TUNE

Triton Unveiler & Neptune Explorer

TUNE Project Team

We are Team Blue ♡

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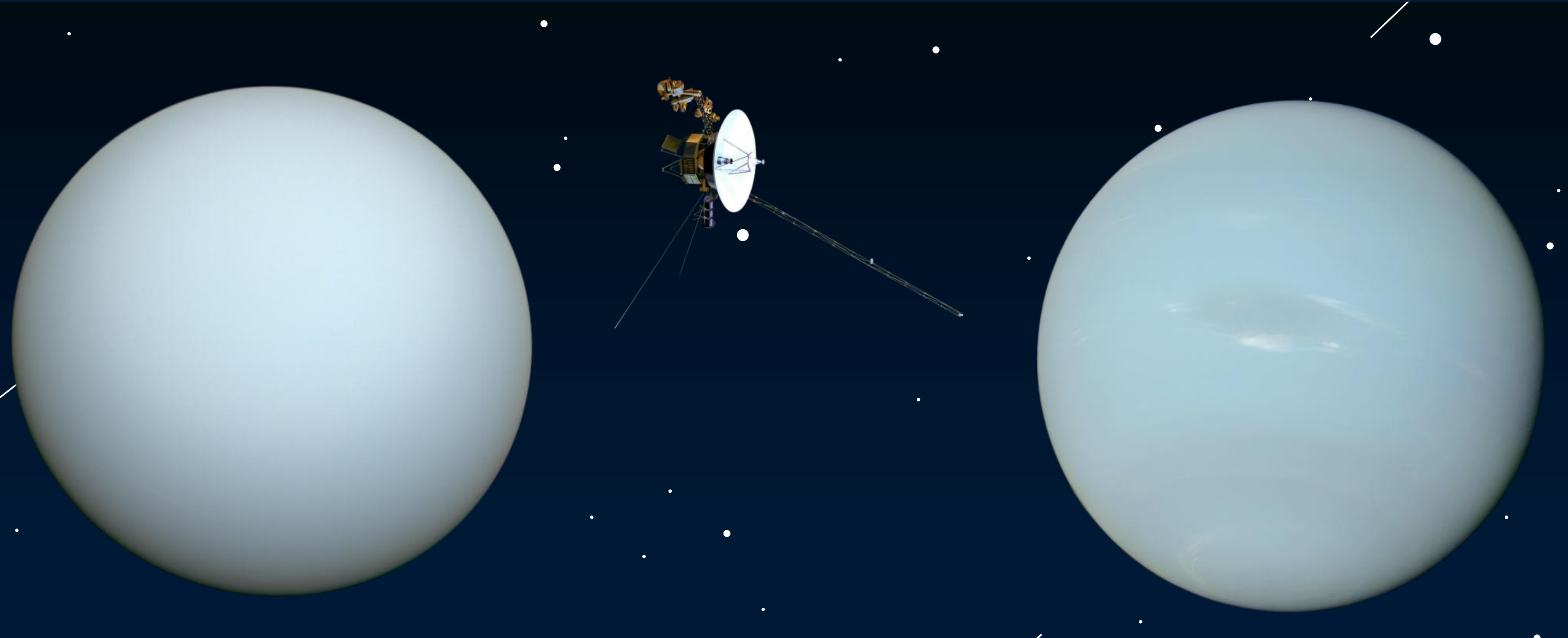
Understanding Ice Giants and their Environment

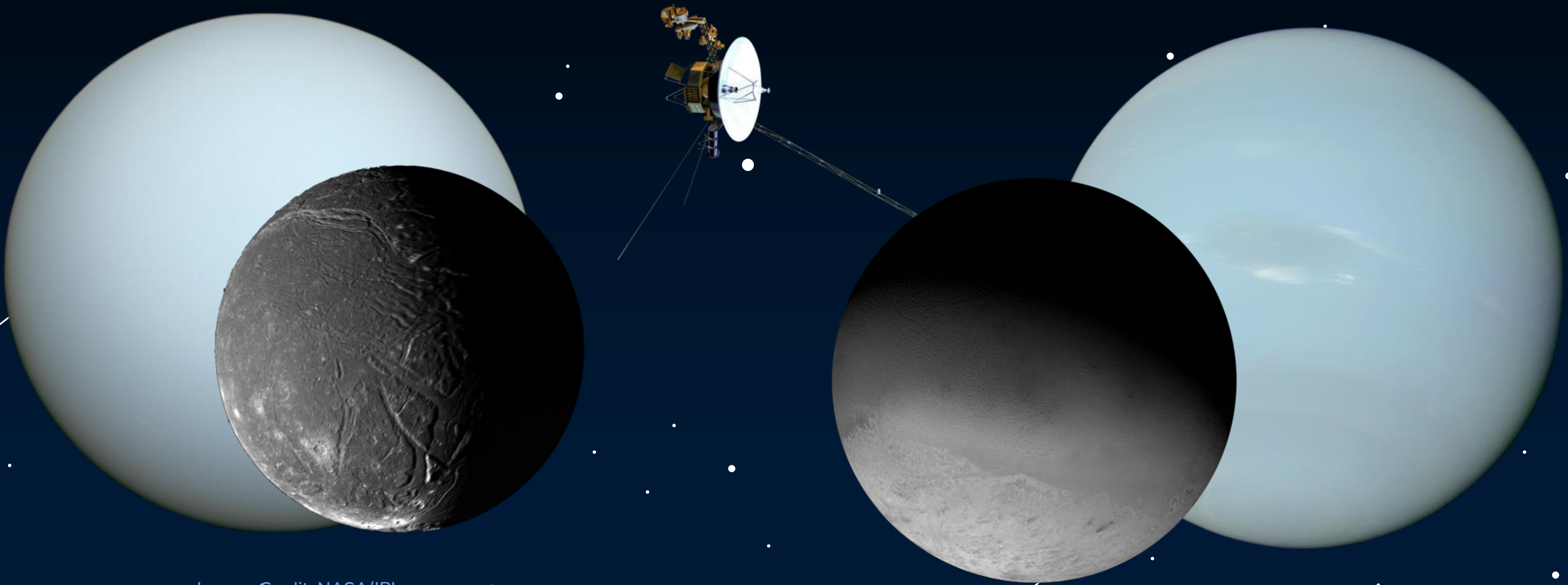
Following ESA's Voyage2050: Moons of the Giant Planets, Missions to Ice Giants

Our First Look



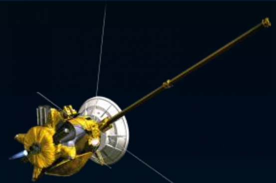
Images Credit: NASA/JPL

Our First Look



Images Credit: NASA/JPL

Timeline of missions

Voyager 2
- NASA
- 1977 launch
- 1989 Neptune arrival

Galileo
- NASA
- 1989 launch
- 1995 Jupiter arrival

Cassini-Huygens
- NASA-ESA
- 1997 launch
- 2004 Saturn arrival

New Horizons
- NASA
- 2006 launch
- 2015 Pluto arrival

JUNO
- NASA
- 2011 launch
- 2016 Jupiter Arrival

JUICE
- ESA
- 2023 launch
- 2031 Jupiter Arrival

Present Day

Europa Clipper
- NASA
- 2024 launch
- 2030 Jupiter Arrival

TUNE
- ASA
- 2038 launch
- 2050-60's Neptune Arrival

L4 Icy Moon Mission
- ESA
- 2040-50's Landing

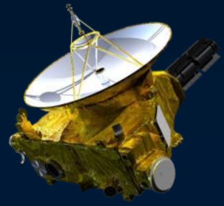
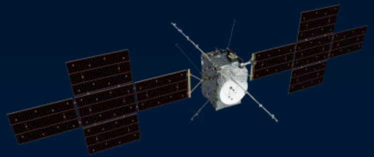




Image Credit: NASA/ JPL/ ESA

Why should we visit the Ice Giants and their Moons?

- Ice giants are key to understanding the formation and uniqueness of the solar system.
- The moons and environment of ice giants are thought to provide many of the conditions necessary to life.
- Ice giants are some of the least studied objects in the solar system.

Major Scientific Themes

T1. How are Ice Giants formed and what is their internal and atmospheric structure?

T2. What is the magnetospheric environment of Ice Giant systems?

T3. Do the conditions around Ice Giants allow for the formation of habitable subsurface environments?

Why Neptune?

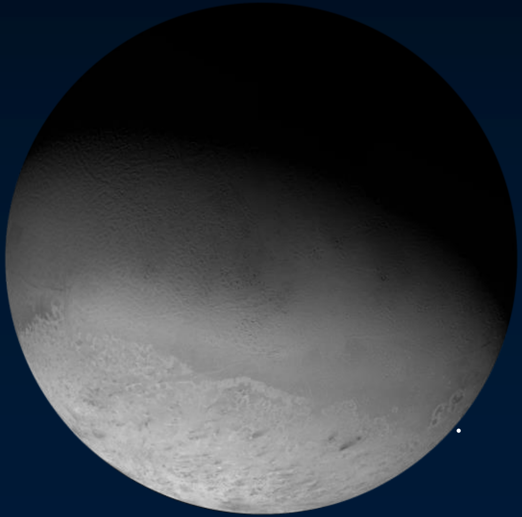


Image Credit: NASA/JPL

Image Credit: NASA/JPL

Current Knowledge - Triton

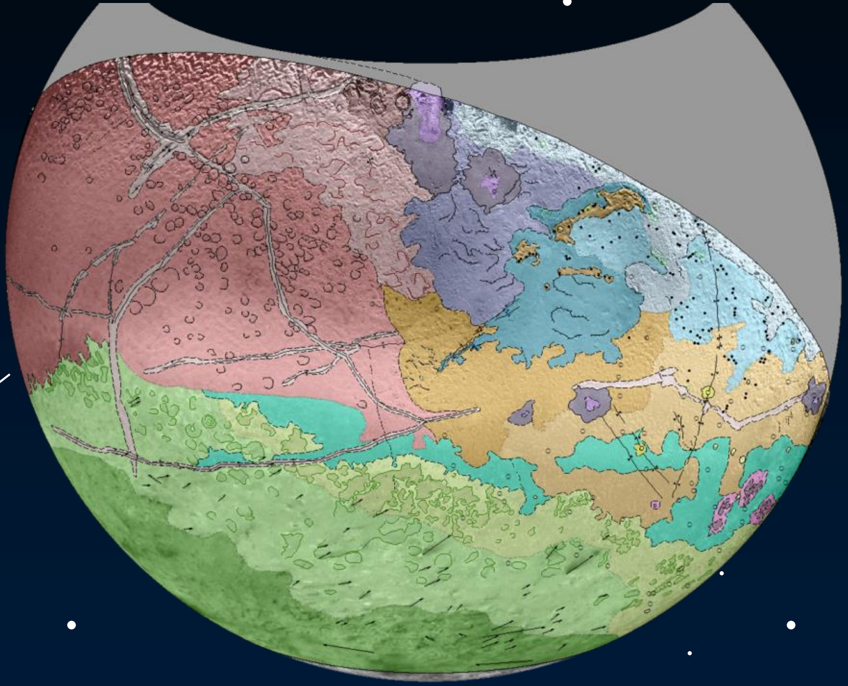


Image Credit: E.S. Martin. Et al. (2023) LPSC LIV, Abstract #1725

- Is Triton a TNO?
- Only 40% of the surface imaged and mapped
- Dark bands in the absorption spectrum
  - Is it liquid Nitrogen?

Current Knowledge - Triton

Image Credit: NASA/JPL

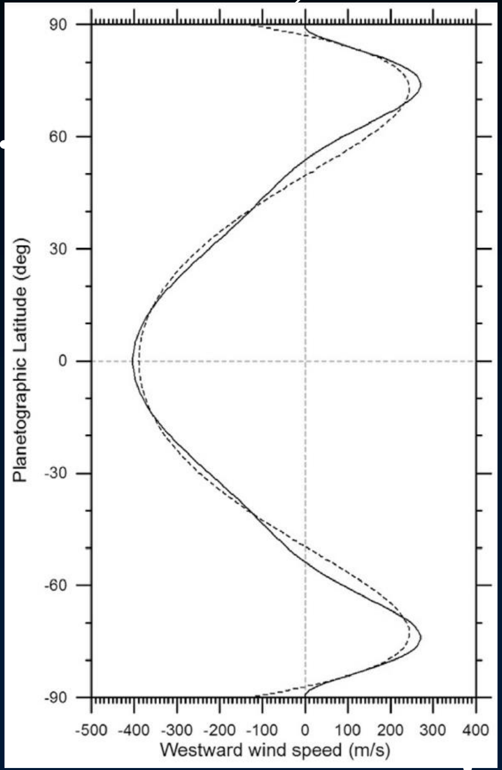
- After capture, enough energy dissipated to melt icy mantle multiple times
- Possibility of a subsurface ocean?
- Atmosphere is warming up but why?
- Investigate the nature of the plumes

Current Knowledge - Neptune's atmosphere

- We know the main atmospheric constituents (H and He)
  - But what are the isotopic ratios and (noble) gas abundances?
- Methane clouds and hazes are expected to exist
  - But measurements will be crucial to be sure
- Highest wind speeds in the solar system
  - But why?

Isotopic ratio	Jupiter	Saturn	Uranus	Neptune
D/H (in H_2)[(1)]	$(2.60 \pm 0.7) \times 10^{-5}$	$1.70^{+0.75}_{-0.45} \times 10^{-5}$	$(4.4 \pm 0.4) \times 10^{-5}$	$(4.1 \pm 0.4) \times 10^{-5}$
$^3He/^4He$[(2)]	$(1.66 \pm 0.05) \times 10^{-4}$	–	–	–
$^{12}C/^{13}C$ (in CH_4)[(3)]	$92.6^{+4.5}_{-4.1}$	$91.8^{+8.4}_{-7.8}$	–	–
$^{14}N/^{15}N$ (in NH_3)[(4)]	434.8^{+65}_{-50}	> 357	–	–
$^{20}Ne/^{22}Ne$[(5)]	13 ± 2	–	–	–
$^{36}Ar/^{38}Ar$[(6)]	5.6 ± 0.25	–	–	–

Jupiter: Mahaffy et al. (1998); Saturn: Lellouch et al. (2001); Uranus+Neptune: Feuchtgruber et al. (2013)



Mousis, O. et al (2018)

Current Knowledge - Magnetic Field

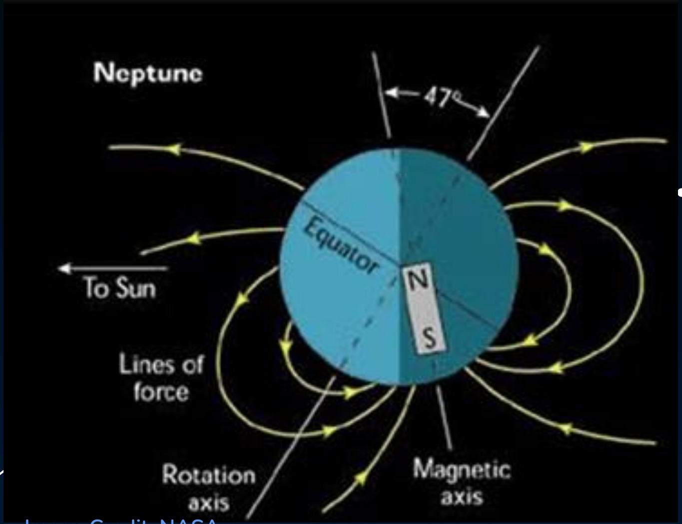


Image Credit: NASA

- Maximum *observed* magnetic field strength of 10 μT
- How does the varying magnetic field affect Triton?

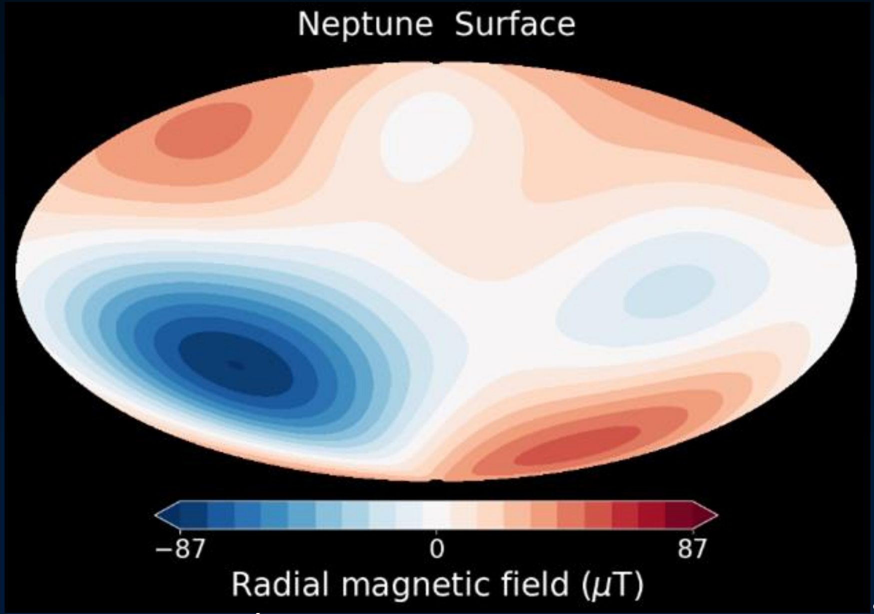


Image Credit: Barik et al., (2024)

- Tilted 47° from rotation axis and offset from planet's center
  - What internal process causes this?

