Interstellar Probe

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With input from

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And other study teams

Heliophysics Subcommittee Meeting

11:15 AM – 12:00 Noon

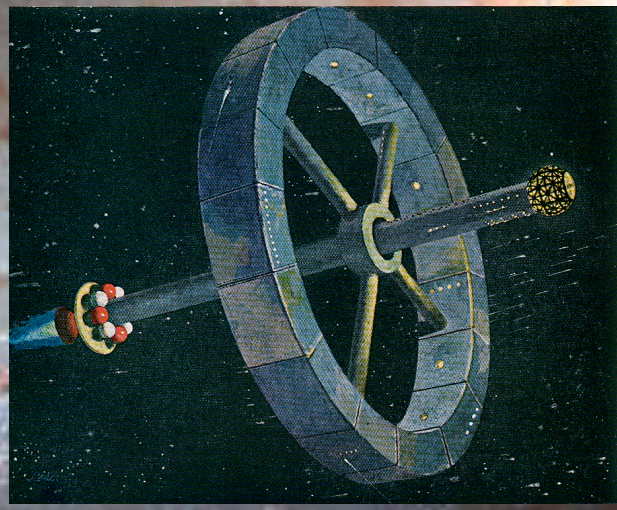
NASA Headquarters MIC 6H41

This is **not** about "Interstellar Travel"

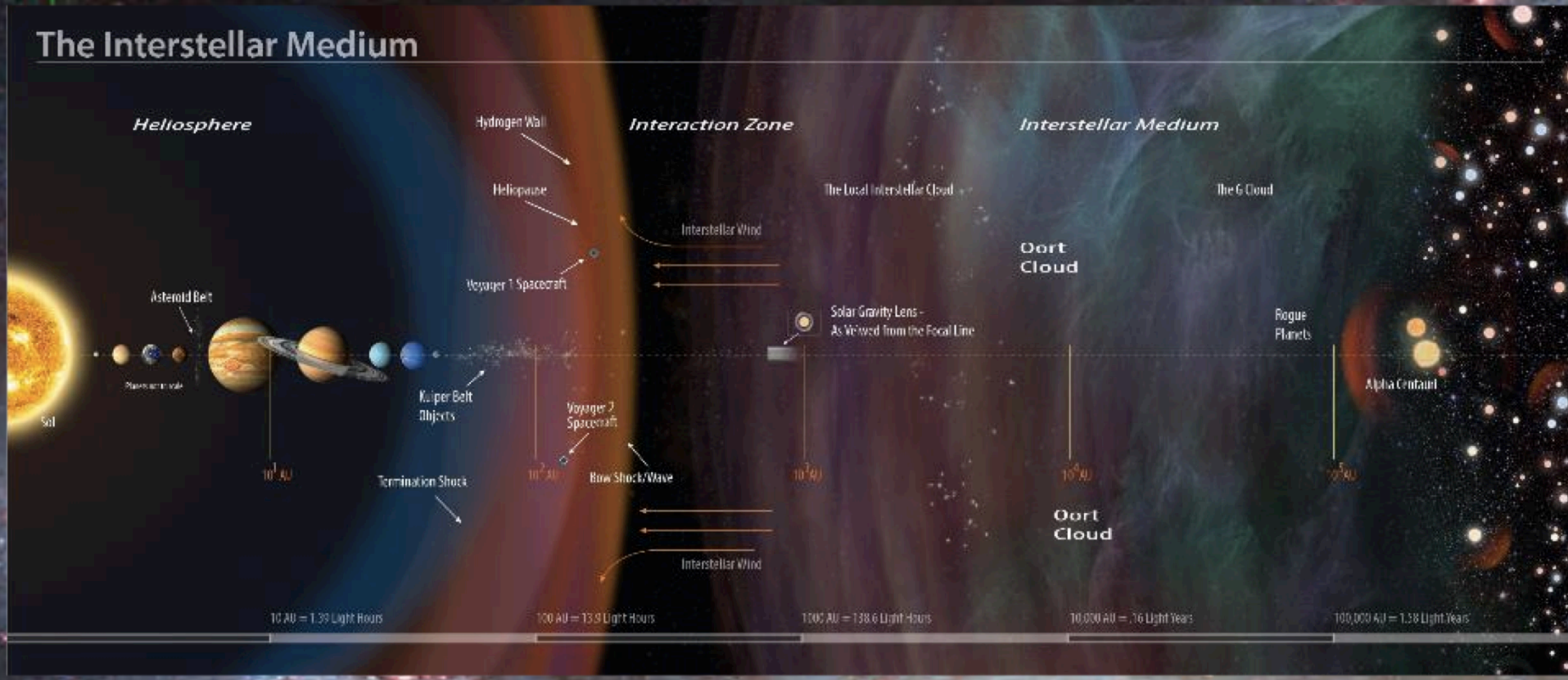
- Robert Goddard "Great Migration" (14 January 1918)
- F. A. Tsander "Flights to Other Planets and to the Moon" (notes, 1920s)
- J. Ackeret Relativistic rocket mechanics (1946)
- E. Sänger Photon rockets (1956)
- W. Peschka Reaching the nearer stars (<25 light years) (1956)
- R. W. Bussard Interstellar fusion ramjets (1960)
- S. V. Hoerner Ultimate limits to space travel (1962)

Or Colonization (!)

- J. D. Bernal "The World, The Flesh, and The Devil" (1929)
- A. G. W. Cameron, ed."Interstellar Communication" (1963)
- Stephen H. Dole "Habitable Planets for Man" (1964)
- Dandridge M. Cole and Roy G. Scarfo "Beyond Tomorrow: The Next 50 Years in Space" (1965)
- Isaac Asimiov "How Far Will We Go in Space?" (1966)
- Robert L. Forward "A Program for Interstellar Exploration" (1976)



It **is** about the The New Frontier in deep space exploration: the Interstellar Medium itself



"Across the sea of space, the stars are other Suns"

Carl Sagan

Heliosphere Concept (1971)

A possible interaction configuration is sketched in Fig. 2. The subsonic plasma beyond the shock forms a boundary shell. Behond this shell lies the interstellar medium.

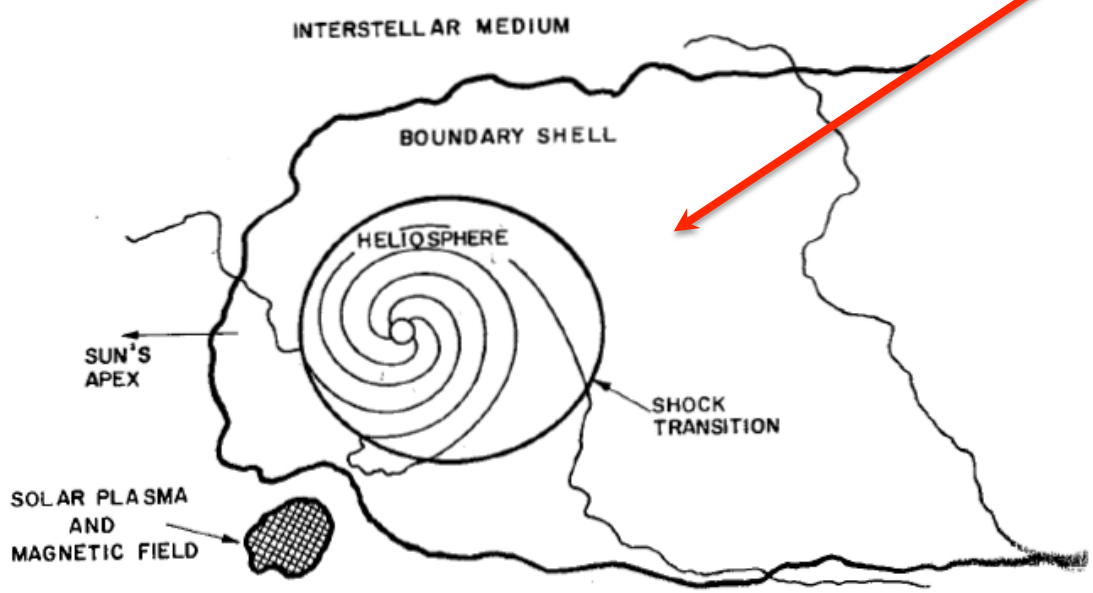


Fig. 2 Illustrative Sketch Showing Possible Interaction Between Interplanetary Medium (the Heliosphere) and the Interstellar Medium

From Dessler and Park (1971)

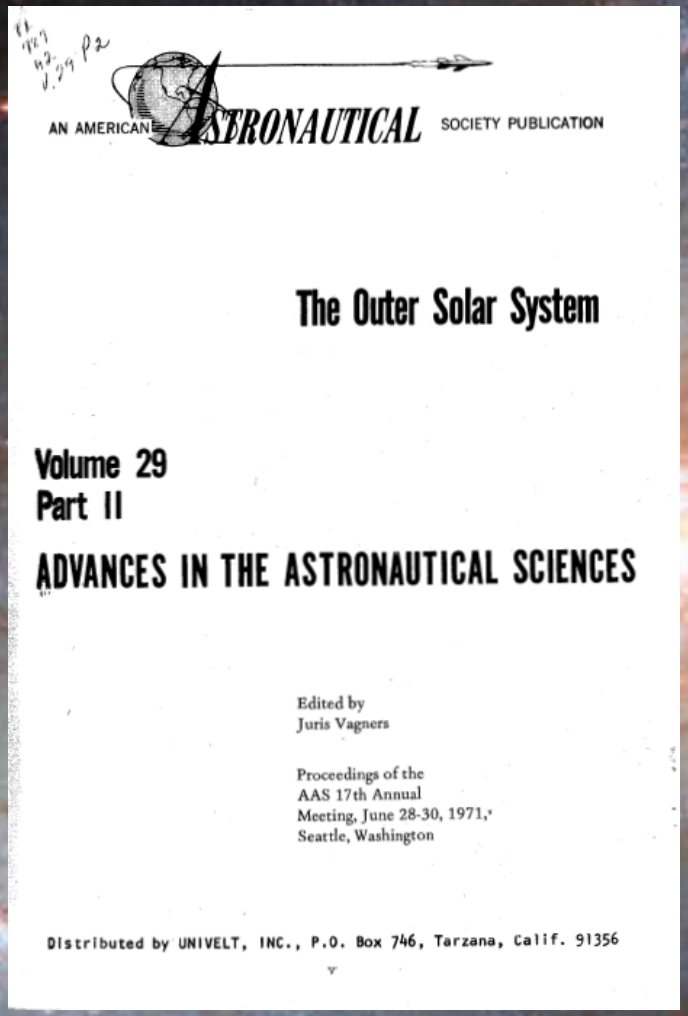
Draws on work by

- Davis (1955)
- Parker (1961, 1963)
- Axford et al (1963)
- Dessler (1967)

17th AAS Meeting in Seattle, Washington, 28 – 30 June 1971

Scientific and technical bases for solar system escape missions were discussed

The forthcoming flights of Pioneers F and G will see the launch from earth of the first spacecraft to leave the solar system. In this paper, we describe the solar wind and how it forms a region of interplanetary space called the heliosphere. **There is little known about how (or even where) the solar wind interacts with the local interstellar medium. Our understanding of the plasma/magnetic-field interaction between the solar wind and insterstellar medium will be placed on a definitive basis by information obtained by the spacecraft that obtain data from penetration of the interaction region**.



AN AMERICAN ASTRONAUTICAL SOCIETY PUBLICATION

The Outer Solar System

Volume 29
Part II

ADVANCES IN THE ASTRONAUTICAL SCIENCES

Edited by
Juris Vagners

Proceedings of the
AAS 17th Annual
Meeting, June 28-30, 1971,
Seattle, Washington

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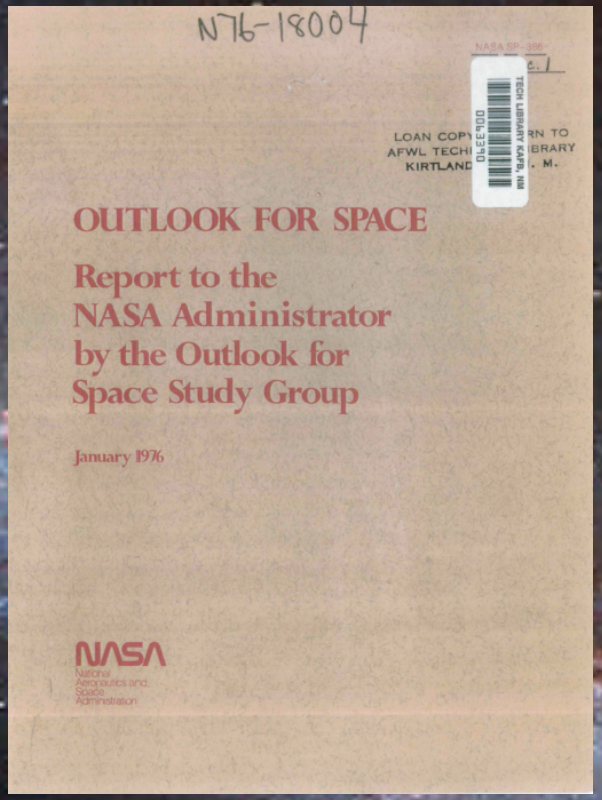
Science Formulation – mid 1970s

- By 1976 A "modest" proposal had been incorporated in the massive NASA *Outlook for Space* report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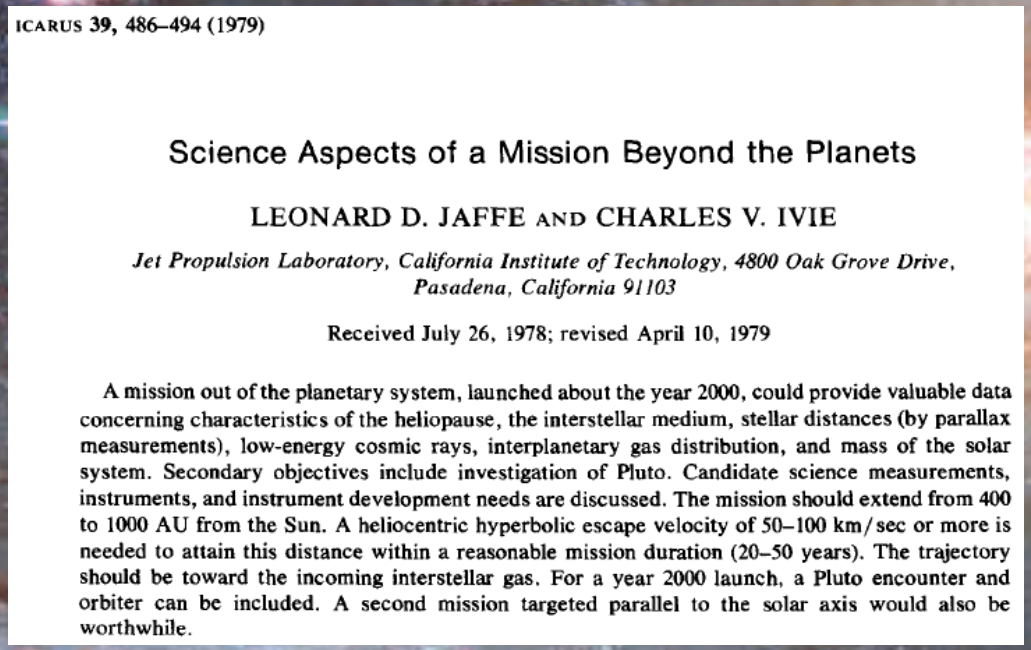
OUTLOOK FOR SPACE

Report to the NASA Administrator by the Outlook for Space Study Group

January 1976

NASA
National Aeronautics and Space Administration

The 1976 – 1977 JPL effort had a significant science driver



ICARUS 39, 486–494 (1979)

Science Aspects of a Mission Beyond the Planets

LEONARD D. JAFFE AND CHARLES V. IVIE

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91103

Received July 26, 1978; revised April 10, 1979

A mission out of the planetary system, launched about the year 2000, could provide valuable data concerning characteristics of the heliopause, the interstellar medium, stellar distances (by parallax measurements), low-energy cosmic rays, interplanetary gas distribution, and mass of the solar system. Secondary objectives include investigation of Pluto. Candidate science measurements, instruments, and instrument development needs are discussed. The mission should extend from 400 to 1000 AU from the Sun. A heliocentric hyperbolic escape velocity of 50–100 km/sec or more is needed to attain this distance within a reasonable mission duration (20–50 years). The trajectory should be toward the incoming interstellar gas. For a year 2000 launch, a Pluto encounter and orbiter can be included. A second mission targeted parallel to the solar axis would also be worthwhile.

