Innovative Interstellar Explorer

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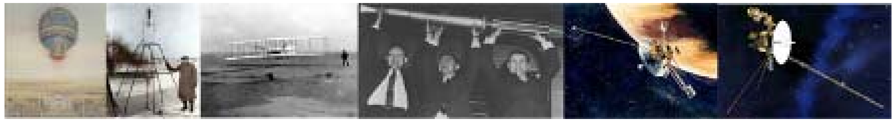
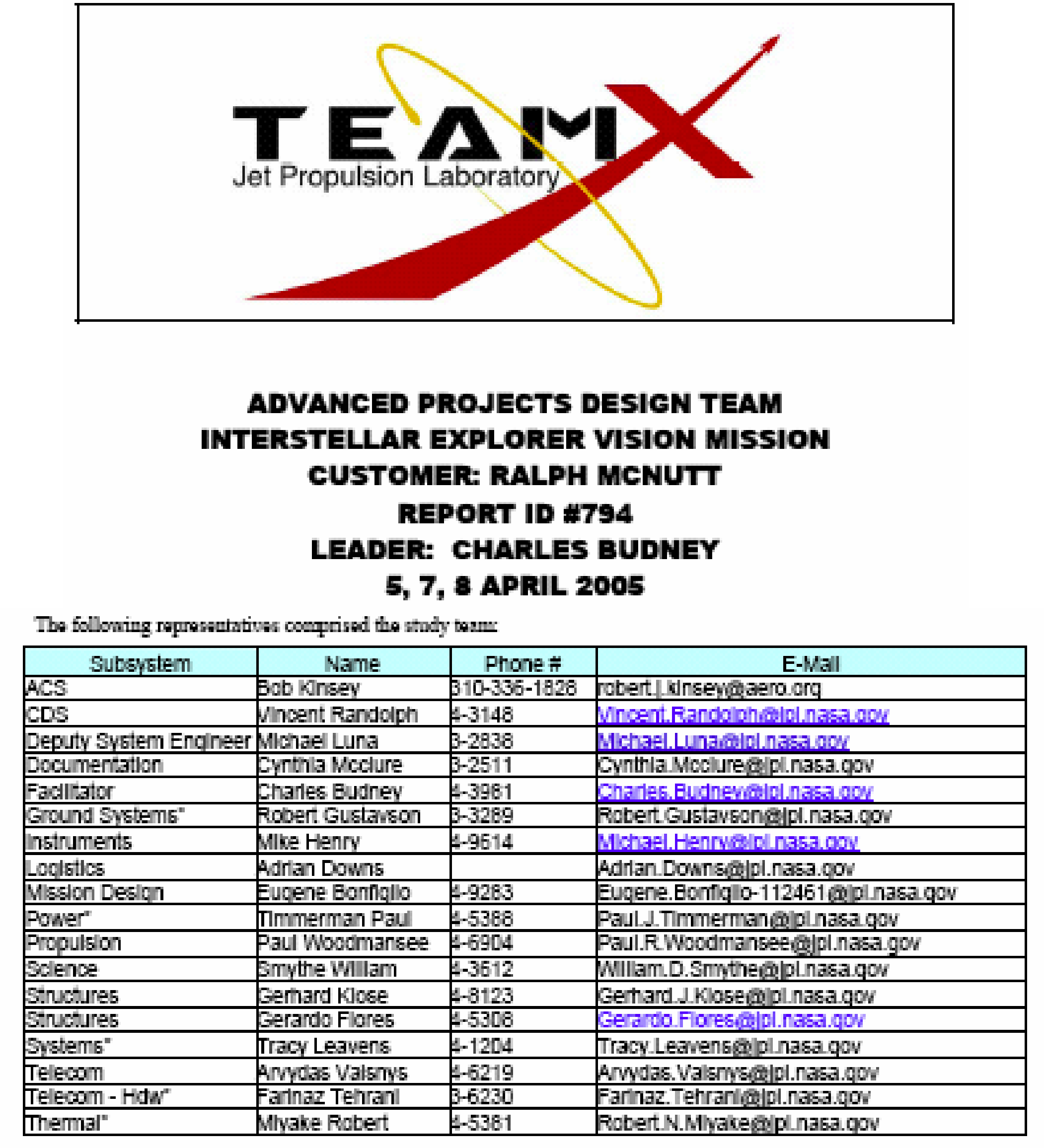
Noordwijk, The Netherlands
21 February 2006

Workshop on Innovative System Concepts
ESTEC





ADVANCED PROJECTS DESIGN TEAM
INTERSTELLAR EXPLORER VISION MISSION
CUSTOMER: RALPH MCNUTT
REPORT ID #794
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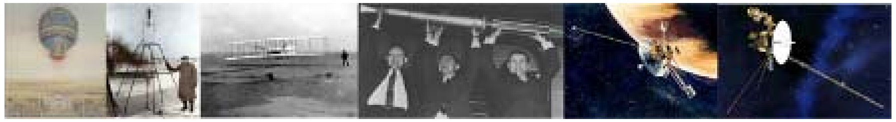
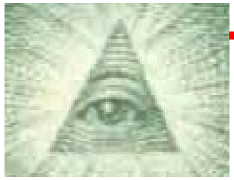
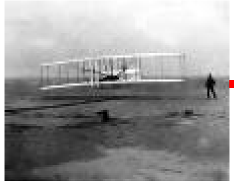


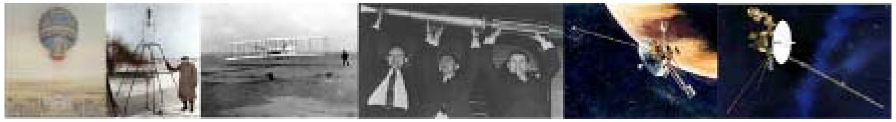
I^2E is a NASA “Vision Mission”



Si requiritis
futurum nostrum,
spectate astra!



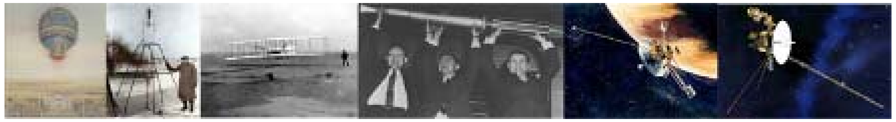
- **The “all-seeing eye”; “Novus Ordo Seclorum”: The new order of the ages**
- **The Pleiades - or “Seven Sisters” Messier 45; 425 L.Y.; also “Subaru”**
- **“If you seek our future, look to the stars” (Latin - cf. C. Wren)**
- **The Montgolfier brothers, Paris 4 June 1783**
- **Robert Goddard, 16 March 1926**
- **The Wright Brothers, 17 Dec 1903**
- **Explorer I, 1 February 1958 - Pickering, Van Allen, Von Braun**
- **Pioneer 10 at Jupiter, 3 Dec 1973**
- **Voyager 1 and 2 launched 1977**



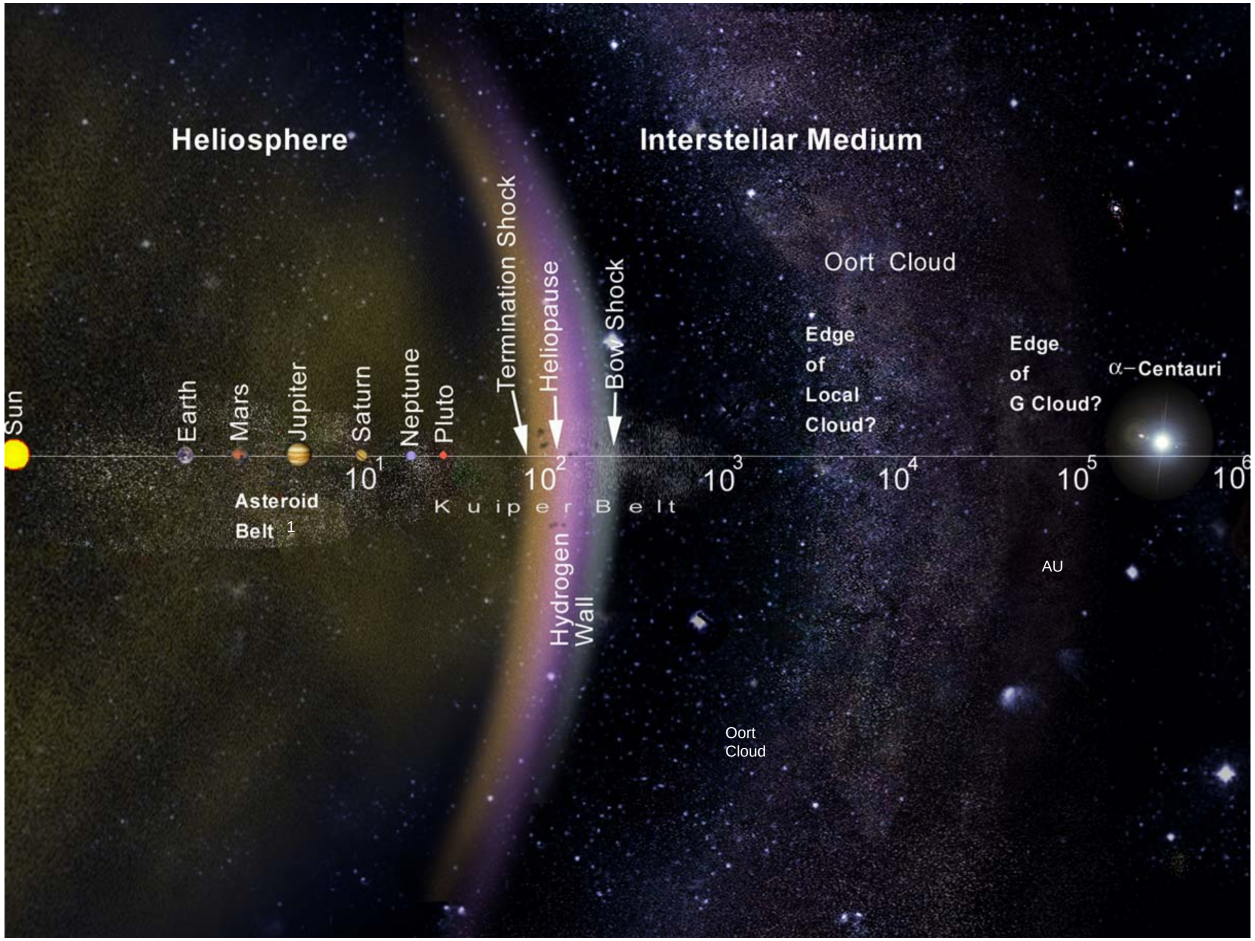
For Any Mission There Are Four Key Elements

• Science	the case for going
• Technology	the means to go
• Strategy	all agree to go
• Programmatics	money in place

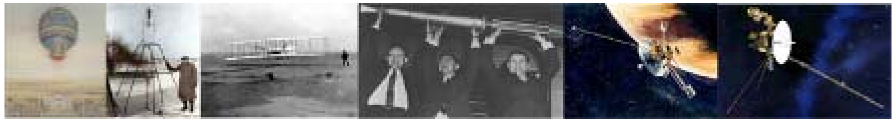
A well-thought-out systems approach incorporating all key elements is required to promote and accomplish a successful exploration plan



