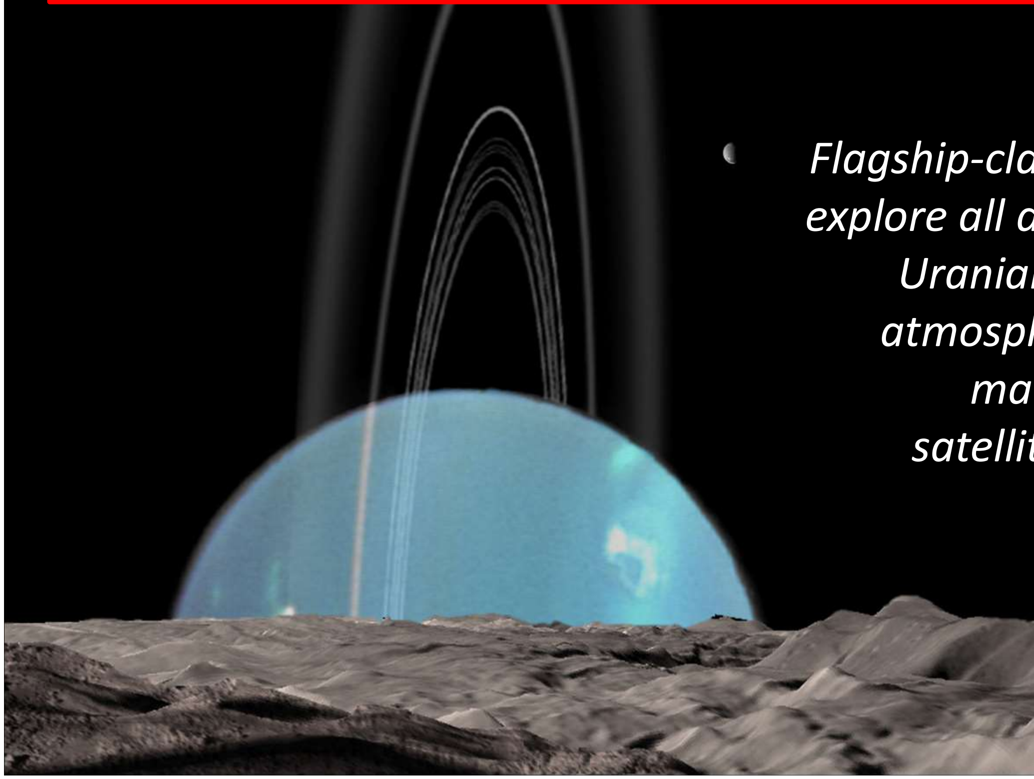
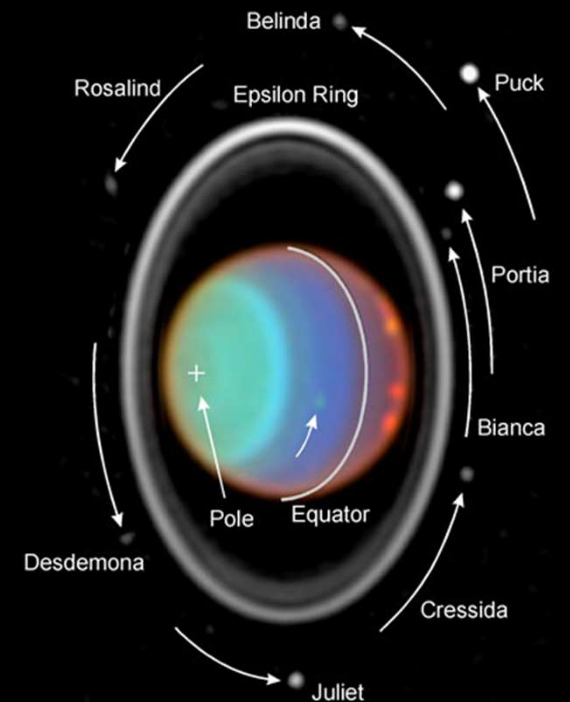
Uranus: Exemplar of the Ice Giant Class?



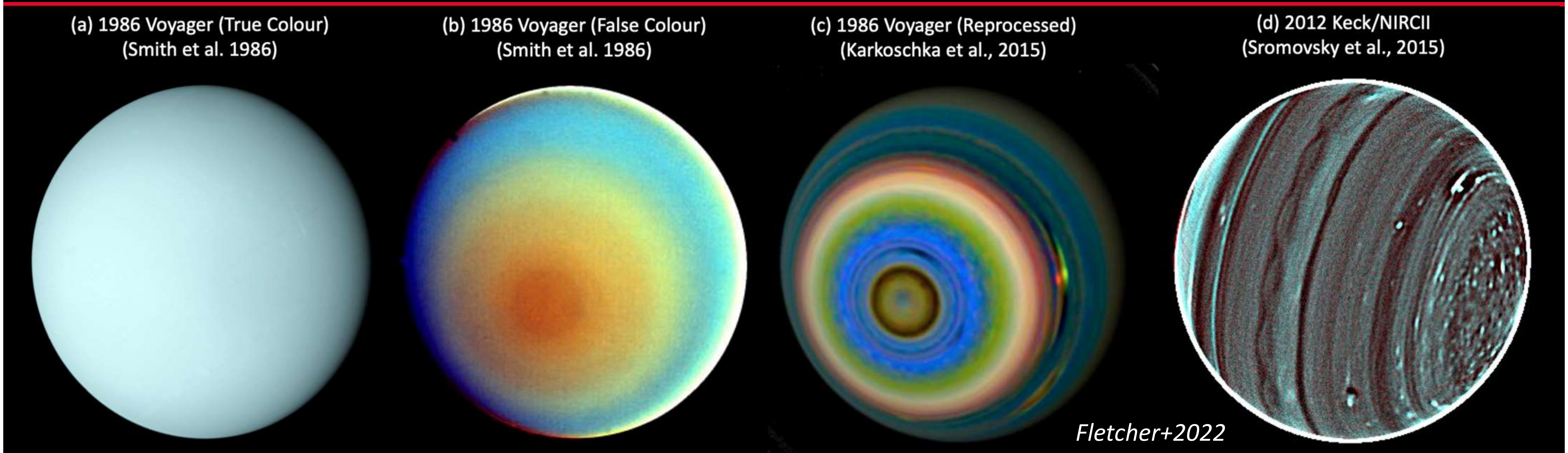
Flagship-class mission to explore all aspects of the Uranian system: the atmosphere, interior, magnetosphere, satellites, and rings