Exoplanets

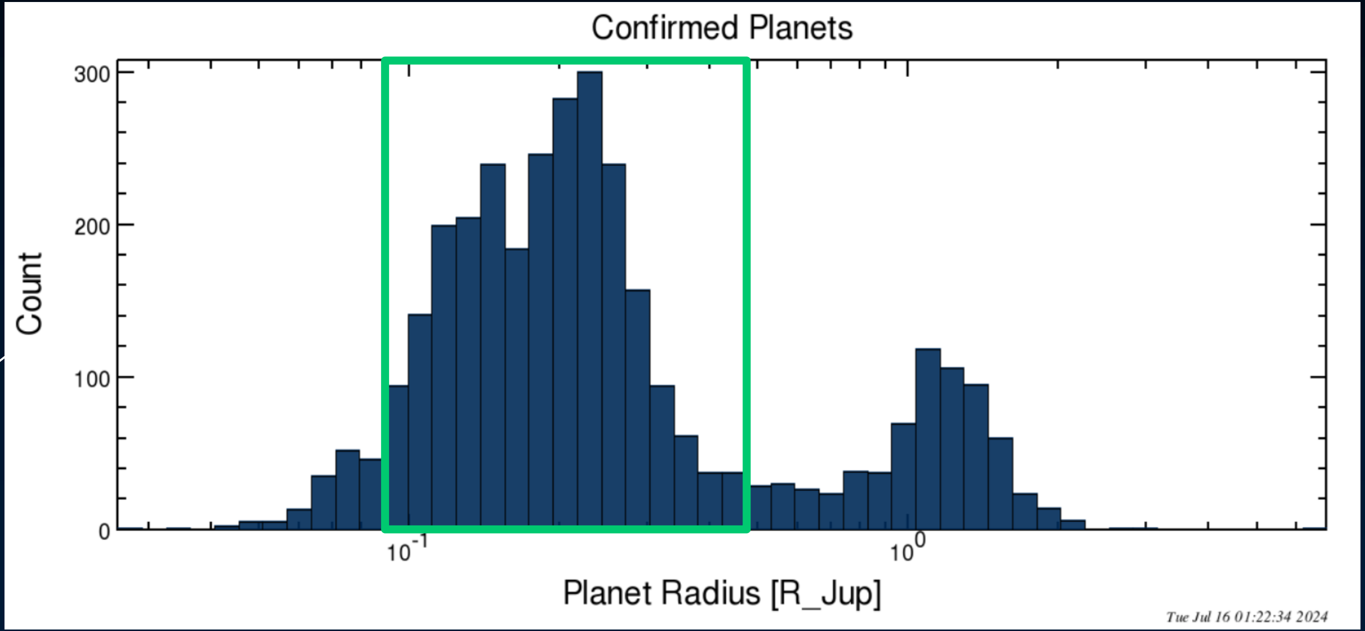


Image Credit: NASA Exoplanet Archives

- Around 40% of confirmed exoplanets are Neptune / Sub-Neptune sized.
- Wide range of possible atmospheric and interior models can explain data.
- Proximity differences.

Why go there?

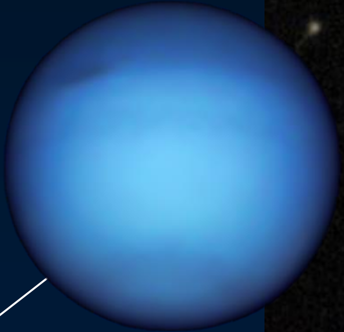
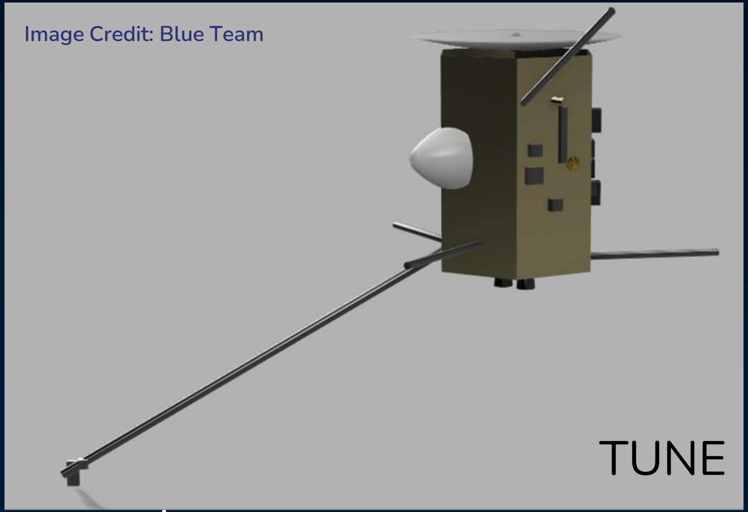
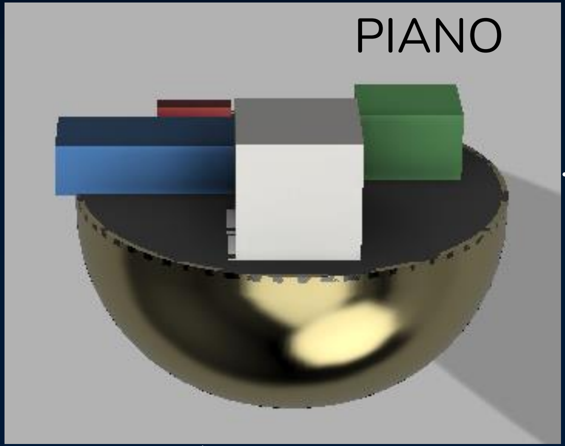


Image Credit: NASA/JPL, ESA Hubble

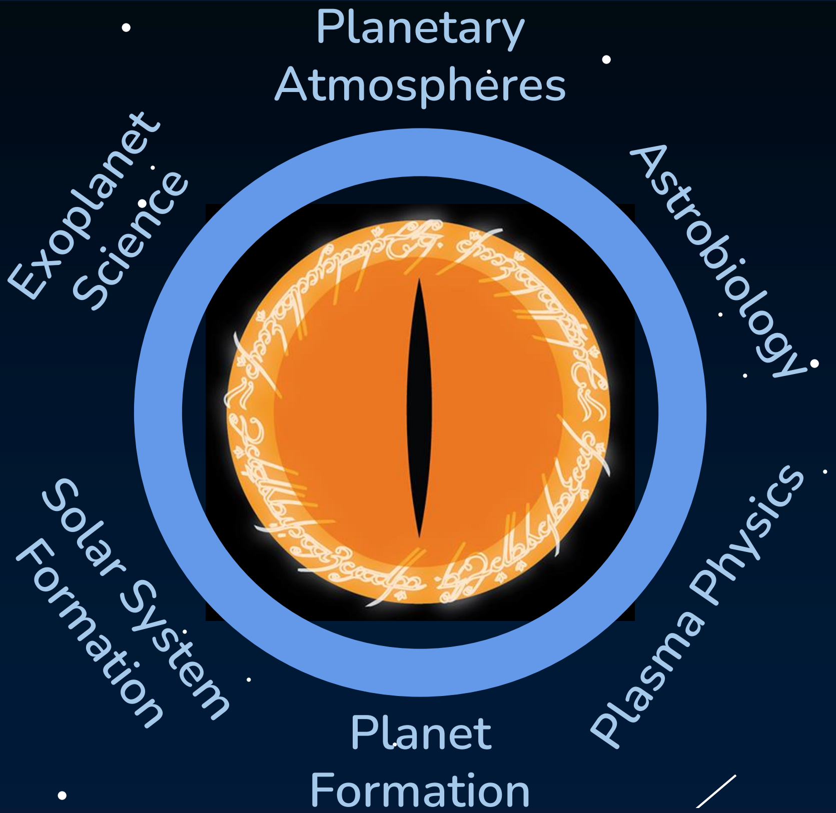
TUNE and PIANO - Mission profile

- Neptune orbiter
  - Multiple flyby's of **Triton** and orbit around **Neptune**
- Atmospheric probe for Neptune





TUNE and PIANO: One mission to rule them all



Major Scientific Themes

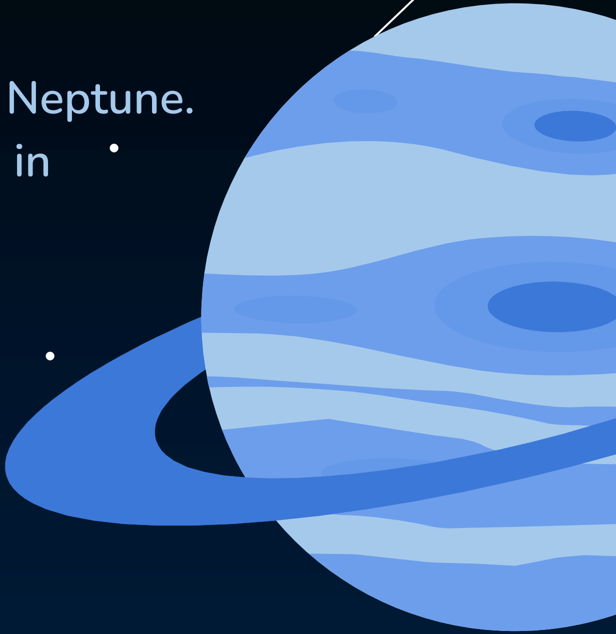
T1. How are Ice Giants formed and what is their internal and atmospheric structure?

T2. What is the magnetospheric environment of Ice Giant systems?

T3. Do the conditions around Ice Giants allow for the formation of habitable subsurface environments?

Theme 1 Scientific Objectives

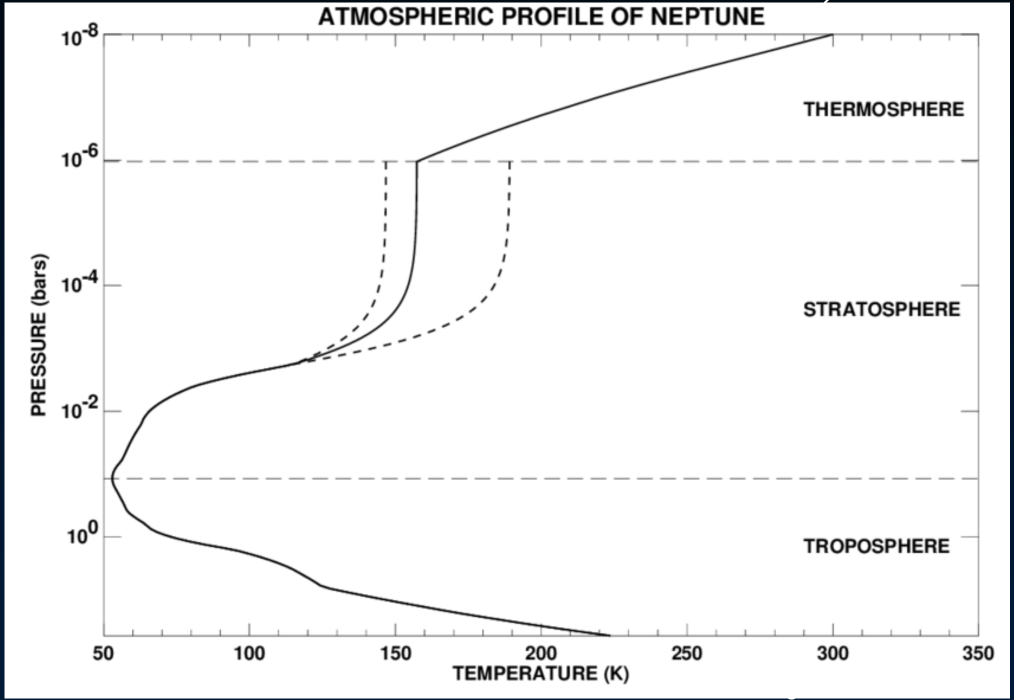
1. Determine the inner structure and composition of Neptune.
2. Determine the composition and key isotope ratios in Neptune's atmosphere as a function of altitude.
3. Determine the pressure-temperature profile
4. Measure wind speeds and directions
5. Study the composition and dynamics of clouds, hazes and dark spots in Neptune's atmosphere
6. Measure energy balance and study energy transport mechanisms
7. Understand the history and formation of Neptune's ring system and moons



PIANO - Probe for Inner Atmospheric Neptune Observations

- In-situ provides information up to ~10 bar vs remote sensing to ~1 bar
- Generate profiles of pressure, temperature, density and abundance changes with height
  - dynamics, inner structure, energy transport, mixing

➡ better atmospheric models



Hesman, 2018

Major Scientific Themes

T1. How are Ice Giants formed and what is their internal and atmospheric structure?

T2. What is the magnetospheric environment of Ice Giant systems?

T3. Do the conditions around Ice Giants allow for the formation of habitable subsurface environments?

Theme 2 Scientific Objectives

1. Determine how Neptune's magnetic field is formed and structured
2. Measure the distribution and composition of the plasma around Neptune
3. Determine the Magnetospheric Interaction between Neptune and Triton
4. Determine how the atmospheres of Neptune and Triton interact with the plasma environment
5. Measure Triton's contribution to the plasma environment
6. Determine the sources and losses regulating the ionosphere of Triton
7. Measure the shape and dynamics of the Neptunian radiation Belts
8. Determine how the magnetic field of Neptune interacts with the interior of Triton
9. Determine the particle acceleration processes within the magnetosphere of Neptune

Major Scientific Themes

T1. How are Ice Giants formed and what is their internal and atmospheric structure?

T2. What is the magnetospheric environment of Ice Giant systems?

T3. Do the conditions around Ice Giants allow for the formation of habitable subsurface environments?

Theme 3 Scientific Objectives

1. Map Triton's surface.
2. Determine the composition of Triton’s atmosphere and surface
3. Examine surface processes such as plasma precipitation and loss processes.
4. Measure Triton's atmosphere and ionosphere temperature, neutral density, and electron density profiles.
5. Measure temperature, composition, and height of the plumes
6. Determine the interior structure and geological processes of Triton.

Science Traceability Example - Neptune (Probe)

Scientific Requirements
SCI-1.20: Determine the composition and the key isotope ratios in Neptune's atmosphere as a function of altitude.