An Interstellar Probe Has Been Advocated by the Science Community for Over 35 Years

NASA Studies	National Academy Studies
Outlook for Space, 1976	Physics through the 1990's - Panel on Gravitation, Cosmology, and Cosmic Rays (D. T. Wilkinson, chair), 1986 NRC report
An implementation plan for solar system space physics, S. M. Krimigis, chair, 1985	Solar and Space Physics Task Group Report (F. Scarf, chair),1988 NRC study Space Science in the 21st Century - Imperatives for the Decade 1995-2015
Space Physics Strategy-Implementation Study: The NASA Space Physics Program for 1995-2010	Astronomy and Astrophysics Task Group Report (B. Burke, chair), 1988 NRC study Space Science in the 21st Century - Imperatives for the Decade 1995-2015
Sun-Earth Connection Technology Roadmap, 1997	The Decade of Discovery in Astronomy and Astrophysics (John N. Bahcall, chair)
Space Science Strategic Plan, The Space Science Enterprise, 2000	The Committee on Cosmic Ray Physics of the NRC Board on Physics and Astronomy (T. K. Gaisser, chair), 1995 report Opportunities in Cosmic Ray Physics
Sun-Earth Connection Roadmaps, 1997, 2000, 2003	A Science Strategy for Space Physics, Space Studies Board, NRC, National Academy Press, 1995 (M. Negebauer, chair)
NASA 2003 Strategic Plan	The Sun to the Earth - and Beyond: A Decadal Research Strategy in Solar and Space Physics, 2003
The New Science of the Sun - Solar System: Recommended Roadmap for Science and Technology 2005 - 2035, 2006	Exploration of the Outer Heliosphere and the Local Interstellar Medium, 2004
Heliophysics: THE SOLAR AND SPACE PHYSICS OF A NEW ERA; Recommended Roadmap for Science and Technology 2009–2030, May 2009	Priorities in Space Science Enabled by Nuclear Power and Propulsion, 2006

Keck Institute of Space Studies (KISS), Caltech: Workshops

- The Science and Enabling Technologies for the Exploration of the Interstellar Medium (ISM), Edward C. Stone, Leon Alkalai, Lou Friedman.
- Two workshops held: September 2014, January 2015
- ~ 32 participants
- Final Report, July 2015

3 Study Leads: Caltech/JPL/TPS

1 Great Study Team

Goals of the KISS Workshops

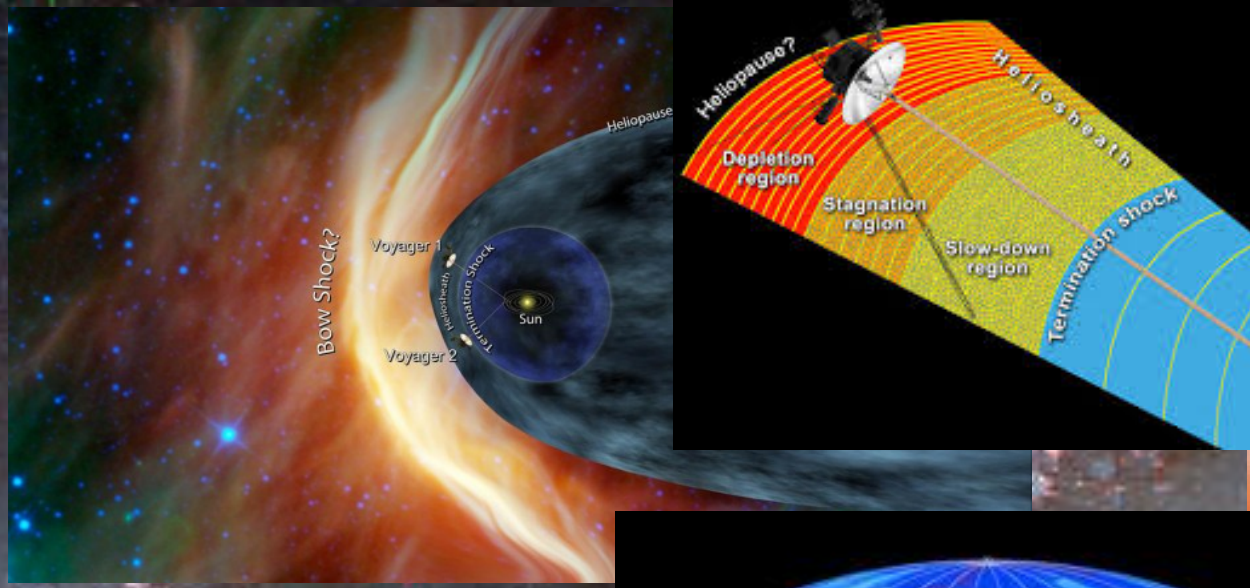
Capability Push:

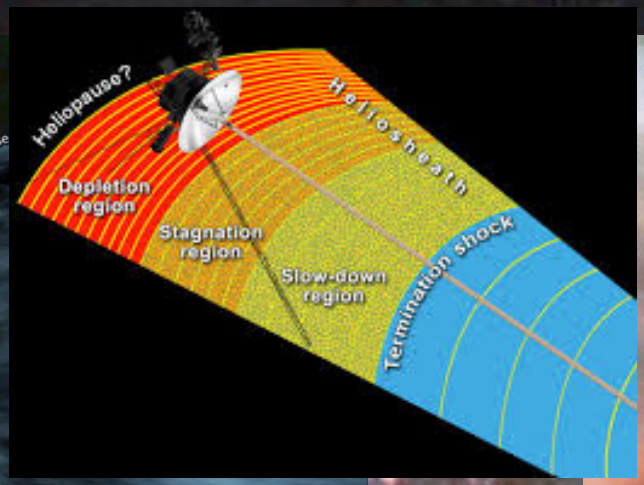
- Can we reach the ISM in 10-15 years, rather than 36 (Voyager 1/2)?
- Can we achieve solar-system escape velocity of > 12 AU/Yr. and venture deep into the ISM, as a first step towards reaching to another star?
  - Voyager 1 ~3.6 AU/Yr.; Voyager 2 ~3.1 AU/Yr.; New Horizons ~ 2.75 AU/Yr.
- Can we build a low power, autonomous robotic systems to survive > 50 years?

Science Pull:

- Compelling science goals in exploring the ISM: 100 – 300 AU
- Compelling science to be done on the way to the ISM.
- Visiting a large KBO

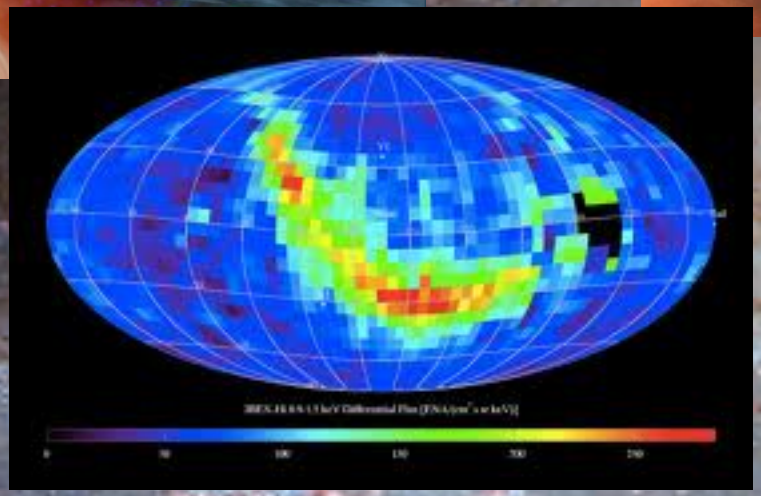
The Heliosphere – and Questions – Now





Astrosphere of LL Orionis (Hubble Space Telescope)

Voyager 1 entering interstellar space?
Differences at Voyager 2
Is there an external bow shock?

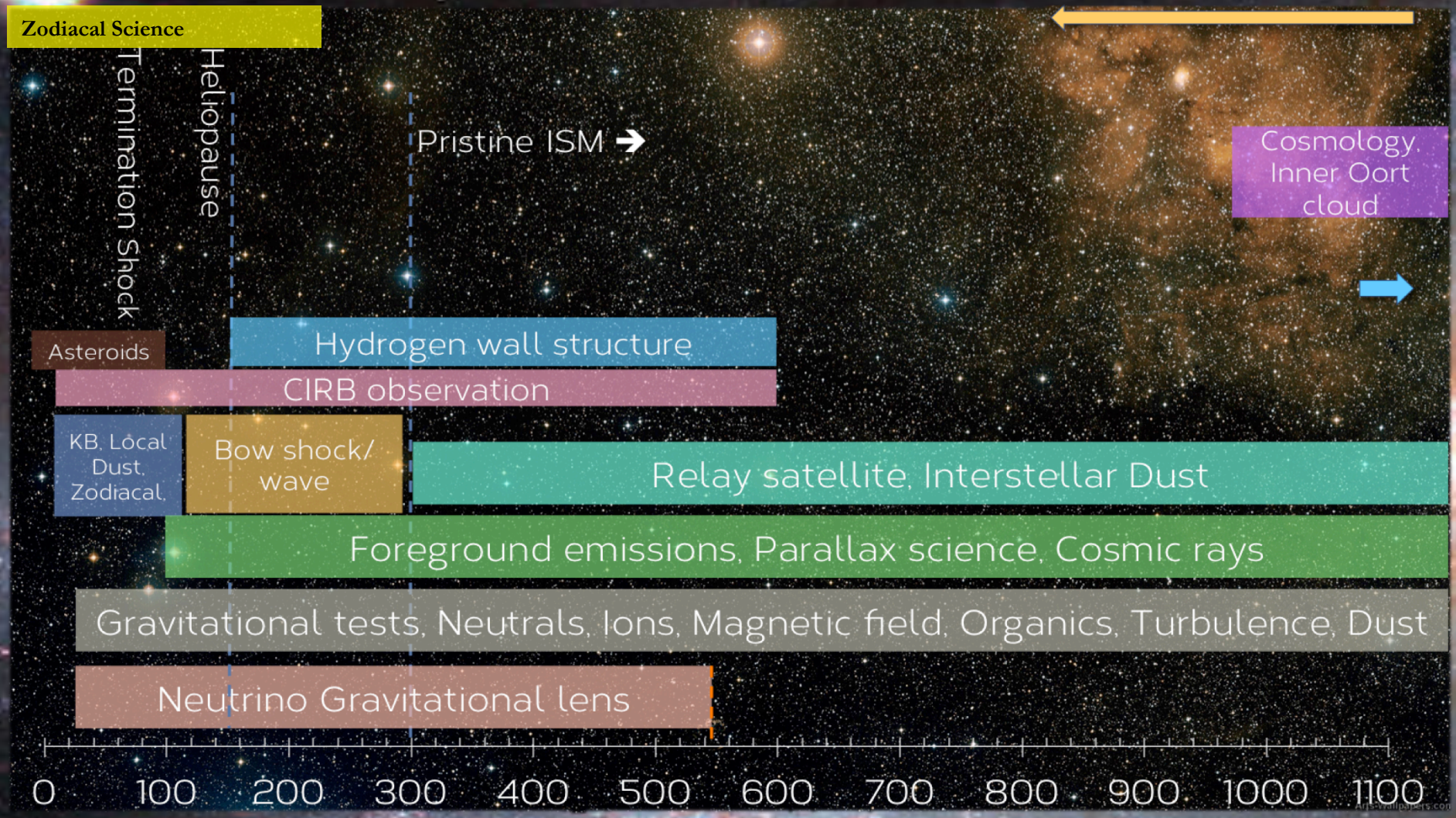


The IBEX ribbon of energetic neutral atoms (ENAs)

Also seen by Cassini

Key Result of 2 KISS Workshops:

"There is compelling science on the way to the ISM, at the ISM, and from the ISM", Stone, Alkalai, Friedman



Distance from the Sun (AU) →

Key Heliophysics Science Questions

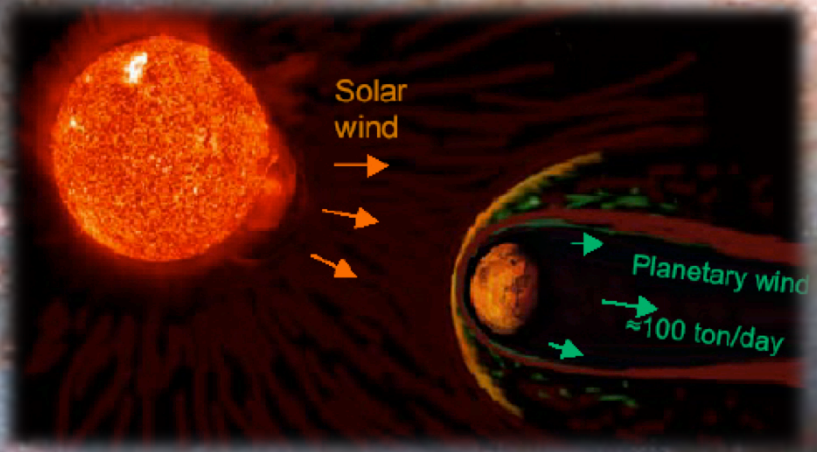
- What are the characteristics of the termination shock, the heliopause and the region in between?
- What is the influence of the interplanetary magnetic field on these structure?
- What are the transport and acceleration processes in these regions?
- How does the distribution functions of the ions and neutrals evolve along the trajectory of the spacecraft?
- Does the solar cycle influence the dynamics of these structures?
- How does the heliosheath shield against cosmic rays and neutral particles?
- and what role does it play in the interstellar-terrestrial relations?

Key Astrophysics Science Questions

- What is the nature of the Zodiacal background?
- What is the physical state of the interstellar medium, its composition and its magnetic field?
- What is the undisturbed interstellar spectrum of galactic cosmic rays?
- What can we learn from the composition and dynamics of interstellar dust grains?

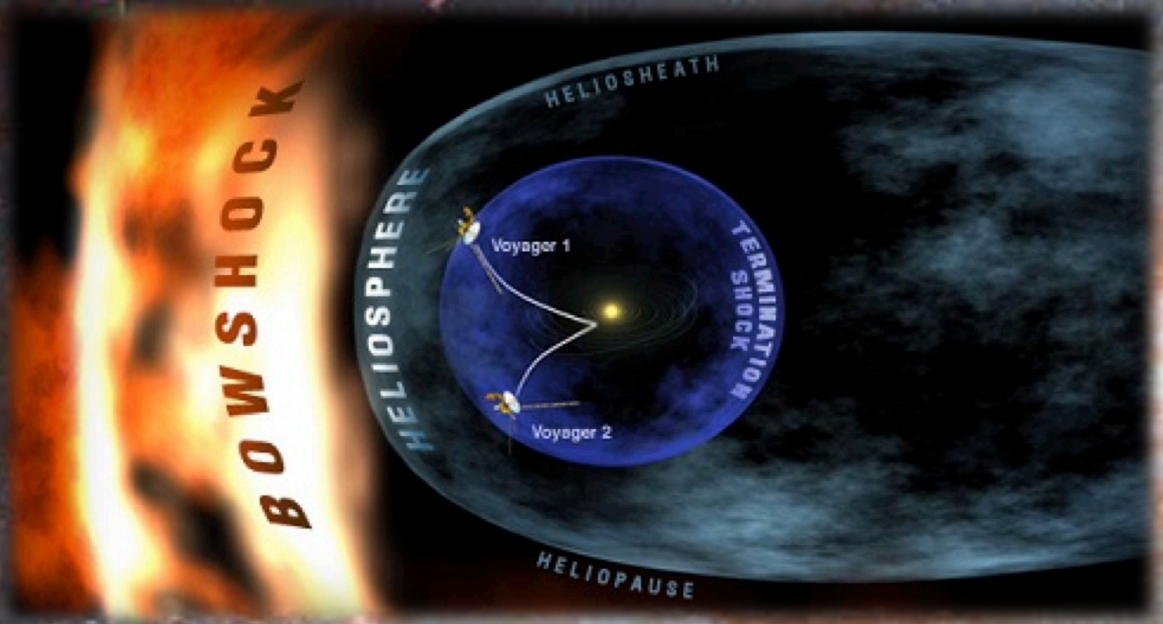
Science on the way to the ISM and within our solar system

- Zodiacal/Cosmic background science
- Solar-wind Science
- Parallax science, radio Science & astrometry
- Science close to the Sun



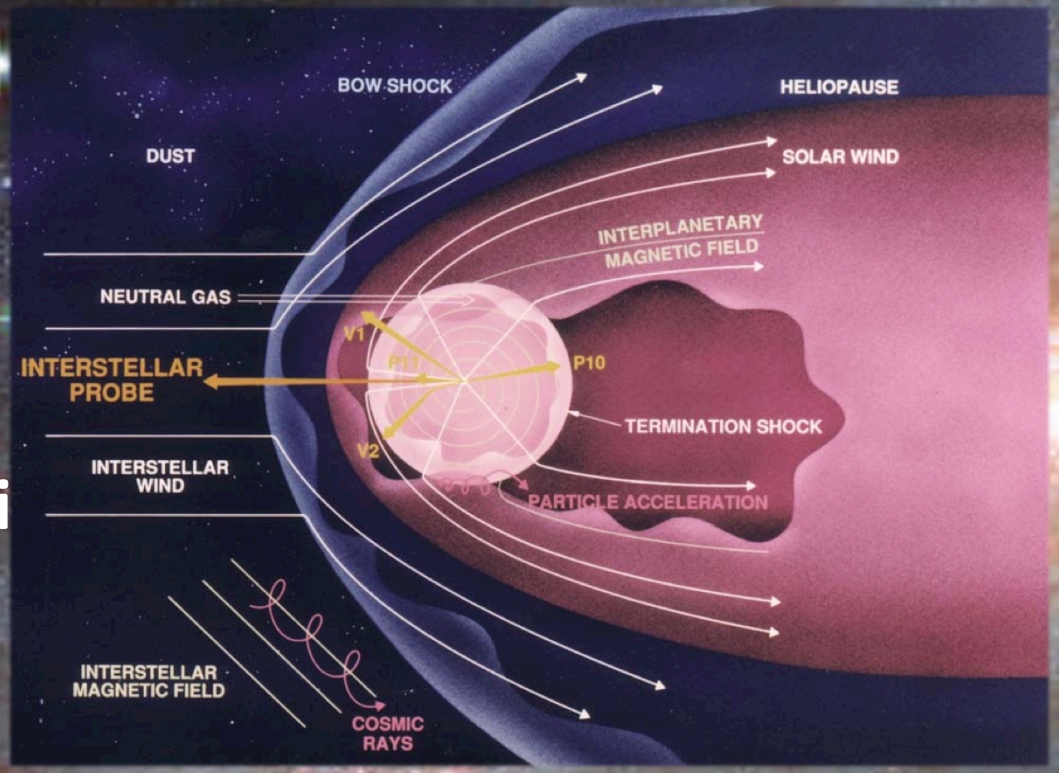
Science of the Local ISM (> 50 AU)

- Termination shock
- Heliopause
- Hydrogen Wall
- Bow-shock
- Bow-wave
- Organics
- Dust composition



Science of the Pristine ISM (>200 AU)

- Interstellar magnetic field: direction, strength and turbulence
- Cosmic-ray science
- Interstellar winds
- Primordial Blackholes
- WIMS (weakly-interacti massive particles)
- Organics
- Dust composition of the Pristine ISM