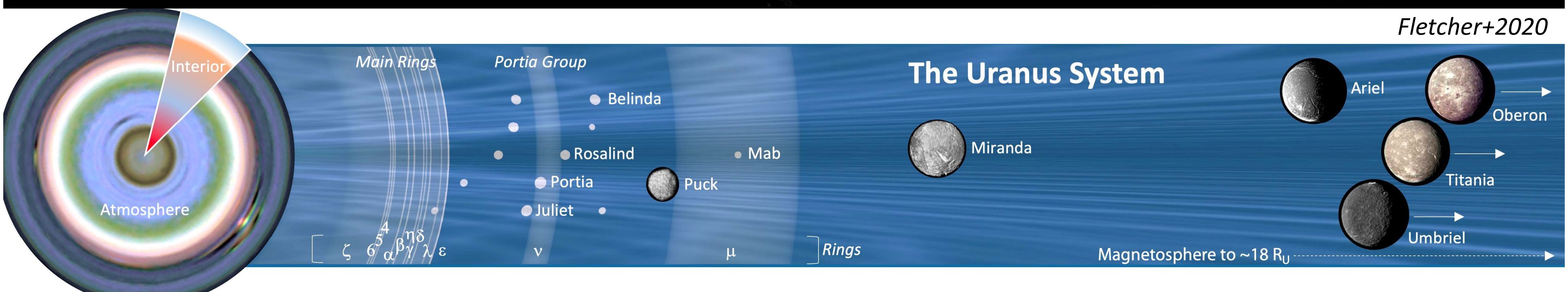


Leigh N. Fletcher

UNIVERSITY OF LEICESTER

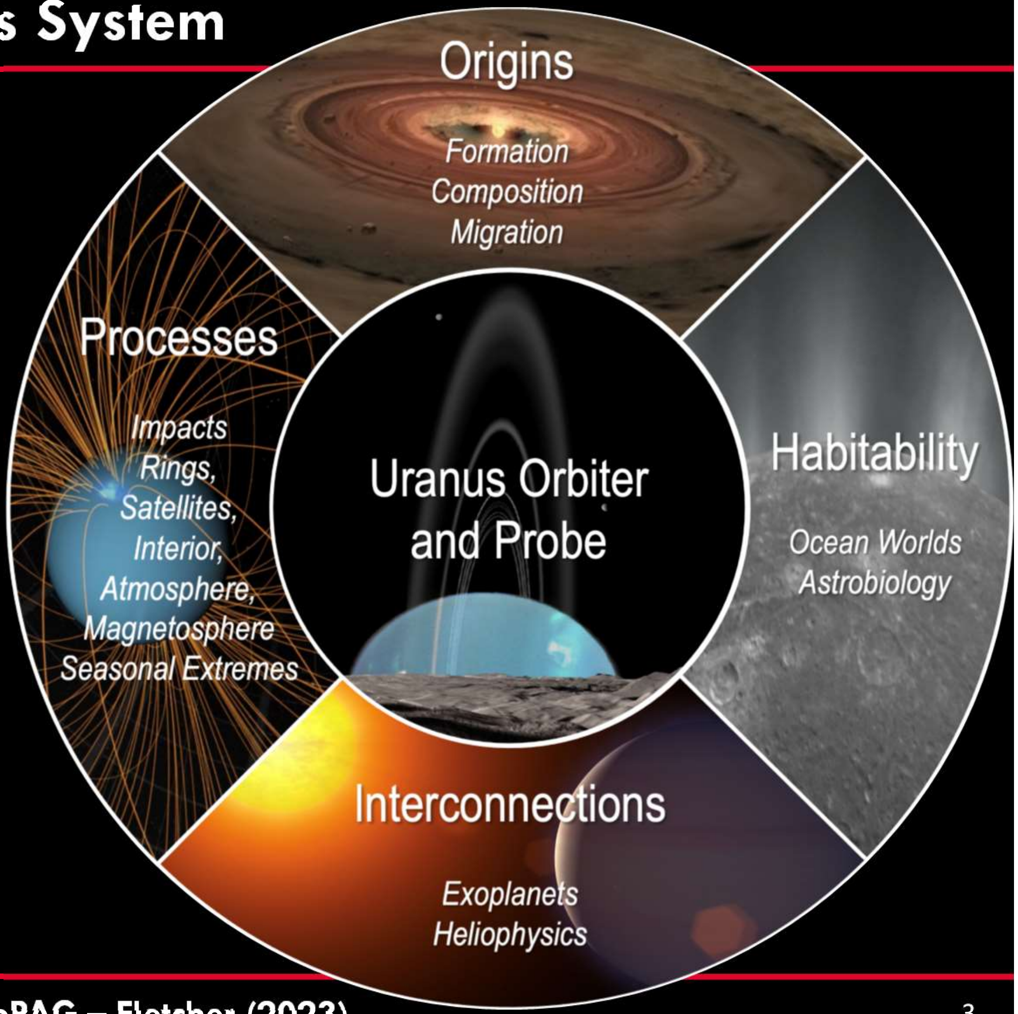
The Basics: Dispelling Myths





Motivation: Journey to the Uranus System

- **Next Step beyond Cassini:**
  - Inspiring the next generation of planetary explorers
- **Enables System-Level Science:**
  - Tracking the responses of atmosphere, magnetosphere, moons, and rings to extreme orientation.
  - Exploring ocean worlds in the Outer Solar System
- **Reveals origin and evolution**
  - Sampling the atmosphere for clues to planetary origins
- **Interdisciplinary:**
  - Heliophysics & exoplanets



Cross-Disciplinarity

- **Strong international interest**
  - Many reports, ESA/NASA studies, workshops since 2013
- **Strong NASA cross-divisional interest**
  - Recommended in both the Planetary and Solar and Space Physics 2013 Decadal Reports

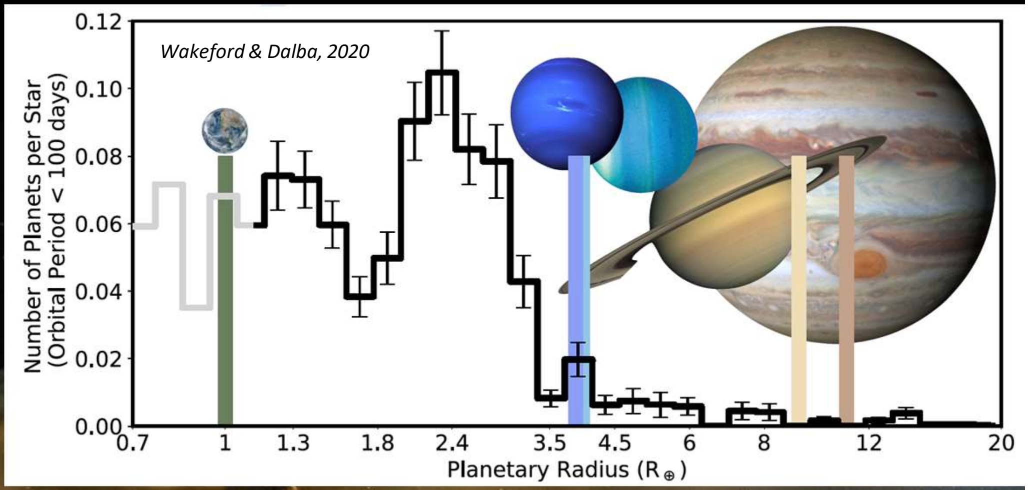
Ten Questions: Uranus as an Exoplanetary System

Uranus,
Feb 1[st]
1986

1	**What makes an Ice Giant?**
2	**What does the Inside of an Ice Giant look like?**
3	**Why did Uranus & Neptune diverge?**
4	**How does the Sun Influence Ice Giant Atmospheres?**
5	**How does Weather Work in H_2-Dominated Atmospheres?**
6	**Is Ice Giant Composition shaped by External Influx?**
7	**How does Uranus interact with the Solar Wind?**
8	**Can we explore complex magnetospheres remotely?**
9	**Do Ice Giant Systems Harbor Ocean Worlds?**
10	**Can Rings Reveal Gravitational Processes?**

Q1: What makes an Ice Giant?