Science Traceability Example - Neptune (Probe)

Scientific Requirements	Physical Observable
SCI-1.20: Determine the composition and the key isotope ratios in Neptune's atmosphere as a function of altitude.	Molecular abundances: H_2O, CH_4, NH_3, H_2S, CO, HCN Abundances of C, N, S, O, P, As, Ge, Si
	Isotope Ratios: C, H, O, N, S, Kr, Ar, D/H, $^3He/^4He$, $^{14}N/^{15}N$, $^{16}O/^{17}O/^{18}O$, 13C/14C

Science Traceability Example - Neptune (Probe)

Scientific Requirements	Physical Observable	Resolution
SCI-1.20: Determine the composition and the key isotope ratios in Neptune's atmosphere as a function of altitude.	Molecular abundances: H_2O, CH_4, NH_3, H_2S, CO, HCN	Spectral lines in range 0.5-5.5μm
	Abundances of C, N, S, O, P, As, Ge, Si	Spectral lines in range 200-1000μm
	Isotope Ratios: C, H, O, N, S, Kr, Ar, D/H, $^{3}He/^{4}He$, $^{14}N/^{15}N$, $^{16}O/^{17}O/^{18}O$, 13C/14C	Masses of elements and isotopes

Science Traceability Example - Neptune (Probe)

Scientific Requirements	Physical Observable	Resolution	Instrument Requirements
SCI-1.20: Determine the composition and the key isotope ratios in Neptune's atmosphere as a function of altitude.	Molecular abundances: H_2O, CH_4, NH_3, H_2S, CO, HCN Abundances of C, N, S, O, P, As, Ge, Si	Spectral lines in range 0.5-5.5µm	Ground res: 30km/pix Spectral res: 5nm
		Spectral lines in range 200-1000µm	Ground res: 30km/pix Resolving power: 10^8
	Isotope Ratios: C, H, O, N, S, Kr, Ar, D/H, $^3He/^4He$, $^{14}N/^{15}N$, $^{16}O/^{17}O/^{18}O$, 13C/14C	Masses of elements and isotopes	Mass range: 1-140amu
			Mass resolution: Distinguish O and CH_4
			Dynamic range: 10^4

Science Traceability Example - Neptune (Probe)

Scientific Requirements	Physical Observable	Resolution	Instrument Requirements	Measurement Approaches
SCI-1.20: Determine the composition and the key isotope ratios in Neptune's atmosphere as a function of altitude.	Molecular abundances: H_2O, CH_4, NH_3, H_2S, CO, HCN Abundances of C, N, S, O, P, As, Ge, Si	Spectral lines in range 0.5-5.5µm	Ground res: 30km/pix Spectral res: 5nm	Orbits for global mapping of day- and nightside, feature tracking from nadir to limb at distances form 1-6 R_N. Repeat global dayside coverage at least once a year.
		Spectral lines in range 200-1000µm	Ground res: 30km/pix Resolving power: 10^8	
	Isotope Ratios: C, H, O, N, S, Kr, Ar, D/H, $^3He/^4He$, $^{14}N/^{15}N$, $^{16}O/^{17}O/^{18}O$, 13C/14C	Masses of elements and isotopes	Mass range: 1-140amu	Send probe through Neptune's atmosphere within the equatorial region.
			Mass resolution: Distinguish O and CH_4	
			Dynamic range: 10^4	

Science Traceability Example - Neptune (Probe)

Scientific Requirements	Physical Observable	Resolution	Instrument Requirements	Measurement Approaches	Instrument and Heritage
SCI-1.20: Determine the composition and the key isotope ratios in Neptune's atmosphere as a function of altitude.	Molecular abundances: H_2O, CH_4, NH_3, H_2S, CO, HCN Abundances of C, N, S, O, P, As, Ge, Si	Spectral lines in range 0.5-5.5μm	Ground res: 30km/pix Spectral res: 5nm	Orbits for global mapping of day- and nightside, feature tracking from nadir to limb at distances form 1-6 R_N. Repeat global dayside coverage at least once a year.	Pushbroom Hyperspectral Imager (MAJIS: JUICE)
		Spectral lines in range 200-1000μm	Ground res: 30km/pix Resolving power: 10^8		Sub-mm heterodyne radiometer (SWI: JUICE)
	Isotope Ratios: C, H, O, N, S, Kr, Ar, D/H, $^3He/^4He$, $^{14}N/^{15}N$, $^{16}O/^{17}O/^{18}O$, 13C/14C	Masses of elements and isotopes	Mass range: 1-140amu	Send probe through Neptune's atmosphere within the equatorial region.	Time of Flight Mass Spectrometer (GPMS: Galileo)
			Mass resolution: Distinguish O and CH_4		
			Dynamic range: 10^4		

Science Traceability Example - Triton

Scientific Requirements
SCI-3.60: Determine the interior structure and geological processes of Triton.

Science Traceability Example - Triton

Scientific Requirements	Physical Observable
SCI-3.60: Determine the interior structure and geological processes of Triton.	The tidal response of Triton
	Radial density profile
	Diapirs

Science Traceability Example - Triton

Scientific Requirements	Physical Observable	Instrument Requirements
SCI-3.60: Determine the interior structure and geological processes of Triton.	The tidal response of Triton	The *k* Love Numbers to at least degree 2
		The *h* Love Numbers to at least degree 2
	Radial density profile	Measure Low degree static gravity coefficients
	Diapirs	Measure high degree gravity coeffcients

Science Traceability Example - Triton

Scientific Requirements	Physical Observable	Instrument Requirements	Measurement Approaches
SCI-3.60: Determine the interior structure and geological processes of Triton.	The tidal response of Triton	The *k* Love Numbers to at least degree 2	Minimum of 10 flybys. Altitude of 500km or lower
		The *h* Love Numbers to at least degree 2	
	Radial density profile	Measure Low degree static gravity coefficients	
	Diapirs	Measure high degree gravity coeffcients	

Science Traceability Example - Triton

Scientific Requirements	Physical Observable	Instrument Requirements	Measurement Approaches	Instrument and Heritage
SCI-3.60: Determine the interior structure and geological processes of Triton.	The tidal response of Triton	The *k* Love Numbers to at least degree 2	Minimum of 10 flybys. Altitude of 500km or lower	USO and Medium Gain Antenna (3GM:JUICE)
		The *h* Love Numbers to at least degree 2		Altimeter (GALA:JUICE)
	Radial density profile	Measure Low degree static gravity coefficients		USO and Medium Gain Antenna (3GM:JUICE)
	Diapirs	Measure high degree gravity coeffcients		

Payload Overview (Orbiter)

- High-Resolution Optical Cameras (HRC)
  - Wide and narrow FOV, 13 spectral bands: 350-1050 nm
  - Heritage: JANUS (JUICE) and RALPH (New Horizons)
- IR-VIS Hyperspectral imager (IVHI)
  - Narrow FOV, range 500-5500 nm, 5 nm resolution
  - Heritage: MAJIS (JUICE)
- Sub-mm Heterodyne Spectrometer (SHS)
  - Heritage: SWI (JUICE)

Payload Overview (Orbiter)

- Plasma Environment Investigator (PEI)
  - Ion mass analyser, Electron energy analyser, Mass spectrometer, ENA imager, Energetic particles detector
  - Heritage: PEP (JUICE)
- Plasma Wave Investigator (PWI)
  - HF magnetometer and Langmuir probes
  - Heritage: RPWI (JUICE)
- Magnetometer (MAG)
- Radio Science Experiment (RSE)
  - Ultra stable oscillator needed
  - Heritage: 3GM (JUICE)

Payload Overview (Probe)

- Time of Flight mass spectrometer (TOFMS)
- Atmospheric Structure Instrument (ASI)
  - Pressure and temperature sensors
- Doppler wind experiment (DWE)
  - Heritage: Galileo probe
- Nephelometer
  - Scattering properties
- Net flux radiometer (NFR)
  - Heritage: Galileo probe
- HE abundance detector (HAD)
  - Heritage: Galileo probe

Payload Overview

System		Mass (kg)
Instruments (Orbiter)		163
Probe	Instruments	27
	Structure	337
Spacecraft Dry		2255
Spacecraft Wet		6560

End-to-end Mission Profile

Launch Segment

Ariane 64 Evo

- Able to take 8500 kg to v-inf of 3.4 km/s

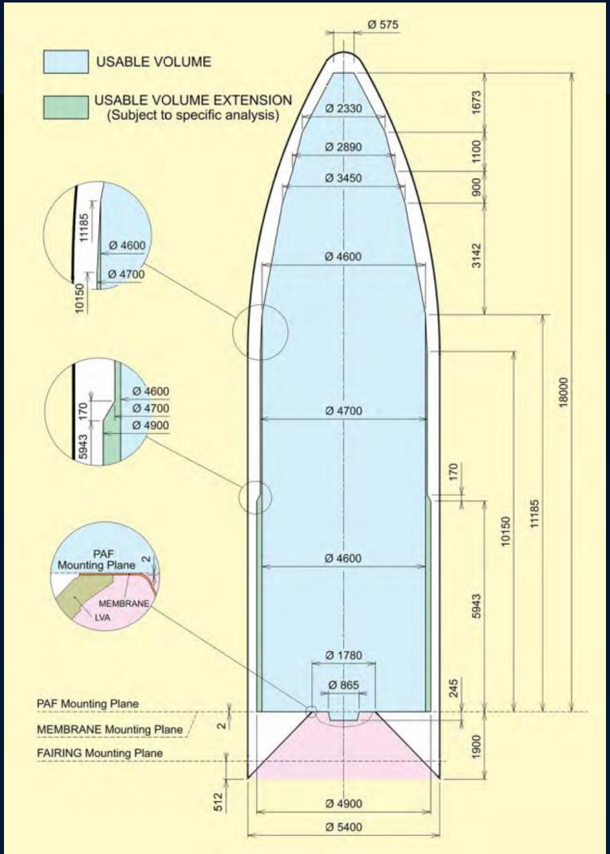
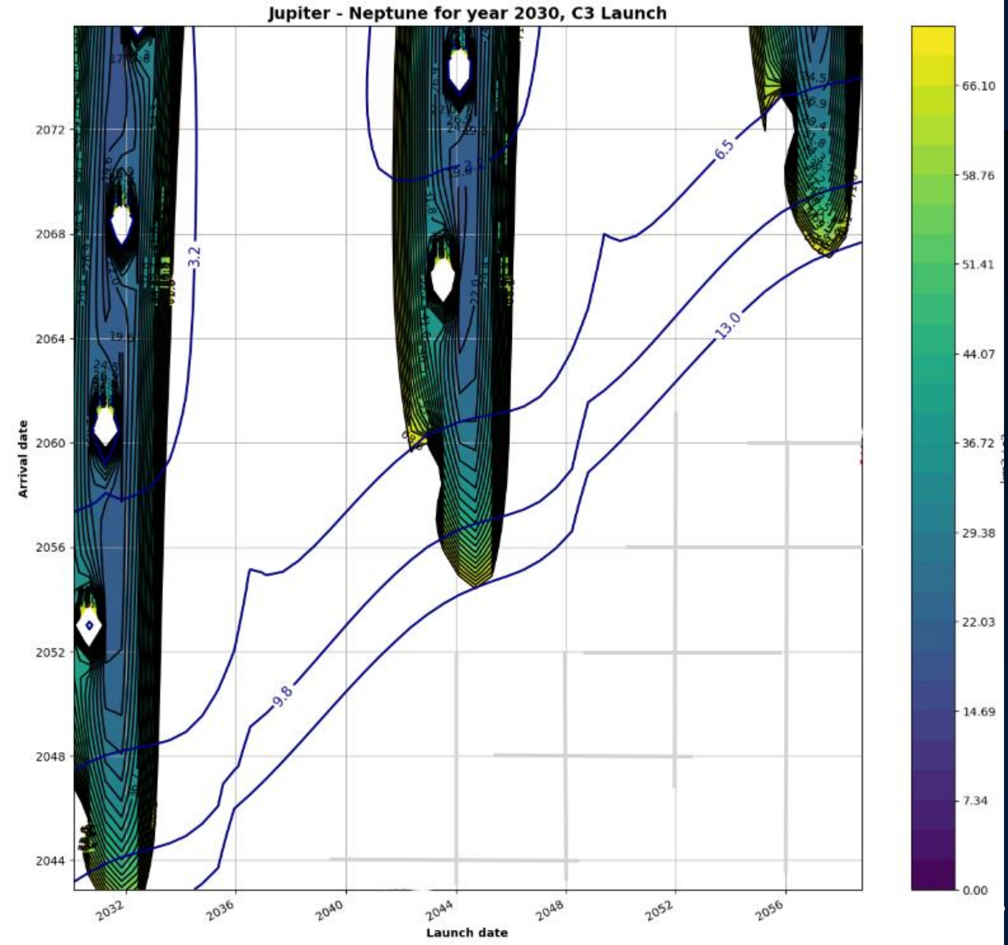


Image Credit: Ariane 64 User manual

Image Credit: SkywalkerPL

How to get to Neptune

- Orbit SMA of 30 AU
- Multiple Gravity assist trajectory was chosen
- main tradeoff between required delta-v and travel time
- Jupiter↔Neptune relative positions are main driver



Trajectory Concept

Launch
Windows:
September-November 2037
October-December 2038

Commissioning
Testing of instruments
Oct 2037
V_{inf}: 3.4 kms^{-1}

Venus Flyby
March 2038
V_{inf}: 5.3 kms^{-1}

2 Earth Flybys
January 2039 and
January 2041
V_{inf}: 9 kms^{-1} (for both)

Jupiter Flyby
September 2044
V_{inf}: 6.8 kms^{-1}

Probe Deployment
1 month to NOI

Arrival at Neptune
November 2056
V_{inf}: 9.8 kms^{-1}

- The limited v-inf envelope of Ariane 64 → multiple gravity-assists necessary

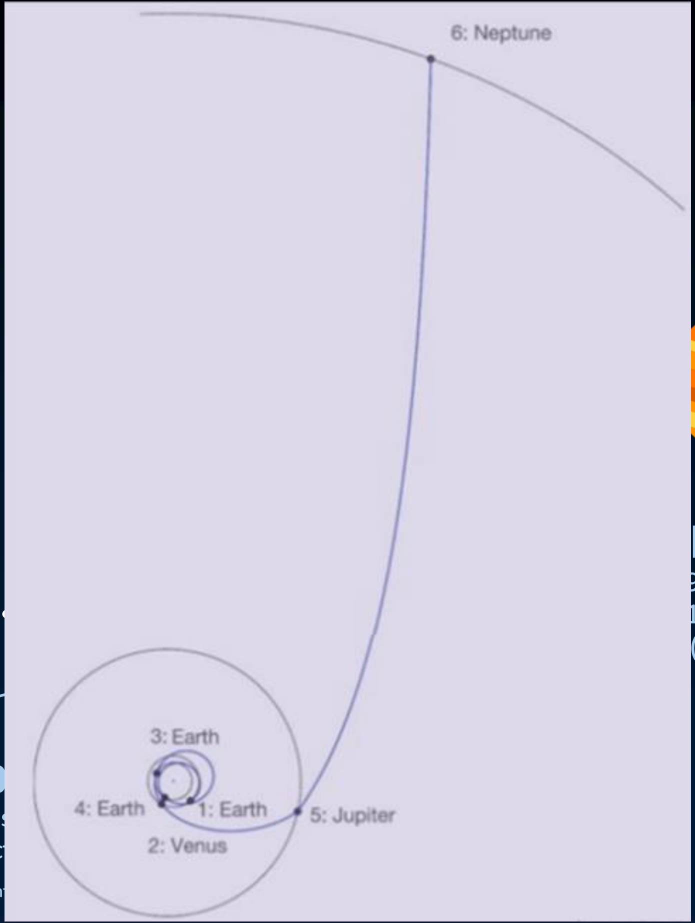
Trajectory Concept

Launch

Windows:

September-November 2037

October-December 2038



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(for both)

