Neptune Mission, Satellite Science

A Voyage Through the Outer Solar System

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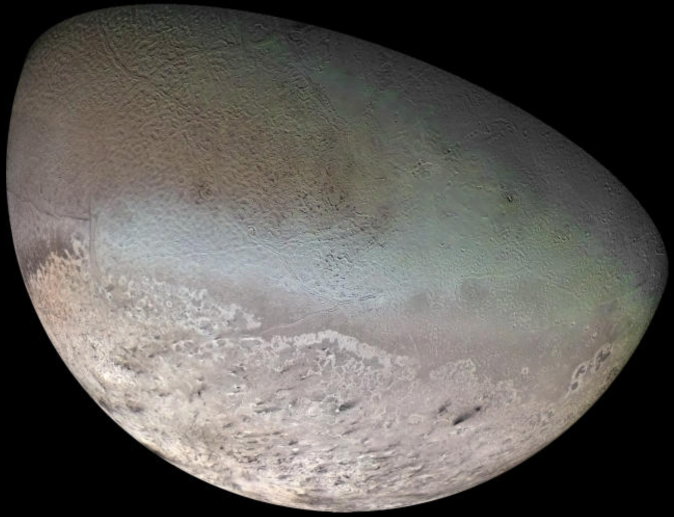
Argo: a New Frontiers 4 Mission Concept

A *small body explorer* doing *exceptional ice giant science*

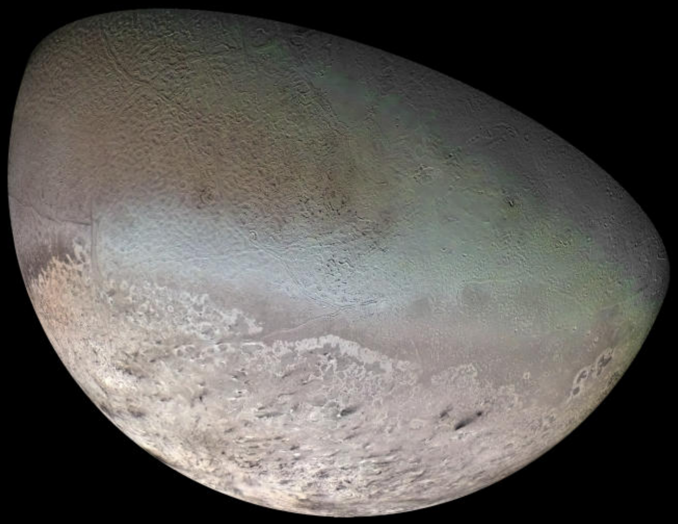
- Flyby Neptune
- Close flyby of Triton
- Flyby a scientifically-selected Kuiper Belt Object
- Gravity assist from Jupiter and Saturn



Exploration of Neptune & Triton 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

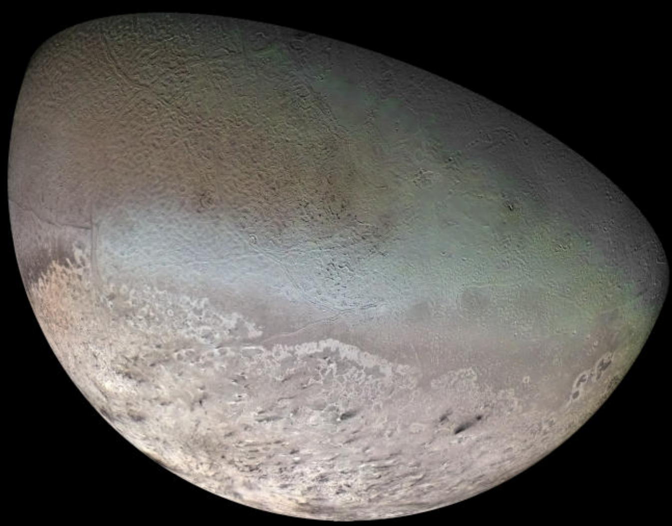


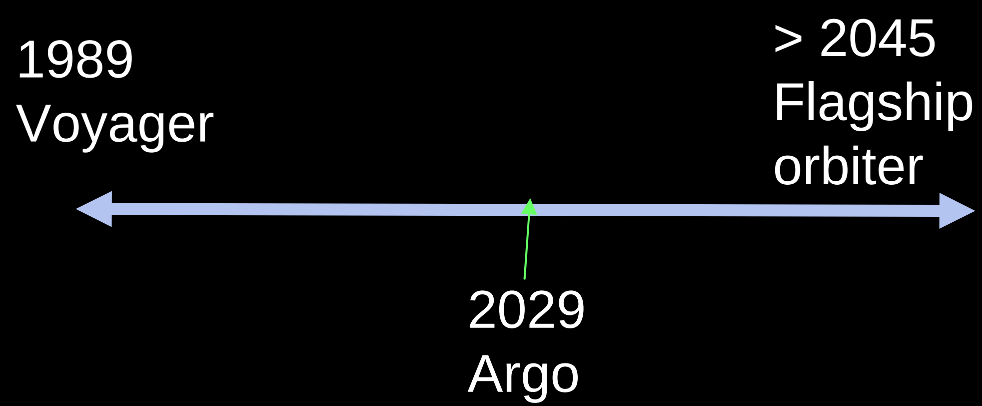
Key Characteristics:

- 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 and Triton





And goes on to a scientifically-selected KBO

Presentation Outline

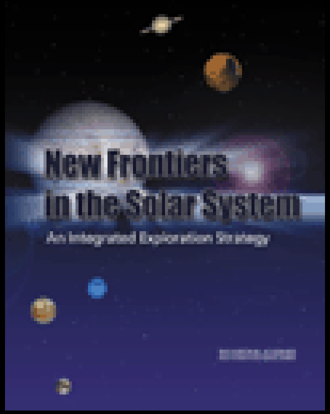
- Community support for a Neptune / Triton mission
- Science
- Mission, Payload, Spacecraft
- Observational timeline
- Summary

academy interest in **neptune**

2003 planetary decadal survey explicitly discusses neptune

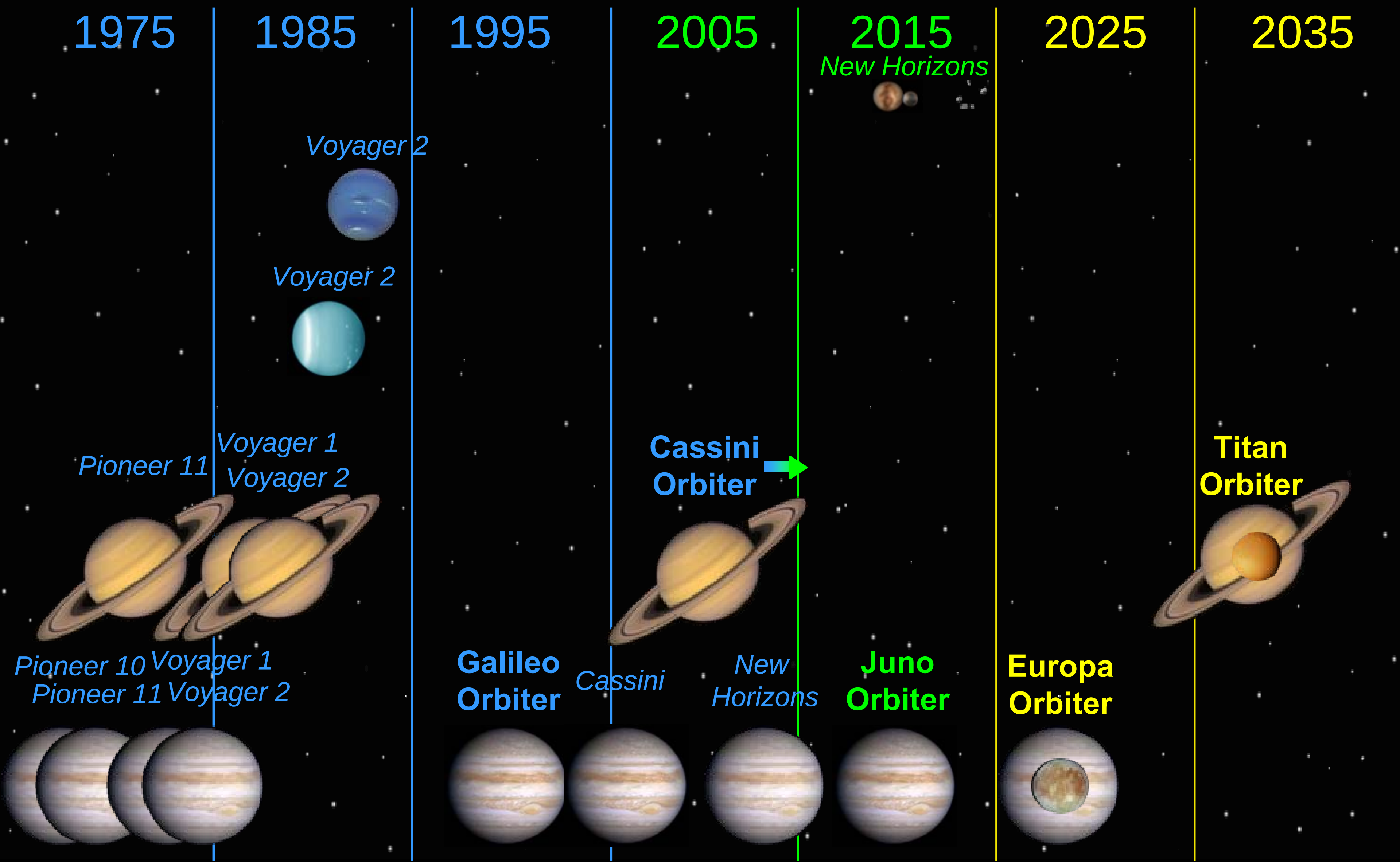
but Neptune set **three decades out (post 2035)** because

flagship-class orbiter assumed to be next step

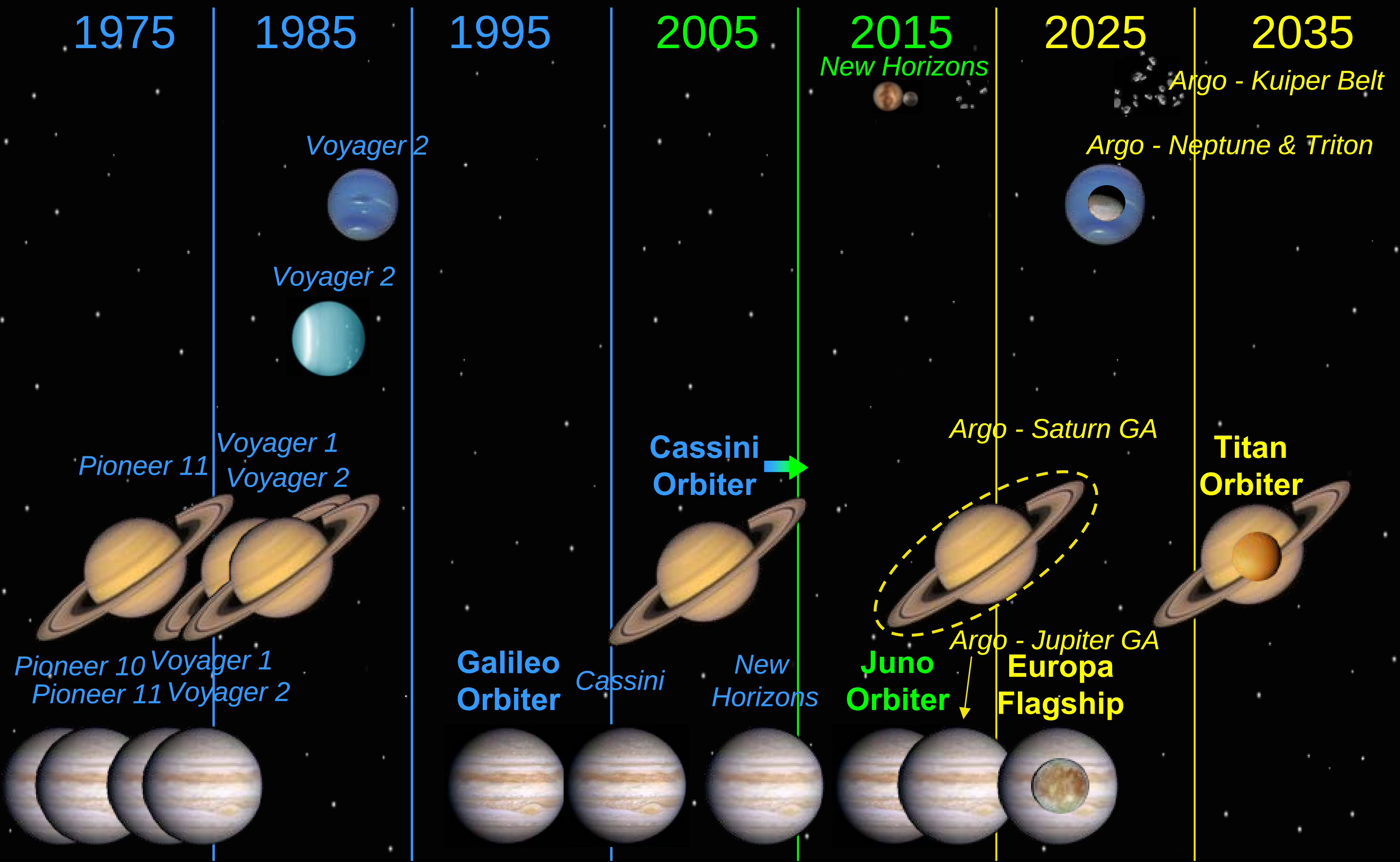


Our experience exploring Jupiter and Saturn belies this notion

Past, Present, and Future of **Outer Solar System Exploration**



Past, Present, and Future of
Outer Solar System Exploration



academy midterm report on decadal

committee on **a**ssessing **s**olar **s**ystem **e**xploration

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**”

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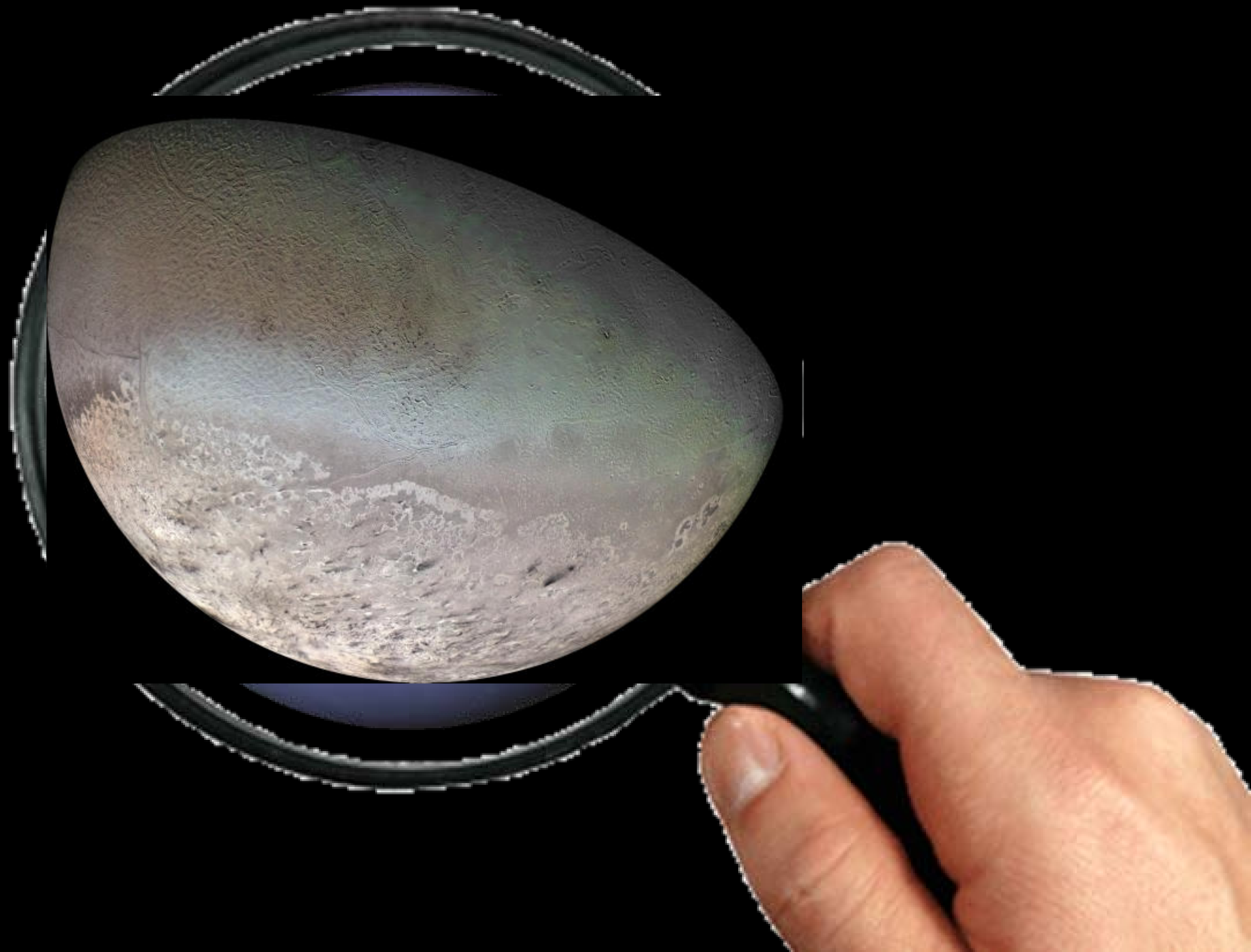
Focus on

Triton



Triton Level 1 Science Objectives
Interior

Triton has a youthful surface, likely substantially modified when Triton was captured by Neptune.