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

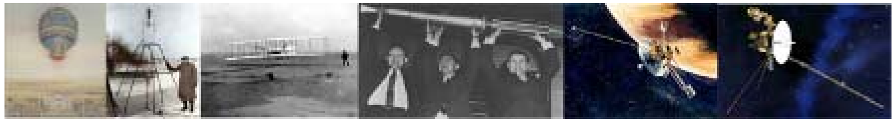


Graphic from the Interstellar Probe Science and Technology Definition Team NASA/JPL



An Interstellar Probe Has Been Advocated for Almost 30 Years

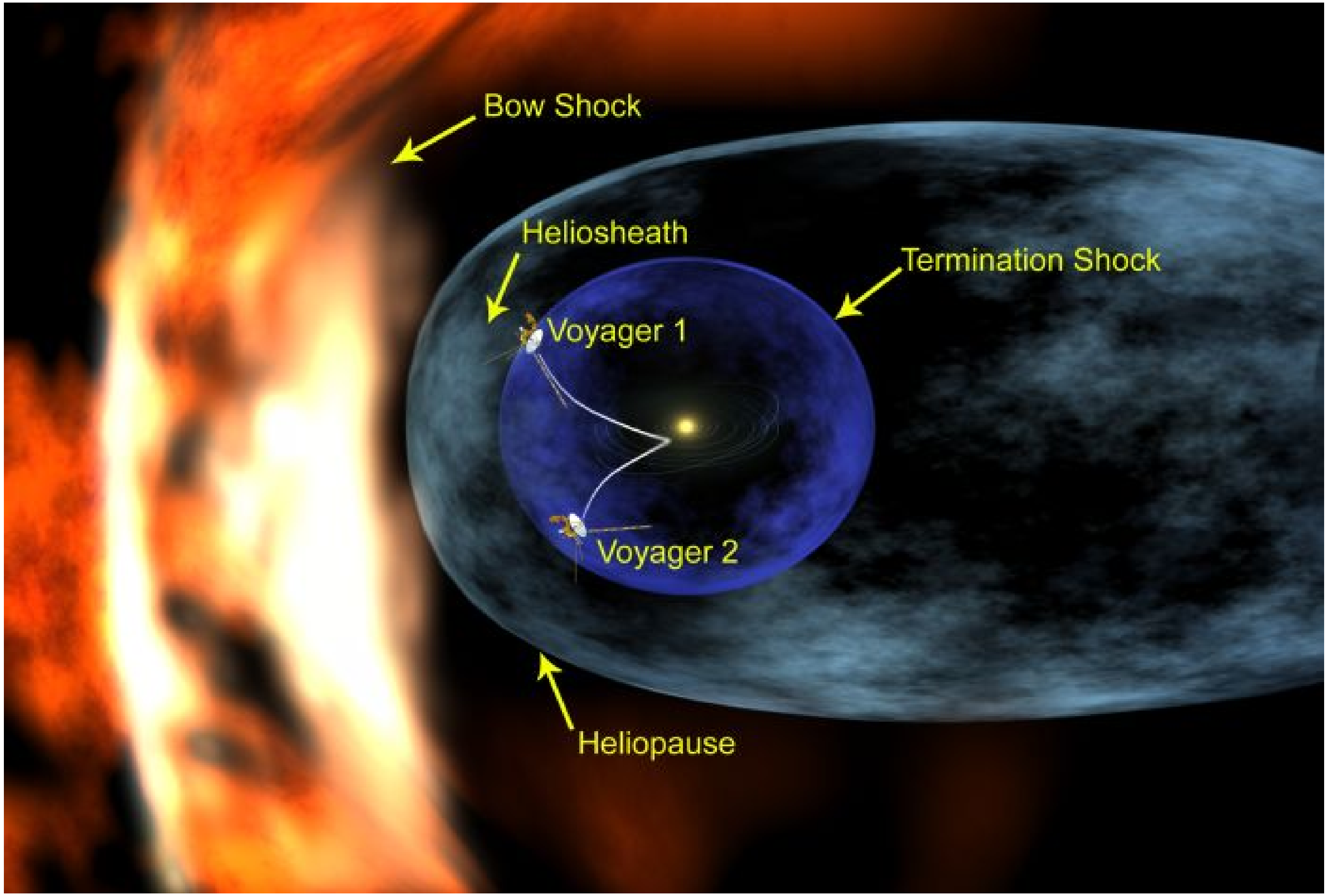
NASA Studies	National Academy Studies
Outlook for Space, 1976	Physics through the 1990's - Panel on Gravitation, Cosmology, and Cosmic Rays (D. T. Wilkinson, chair), 1986 NRC report
An implementation plan for solar system space physics, S. M. Krimigis, chair, 1985	Solar and Space Physics Task Group Report (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

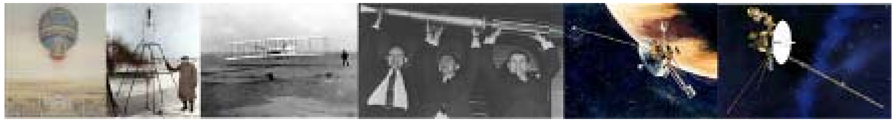


Guiding Science Questions Were Posed by NASA's Interstellar Probe Science and Technology Definition Team in 1999

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

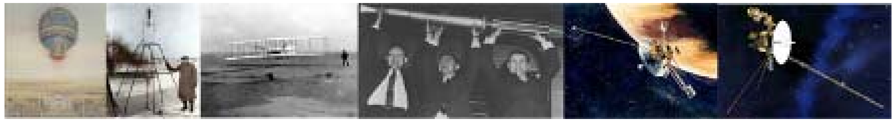
Artist's Concept of Heliosphere and Trajectories of the Voyagers



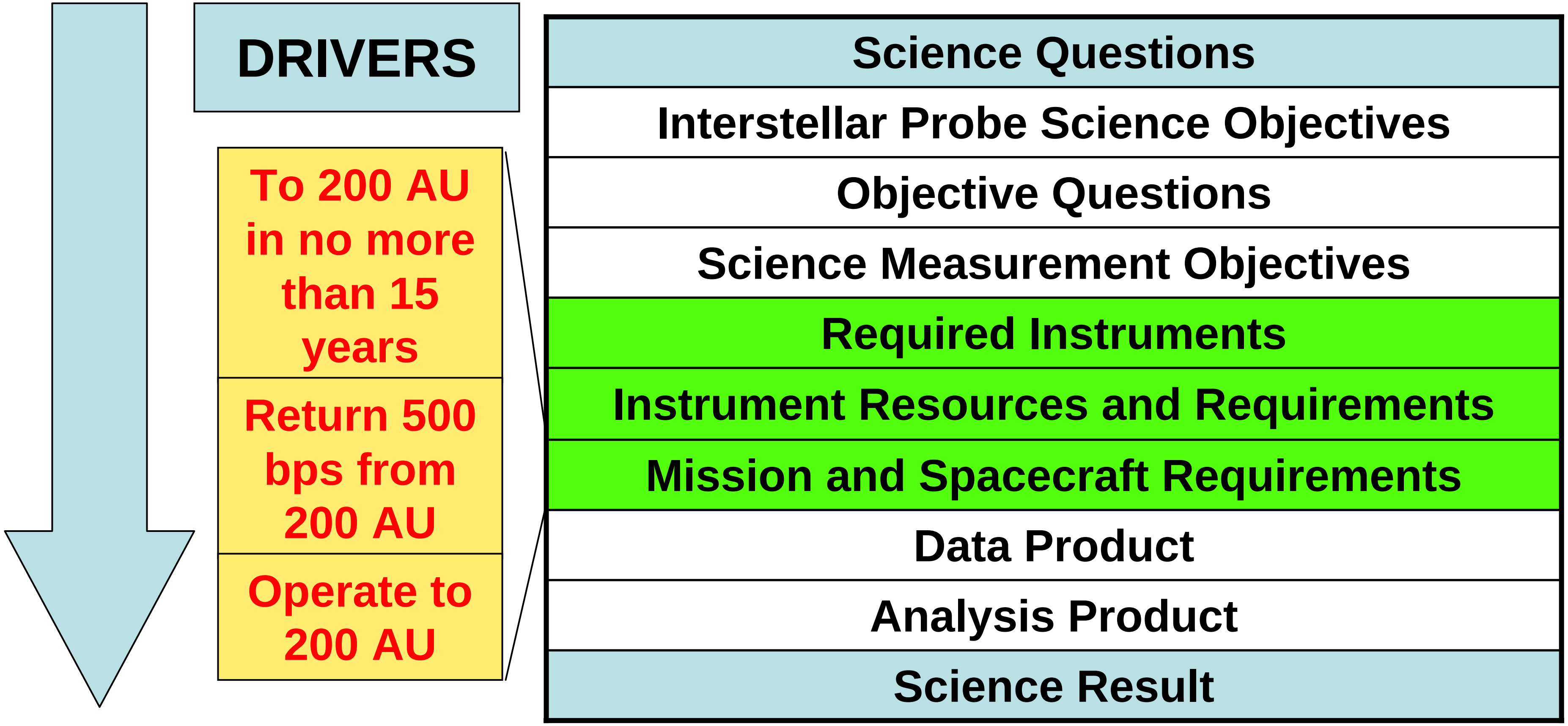


Top Level Mission Requirements

- **Launch spacecraft to have an asymptotic trajectory within a 20° cone of the "heliospheric nose" (+7°, 252° Earth ecliptic coordinates)**
- **Provide data from 10 AU to 200 AU**
- **Arrive at 200 AU "as fast as possible"**
- **Consider all possible missions that launch between 2010 and 2050**
- **Use existing launch hardware**
- **No "in-space"assembly**
- **Launch to escape velocity**
- **Keep new hardware and technology to a minimum**
- **Provide accepted "adequate" margins**



Answering the Science Questions is a "System of Systems" Problem



DRIVERS

To 200 AU in no more than 15 years

Return 500 bps from 200 AU

Operate to 200 AU

Science Questions

Interstellar Probe Science Objectives

Objective Questions

Science Measurement Objectives

Required Instruments

Instrument Resources and Requirements

Mission and Spacecraft Requirements

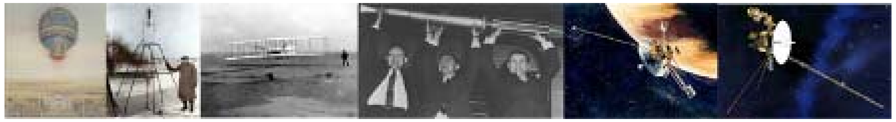
Data Product

Analysis Product

Science Result

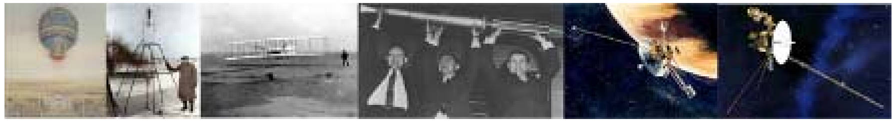
Science Traceability Matrix

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-α 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	



