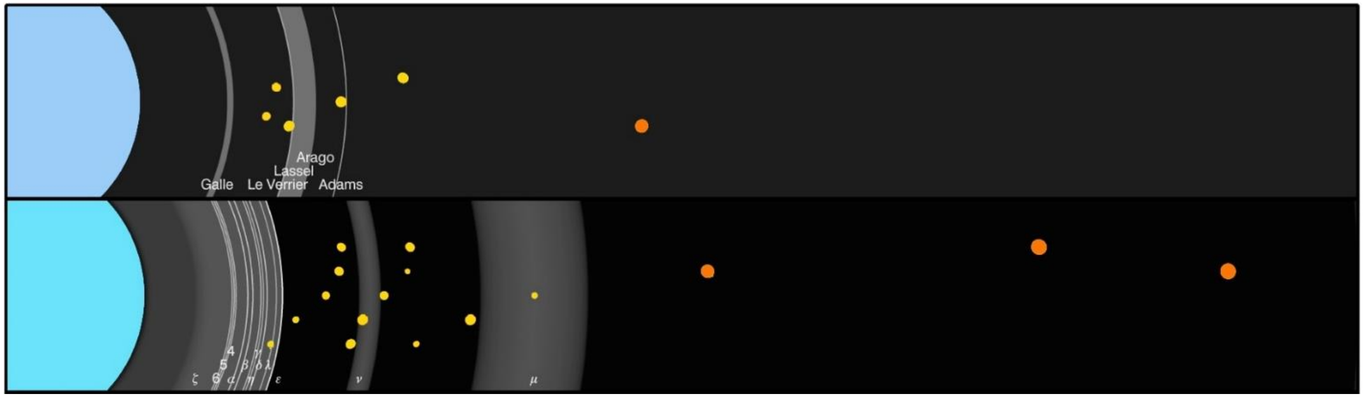
Ice Giants

Pre-Decadal Study Summary

ESA Headquarters, 31 January 2017

Mark Hofstadter, Kim Reh



Predecisional - For planning and discussion purposes only.
URS CL#17-0488

Study Goal and Objectives

Goal

- Assess science priorities and affordable mission concepts & options for exploration of the Ice Giant planets, Uranus and Neptune in preparation for the next Decadal Survey.

Objectives

- Evaluate alternative architectures to determine the most compelling science mission(s) that can be feasibly performed within $2B ($FY15)
  - Identify potential concepts across a spectrum of price points
- Identify mission concepts that can address science priorities based on what has been learned since the 2013–2022 Decadal Survey
- Identify enabling/enhancing technologies
- Assess capabilities afforded by SLS

Key Study Guidelines
(Excerpted from Study Guidelines Document)

- Establish a Science Definition Team
- Address both Uranus and Neptune systems
- Determine pros/cons of using one spacecraft design for both missions (possibility of joint development of two copies)
- Identify missions across a range of price points, with a cost not to exceed $2B ($FY15) per mission
- Perform independent cost estimate and reconciliation with study team
- Identify model payload for accommodation assessment for each candidate mission.
- Constrain missions to fit on a commercial LV
  - Also identify benefits/cost savings if SLS were available (e.g., time, traj., etc.)
- Launch dates from 2024 to 2037 (focus on the next decadal period)
- Evaluate use of realistic emerging enabling technologies; distinguish mission specific vs. broad applicability
- Identify clean interface roles for potential international partnerships

Mission Study Team – Chartered by Jim Green

- **NASA Interface:** Curt Niebur **ESA Interface:** Luigi Colangeli
- **Study Lead:** John Elliott **JPL Study Manager:** Kim Reh

Mission Concept Design
Terri Anderson (costing)
David Atkinson (probes)
Nitin Arora (trajectory)
Chester Borden (system eng.)
Jim Cutts (technology)
Young Lee (RPS)
Anastassios Petropoulos (trajectory)
Tom Spilker (science, system eng.)
David Woerner (RPS)

Science Definition Team
Co-Chairs: M. Hofstadter/A. Simon
Members: See next slide

Other Organizations
Langley Research Center (TPS)
Ames Research Center (TPS)
Purdue University (mission design)
Aerospace Corp. (ICE)

Science Definition Team – selected by NASA

- **Chairs:** Mark Hofstadter (JPL), Amy Simon (Goddard)

Sushil Atreya (Univ. Mich.)
Donald Banfield (Cornell)
Jonathan Fortney (UCSC)
Alexander Hayes (Cornell)
Matthew Hedman (Univ. Idaho)
George Hospodarsky (Univ. Iowa)

ESA Members:
Adam Masters (Imp. College)
Diego Turrini (INAF-IAPS/UDA)

Kathleen Mandt (SwRI)
Mark Showalter (SETI Inst.)
Krista Soderlund (Univ. Texas)
Elizabeth Turtle (APL)

Community Engagement

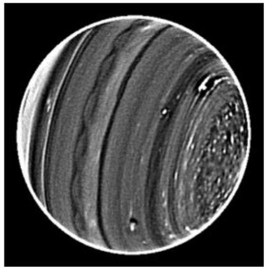
- Completed
  - CAPS in September 2015; Irvine, California
  - DPS November 2015; National Harbor, Maryland
  - OPAG Feb/Aug 2016; SDT announced in Feb.
  - LPSC Town Hall; March 2016, The Woodlands, Tx

- Planned 2017
  - OPAG in February; Atlanta, Georgia
  - LPSC in March; The Woodlands, Tx
  - EGU April (Town Hall and Oral); Vienna Austria
  - CAPS in April, Washington DC

Why are Uranus and Neptune Important?