What does this tell us about the capture process? What level of heating did Triton experience? Did it differentiate?

- Determining the moment of inertia will tell us whether Triton has a differentiated core
- Detection of an intrinsic or induced magnetic field will tell us whether there is an internal conducting layer
  - Voyager closest approach was at an altitude of ~40k km, too far away to measure Triton's gravity field or any intrinsic magnetic field

Science Objective: fly close enough to Triton to measure the moment of inertia and detect the existence of an intrinsic or induced magnetic field, > 0.5 R_T

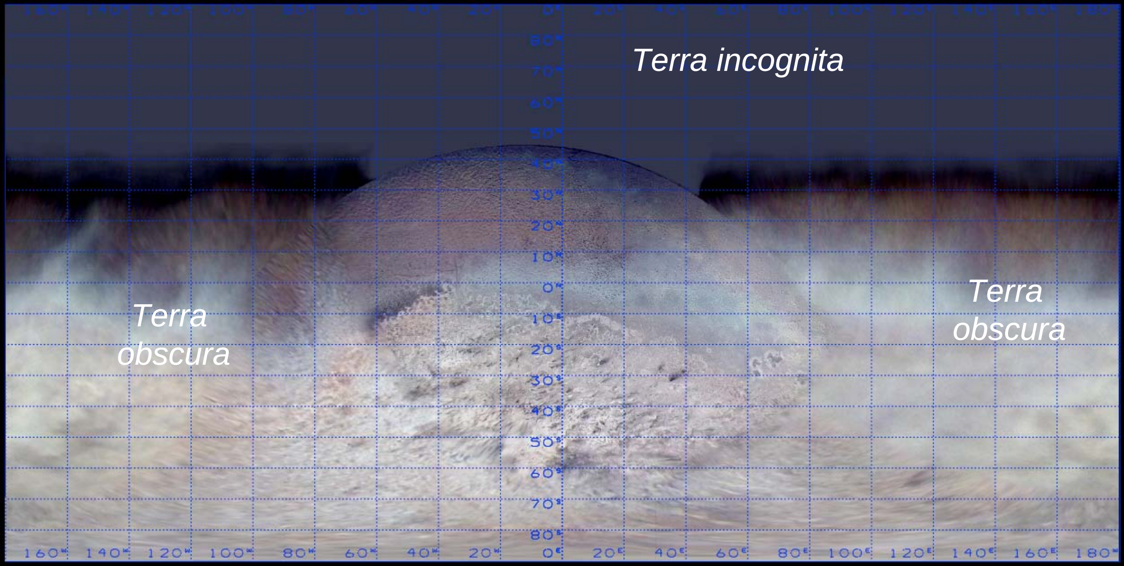
Triton Level 1 Science Objectives
Surface History

One side of Triton was seen only at a distance by Voyager (‘terra obscura”) and more of the northern hemisphere will be illuminated in 2029. 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

Terminator in 2027: 60°

Terminator in 1989 for VGR flyby: 45°



Anti-Neptune hemisphere observed only at low resolution (~60 Km) by Voyager. Best resolution ~1 km

Triton Level 1 Science Objectives
Surface History

Triton's surface is only lightly peppered with craters

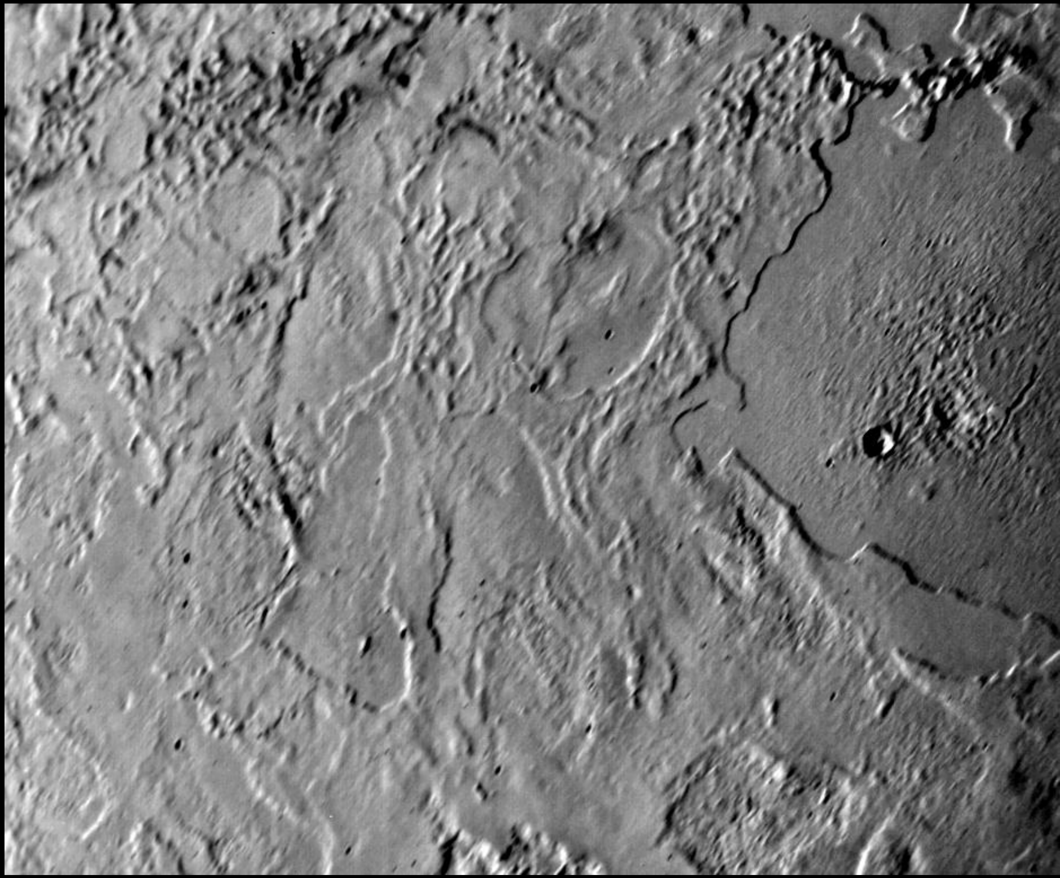
If Triton was captured very early in the history of the Solar System, aided by an extended proto-Neptunian atmosphere, then tidal evolution to a circular orbit and differentiation should have been complete in order 10^8 yrs, followed by billions of years of impact cratering. Yet the surface is lightly cratered. Was it actually captured much more recently?

High resolution images of the hemisphere observed only at low resolution by Voyager, to complete the geologic history

Triton Level 1 Science Objectives
Surface History

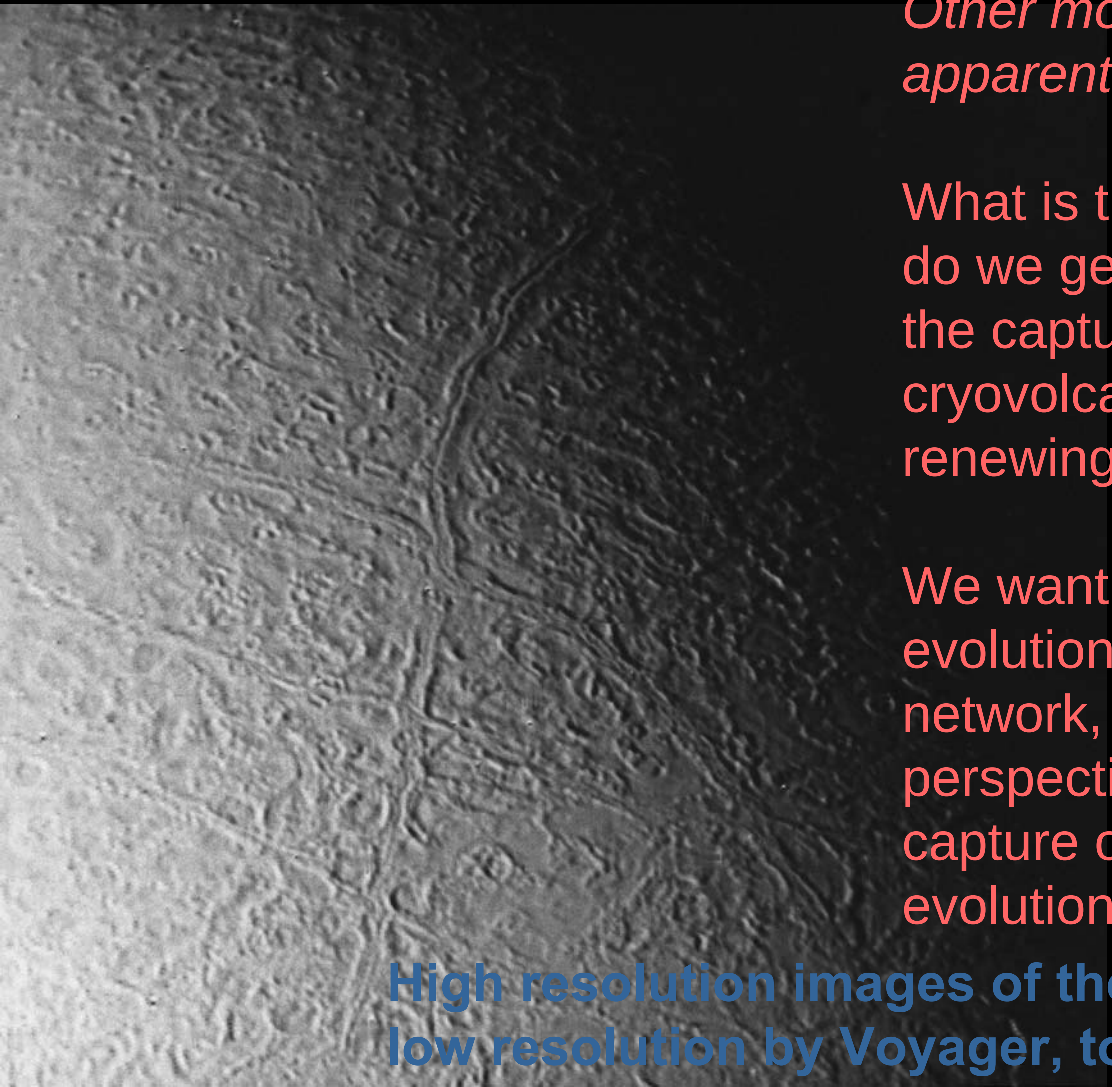
Since Triton is the only major satellite around Neptune, it probably has not been received many sesquinary craters, i.e. from ejecta from large impacts onto other satellites

Triton may provide the very best place to measure the size-frequency distribution of comet-formed impact craters, which in turn will help us to understand cratering chronology throughout the Solar System



High resolution images of the hemisphere observed only at low resolution by Voyager, to complete the geologic history

Triton Level 1 Science Objectives
Surface History



Other modification of Triton's surface is apparent in Voyager images

What is the tectonic history? What insight do we get from the tectonic history into the capture? Are there diapirs? Has cryovolcanism played a major role in renewing the surface?

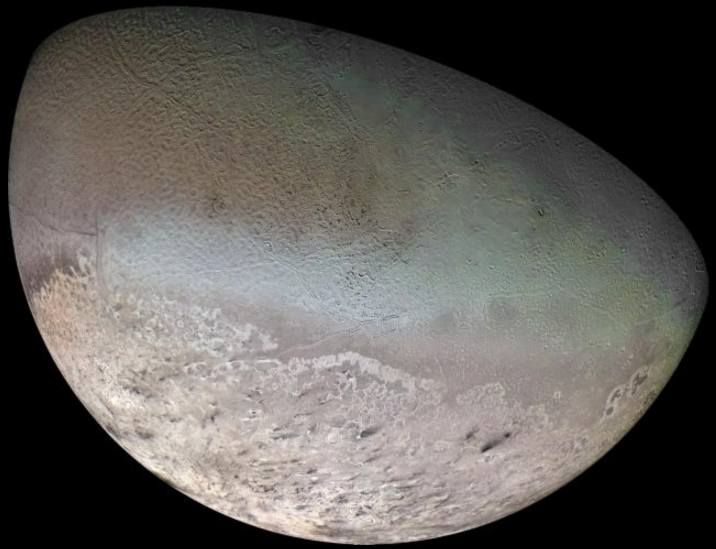
We want to determine the surface evolution chronology, study the tectonic network, and interpret new data with the perspective of what this tells us about the capture of Triton and its subsequent evolution.

High resolution images of the hemisphere observed only at low resolution by Voyager, to complete the geologic history

Triton Level 1 Science Objectives Volatile Ices and Seasonal Processes

Triton's climate is controlled by its nitrogen atmosphere in vapor equilibrium with surface frost.