Jupiter Flyby

September 2044

V_{inf}: 6.8 kms^{-1}

Probe Deployment

1 month to NOI

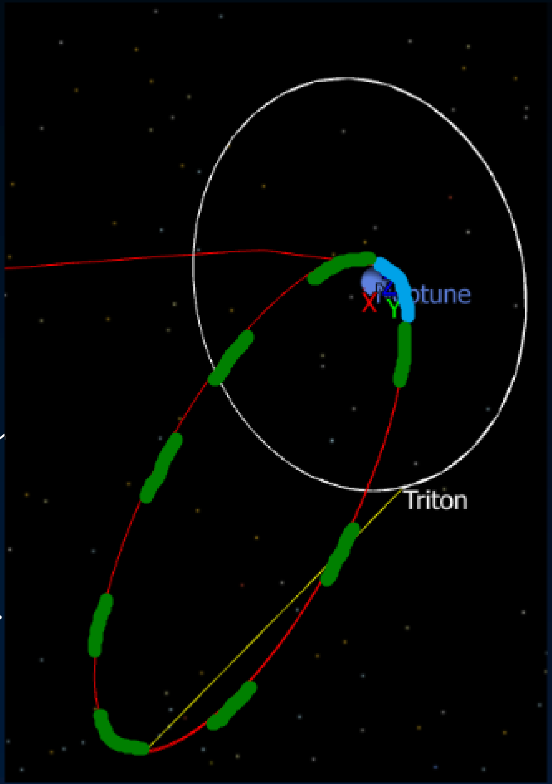
Arrival at Neptune

November 2056

V_{inf}: 9.8 kms^{-1}

- The limited v-inf envelope of Ariane 64 → multiple gravity-assists necessary

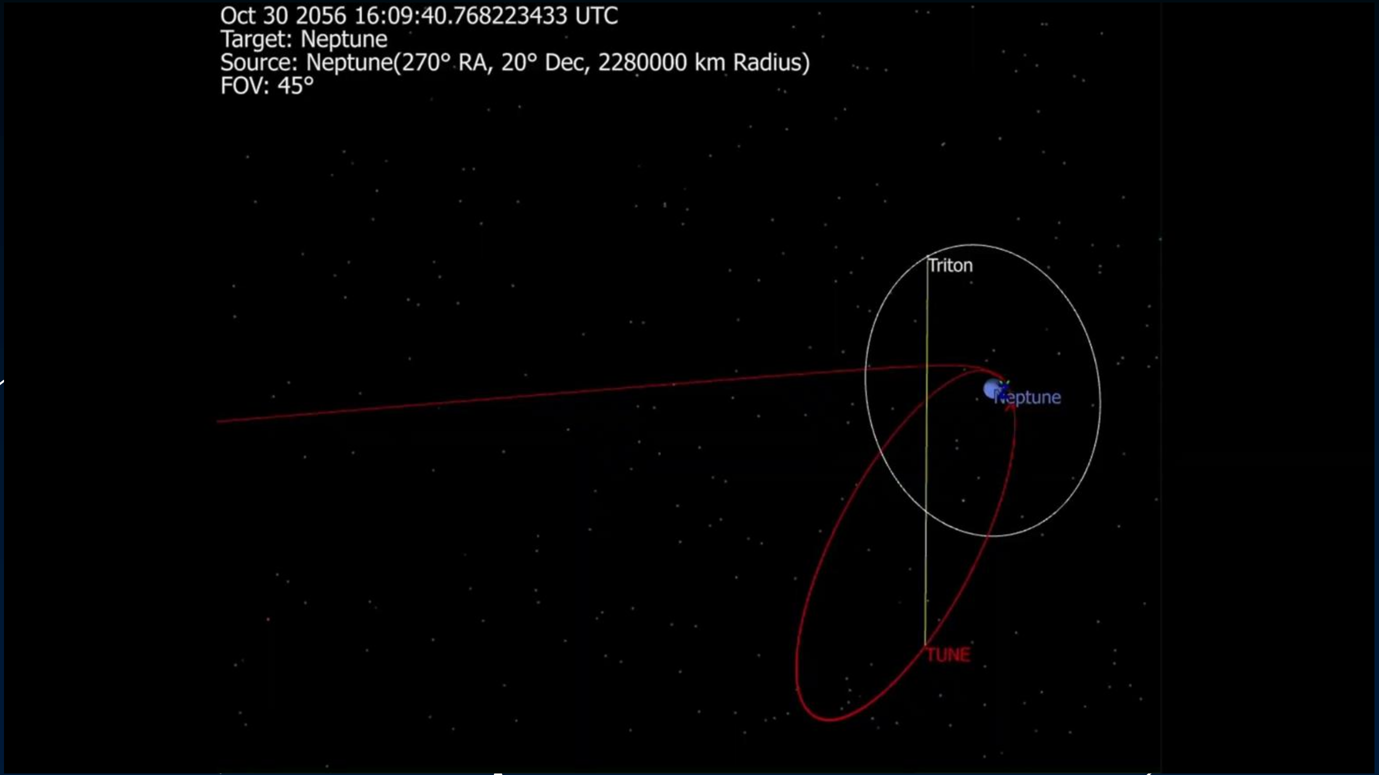
Observation Plan



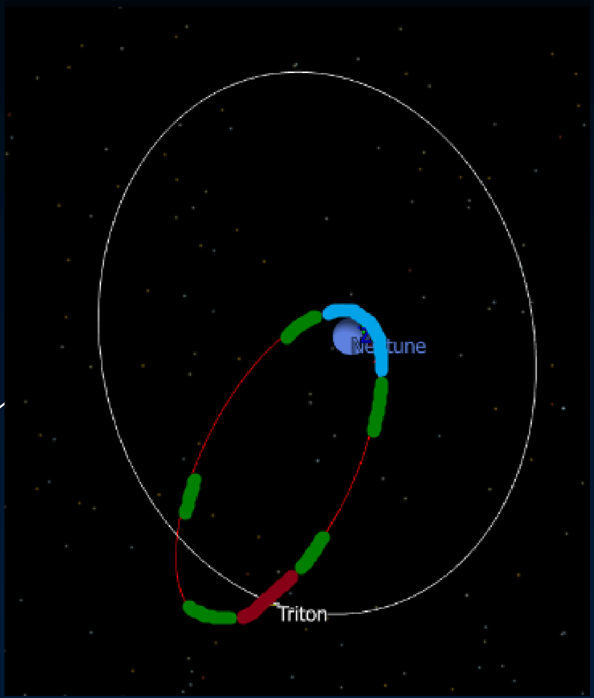
High eccentricity orbit

- Highly-eccentric allowing to explore the magnetospheric environment and boundaries (bow shock)
- Periapsis: 2 R_N
- Apoapsis: 50 R_N
- Triton swing-bys used to rotate the argument of perigee
- Close Neptune orbit distances down to 1 R_N for Neptune interior and atmosphere observations (radioscience, atmospheric remote sensing)

Observation Plan



Observation Plan



Triton investigating orbit

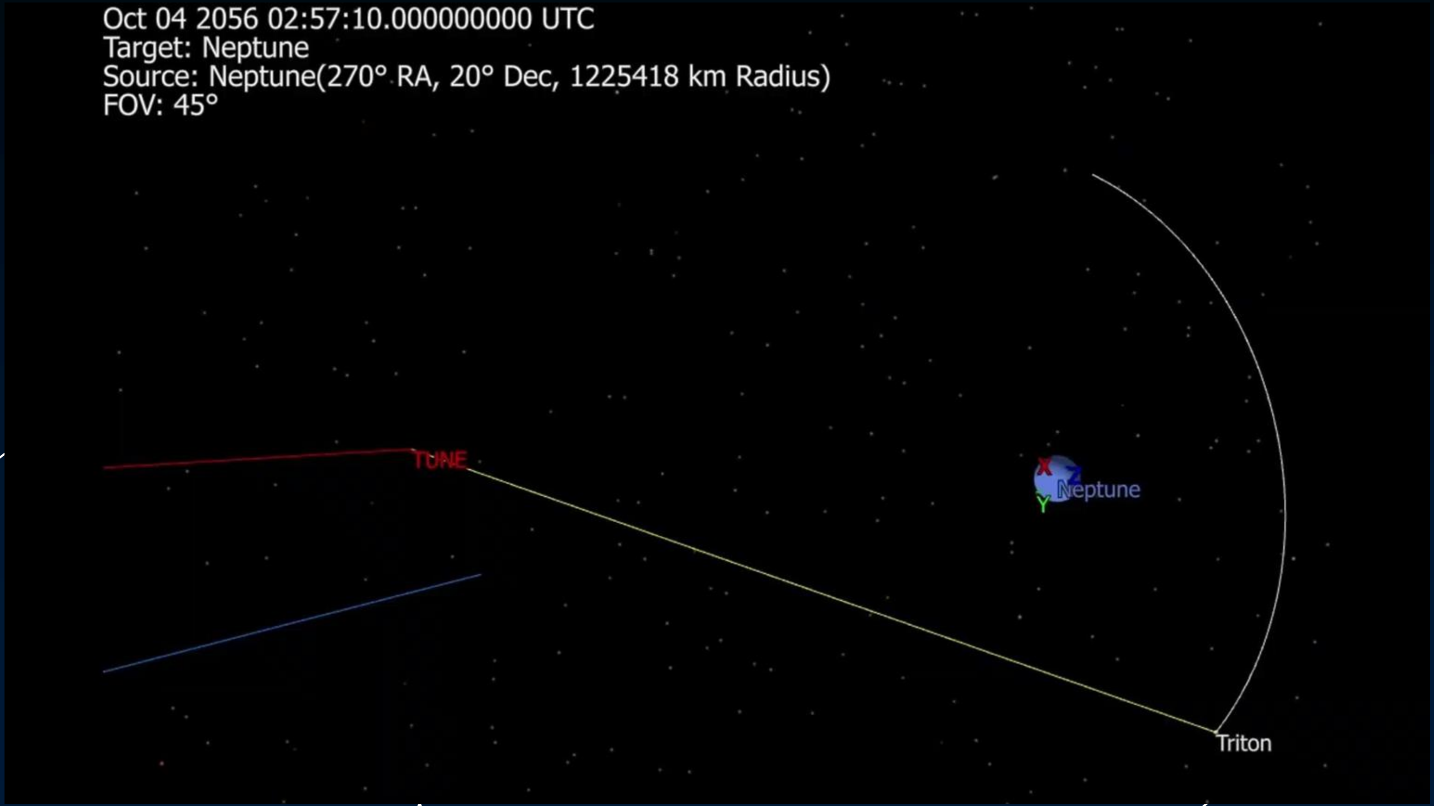
- Elliptical orbit around Neptune focusing on Triton close encounters
- Periapsis: 2 R_N
- Apoapsis: 15 R_N
- Triton swing-bys used to reduce SMA and rotate argument of perigee

- Close Triton flybys down to 200km altitude for surface, atmosphere and interior observations of Triton

Delta-v budget

	Delta v
Neptune Orbit Insertion	2.7 km/s
Periapsis raising maneuver	0.22 km/s
Triton swing-bys	50* 0.01 km/s=0.5 km/s
Total delta-v including 20% margin	**3.76 km/s**

Orbit for Probe Insertion



Phases of Probe Insertion

Probe deployment	Probe entry	Drogue parachute	Main parachute deployment	Separation of heat shield	End of life
Cruise				Science	
1 month	~120 sec	<5 sec	~10 sec	~60 min	
	P < 0.1 bar	P < 0.1 bar	P = 0.1 bar	P = 1 bar	P > 10 bars

Design and Subsystems

Key System Drivers

Distance
- Long travel time
- Communication constraints

Thermal
- Venus, hot case
- Neptune, cold case

Instrument requirements
- Resolution
- Orbits and flybys

Power
- Solar panels are ineffective

Science Lifetime
- Multiple years of operations

Communication to Probe
- Short visibility time

Preliminary S/C Design

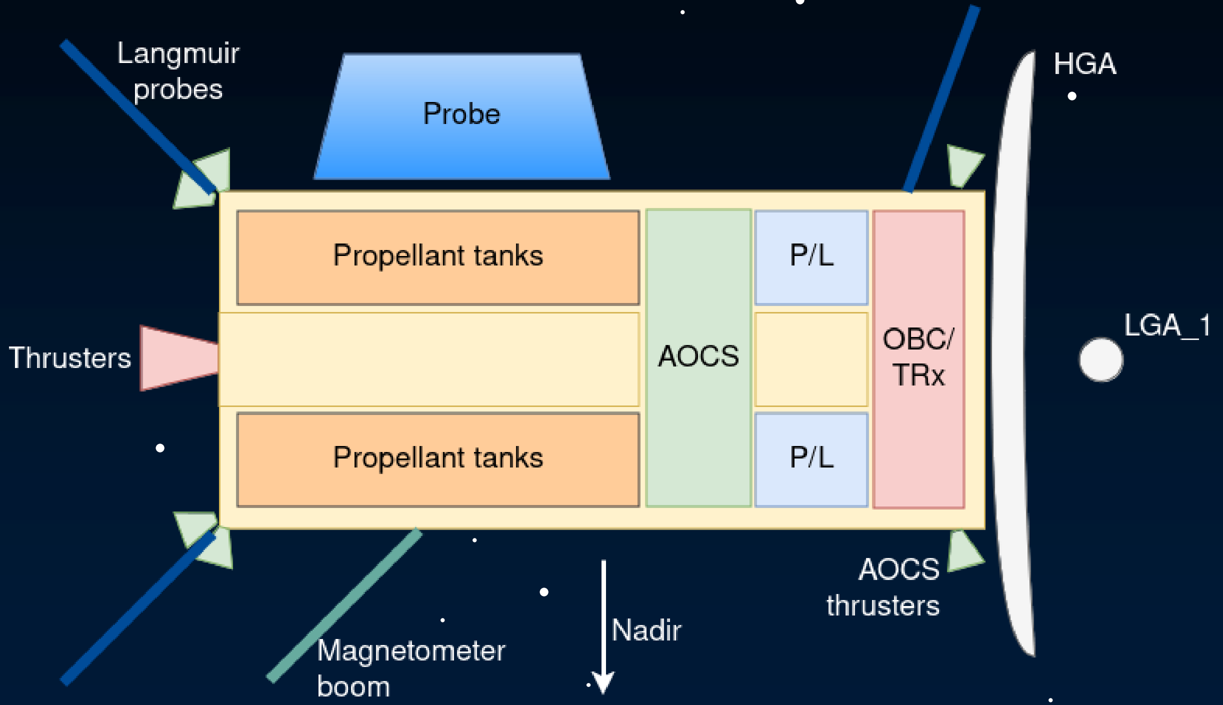
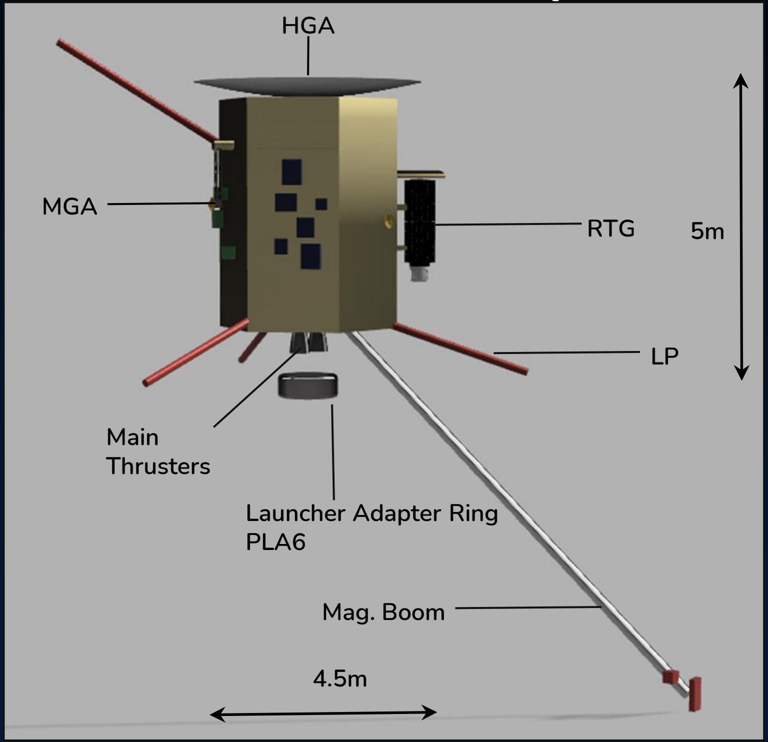


Image Credit: Blue Team

Preliminary S/C Design



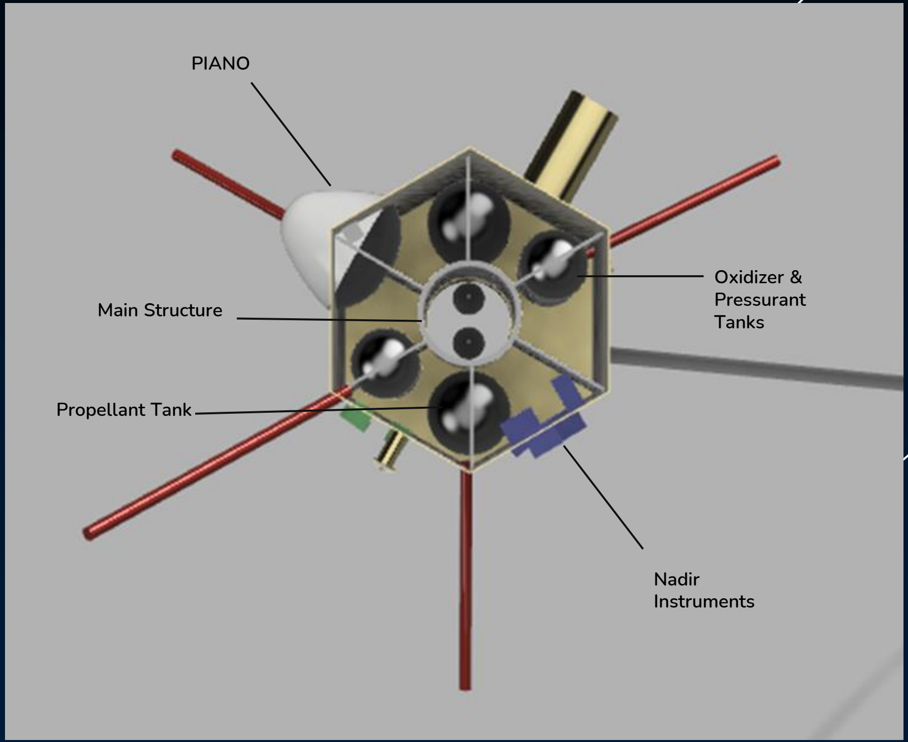


Image Credit: Blue Team

Propulsion

- Chemical liquid propulsion only viable option to meet I_{sp} and Thrust requirements
- MMH & N_2O_4 bipropellant chosen due to:
  - low freeze temperature
  - strong heritage
  - low pressure storage
- Propellant used for orbital maneuvers as well as AOCS thrusting

