Neptune Mission Concept

A Voyage Through the Outer Solar System

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Argo: a New Frontiers 4 Mission Concept

A small body explorer doing exceptional ice giant science
- Flyby Neptune
- Close flyby of Triton
- Flyby a Kuiper Belt Object
- Gravity assist from Jupiter and Saturn

Exploration of Neptune has been stymied by the perception that a flagship-class orbiter is required to make scientific progress
A Neptune flyby mission is a Pragmatic approach ... with rich science results

Key Characteristics:
- Focused science mission
- Simple mission profile
- Current instrument technology
- Current spacecraft technology
- Capable payload
- Nuclear power
A Neptune flyby mission is not in competition with a flagship orbiter.

Rather, it plugs a ~50 year gap in our study of Neptune.
Presentation Outline

• Community support for a Neptune / Triton mission
• Science
• Mission, Payload, Spacecraft
• Observational timeline
• Summary
academy interest in Neptune

2003 planetary decadal survey explicitly discusses Neptune but Neptune set three decades out (post 2035) because flagship-class orbiter assumed to be next step

Our experience exploring Jupiter and Saturn belies this notion
Past, Present, and Future of Outer Solar System Exploration

1975
- Pioneer 11
- Voyager 2
- Voyager 1

1985
- Voyager 2

1995
- Pioneer 11
- Voyager 1
- Pioneer 11

2005
- Galileo Orbiter
- Cassini Orbiter
- New Horizons
- Voyager 1
- Voyager 2

2015
- Juno Orbiter
- Argo - Saturn GA
- Europa Flagship
- Argo - Jupiter GA
- Argo - Neptune & Triton

2025
- Titan Orbiter

2035
- Argo - Kuiper Belt
Committee on Assessing Solar System Exploration

Nasa activity on science question 2 (giant planet formation) graded C

with the specific recommendation:

“the [next] solar system exploration decadal survey should address the objectives and merit of a neptune/triton mission”
Presentation Outline

- Community support
- Science
- Mission, Payload, Spacecraft
- Observational Timeline
- Summary
Why study Neptune? Local Outlook

- Relevance to life and habitability
  - "The giant planet story is the story of the Solar System." *
  - Direct implications for habitability
  - Delivery of volatiles to inner solar system

* From the NAS NRC study: *New Frontiers in the Solar System: An Integrated Exploration Strategy*, often called the "Planetary Decadal Survey"
Why study Neptune? Broader Perspective

- Planetary System Architecture
  - Exoplanet population increasing dramatically
    - Growing number of ice-giant-mass objects
    - Pushing towards U/N equivalent distances in near future
      - Microlensing
      - Near-IR radial velocity
  - Knowledge of local ice giants extremely limited
    - Earth-based efforts extraordinarily challenging compared to J & S
      - Ice giants smaller
      - Ice giants much more distant
      - Ice giants colder

Adapted from the ExoPlanet Task Force Presentation to the AAS, Austin, TX (Jan 2008)
Focus on Neptune
neptune’s dynamic atmosphere

Nearly all aspects of Neptune detectable from Earth have changed significantly since Voyager fly-by in 1989

- Neptune's atmosphere shows fundamental differences in large-scale structure
  - GDS gone (all of them)
  - significant atmospheric evolution on <5-yr timescale

Voyager c. 1989 compared with Hubble c. 1994
neptune’s energy balance

Evidence for stratospheric heating since Voyager

- BASS mid-IR data
- CO sub-millimeter data
- Voyager

Neptune's visible brightness
Lockwood & Jerzykiewicz 2006
Hammel & Lockwood 2007
Neptune mid-IR

Gemini/Michelle at 11.7 µm
Ethane Emission
from the stratosphere

Gemini/Michelle at 7.7 µm
Methane Emission
from the stratosphere

Keck/NIRC2+AO at 1.6 µm
Sunlight Scattering from
tropospheric Clouds

All 3 images taken within a few minutes on 5 July 2005

Hammel et al. (2007)
Overarching Science Objective

• understand the processes that control the three-dimensional distribution of gas composition, clouds, temperatures, and winds in Neptune's atmosphere.
Level 1 Science Investigations

• Question - Does the conversion of hydrogen from its ortho- to para- state supply energy and modulate excess thermal IR radiated from neptune? (Smith and Gierasch 1995)