Notional Model Science Payload

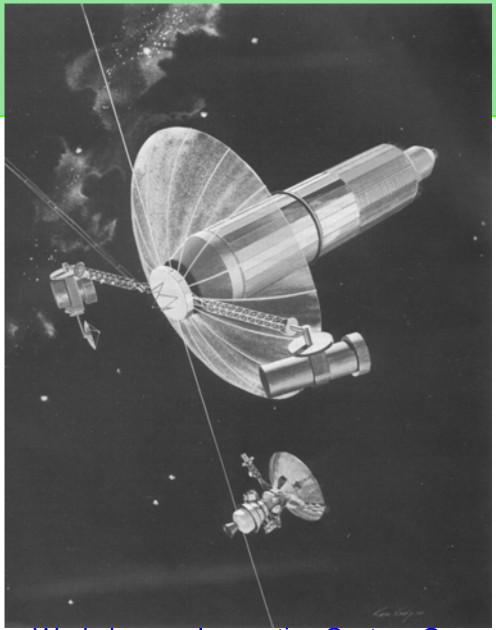
Material Measured	Number of instruments	Notional instrument from 3rd Interstellar Probe Science and Technology Definition Team meeting, 17-19 May 1999, JPL			Comparable performance of instrument at TRL of 9 (An example ideal payload)		
Instrument Resources		Mass (kg)	Power (W)	Data Rate (bps)	Mass (kg)	Power (W)	Data Rate (bps)
Fields	2	1.0	1.3	3.6	12.77	12.00	95,760
Plasma; suprathermal particles	3	8.5	6	12	12.17	10.75	1,503
Energetic particles	3	6.4	4.6	7	103.1	63.0	3,224
Neutral material	3	7.3	6.5	1.4	51.01	46.98	5,324
Photons	2	3.4	0.9	0.6	40.65	105.1	1,900
Totals	**13**	**26.6**	**19.3**	**24.6**	**219.7**	**237.83**	**107,711**



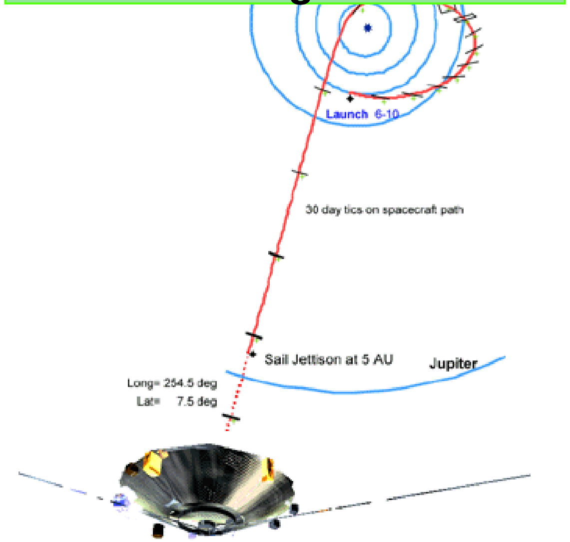
All Approaches to an Interstellar Probe Mission Need Propulsion Development

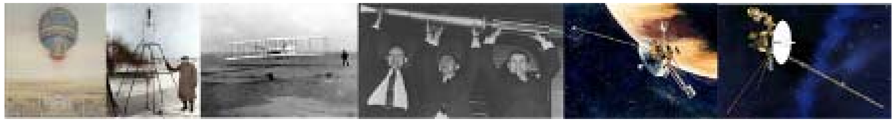
- **Ballistic**
  - optimized launch 20 Feb 2019
  - Jupiter flyby 19 June 2020
  - Perihelion maneuver 4 Nov 2021 at 4 RS
  - 1000 AU 17 Oct 2071
  - 12.16 kg science
  - 1.1 MT

- **Nuclear Electric**
  - 2015 departure 20 years to 200 AU
  - 30 kg science package
  - Bimodal nuclear propulsion
  - 11.4 MT



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





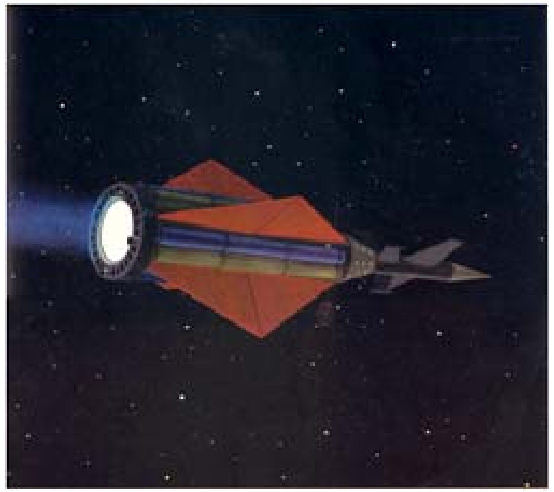
NEP Craft and Interstellar Mission from Willey Ley and Chesley Bonestell - 1960s

Issues are similar to those faced today with a “Prometheus” vehicle

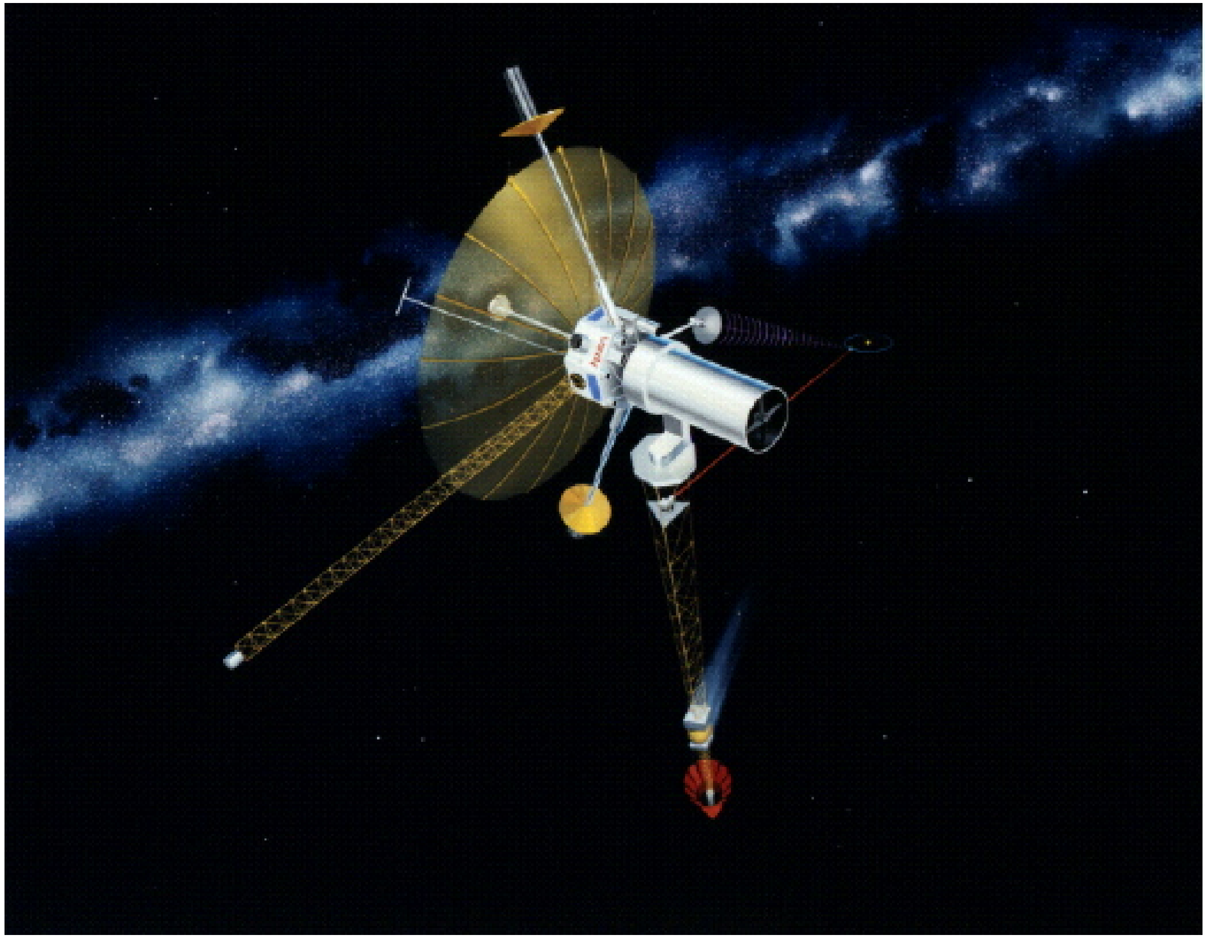
1. Transport of Empty Craft to LEO With an HLLV

2. Orbital Assembly of the Deep-Space Craft

3. Crossing Neptune’s Orbit



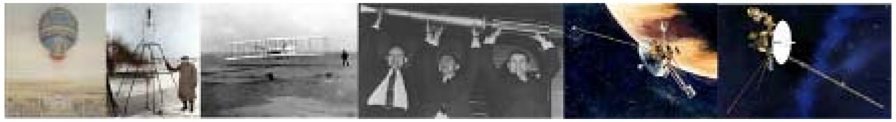
Previous Concepts Were BIG



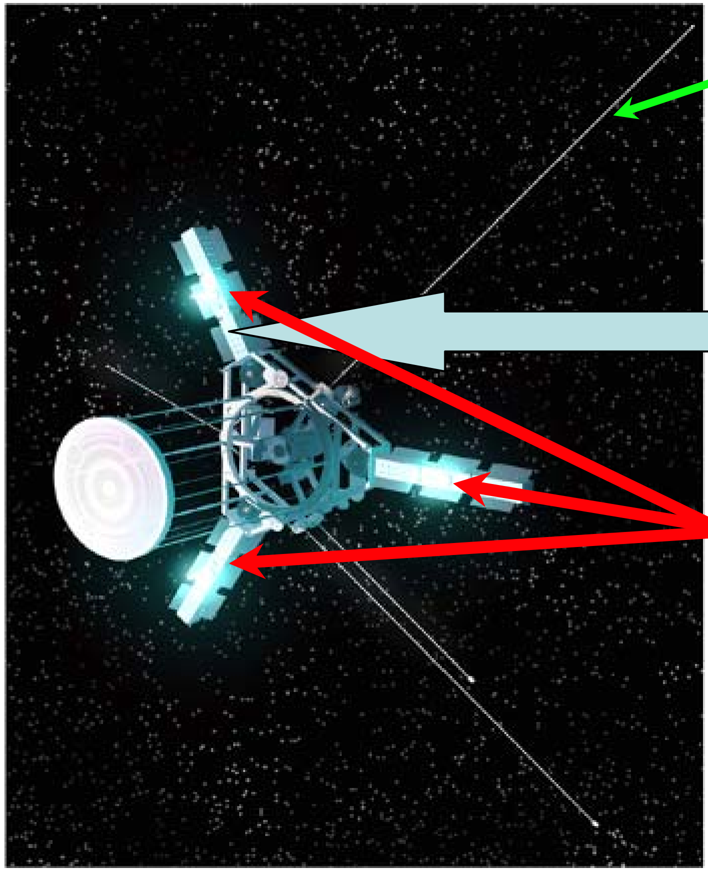
- Thousand AU Mission (TAU)
- Nuclear Electric to 1000 AU
- 60 Metric Ton launch mass
  - 40 MT Xe
  - Apollo Moon missions were ~35 MT and required a Saturn V to launch

