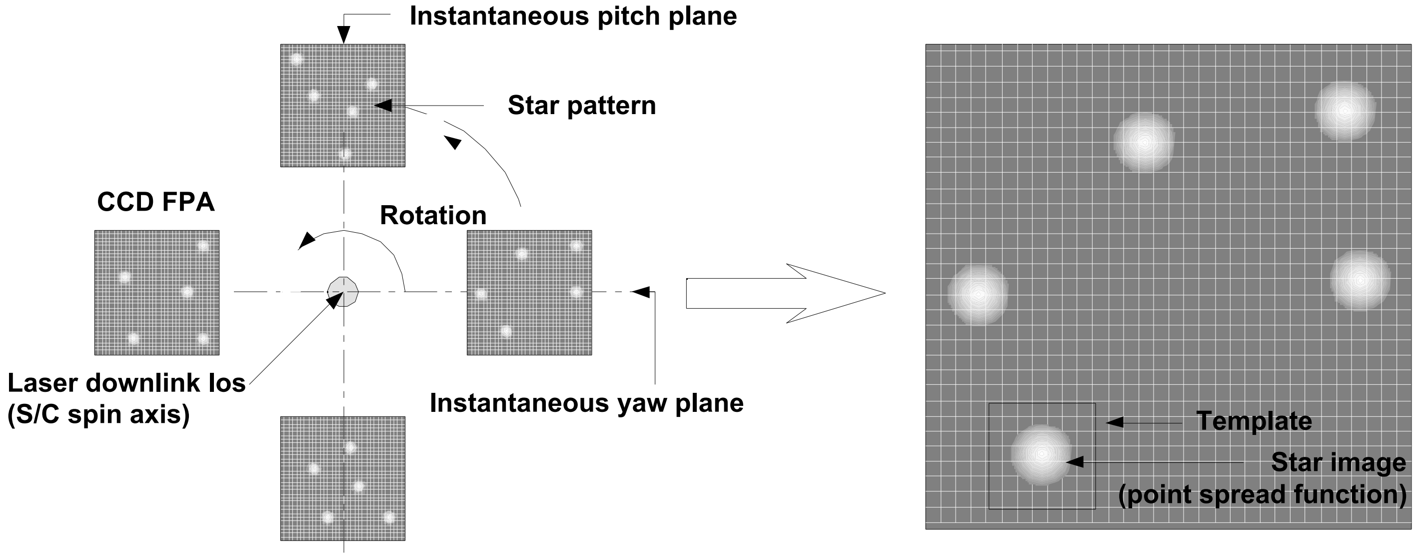
Example System Properties

Property	**Description**
Probe light source	Quantum cascade (QC) laser
Wavelength[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

Laser Communications and Star Tracker System

- **Basic subsystems:**
  - Laser transmitter (two-stage beam expander, 1 meter exit beam)
  - Beam steerer (meso or micro-scale, sub-microradian accuracy)
  - Star tracker (multiple FPA with centroid/correlation algorithms)
  - INS updated via RF uplink clock and emphemeris correction
- **Requirements:**
  - Transmitter: 50 W minimum power, near-IR wavelength, solid state
  - Modulator: 4-ary PPM or OOK, 500 Hz bandwidth
  - Star tracker: 1 megapixel FPA's with 10 mm pixels
- **Structural features:**
  - Integrated FPA, beam steerer, and INS mounted on monolithic composite mini-bench
  - Second stage beam expander uses diffractive quasi-membrane optics
  - Uses Shack-Hartmann array in first stage beam expander for beam-steering feedback
  - Uses piezo-actuated guy-wires to adjust spring-loaded exit aperture