• Observation - map ortho- and para-hydrogen as a function of altitude, latitude, and time via NIR spectroscopy
Level 1 Science Investigations

• **Question** - Why are wind speeds faster at Neptune than Jupiter and Saturn? Is it because atmospheric turbulence is less, because less power is available? Less turbulence allows the large-scale winds to coast along without dissipation of energy. *(Ingersoll et al 1995)*

• **Observation** - Map and make movies of convective patterns and zonal circulation in the thermal IR
Level 1 Science Investigations

• **Question** - What is *Neptune's temperature field*; how does it affect Neptune's internal heat flux? What powers the winds? Ground-based midIR images show emission primarily from the south polar region. Need to develop model for Neptune’s global energy balance.

• **Observation** - Map and make movies of convective patterns and zonal circulation in the near IR. Map thermal emission as a function of altitude, latitude and time
Level 1 Science Investigations

• Question - What is the *tropospheric aerosol composition and particle size* in discrete features? What is the *aerosol composition and particle size in the stratosphere and upper troposphere*? The bulk of Neptune’s atmosphere is H and He. CH$_4$, NH$_3$, H$_2$S, and H$_2$O, condense or chemically combine in the atmosphere of Neptune to form clouds.

• Observation - Image atmospheric features at high resolution in near IR and UV wavelengths. Stellar occultations will reveal haze layers; visible and near IR observations at a variety of phase angles yield particle sizes.
What a neptune flyby can do

• Neptune Measurement Goals
  – new visible and first-ever near-infrared mapping of small-scale cloud dynamics and evolution
  – first detailed spatially-resolved spectroscopic mapping of cloud composition
  – first auroral ultraviolet images
  – first detailed infrared map
  – gravitational moments refined for interior models
Neptune’s Magnetosphere

- Magnetic dipole is highly tilted and offset from the planet’s center
- Changes in the magnetosphere are dramatic as the planet rotates and different parts of the field encounter the solar wind

Not like Jupiter or Saturn
Undetectable from Earth
Level 1 Science Investigations

• **Question** - What is the generation mechanism of Neptune’s unusual field?

• **Observation** - Improve quadrupolar and octopolar terms of the magnetic field by flying by Neptune at a different latitude / longitude than Voyager, preferably over the south polar region
Level 1 Science Investigations

- **Question** - What are the operational dynamics of a highly-tilted magnetosphere that refills and empties over diurnal time scales? Is magnetic reconnection important for the motions of plasma?

- **Observation** - Measure field and plasma parameters along the spacecraft trajectory with modern instrumentation to understand plasma generation, convection, and diffusion processes.

The UV instrument will look for aurorae on Neptune and relate them to the reconnection electric field imposed by the solar wind.
Neptune’s Rings

- Narrow rings
- Arcs
- Dust bands
- Small moons
Nearly all aspects of the Neptune system detectable from Earth have changed significantly since Voyager fly-by in 1989.

The arcs have fallen behind their predicted location and definitively outside the resonance, contradicting the confinement model.

The leading arcs have also shifted forward and decreased in brightness relative to the others.

The trailing arc, Fraternite, is the most stable and seems to track at the exact resonance rate.

The other arcs continue to evolve, with the leading arcs Courage and Liberte now almost completely gone.

The narrow Le Verrier ring, interior to the Adams ring, has also brightened by a factor of four since Voyager.
Level 1 Science Investigations

• Question - Where are the arcs now? What is the current configuration of the rings, dust disk, and ring arcs and how has that configuration evolved since the Voyager flyby in 1989? Test confinement and resonance models by getting updated positions for the arcs, mapping their orbital motion since Voyager.

• Observation - Map and make movies of ring arcs at high phase. Acquire images of the dust bands and narrow rings.

• Question - What are the particle size distributions in the rings and ring arcs? Do larger parent bodies too small to be detected by Voyager populate and/or confine the ring arcs? Because dust lifetimes are short, identifying the full size distribution is critical to understanding the timescales for ring evolution.

• Observation - The combination of phase coverage from a flyby with the vastly improved capability of a modern imaging system will allow us to measure the phase curve in the visual and near-IR.
Triton Science Objectives

Triton Science Objective 1: Triton has a youthful surface, substantially modified when Triton was captured by Neptune. Argo will map the side of Triton seen only at a distance by Voyager ("terra obscura") and more of the northern hemisphere. Near-global surface coverage will extend the post-capture cratering history and other modification of Triton’s surface.