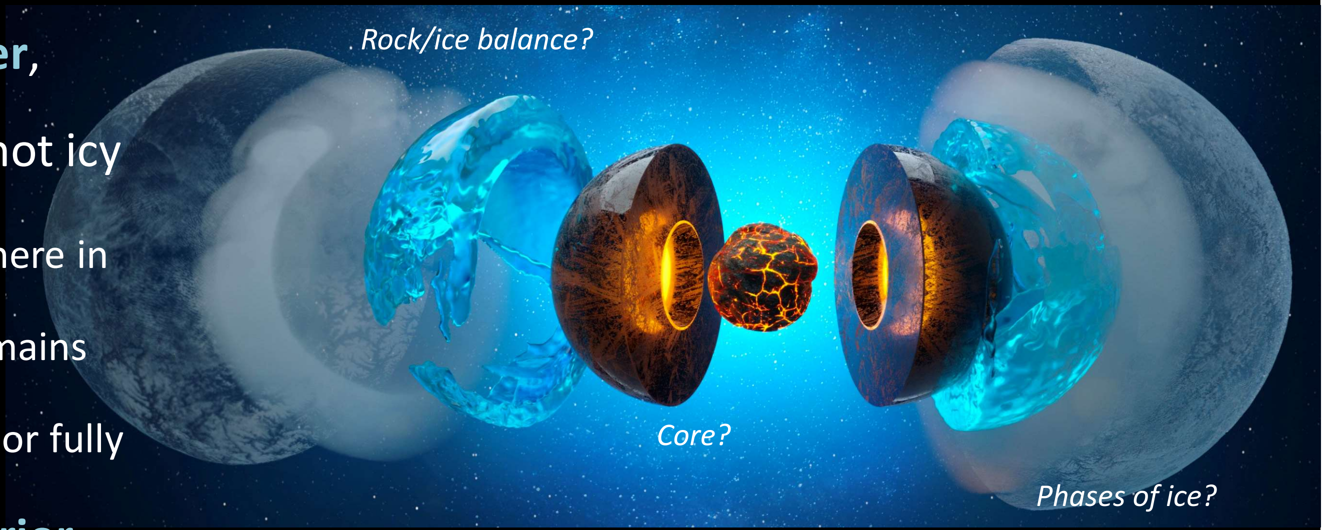
- **Does size matter?**
  - Intermediate-radii planets, between gas giants & terrestrial.
  - Does something arrest the growth of proto-Uranus & proto-Neptune?
- **Or is composition key?**
  - Water-rock mix; H_2-He atmosphere with 10-100x enrichment.
  - Gas phase or solid-phase accretion?
  - Reveals source reservoirs for worlds at Solar System's edge.



Are these common products of planetary formation?
What controls the cross-overs from Uranus, to sub-Neptune, to super-Earths?
How does accretion work in the outer Solar System?

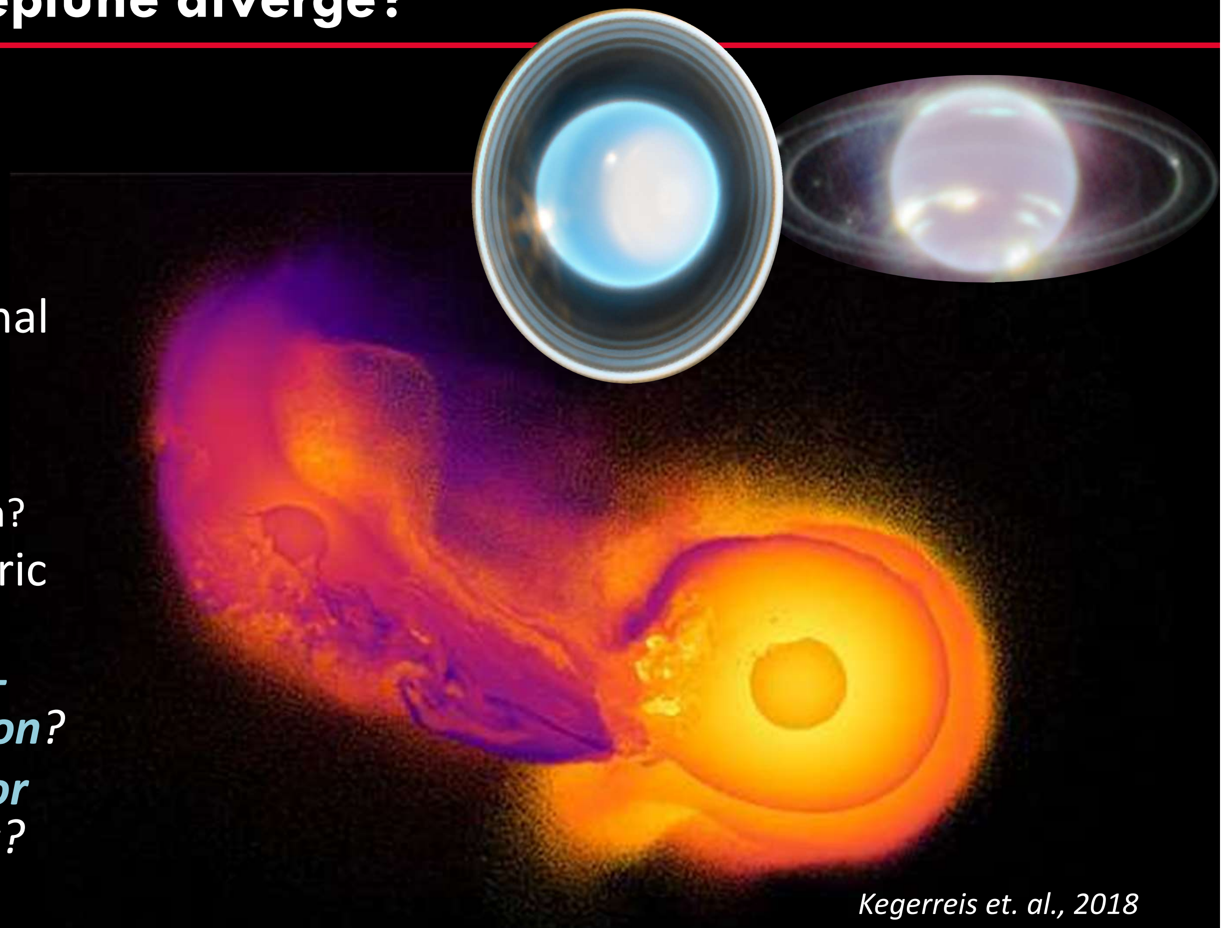
Q2: What does the Inside of an Ice Giant look like?

- H_2-rich Jupiter as a source of bias!
- **Exotic phases of matter**, from atmosphere, to superionic oceans, to hot icy mantles…
  - Phases not seen elsewhere in Solar System.
  - Density distribution remains unknown.
  - Are their diffuse cores, or fully differentiated?
- Consequences **for interior-atmosphere-magnetosphere** connections?



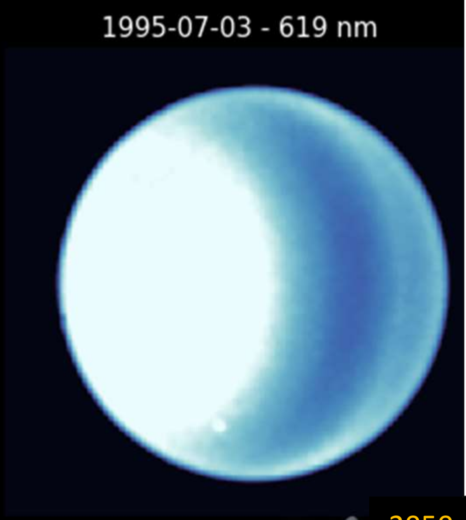
Q3: Why did Uranus & Neptune diverge?