Interstellar Probe Instrument Resources and Requirements

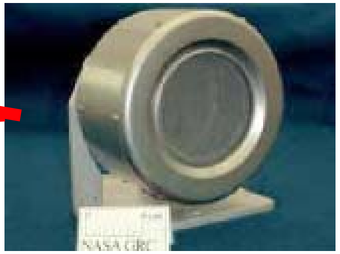
THIS WORK	IIE Team Consensus Payload							Mission and Spacecraft Requirements	Data Product
Material Measured	Acronym	Instrument	Mass (kg)	Power (W)	Acquisition data rate (bps)	Capabilities	Implementation	THIS WORK	THIS WORK
Fields	MAG	Magnetometer	8.81	5.30	130.00	2- three-axis fluxgate magnetometers; do one sample per day from each magnetometer (onboard processing from multiple samples per spacecraft roll period which is TBD)	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 detector	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**				



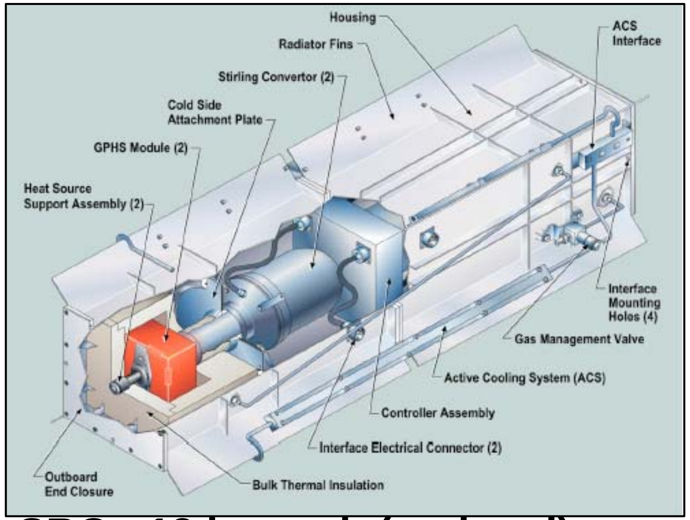
Initial Concept Based Upon NIAC Probe - Change to Radioisotope Electric Propulsion (REP)



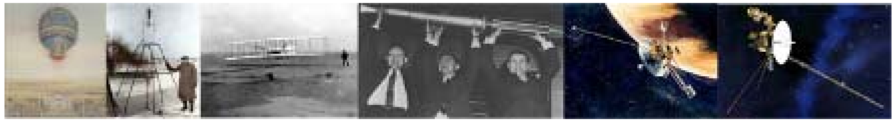
- Booms for plasma waves and magnetometer
- 9 Stirling Radioiostope Generators (SRG) for ~1 kWe
- 3 high Isp (~10,000s) Xe engines



3 Sub-kW Xe engines

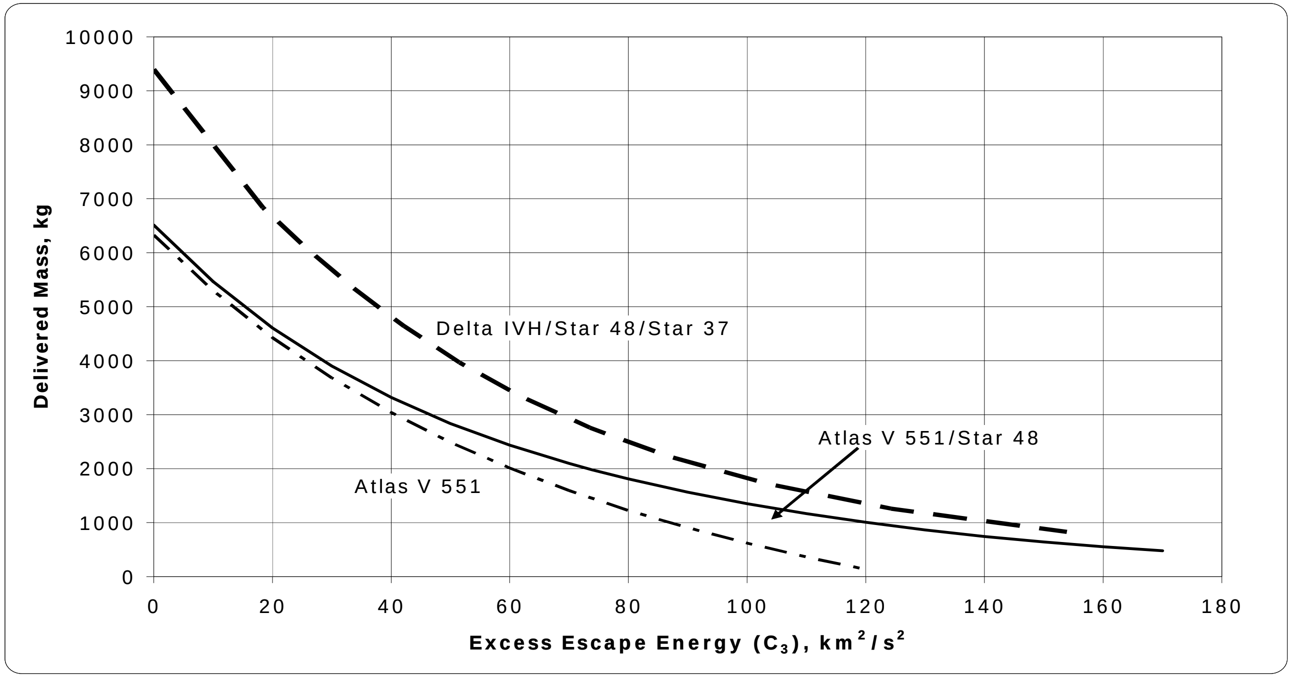


- 2nd gen SRG ~13 kg each (notional)



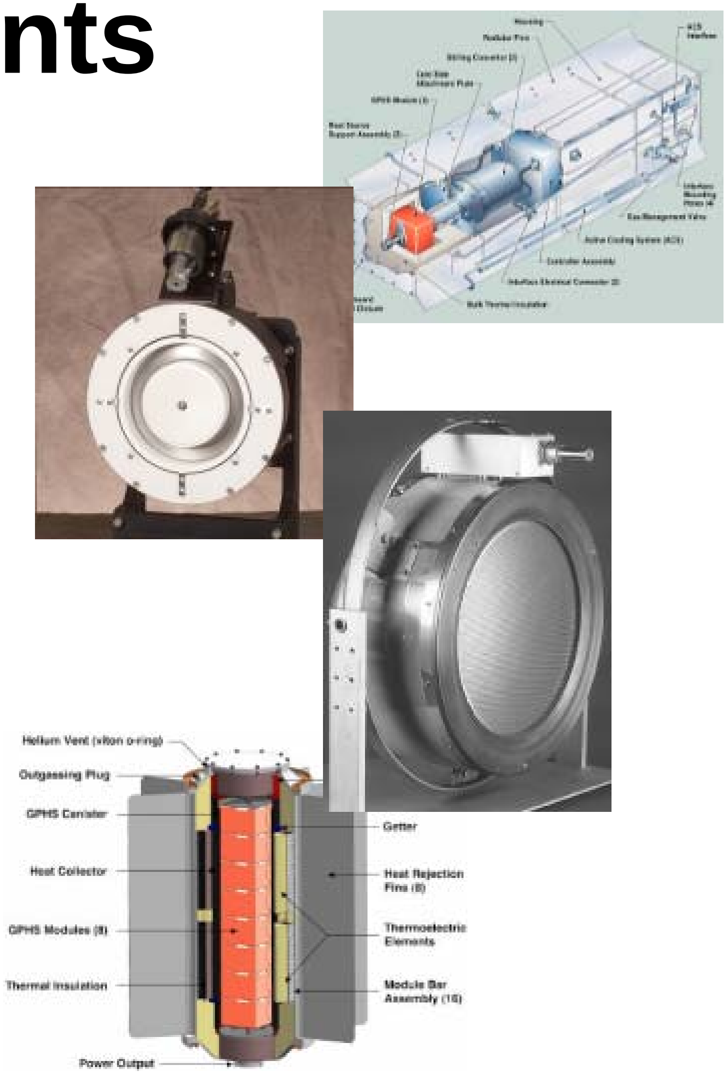
Launch Vehicle Constraints: Initial Mission Designs Used 519 kg Dry Mass

- Delta IV Heavy used with Star 48 + Star 37 to provide best performance
- Maximized performance for direct, single gravity assists at Jupiter, Saturn, Uranus, and Neptune as well as Jupiter+Saturn gravity assist
- Required 20-day launch window



Hardware Constraints

- Missions are mass-constrained
- Requires innovative approaches to spacecraft design
  - Efficient, lightweight electric propulsion
  - Lightweight power system
  - Small science payload (~50 kg)
  - Lightweight structures, communications, attitude control
  - Total dry mass of approximately 500 kg