- These relatively unexplored systems are fundamentally different from the gas giants (Jupiter and Saturn) and the terrestrial planets
  - Uranus and Neptune are ~65% water by mass (plus some methane, ammonia and other so-called “ices”). Terrestrial planets are 100% rock; Jupiter and Saturn are ~85% H_2 and He
- Ice giants appear to be very common in our galaxy; most planets known today are ice giants
- They challenge our understanding of planetary formation, evolution, and physics
  - Models suggest ice giants have a narrow time window for formation. If that is correct, why are they so common in other planetary systems?
  - Why is Uranus not releasing significant amounts of internal heat? Does its output vary seasonally?
  - Why are the ice giant magnetic fields so complex? How do the unusual geometries affect interactions with the solar wind?

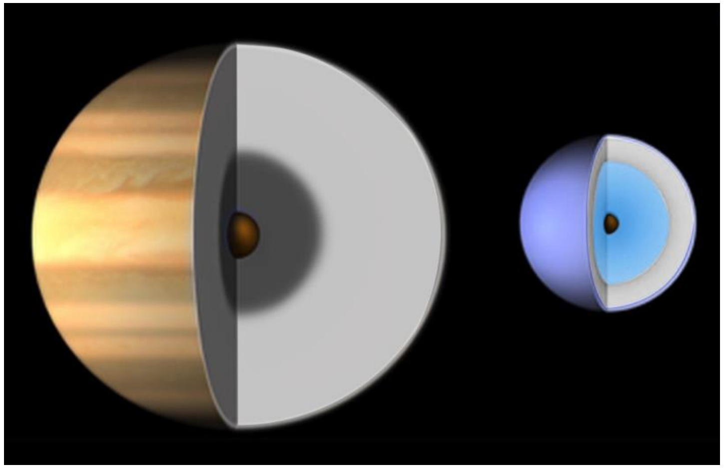
Ice Giants are critical to our understanding of how planetary systems form and evolve



Uranus in 2012 (left, Sromovsky et al. 2015) and 1986 (right, Voyager)

Science Objectives Summary

- All elements of the Ice Giant systems (interior, atmosphere, rings, satellites, magnetosphere) have important science objectives that cannot be met through Earth-based observations
- Determining the interior structure and bulk composition of the ice giants is identified as the highest-payoff science
- Scientific and technological advances, and improved trajectories, make these measurements higher priority than in the Decadal Survey
- 12 key science objectives drive mission architectures (next slide)



- All science objectives are consistent with and traceable to the decadal survey

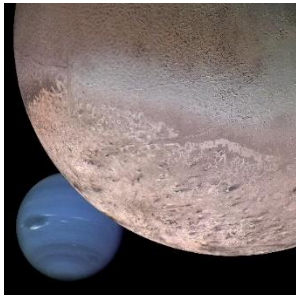
12 Key Science Objectives

Highest Priority

- Interior structure of the planet
- Bulk composition of the planet (including isotopes and noble gases)

Planetary Interior/Atmosphere

- Planetary dynamo
- Atmospheric heat balance
- Tropospheric 3-D flow

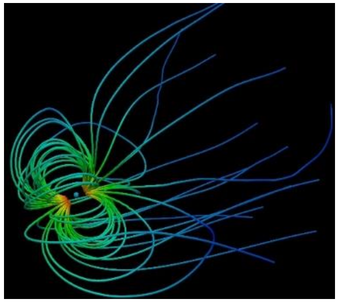


Rings/Satellites

- Internal structure of satellites
- Inventory of small moons, including those in rings
- Ring and satellite surface composition
- Ring structures and temporal variability
- Shape and surface geology of satellites
- Triton's atmosphere: origin, evolution, and dynamics

Magnetosphere

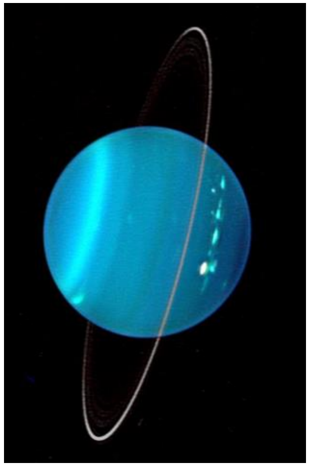
- Solar wind-magnetosphere-ionosphere interactions and plasma transport

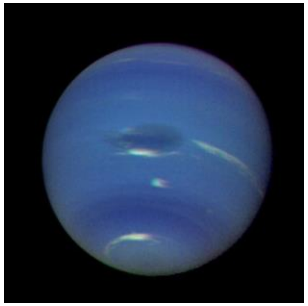


Predecisional - For planning and discussion purposes only. URS CL#17-0488

Uranus or Neptune?

- Uranus and Neptune systems are equally important
- A Flagship mission to either is scientifically compelling
- It is important to recognize, however, that Uranus and Neptune are not equivalent. Each has things to teach us the other cannot. For example
  - Native ice-giant satellites (Uranus) vs. captured Kuiper Belt object (Neptune)
  - The smallest (Uranus) and largest (Neptune) releases of internal heat, relative to input solar, of any giant planet
  - Dynamics of thin, dense rings and densely packed satellites (Uranus) vs. clumpy rings (Neptune)





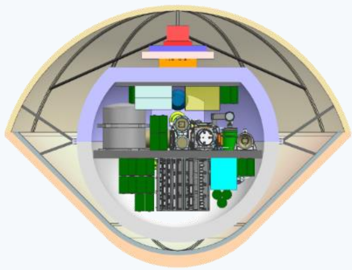
Uranus (top, Sromovsky et al. 2007) and Neptune (bottom, Voyager)

Model Payloads

Chosen to maximize science return. Similar for Uranus and Neptune, and whether flyby or orbiter.

Model payload for probe:

- Mass spectrometer
- ASI (density, pressure and temperature profile)
- Hydrogen ortho-para instrument
- Nephelometer



Model payload for orbiter

50 kg orbiter payload addresses minimum acceptable science

- NAC,
- Doppler Imager,
- Magnetometer.