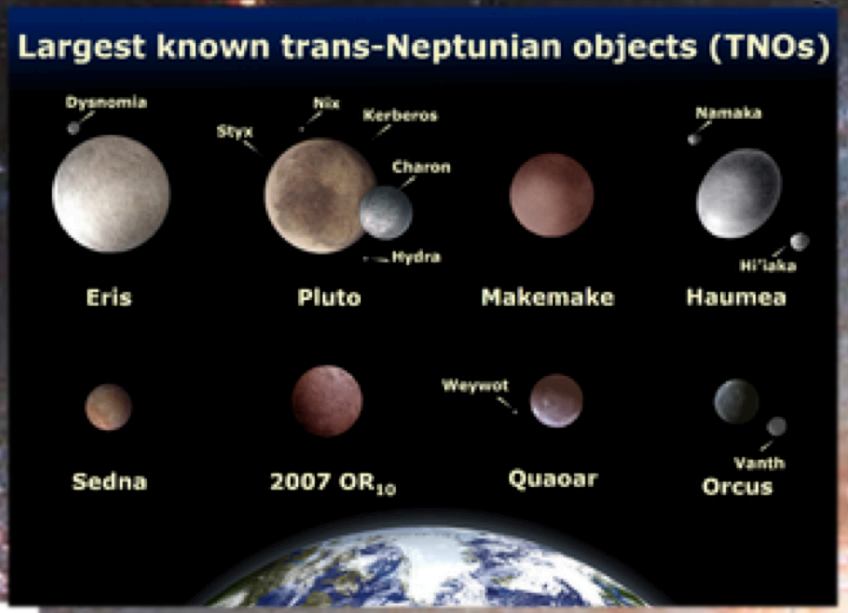


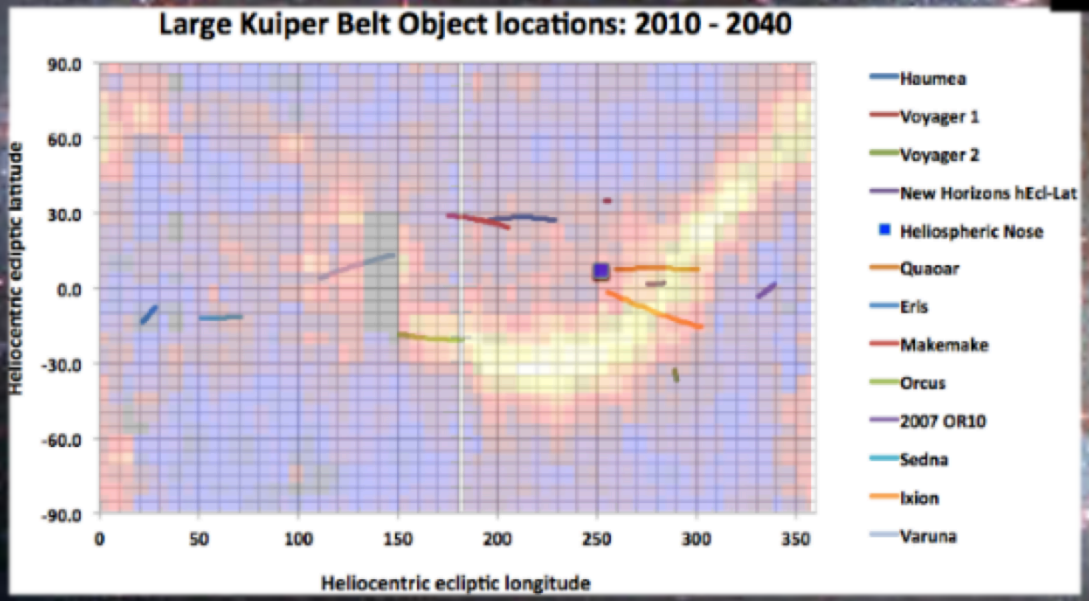
http://interstellar.jpl.nasa.gov/

KBO Science (~ 30-50 AU)

KBO science with very fast flyby

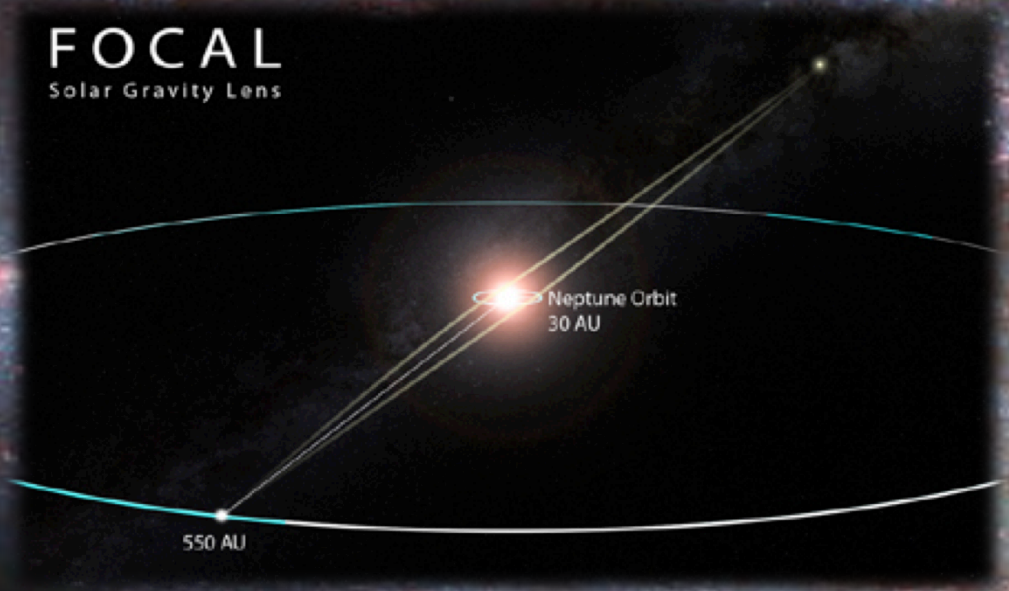
- Flyby speed > 60 km/s
- Cubesat impactor ??

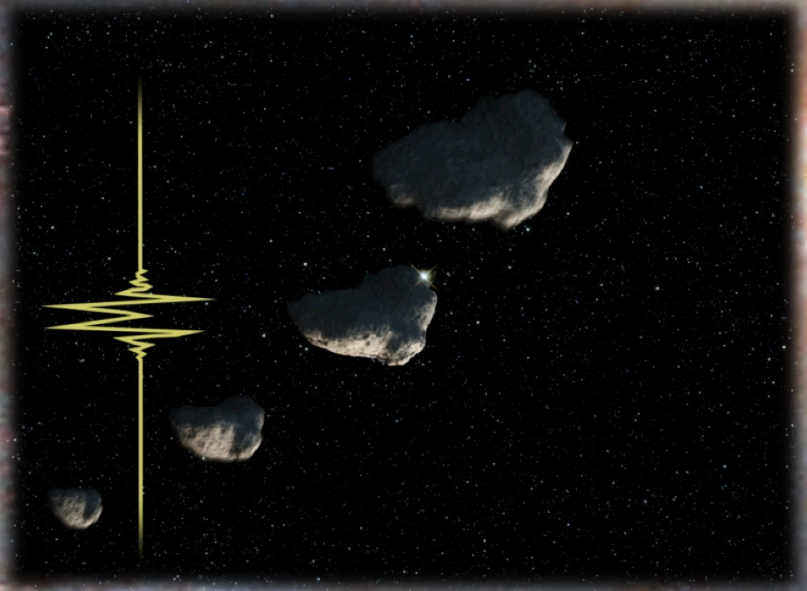




Science from the ISM (>50 AU)

- Radio Science
- Solar gravity lens focus (550 AU and beyond)
- Exoplanets and KBO detection detection





Taking a first step towards another star:

Explore the local environment first!

Science Goals

From ISP STDT 1999:

1. Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our Galaxy and the Universe;
2. Explore the influence of the interstellar medium on the solar system, its dynamics, and its evolution;
3. Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment;
4. Explore the outer solar system in search of clues to its origin, and to the nature of other planetary systems.

Shortened version (McNutt):

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

Interstellar Probe Instrument Payload

(from Mewalt et al., 2000)

TABLE 1. Strawman Instrument Payload

Instrument	**Additional Candidates**
Magnetometer	Kuiper Belt Imager
Plasma and Radio Waves	New Concept Molecular Analyzer
Solar Wind/Interstellar Plasma/Electrons	Suprathermal Ion Charge-States
Pickup and Interstellar Ion Composition	Cosmic Ray Antiprotons
Interstellar Neutral Atoms	
Suprathermal Ions/Electrons	
Cosmic Ray H, He, Electrons, Positrons	**Resource Requirements**
Anomalous & Galactic Cosmic Ray Composition	• Mass: 25 kg
Dust Composition	• Bit Rate: 25 bps
Infrared Instrument	• Power 20 W
Energetic Neutral Atom (ENA) Imaging	
UV Photometer	

Science Traceability Matrix

(2005 Interstellar Vision Mission)

Science Questions	Interstellar Probe Science Objectives	Objective Questions	Science Measurement Objectives	Required Instruments	Analysis Product	Science Result
3rd Interstellar Probe Science and Technology Definition Team Mtg, 17-19 May 1999, JPL	**From NASA's Interstellar Probe Science and Technology Definition Team Report**		**THIS WORK**	**THIS WORK**	**THIS WORK**	
What is the nature of the nearby interstellar medium?	Explore the interstellar medium and determine directly the properties of the interstellar gas, the interstellar magnetic field, low-energy cosmic rays, and interstellar dust	How does the composition of interstellar matter differ from that of the solar system?	Elemental and isotopic abundances of significant species	PLS, EPS, CRS	Interstellar medium composition	**Composition differential between the solar system and current local interstellar medium**
		What constraints do the interstellar abundances of ^{2}H and ^{3}He place on Big Bang and chemical evolution theories?	^{2}H, ^{3}He, and ^{4}He abundances in the interstellar medium	CRS - LoZCR		
		Is there evidence for recent nucleosynthesis in the interstellar medium?	Isotopic abundances of "light" elements	CRS		
		What is the density, temperature, and ionization state of the interstellar gas, and the strength and direction of the interstellar magnetic field?	Bulk plasma properties, composition, and ionization state and vector magnetic field in the interstellar medium	MAG, PLS	Thermodynamic and physical state of the very local interstellar medium (VLISM)	**Physical state of the VLISM**
		What processes control the ionization state, heating, and dynamics of the interstellar medium?	Charge state, electron properties, Ly-a flux, neutral component properties	PLS, LAD, NAI, ENA	Energy inputs in the VLISM	
		How much interstellar matter is in the form of dust and where did it originate?	Dust flux, composition, pickup ion composition (from sputtering)	CDS, (PWS), PLS	Neutral matter assay for the VLISM	
		How much greater are cosmic ray nuclei and electron intensities outside the heliosphere, and what is their relation to galactic gamma ray and radio emission?	Cosmic ray ion and electron energy spectra; low frequency radio emissions	CRS, PWS	Low-energy galactic cosmic rays	
		What spectrum of 10-100 micron galactic infrared and Cosmic Infrared Background Radiation is hidden by emission from the zodiacal dust?	Infrared spectral measurements from 10 to 100 microns	Not measured	IR absorption by solar system dust	
How do the Sun and galaxy affect the dynamics of the heliosphere?	Explore the influence of the interstellar medium on the Solar System, its dynamics, and its evolution	What is the size and structure of the heliosphere?	Detect heliospheric boundaries from their plasma, field, and radio signatures	MAG, PWS, PLS, EPS, LAD, ENA	Heliospheric spatial scales	**Structure and dynamics of the heliosphere in the upwind direction**
		How do the termination shock and heliopause respond to solar variations and interstellar pressure?	*In situ* plasma and field measurements on the time scale of a fraction of a solar rotation (~days)	MAG, PLS	Heliospheric temporal variably	
		How does the interstellar medium affect the inner heliosphere and solar wind dynamics?	Pickup ions and anomalous cosmic rays, high energy electrons within the heliosphere	PLS, EPS, CRS	Spatial and temporal variability of the interstellar medium properties	**Effects of the VLISM on the heliosphere**
		What roles do thermal plasma, pickup ions, waves, and anomalous cosmic rays play in determining the structure of the termination shock?	Thermal plasma, pickup ions, wave, and anomalous cosmic rays properties on the scale of the scale of c/w_{pi}	PLS, EPS, PWS, CRS - AGCR	Inputs from heliospheric interaction into the solar wind	
		What are the properties of interstellar gas and dust that penetrate into the heliosphere?	Thermodynamic properties and composition of neutral gas; dust flux and composition	NAI, ENA, CDS	Properties of interstellar gas and dust in the outer heliosphere	
What is the structure of the heliosphere?	Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment	Does the heliosphere create a bow shock in the interstellar medium?	Plasma and magnetic field measurements at ion-inertial scale length from the heliosheath into the interstellar medium (telemeter changes)	MAG, PWS, PLS	Determination of whether the solar system produces an external shock	**Impact of the solar system on the local composition and thermodynamic properties of the VLISM**
		What is the relation of the hydrogen wall outside the heliopause to similar structures and winds observed in neighboring systems?	Neutral atom and plasma ion distribution functions from the heliopause through the heliosheath	NAI, ENA, PLS	Structure and properties of the predicted hydrogen wall	
		How do the Sun and heliosphere influence the temperature, ionization state, and energetic particle environment of the local interstellar medium? How far does the influence extend?	Particle properties from thermal plasma to galactic cosmic rays from inside the heliosphere at regular intervals though the heliospheric structure and into the interstellar medium	NAI, ENA, PLS, EPS, CRS	Penetration of heliosheath properties into the VLISM	
		How does particle acceleration occur at the termination shock and at other astrophysical shocks?	Ion and electron measurements from thermal plasma to low-energy cosmic rays on scales small compared with the shock passage time by the spacecraft	PLS, EPS, CRS - Autonomous burst mode for instruments as appropriate	Characterization of particle acceleration at the termination shock	
How did matter in the solar system and interstellar medium originate and evolve?	Explore the outer Solar System in search of clues to its origin, and to the nature of other planetary systems	Is there structure in the Zodiacal cloud due to dynamical processes associated with solar activity, planets, asteroids, comets, and Kuiper Belt objects?	Plasma and dust measurements on time scales of the solar rotation period	PLS, CDS, (PWS)	Structure and dynamics of the Zodiacal dust cloud in the outer heliosphere	**Properties and dynamics of bulk matter in the outer solar system and VLISM**
		What does the distribution of small Kuiper Belt objects and dust tell us about the formation of the solar system?	Dust and pickup ion spatial distribution and composition and composition variation with distance from the Sun	CDS, PLS, EPS, (PWS)		
		How does the structure of the Zodiacal dust cloud impact infrared observations of the galaxy and searches for planets around other stars?	Infrared flux from near IR to at least ten's of microns	Not measured	Quantified extinction from Zodiacal dust	
		What are the origin, nature, and distribution of organic matter in the outer solar system and the interstellar medium?	Dust composition, pickup ions from C, N, O	CDS, PLS, EPS, (PWS)	Identification of *in situ* organic materials or fragments in the heliospheric boundary regions and/or VLISM	

CubeSat Plasma and Energetic Particle Instruments – (*from M. Desai, SWRI)*

Payload	FC	SIS	SIT	MERIT	EIS	REPT
Measurement type	Solar Wind ions	Supra-thermal Ions	Ions	Electrons and protons	Electrons and Ions	Electrons and Ions
Composition	Protons & alphas	Protons & alphas	H, He, C, N,O, Ne, Mg, Si, S, Fe		H, He, C, N, O, Ne, Mg, Si, S, Fe	H, He, heavy ions
Energy range	0.2-5 keV	3-70 keV/Q	30 keV-4 MeV/n	Electrons: 5 keV-10 MeV; Protons 200 keV-100 MeV	Electrons: 100 keV-4 MeV; Ions: 1-50 MeV/n	Electrons: 100 keV-4 MeV; Ions: 2-40 MeV/n
FOV	±45°	~20° x 270°	±4°	±45°	±40°	±45°
Power (W)	1.9	4.5	2-3	1.04	2	1.04
Mass (g)	500	1200	~1000	1100	500	1100
Volume	0.5 U	1.5 U	1 U	0.9 U	0.4 U	0.9 U
Prototype	Yes	Yes		Yes		Yes
Similar instruments	WIND/ SWE/FC	Wind/STICS	WIND/ STEP	N/A	STEREO/ LET	STEREO/ HET
Institution	SwRI	SwRI	SwRI	GSFC/SwRI	GSFC/SwRI	GSFC
TRL	5	6	3	6	3	9

Comparison of 1999 and Cubesat Instruments

Disclaimer: Includes only instruments for which minaturized versions have been proposed, not flown

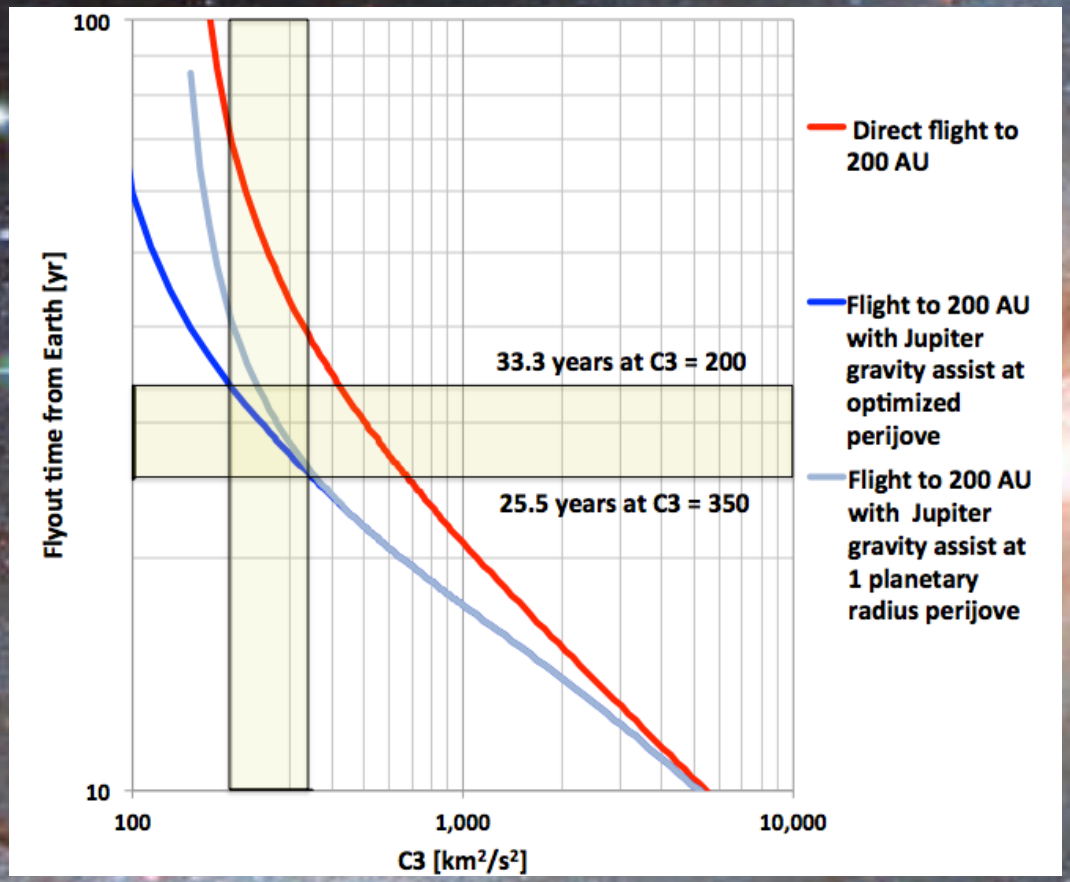
	1999 NASA ISPSTD Report		Miniaturized Versions		
Instrument	Mass (kg)	Power (kW)	Mass (kg)	Power (kW)	Vol (U=10 cm cube)
Magnetometer	0.5	0.5	0.436	0.004	0.5U
Plasma Waves/Radio	0.5	0.8	0.5	0.002	0.25
Solar Wind/ISM Plasma/Electrons	3.5	2.0	0.5	0.0019	0.5
Pickup and Interstellar Ion Composition	5.0	4.0	1.2	0.0045	1.5
Suprathermal Ions/Electrons	1.5	1.5	1.2	0.0045	1.5
Cosmic Ray H, He, (H, He @ 3 to 130 MeV)	2.4	1.5	1.6	0.003	1.3
Subtotals	13.4	10.3	5.436	0.0199	5.05