Direct

Launch 3 February any year

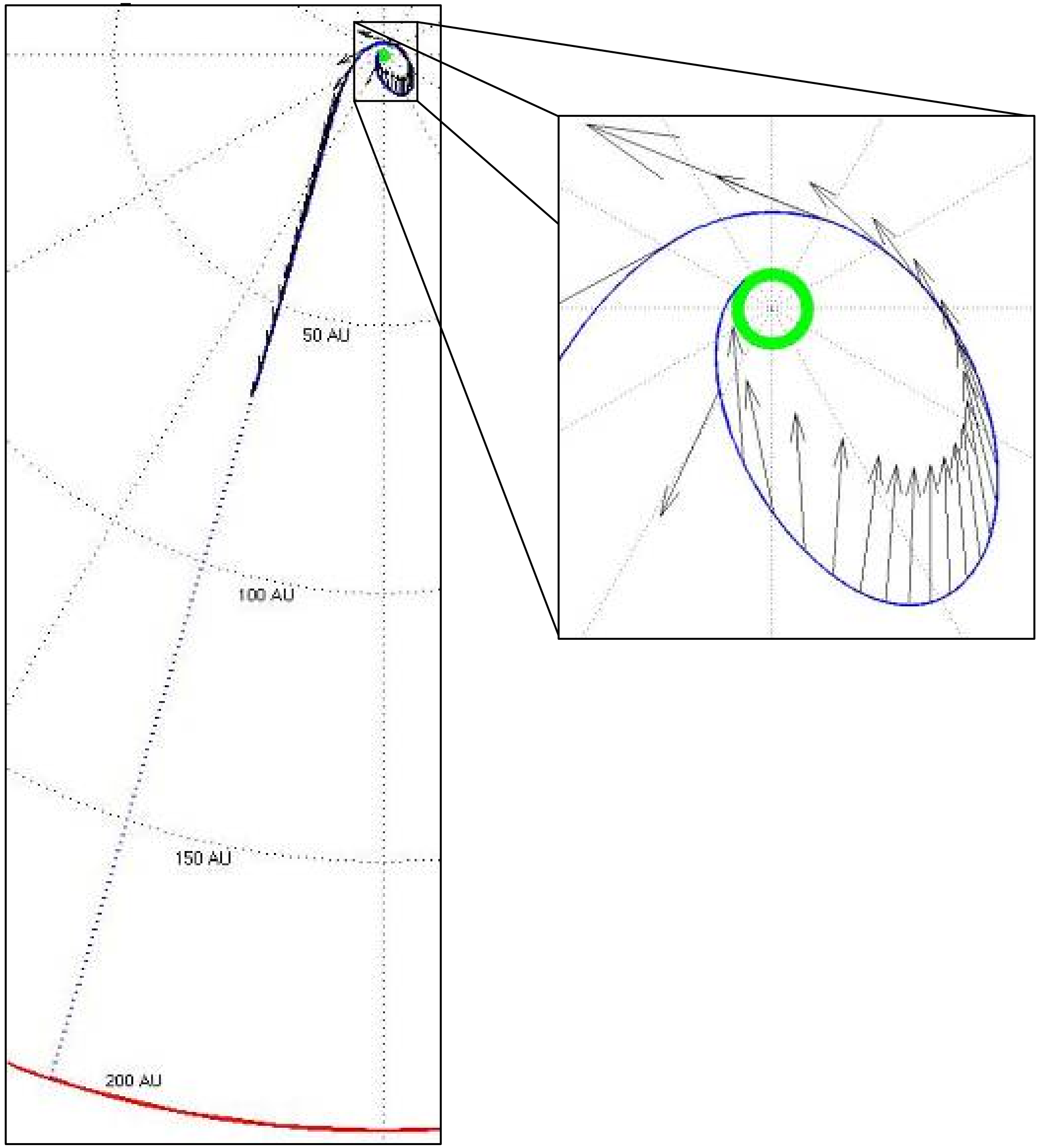
C_3 = 103.8 km^2/s^2

Wet mass 1885 kg

For launch in 2010, window is 7 Dec 2009 - 22 March 2010

Burnout 17 Apr 2036 at 66 AU and 6.6 AU/yr

200 AU reached 18 July 2056 after 46.5 years of flight time



Jupiter Gravity Assist

4 opportunities

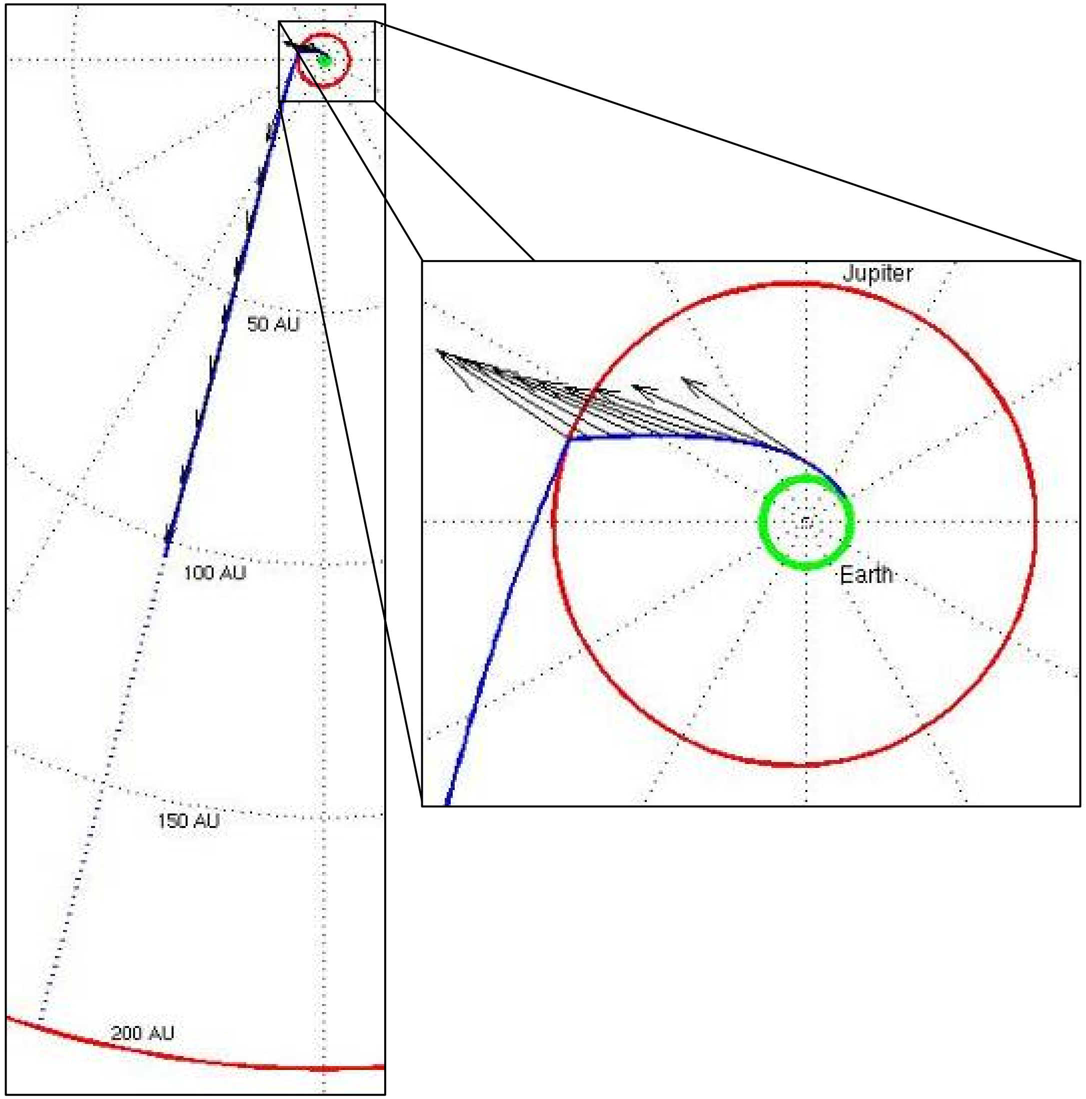
$C_3 = 152.6\ \mathrm{km}^2/\mathrm{s}^2$

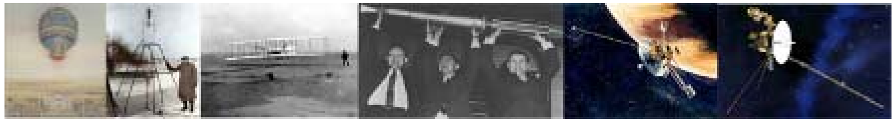
Wet mass 913 kg

For launch in 2014, window is 15 Oct - 3 Nov; next window in ~12 years

Burnout 2 Nov 2029 at 103 AU and 9.5 AU/yr

200 AU reached 13 Jan 2040 after 25.2 years of flight time





Jupiter-Saturn Gravity Assist

1 opportunity

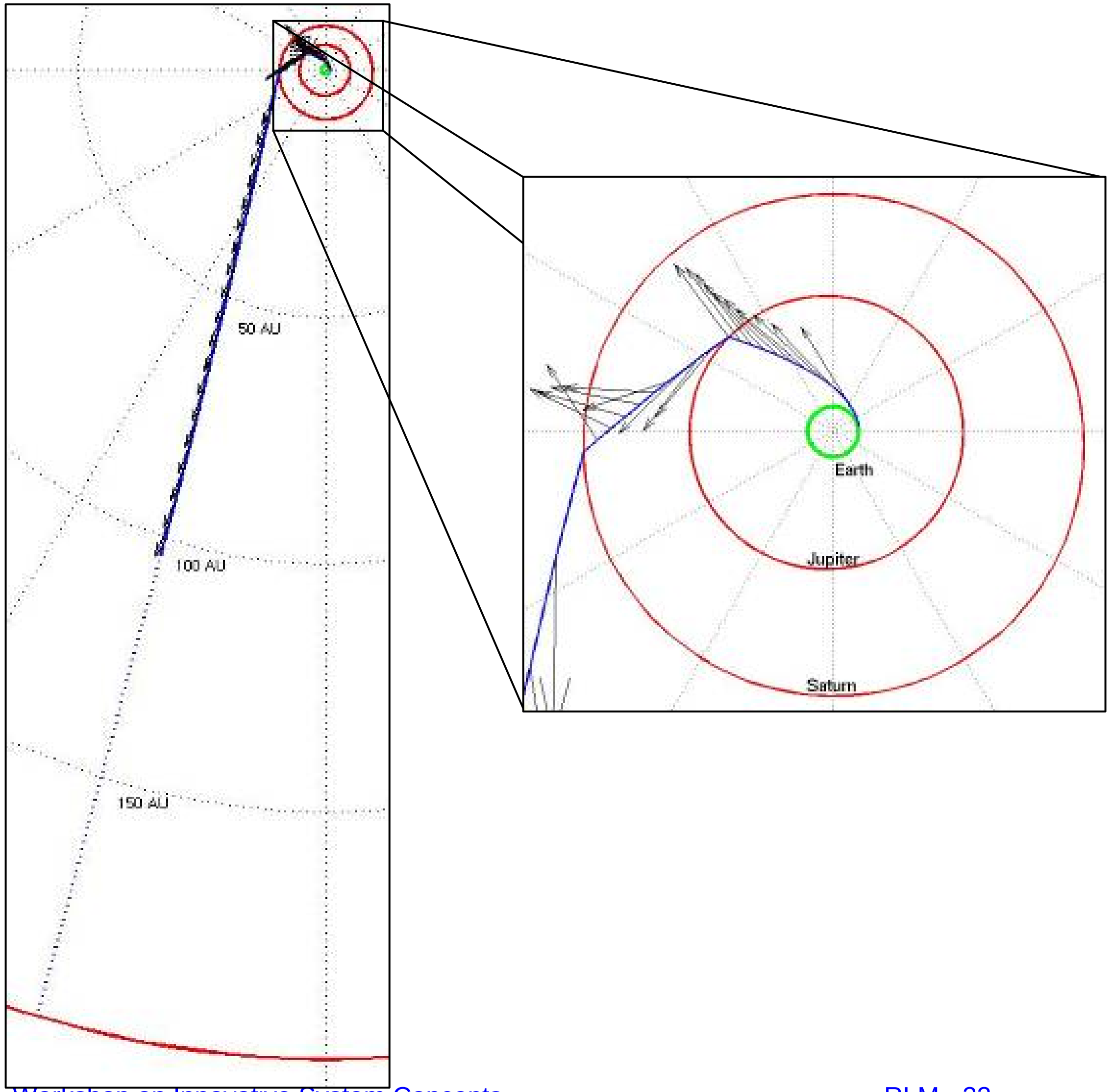
$C_3 = 152.6\ \text{km}^2/\text{s}^2$

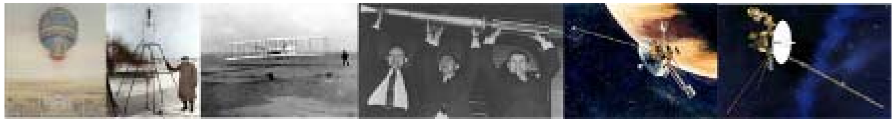
Wet mass 894 kg

Optimal launch 3 October 2037; next window in ~60 years

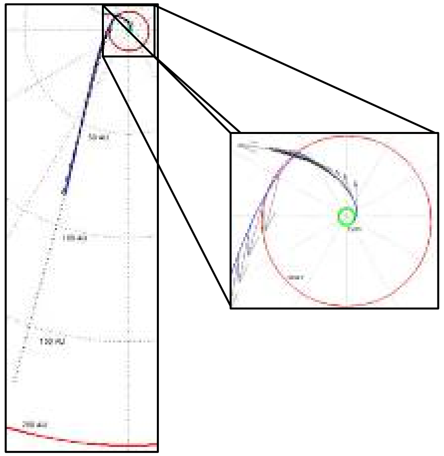
Burnout 21 Dec 2051 at 103 AU and 10.1 AU/yr