90 kg orbiter payload partially addresses each science objective. Add to 50 kg case:

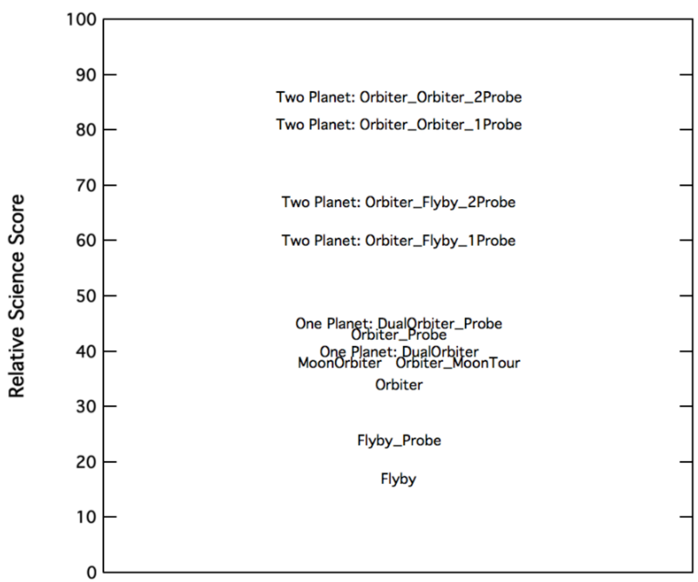
- Vis/NIR imaging spectrometer,
- Radio and Plasma suite,
- Thermal IR,
- Mid-IR (Uranus) or UV (Neptune) spectrometer.

150 kg orbiter payload comprehensively addresses all science objectives. Add to 90 kg case:

- WAC,
- USO,
- Energetic Neutral Atoms,
- Dust detector,
- Langmuir probe,
- Microwave sounder/Mass spec.

Mission Architectures

- Wide range of architectures assessed; ranked scientifically and costed
- An orbiter with probe meets the science requirements and study cost target
- Adding a second spacecraft to the other ice giant significantly enhances the science return at a proportionally higher cost



Getting to the Ice Giants

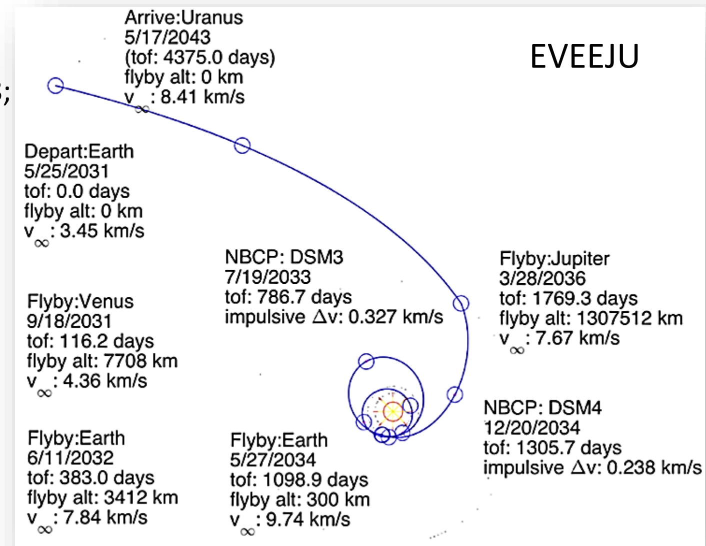
- Launch interval studied: [2024 – 2037]
- Total mission duration < 15 years including at least 2 years of science
- Interplanetary flight time:
  - 6 – 12 years to Uranus
  - 8 – 13 years to Neptune

Launch Vehicles	Interplanetary Trajectory	Gravity Assist (up to 4 per Traj.)	Target Bodies	SEP Power	EP Engines	Orbit Insertion
•Atlas V •Delta-IV Heavy •SLS-1B	•Chemical + DSM + GA •SEP + GA •REP + GA •Dual Spacecraft	•Venus •Earth •Mars •Jupiter •Saturn	•Uranus •Neptune	•15 kW •25 kW •35 kW	•NEXT 1+1 (SEP) •NEXT 2+1 (SEP) •NEXT 3+1 (SEP) •XIPS (REP)	•Chemical (Bi-Prop) •Chemical (cryo) •REP •Aerocapture

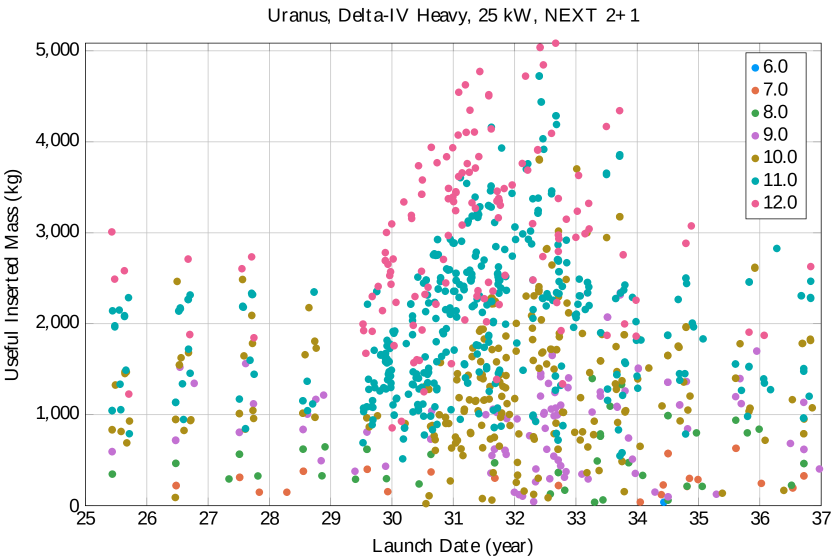
Tens of thousands of trajectory options to both planets were examined