Interstellar Probe Instrument Resources and Requirements

THIS WORK	IIE Team Consensus Payload							Mission and Spacecraft Requirements	Data Product
Material Measured	Acronym	Instrument	Mass (kg)	Power (W)	Acquisition data rate (bps)	Capabilities	Implementation	THIS WORK	THIS WORK
Fields	MAG	Magnetometer	8.81	5.30	130.00	2- three-axis fluxgate magnetometers; do one sample per day from each magnetometer (onboard processing from multiple samples per spacecraft roll period which is	65 bits/sample x number of samples per day x number of sensors; inboard and outboard fluxgate magnetometers mounted on 5.1 m, self-deployed	Magnetically clean spacecraft	**B**-field vectors
	PWS	Plasma wave sensor	10.00	1.60	65.00	Three 20-m self-supported antennas; measure E-field vectros up to 5 kHz; no search coils (no B-field components)	From Voyager: 115,000 kbps -> 12.5 kilosamples per second with a 14 bit A/D. Collect 2048 samples and do onboard FFT- frequency of processing limited by	Antenna at least ~20m length	**E**-field power spectra
Plasma and suprathermal particles	PLS	Plasma	2.00	2.30	10.00	Plasma ions and electrons from the solar wind, interstellar wind, and interaction region; thermal, suprathermal, and pickup component properties and composition	Mount perpendicular to spin axis; need clear FOV for a wedge 360° around by ~±30°	Clear FOV in direction to Sun, clear FOV in direction anti-Sun; equipotential spacecraft	Ion and electron distribution function; composition
Solar energetic particles through galactic cosmic rays	EPS	Energetic particle spectrometer	1.50	2.50	10.00	TOF plus energy measurements give composition and energy spectra; ~20 keV/nuc to ~5 MeV total energy for ions in 6 pixels; electrons ~25 keV to ~800 keV	Mount perpendicular to spacecraft spin axis; clear FOV of 160° x 12° wedge; on-board processing with magnetometer output to get pitch-angle distributions fordownlink	Clear FOV	Ion and electron pitch angledistributions functions; composition
	CRS - ACR/GCR	Cosmic-ray spectrometer: anomalous and galactic cosmic rays	3.50	2.50	5.00	Energy Range on ACR end (stopping particles) H, He: 1 to 15 MeV/nuc Oxygen: ~2 to 130 MeV/nuc Fe: ~2 to 260 MeV/nuc Energy Range on GCR end Electrons: ~0.5 to ~15 MeV P, He: 10 to 100 MeV/nuc stopping 100 - 500 MeV/nuc penetrating Oxygen	Measure ACRs and GCRs with 1 > Z > 30: double-ended telescope with one end optimized for ACRs and the other for GCRs. It would also measure penetrating particles as is done on Voyager so that both ends need to have clear FOVs. GCR end FOV = 35° ACR en	Clear FOV	Differential flux spectra by composition
	CRS - LoZCR	Cosmic-ray spectrometer: electrons/positrons, protons, helium	2.30	2.00	3.00	Energy Range: positrons: 0.1 to 3 MeV electrons: 0.1 to 30 MeV gamma-rays: 0.1 to 5 MeV H: 4 to 130 MeV/nuc He: 4 to 260 MeV/nuc	FOV = 46° full cone Geometry Factor = 2.5 cm2sr Measurement technique DE X E (e-, H, He) annihilation (e+) Dröge, W., B. Neber, M. S. Potgieter, G. P. Zank, and R. A. Mewaldt, A cosmic ray dectector for an interstellr probe, pp. 471-474, in "The Outer H	Clear FOV	Differential flux spectra
Neutral material	CDS	Cosmic dust sensor	1.75	5.00	0.05	Same capabilities as the student dust counter (SDC) on New Horizons	Mount within 5° of ram direction; sesnor area/FOV of 30 cm x 50 cm must not be obscurred	Clear FOV in ram direction	Dust particle mass and limited composition
	NAI	Neutral atom detectror	2.50	4.00	1.00	Measure neutral H and O at >10 eV/nucleon incoming from interstellar medium [10 eV/nuc ~44 km/s; incoming neutrals are at ~25 km/s with respect to the	Single pixel; mount looking into ram direction; conversion-plate technology	Clear FOV in anti-Sun (ram) direction	Neutral distribution functions
	ENA	Energetic neutral atom imager	2.50	4.00	1.00	Views 0.2 to 10 keV neutral atoms, 1 pixel;	~6° x 6° FOV, mount with sensor looking perpendicular to spacecraft spin axis	1-axis scanner perpendicular to spin axis	Energetic neutral atom energy flux
Photons	LAD	Lyman-alpha detector	0.30	0.20	1.00	Single-channel/single-pixel photometer (at 121.6 nm) similar to those on Pioneer 10/11 (but without the 58.4 nm channel)	Mount perpendicular to nominal spin axis; need clear field of view (~4° x 4°); average over azimuthal scan provided by spacecraft motion	1-axis scanner perpendicular to spin axis	Lyman alpha flux
			35.16	**29.40**	**226.05**				

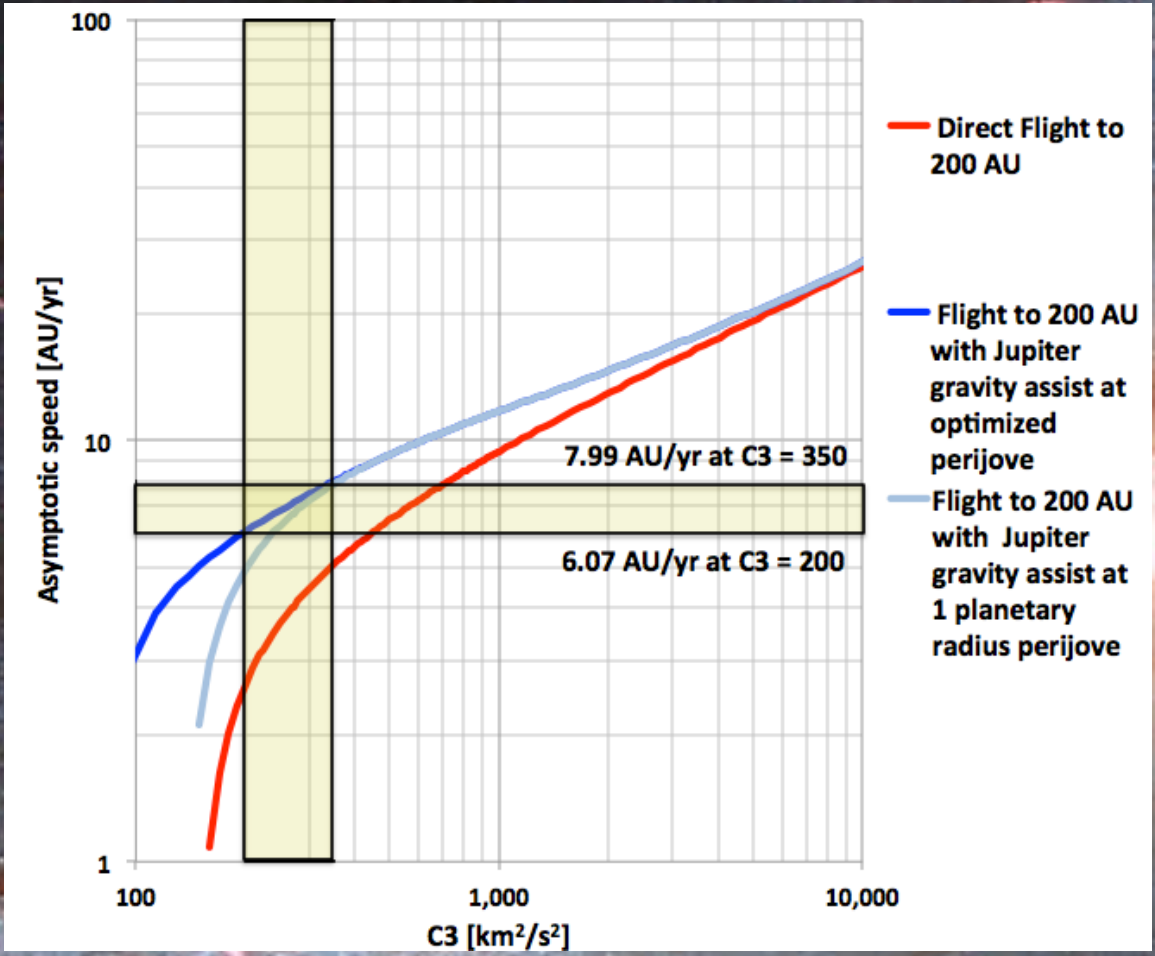
Physics Limits - Distance

- Transit times from Earth to 200 AU
  - Ballistic trajectories both with and without Jupiter gravity assists
- Optimized gravity assist cuts transit time by factor >2 for C3 < 350 km^2/s^2
- Voyager 1
  - 129.5 AU (18 light hours)
  - 37 years en route
  - C3 ~100 km^2/s^2
  - Jupiter and Saturn assists



Physics Limits - Speed

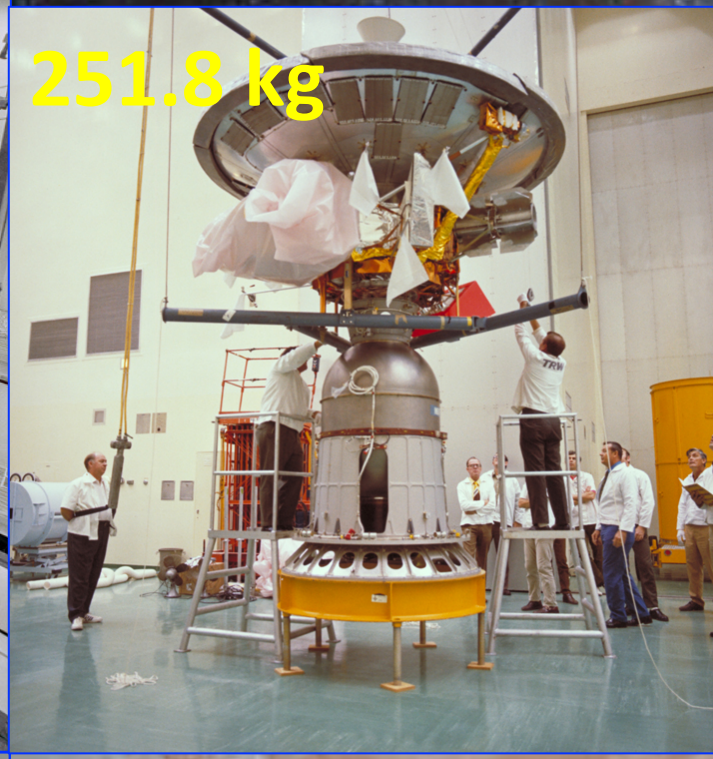
- Voyager 1 is the fastest object leaving the solar system
  - Speed is 3.6 AU per year (17 km/s)
- Twice that speed is 7.2 AU/yr (34 km/s)
  - Achieved for a launch C3 of 278 km^2/s^2



Prototype Examples

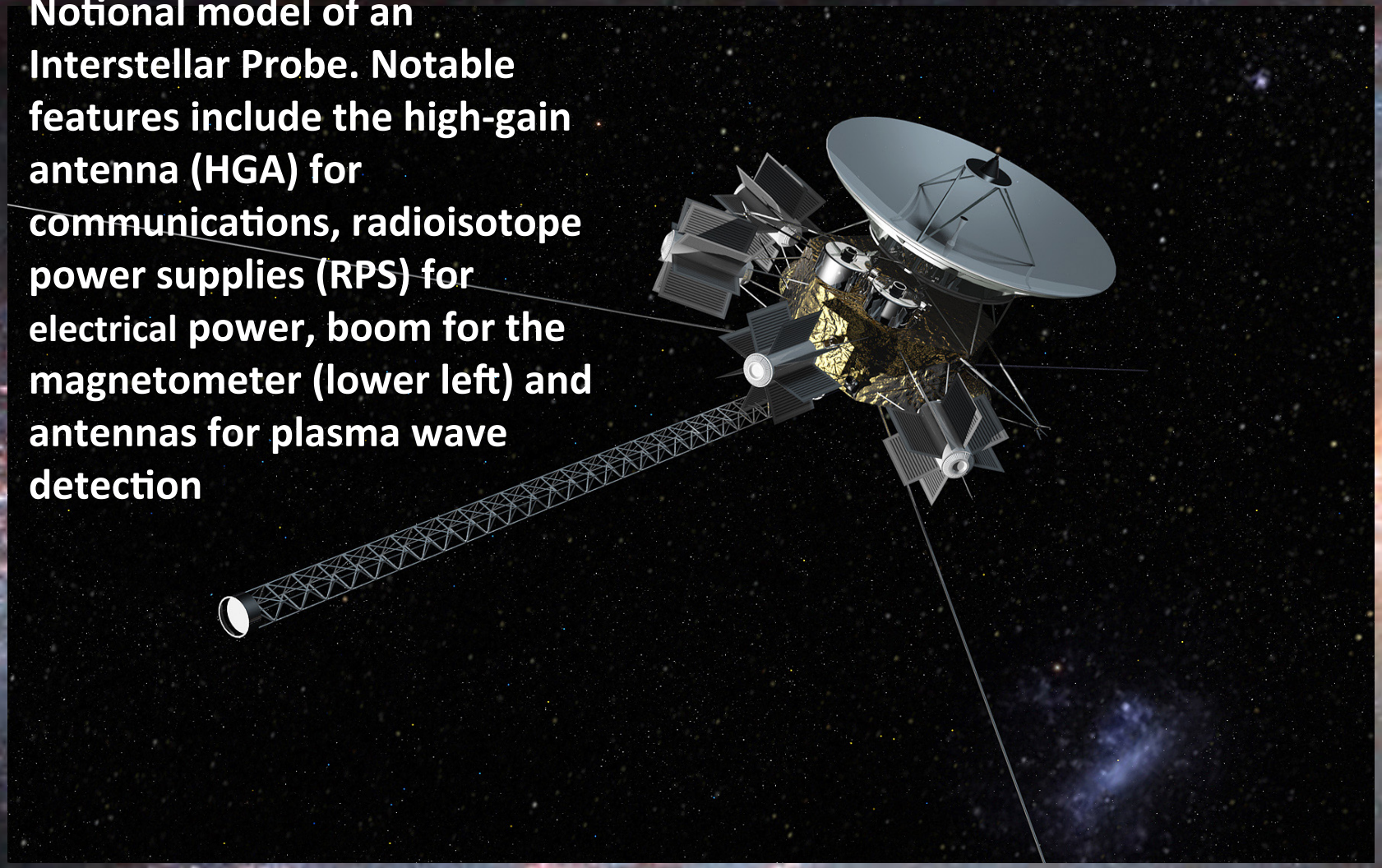
The Pluto/New Horizons spacecraft and upper stage system inside the Payload Hazardous Servicing Facility

Ulysses spacecraft and upper stage system being transferred into its payload canister at the Vertical Processing Facility



Pioneer 10 spacecraft and its STAR 37 kick stage after delivery to Kennedy Space Center on 26 February 1972.