- Triton's atmosphere has changed significantly since the Voyager flyby in 1989 (ground-based stellar occultation data)

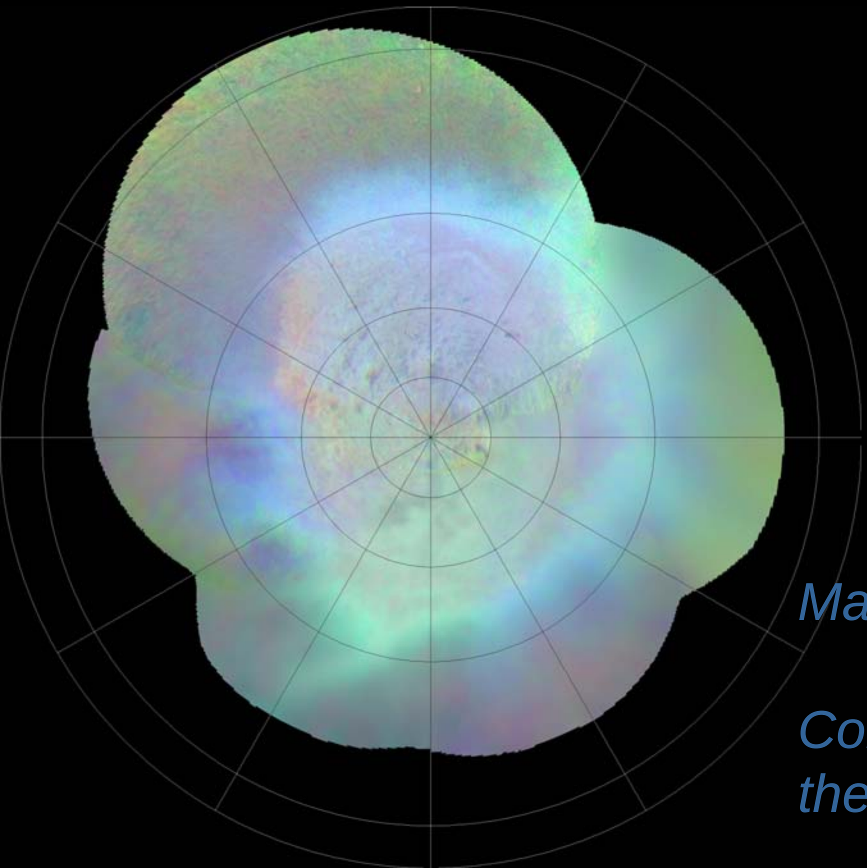


Measure atmospheric pressure - calculate mass moved seasonally

Measure surface temperatures - energy balance models

Triton Level 1 Science Objectives Volatile Ices and Seasonal Processes

Nitrogen and methane ices move seasonally from hemisphere to hemisphere and the pressure of the atmosphere increases and decreases seasonally

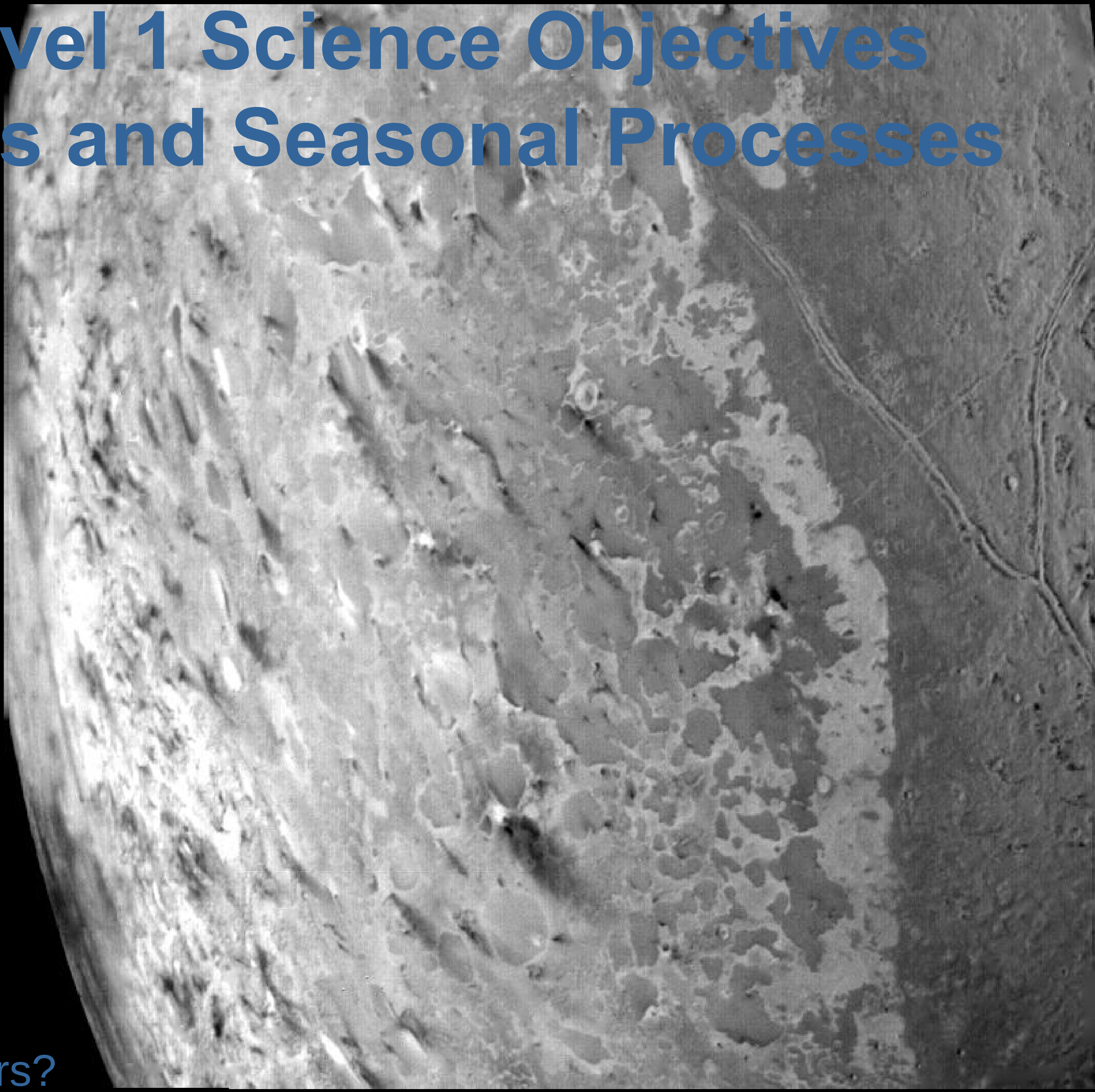


- Voyager had no means (no NIR spectrometer) of mapping surface ices - existing compositional data is earth-based, thus full-disk
- Ground-based data shows N_2 ice , with trace amounts of CH_4, CO_2 and CO ices

Map the distribution of ices on Triton's surface

Compare to Pluto, KBOs - volatile inventory in the solar system

Triton Level 1 Science Objectives
Volatile Ices and Seasonal Processes



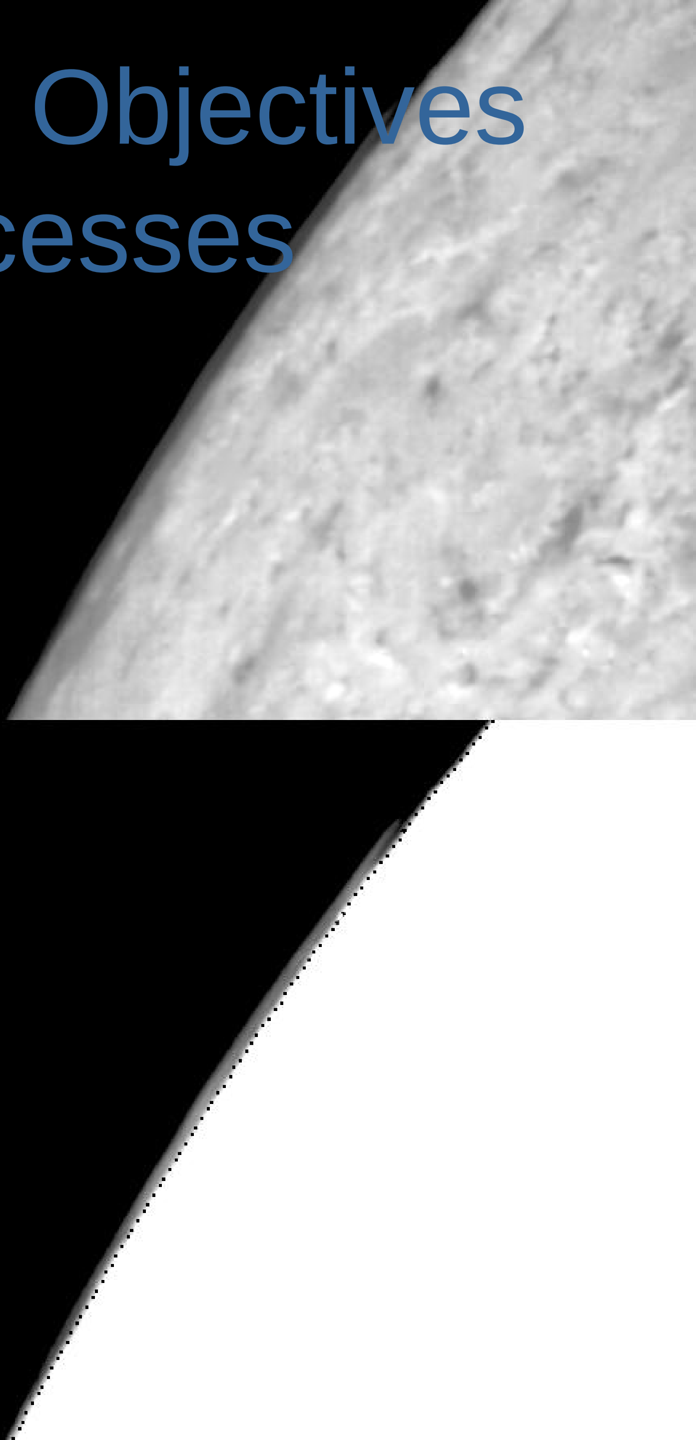
Triton's astonishing geysers

What powers these plumes?
Evidence for solid state greenhouse in the surface ice?

Similar to Mars?

Will Triton's enigmatic plumes still be active? Are they a seasonal phenomenon, like on Mars?

Triton Level 1 Science Objectives
Atmospheric Processes



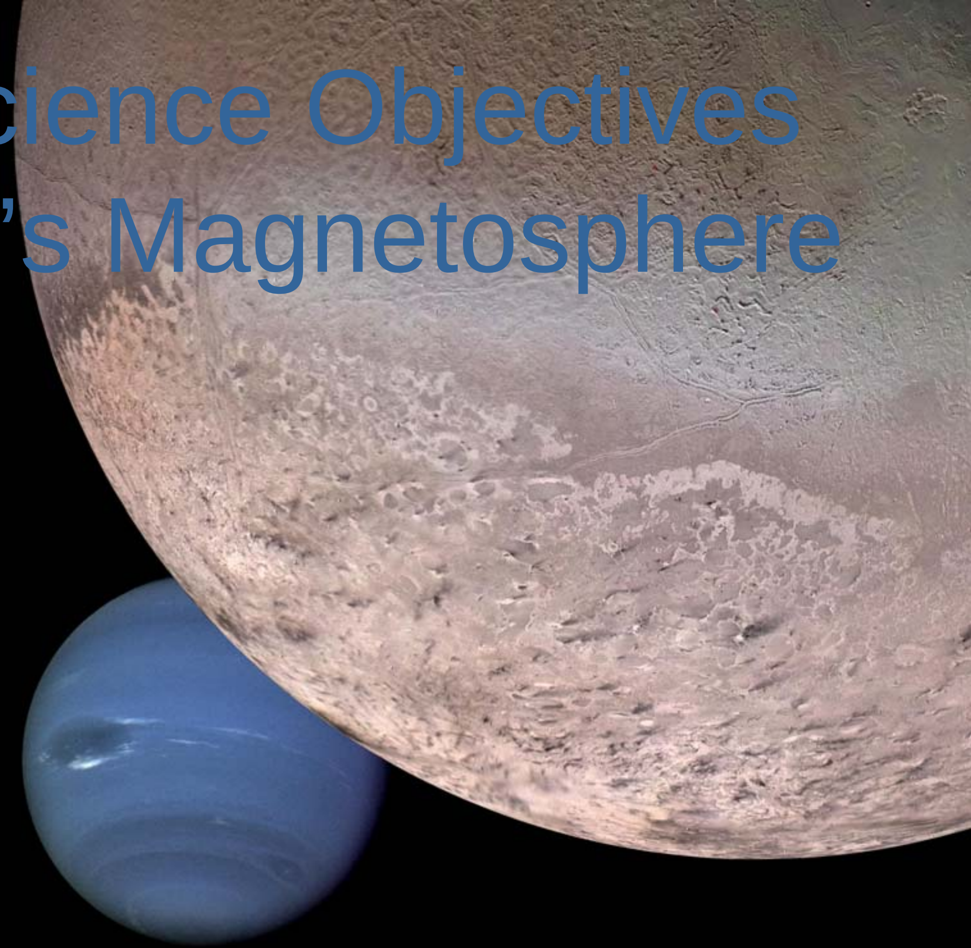
Triton's haze layer - what are the aerosol properties? Have they changed since Voyager? Where do they come from?

Winds distribute fine material across the surface - Have the winds changed direction? What does that imply for the sublimation process?

Image hazes at variety of phase angles and wavelengths to get particle size distribution

Map direction of fan of fines on the surface

Triton Level 1 Science Objectives
Triton in Neptune's Magnetosphere



How is the relatively *dense neutral torus* of Triton formed, and what is its relationship, if any, to active vents on Triton and/or loss processes from Triton's atmosphere?

What is the *composition of the plasma* in Neptune's magnetosphere?
Composition will reveal information about the surface and atmosphere of Triton as well as possible contributions to the plasma from Neptune and the solar wind.

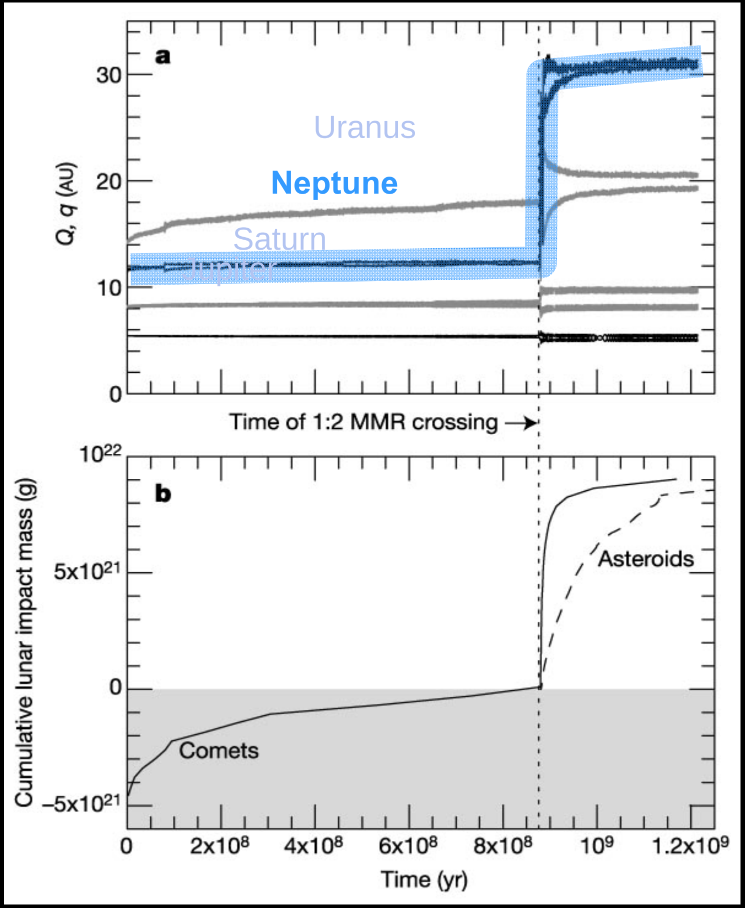
Measurements of ions and electron fluxes as a function of energy-per-charge and composition of the ions along the trajectory of the spacecraft can be related to the neutral torus densities by modeling charge-exchange and ionization processes.