Star Tracker Design Concept



Star Tracker Features

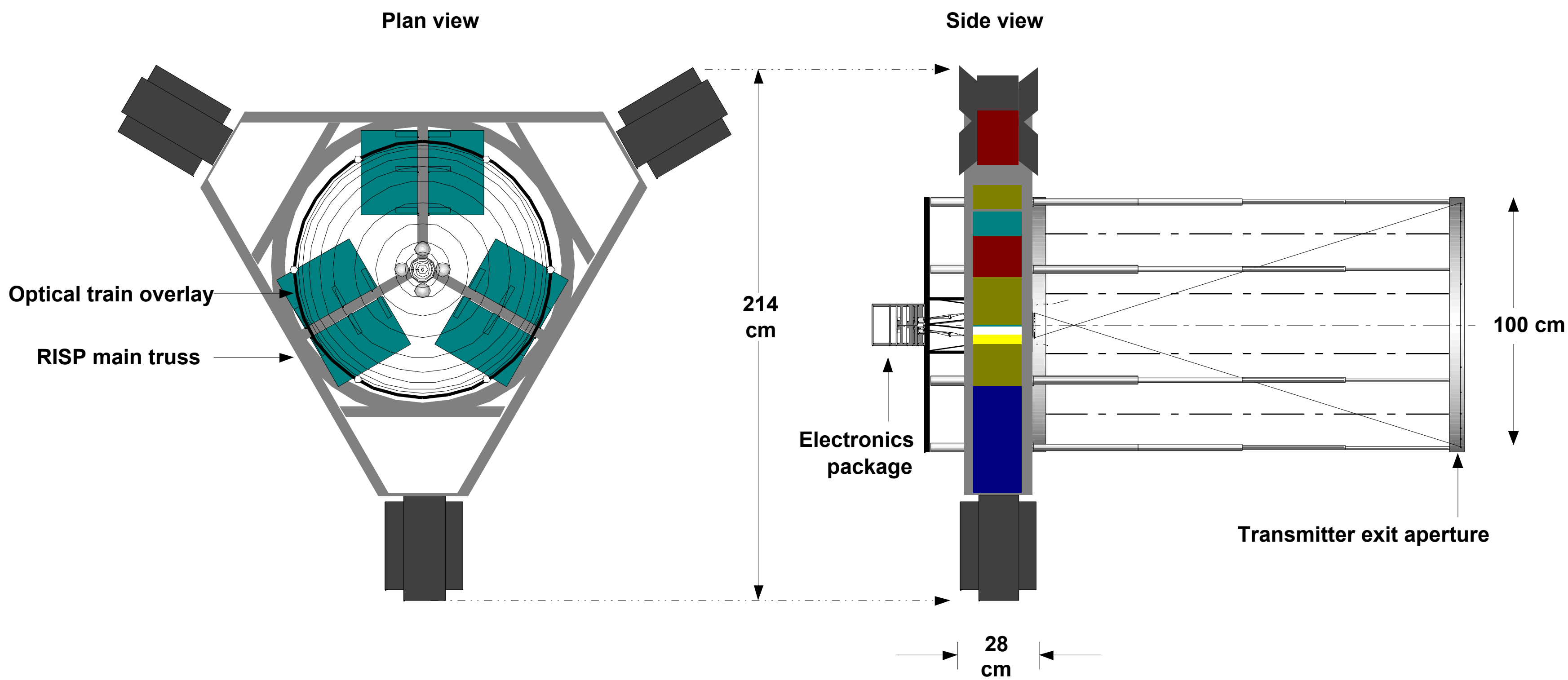
- FPA redundancy can be two, three or four
- Redundancy minimizes ambiguity of star patterns to support "open loop" attitude estimation
- Squnt angle off laser boresight is ~ 7.5 deg*
- FOV is ~ 25 mrad
- IFOV ~ 25 μ rad
- Angle accuracy must be ~ 250 nrad
- Requires minimum SNR ~ 10000
- Star tracker fuses multiple views and inertial measurement unit attitude estimation
- * Squint angle can be unique for each FPA to increase coverage and minimize ambiguity

Optical and FPA error sources:

- Defocus
- Spherical aberration
- Coma
- Astigmatism
- Geometric distortion
- Chromatic aberration
- Motion blur
- Temporal noise
- Fixed pattrern noise