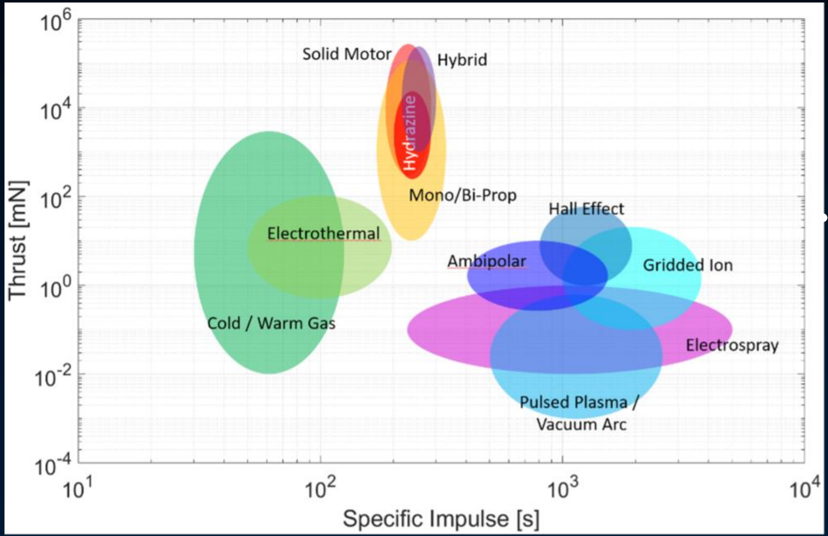


Image credit: NASA In-space propulsion

Component Examples (all having a TRL of >6)

Engine

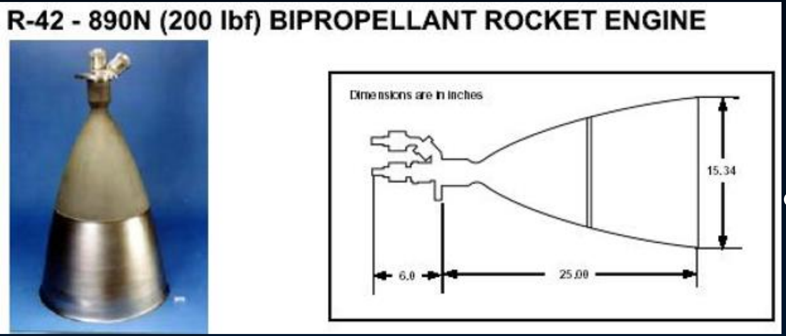


Image Credit: R-42

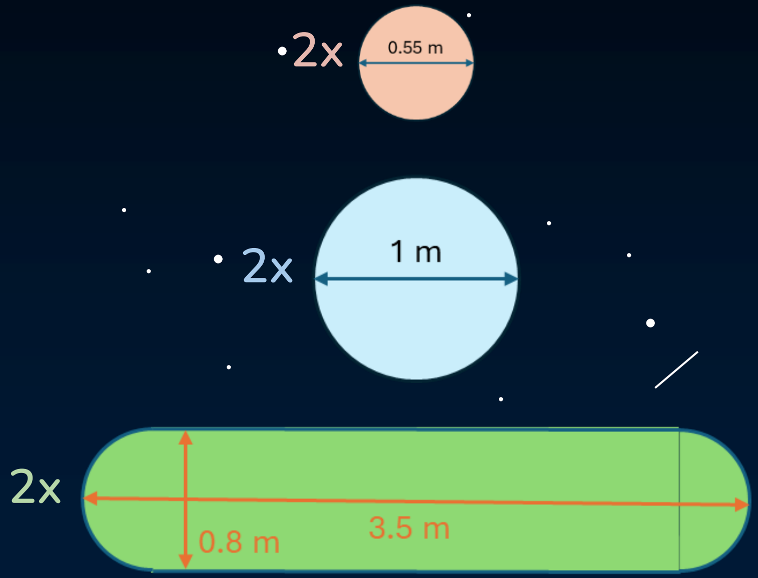
Pressurization Tanks

Propellant Tank

Image Credit: Ariane Group

Propulsion

Total propellant mass	4100 kg
MMH mass	2800 kg
N_2O_4 mass	1300 kg
Total tank mass (2x Fuel tanks, 2x Oxidizer, 2x Pressurizer)	215 kg
Total propulsion system mass including 15 % for pipes & valves & 10% margin	**300 kg**



Attitude and Orbit Control System

- 4x reaction wheels and 12x thrusters (10N)
  - Mounting close to center of gravity
  - EMC

	Requirements		AOCS Performance
Slew rate	8t S/C (BoL)	360° in < **100 s**	**97s** for 360° rotation (8t) **60s** for 360° rotation (3t)
	3t S/C (operations)	180° in < 20 mins	4 reaction wheels: 0.2 Nm
Pointing accuracy	3t S/C (Comms & measurements)	> 0.01°	4 reaction wheels: **0.01°**

Attitude and Orbit Control System

- Sensors and actuators
  - 3x IMUs (2/3 redundancy)
  - 2x star trackers
  - 2x sun sensors
  - 4x reaction wheels (0.3 Nm)
  - 12x thrusters (10N)
  - Navigation camera

- Summary
  - Total AOCS mass: 137 kg (20% margin)
  - Peak power: 112 W (10% margin)

Power

Radioisotope Thermal Generator (RTG)

- ASRG-500 (NASA)
    - Plutonium-238 fuel
    - 2500 $W_{thermal}$ @ BOL
    - Stirling engine (Efficiency: ~20%)
    - 500 $W_{electrical}$ @ BOL
    - 1% degradation per year
    - Identified as a likely successor to current RTG
    - TRL 3, smaller version TRL 5 (lab tested)
- European RTG project far behind & less efficient fuel
- Supplemented by a Li-Ion battery

ASRG EU2 test setup,
Image Credit: Lewandowski et al. (2016)

Radiation Considerations

- Jupiter Flyby at >30 $R_{Jupiter}$
  → TUNE avoids the hottest zones of the Jupiter radiation belts

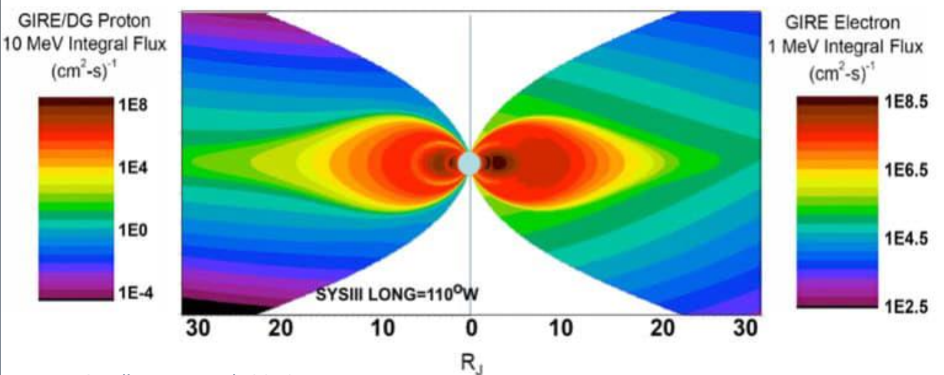


Image Credit: Jun et al. 2019

- Solar particle TID < 1krad/year behind 2.5mm of aluminium at 30 AU (if no Carrington Event)

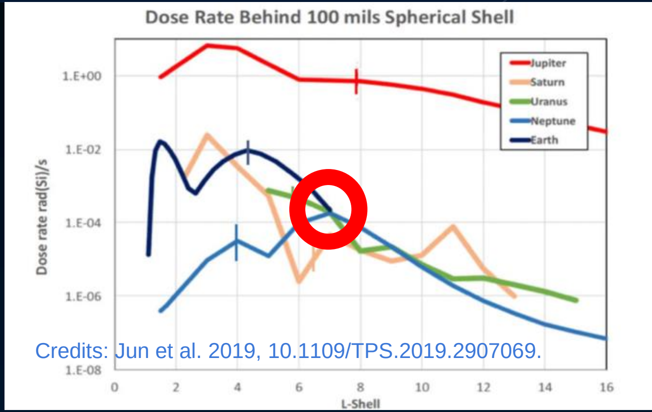
- Cosmic rays at Neptune:
  - ~4x higher flux than at Earth
  - < 4x higher Single Event Effect rates

Mitigation:

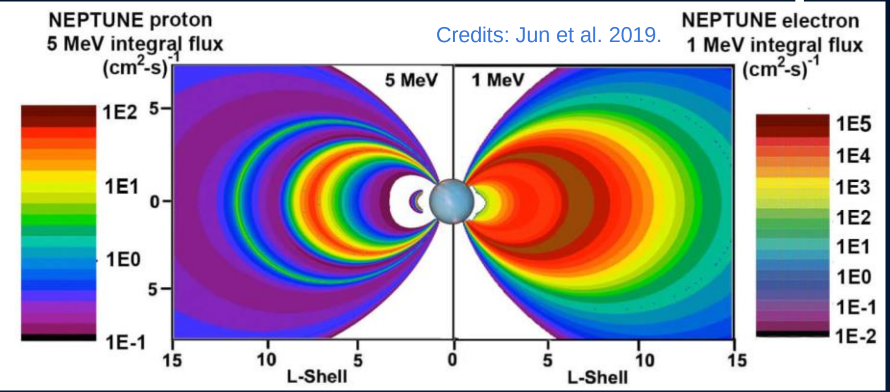
→ Latchup protection
→ Redundant Software
→ Bit error correction

Radiation Considerations (Trapped Particles at Neptune)

- Trapped particle spectra mostly electrons → Optimised Z-graded multilayer shielding could reduce shielding mass by 50% compared to aluminium
- Worst-case ionising dose rate inside radiation belts behind 2.54 mm of aluminium shielding:
  < 500 rad/month = 6krad/year
  -> = 30krad/5 years at Neptune
- Mission TID behind 2.54mm Al:
  < 50 krad → COTS electronics ?



Credits: Jun et al. 2019, 10.1109/TPS.2019.2907069.



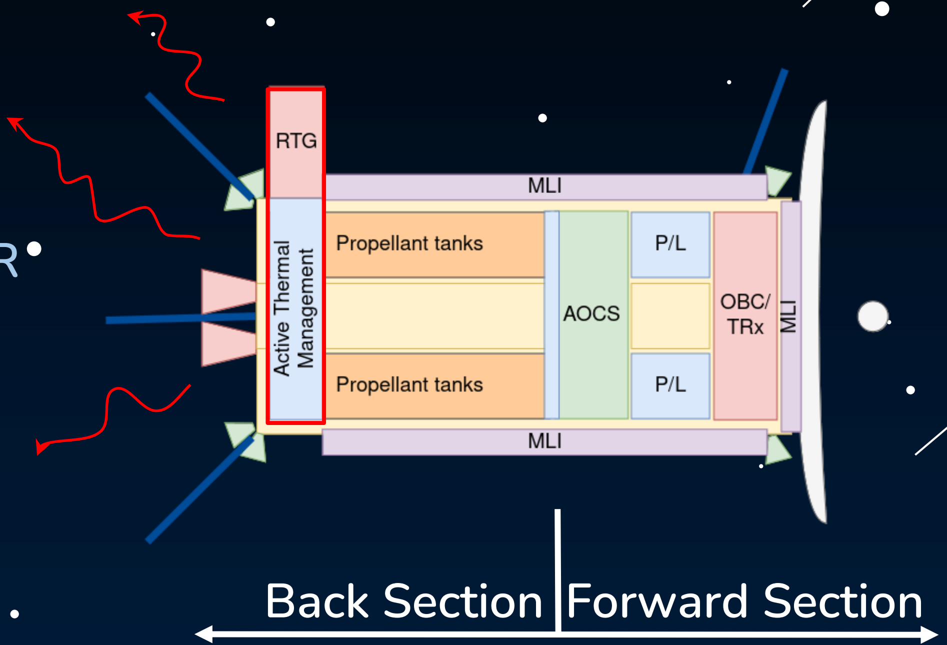
Credits: Jun et al. 2019.

Thermal Analysis - Cold Case

Forward Section @ Neptune

- Solar flux = 1.5 W/m^2
- P_{el} = 300W
  → Solar flux & Neptune Albedo/IR flux can be neglected
- 25 m^2 covered by MLI
  → ε = 0.01
  +1m^2 exposed with ε = 0.7

→ T_{eq} = 273 K = 0°C

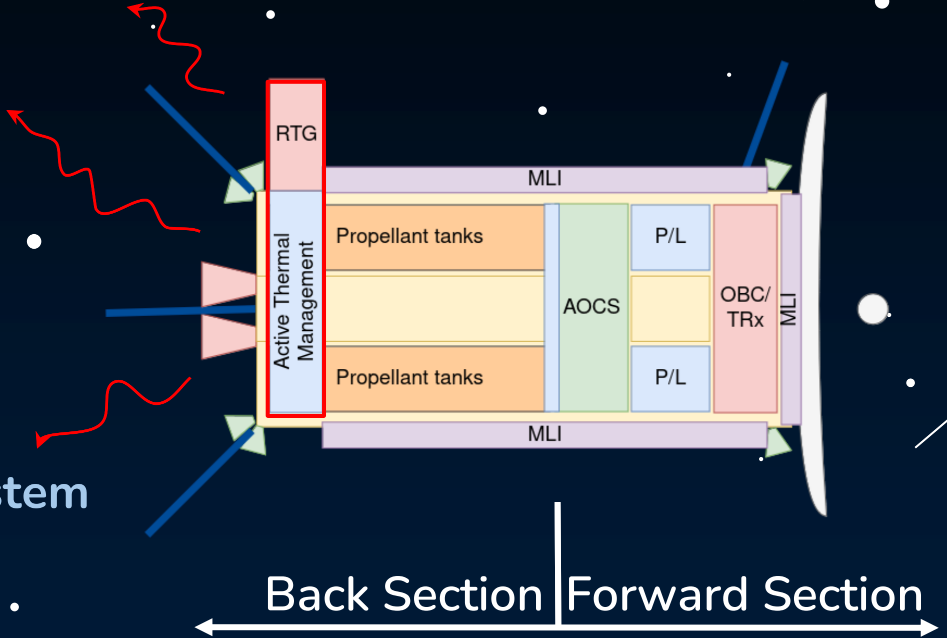


Thermal Analysis - Cold Case

Back Section @ Neptune

- RTG P_{therm} = 2500 W
- RTG “Cold Side” T_{max}= 360 K
- $8m^2$ with ε=0.7 → T_{eq} = 20°C

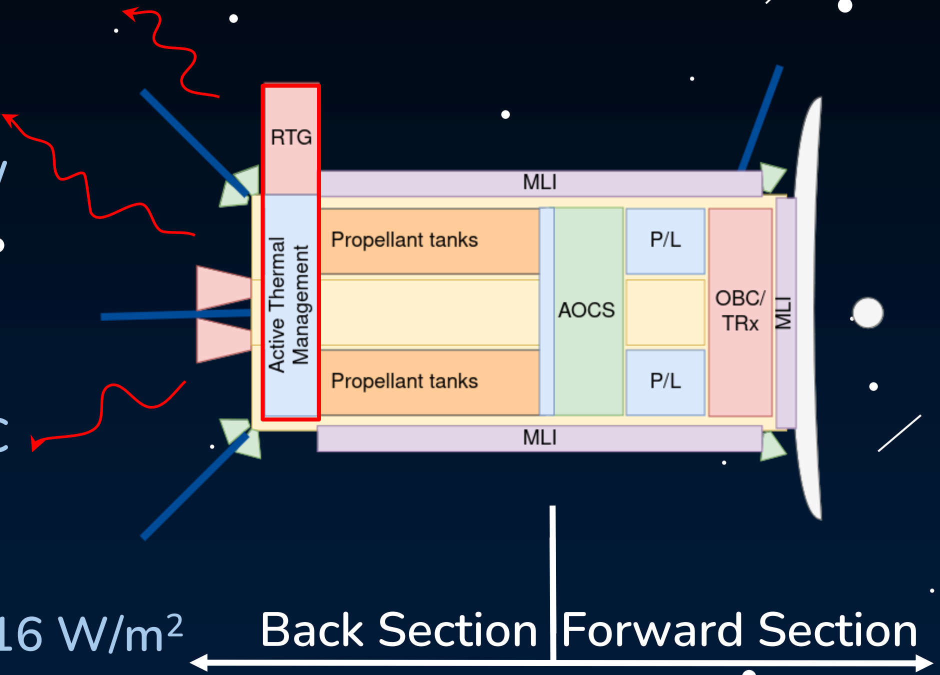
- Active Thermal Management System
  → distribute RTG waste heat
  → control tank and thruster temperature