Derived Requirements

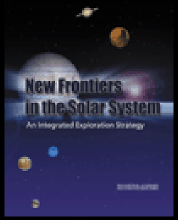
- Interior studies - Close flyby (< 0.5 Triton radius), magnetometer
- Surface geology - long focal length, high snr camera
- Volatile ices - near IR imager, thermal mapper
- Atmosphere, climate change - ultraviolet spectrometer
- Interaction with Neptune’s magnetosphere - plasma spectrometer, magnetometer, radio science

Our Picture of Solar System Evolution has changed dramatically

- 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"



From "Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets," R. Gomes, H. F. Levison, K. Tsiganis and A. Morbidelli 2005. *Nature* **435**, 466-469.

Neptune flyby enables KBO science

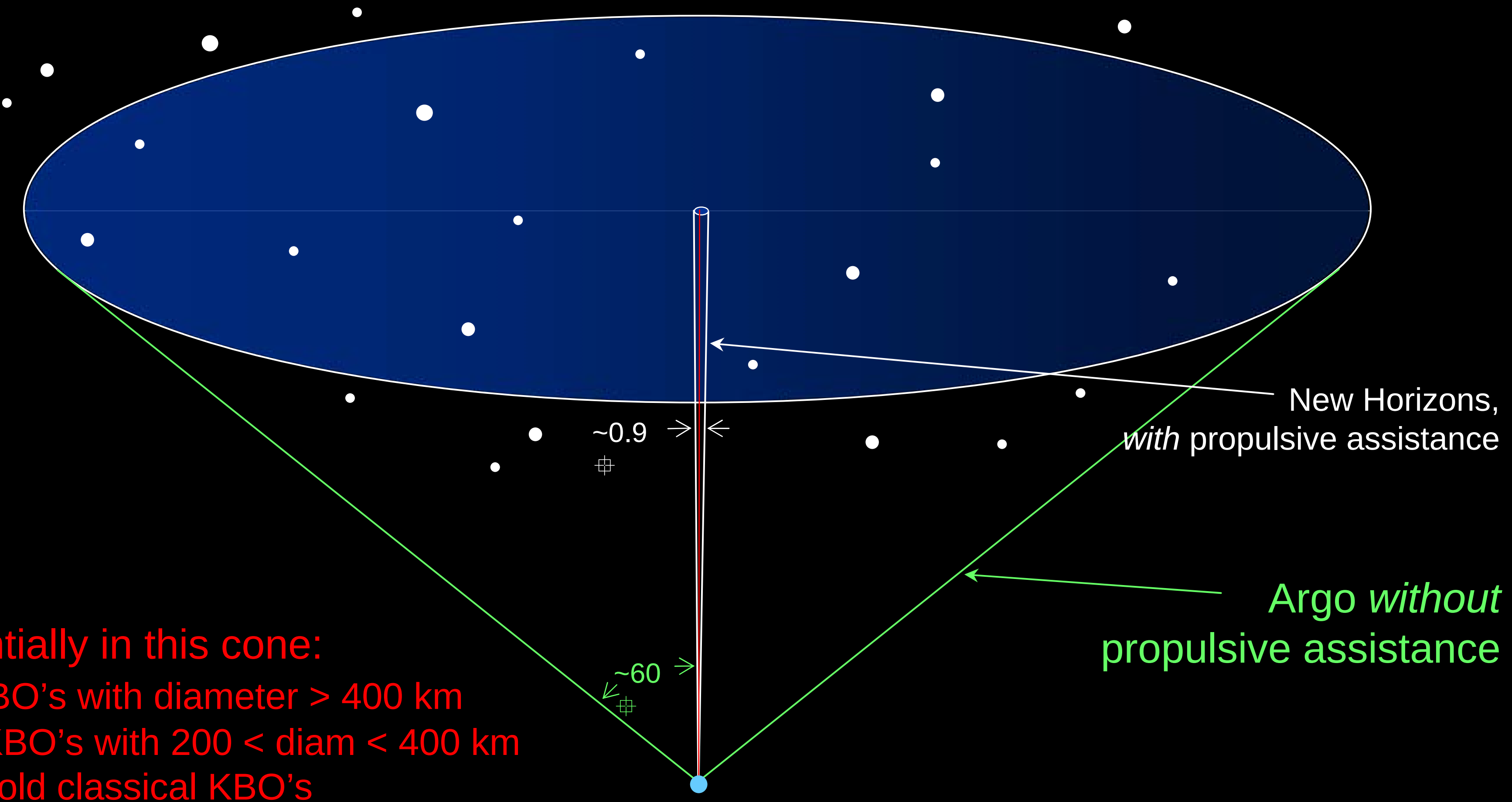
- Opportunity to continue on to a KBO!
- Potential KBO Targets
  - The cone of accessibility includes ~40 of the largest KBOs
  - Several binary KBOs
  - Many objects in the cold classical disk

- 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 ~4000x 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

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 situu*
- 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

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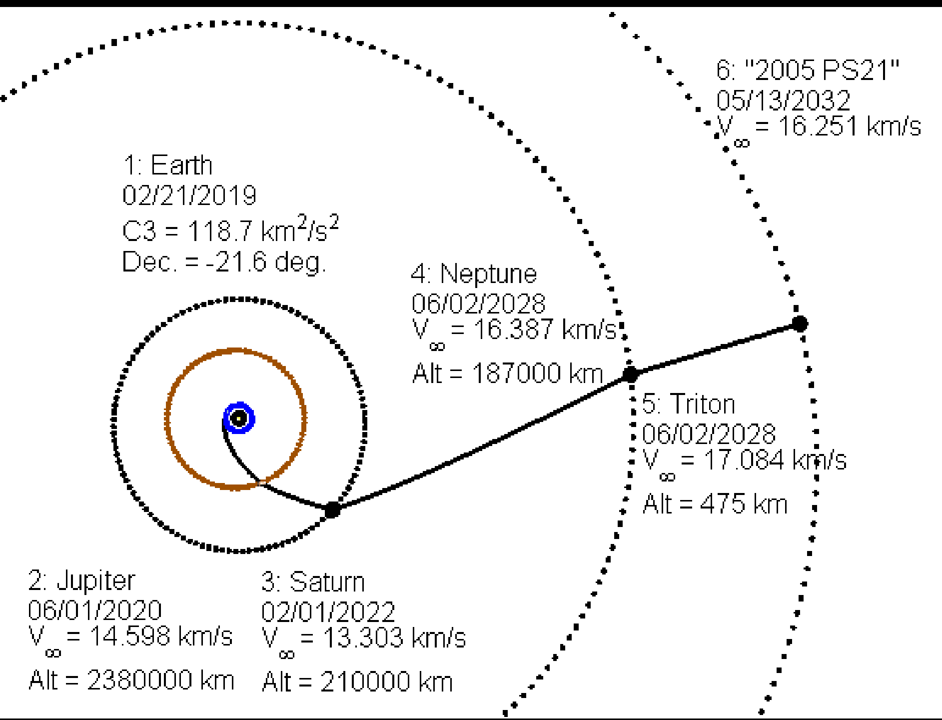
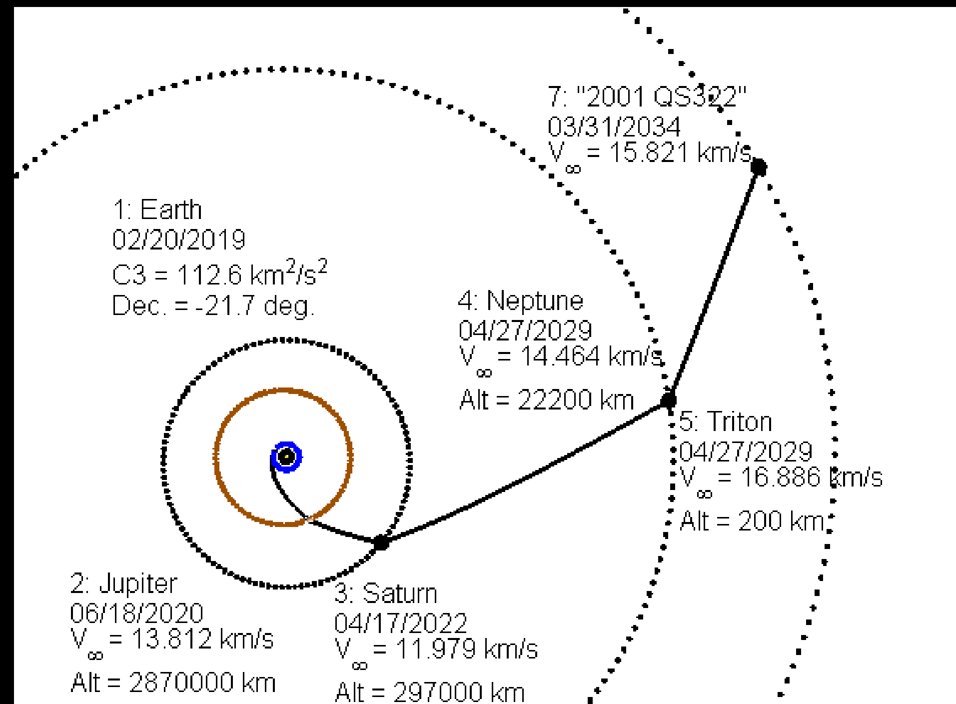
Example 2019 Launch Options

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



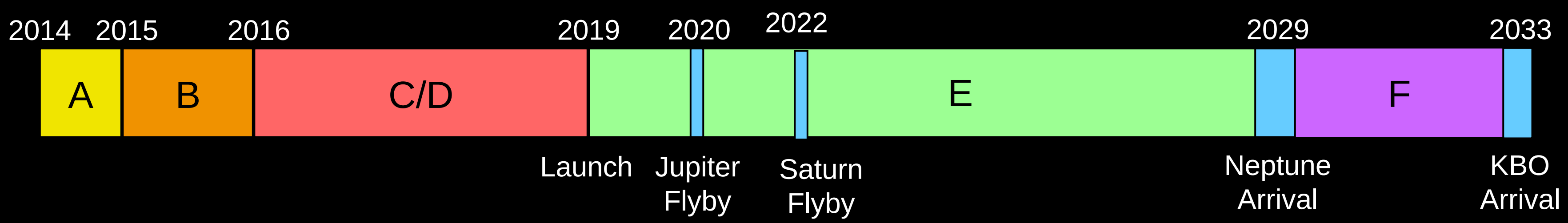


Time of Flight = 9.3 yr
Neptune flyby 2028
38S Neptune periapsis
KBO: 2005 PS21

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

Project Timeline

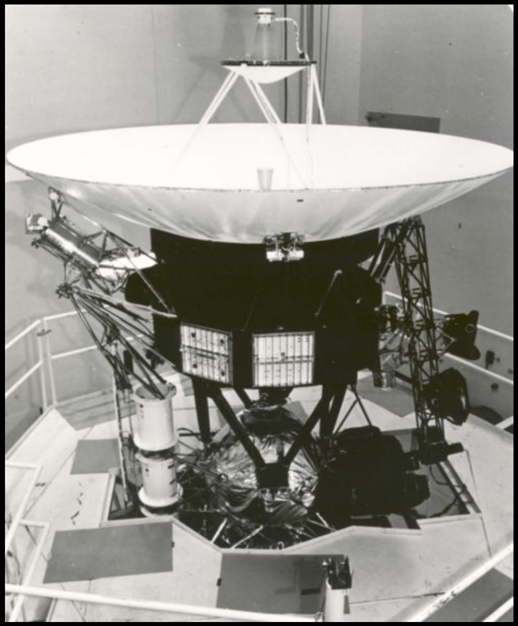
- Phases A, B, C/D, E, F (with science windows)



- 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
- Gimballed 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

Figure 1. The MCS flight instrument photographed during calibration at JPL. Major elements of the instrument are identified.

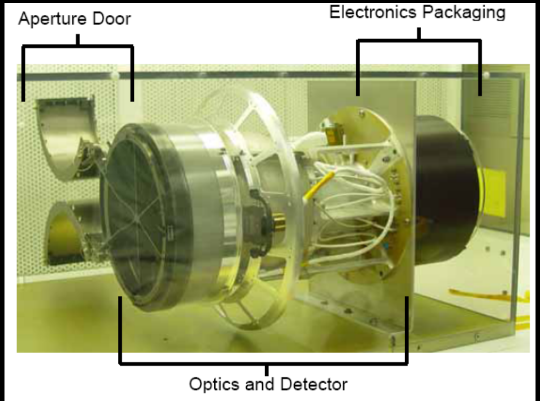


Figure 18. Photograph of SWAP instrument highlighting subassemblies

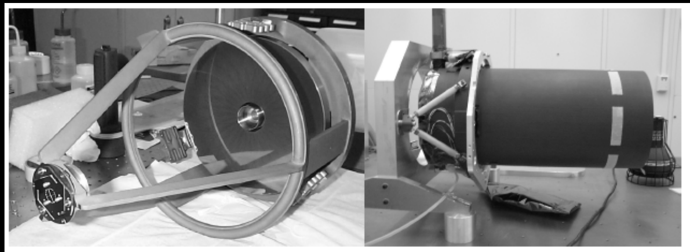


Figure 1 (left) LORRI telescope assembly, showing SiC mirrors and metering structure; (right) LORRI composite baffle and flexure mount on test stand

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

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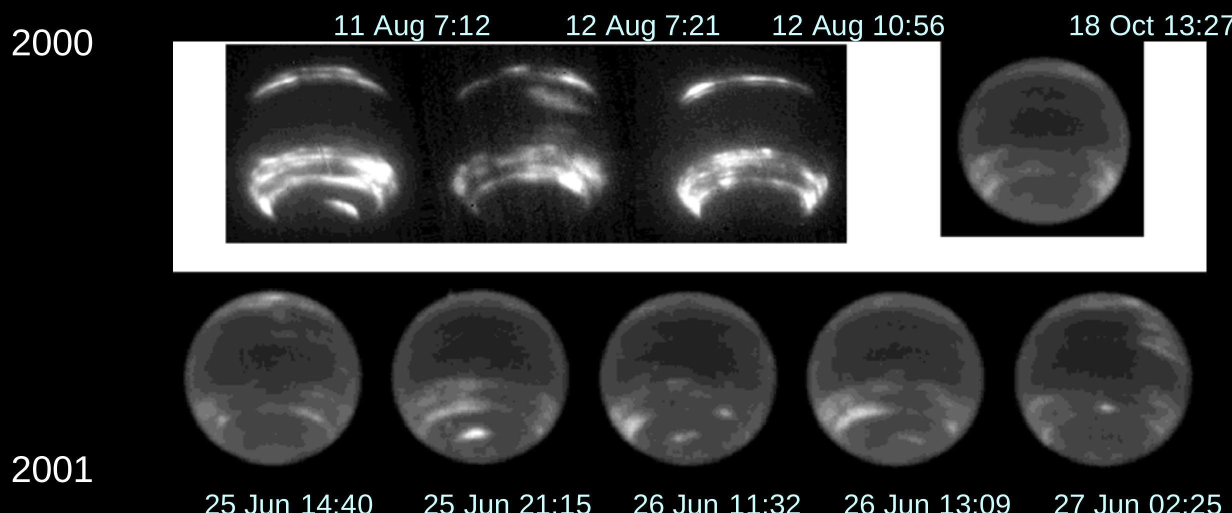
Observational Timeline