200 AU reached 4 Jul 2061 after 23.8 years of flight time

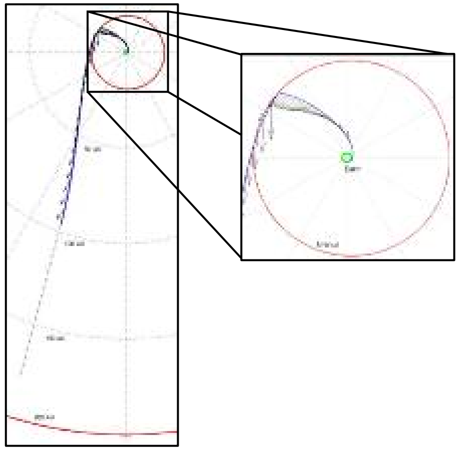




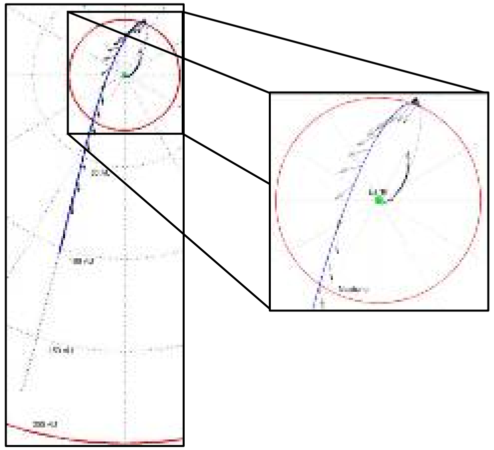
Saturn Gravity Assist

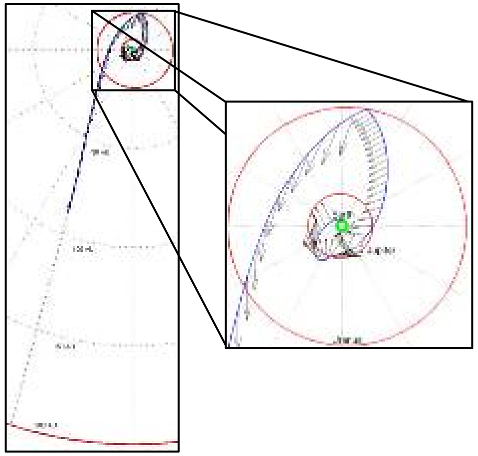


Uranus Gravity Assist

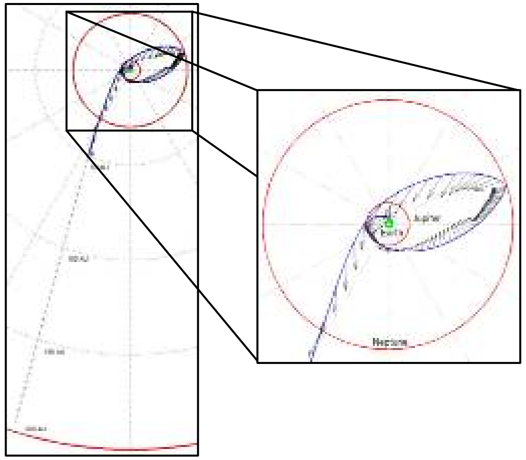


Neptune Gravity Assist





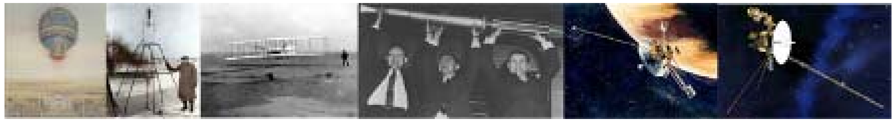
Jupiter-Uranus
Gravity Assist



Jupiter-Neptune
Gravity Assist

Did not explicitly examine Saturn-Uranus, Saturn-Neptune, or Uranus-Neptune combinations

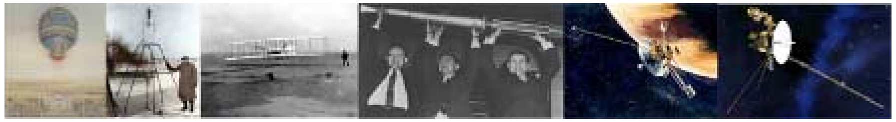
Planetary placement appears to offer no advantage



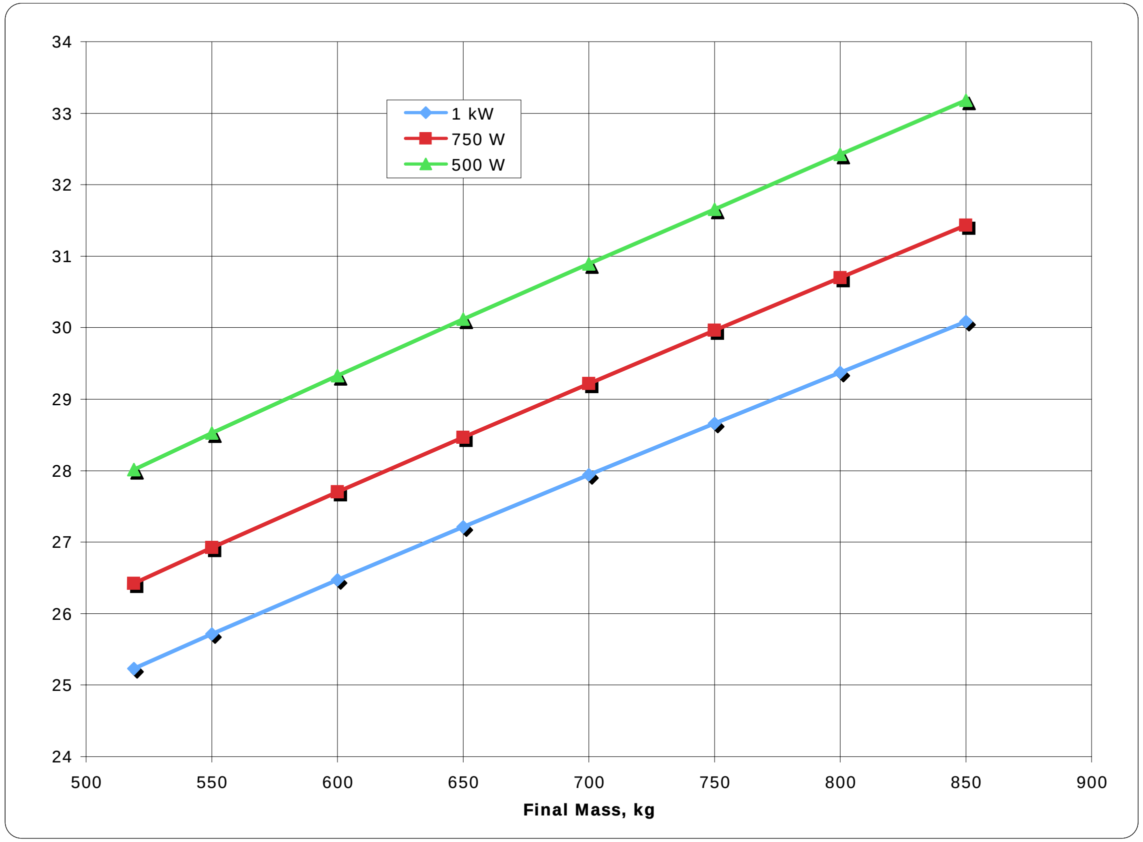
Mission Design Trades

Trajectory	1st Launch Possible	Trip Time (years)	Arrival at 200 AU	Comments
Direct	3 Feb 2010	46.5	18 July 2056	Maximum flexibility
JGA	26 Oct 2014	25.2	13 Jan 2040	Short flight time; radiation hazard; backup in 2026
SGA	26 Aug 2032	33.5	4 Nov 2053	Late launch
JSGA	3 Oct 2037	23.8	4 Jul 2061	Short flight time; late arrival
UGA	15 Aug 2035	42.1	9 Sep 2077	Late arrival
NGA	20 May 2035	69.0	11 May 2104	Late arrival, long flight time
JUGA	15 Dec 2013	55.8	5 Oct 2069	
JNGA	13 Oct 2013	64.6	25 Apr 2078	

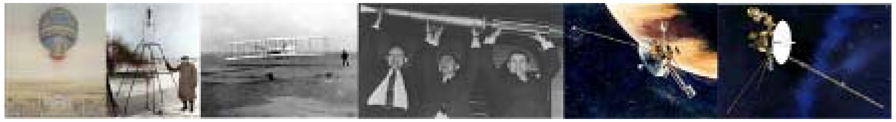
BASELINED



Flyout Time Scales with Dry Mass for Fixed Power



Lower system dry masses decrease flyout time



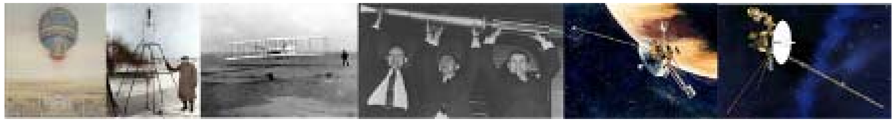
Four Options Studied

1 - 5.8 kbps (200 AU) = 500 bps accumulation 24/7
  - 586.1 kg dry/761.9 kg with contingency/1283.3 kg wet
  - Three 1000 W ion engines, 2.1-m HGA, 4 CDS strings

2 - same as 1 with aggressive technology
  - 518.5 kg dry/674.0 kg with contingency/1191.4 kg wet
  - Two 1000 W ion engines, 3-m HGA, 2 CDS strings

3 - 500 bps (200 AU); baseline with reduced data rate
  - 571.4 kg dry/742.8 kg with contingency/1262.8 kg wet
  - Three 1000 W ion engines, 2.1-m HGA, 4 CDS strings

- 4 - Aggressive technology; 500 bps rate; low power
  - 465.3 kg dry/604.9 kg with contingency/1066.2 kg wet
  - Two 750 W ion engines, 2.1-m HGA, 2 CDS strings



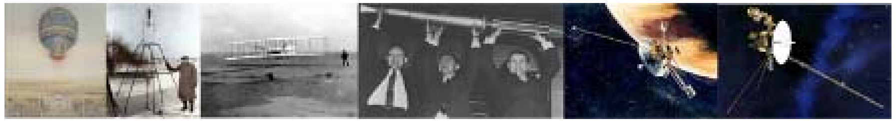
Enabling Infrastructure and Technologies