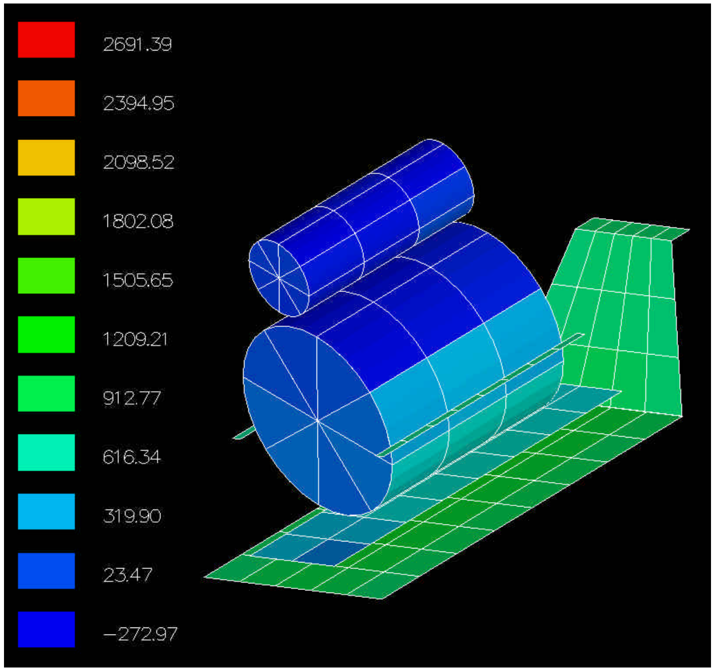
Coma and geometric distortion create bias errors

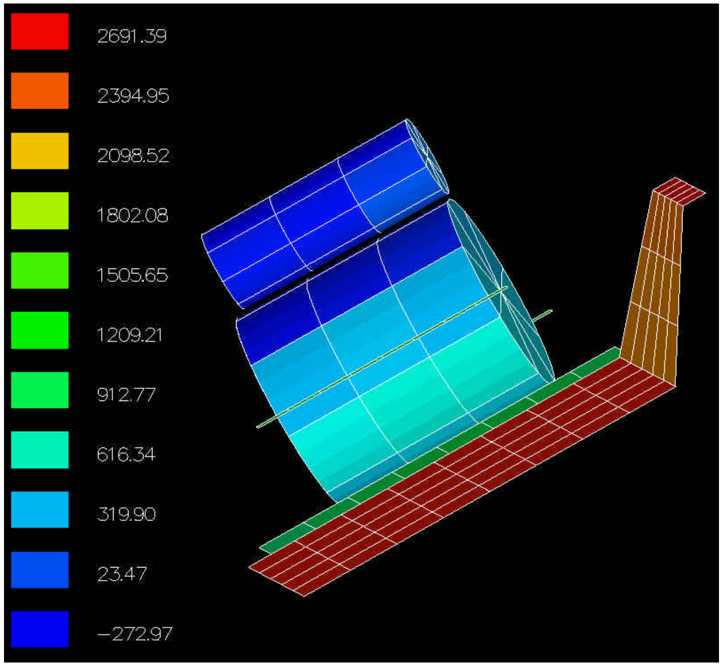
Laser Communication and Star Tracker Overall Opto-mechanical and Electronics Packages Superposed on Basic Spacecraft Structure



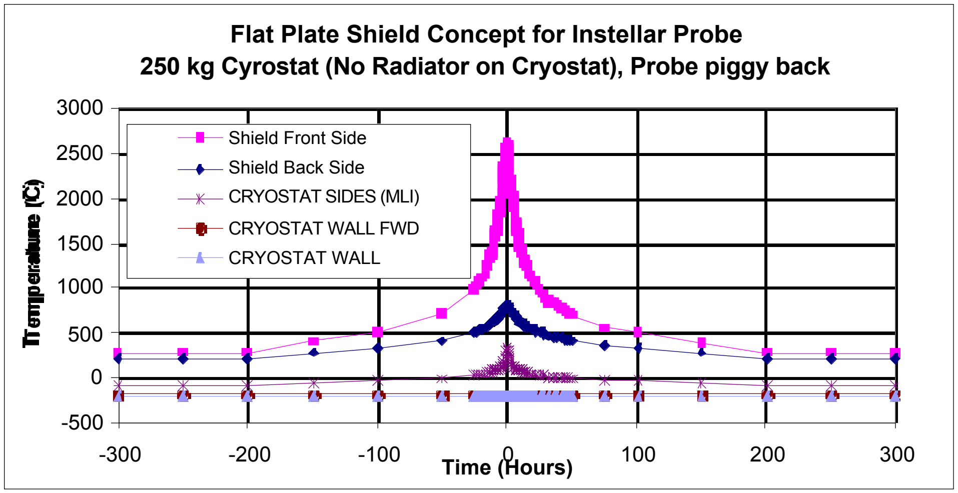
Thermal Constraints Are Met

- Analysis with Thermal Synthesis System (TSS) software
- CC primary shield with 0.85/0.55 α/ε at temperature (2964K)
- ~100 kg of CC aerogel backing on primary shield