Atmospheric Movies

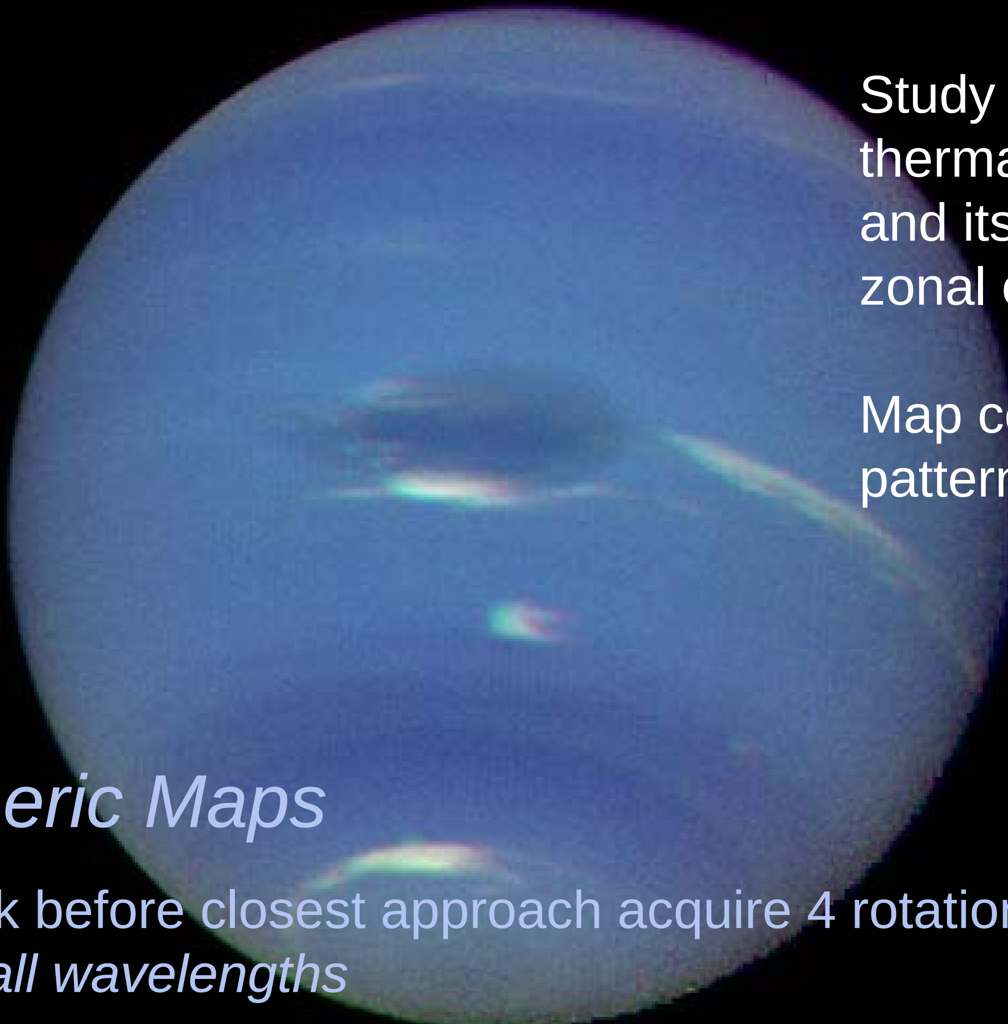
- Beginning at closest approach - 6 months observe Neptune every 36 deg of longitude, in visible, near IR and thermal wavelengths.
- Receding from Neptune, from closest approach to + 6 months observe Neptune every 36 deg of longitude, in visible, near IR and thermal wavelengths



Study Neptune's dynamic atmosphere on short timescales

Map zonal winds

Observational Timeline



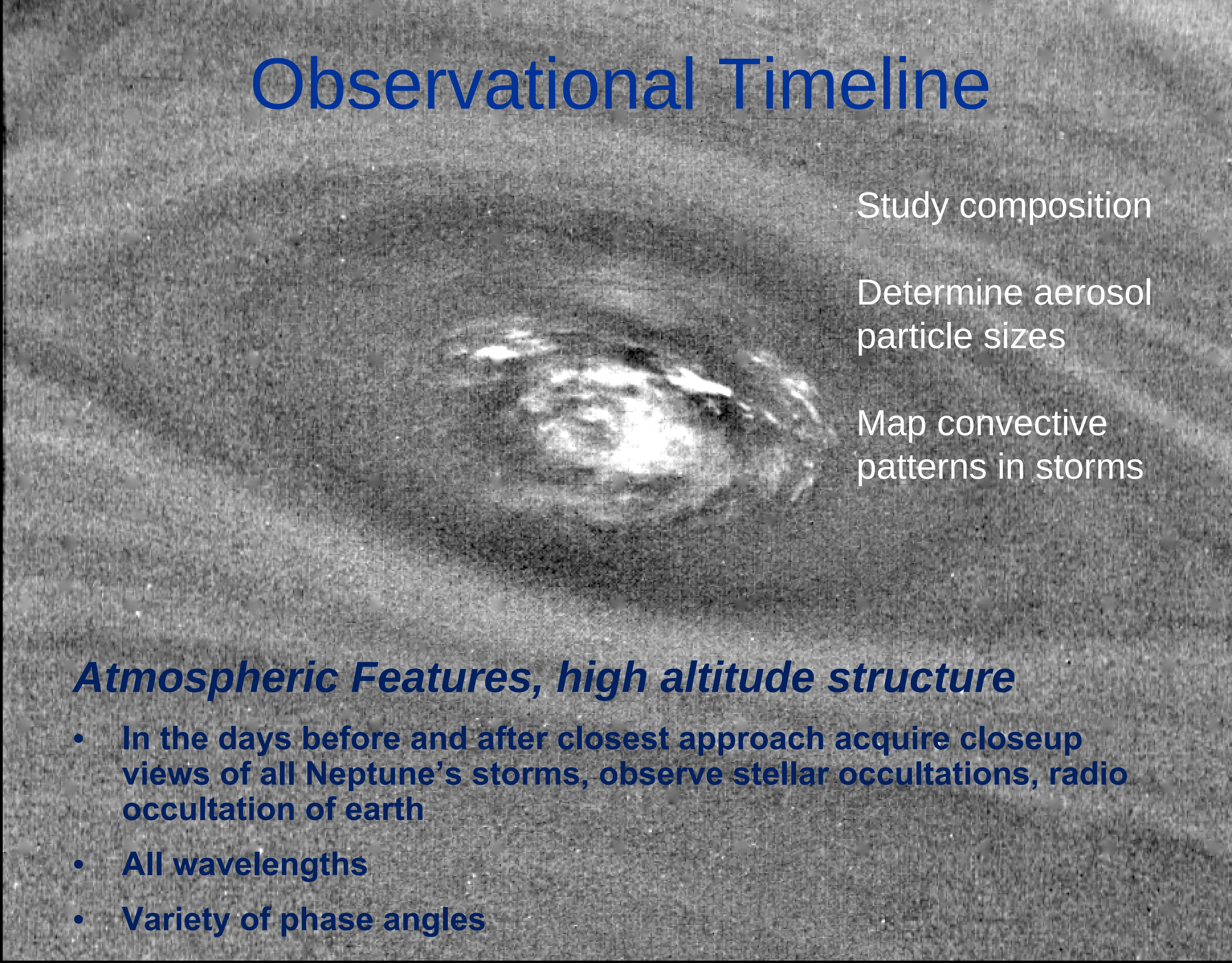
Study Neptune’s thermal emission and its effect on zonal circulation

Map convective patterns

Atmospheric Maps

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

Observational Timeline



Study composition

Determine aerosol particle sizes

Map convective patterns in storms

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**

Observational Timeline

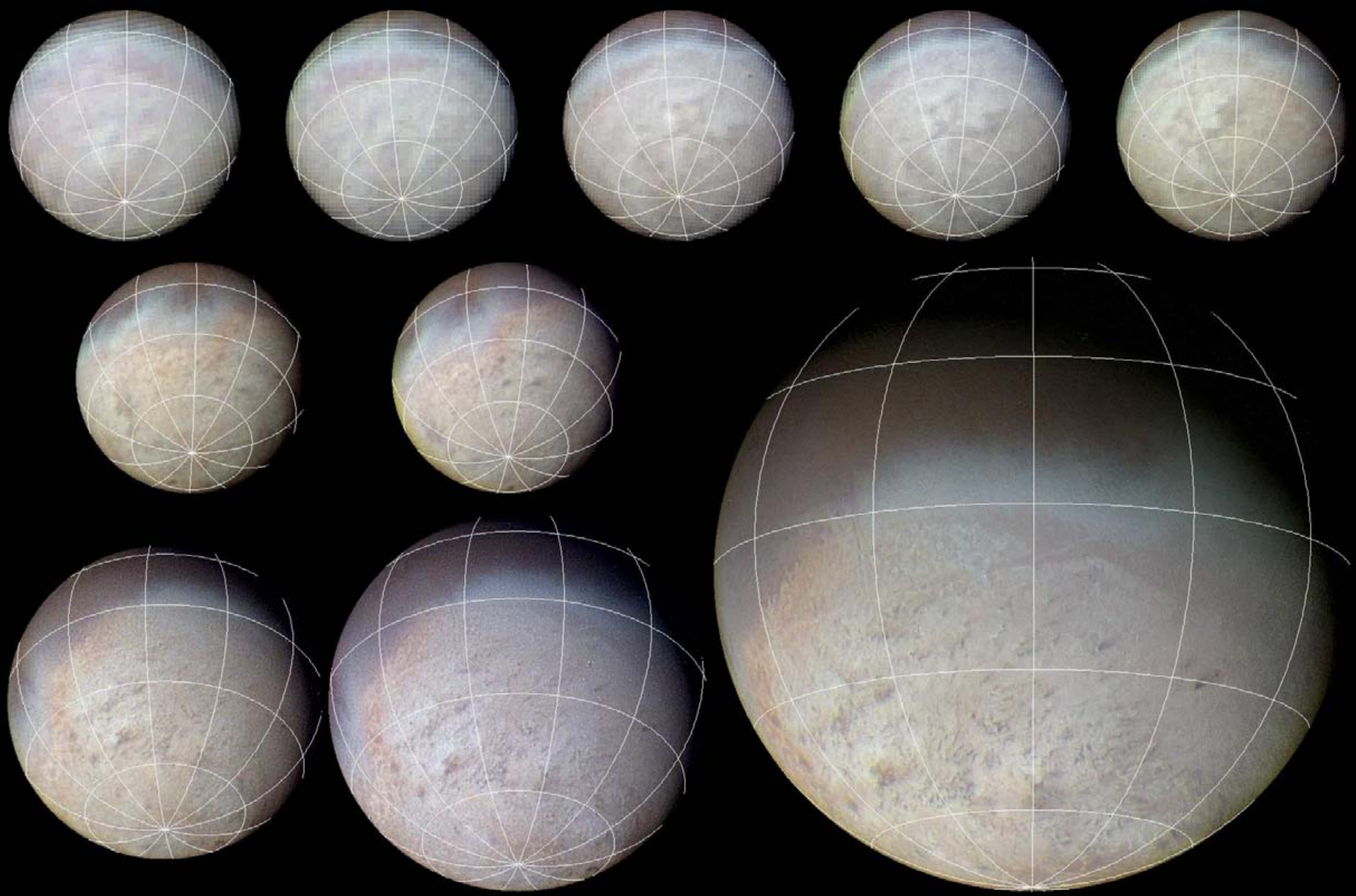
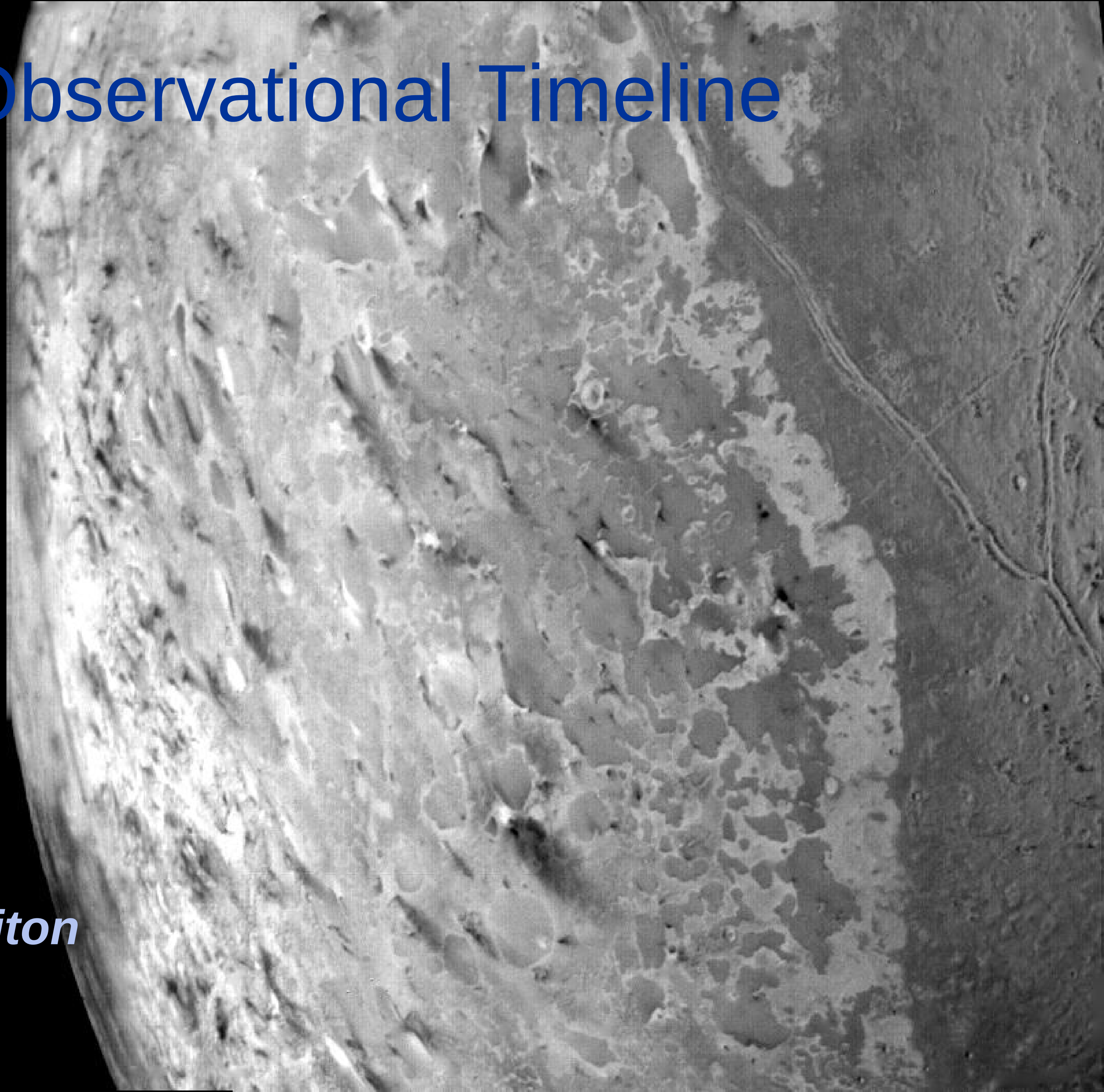