- More of Triton's northern hemisphere will be sunlit
  - Most of it was in seasonal darkness for Voyager
Triton Science Objectives

Triton Science Objective 2: Triton’s climate is controlled by its nitrogen atmosphere in vapor equilibrium with surface frost. Argo will map the distribution of ices on Triton’s surface and measure the atmospheric pressure to capture another point in time for modelling climate change on an icy body.

- Triton's atmosphere has changed significantly since the Voyager flyby in 1989
  - Nitrogen and methane ices move seasonally from hemisphere to hemisphere and the pressure of the atmosphere increases and decreases seasonally.

Will Triton’s enigmatic plumes still be active? Are they a seasonal phenomenon, like on Mars?
Neptune flyby enables KBO science

- **Opportunity** to continue on to a KBO!
- **Potential KBO Targets**
  - The cone of accessibility includes ~40 of the largest KBOs
  - Several binary KBOs
  - Many objects in the cold classical disk

- Neptune flyby permits selection of KBO with highest scientific interest

Address evolution of the solar system...
Access to Kuiper Belt Objects

Argo’s accessible volume is \(~4000\)x that of New Horizons
Flight time to KBO is just \(~1.5 - 3\) years (KBO at 35-39 AU)

Potentially in this cone:
- 9 KBO’s with diameter > 400 km
- 40 KBO’s with 200 < diam < 400 km
- 18 cold classical KBO’s

New Horizons, with propulsive assistance
Argo without propulsive assistance
KBO Science Objectives

• Reconnaissance of primitive solar system body that is member of a much larger population

• Determine comparative properties of captured KBO Triton and a KBO *in situ*

• Expand the diversity of volatile-rich small bodies explored in the outer solar system
  – Between Argo and New Horizons *(shown here)* we will double the number of explored KBOs
    • Pluto
    • New Horizons *in situ* KBO
    • Triton
    • Argo *in situ* KBO
Presentation Outline

• Community support
• Science
• Mission, Payload, Spacecraft
• Observational Timeline
• Summary
Example 2019 Launch Options

Voyager-like flight times to Jupiter and Saturn; even faster to Neptune

**Time of Flight = 9.3 yr**
Neptune flyby 2028
38S Neptune periapsis
KBO: 2005 PS21

**Time of Flight = 10.2 yr**
Neptune flyby 2029
21N Neptune periapsis
KBO: 2001 QS 322
Project Timeline

- Phases A, B, C/D, E, F (with science windows)

- Project start in 2014 for 2019 launch, ~9-year flight, 6-month Neptune science phase
- Launch opportunities occur between 2015 and 2019; such windows only occur every 12 years
- KBO arrival date depends on which KBO is selected
Modern Technology

• Voyager launched in 1977
• Voyager technology now >35 years old!
• Technology that could fly on Argo today (no technology development needed)
  – Visible camera with a CCD, not a vidicon
  – Near-IR array, not single channel bolometer
  – UV multi-pixel imaging, not single channel
  – Solid-state recorders, not tape recorders
  – Ka band for telecom and radio science
Spacecraft

• Envision a spacecraft similar to New Horizons spacecraft
  – Similar total mass and mass distributions (~400 kg dry mass)
  – Similar power needs (200 W)

• Must use nuclear power

• By maintaining similar scope we expect to remain in the New Frontiers budget envelope
Notional Argo Payload

Preliminary suite based on science traceability matrix

- High resolution visible camera - New Horizons (NH) level
- Near-Infrared spectrometer - NH heritage
- UV solar & stellar occ. spectrometer - reduced Cassini heritage
- Far-infrared linear radiometer - Diviner heritage
- Magnetometer - ST5 (UCLA)
- Charged particle spectrometer – Messenger heritage
- Gimbaled high-gain antenna - heritage radio science instrument

Beyond this: explore trade space for other instrumentation in terms of science, cost, power, and mass
Payload mass

8.6 kg  Lorri
10.5  Ralph
5.0  UV
12.0  Diviner
10.0  Magnetometer w/ boom
3.5  Charged particle spectrometer
1.5  USO