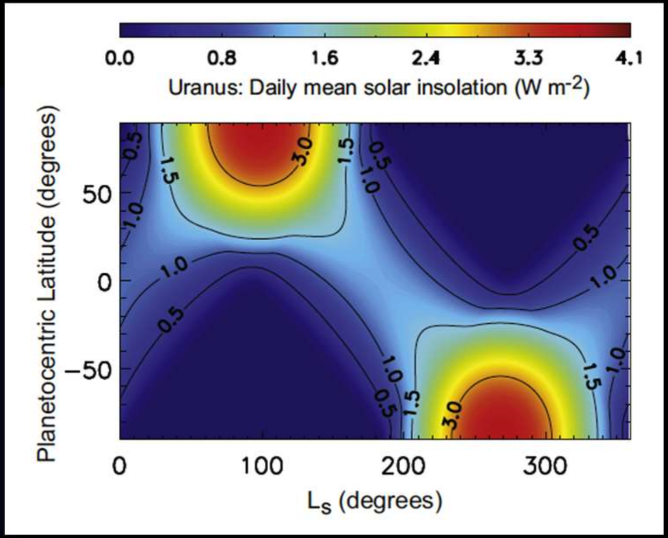
- Extreme **differences** (tilt, seasons, internal energy) despite **shared origins**.
- Uranus with negligible internal heat; Neptune with 2.5x
  - Layering and trapping, or primordial heat loss?
  - Consequence of early collision?
- Driver of episodic atmospheric phenomena & outbursts.
- *Which is the more likely **end-product of Ice Giant evolution**?*
- *What are the **implications for the cooling** of exo-Ice Giants?*

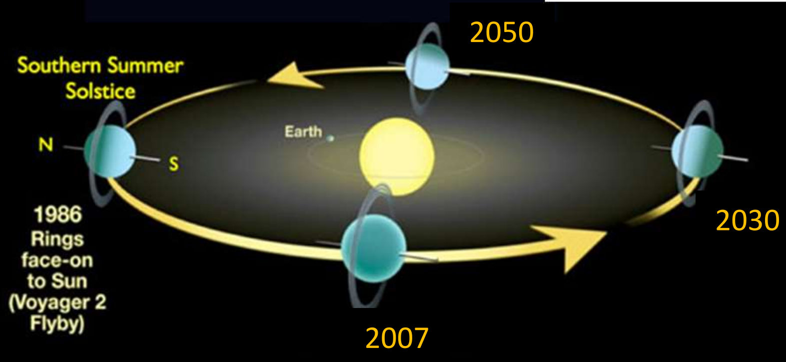


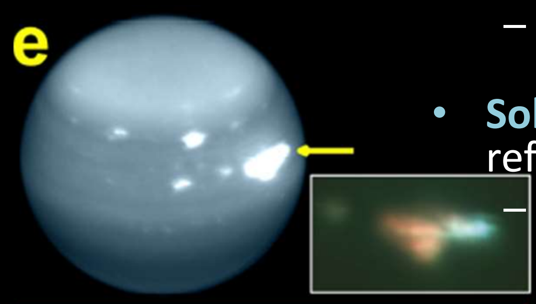
Kegerreis et. al., 2018

Q4: How does the Sun Influence Ice Giant Atmospheres?





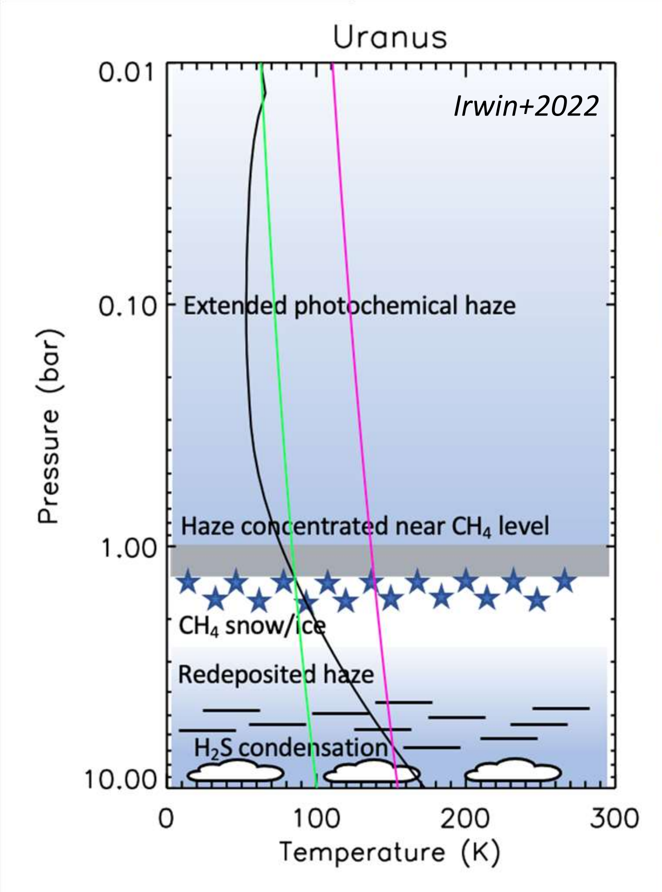


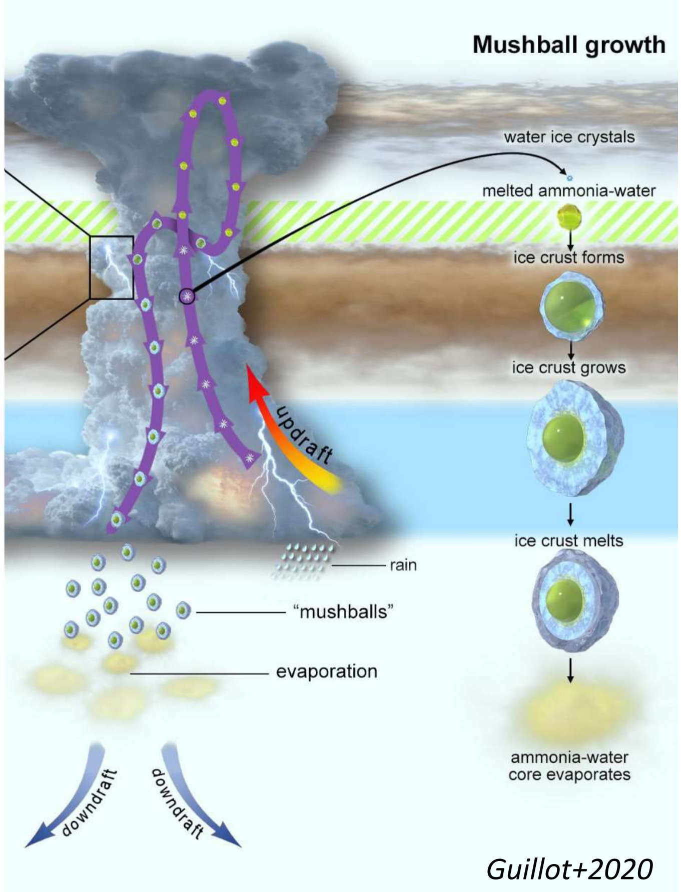


- Banded atmospheres due to rotation (Coriolis).
  - *Spatially unresolved exo-Ice Giants?*
- **Seasonal insolation** alters (i) stability and (ii) (photo)chemistry
  - Uranus episodic outbursts in certain seasons? [de Pater+2014]
  - Seasonal polar hood of aerosols.
  - Seasonal circulation of stratospheric hydrocarbons [Moses+2018].
  - *Alter light curves on daily/annual timescales?*
- **Solar cycle** influence on reflectivity and clouds:
  - UV irradiance, or GCRs seeding cloud microphysics? [Aplin+2016]

Q5: How does Weather Work in H_2-Dominated Atmospheres?