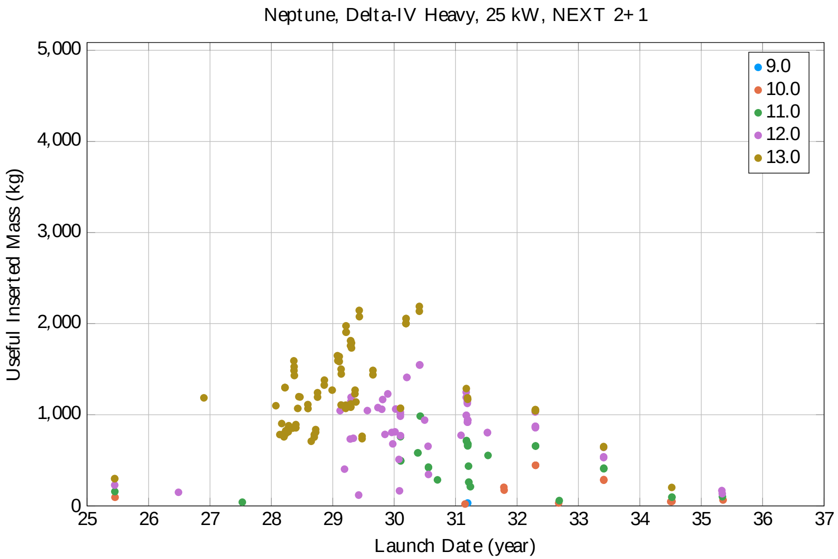
Mission Design Takeaways

- Optimal launch opportunities to Uranus and Neptune are in 2029-2032, using Jupiter gravity assist
  - Missions to Uranus via Saturn are possible through mid-2028; JGA takes over in the 2030s
  - No such mission options (via Saturn) exist for Neptune
  - Launches are possible any year
- Chemical trajectories deliver a flagship class orbiter (>1500 kg dry mass) to Uranus in < 12 years using Atlas V
  - Delta-IV Heavy can reduce interplanetary flight time by 1.5 years
- No chemical trajectories exist for delivering a flagship class orbiter to Neptune in < 13 years using Atlas V or Delta-IV Heavy launch vehicles. SLS or Longer flight times would be needed.
- SEP Enables a flagship orbiter to Neptune in 12-13 years
  - Implemented as separable stage to minimize propellant required for insertion
- Orbit insertion ΔV at both Uranus and Neptune is high
  - Neptune: 2.3-3.5 km/s
  - Uranus: 1.5-2.5 km/s



SEP Tradespace Example





- Useful Inserted Mass = Mass after Orbit insertion – Propellant Tanks
- The colored legend depicts interplanetary flight time in years. **Note that the colors are unique to each plot.**
- Tradespace highlights high performing trajectories, backup launch opportunities and allows us to pick a baseline mission trajectory for further refinements

Figures shown are for Delta-IV heavy launch vehicle with 25 kW SEP stage only

Benefits of SLS

All single planet missions studied are achievable with existing ELVs

SLS can provide enhancing benefits:

- Increases deliverable mass and lowers flight time by 3 to 4 years
- Enables chemical Neptune mission in 11.5 yr.
- Enables two spacecraft missions with a single launch
- Increases launch opportunities

When combined with aerocapture capability, enables very low flight times for both Uranus (< 5 yr.) and Neptune (< 7 yr.)

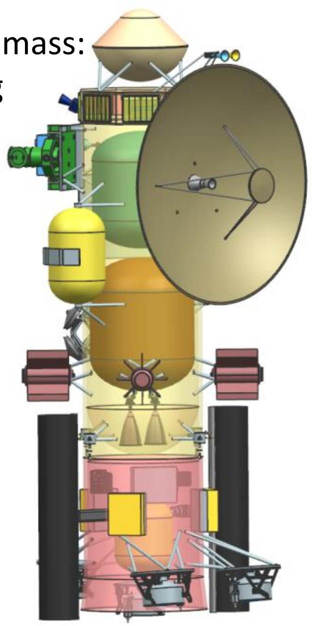
Mission Concept Point Designs

Four basic mission concepts were taken through Team X for point design and costing. These concepts were chosen to constrain the science/cost parameter space:

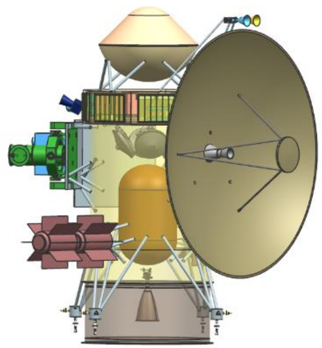
- Uranus orbiter with ~50 kg payload and atmospheric probe
- Uranus orbiter with ~150 kg payload without a probe
- Neptune orbiter with ~50 kg payload and atmospheric probe
- Uranus flyby spacecraft with ~50 kg payload and atmospheric probe

Key architectures fully assessed using common building blocks

Launch mass:
7364 kg

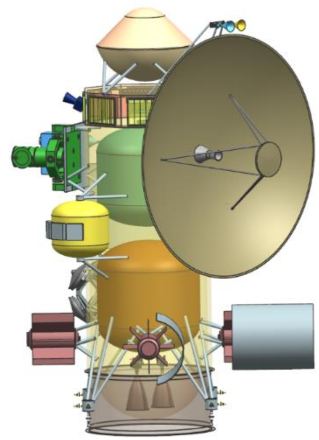


Neptune Orbiter with Probe, SEP, and 50 kg payload



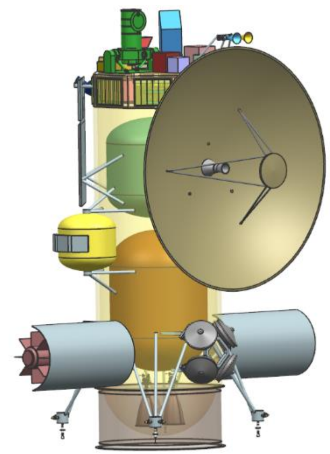
Launch mass:
1525 kg

Uranus Flyby with Probe and 50 kg payload



Launch mass:
4345 kg

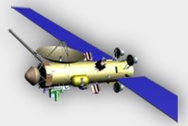
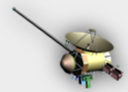
Uranus Orbiter with Probe and 50 kg payload