51.1 kg  Total
Telecommunication Options

• Use existing DSN facilities with flight-proven high gain antenna

• X-band downlink to a 70-m DSN station
  – Voyager 2 transmitted 21 kbps from Neptune (with arraying)
  – NH will send 0.7-1.2 kbps from Pluto

• Ka-band downlink
  – 14-16 kbps to a 70-m DSN station; ~4 kbps to 34-m
    • Assuming smaller 2 - 2.5 m HGA

• Design for simultaneous observation and downlink (gimballed high gain antenna)
  – Significantly improves science yield for one-time science opportunities
  – Saves costs in Phase E
Presentation Outline

- Community support
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Observational Timeline

Atmospheric Movies

- Beginning at closest approach - 6 months observe Neptune every 36 deg of longitude, in visible, near IR and thermal wavelengths.
- Receding from Neptune, from closest approach to + 6 months observe Neptune every 36 deg of longitude, in visible, near IR and thermal wavelengths

Study Neptune’s dynamic atmosphere on short timescales
Map zonal winds
Observational Timeline

Atmospheric Maps

- One week before closest approach acquire 4 rotations of global maps at all wavelengths
- Particularly important in the thermal IR

Study Neptune’s thermal emission and its effect on zonal circulation
Map convective patterns

Atmospheric Maps
Observational Timeline

Atmospheric Features, high altitude structure

- In the days before and after closest approach acquire closeup views of all Neptune's storms, observe stellar occultations, radio occultation of earth
- All wavelengths
- Variety of phase angles

Study composition
Determine aerosol particle sizes
Map convective patterns in storms
Observational Timeline

Ring structure
- after closest approach acquire closeup views of Neptune’s rings, ring arcs and dust bands; observe stellar occultations
- All wavelengths
- Variety of phase angles
Observational Timeline

Encounter Triton
Presentation Outline

- Community support
- Science
- Mission, Payload, Spacecraft
- Observational Timeline
- Summary
2003 Planetary Decadal Survey explicitly discusses Neptune
- Flybys/orbiters in “Giant Planets,” “Large Satellites,” and “Primitive Bodies”
- Community Papers highlight Neptune Atmosphere and System Exploration
- Set in third decade because Flagship-class orbiter assumed

NASA Vision Missions: Two independent Neptune studies

NASA’s 2006 Solar System Exploration Roadmap explicitly discussed Neptune
- Again, late in the queue because Flagship-class orbiter assumed

Would engage a broad swath of the planetary community
- Rich scientific return: thick atmosphere, thin atmosphere, rings, satellites, surface geology, magnetospheres, interiors, KBOs…

A flyby mission addresses important science objectives, is much less expensive and less complex than an orbiter, and is achievable within New Frontiers resources
Summary

• **Neptune and Triton are compelling flyby targets**
  – Dynamic worlds, rich opportunities for new science discoveries
  – Trajectories identified with reasonable trip times and approach velocities

• A **KBO encounter** explores another primitive outer solar system body
  – Triton / KBO comparison
  – Pluto / KBO comparison
  – Numerous potential targets

• **This Mission is feasible for New Frontiers**
  – Key science addressed by instrument package based on New Horizons heritage
  – Avenues available for additional cost savings in development, operations, and launch vehicle
  – Mission can be accomplished within New Frontiers cost cap
Backup Slides
NRC Midterm Report

• The Committee on Assessing the Solar System Exploration (CASSE) Program gave NASA a “C” in its 2008 Report, on Science Question #2*, and made the specific recommendation:
  – “The next solar system exploration decadal survey should address the objectives and merit of a Neptune/Triton mission”

• NF4 can raise this grade without a flagship

* How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn?
Argo Mission Statement

Argo is the next step for outer solar system exploration, illuminating the genesis and evolution of the solar system by

- characterizing Kuiper Belt objects with diverse evolutionary paths ranging from captured KBO Triton to an *in situ* KBO, and

- accomplishing ground-breaking science at Neptune by opening a window on the dynamical nature of the atmosphere, rings, and magnetic field, and laying the groundwork for future ice-giant missions.
Why Now?