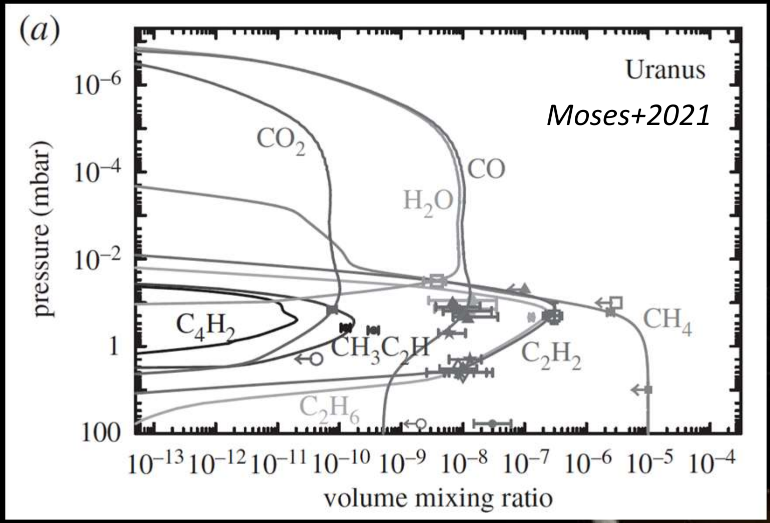
- Bottomless atmospheres – precipitation & "virga."
- Moist air heavier than "dry" H_2-He.
- **Chemical and phase transformations** govern the aerosols we see at cloud-tops.
- **Sensitive to:**
  - chemical abundance (e.g., CH_4),
  - temperature profile,
  - availability of cloud nuclei,
  - Seasonal insolation
  - Local dynamics (storms)
  - Global circulation (bands).

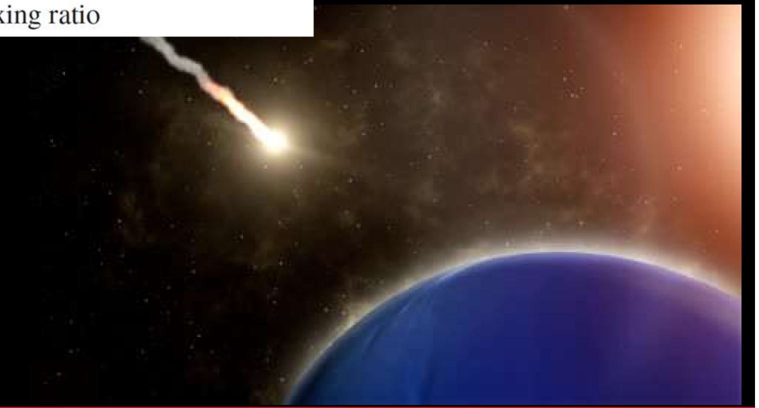




Q6: Is Ice Giant Composition shaped by External Influx?

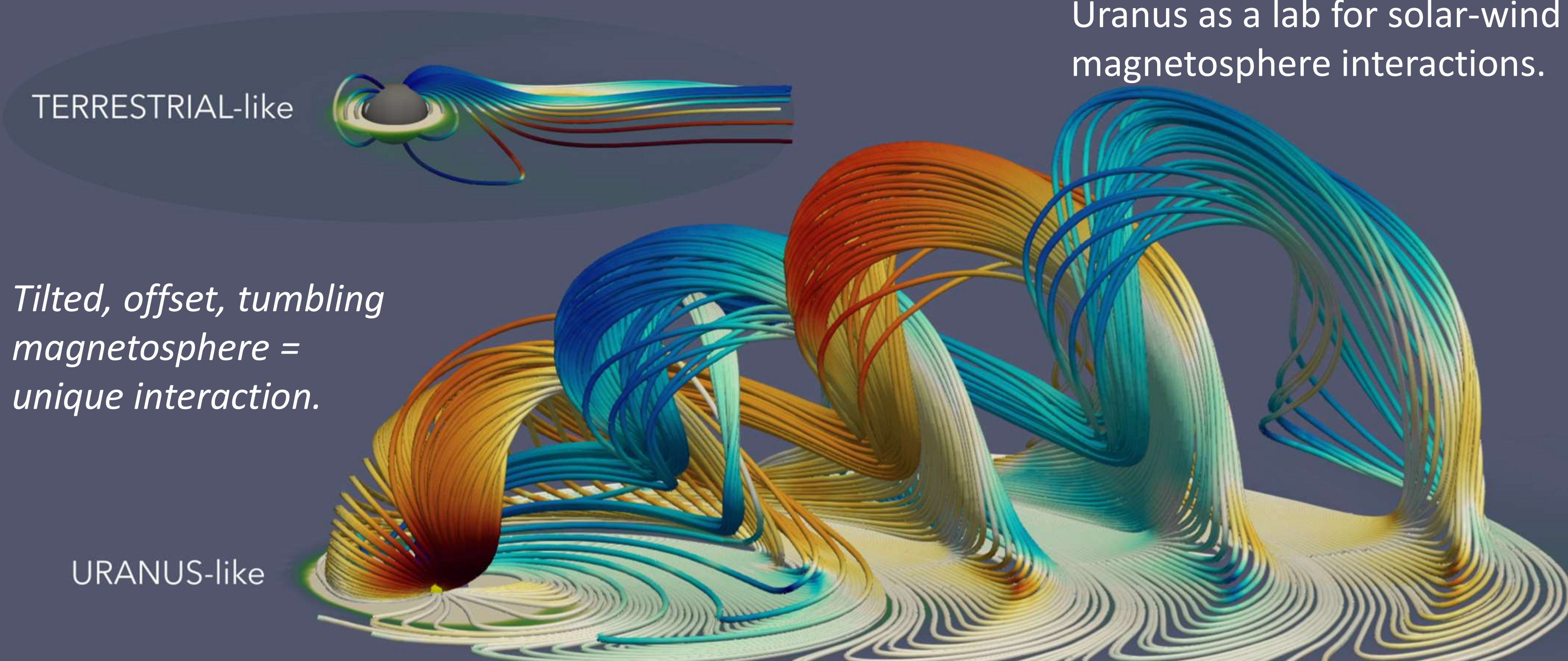
- Upper atmospheric chemicals from external sources:
  - Comets, interplanetary dust, ring rain, satellite material.
  - Often O-rich (H_2O, CO, CO_2)
- Some chemicals last decades (HCN on Jupiter from SL9 comet).
- Could this **influx dominate composition**, rather than being primordial?
- Does atmosphere **represent bulk composition**?





Q7: How does Uranus interact with the Solar Wind?

Uranus as a lab for solar-wind magnetosphere interactions.