Launch mass:
4718 kg

Uranus Orbiter with 150 kg payload

Concept Summary

				
Case Description	Neptune Orbiter with probe and <50 kg science payload. Includes SEP stage for inner solar system thrusting.	Uranus Flyby spacecraft with probe and <50 kg science payload	Uranus Orbiter with probe and <50 kg science payload. Chemical only mission.	Uranus Orbiter without a probe, but with 150 kg science payload. Chemical only mission.
Science	Highest priority plus additional system science (rings, sats, magnetospheres)	Highest priority science (interior structure and composition)	Highest priority plus additional system science (rings, sats, magnetospheres)	All remote sensing objectives
Team X Cost Estimate* ($k, FY15)	1971	1493	1700	1985
Aerospace ICE ($k, FY15)	2280	1643	1993	2321
Payload	3 instruments† + atmospheric probe	3 instruments† + atmospheric probe	3 instruments† + atmospheric probe	15 instruments‡
Payload Mass MEV (kg)	45	45	45	170
Launch Mass (kg)	7365	1524	4345	4717
Launch Year	2030	2030	2031	2031
Flight Time (yr)	13	10	12	12
Time in Orbit(yr)	2	Flyby	3	3
Total Mission Length (yr)	15	10	15	15
RPS use/EOM Power	4 eMMRTGs/ 376W	4 eMMRTGs/ 425W	4 eMMRTGs/ 376W	5 eMMRTGs/ 470W
LV	Delta IVH + 25 kW SEP	Atlas V 541	Atlas V 551	Atlas V 551
Prop System	Dual Mode/NEXT EP	Monopropellant	Dual Mode	Dual Mode

**Includes cost of eMMRTGs, NEPA/LA, and standard minimal operations, LV cost not included*

†includes Narrow Angle Camera, Doppler Imager, Magnetometer *‡includes* Narrow Angle Camera, Doppler Imager, Magnetometer, Vis-NIR Mapping Spec., Mid-IR Spec., UV Imaging Spec., Plasma Suite, Thermal IR, Energetic Neutral Atoms, Dust Detector, Langmuir Probe, Microwave Sounder, Wide Angle Camera

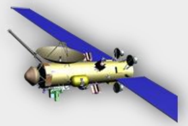
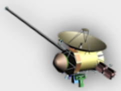
Costing Approach

- Cost estimates developed by JPL's Team X and the Aerospace Corporation

- Assumptions used for costing come from Study Ground Rules:
  - All costs in $FY15; Include minimum 30% reserves (A–D), 15% (E-F)
  - Assume Class B (per NPR 8705.4), Category I (per NPR 7120.5) mission
  - Exclude LV
  - Include cost of RPS including NEPA/LA
  - Include operations (full life cycle mission cost)
  - Include DSN as separate line item
  - Reserves excluded on RPS and LV

- Aerospace independent cost estimate (ICE) generally higher than Team X as a result of modeling differences for flight system and operations
  - Differences within the error bars of the estimation techniques

Cost Summary

				
Case Description	Neptune Orbiter with probe and <50 kg science payload. Includes SEP stage for inner solar system thrusting	Uranus Flyby spacecraft with probe and <50 kg science payload	Uranus Orbiter with probe and <50 kg science payload. Chemical only mission.	Uranus Orbiter without a probe, and 150 kg science payload. Chemical only mission.
Team X Cost Estimates ($k, FY15)				
Total Mission Cost*	1971	1493	1700	1985
Phase A-D Cost (incl. Reserves)	1637	1293	1406	1418
Phase E Cost (incl. Reserves)	334	200	295	568
Aerospace ICE ($k, FY15)				
Total Mission Cost*	2280	1643	1993	2321
Phase A-D Cost (incl. Reserves)	1880	1396	1559	1709
Phase E Cost (incl. Reserves)	400	247	433	612

**Includes cost of eMMRTGs, NEPA/LA, and standard minimal operations, LV cost not included.*

- The Uranus orbiter with probe mission is estimated to be in the range of $1.7 to $2.6B depending on the orbiter payload (50-150 kg range); sliding scale can be optimized through cost share
- Neptune missions cost ~$300M more than Uranus for comparable science return (driven by SEP)

Technology Considerations

- In Space Transportation
  - Aerocapture
  - LOX-LH2 chemical propulsion
  - Radioisotope Electric Propulsion (REP)
- Optical Communications (Beyond 3AU)
- Small satellites in mass range 100 to 400 kg, CubeSats
- Advanced Radioisotope Power
  - eMMRTG
  - Segmented Modular Radioisotope Thermoelectric Generator (SMRTG)
  - High Power Stirling Radioisotope Generator (HPSRG)
- HEEET thermal protection system

> - Ice Giants concepts can be implemented with eMMRTG and HEEET technology currently in development

Primary Study Findings

- A Uranus orbiter with probe, launching near 2030, remains the highest priority
- Two-planet, two-spacecraft mission options are highly valuable scientifically at proportionally higher cost, yet less than the cost of two independent missions
- International collaboration is an opportunity to maximize science return while minimizing cost to each partner; makes best use of once-in-lifetime opportunity
- A follow-on mission study should be performed that uses refined programmatic ground-rules to better target the mission likely to fly