• Launch opportunity window from 2015 - 2019
  – Such windows occur every 12 years due to Jupiter gravity assist

• Waiting for flagship, or next window, will result in ~50-year gap in observations of a Triton dynamic system

• Neptune / Triton Flyby is complementary to eventual Neptune system orbiter
  – Outstanding ice giant science can also be obtained on the way to the KBO

• Exoplanetary Neptunes are now known to exist
  – Knowledge of local ice giants is substantially less than gas giants

• Current technology far surpasses Voyager-era technology

• Need time to resolve nuclear power issues
## NF3 vs. NF4

<table>
<thead>
<tr>
<th>New Frontiers 3</th>
<th>New Frontiers 4</th>
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<tbody>
<tr>
<td>AO out</td>
<td>2009</td>
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<td>2010</td>
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<td></td>
<td>2011</td>
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<td>2012</td>
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<td></td>
<td>2013</td>
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<td></td>
<td><strong>AO comes out 54 months after NF3 AO, write proposal</strong></td>
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<tr>
<td></td>
<td>2014</td>
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<td><strong>Downselect, Step 2 = Phase A</strong></td>
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<tr>
<td></td>
<td>2015</td>
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<td><strong>Phase B</strong></td>
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<td>2016</td>
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<td><strong>Phase C/D</strong></td>
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<td><strong>Phase C/D</strong></td>
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<tr>
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<td>2018</td>
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<td></td>
<td><strong>Phase C/D</strong></td>
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<tr>
<td></td>
<td>2019</td>
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<td><strong>Launch in February</strong></td>
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<td></td>
<td>2020</td>
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<td><strong>Backup launch in January</strong></td>
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</tbody>
</table>

The schedule for NF4 is tight but not out of the question.
Argo Launch Vehicle Requirements

- Criteria for launch vehicle choice
  - Desired trip time
  - Spacecraft mass
  - Launch trajectory $C_3$
- For a given launch vehicle:
  - higher $C_3 \rightarrow$ faster trip time BUT smaller spacecraft mass that vehicle can launch

$C_3$ (km²/sec²) ≡ square of the hyperbolic excess velocity

Hyperbolic excess velocity ≡ craft’s speed when it “breaks free of Earth’s gravity” (i.e., has just climbed out of Earth’s gravity well)

Example trajectories aimed at Jupiter gravity assists (to Neptune, for instance)

<table>
<thead>
<tr>
<th>$C_3$</th>
<th>Trajectory</th>
<th>Launch Vehicle and Mass</th>
<th>Trip time to Jupiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Delta-VEGA (Propulsive Deep Space Maneuver, single Earth gravity assist)</td>
<td>Smallest Atlas V can propel &gt;1000 kg to this $C_3$</td>
<td>4-5 years</td>
</tr>
<tr>
<td>80</td>
<td>Direct Earth-to-Jupiter, “just barely getting there”</td>
<td>Mid-sized Atlas V can propel &gt;500 kg to this $C_3$</td>
<td>2-2.5 years</td>
</tr>
<tr>
<td>162</td>
<td>New Horizons, high-speed Jupiter gravity assist to Pluto</td>
<td>Largest Atlas V with an additional Star-48 upper stage to propel 478 kg to this $C_3$</td>
<td>13 months</td>
</tr>
</tbody>
</table>

- Currently examining trades among launch mass capacity, $C_3$, and trip time to Neptune (next slide)
Argo Discovery Opportunities

These measurement objectives are accessible to a flyby, but are impossible from L2, from near-Earth orbit, and from Earth even with a 30-m telescope

- Neptune
  - Small-scale cloud distribution
  - Atmospheric lightning
  - Magnetic field measurements in completely different orientation
  - First detailed compositional/spectral map
  - First detailed infrared map
  - Gravitational moments refined for interior models

- Triton & in situ KBO
  - Geologic mapping (and for Triton: mapping expanded beyond Voyager with improved resolution)
  - Surface evolution & atmospheric structure
  - Magnetic field
  - First compositional/spectral map
  - First detailed infrared map

- Nereid and perhaps other moons
  - First detailed images

- Ring system
  - Detailed structure and evolution

Overall unique viewing geometry
  - High-phase angle observations of atmospheres of Neptune & Triton, rings
Presentation Outline

• Context
• Science
• Mission
• Cost
• Summary
Of $1B Boxes and Bricks

“I heard that a joint NASA study by JPL and APL said NASA couldn’t send any mission to the outer Solar System for less than $1B.”