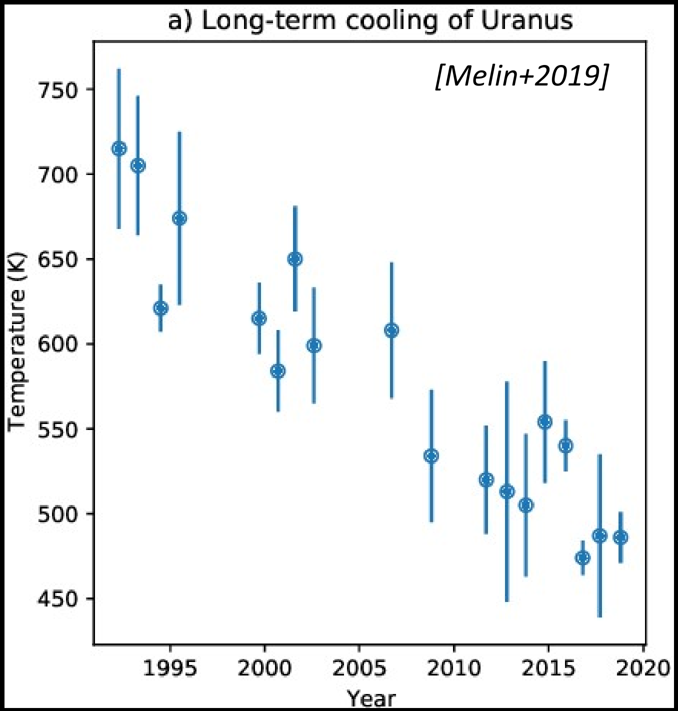


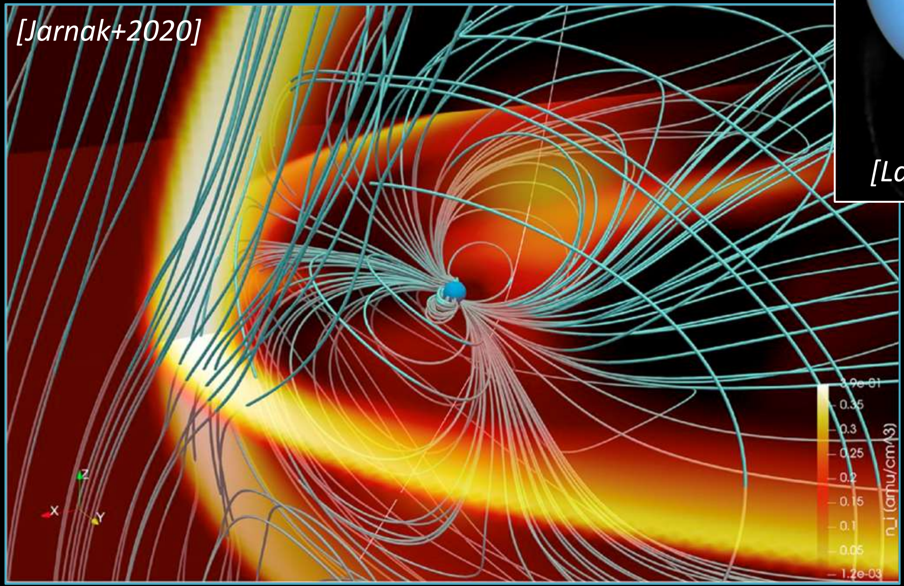
Tilted, offset, tumbling magnetosphere = unique interaction.

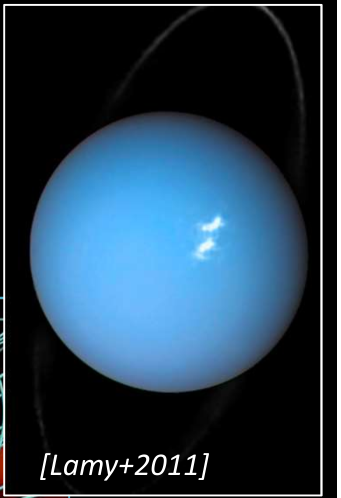
What can this say about magnetic field generation in exo-Ice Giants?

Q8: Can we explore complex magnetospheres remotely?

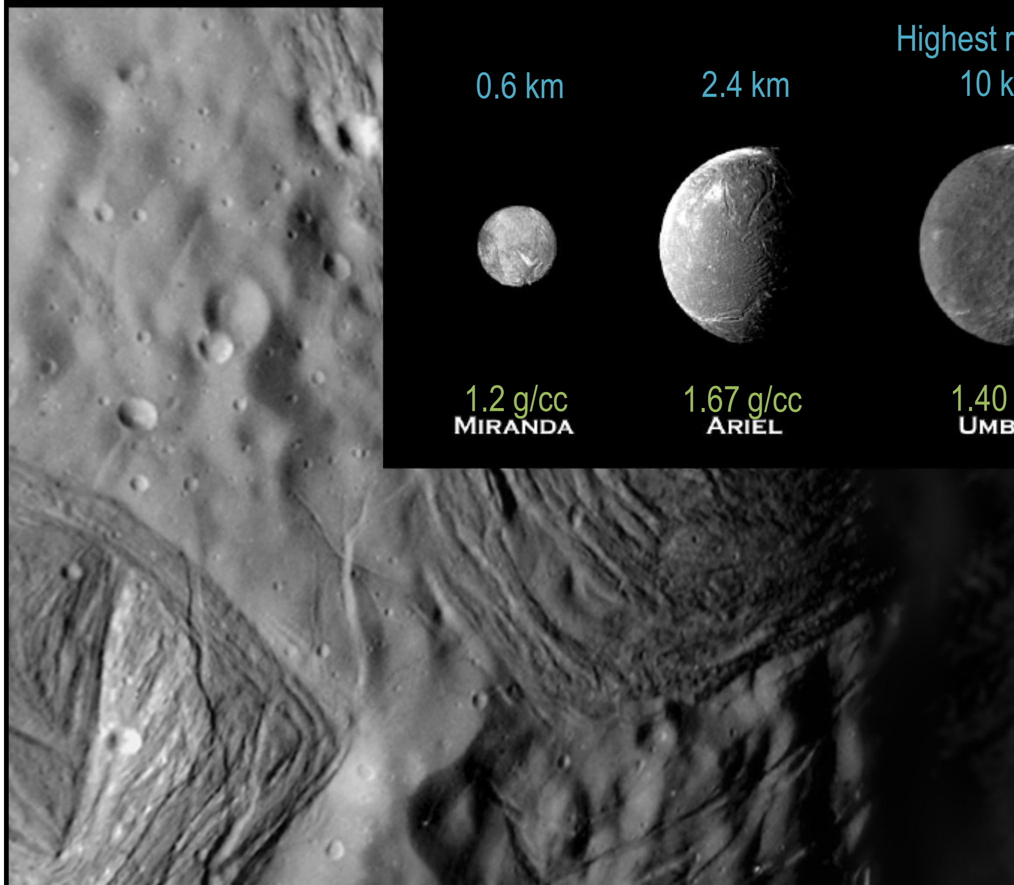
- UV and IR emissions from **aurora** reveal multi-polar magnetic field.
- X-ray emissions detectable.
- *Could these be seen influencing phase curves/emissions from exo-Ice Giants?*







Q9: Do (Exo)Ice Giant Systems Harbor Ocean Worlds?