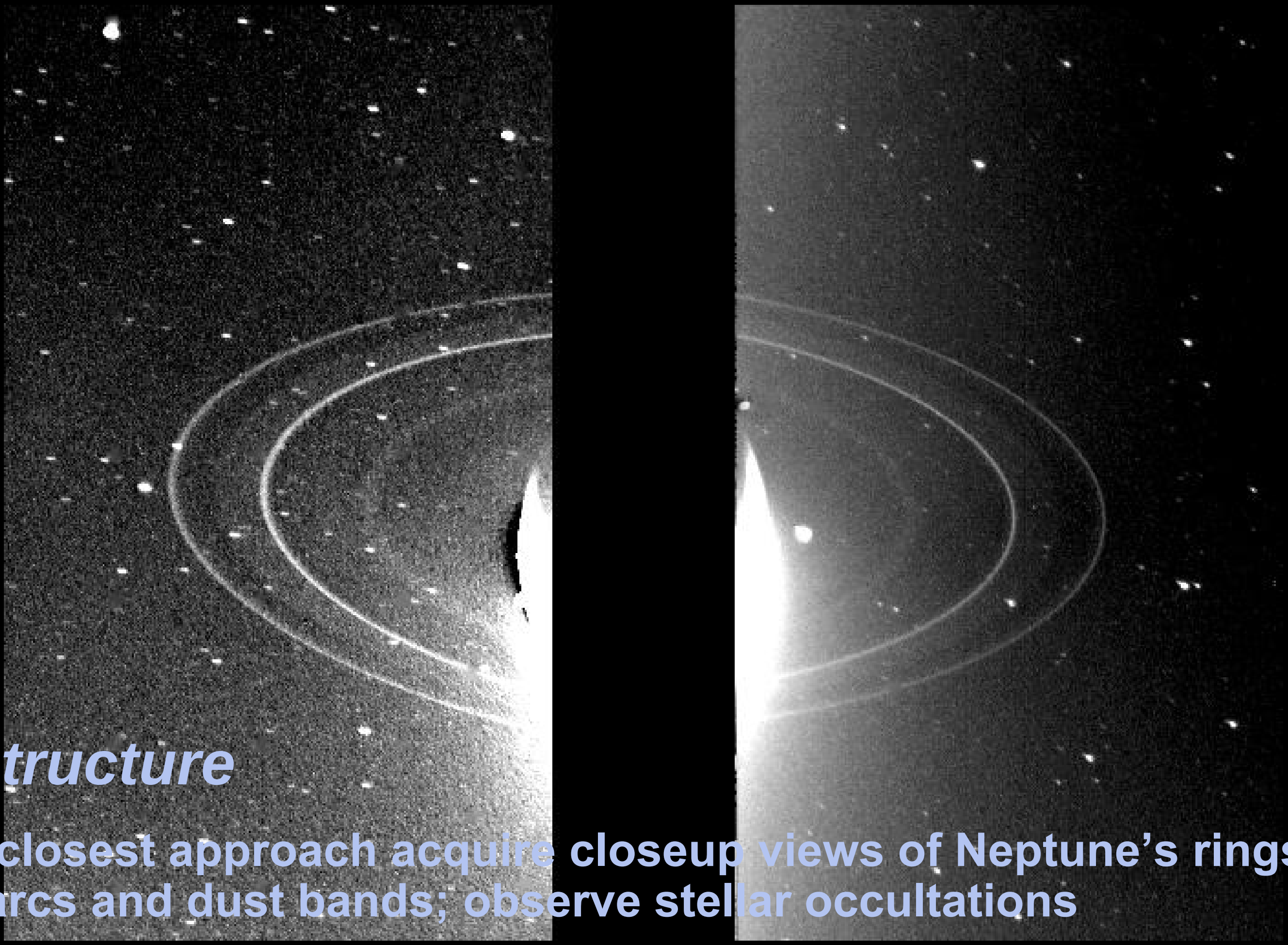
Image Triton at all wavelengths, starting 3 days from closest approach

Observational Timeline



Encounter Triton

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**

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Academy and Community Interest

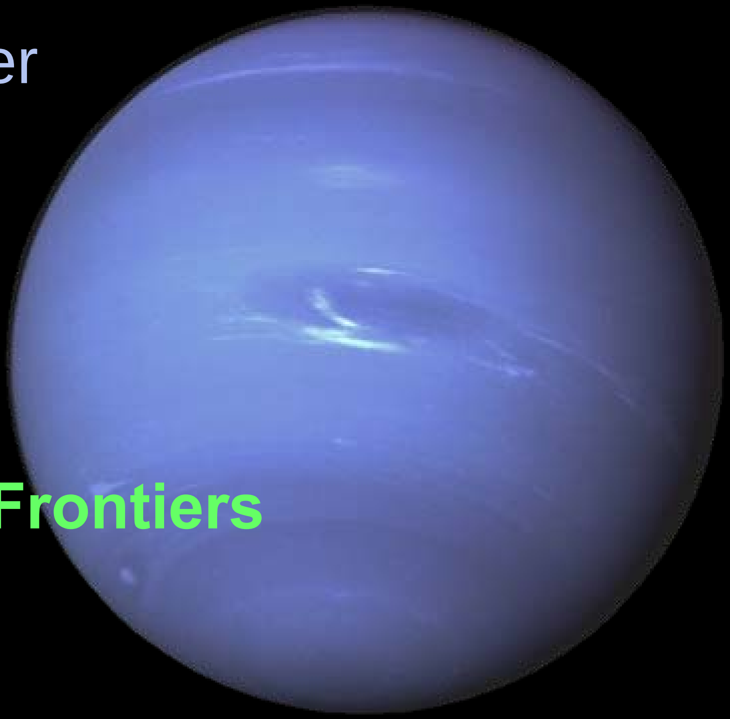
- 2003 Planetary Decadal Survey explicitly discusses Neptune
  - Flybys/orbiters in “Giant Planets,” “Large Satellites,” and “Primitive Bodies”
  - Community Papers highlight Neptune Atmosphere and System Exploration
  - Set in third decade because Flagship-class orbiter assumed
- NASA Vision Missions: 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

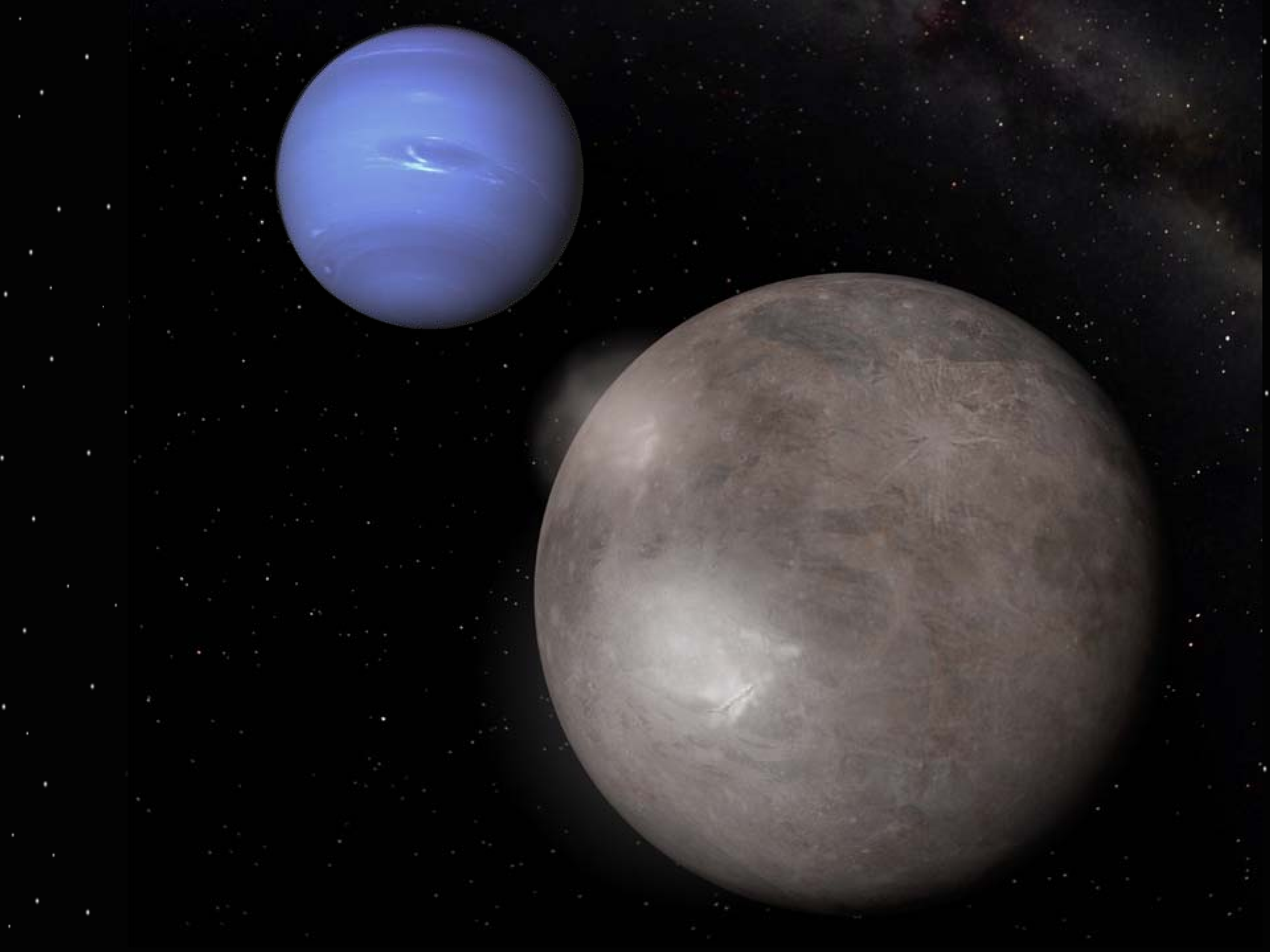
- **Neptune and Triton are compelling flyby targets**
  - Dynamic worlds, rich opportunities for new science discoveries
  - Trajectories identified with reasonable trip times and approach velocities

- 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

New Frontiers 3		**New Frontiers 4**
AO out	2009	
	2010	
	2011	
	2012	
	2013	AO comes out 54 months after NF3 AO, write proposal
	2014	Downselect, Step 2 = Phase A
	2015	Phase B
	2016	Phase C/D
	2017	Phase C/D
	2018	Phase C/D
	2019	Launch in February
	2020	Backup launch in January

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

C_3 (km^2/sec^2) ≡ 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)

- For a given launch vehicle:
  - higher C_3 → faster trip time BUT smaller spacecraft mass that vehicle can launch

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

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

- 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

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

- 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

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."

Neptune cost mitigators: Can use an Atlas 541 instead of a 551.
Do not require Star-48 upper stage. Other savings under study.

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

** Atlas 541 is ~$190M; if Star-48 upper stage not needed, then get additional ~$10M savings*

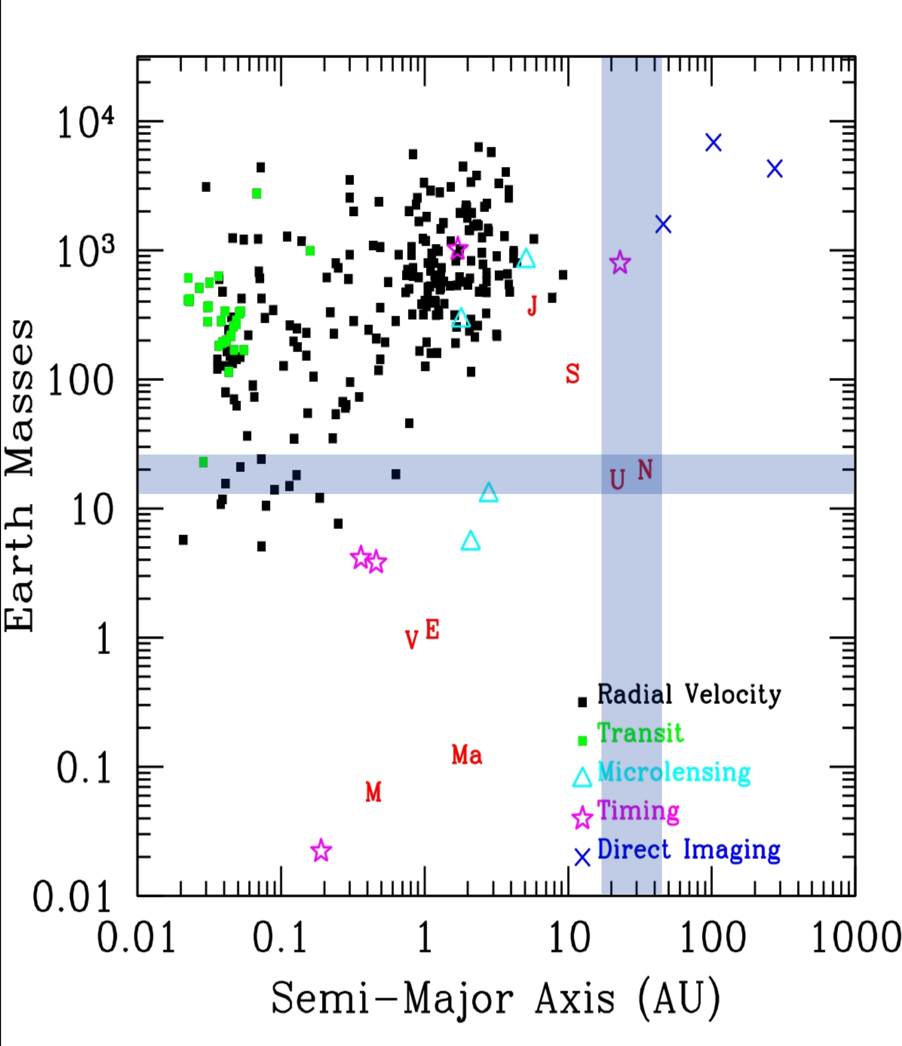
- Plan to size the requirements to the $ available
  - Have identified options to explore to fit comfortably within NF budget resources (next slide)

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 $

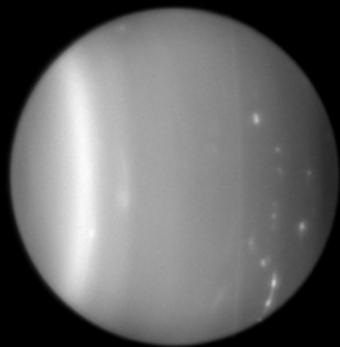
Why study Neptune? Broader Perspective

- 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



Which Ice Giant?