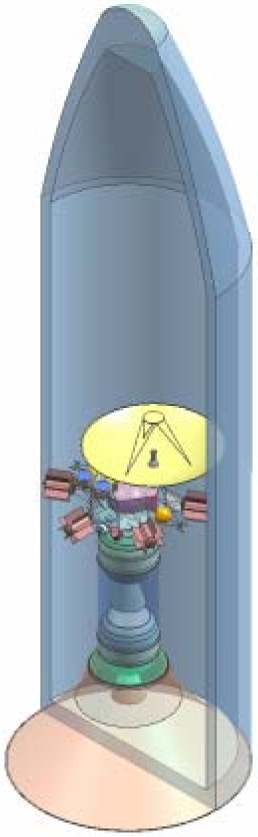
Technology

- **Advanced high mass-to-power radioactive power sources (RPS)**
  - **2nd gen EMI-quiet Stirling Radioisotope Generator**
  - **Advanced high-temperature RTG, e.g. skutterudite converters**
- **Low-power (~1 kW), low-mass, 3800s $I_{sp,}$ Xe-ion thrusters**
- **DSN Ka-band "antenna farm" of massively phased array (180 12-m antennas)**
- **Space-flight parts and subsystems qualified for 30 to 50 year missions**

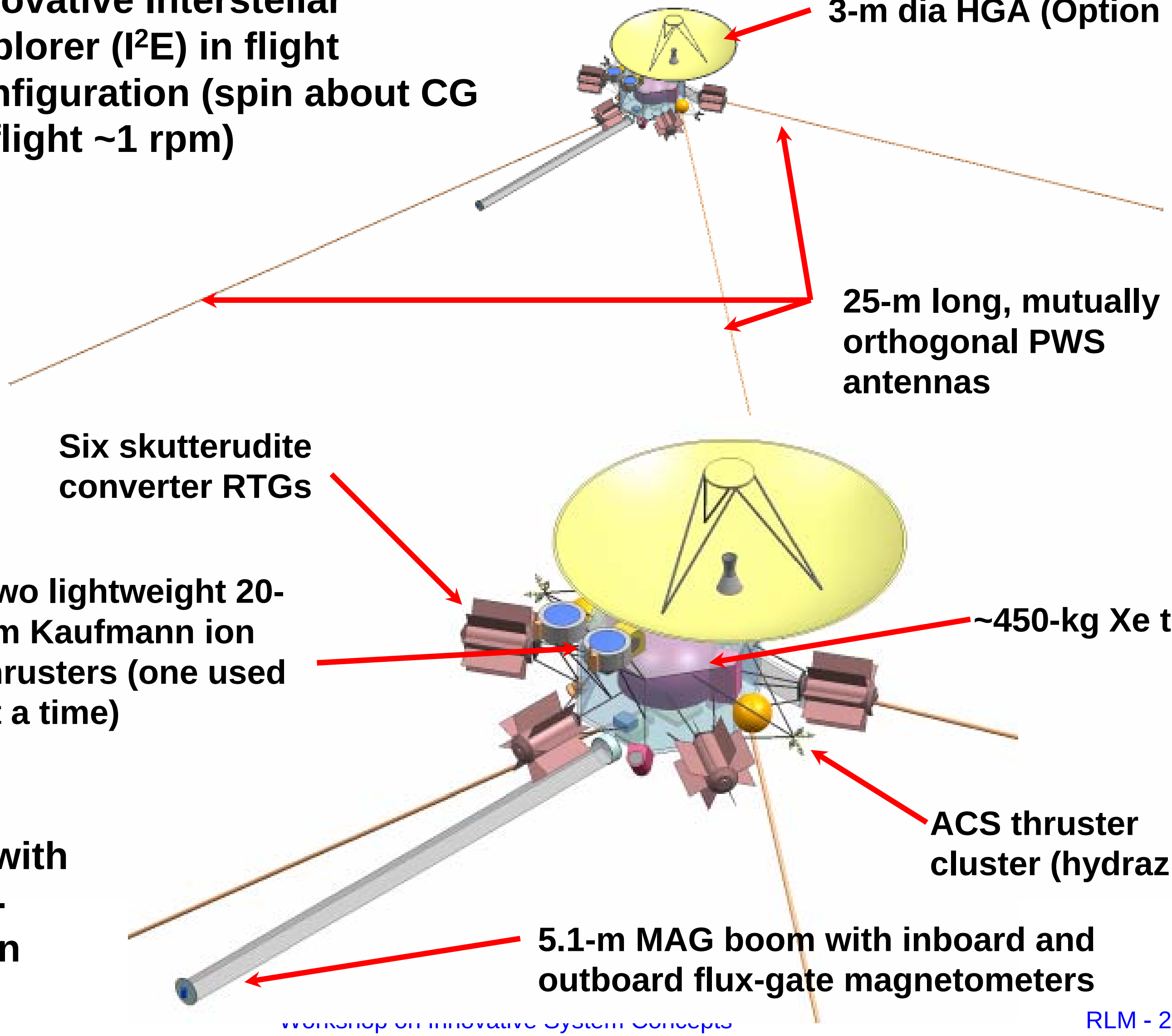
Infrastructure

- **Cost-efficient, high-performance EELVs**
- **Affordable DSN aperture time for the "antenna farm"**





Innovative Interstellar Explorer (I^{2}E) in flight configuration (spin about CG in flight ~1 rpm)



3-m dia HGA (Option 2)

25-m long, mutually orthogonal PWS antennas

Six skutterudite converter RTGs

Two lightweight 20-cm Kaufmann ion thrusters (one used at a time)

~450-kg Xe tank

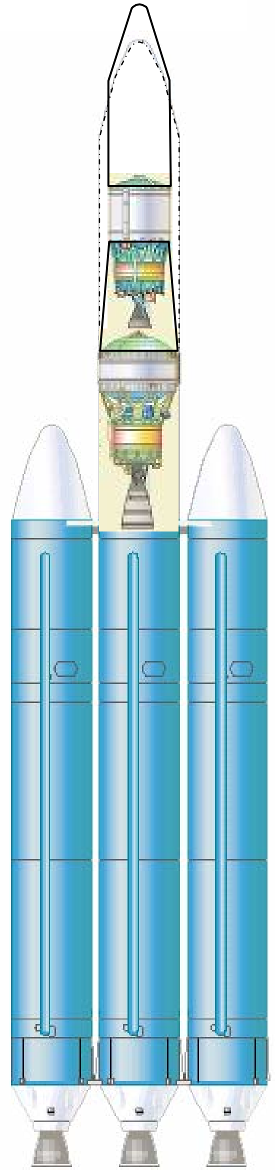
ACS thruster cluster (hydrazine)

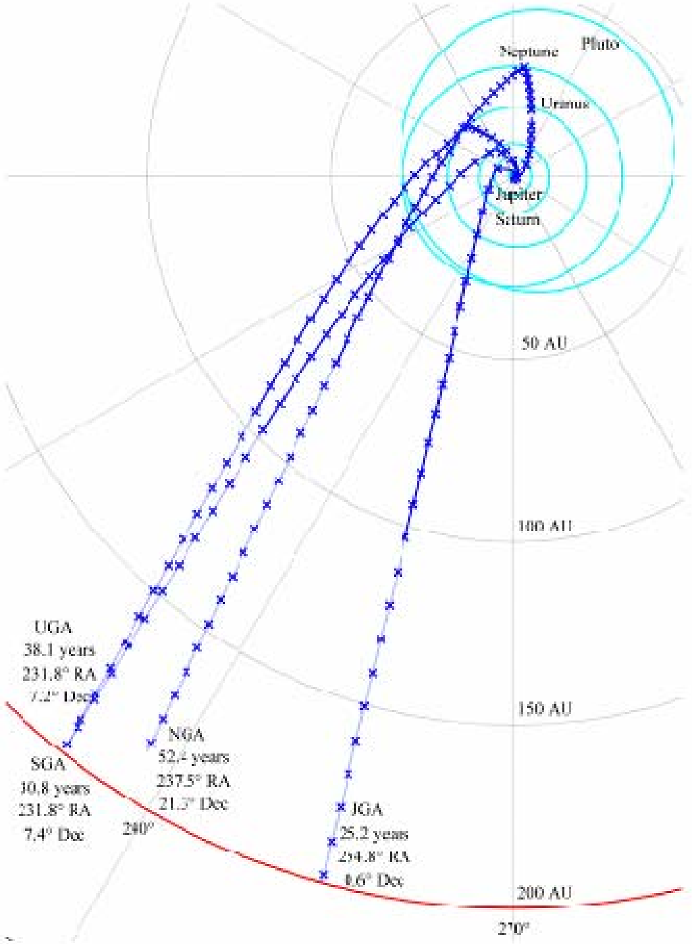
5.1-m MAG boom with inboard and outboard flux-gate magnetometers

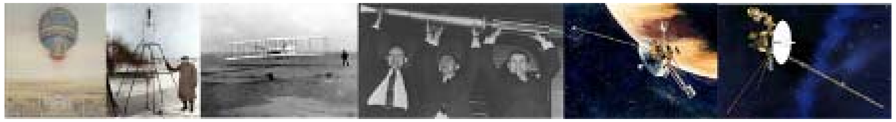
I^{2}E in Titan shroud with stacked Star 48As - launch configuration

Mission Design Options

- **Upper stage options for Delta IV H are still under study**

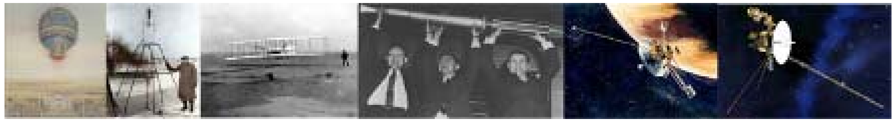






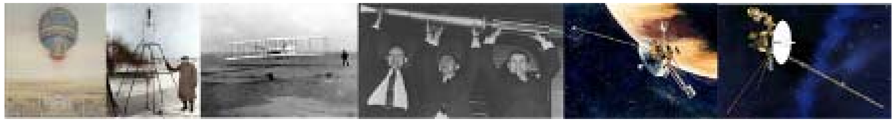
Option Mission Designs

	Option 1	Option 2	Option 3	Option 4
Launch Date	October 22, 2014	October 23, 2014	October 22, 2014	October 24, 2014
Gravity Assist Body	Jupiter	Jupiter	Jupiter	Jupiter
Gravity Assist Date	February 5, 2016	January 21, 2016	February 2, 2016	January 8, 2016
Gravity Assist Altitude	75150 km	67658 km	73695 km	61904 km
Gravity Assist Radius	2.05 Rj	1.95 Rj	2.03 Rj	1.87 Rj
Gravity Assist ²v	23.8 km/s	24.8 km/s	24.0 km/s	25.5 km/s
Burnout Date	October 13, 2032	December 4, 2031	August 9, 2032	April 10, 2032
Burnout Distance	104 AU	104 AU	104 AU	106 AU
Burnout Speed	7.9 AU/year	8.3 AU/year	7.9 AU/year	8.1 AU/year
Date 200 AU Reached	December 31, 2044	July 24, 2043	September 12, 2044	October 31, 2043
Minimum Trip Time to 200 AU	30.2 years	28.8 years	29.9 years	29.0 years
Speed at 200 AU	7.8 AU/year	8.3 AU/year	7.9 AU/year	8.1 AU/year
Right Ascension at 200 AU	263.8Þ	261.5Þ	263.4Þ	259.9Þ
Declination at 200 AU	0.0Þ	0.0Þ	0.0Þ	0.0Þ
Launch Mass	1230 kg	1135 kg	1210 kg	1013 kg
Propellant Mass	440 kg	433 kg	439 kg	380 kg
Final Mass	790 kg	702 kg	771 kg	633 kg
Power	1.0 kW	1.0 kW	1.0 kW	0.75 kW
Isp	3800 s	3734 s	3784 s	3479 s
EP System Efficiency	53.8%	53.8%	53.8%	53.5%
Total Stack C3	123.3 km2/s2	129.0 km2/s2	124.3 km2/s2	136.0 km2/s2
Delta IV H C3	16.8 km2/s2	17.6 km2/s2	16.9 km2/s2	18.5 km2/s2
Delta IV H Launch Mass	6851 kg	6743 kg	6832 kg	6622 kg
EP ²v	16.5 km/s	17.6 km/s	16.7 km/s	16.1 km/s
Thrust Time	18.0 years	17.1 years	17.8 years	17.5 years