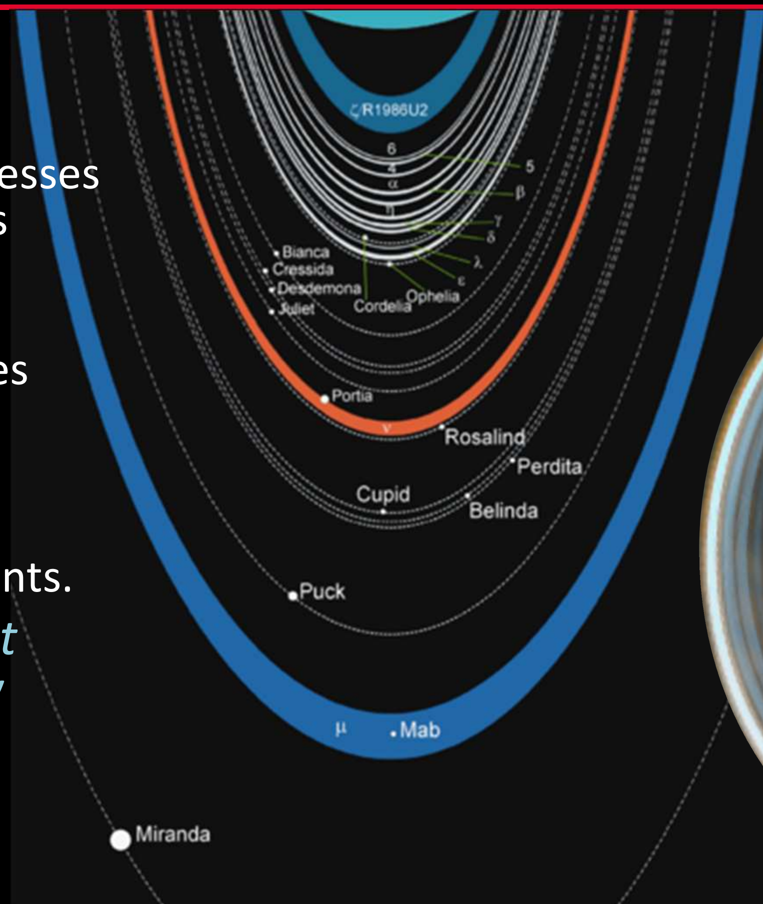


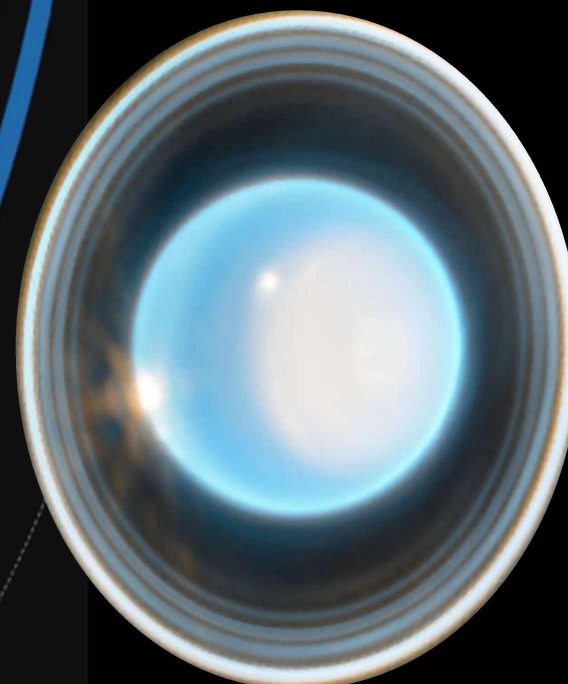
NASA / JPL / Ted Stryk

- Last unexplored regular satellite system.
- Potential ocean worlds, past resurfacing – subsurface oceans?
- Tectonics and cryovolcanism – active plumes?
- Dark surfaces (organics?) and CO_2 frosts.
- Distant oceans, ancient or modern, have **implications for habitability of exomoons**.

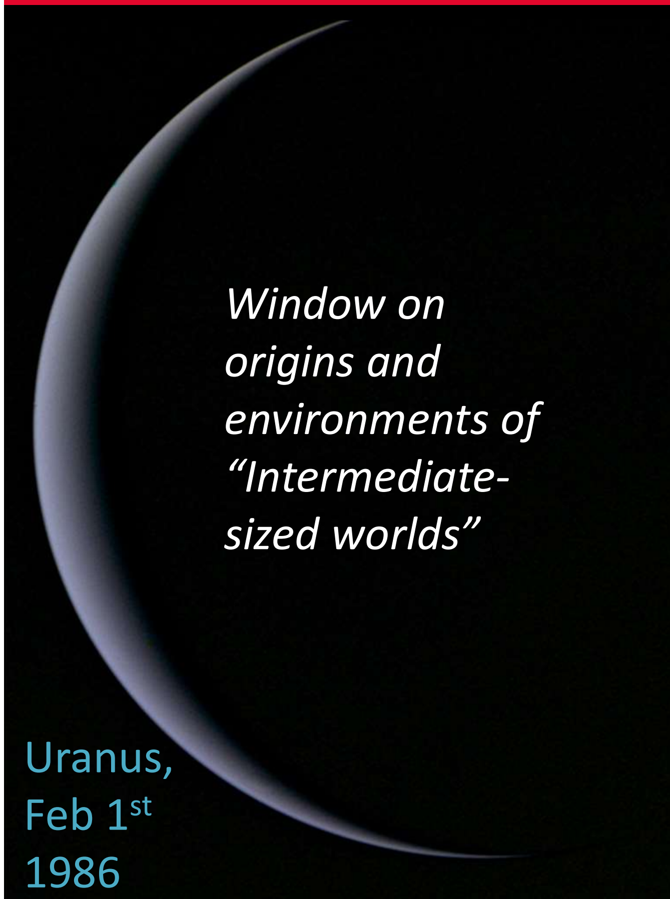
Q10: Can Rings Reveal Gravitational Processes?

- **Planetary rings probe:**
  - Material exchange processes in circumplanetary discs (destruction and reformation).
  - Interplay and resonances with satellites.
  - Seismological tools for planetary interiors.
  - Detector for impact events.
- *What could exo-Ice Giant rings or circumplanetary discs tell us?*





Ten Questions: Uranus as an Exoplanetary System



Window on origins and environments of "Intermediate-sized worlds"

Uranus, Feb 1st 1986

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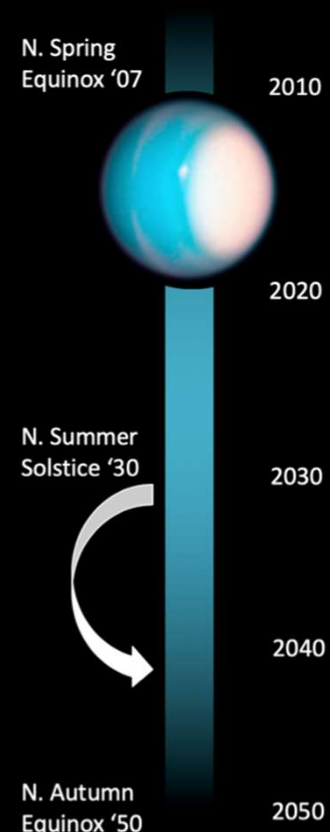
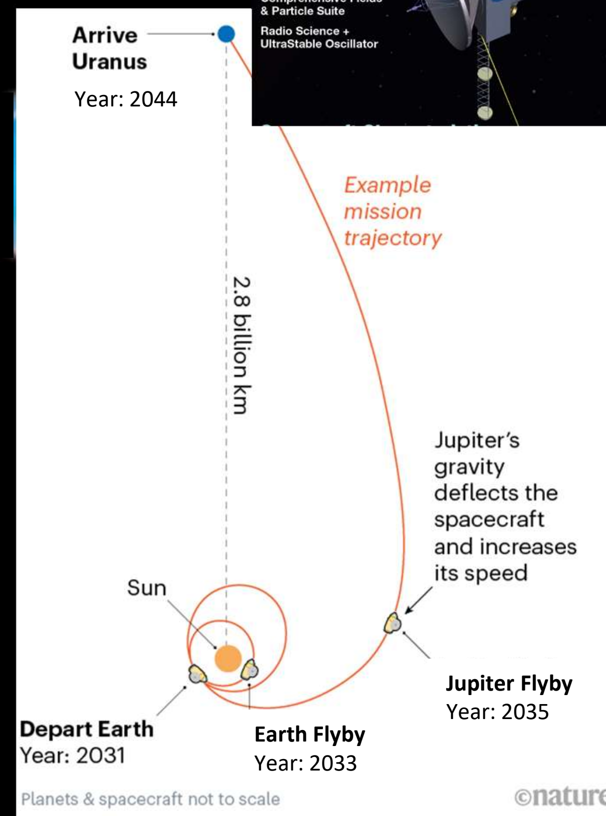
Uranus Orbiter and Probe (UOP)