This is wrong.

The “Titan and Enceladus $1B Mission Feasibility Study” actually said:

Pg 1-1: “no missions to Titan or Enceladus that achieve at least a moderate understanding beyond Cassini-Huygens were found to fit within the cost cap of 1 billion dollars (FY’06).”

Relevance to Neptune: None

“But I also heard that the study said NASA couldn’t even send a BRICK (spacecraft with no instruments) to the outer Solar System for less than $800M.”

This is only partially correct.

CORRECT Pg 1-11: “Even the lowest cost mission studied [Enceladus flyby], without the cost of science payload, has a minimum expected cost of ~$800M.”

HOWEVER Pg 2-4: “[The Enceladus flyby’s] design (and therefore cost) was uniquely derived using actual cost data from the NH mission.”


Result: $$ available for Argo science payload within $800M cap
Cost-Saving Options

- Use simple spacecraft with current (New Horizons) heritage
  - Experience base and corporate knowledge available
  - No miracle developments required
- Identify many trajectories, some of which offer mass relief
  - NH’s Star 48 upper stage may not be needed
- Use smaller Atlas V launch vehicle
  - 541 instead of 551 -- promising for some trajectories
- Scale instrument requirements to available $
- Use the market-based approach that Cassini followed for payload development (power, mass, dollars were trade-able)
  - No instruments over-ran or were descoped from payload
- Science ops at Jupiter or Saturn will be a mission of opportunity
  - Under SALMON umbrella
Argo Notional Cost

• Delta to New Horizons cost outline
  – $566 M in real year dollars = NH Phase C/D cost including launch vehicle, ops to launch + 9 months

• Notional allocation for $800M available:

  $ 200M * Launch vehicle (Atlas V 551)
  105M Power sources (assumes 3 MMRTGs)
  40M 9 yrs cruise ops
  27M Neptune flyby ops, Operational Readiness Tests
  100M Payload and Science Team
  320M Project Management, Spacecraft and Launch approval
  8M Education and Public Outreach

• Plan to size the requirements to the $ available
  – Have identified options to explore to fit comfortably within NF budget resources (next slide)
Cost-Saving Options

• Use simple spacecraft with current (New Horizons) heritage
  – Experience base and corporate knowledge available
  – No miracle developments required

• Use smaller Atlas V launch vehicle
  – 541 instead of 551 -- promising for some trajectories

• Identify trajectories which offer mass relief
  – NH’s Star 48 upper stage likely not needed

• Use the market-based approach that Cassini followed for payload development (power, mass, dollars were trade-able)
  – No instruments over-ran or were descoped from payload

• Offer KBO flyby option as Phase F extended mission
  – Not part of primary mission

• Scale instrument requirements to available $
Which Ice Giant?

Uranus Pros
• Closer; shorter trip time
• Full retinue of original satellites
• Dynamic ring system
• Interesting magnetic field

Uranus Cons
• Fly-by at equinox (2007, 2049) to get active atmosphere (see equinoctial above) and full heliotilt

Neptune Pros
• Triton (captured KBO[?], active)
• Atmosphere always active
• Dynamic ring system
• Interesting magnetic field

Neptune Cons
• Farther away; longer trip time
KBO Accessibility - top view
<table>
<thead>
<tr>
<th>Class of Question</th>
<th>Scientific Themes</th>
<th>Earth-Based Orbiting Facilities</th>
<th>Neptune POP</th>
<th>Analysis and Modeling</th>
<th>Lab</th>
<th>ARGO</th>
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<tbody>
<tr>
<td><strong>Theme 1. ORIGIN AND EVOLUTION</strong></td>
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<td><strong>Solar-System Giant Planets</strong></td>
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<tr>
<td>Paradigm altering</td>
<td>How did the giant planets form?</td>
<td>x</td>
<td>xxx</td>
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<td>What are the orbital evolutionary paths of giant planets?</td>
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<td>Pivotal</td>
<td>What are the elemental compositions of the giant planets?</td>
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<td></td>
<td>What are the internal structures and dynamics of giant planets?</td>
<td>xx(1)</td>
<td>xxx</td>
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<td><strong>Extrasolar Giant Planets and Brown Dwarfs</strong></td>
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<tr>
<td>Pivotal</td>
<td>How can we use the giant planets in our solar system to calibrate spectroscopic observations (optical, infrared, radio) of extrasolar giant planets?</td>
<td>xx</td>
<td>xxx</td>
<td>xxx</td>
<td>x</td>
<td>xxx</td>
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### Decadal Priorities, 2 of 3