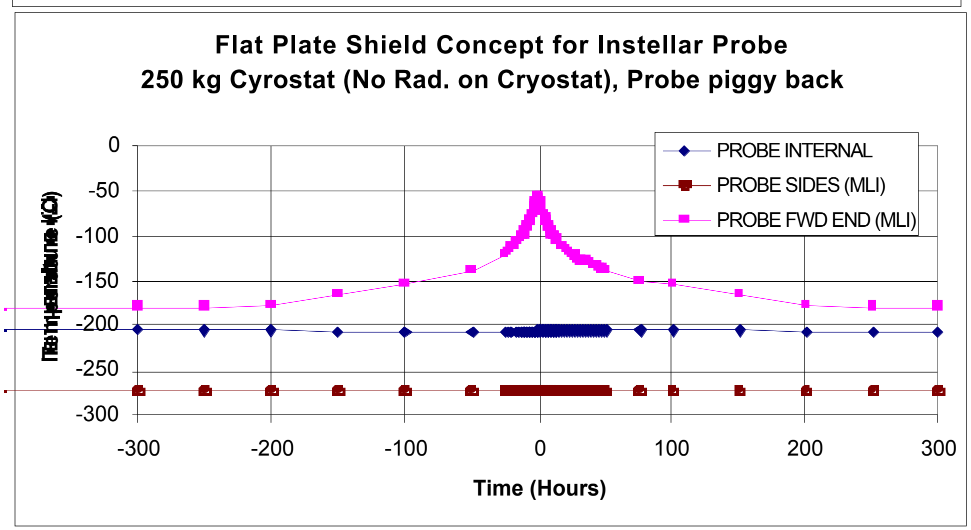




LH_2 Thermally Isolated Until Needed



Overall temperatures



Internal temperatures

Prime Science Period

- Two-way communication established following perihelion maneuver through probe deployment using X-band
- Final guidance and other updates
- Establish lock for optical communications downlink
- 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.

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Accomplishments to Date

- **Finalized probe configuration**
  - Mass estimate by subsystem: 147.15 kg using Be structure
  - Power estimate by subsystem: 19.81 W using ULP
- **Finalized integrated optical communications, attitude, guidance, and control approach**
- **Selection of LH2 over NH_3 as primary STP system propellant**
  - Mass trades based upon higher NH_3 density - lower thermal shield mass - and more massive cryostat/cooling for LH2
  - Higher I_{sp} for LH2 and more packaging room for probe
  - Requirements for heat exchanger coating due to hot propellant erosion of carbon-carbon; options are CVD Re or, possibly, CVD HfC (CTE problem still under study)
- **Identified Am-241 as viable RTG fuel**
  - Extended lifetime trades for lower power level
  - Thermal design changes identified to maximize efficiency

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 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)
- 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
- 2012 Test of Solar Probe performance in perihelion pass
- 2012-2015 Design and launch second generation probe 1000 AU in 50 years
- 2015-2065 Data return from 1000 AU and “beyond the infinite”
- 2030-2040 Design and launch third generation probe with 200 AU/yr goal
- 5450-5500 Data return from Epsilon Eridani system(third generation probe)
- 35,800 CE Second generation probe reaches Epsilon Eridani system

This Step

- 50-kg probe is difficult
- Robust probe with good payload more likely to be ~150 kg, even with new technologies and materials
- Novel propulsion system is key
  - Three-stage Delta III with 50-kg probe leaves only 250 kg for perihelion-burn propulsion system
  - Realism forces more capable launch vehicle (Delta IV 4050H + Star 48)
  - Problem is mass of cryostat and/or active system for multiyear low-mass LH2 storage
  - 20 AU/yr goal may not be realizable

The Next Step ...

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

200 AU yr^{-1}, at which the crossing to Epsilon Eridani will take ~3400 years, the age of the Colossi of Memnon (Amenhotep III - 18th dyn)

using ...

"Low-thrust" fission propulsion
~5 MW of electrical power
(1000 A @ 5 kV)
~16,000 kg of H_2
(10 mg/s for 50 years)
~ 4200 AU travel during "burn"

The stars would be within our reach

Jupiter Gravity Assist

26 October 2012

Ad Astra!