Open Discussion

- A broad option space exists for international partnerships
  - Scientists
  - Instruments
  - Probes
  - Spacecraft or spacecraft subsystems
  - Ground stations
  - Possible second spacecraft on either a shared or separate launch vehicle

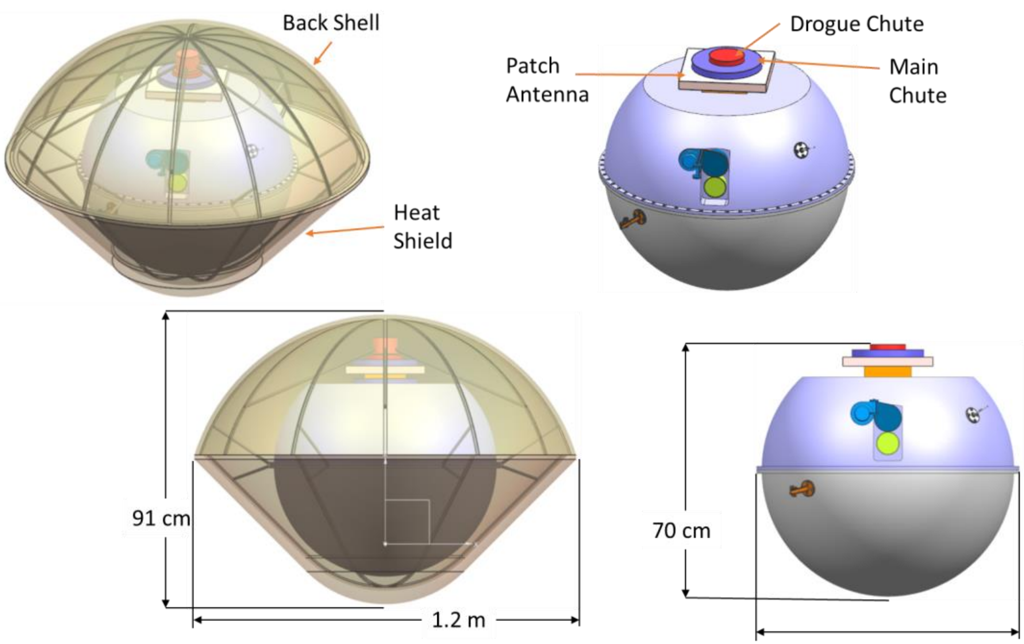
- Enables shaping of partnership within constraints

Backup

Study Recommendations

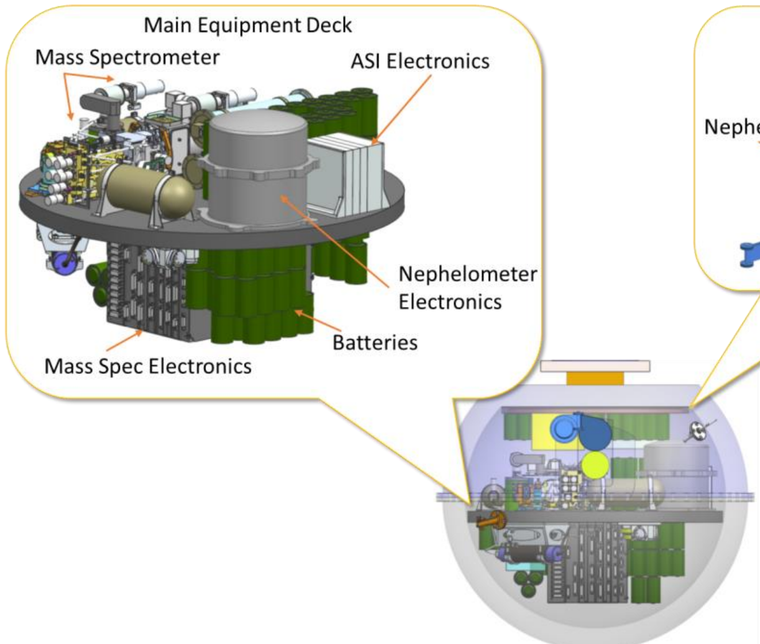
- The development of eMMRTGs is enabling and should be completed as planned
- There should be continued investments in ground-based research (theoretical and observational) and instrumentation. Important areas include upper-atmospheric properties, ring-particle impact hazard, and giant-planet seismology
- An orbiter with probe be flown to Uranus, launching near 2030
- A Uranus or Neptune orbiter should carry a payload between 90 and 150 kg
- Two-planet, two-spacecraft mission options should be explored
- International collaborations should be leveraged to maximize the science return while minimizing the cost to each partner
- An additional mission study should be performed that uses refined programmatic ground-rules to better target the mission likely to fly

Atmospheric Probe Concept



- Instruments
  - Mass Spectrometer (MS)
  - Atmospheric Structure Instrument (ASI)
  - Nephelometer
  - Ortho-para Hydrogen Measurement Instrument
- CDS
  - Redundant Sphinx Avionics
- Power
  - Primary batteries
    - 17.1kg, 1.0 kW-hr EOM
  - Redundant Power Electronics
- Thermal
  - RHU heating, passive cooling
  - Vented probe design
  - Thermally isolating struts
- Telecom
  - Redundant IRIS radio
  - UHF SSPA
  - UHF Low Gain Antenna (similar to MSL)
- Structures
  - ~50kg Heatshield
    - 1.2m diameter, 45deg sphere cone
  - ~15kg Backshell
  - ~10kg Parachutes
  - ~15kg Probe Aerofairing