Uranus



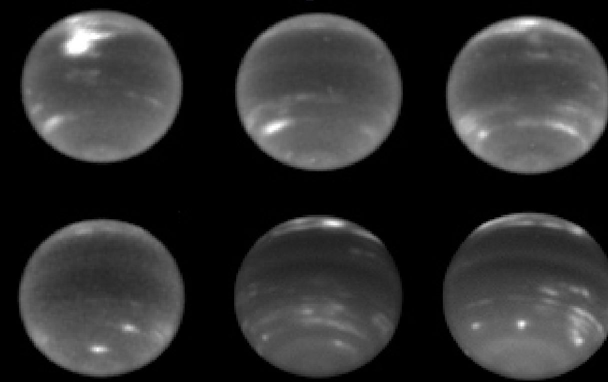
Uranus Pros

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

Uranus Cons

- ▯💧♒□◆●♎ ♎□ ♦♒♏ ♐ly-by at equinox (2007, 2049) to get active atmosphere (see equinoctial above) and full

Neptune



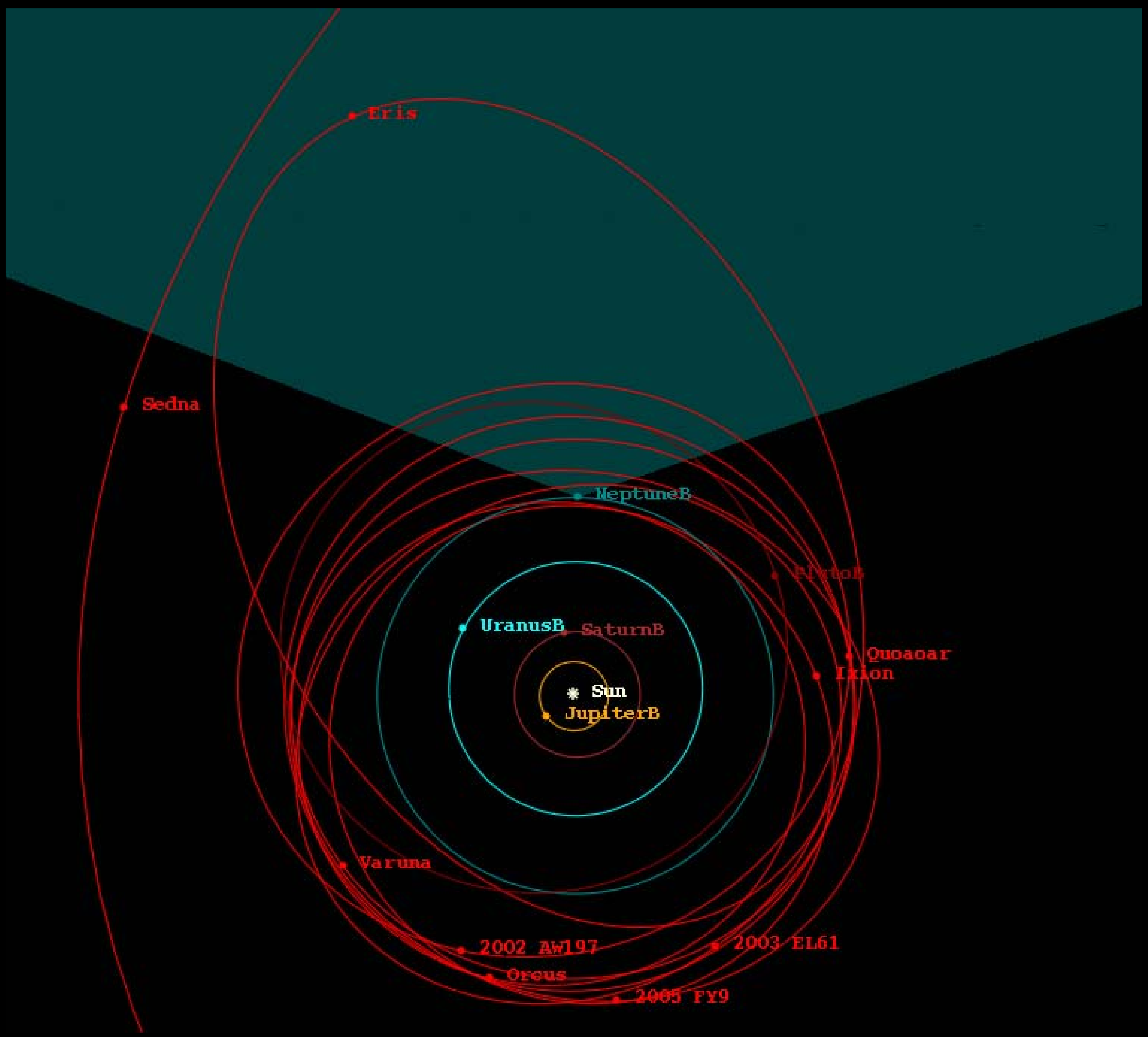
Neptune Pros

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

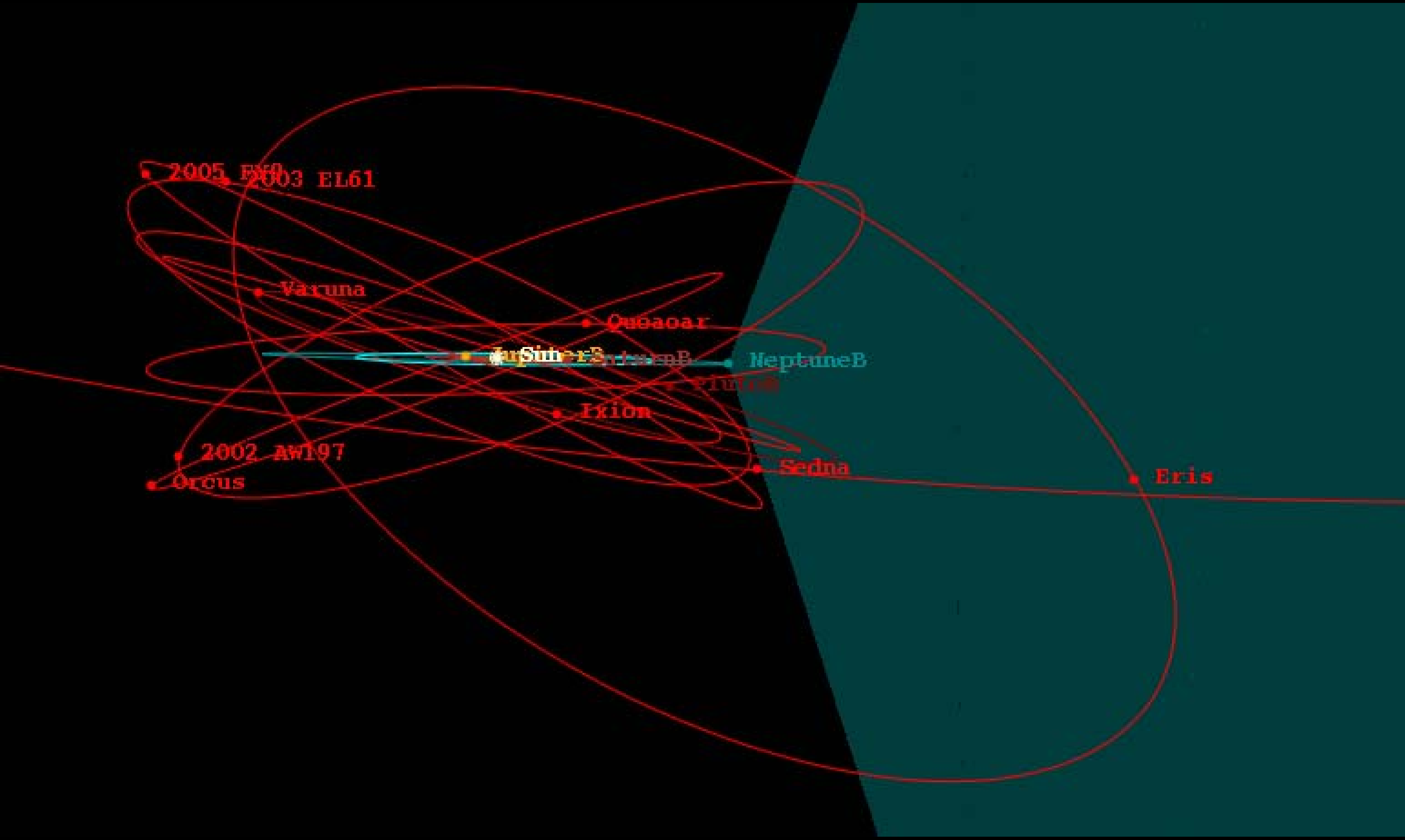
Neptune Cons

- Farther away; longer trip time

KBO Accessibility - top view



KBO Accessibility - side view



Decadal Priorities, 1 of 3

Class of Question	Scientific Themes	Earth-Based Orbiting Facilities	Neptune POP	Analysis and Modeling	Lab	ARGO
	Theme 1. ORIGIN AND EVOLUTION					
	Solar-System Giant Planets					
Paradigm altering	How did the giant planets form?	x	xxx	xx	xx	xx
"	What are the orbital evolutionary paths of giant planets?	o	xxx	xxx	o	x
Pivotal	What are the elemental compositions of the giant planets?	x	xxx	xx	x	xx
"	What are the internal structures and dynamics of giant planets?	xx(1)	xxx	xxx	x	xx
	Extrasolar Giant Planets and Brown Dwarfs					
Pivotal	How can we use the giant planets in our solar system to calibrate spectroscopic observations (optical, infrared, radio) of extrasolar giant planets?	xx	xxx	xxx	x	xxx

Decadal Priorities, 2 of 3

Class of Question	Scientific Themes	Earth-Based Orbiting Facilities	Neptune POP	Analysis and Modeling	Lab	ARGO
	Theme 2. INTERIORS AND ATMOSPHERES					
	Interiors					
Pivotal	What is the nature of phase transitions within the giant planets?	xx(1)	xxx	xx	x	xx
"	How is energy transported through the deep atmosphere? Do radiative layers exist?	xx(1)	xxx	xx	x	xx
"	How and where are planetary magnetic fields generated?	x(1)	xxx	xxx	o	xxx
Foundation building	What is the nature of convection in giant planet interiors?	xx(1)	xxx	xxx	o	xx
"	How does the composition vary with depth?	x(1)	xxx	xx	o	xx

Decadal Priorities, 3 of 3

Class of Question	Scientific Themes	Earth-Based Orbiting Facilities	Neptune POP	Analysis and Modeling	Lab	ARGO
	Theme 2. continued: *Atmospheres*					
Pivotal	What energy source maintains the zonal winds, and how do they vary with depth? What role does water and moist convection play?	x	xxx	xx	x	xxx
"	What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?	x	xxx	xx	x	xxx
Foundation building	How and why does atmospheric temperature vary with depth, latitude, and longitude?	x	xxx	xx	x	xxx
"	How does the aurora affect the global composition, temperature, and haze formation?	x	x	xx	x	x
"	What produces the intricate vertical structure of giant planet ionospheres?	x	xx	xx	x	xx
"	At what rate does external material enter giant planet atmospheres, and where does this material come from?	x	o	xx	x	o
"	What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?	x	x	xx	x	x

Power Source Options

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

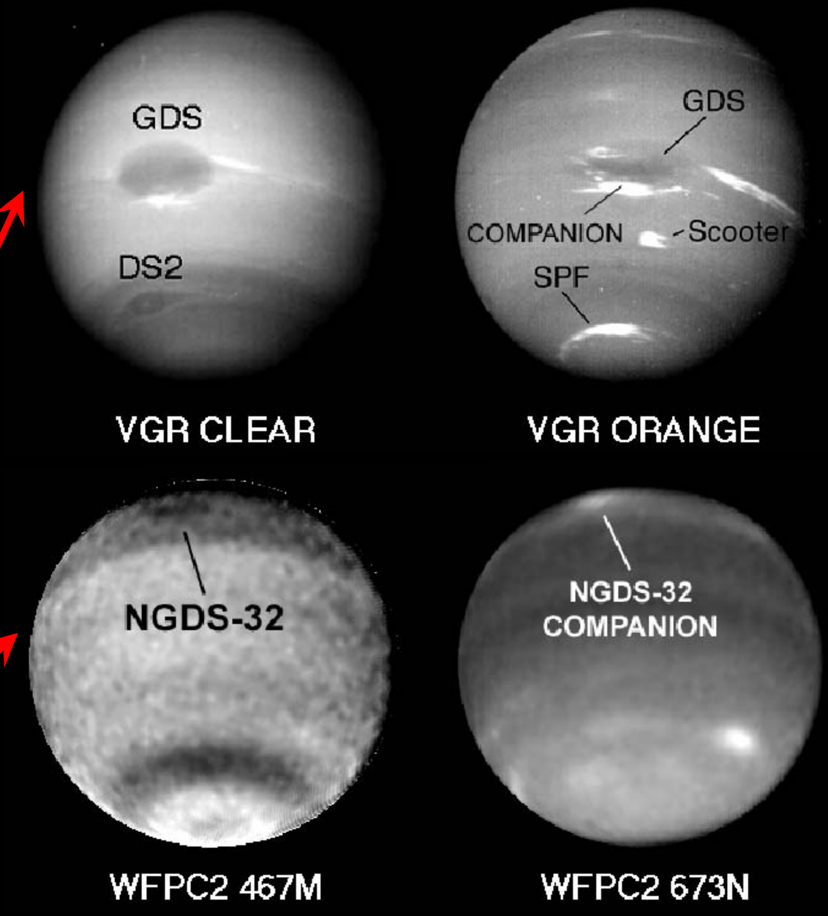
* New Horizons' GPHS-RTG used a mix of old and new Pu; BOL power for that unit was only 240 W

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).

neptune's dynamic atmosphere

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

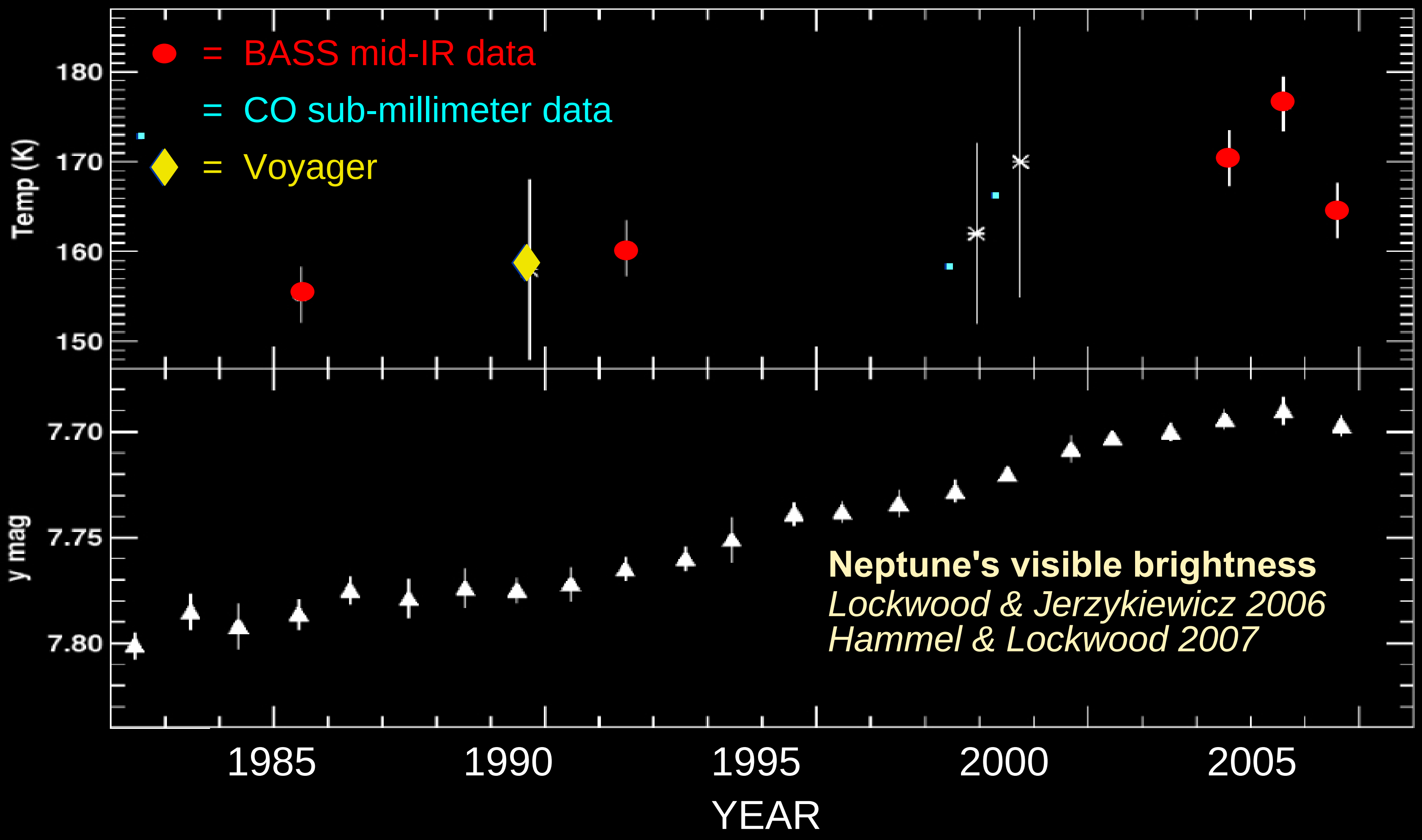
- Neptune's atmosphere shows fundamental differences in large-scale structure
  - GDS gone (all of them)
  - significant atmospheric evolution on <5-yr timescale