<table>
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<th>Class of Question</th>
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</thead>
<tbody>
<tr>
<td><strong>Theme 2. INTERIORS AND ATMOSPHERES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Interiors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pivotal</strong></td>
<td>What is the nature of phase transitions within the giant planets?</td>
<td>xx(1)</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>xx</td>
</tr>
<tr>
<td>&quot;</td>
<td>How is energy transported through the deep atmosphere? Do radiative layers exist?</td>
<td>xx(1)</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>xx</td>
</tr>
<tr>
<td>&quot;</td>
<td>How and where are planetary magnetic fields generated?</td>
<td>x(1)</td>
<td>xxx</td>
<td>xxx</td>
<td>o</td>
<td>xxx</td>
</tr>
<tr>
<td><strong>Foundation building</strong></td>
<td>What is the nature of convection in giant planet interiors?</td>
<td>xx(1)</td>
<td>xxx</td>
<td>xxx</td>
<td>o</td>
<td>xx</td>
</tr>
<tr>
<td>&quot;</td>
<td>How does the composition vary with depth?</td>
<td>x(1)</td>
<td>xxx</td>
<td>xx</td>
<td>o</td>
<td>xx</td>
</tr>
<tr>
<td>Class of Question</td>
<td>Scientific Themes</td>
<td>Earth-Based Orbiting Facilities</td>
<td>Neptune POP</td>
<td>Analysis and Modeling</td>
<td>Lab</td>
<td>ARGO</td>
</tr>
<tr>
<td>-------------------</td>
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<td>---------------------------------</td>
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</tr>
<tr>
<td><strong>Pivotal</strong></td>
<td>What energy source maintains the zonal winds, and how do they vary with depth? What role does water and moist convection play?</td>
<td>x</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>xxx</td>
</tr>
<tr>
<td>&quot;</td>
<td>What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?</td>
<td>x</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>xxx</td>
</tr>
<tr>
<td><strong>Foundation building</strong></td>
<td>How and why does atmospheric temperature vary with depth, latitude, and longitude?</td>
<td>x</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>xxx</td>
</tr>
<tr>
<td>&quot;</td>
<td>How does the aurora affect the global composition, temperature, and haze formation?</td>
<td>x</td>
<td>x</td>
<td>xx</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>&quot;</td>
<td>What produces the intricate vertical structure of giant planet ionospheres?</td>
<td>x</td>
<td>xx</td>
<td>xx</td>
<td>x</td>
<td>xx</td>
</tr>
<tr>
<td>&quot;</td>
<td>At what rate does external material enter giant planet atmospheres, and where does this material come from?</td>
<td>x</td>
<td>o</td>
<td>xx</td>
<td>x</td>
<td>o</td>
</tr>
<tr>
<td>&quot;</td>
<td>What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?</td>
<td>x</td>
<td>x</td>
<td>xx</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
Power Source Options

<table>
<thead>
<tr>
<th></th>
<th>BOL Electric Power (W)</th>
<th>EOL (14 yrs) Electric Power (W)</th>
<th>Unit Mass (kg)</th>
<th>Estimated Unit Cost</th>
<th># Units Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMRTG</td>
<td>115</td>
<td>103</td>
<td>44</td>
<td>$35M</td>
<td>3 (or even 2)</td>
</tr>
<tr>
<td>ASRG</td>
<td>140</td>
<td>127</td>
<td>20</td>
<td>$20M</td>
<td>2</td>
</tr>
<tr>
<td>GPHS-RTG (unit F-5)</td>
<td>300 *</td>
<td>228</td>
<td>55</td>
<td>?</td>
<td>1</td>
</tr>
</tbody>
</table>

* New Horizons’ GPHS-RTG used a mix of old and new Pu; BOL power for that unit was only 240 W

If NF-03 AO excludes nuclear-powered missions, then no outer Solar System missions are possible other than flagship. If NF-03 AO is broader, missions may be possible (J-N-KBO; J-S-N-KBO).