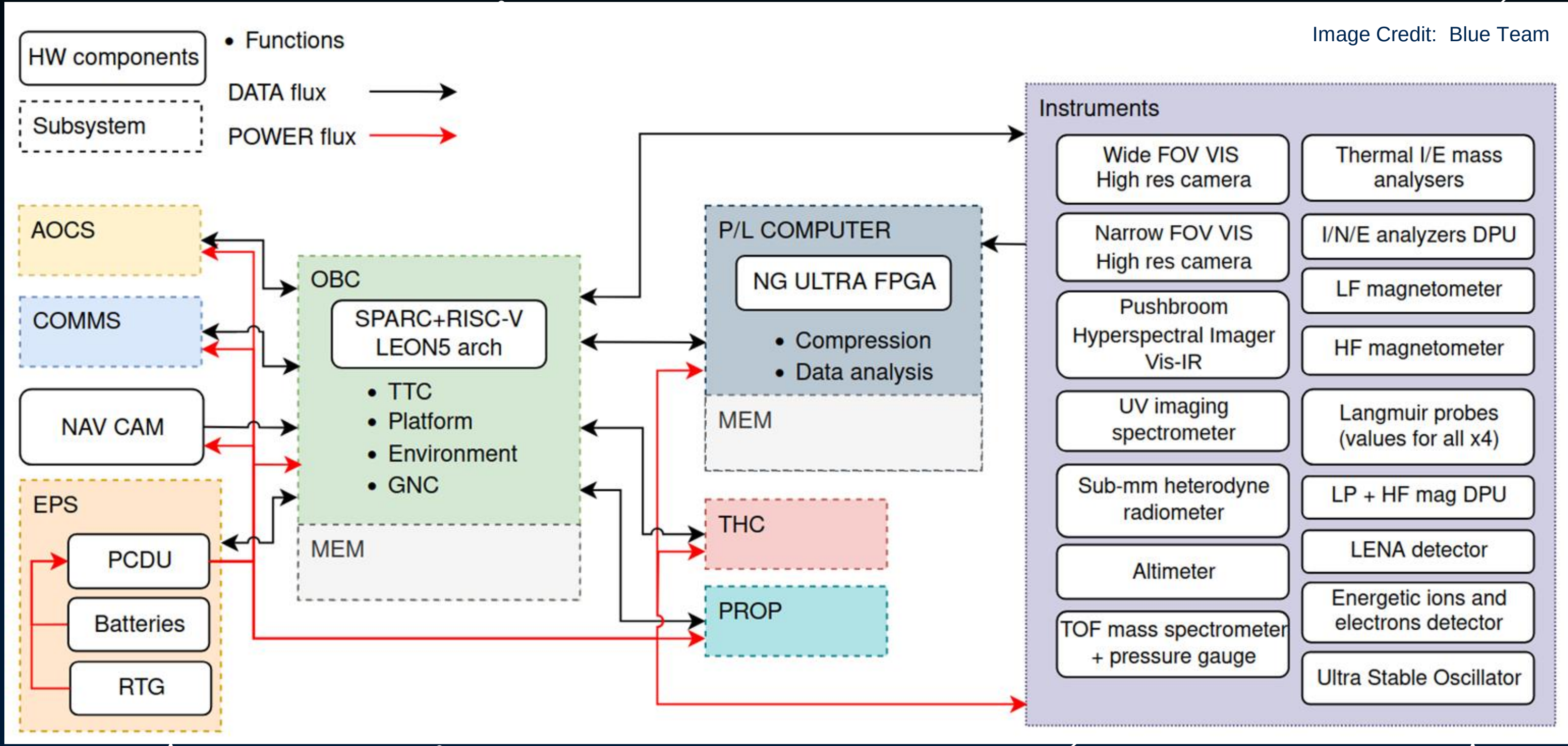
Thermal Analysis - Hot Case

Venus Flyby at 2 Venus Radii (R_V)

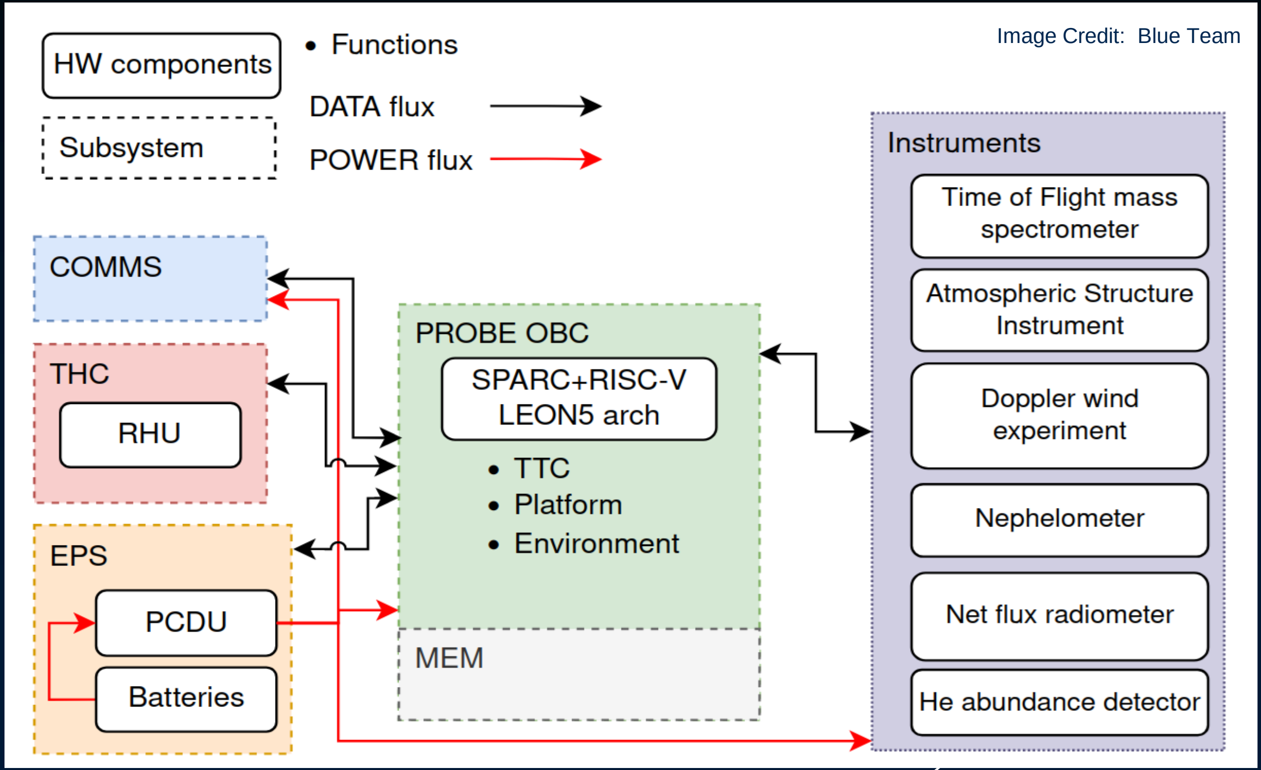
- Solar flux: 2600 W/m²
  → all instruments off → P_{el}=160W
- High-gain Antenna = Heat Shield:
  - Thermal coating
    (e.g.: AZ-93 → α=0.2, ε=0.9)
  - Thermally decoupled from S/C
    → T_{eq_dish} ~ 45°C
- Bottom plate:
  - Albedo ~225 W/m², IR flux ~16 W/m²
    → T_{eq_bottom} ~ 35°C



OBC subsystem



OBC subsystem Probe



Preliminary Probe Design

Back shell

Parachute

Data relay

Thermal control

Data management

Power supply

Heat shield

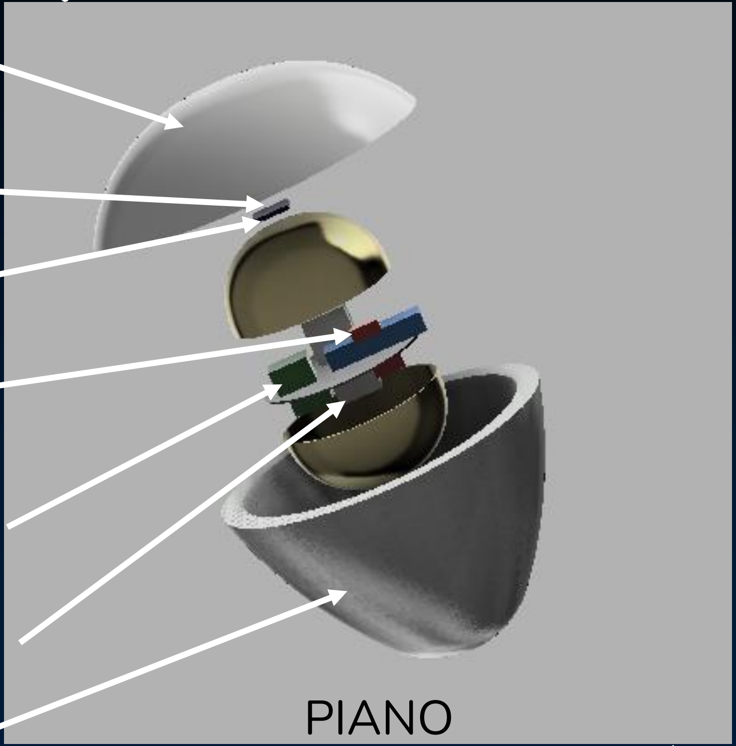


Image Credit: Blue team

Probe Heat shield

- Heating load: one order of magnitude less than for Galileo
- Thermal protection designed in Europe: NAXECO
- Ablation materials need development in Europe
- Simulation with parameters:
  - Flight path angle: -25°
  - Relative velocity: 28 km/s
  - Probe mass: 350 kg
  - Area: 1.8 m^2

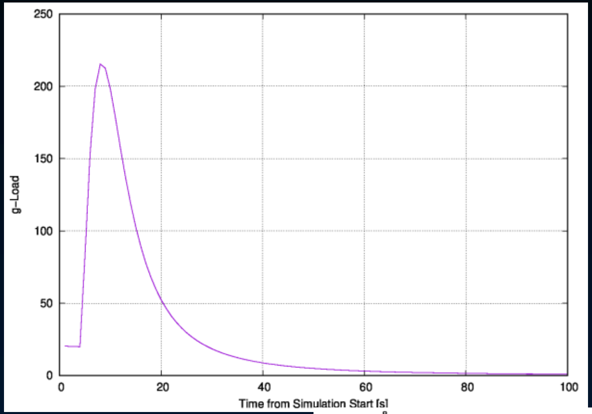
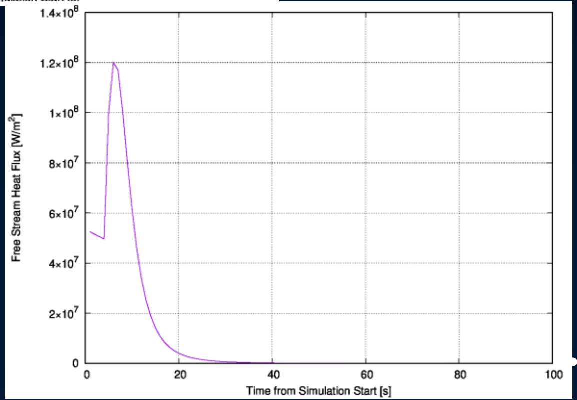


Image Credit: ESTEC

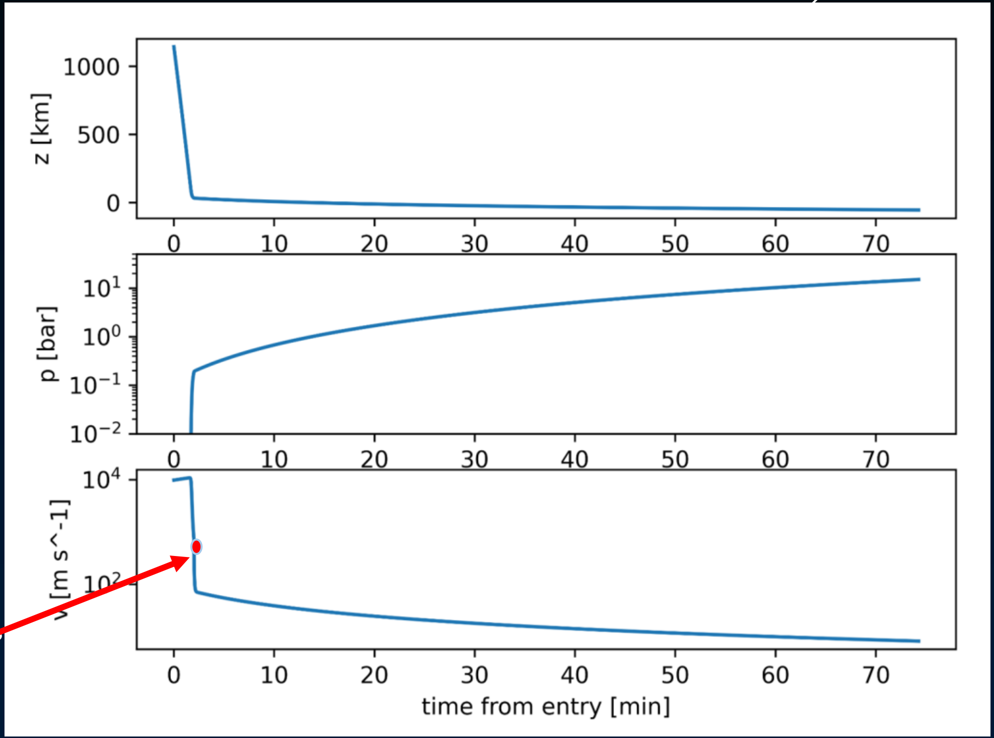


Probe Parachute

- Simple simulation of Neptune's atmosphere with scale height
- multiple parachute sizes explored

Results:

- Parachute size: 15 m^2
- Allows to reach 15 bar in 60min



Parachute deployment

Image Credit: Blue team

Probe Power System

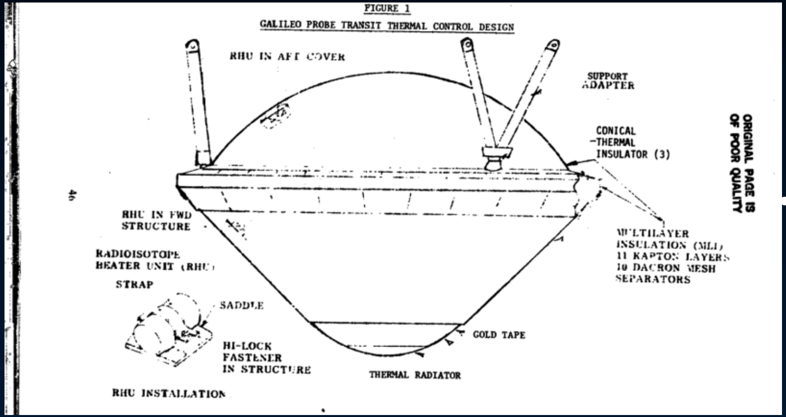
- Primary batteries : 2 Lithium thionyl chloride
  → high energy density & long storage life
- Low-Voltage Battery (6,8V) : used for low-power timer circuit
- High-Voltage Battery (26V) : used during peak performance

- Power draw needed: **148 W** (peak: 163.4W)

Image Credit: JPL

Probe Thermal System - RHUs

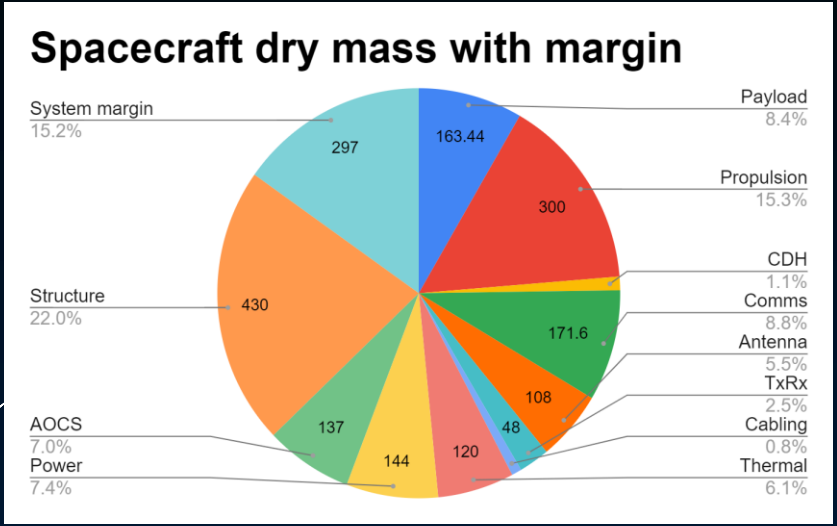
- Number of RHUs: 37
- Mass of one RHU: 40g
- Total mass: **1.48 kg**
- Multi layer insulation (MLI)will be used
- Passive thermal control relying on thermal inertia during reentry
- Based on Galileo entry probe heritage