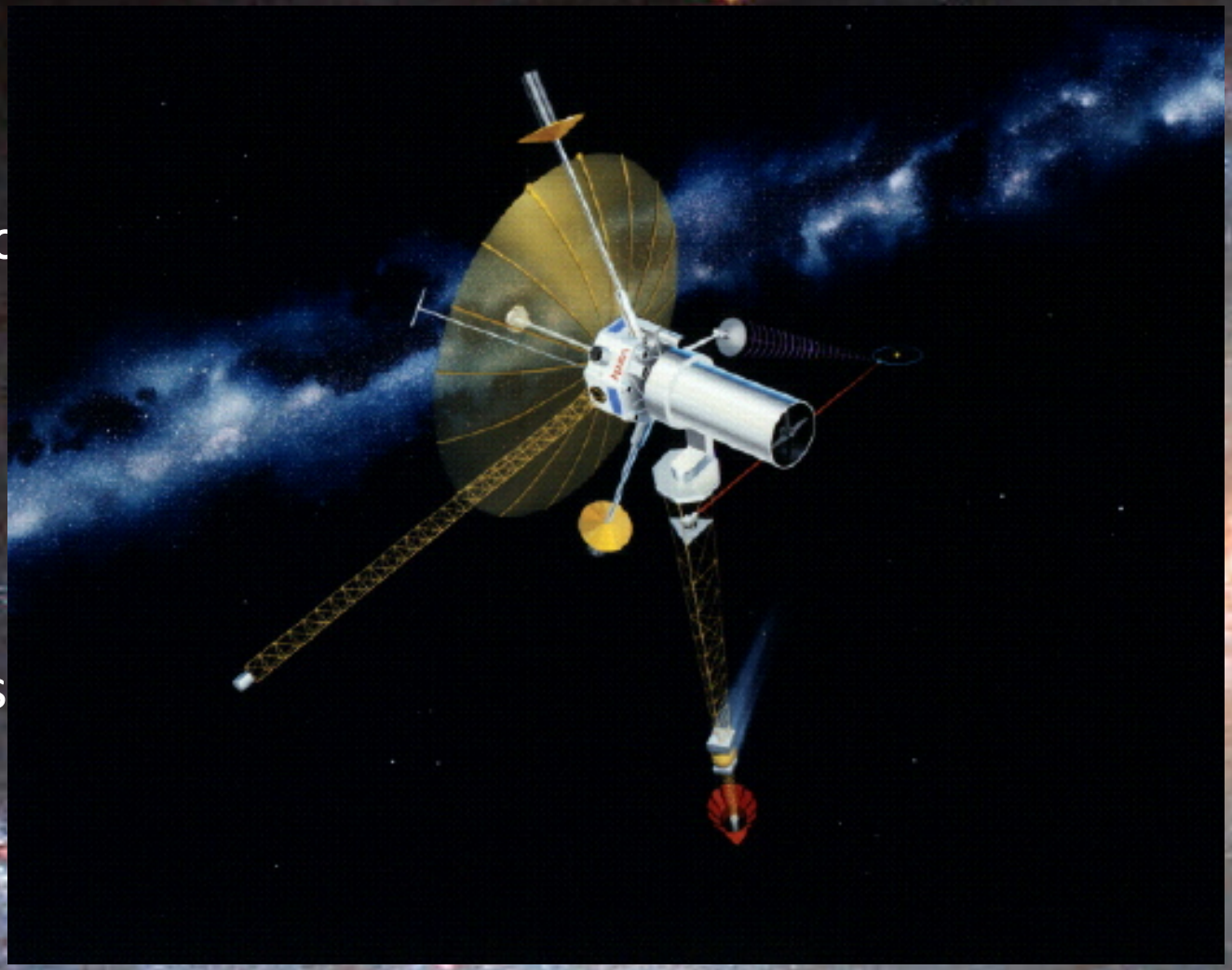
Interstellar Probe



Notional model of an Interstellar Probe. Notable features include the high-gain antenna (HGA) for communications, radioisotope power supplies (RPS) for electrical power, boom for the magnetometer (lower left) and antennas for plasma wave detection

Large NEP Systems?

- Thousand AU Mission (TAU) (Nock, 1987)
- Nuclear Electric to 1000 AU
  - 1 MWe
  - 12.5 kg/kW specific mass
- 60 mt launch mass
- 10 mt dry mass
- 40 MT Xe
- 1000 AU in 50 years



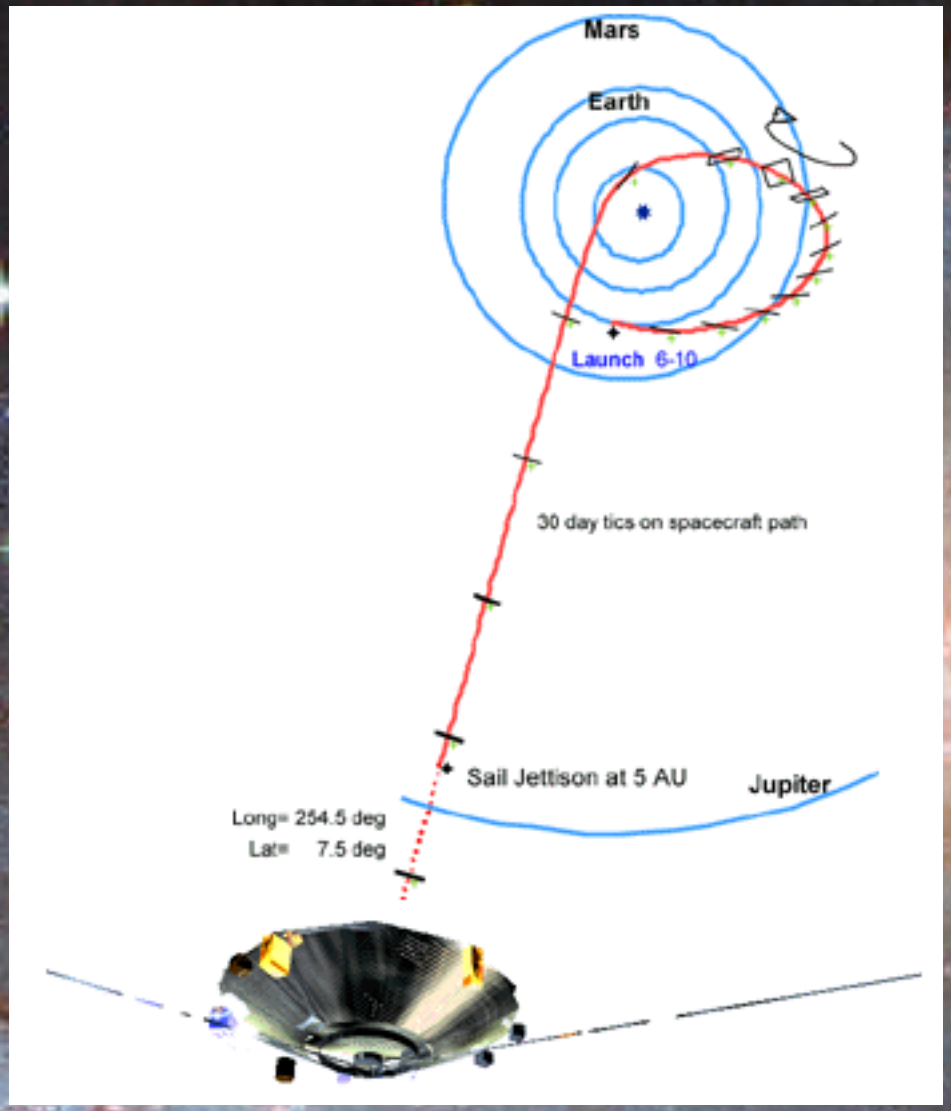
Or back to small?

- NASA Interstellar Probe Science and Technology Definition Team (IPSTDT) stood up in 1999 to relook at the precursor "problem"

A small spacecraft using a solar sail for propulsion and a near Sun encounter was baselined

To 200 AU in 15 years

Payload requirements similar to those of Pioneer 10

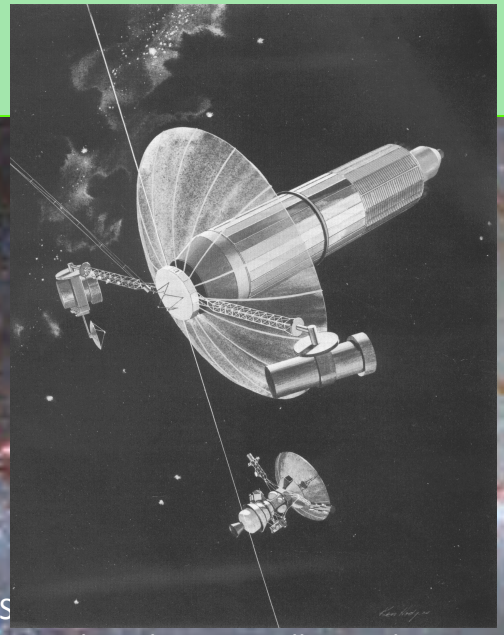


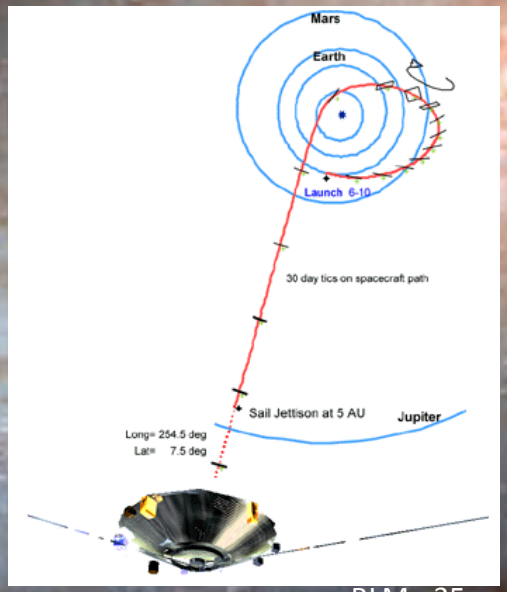
All in-space propulsion approaches to an Interstellar Probe Mission Need Propulsion Development

- Ballistic (NIAC 2004)
  - optimized launch 20 Feb 2019
  - Jupiter flyby 19 June 2020
  - Perihelion maneuver 4 Nov 2021 at 4 RS
  - 1000 AU 17 Oct 2071
  - 12.16 kg science
  - 1.1 MT

- Nuclear Electric (JPL 1980)
  - 2015 departure 20 years to 200 AU
  - 30 kg science package
  - Bimodal nuclear propulsion
  - 11.4 MT

- Solar Sail (NASA 1999)
  - 200 AU in 15 years
  - Perihelion at 0.25 AU
  - Jettison 400m dia sail at ~5 AU
  - 25 kg science
  - 246 kg





Radioisotope Electric Propulsion (REP) and Solar Sail Implementations have been examined in some depth

REP Implementation (IIE)

TEAMX
Jet Propulsion Laboratory

ADVANCED PROJECTS DESIGN TEAM
INTERSTELLAR EXPLORER VISION MISSION
CUSTOMER: RALPH MCNUTT
REPORT ID #794
LEADER: CHARLES BUDNEY
5, 7, 8 APRIL 2005

The following representatives comprised the study team:

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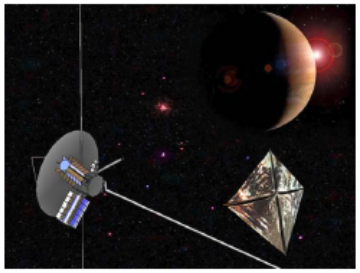
Solar Sail Implementation (IHP/HEX)

esa

INTERSTELLAR HELIOPAUSE PROBE

STUDY OVERVIEW OF THE INTERSTELLAR HELIOPAUSE PROBE



AN ESA TECHNOLOGY REFERENCE STUDY

Planetary Exploration Studies Section (SCI-AP)
Science Payload and Advanced Concepts Office (SCI-A)

prepared by/préparé par	A.E. Lyngvi, M.L. van den Berg, P. Falkner
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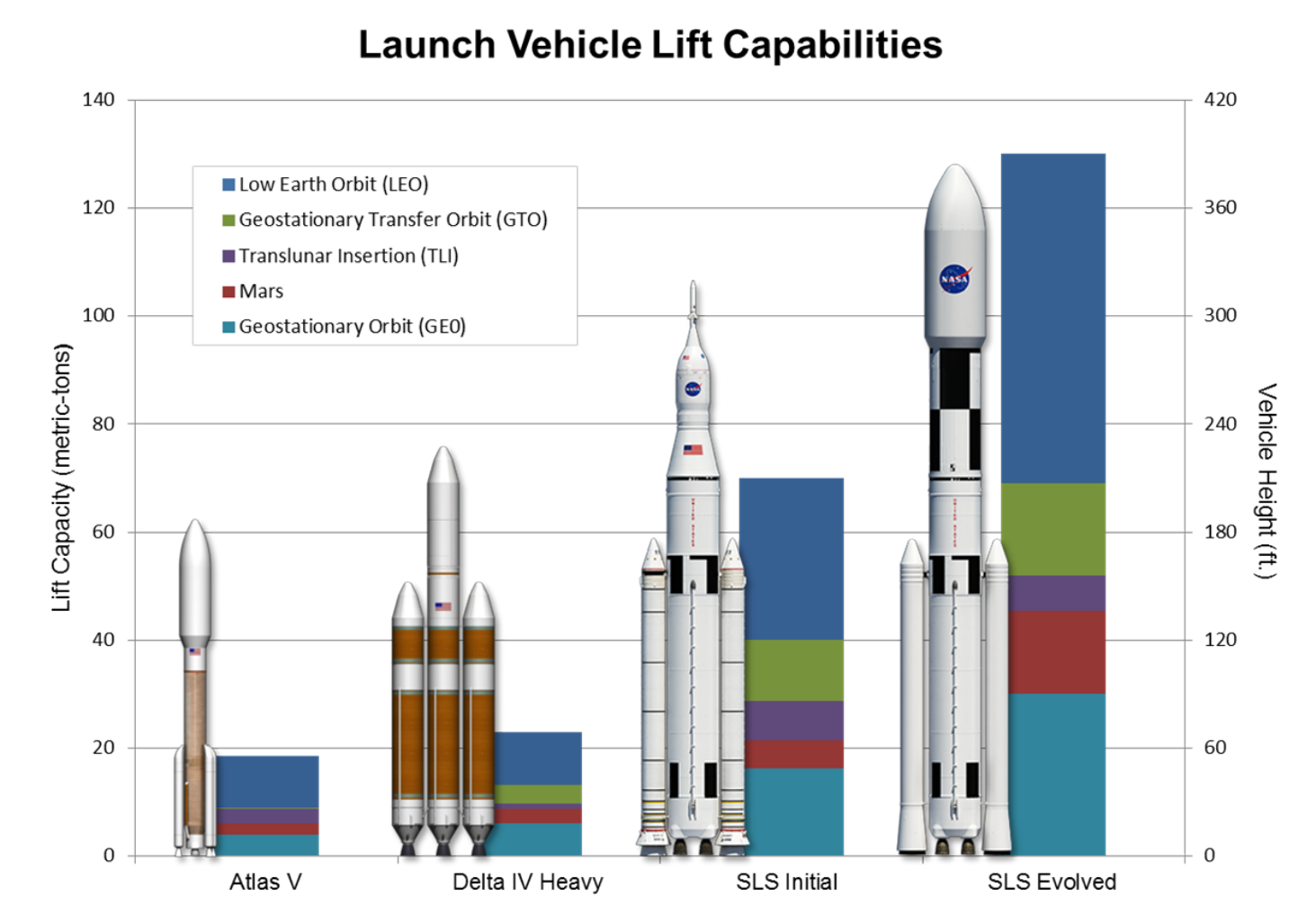
Document type/type de document	Public report

Launch Vehicles

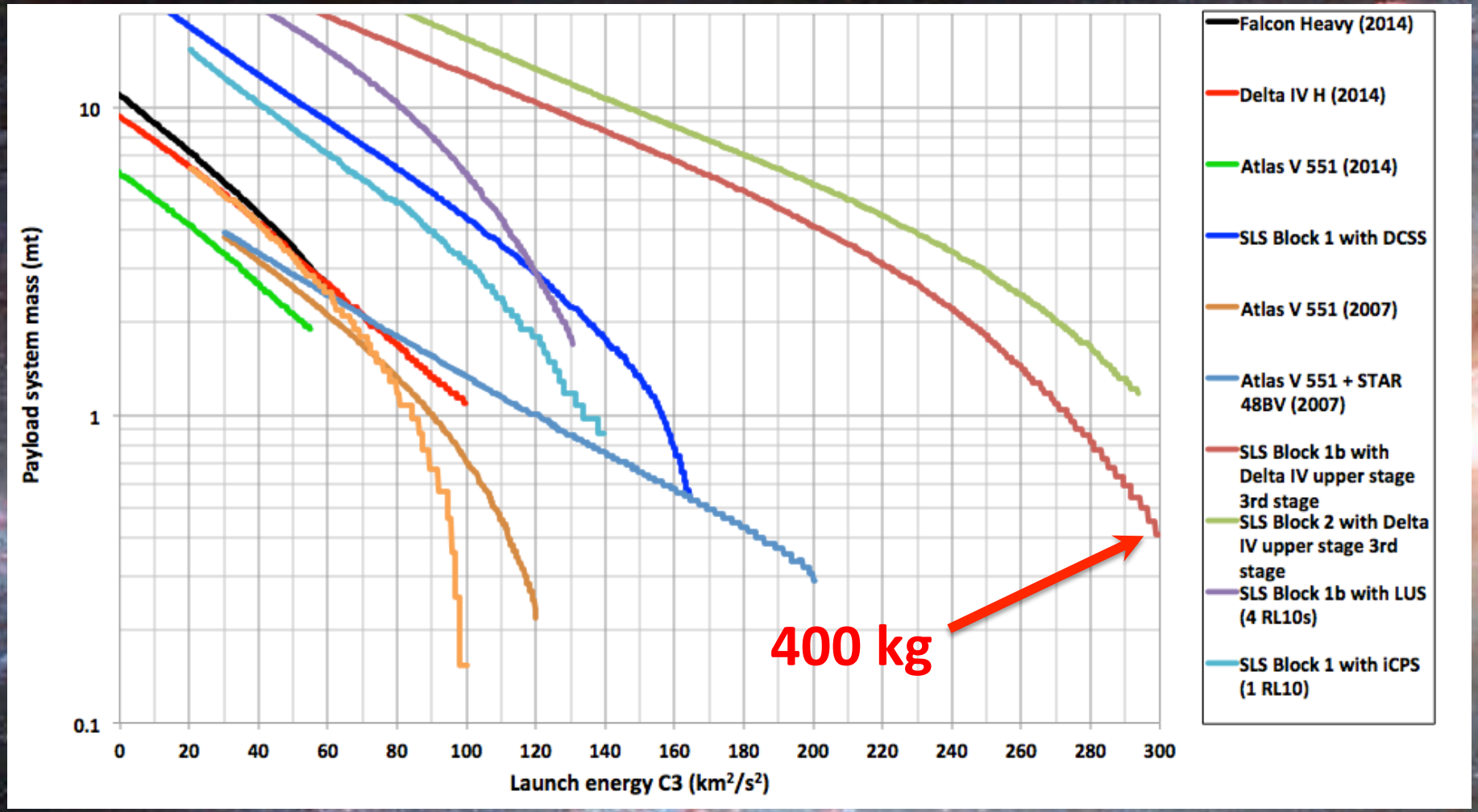


Comparison of current and notional launch vehicle capabilities for some of the vehicles usable for high-C3 and/or heavy – lift, robotic space missions

The SLS Block 1B Could be Enabling

- Four notional approaches:
  1) High C3 launch
  2) Add Jupiter gravity assist
  3) Add powered Jupiter gravity assist
  4) Use Jupiter (and other gravity assists) to enable Obert maneuver close to the Sun
- **Increasing difficulty couples to increasing performance**