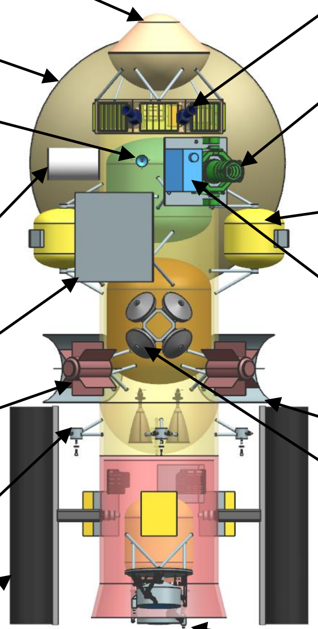
Descent Module Concept



Uranus Probe	CBE Mass (kg)	Contin gency (%)	Total Mass (kg)
Instruments	25.3	29%	32.5
C&DH	0.6	17%	0.7
Power	20.1	26%	25.4
Telecom	6.2	26%	7.8
Structures	61.3	30%	79.7
Thermal	8.0	3%	8.2
Probe Total	**121.5**	**27%**	**154.3**
System Margin			19.4
Dry Mass Total		**43%**	**173.7**
Entry System	102.8	43%	147.0
Probe Entry Mass Total			**320.7**

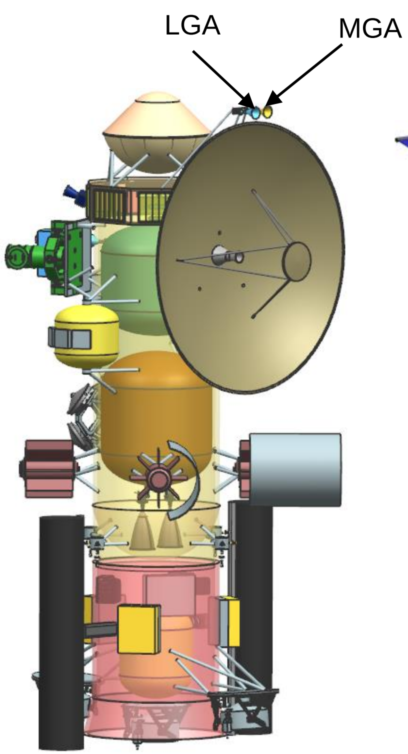
Neptune Probe	CBE Mass (kg)	Contin gency (%)	Total Mass (kg)
Instruments	25.3	29%	32.5
C&DH	0.6	17%	0.7
Power	20.1	26%	25.4
Telecom	6.2	26%	7.8
Structures	61.3	30%	79.7
Thermal	8.0	3%	8.2
Probe Total	**121.5**	**27%**	**154.3**
System Margin			19.4
Dry Mass Total		**43%**	**173.7**
Entry System	103.4	43%	147.9
Probe Entry Mass Total			**321.5**

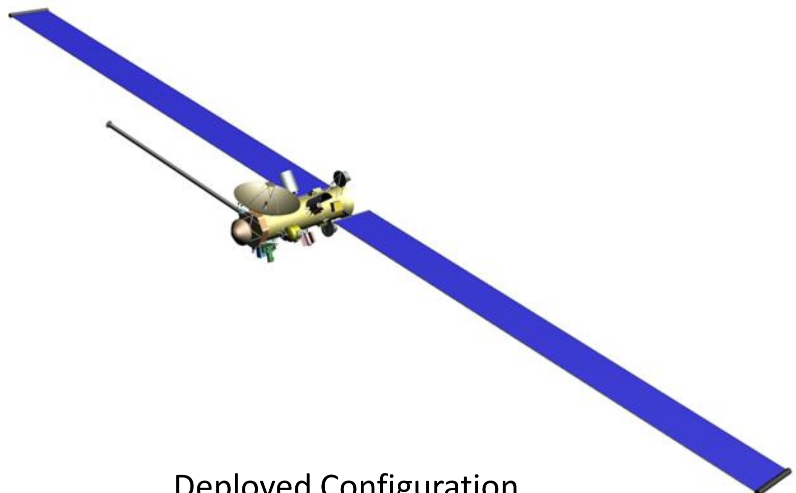
Flight System Concept: Orbiter/Probe/SEP w/50 kg payload



- Instruments
  - Narrow Angle Camera (NAC)
  - Doppler Imager
  - Magnetometer
- CDS
  - Redundant JPL Reference Bus Avionics
- Power
  - Orbiter uses 4 eMMRTGs
  - SEP stage uses 25 kW ROSA arrays
  - Redundant Power Electronics
- Thermal
  - Cassini-heritage waste heat recovery
  - RHUs provide local heating
  - Louvers on Avionics module
- Telecom
  - 35W Ka-Band, 25W X-Band TWTAs
  - Two X/X/Ka SDST transponders, two IRIS radio UHF receivers
  - 3m X/Ka HGA, one X-Band MGA, two X-Band LGAs, UHF patch array.
  - Supports a data rate at Uranus of 15 kbps into 34m BWG ground station.
- Propulsion
  - SEP Stage: 2+1 system using NEXT Engines
  - Chemical System: Two 890N main engines used to achieve UOI burn time < 1hr