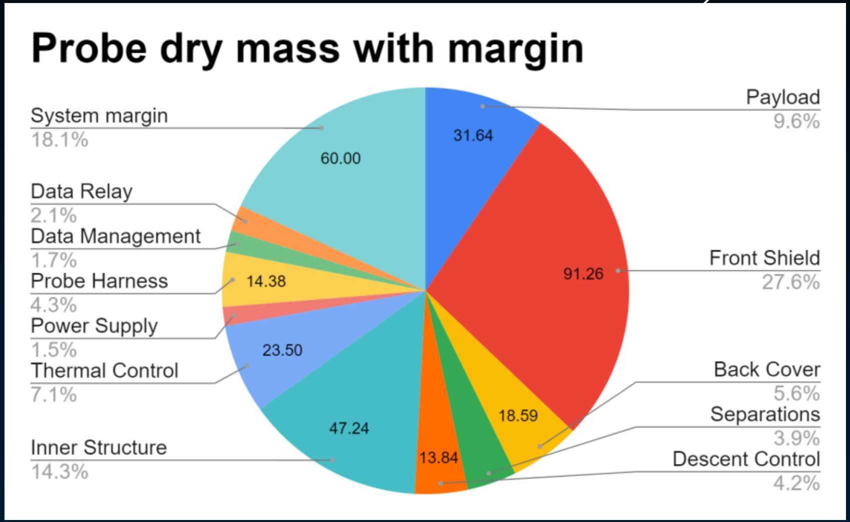


Haverly, G.C. and Pitts, W., 1982

System Budgets

Mass Budget





- Bottom-up mass estimation for Orbiter
- Total mass with margin: 1784 kg

- Estimation based on previous probes
- Total mass with margin: 364 kg

- Total dry mass 2255 kg with margin
- Wet mass 6560 kg

Power Budget

Power demand

	Power @ comms (W)	Power @ science (W)
Grand total	329.70	352.70
Grand total +10% margin	362.67	387.97

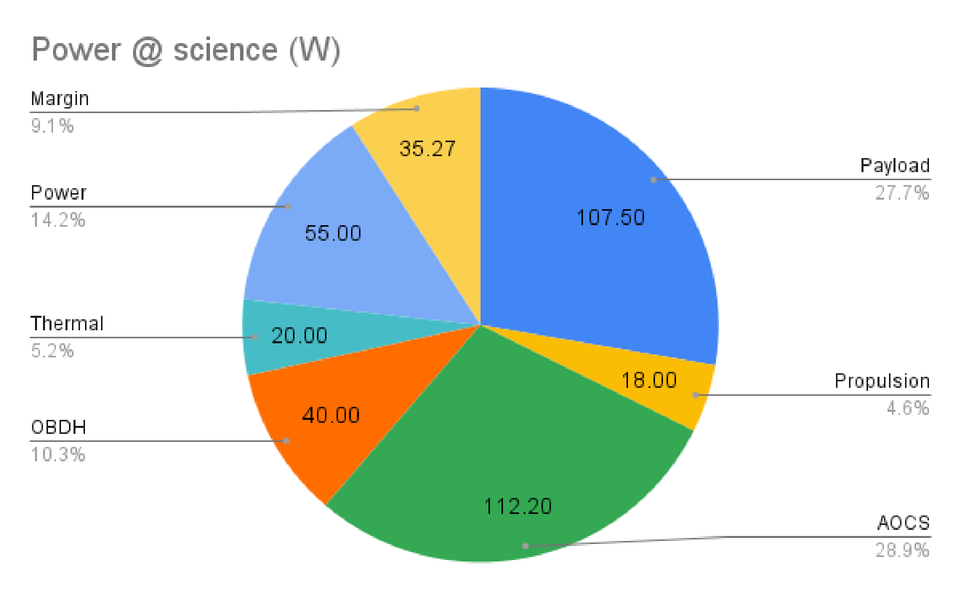
Power generated

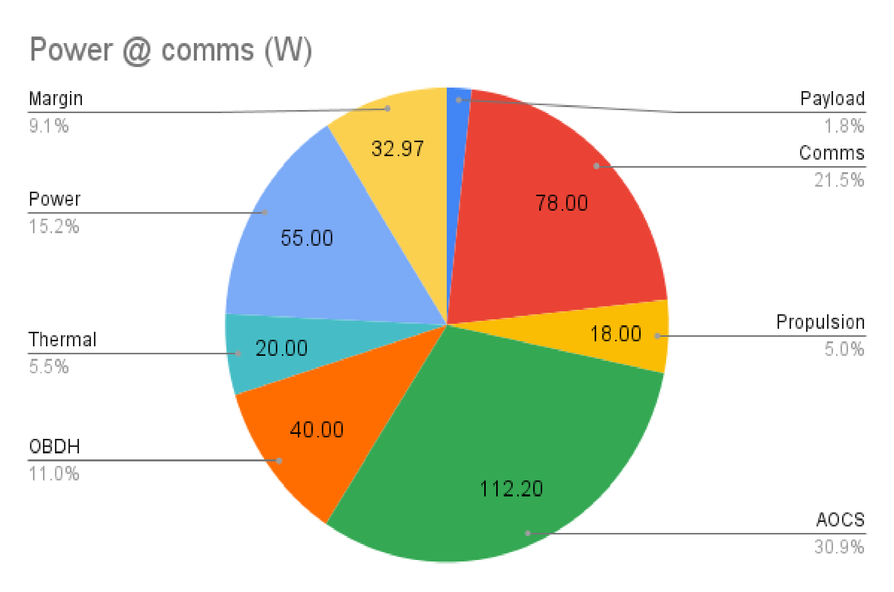
	BOL	Arrival to Neptune	EOM
RTG power (W)	500	405	385
Batteries power (Wh)	415	~415	~415

Worst-Case Power Consumption Scenario:

- Beginning of Mission (BOM)
  Power Consumption margin: 24.34W
- End of Mission (EOM)
  Power Consumption margin: 4.34W

Power Budget





COMMS subsystem: Science data budget

- Mission objectives → possibilities (HGA+MGA+LGA / Optical / Quantum)
- Data rates for the links
- Compression factor
  - VIS/IR spectro-imager: 6
  - Other instruments: 3
- Band selection and antenna design

	High eccentricity orbit (15 earth days)	Triton investigating orbit (2.5 earth days)
Neptune encounter	0.54 GB/orbit	0.08 GB/orbit
Triton encounter	0.7 GB/orbit	0.14 GB/orbit
Magnetosphere	0.08 GB/orbit	0.02 GB/orbit
Link margin	10%	10%
Error correction	30%	30%
Total w/ margin	1.80 GB/orbit	0.33 GB/orbit

COMMS subsystem: Link Budget

		HGA (data)	MGA (TTC)	LGA (Orbiter Detumbling/ safe mode)
Downlink	Band	Ka (32GHz)	X (8.5GHz)	S (2 GHz)
	Tx diameter	4.5m	0.6m	0.05m (OMNI)
	Tx power	39W + (TWTA)	25W + (TWTA)	10W
	Antenna pointing	0.01° (orbiter orientation)	0.01° (MGA APM)	120°
	Total	0.14 GB/day (8h)	0.12 MB/day (8h)	Depends on receiver

COMMS subsystem: Summary

- Science data to transmit (requirement):
  - Tritan investigating orbit: 1.8 GB/orbit
  - High eccentricity orbit: 0.3 GB/orbit

- Max transmittable data HGA (@ 0.14 GB/day):
  - Tritan investigating orbit: 2.3 GB/orbit - ok
  - High eccentricity orbit: 0.4 GB/orbit - ok

COMMS subsystem: antenna design

- Antenna geometry (ADE)
- Coverage flexibility
- Articulation for apertures stowed during launch (MGA)

	Mass w/ margin	Diameter
HGA	70 kg	4.50 m
MGA	30 kg	0.60 m
LGA_1/LGA_2	8 kg	0.05 m
Total	108 kg	

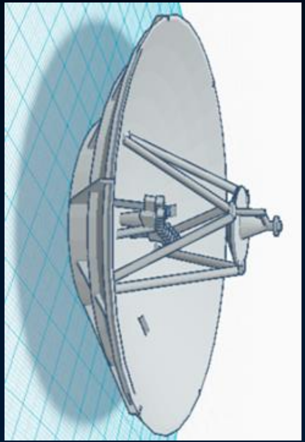


Image Credit: Cassini HGA - NASA

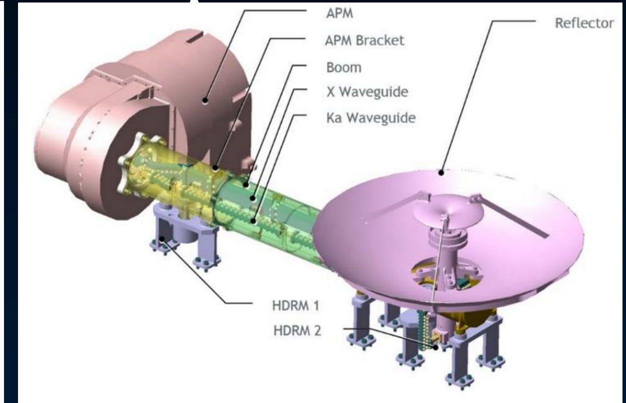
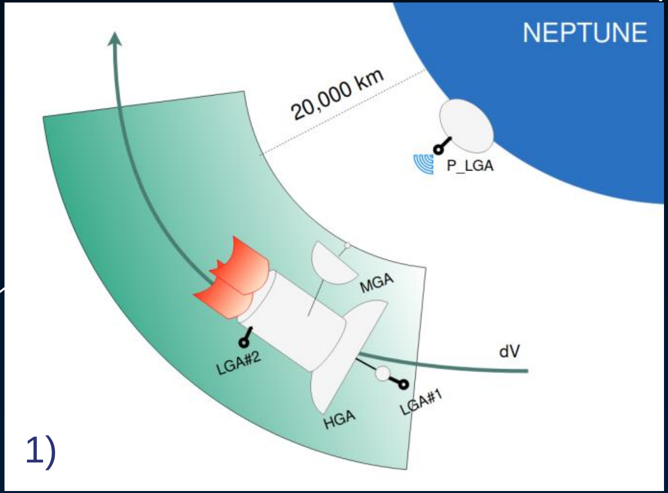
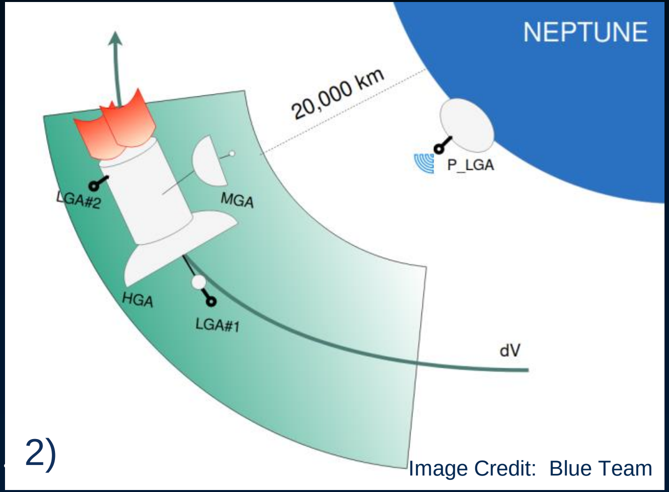


Figure 1. Medium Gain Antenna 3D view with main components

Image Credit: JUICE MGA - Sener

COMMS subsystem: Probe COMM





Band	S (2GHz)
Tx diameter	0.05 (OMNI)
Tx power	15W
Antenna pointing	120° (+MGA APM)
Total	2kbps 0.95 MB/h (total: 0.95 MB)

Ground Segment

- ESA ESTRACK ground antenna system 35m
  - Cebreros Spain, New Norcia Australia and Malargue Argentina
  - X, Ka-band
- Control center: ESOC (Darmstadt)
- Data center: ESAC Science Data Centre Madrid
  - ESA Planetary Science Archive

Cost Budget

Item	M €
RTG	150
Probe	350
Orbiter	500
ESA Project Team (+25 % Industry)	312.5
MOC (+ 20 % Industry)	180
SOC (+ 20 % Industry)	180
Launch cost	150
Sub Total	1818
+10% Inflation	1 999
TOTAL + P/L	2 500

- L4 mission
- Payload by member states
- Benchmarking with other missions (+inflation)

Descoping Options

Our mission	Descoping option 1	Descoping Option 2	Descoping Option 3
Orbiter + Probe	Removal of altimeter	Orbiter + LF-Radar	Orbiter (+ extra fuel for maneuvers)

Scientific objectives we can answer

Risk Analysis

Risk Assessment

Risk	Mitigations
Probe deployment	Keep the probe onboard and have enough propellant
Instrument malfunction	Perform extensive ground tests and include redundant deployment systems.
Radiation damage	Implement latch up protection, redundant software, and bit error correction.
Failure of deployable instruments (eg: Langmuir probe, boom)	Conduct thorough pre-launch testing and validation of deployment mechanisms, include redundancy in design.
OBC does not have heritage	Long haul testing for space conditions.
Overheating of RTG	Implement robust thermal management systems and regular monitoring of RTG temperatures.

Risk Matrix

Impact Rating

Probability Score

PS\IR	1	2	3	4	5
1			Probe deployment		
2					Instrument malfunction OBC heritage
3				Radiation damage Deployable instruments	Overheating of RTG
4					
5					

Technology Readiness Level

- Payload:
  - Sub-mm wave instrument (SWI) ~ 6
  - Other instruments > 6

- Platform:
  - Power (RTG): 2
  - Telecoms: 6
  - OBC: 5
  - Propulsion: > 6

- Probe: < 6

Planetary Protection Plan I

Celestial body	Neptune	Triton
Type of mission	Flyby, Probe, Eventual Grand Finale	Flyby
Category	Cat II	Cat II*
Prevention of biological contamination	Terrestrial organisms	
Level of precaution	Significant	
Probability of contamination	Remote	
Degree of concern	Record of planned impact probability and contamination control measures	
Representative range of requirements	PP plan Pre-launch report Post-launch report Post-encounter report End-of-mission report	

Planetary Protection Plan II

- COSPAR indications might evolve during mission development for Triton
- “The bio-burden brought to either Triton and Neptune shall be controlled and limited” (COSPAR 2020)
- Monitoring through essays taken at regular intervals and recorded in a DB of biological presence

Public Outreach

- For children, students, the general public, scientific community...
- A Mission "To-Grow-up-with"

Image Credit: Silvia Romero Azpitarte

PROJECTS:

- School (ESERO) & university projects
- Instagram, X, website...

COMPETITION:

- "TUNE's Odyssey: Create the Soundtrack to Space" music competition to send your song to space

Public Outreach

Image Credit: Blue Team

Thank you!

Tune in with us for more!