Performance of various large launch vehicles to large launch energies



Reference Mission Goals

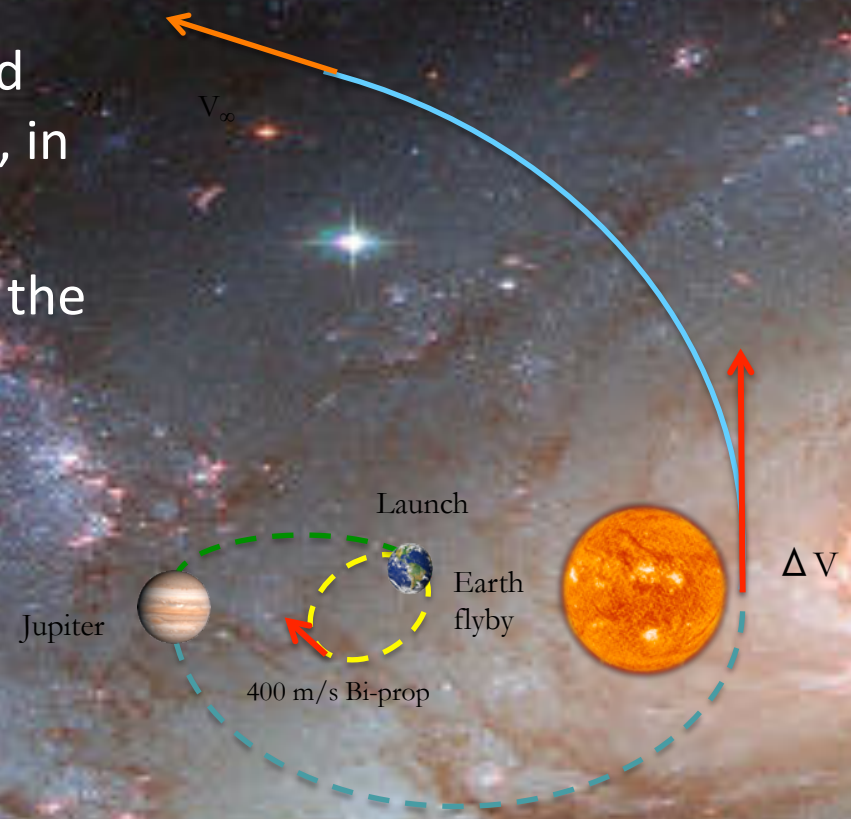
Send a spacecraft to the interstellar medium, capable of:

1. Reaching ~200 AU in ~20 years from launch
2. Travelling at high solar system escape velocity (13 AU / Yr.)
   - > 500 AU in 50 years (option 4)
   - Voyager 1 ~ 3.5 AU/Yr., New Horizons ~2.5 AU/Yr.
3. Survivability
   - Design for 20 years; good to last for 50 years
4. Cost ~ $ 1 Billion or less (Team-X cost estimates)
   - Excluding launch vehicle and phase E cost
5. Fit on an SLS Block 1B

Mission Design Overview

- A reference mission was designed between the two KISS workshops, in conjunction with Team-X (JPL)
- KBO flyby was not considered for the Team-X design. Simpler problem.

Options	Launch energy (C3, km²/s²)	Launch mass (Metric Ton)
E-J-Sun-Escape	116	7.3
E-ΔV-E-J-Sun-Escape	47.3	16.8

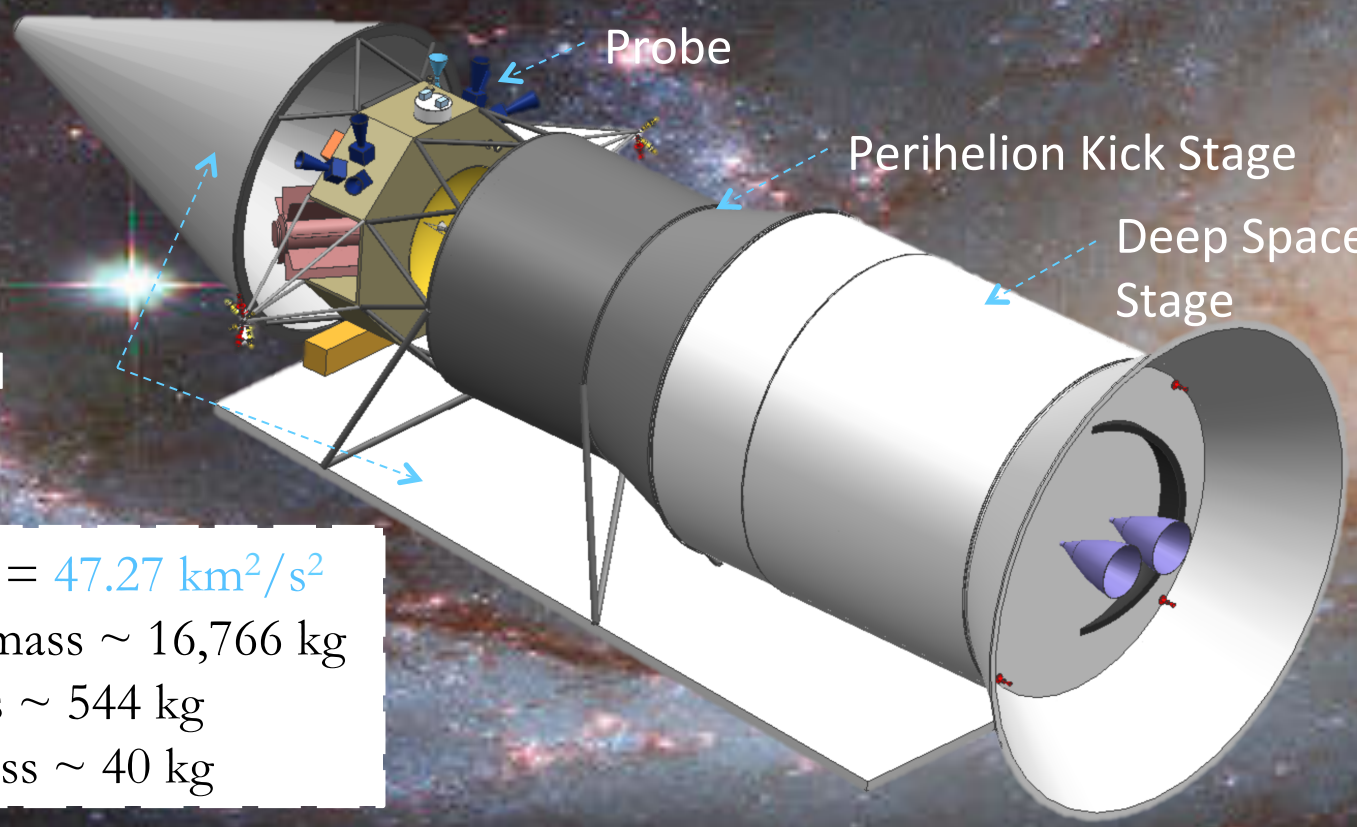


Enabling Features:

- Perihelion burn provides breakthrough escape velocity of > 13 AU/Yr.
- Low launch C3 'banks' delta-V for use at perihelion
- Launch on a near term SLS-1B

Spacecraft Overview

One probe with a single solid rocket motor "Perihelion Kick Stage" and another bi-propellant "Deep Space Maneuver" stage for ~500m/s of Delta-V prior to the perihelion burn.



Launch C3 = 47.27 km^2/s^2
Total S/C mass ~ 16,766 kg
Probe mass ~ 544 kg
Payload mass ~ 40 kg

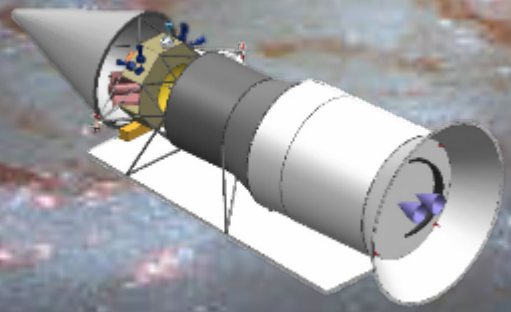
Flight System Elements

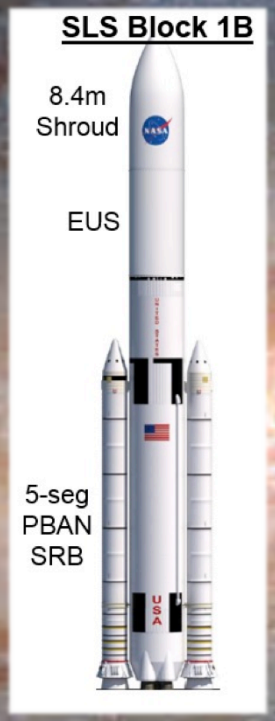
Three Stages

1. ISM Probe
   - Spinner
   - Big ACS (22N and 0.9N thrusters)
   - ~500 KG

2. Perihelion Kick Stage
   - 3 axis stabilized
   - Heat shield
   - Truss and support structure
   - SRM (deployed)

3. Deep Space Maneuver stage
   - 3 axis stabilized
   - Bi-Prop system
   - Load bearing structure (one of the mass and cost drivers)





Mission Design Overview

1.a Launch V_∞ = 6.875 km/sec
1.b Launch Date = Feb-19-2027

2.a DSM date = Dec-27-2028
2.b DSM ΔV = ~0.4 km/sec
2.c Post DSM Earth Flyby date = Jan-12-2030

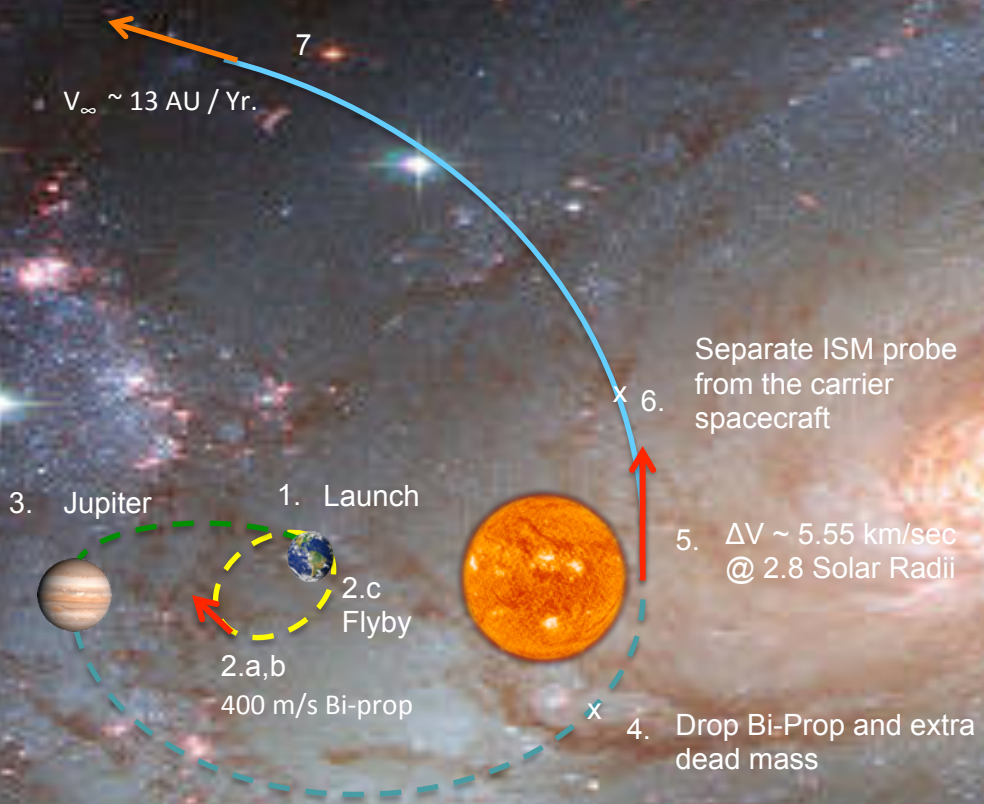
3.a Jupiter Arrival date = July-15-2031
3.b Jupiter Flyby alt. (km) = 621781
3.c Jupiter Flyby V_∞ (km/s) = 12.01

4.a Drop Bi-prop stage and associated mass
4.b Drop off distance = before perihelion

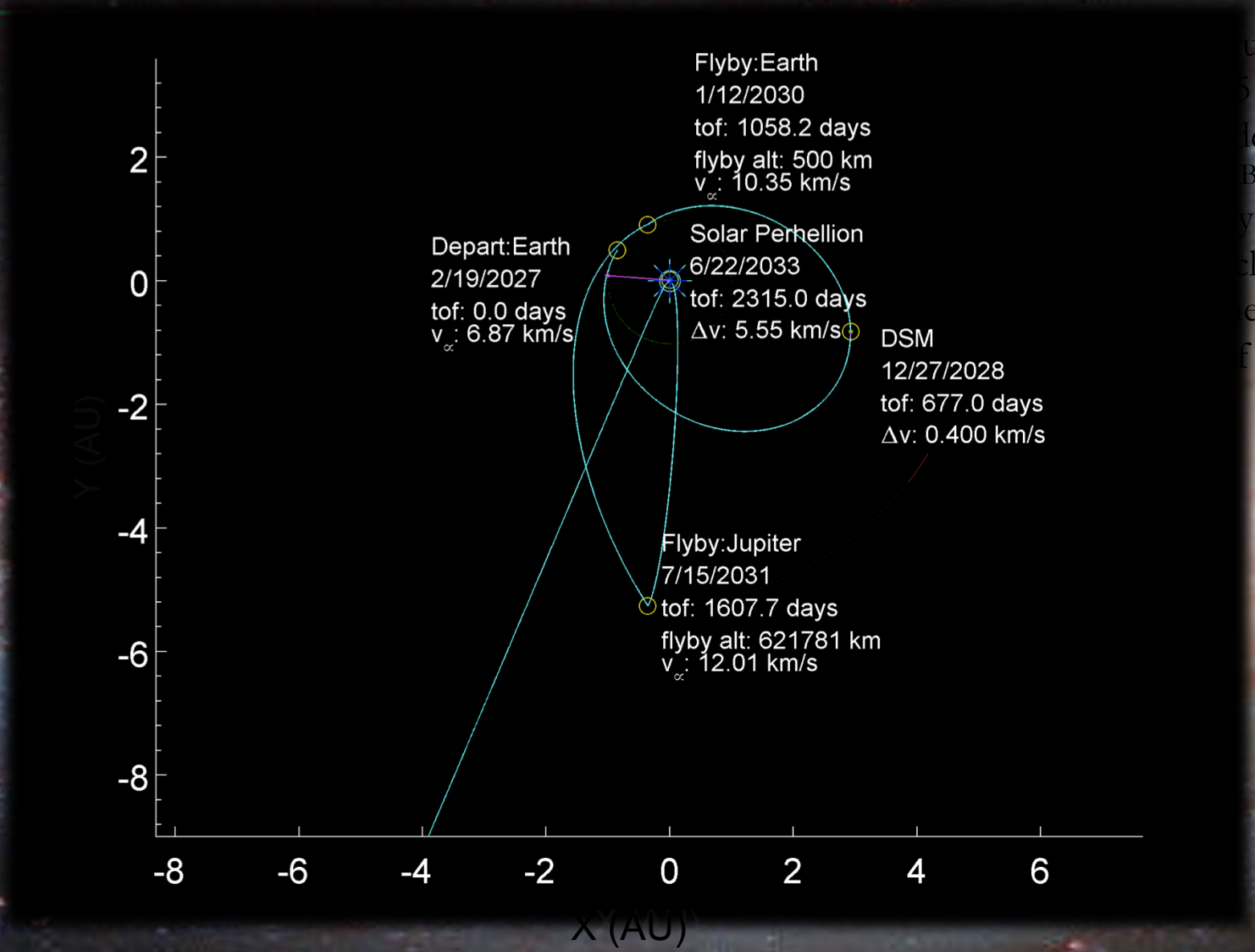
5.a Solar Encounter date = June-22-2033
5.b Perihelion distance = 2.8 solar radii
5.c SRM ΔV (km/s) = ~5.55
5.d Time from launch to perihelion= ~6.34 yrs.