Voyager c. 1989 compared with Hubble c. 1994

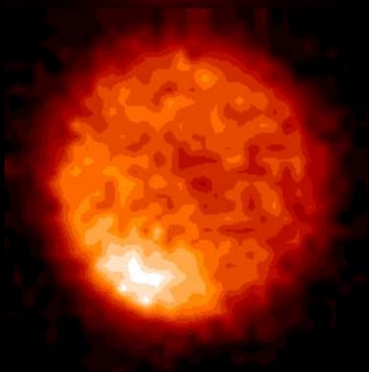
neptune's energy balance

Evidence for stratospheric heating since Voyager



Neptune mid-IR

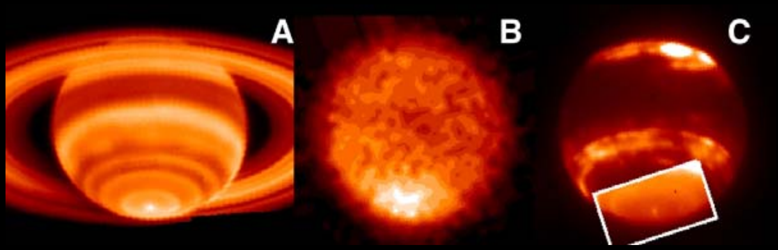
Gemini/Michelle at 11.7 µm
Ethane Emission
from the stratosphere



Gemini/Michelle at 7.7 µm
Methane Emission
from the stratosphere

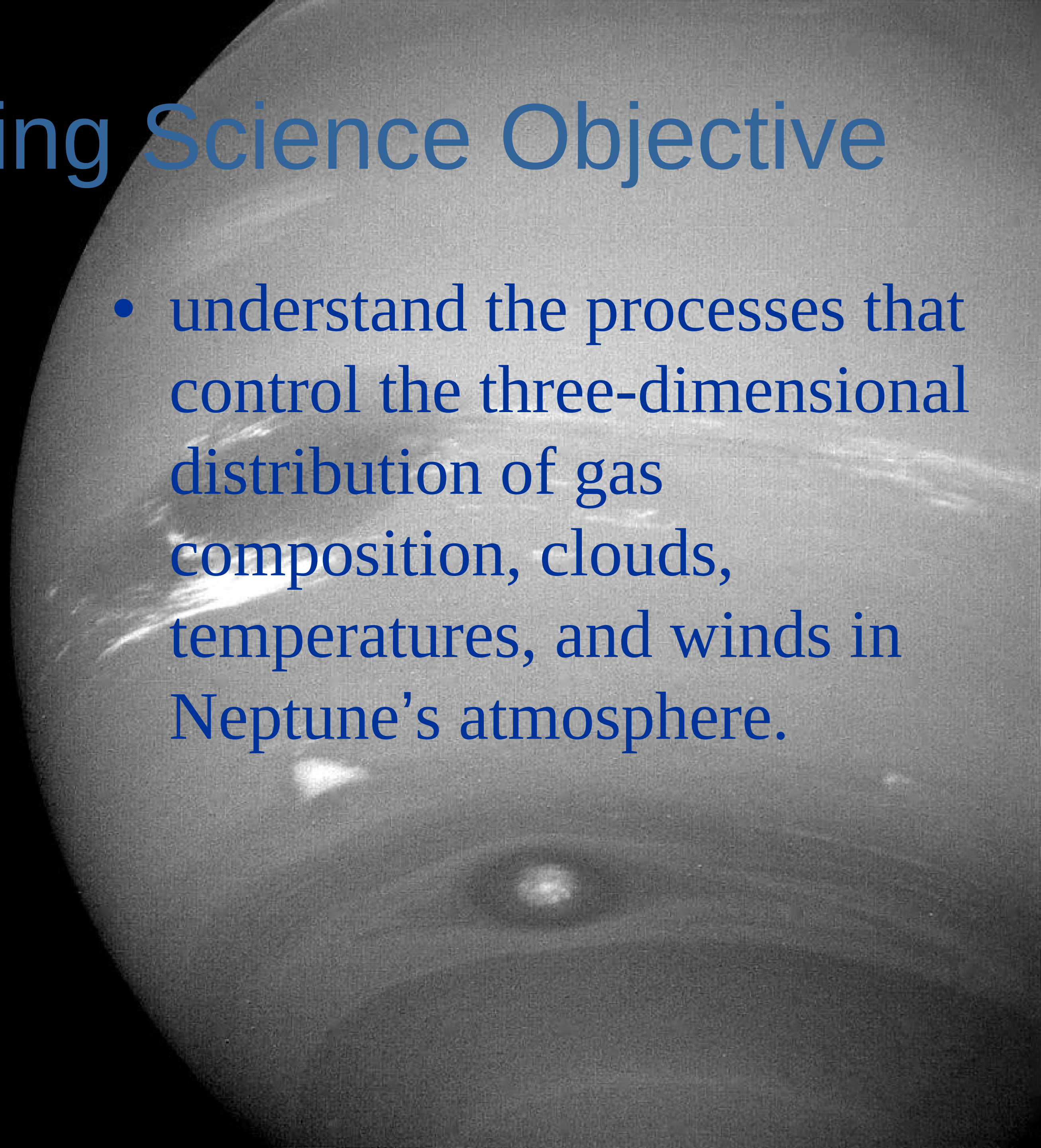
Keck/NIRC2+AO at 1.6 µm
Sunlight Scattering from
tropospheric Clouds

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

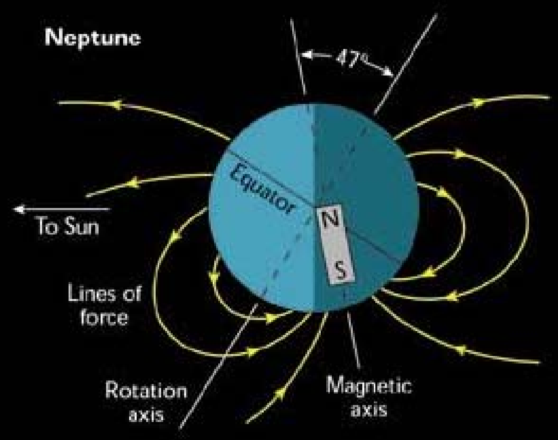
- Question - What is the *tropospheric aerosol composition and particle size* in discrete features? What is the *aerosol composition and particle size in the stratosphere and upper troposphere?* The bulk of Neptune's atmosphere is H and He. CH_4, NH_3, H_2S, and H_2O, condense or chemically combine in 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-ir 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



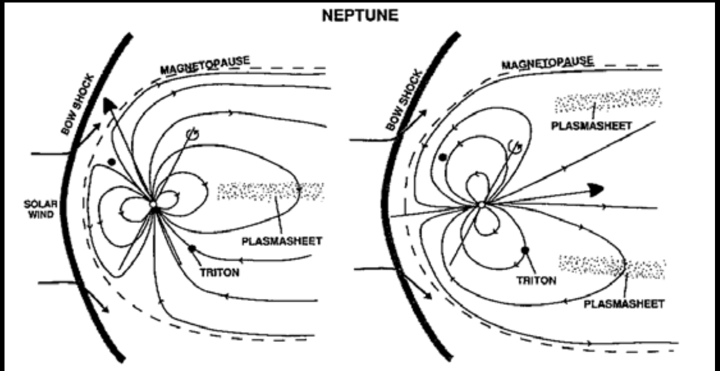


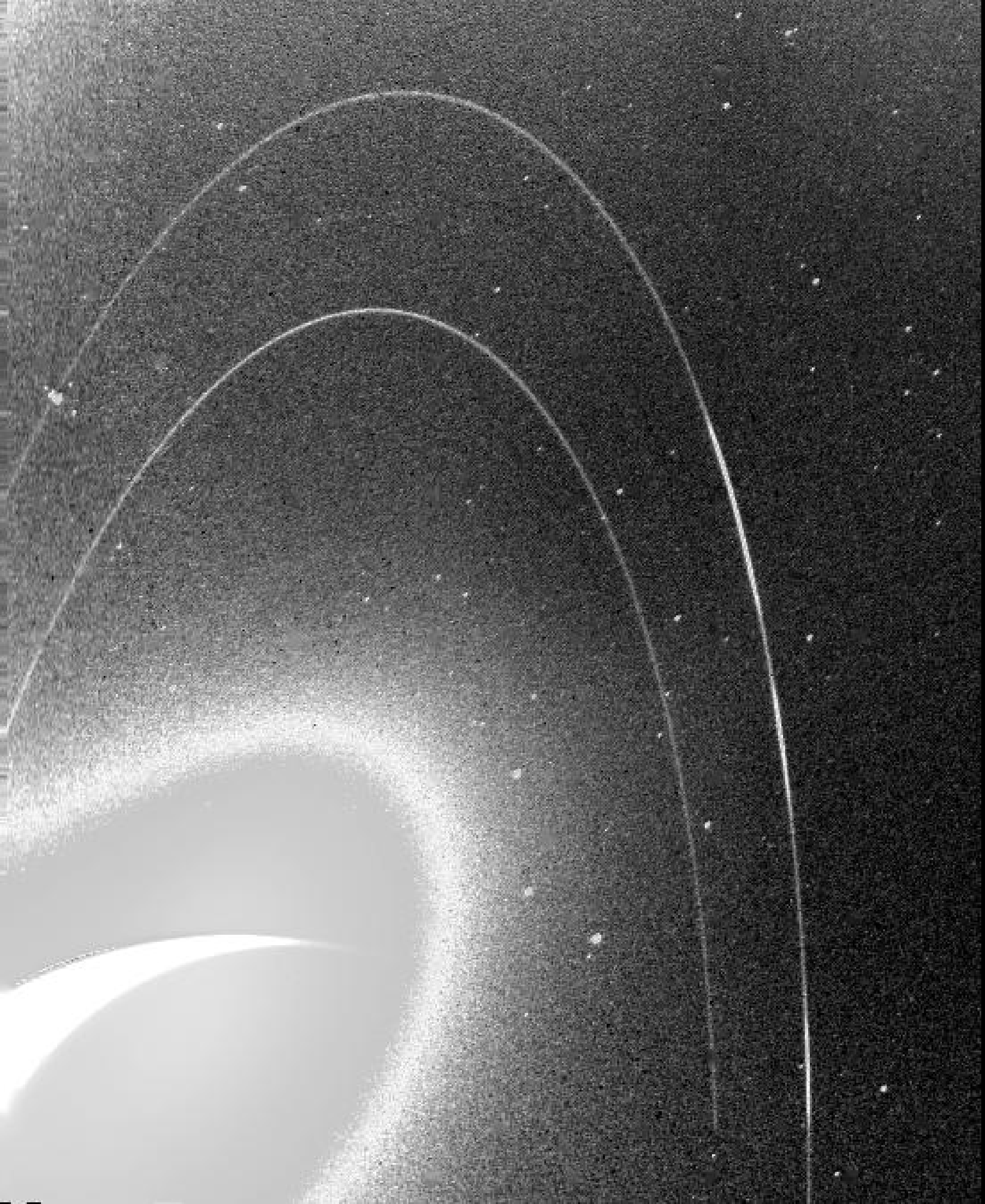
Figure 9 The magnetosphere of Neptune. Left and right are separated by half a planetary rotation.

Not like Jupiter or Saturn
Undetectable from Earth

Level 1 Science Investigations

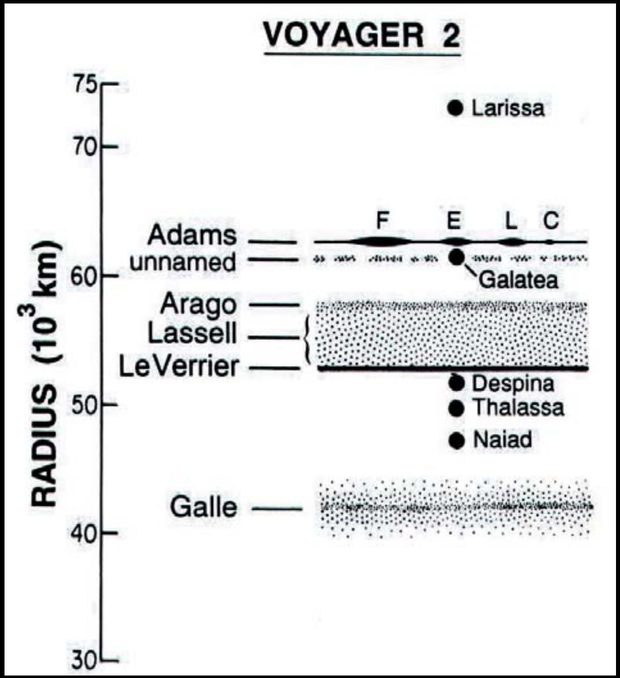
- Question - What is the generation mechanism of Neptune's unusual field
- Observation - Improve quadropolar and octopolar terms of the magnetic field by flying by Neptune at a different latitude / longitude than Voyager, preferably over the south polar region

- 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.



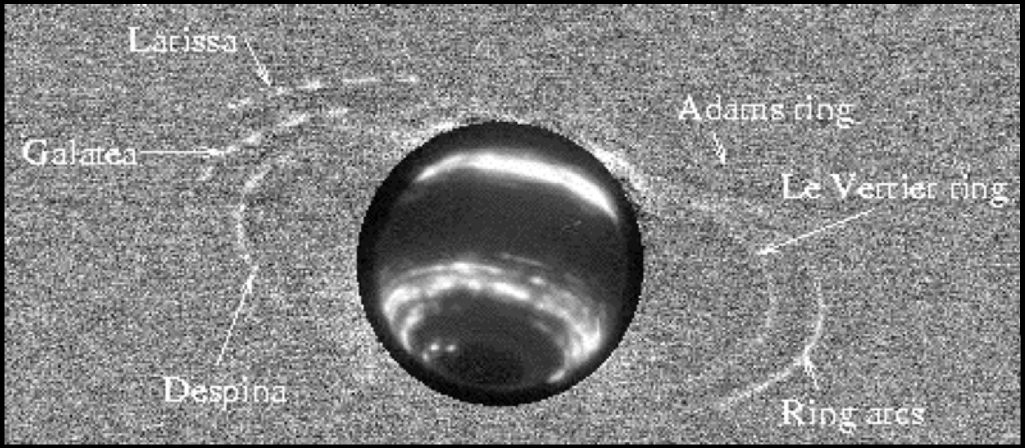
Neptune's Rings

- Narrow rings
- Arcs
- Dust bands
- Small moons



Neptune’s Rings

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.