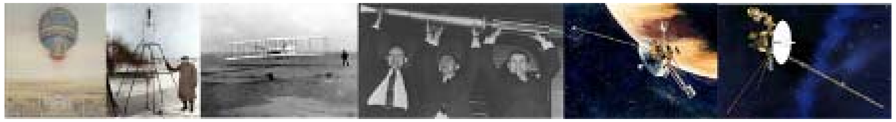
Mission Backups

- Xe propellant ~430 kg to 450 kg across options
- October 2014 launch prime with 20+ day window
- Backups at ~13-month intervals (Nov 2015, December 2016, January 2018) with same spacecraft
- Cycle repeats ~every 12 years (2014, 2026, 2038, 2050)



Team X Exercise

- Provided input:
  - Instrument list: 9 at 35.16 kg and 29.40 W
  - Trades, studies, and risks: 12 studies with 19 issues and potential resolutions
  - Master Equipment List (preliminary):by subsystem
  - Initial Mission Designs: down select to Jupiter flyby
- Three 3-hour sessions at JPL to work tradespace interactively and realtime



Mission Configurations:
4 options, 6 power modes, 30% mass contingency

Stabilization - cruise	**Spin**	
Stabilization - science	**Spin**	
Pointing Control	**180**	arcsec
Pointing Knowledge	**90**	arcsec
Pointing Stability	**10**	arcsec/sec
Determined by:	**Telecom**	

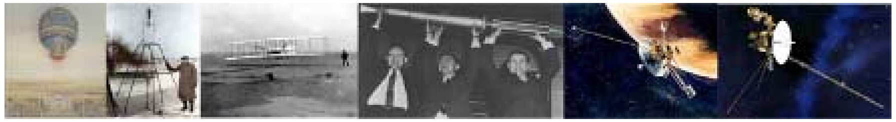
Legend	
🟦	Inputs from Subsystems
🟥	Inputs from Systems
🟩	Calculated

Pointing Direction - cruise	**Earth**
Pointing Direction - science	**Space**
Radiation Total Dose, krad	**65**
Science FER	**1.00E-04**
Redundancy	**Selected**
Technology Cutoff	**2010**

Mission Duration	**25.2**	years
Max probe Sun distance	**200**	AU
Instrument Data Rate	**0.5**	kb/s
Data Storage	**8.0**	Gb
Total Mission Data Volume	**6.6E+12**	Mbits
Maximum Link Distance	**201**	AU
Return Data Rate for Baseline	**5.8**	kb/s <-- from 200 AU with 2 passes per week

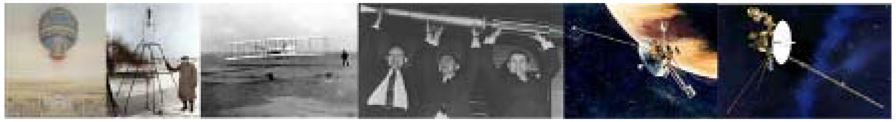
	Mass Fraction	**Input** **Master Equipment List (MEL) (kg)** Customer Input	**Team X** **Mass (kg)** Option 1 Baseline	**Team X** **Mass (kg)** Option 2 Aggressive Technology Assumptions	**Team X** **Mass (kg)** Option 3 Reduced Downlink Rate	**Team X** **Mass (kg)** Option 4 Aggressive Technology and Reduced Downlink Rate	**Subsys** **Contingency %**	**CBE+** **Contingency (kg)**	**Mode 1** **Power (W)** Safing	**Mode 2** **Power (W)** Telecom beyond 103 AU (2 8hr passes per week at 200AU -- no thrusting, continuous science)	**Mode 3** **Power (W)** Engine-off Cruise 103-200AU (Continuous Science)	**Mode 4** **Power (W)** Engine-on Cruise 10 to 103 AU (Continuous Science)	**Mode 5** **Power (W)** Launch	**Mode 6** **Power (W)** Telecom to 103 AU (1 8hr pass per week -- continuous science, no thrusting during telecom)	**TRL**
Payload															
Instruments	6.0%	35.2	35.2	35.2	35.2	35.2	30%	45.7	9.1	29.4	29.4	29.4	0.0	29.4	
Payload Total	6.0%	35.2	35.2	35.2	35.2	35.2	30%	45.7	9.1	29.4	29.4	29.4	0.0	29.4	
Bus															
Attitude Control	2.5%	16.7	14.9	6.8	14.9	6.8	21%	18.0	9.0	36.0	36.0	36.0	40.0	36.0	5
Command & Data	4.4%	12.2	25.8	13.9	25.8	13.9	30%	33.5	43.0	43.0	43.0	43.0	43.0	43.0	4
Power	31.2%	231.2	182.3	182.3	182.3	154.6	30%	237.0	10.1	46.0	10.4	11.4	8.2	46.5	2
Propulsion1	13.8%	74.9	80.9	61.7	80.9	59.0	20%	97.1	0.7	0.7	0.7	0.7	0.7	0.7	4
Propulsion2	1.8%	32.1	10.4	10.4	10.4	10.3	18%	12.3	41.0	41.0	1.0	1.0	1.0	41.0	6
Structures & Mechanisms	21.6%	134.6	126.5	109.6	124.0	99.0	30%	164.4	0.0	0.0	0.0	0.0	0.0	0.0	6
S/C-side Adapter	0.0%	0.0	0.0	0.0	0.0	0.0	30%	0.0							
Cabling	6.5%	40.0	37.9	30.4	37.2	28.2	30%	49.3							7
Telecomm	3.9%	19.1	23.1	24.2	21.1	21.1	20%	27.7	17.0	522.6	17.0	17.0	17.0	517.0	
Thermal	8.2%	22.3	47.7	41.7	38.5	34.7	30%	61.9	34.5	34.5	32.0	47.5	23.8	47.5	6
Bus Total		583.2	549.5	481.0	534.9	427.7	28%	701.1	155.2	723.8	140.0	156.5	133.6	731.6	
Spacecraft Total (Dry)		618.3	584.6	516.2	570.1	462.8	28%	746.9	164.3	753.2	169.4	185.9	133.6	761.0	
Subsystem Heritage Contingency		33.8%	162.2	144.6	158.1	128.9	28%	28%							
System Contingency		209.2	13.2	10.3	13.0	10.0	2%	2%	49.3	225.9	50.8	55.8	40.1	228.3	
Spacecraft with Contingency		**827.5**	**760.0**	**671.1**	**741.1**	**601.7**	of total	w/o addl pld	**213.6**	**979.1**	**220.3**	**241.7**	**173.6**	**989.4**	
Propellant & Pressurant1	36.8%	400.0	459.4	449.6	460.8	393.8		For S/C mass =	1250		Delta-V, Sys 1	15900	m/s		
Propellant & Pressurant2	2.4%	80.6	30.5	30.5	30.5	30.5		For S/C mass =	1250		Delta-V, Sys 2	0	m/s		
Spacecraft Total (Wet)		**1308.1**	**1249.9**	**1151.2**	**1232.5**	**1026.0**									
2 Star 48A Motors with 2% contingency			5265.2	5265.2	5265.2	5265.2									
Adapter from top Star 48 to s/c w/ 30% cont			45.8	32.1	45.3	28.9									
Adapter between 2 Star 48 Motors w/ 15%			209.3	209.3	209.3	209.3									
Adapter from LV to bottom Star 48 w/ 15%		0.0	104.7	104.7	104.7	104.7									
Launch Mass		**1308.1**	**6874.9**	**6762.4**	**6856.9**	**6634.1**									
Launch Vehicle Capability		1124.0	**6906.0**	**6803.0**	**6887.0**	**6678.0**	Delta IV 4050H								
Launch Vehicle Margin		**-184.1**	**31.1**	**40.6**	**30.1**	**43.9**									
SpaceCraft Mass Margin		**-184.1**	**31.1**	**40.6**	**30.1**	**43.9**									
SpaceCraft Mass Margin (%)			0%	1%	0%	1%									

Contingencies	Mass	Power
Instruments	30%	30%
Electric Propulsion Engine	0%	10%
Additional Payload	0%	0%
Spacecraft Bus, dry	30%	30%
Launch C3		16.3
Mission Unique LV Contingency		0%
Fairing type		standard



Optimized Mission Set (Across All Options)

- Xe - 430 kg to 490 kg across options
- October 2014 launch/20 day window/backups though 2018 (one per year)
- Jupiter flyby early 2016 at ~2 RJ
- “Burnout” in ~2031-2032 at ~105 AU
- Burnout speed ~8 AU /yr (38 km/s)
- 200 AU reached ~2043-45 (~30 year flyout)



Schedule for Baseline Probe

(Option 1 - minimum new technology)

✓ 2004-2005 Update of NASA strategic plan with ISP Vision Mission included

2006-2007 Focused technology development for small probe technologies

2007-2010 Focused technology development for an Interstellar Probe

2010 Start RPS fuel procurement and NEPA approvals

2010-2014 Design and launch I^2E probe

2016 Begin routine data acquisition following Jupiter gravity assist

- 2020 Voyagers cease transmission - V1 at ~150 AU, V2 at ~125 AU
- 2044 Data return from 200 AU [Mission Success]; Launch + 30 yrs
- 2057 Data returned from 300 AU (at 7.8 AU/yr burnout speed); L + 43 yrs
- 2147 Probe at 1000 AU - “Undisturbed” VLISM reached by now; 1.5 half-lives since original Pu-238 procurement; L + 133 yrs

Exploration of near interstellar space in the near term IS possible …but we need to be serious NOW to launch by 2014

REP at Jupiter gravity assist in 2016, spacecraft *en route* to the heliopause ~150 AU away