6.a Distance from Sun = 1 AU
6.b Separate ISM probe

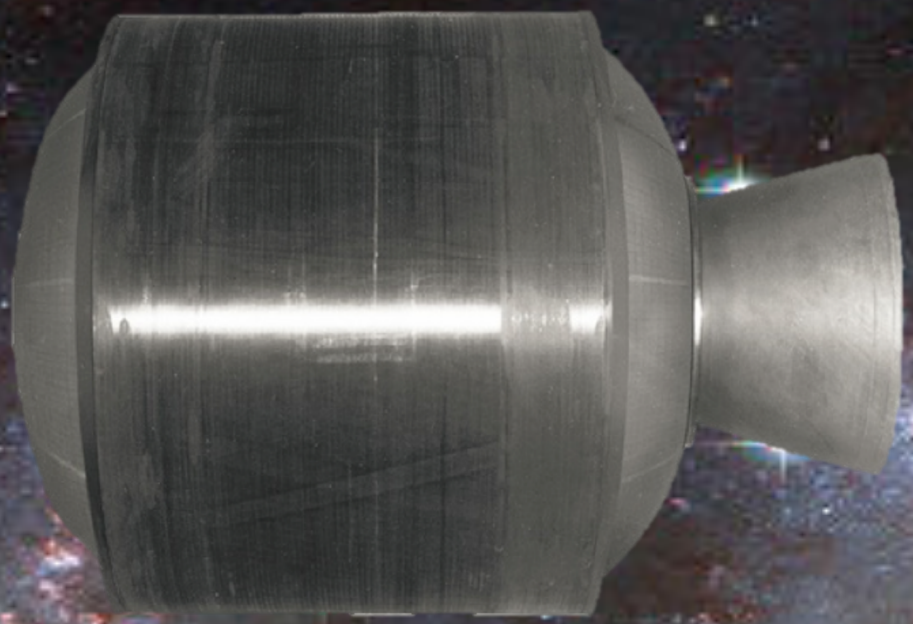
7.a Solar system escape V_∞ =~13 AU/Yr. (~62 km/s)
7.b Time to 200 AU = ~21.5 Years



Computed Trajectory

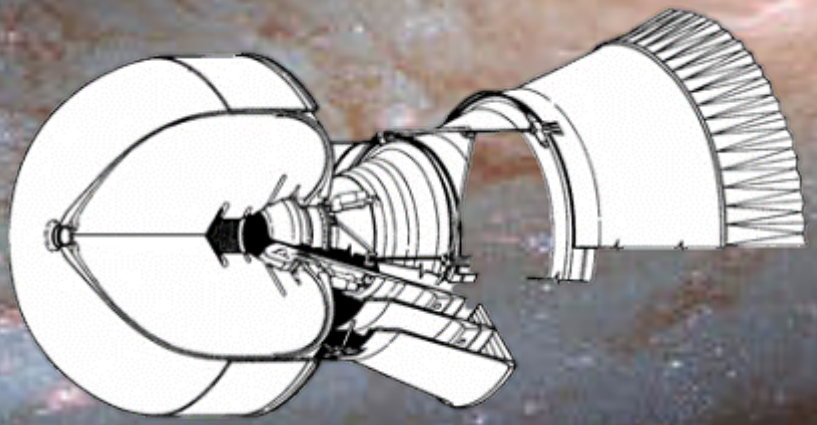


Solar Perihelion Rocket Motor



- **STAR 75 with Graphite case**
- **~10 Tons of fuel**
- **315 ISP**
- **Vector Nozzle**

Concept for deployable gas nozzle extension



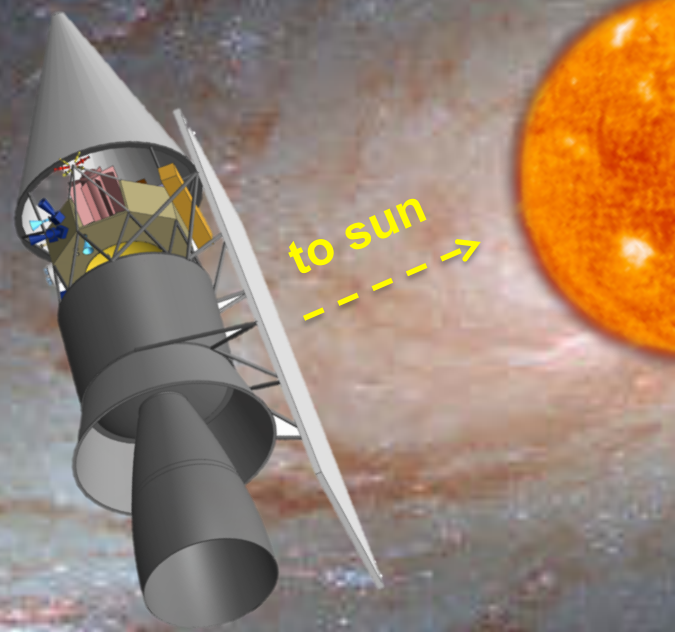
Heat Shield Design Overview

- Slew to make S/C face the Sun as it approaches perihelion
  - Use conical heat shield to protect (like JPL Solar Probe)
  - Slew to face the sun as we approach perihelion
  - CBE Mass, primary conical shield = 183 kg

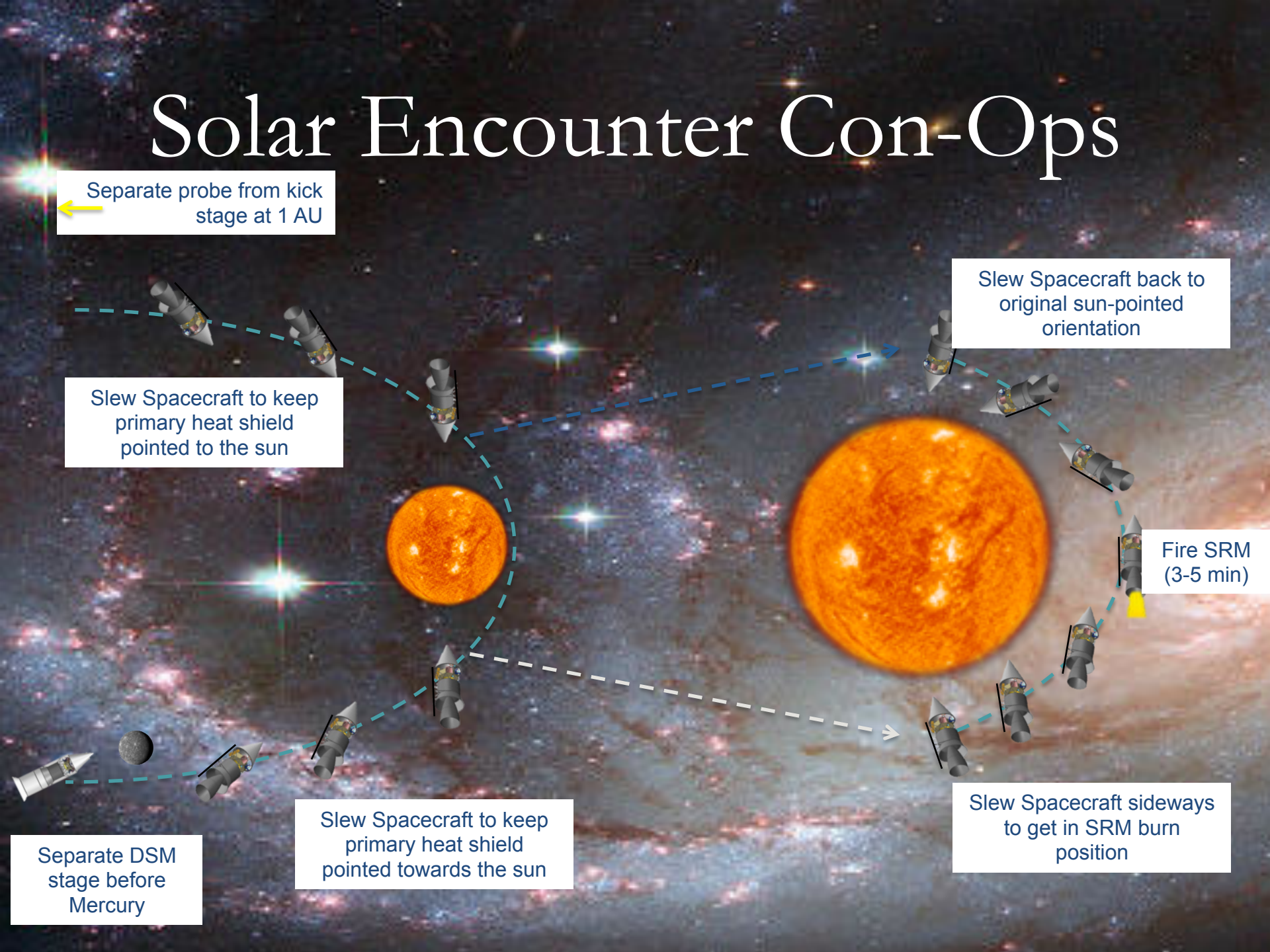
- Slew side ways close to the perihelion burn, fire the SRM and then slew back to the Sun facing mode
  - Need ~ 25-30 mins for the whole event
    - Assume 5 mins burn time (conservative)
    - 25 mins to slew in and slew out
    - ~0.11 deg/sec
    - Design for 0.15 deg/sec
  - Use secondary flat plate heat shield
    - Conservative design
  - CBE Mass, secondary flat plate = 107 kg

- Single, better heat shield design possible (future work)

- Added Material, Environmental etc. Contingency = 30 %

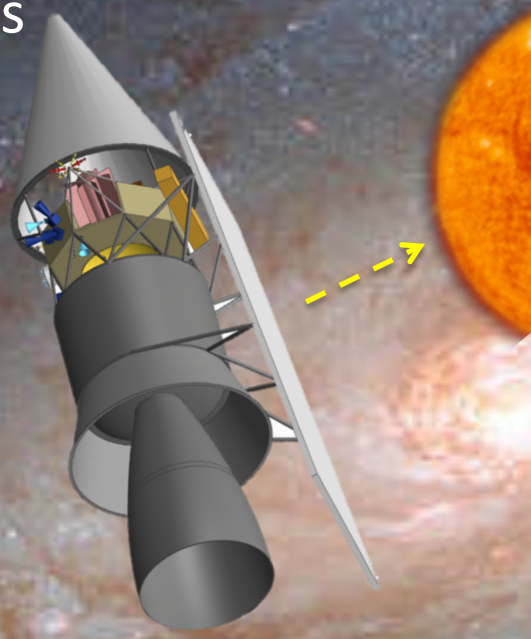


Solar Encounter Con-Ops

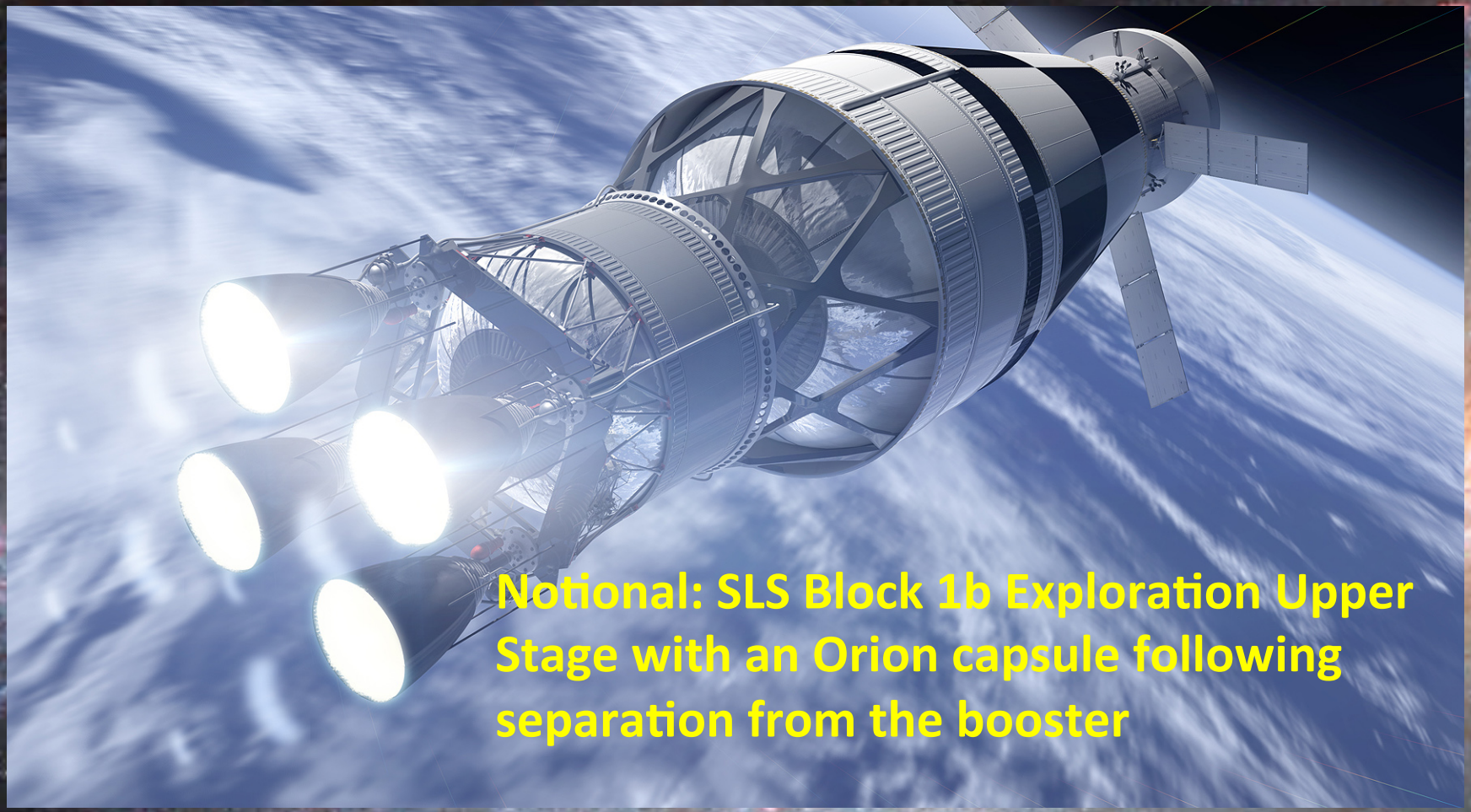


Enabling Technologies for Mission

- Thermal protection system for low solar perihelion burn
- Vector + extended nozzle Star or hybrid motors
- Multi use Optical Instrument:
  1. Optical Science instrument:
     - KBO Imager at high velocities
     - Zodiacal background science instrument
  2. Optical navigation and communication terminal
- Advanced RTG power source
  - eMMRTG already under development
  - ARTG will be better
- Low power spacecraft systems and operations
- Miniaturized instruments, deployable systems (telecom), autonomy & quick hibernation



High C3 Possibilities

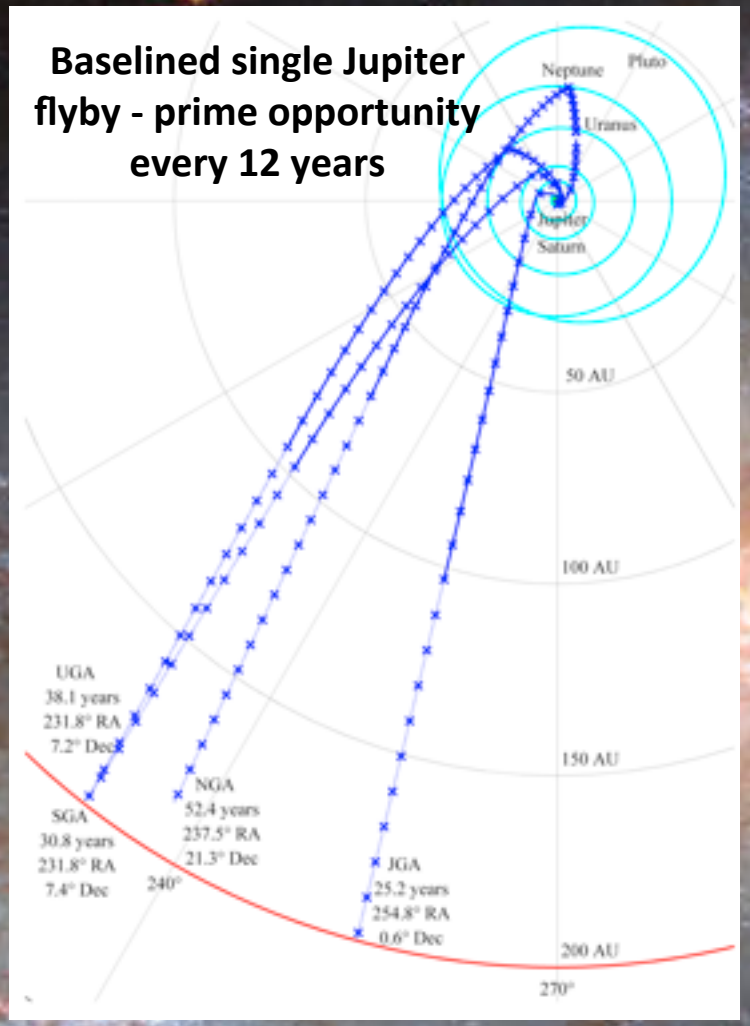


Enablers for ANY Architecture

- "Affordable" launch vehicle including high-energy stage
- kWe power supply with low specific mass
  - Pu-238 is REQUIRED
- Reliable and sensitive deep, space communications at Ka-band
- Mission operations and data analysis (MO&DA)
  - $10 M per year for 30 years at 3% per annum inflation ~$500M

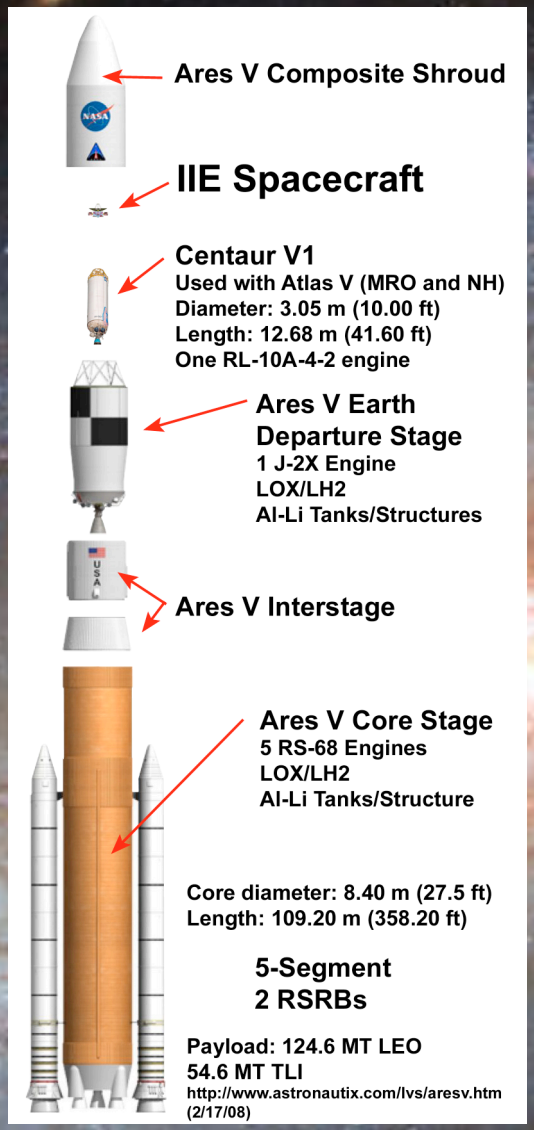
"Vision Mission" REP Mission Design Options

- Various upper stage options for Delta IV H were studied
- Investigated 12 existing and conceptual upper stages
- Final system was too heavy for Star 48 + Star 37 upper "stage"
- Went to a Star 48A "double stack" with custom interfaces



Assembling the Pieces

- Figure is to approximate scale
- Earth Departure Stage is only partially fueled to optimize launch energy
- First iteration: C_3~270 km^2/s^2
  - Corresponding asymptotic speed from the solar system is ~19.0 km/s ~ 4 AU/yr
  - New Horizons
    - Launched to 164 km^2/s^2
    - Pluto flyby at 13.8 km/s = 2.9 AU/yr
  - Voyager 1 current speed = 3.6 AU/yr
  - Voyager 2 current speed = 3.3 AU/yr
- To reach 9.5 AU/yr (45 km/s) with only a launch from Earth would require C_3 = 1,016 km^2/s^2
- Even with an Ares V, launch remains only one component