Option 1: Orbiter/Probe/SEP with 50 kg payload



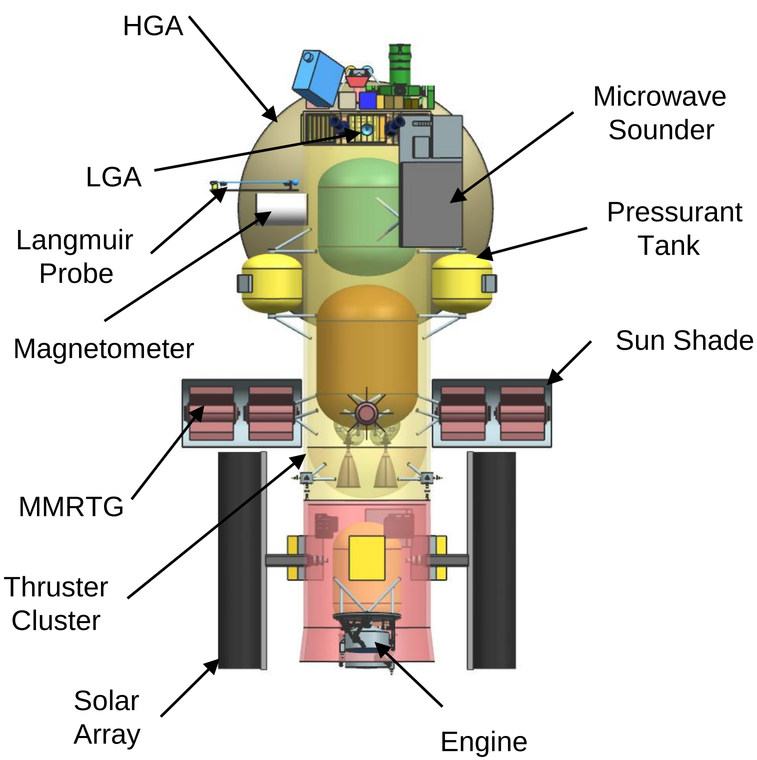


Deployed Configuration

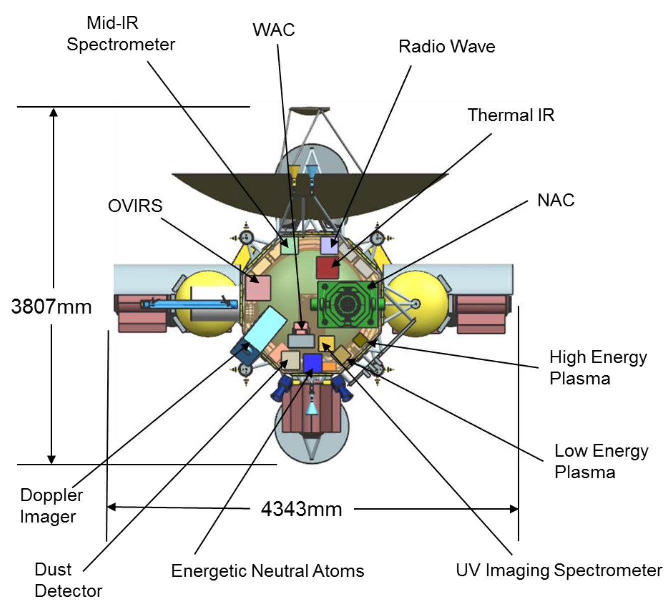
Orbiter	CBE Mass (kg)	Contin-gency (%)	Total Mass (kg)
Instruments	36.7	23%	45.2
C&DH	21.6	10%	23.8
Power	216.6	2%	220.8
Telecom	59.4	16%	68.9
Structures	462.7	30%	601.5
Harness	86.3	30%	112.3
Thermal	112.7	23%	138.9
Propulsion	173.3	5%	182.7
GN&C	63.5	10%	69.8
Orbiter Total	**1232.8**	**19%**	**1463.9**
System Margin			221.7
Dry Mass Total		**43%**	**1685.5**
Propellant			**2354.0**
Wet Mass Total			**4039.5**
SEP Stage	**CBE Mass (kg)**	**Contin-gency (%)**	**Total Mass (kg)**
C&DH	1.6	0.1	1.7
Power	263.9	0.3	340.9
Mechanical	444.0	0.3	577.2
Thermal	78.7	0.0	78.7
Propulsion	245.0	0.2	297.8
GN&C	6.0	0.1	6.4
SEP Stage Total	**1039.2**	**25%**	**1302.7**
System Margin			183.4
Dry Mass Total		**43%**	**1486.1**
Propellant			**1040.0**
Xenon			1040.0
Wet Mass Total			**2526.1**
Mission System	**CBE Mass (kg)**	**Contin-gency (%)**	**Total Mass (kg)**
Probe			320.7
Orbiter			4039.5
SEP Stage			2526.1
Launch Mass Total			**6886.4**
Injected Mass Cap.			10120.0
Remaining LV Cap.			**3233.6**

Predecisional - For planning and discussion purposes only. URS CL#17-0488

Option 2: Orbiter/SEP with 150 kg payload



Instrument Accommodation



Orbiter	CBE Mass (kg)	Contingency (%)	Total Mass (kg)
Instruments	144.8	17%	169.5
C&DH	27.6	18%	32.4
Power	265.3	2%	269.7
Telecom	55.2	15%	63.4
Structures	516.4	30%	671.3
Harness	103.8	30%	135.0
Thermal	121.1	23%	148.5
Propulsion	188.8	5%	198.9
GN&C	63.5	10%	69.8
Orbiter Total	**1486.5**	**18%**	**1758.6**
System Margin			270.3
Dry Mass Total		**43%**	**2028.9**
Propellant			**2770.0**
Wet Mass Total			**4798.9**
SEP Stage	**CBE Mass (kg)**	**Contingency (%)**	**Total Mass (kg)**
C&DH	1.6	0.1	1.7
Power	265.5	0.3	342.9
Mechanical	441.6	0.3	574.1
Thermal	78.7	0.0	78.7
Propulsion	245.0	0.2	297.8
GN&C	6.0	0.1	6.4
SEP Stage Total	**1038.4**	**25%**	**1301.6**
System Margin			183.3
Dry Mass Total		**43%**	**1484.9**
Propellant			**1040.0**
Xenon			1040.0
Wet Mass Total			**2524.9**
Mission System	**CBE Mass (kg)**	**Contingency (%)**	**Total Mass (kg)**
Orbiter			4798.9
SEP Stage			2524.9
Launch Mass Total			**7323.9**
Injected Mass Cap.			10120.0
Remaining LV Cap.			**2796.1**