Backup

Orbiter Instruments Link to Science Objectives

Instrument	Observable	Science Objective
USO and Medium Gain Antenna	Gravitational moments Neutral temperature and density profile of Triton atmosphere	SCI-1.10 - interior structure of Neptune SCI-3.60 - interior structure of Triton SCI-3.30 - Triton surface processes
High Resolution Camera	Waves of Neptune rings Cloud speeds and directions Spatial distribution & morphology Albedo of rings Triton surface features Height and width of plumes	SCI-1.10 - interior structure of Neptune SCI-1.40 - wind speeds & directions in atmosphere SCI-1.50 - dynamics of clouds, hazes, dark spots SCI-1.70 - structure of rings SCI-3.10 - map Triton's surface SCI-3.50 - Triton plumes
Vis-NIR Hyperspectral Imager	Gas abundances in Neptune's atmosphere Vapor abundances of clouds, hazes Bond albedo of Neptune Triton surface features Triton spectral lines of atmosphere	SCI-1.20 - atmospheric composition of Neptune SCI-1.50 - composition of clouds, hazes, dark spots SCI-1.60 - energy balance & transport of Neptune SCI-3.10 - map Triton's surface SCI-3.20 - Triton atmospheric composition

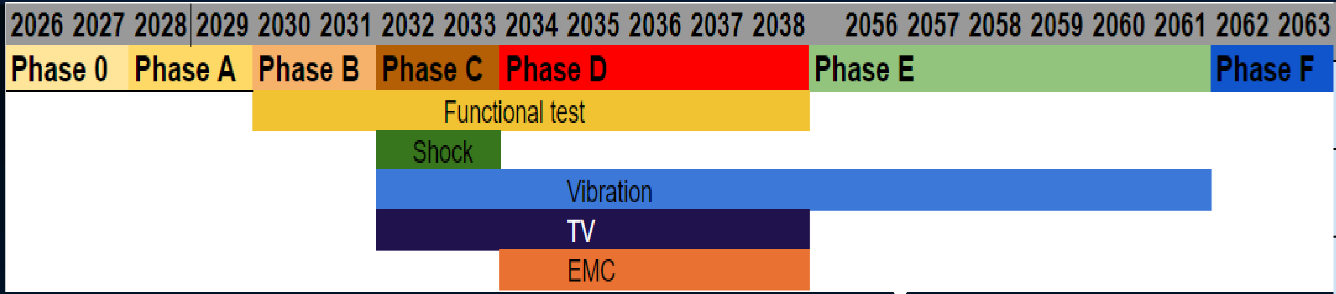
Orbiter Instruments Link to Science Objectives

Instrument	Observable	Science Objective
Sub-mm Heterodyne Radiometer	Isotope ratios in Neptune's atmosphere Scattering properties of clouds Thermal emission of Neptune Spectral lines of gases in atmosphere	SCI-1.20 - atmospheric composition of Neptune SCI-1.50 - composition of clouds, hazes, dark spots SCI-1.60 - energy balance & transport of Neptune SCI-3.20 - atmospheric composition of Triton SCI-3.40 - composition of plumes
UV imaging spectrometer	Stellar occultation UV aurora emission	SCI-1.60 - energy balance & transport of Neptune SCI-3.20 - Triton atmospheric composition SCI-2.40 - atmospheric interaction with plasma
Plasma Wave Investigator	Plasma density and temperature	SCI-2.20 - distribution and composition of plasma SCI-2.30 - magnetospheric interaction N&T SCI-2.90 - particle acceleration process in magnetosphere
Magnetometer	Magnetic field strength	SCI-2.10 - magnetic field formation and structure SCI-2.30 - magnetospheric interaction N&T SCI-2.80 - magnetic field of N interacts with interior of T SCI-2.90 - particle acceleration process in magnetosphere

Orbiter and Probe Instruments Link to Science Objectives

Instrument	Observable	Science Objective
Particle Environment Investigator	Ion and electron energy and mass distributions Ion and electron precipitation Isotope ratios	SCI-2.20 - distribution & density of plasma SCI-2.30 - magnetospheric interaction between N&T SCI-2.40 - atmospheric interaction with plasma for N&T SCI-2.50 - Triton's contribution to plasma environment SCI-2.60 - sources and losses of Triton ionosphere SCI-2.70 - shape & dynamics of Neptune's radiation belts SCI-2.90 - particle acceleration processes in magnetosphere SCI-3.20 - composition of Triton's atmosphere SCI-3.30 - Triton atmosphere isotope ratios SCI-3.40 - Triton atmospheric loss
Probe Instruments	He-H ratio Isotope ratios of key elements and tracers of motion Pressure and temperature Winds speeds Vertical radiative energy flux	SCI-1.10 - interior structure and composition of Neptune SCI-1.20 - composition of Neptune's atmosphere SCI-1.30 - pressure and lapse rate in Neptune atmosphere SCI-1.40 - wind speeds and directions in atmosphere SCI-1.50 - energy balance and transport in atmosphere

Testing



	Needed Tests				
Instruments	Vibration	Functional Tes	Shock	TV	EMC
Wide FOV VIS High res camera	C, D, E	B, C, D	C	C, D	D
Narrow FOV VIS High res camera	C, D, E	B, C, D	C	C, D	D
LF magnetometer	C, D, E	B, C, D	C	C, D	D
HF magnetometer	C, D, E	B, C, D	C	C, D	D
IFU Vis-IR Spectrometer	C, D, E	B, C, D	C	C, D	D
Sub mm wave instrument	C, D, E	B, C, D	C	C, D	D
Ion mass analyser	C, D, E	B, C, D	C	C, D	D
Electron detector	C, D, E	B, C, D	C	C, D	D

Orbiter		Probe
Wide FOV VIS High res camera	Sub mm wave instrument	Time of Flight mass spectrometer
Narrow FOV VIS High res camera	Ion mass analyser	Atmospheric Structure Instrument
LF magnetometer	Electron detector	Doppler wind experiment
HF magnetometer	Langmuir probes (values for all x4)	Nephelometer
IFU Vis-IR Spectrometer	LP + HF mag DPU	Public engagment camera
UV image spectrometer	I/N/E analyzers DPU	Net flux radiometer
Altimeter	Ultra Stable Oscillator	He abundance detector
LENA detector	Time of Flight mass spectrometer + pressure gauge	
Energetic ions and electrons detector		

High-Resolution Optical Cameras (HRC)

- Detector size: 2000 x 1504
- Spectral range: 350 – 1050 nm
- Thirteen spectral bands
- Heritage Instrument: JANUS (JUICE) and RALPH (New Horizons)
- FOV: 1.5°

IR-VIS Hyperspectral Imager (IVHI)

- Pushbroom Hyperspectral Imager
- Spectral range: 0.5 - 5.5 μm
- Spectral resolution: 5 nm
- Heritage instruments: MAJIS (JUICE) and RALPH (New Horizons)
- 500 pix x 500 spectral
- FOV: 5.7°

UV spectral Imager (UVI)

- Pushbroom Spectral Imager
- Spectral range: 55-210 nm
- Spectral resolution: 1.2 nm
- Heritage instruments: UVS (JUICE) and ALICE (New Horizons)
- FOV: 7.3°

Submillimeter Wave Instrument (SWI)

- Passive dual-beam heterodyne radiometer
- Spectral range: 200- 1000 μm
- Resolving power: 10^8
- Heritage instruments: SWI (JUICE) and MIRO (Rosetta)
- 30 cm main mirror
- 2 bands: 600 GHz, 1200 GHz

Magnetometer (MAG)

- **3-axis fluxgate magnetometer** (+/- 50 uT with 0.1nT prec. / 0-10 Hz)
  - Heritage: JMAG (Juice)
- Objectives
  - Structure of Neptune's magnetic field
  - Triton internal structure
- Heritage:
  - Juice J-MAG

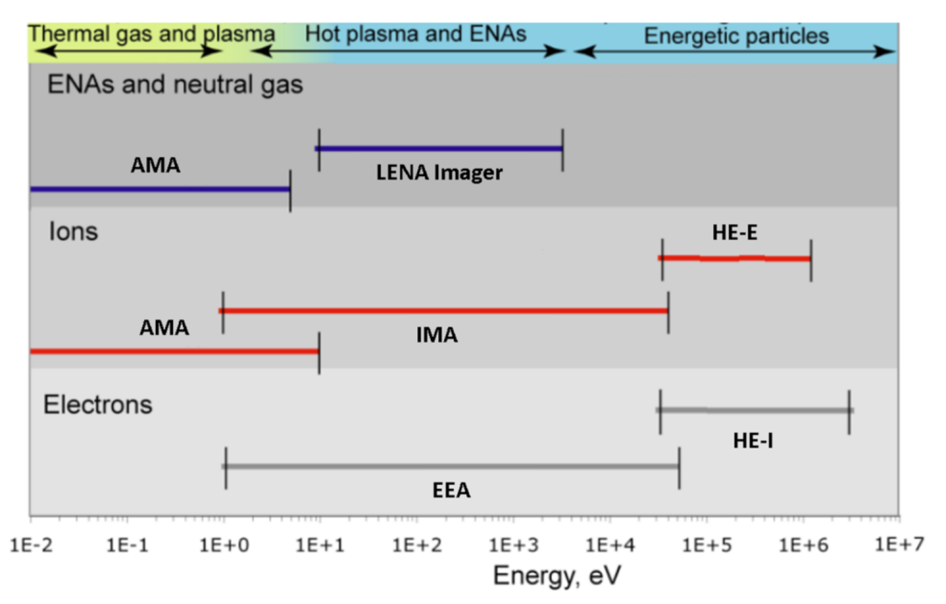
JMAG - JUICE red book

Particle Environment Investigator (PEI)

- 5 sensors measuring electron/ion/ENA from **< 0.01 eV to > 1 MeV**

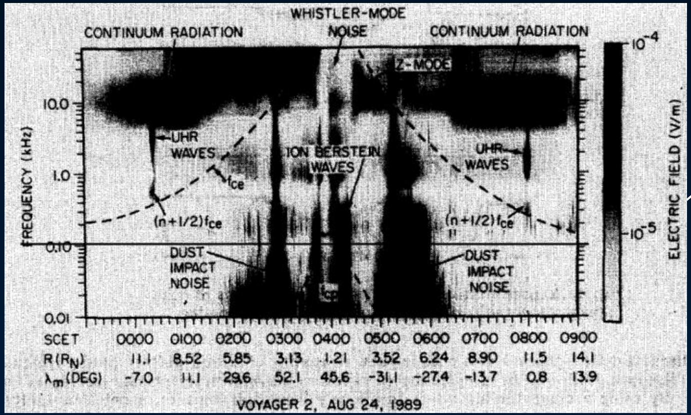
- Objective
  - Particle distributions
  - Radiation belts
  - Atmosphere

- Heritage:
  - PEP (Juice)
  - EPI-Lo (PSP)



Plasma Wave Investigator (PWI)

- E/B-fields, current, and potential between 0 - 60 kHz
  - Langmuir probes (4x tetra): (I, V) -> E field, plasma (n, T)
  - Search coil magnetometers: B field
- Objectives:
  - Dust
  - Macroscopic plasma properties
  - Particle acceleration (waves)
- Heritage:
  - Juice RPWI, Voyager 2 PWS



D. A. Gurnett et al., PLASMA WAVE OBSERVATIONS AT NEPTUNE

Time of Flight mass spectrometer (Probe)

- Resolution: 0.0005 1/cm
- Sensitivity: 10^{12} –10^{13} counts/s/mbar
- Internal pressure range: 10^{-4} –10^{-13} mbar
- Size: 44cm x 22cm x 22cm
- Heritage instruments: Huygens/Galileo

Atmospheric Structure Instrument (Probe)

- Temperature accuracy in upper troposphere: ±0.1 K
- Temperature accuracy in upper troposphere: ±1 K
- Pressure accuracy: 0.5%
- Size: 18cm x 15cm x 12cm
- Heritage instruments: Huygens/Galileo

Doppler Wind Experiment (Probe)

- X- and Ka-Band antenna needed
- Ultrastable oscillator (USO) required
- Accuracy: 10 µm/s
- Operating temperature: 70° C
- Size: 13 cm x 12.0 cm x 11 cm
- Heritage instruments: Huygens/Galileo

Nephelometer (Probe)

- Angular resolution, FWHM, degrees: >0.5 (depending on the channel)
- Sensitivity, m^{-1} sr^{-1} $count^{-1}$: $>1.1 \times 10^{-8}$
- Size: 44cm x 14cm x 9cm
- Heritage instruments: Huygens/Galileo

Net Flux Radiometer (Probe)

- Multiple filter bands spanning the spectral range 0.2 to 300 μm
- FOV: ±2.5
- View angles: ±80°, ±45° and 0°
- Size: 11 × 31 × 14
- Heritage instruments: Huygens/Galileo

He Abundance Detector (Probe)

- Sensitivity: Δq_{He}=0.0006
- Accuracy: δq_{He}=±0.0015
- Temperatures of the structure: -20° C to +50° C
- Size: 13cm x 4cm x 6cm
- Heritage instruments: Huygens/Galileo

AOCS Budget

Component	N. units	Power (peak)	Power Initial (W)	Power pointing (W)	Power Thrusters (W)
Gyroscopes	3	20	40	40	40
Sun sensors	2	0.5	1	0	0
Star sensor	2	5	0	10	10
NavCam	1	2	0	2	2
Reaction wheels	1	50	25	50	12.5
Thrusters	12	4	16	0	16
Total			82	102	80.5
margin			0.1	0.1	0.1
Total (10% margin)			90.2	112.2	88.55

Attitude and Orbit Control System

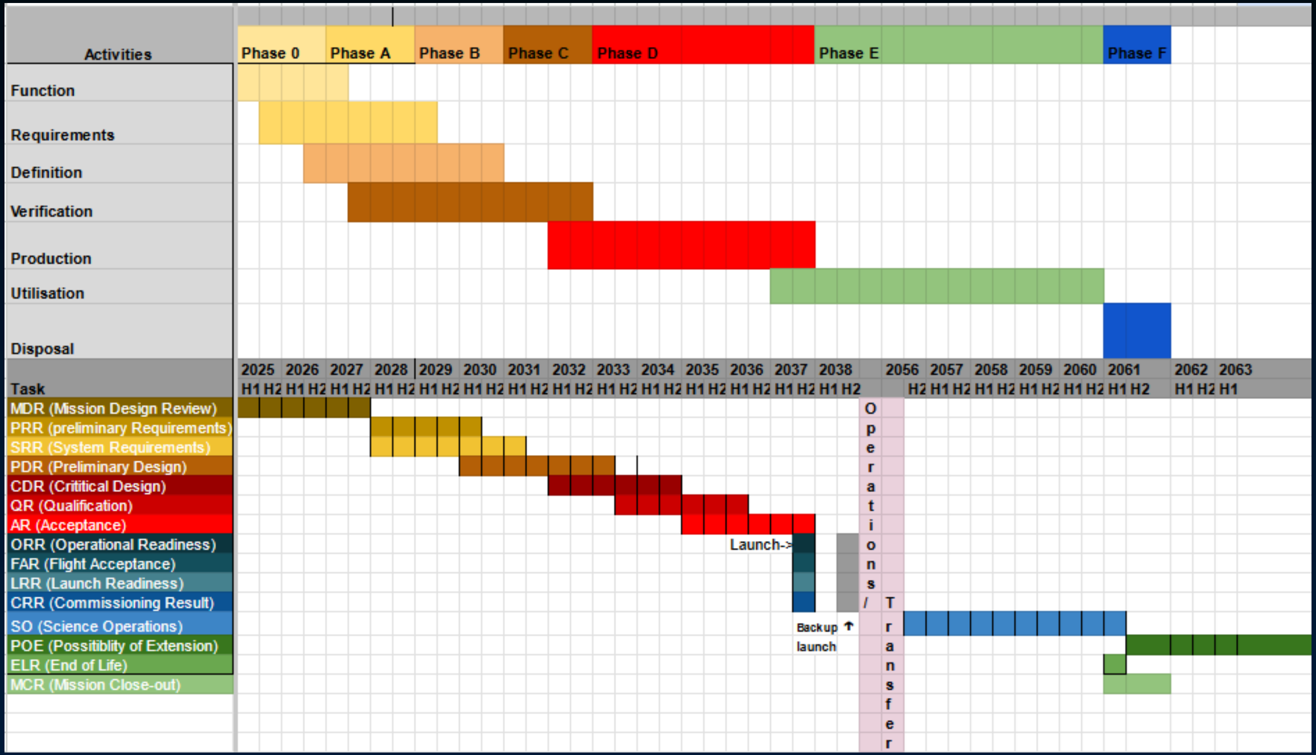
- Requirements
  - Slew rate:
    - Initial navigation (8t S/C): 360° in < 100 s
    - Flybys (3t S/C): 180° in < 20 mins (0.15 °/s)
  - Pointing accuracy:
    - Communication & measurements (3t S/C): > 0.01°
  - Integration:
    - Mounting close to the center of gravity
    - EMC

Attitude and Orbit Control System

- Assumptions:
  - 2x thrusters/axis with 2m lever arm
- Reaction wheels (4x):
  - Triton encounters (3t S/C): 0.15 °/s -> 0.2 Nm - ok
- 10N Bi-propellant thrusters:
  - 8t S/C: 97s for 360° rotation - ok
  - 3t S/C: 60s for 360° rotation - ok

10N Bi-Propellant Thruster with Single Seat Valve, ArianeGroup

Mission Timeline



Testing Timeline

Test phases:

What is tested ->

2026	2027	2028	2039	2030	2031	2032	2033	2034	2035	2036	2037	2038		2056	2057	2058	2059	2060	2061	2062	2063
Phase 0		Phase A		Phase B		Phase C		Phase D					Phase E							Phase F	
				Functional test																	
						Shock															
						Vibration															
						TV															
								EMC													

Orbiter		Probe
Wide FOV VIS High res camera	Sub mm wave instrument	Time of Flight mass spectrometer
Narrow FOV VIS High res camera	Ion mass analyser	Atmospheric Structure Instrument
LF magnetometer	Electron detector	Doppler wind experiment
HF magnetometer	Langmuir probes (values for all x4)	Nephelometer
IFU Vis-IR Spectrometer	LP + HF mag DPU	Public engagment camera
UV image spectrometer	I/N/E analyzers DPU	Net flux radiometer
Altimeter	Ultra Stable Oscillator	He abundance detector
LENA detector	Time of Flight mass spectrometer + pressure gauge	
Energetic ions and electrons detector		

Power budget