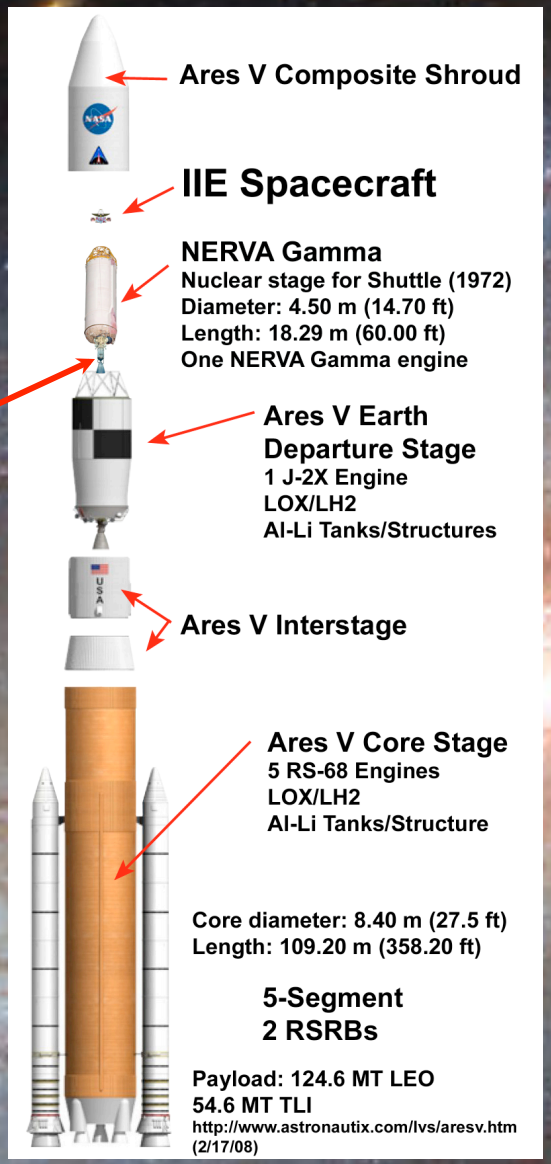


Earth orbital speed = 29.79 km/s; 1 AU/yr = 4.74 km/s

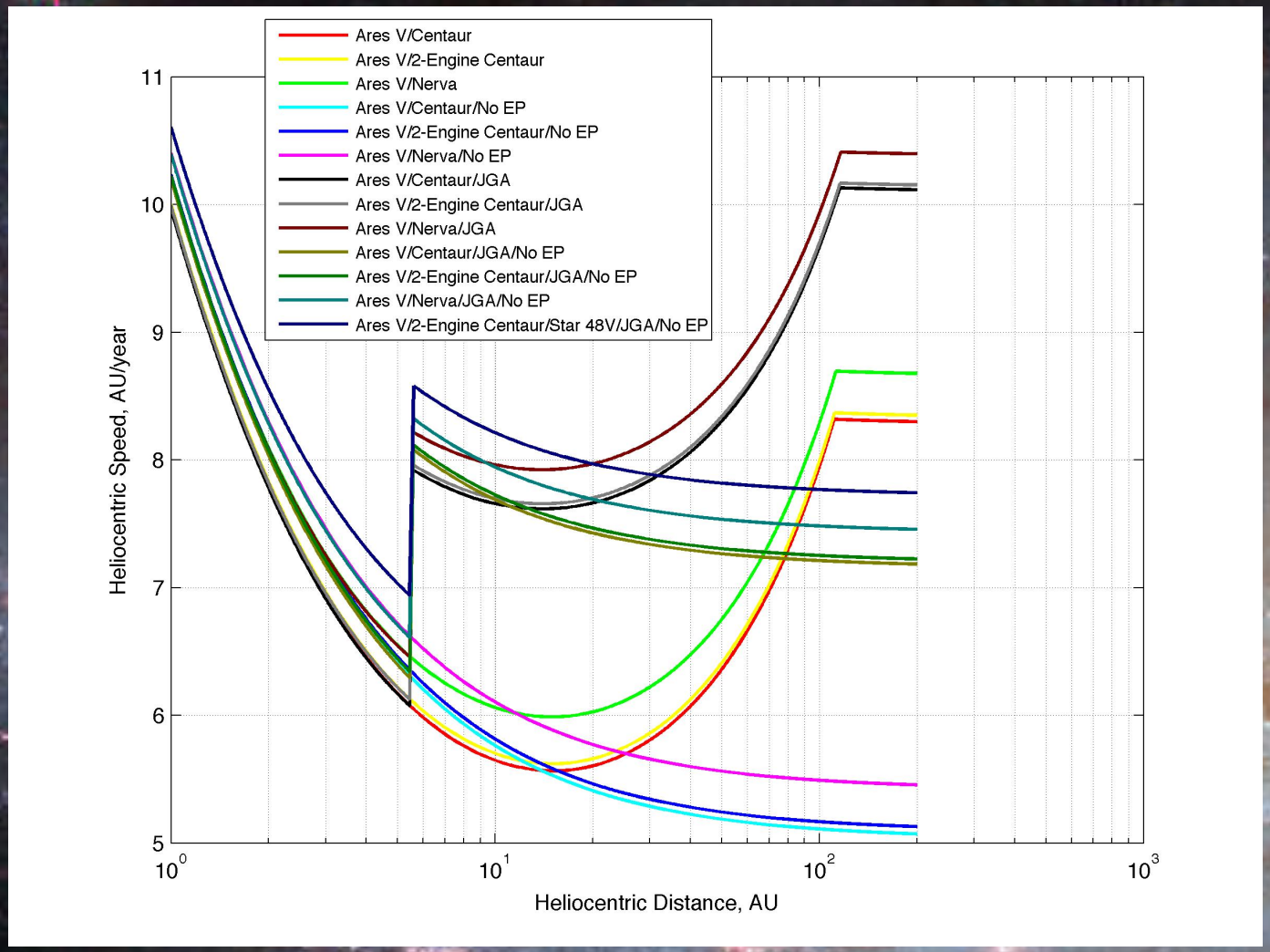
Nuclear Upper Stage ?

- Nuclear stage advantages
  - More performance than Centaur V1
  - Lower mass
  - Earth escape trajectory
  - Fully flight qualified
- Nuclear stage disadvantages
  - More expensive than Centaur
  - Larger (low LH2 volume)
  - Not solar system escape trajectory
  - Requires development
    - Gamma engine thrust 81 kN (18,209 lbf)
    - BNTR engine thrust 66.7 kN (15,000 lbf)
    - 3 BNTR's baselined for Mars DRM 4.0 of 1999
- Nuclear Earth Departure Stage not acceptable
  - Not Earth-escape trajectory
  - Comparable thrust engine to NERVA 2
    - 867.4 kN (195 klbf)
    - Stage mass: 178,321 kg wet, 34,019 kg dry
    - Compare S IVB: 119,900 kg wet, 13,300 kg dry; J-2: 486.2 kN (109.3 lbf)
  - No development plans or identified requirements

15 klbf BNTR engine

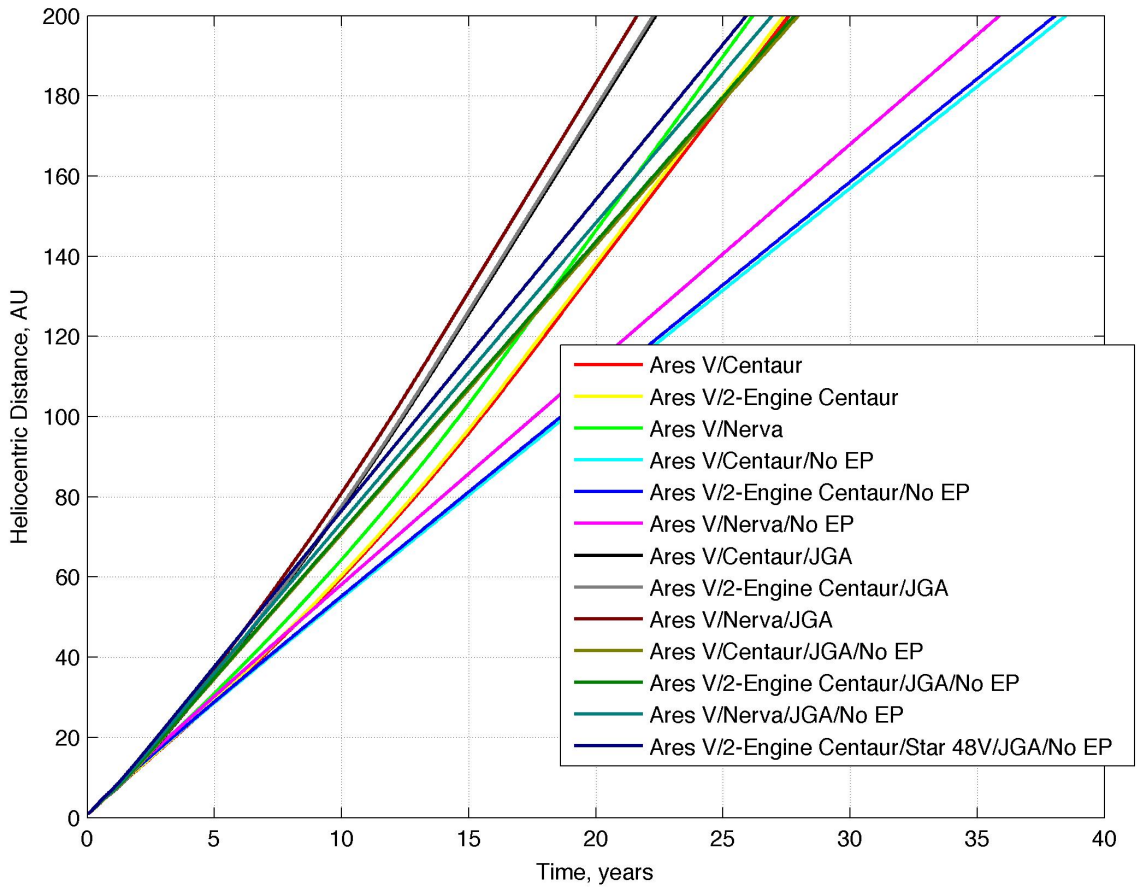


Comparing the Options: Speed to 200 AU and Beyond



- Probe speed versus heliocentric distance
  - To 200 AU
  - Log distance
  - JGA is the discontinuity

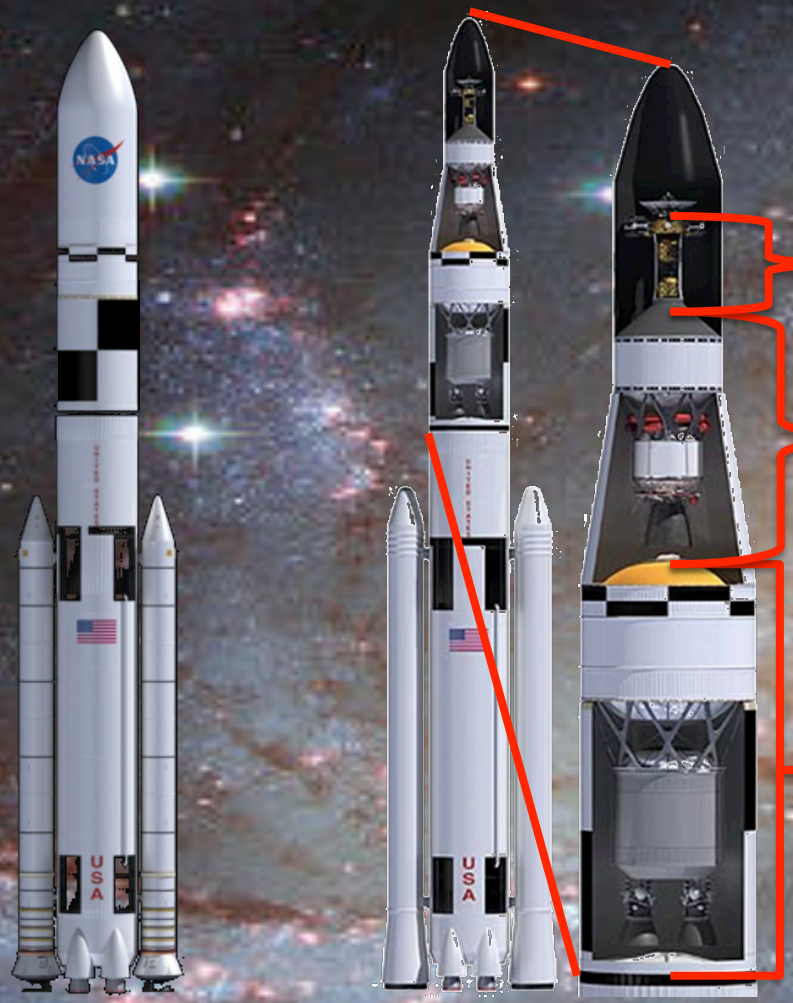
Comparing the Options: Time to 200 AU



- Spread among options is ~22 to 38 years to 200 AU
- Widens in going to even larger distances
- Initial goal had been 15 years to 200 AU

An SLS Solution

- **Notional versions of the SLS**
- The cargo version of SLS Block 1b is to the left
- An "evolved" version with an additional stage is shown in the center with the upper section expanded to the right

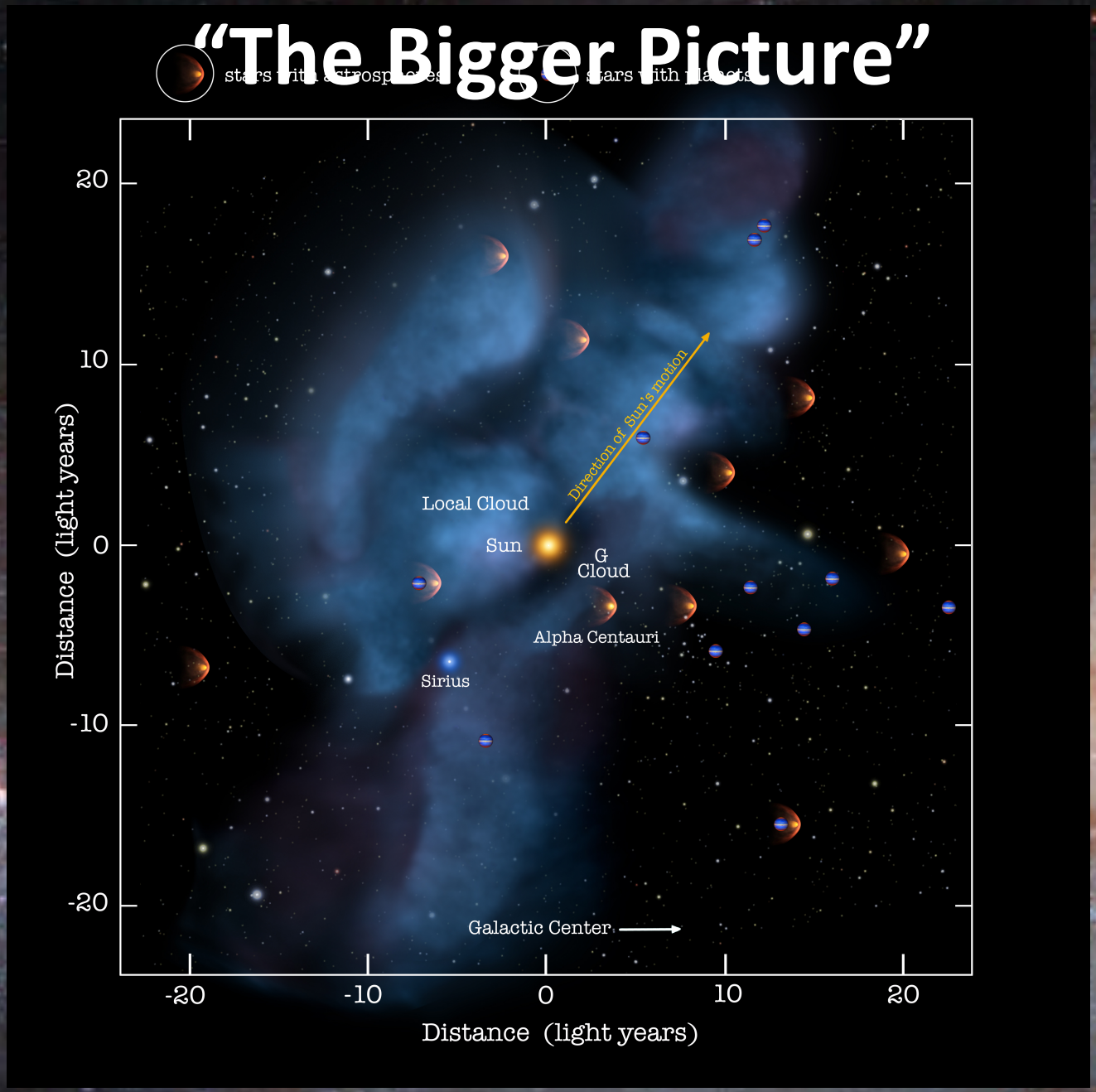


Interstellar Probe

Interim Cryogenic Propulsion Stage

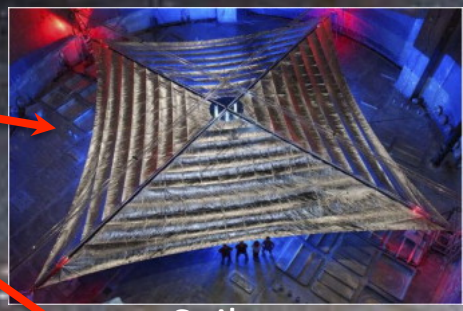
Exploration Upper Stage

Our Heliosphere is the Key to "The Bigger Picture"

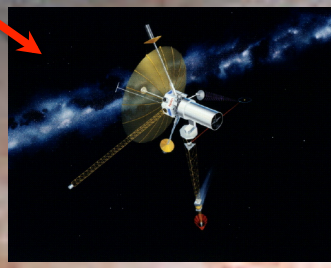


Interstellar Probe Is a High Scientific Priority

- Development of sufficiently large Solar Sails and use of Nuclear Electric Propulsion (NEP) remain problematic
- Radioisotope electric propulsion (REP) offers advantages but also complications
- A ballistic solution is enabled by SLS with upper stages – a solid scientific use of this capability
- Optimal windows open every 12 years (Jupiter revolution about the Sun) to fly to through the heliospheric nose: 2014, 2026, 2038
- 2026 is a technically implementable launch date
- **We can do this!**



Sail prototype



60 mt TAU mission concept

千里之行，始於足下

A journey of a thousand miles begins with a single step

– Lao-Tzu

It is just a question of how and when…

L'Garde Solar Sail prototype (above)
Boeing SLS advanced concept (right)