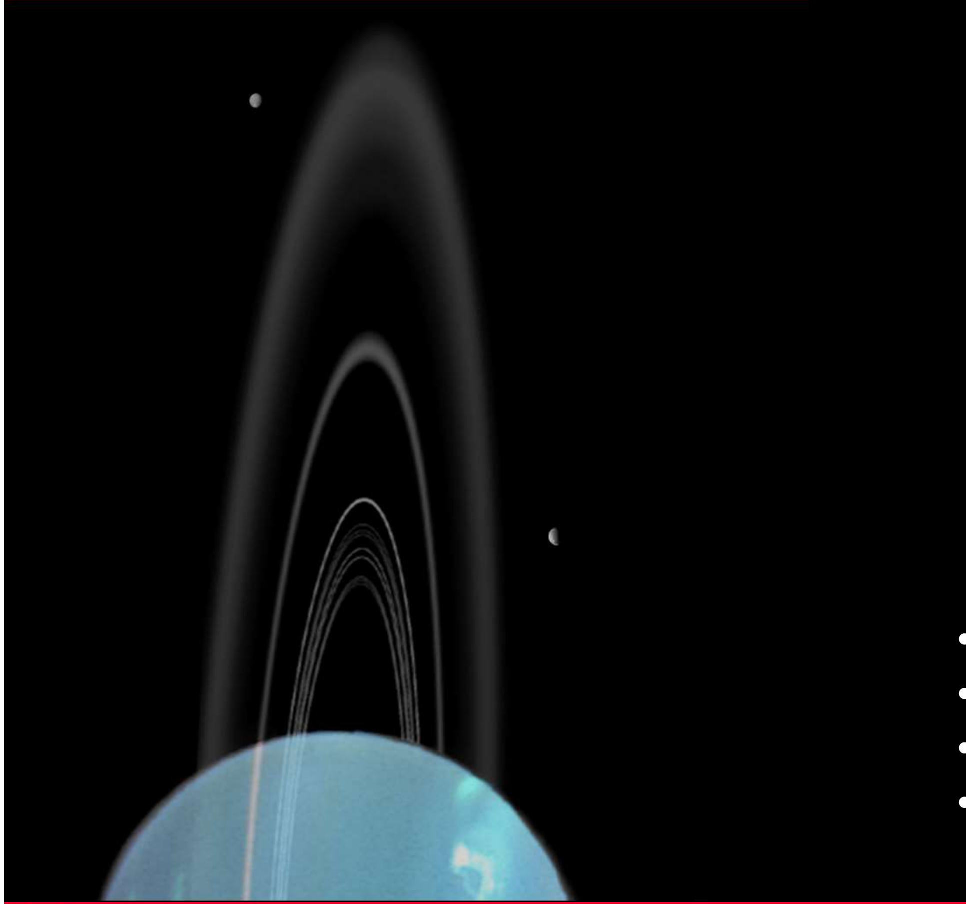
- ***Uranus Orbiter and Probe as top flagship priority***
  - End to end viable concept with no new technologies.
- **Flexible launches** from 2031 on Falcon 9 Heavy
  - Optimal launch in 2031-2032 with Jupiter gravity assist to shorten cruise to 12 to 13 yrs
  - Flexible launch opportunities through 2038 with increased ~15 yr cruise
- **Comprehensive Multi-Year System Tour:**
  - Baseline of 4 years; polar & low-inclination; as close as 1.1 RU (gravity & mag);
  - Flybys of all major moons.
- **In Situ Probe:**
  - Direct measurements of composition.
  - Depth to 5 bars (10 bars preferred)

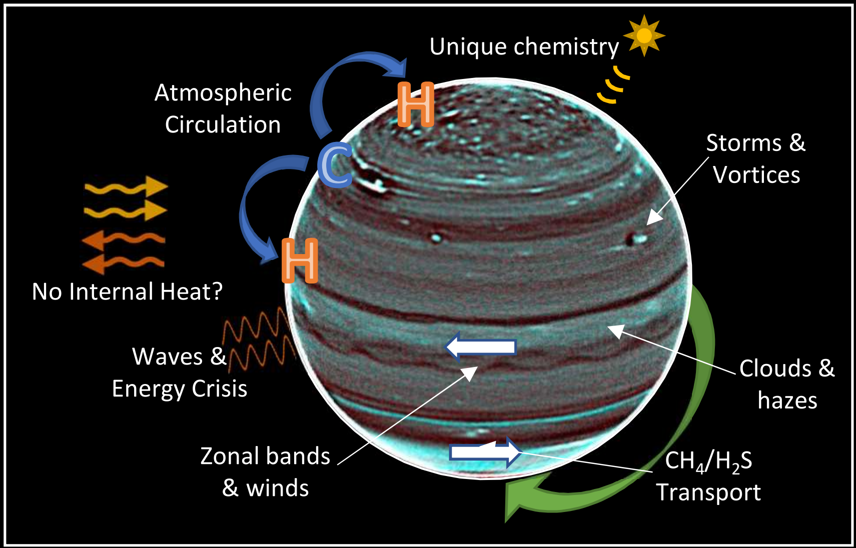




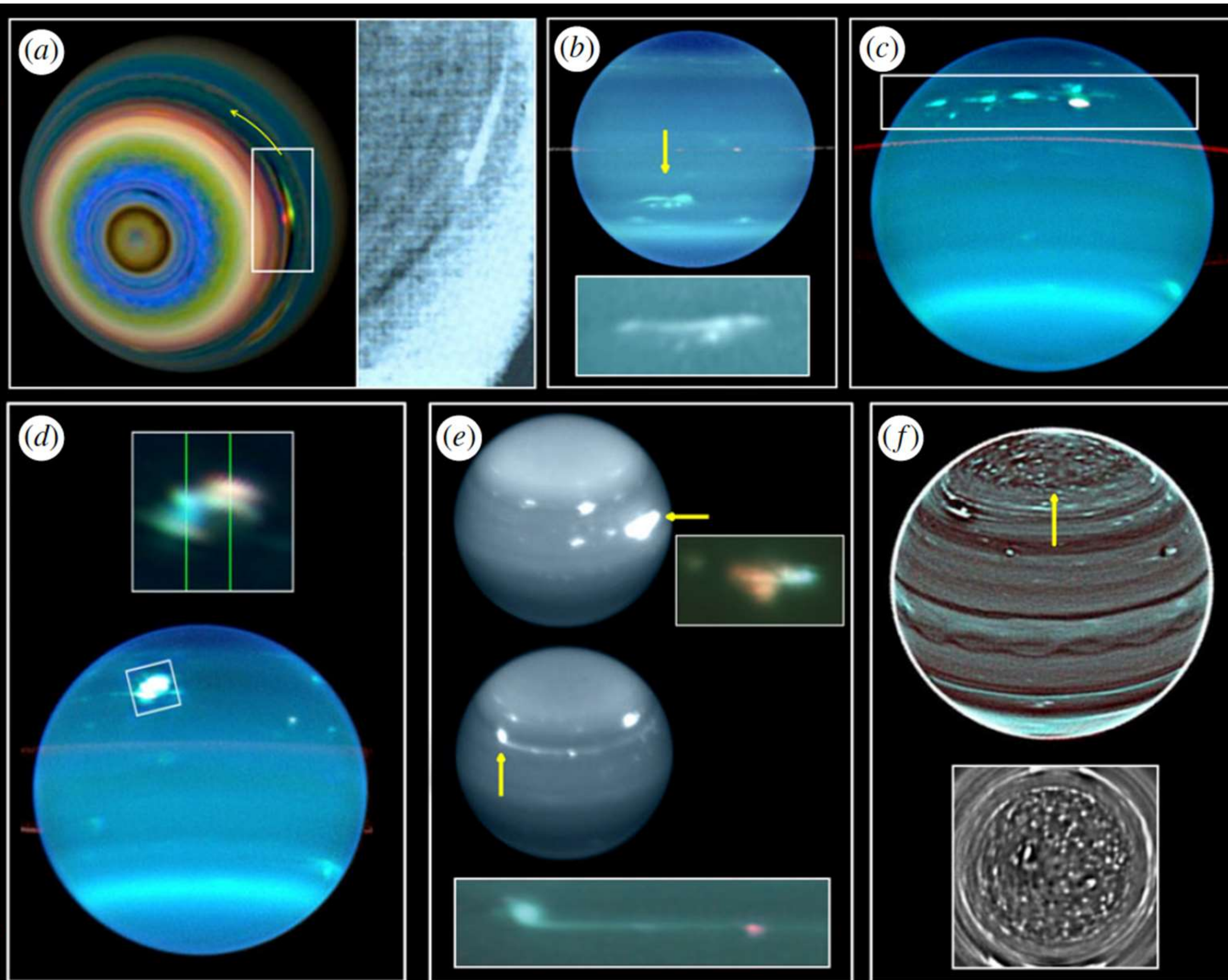
Supplemental Slides

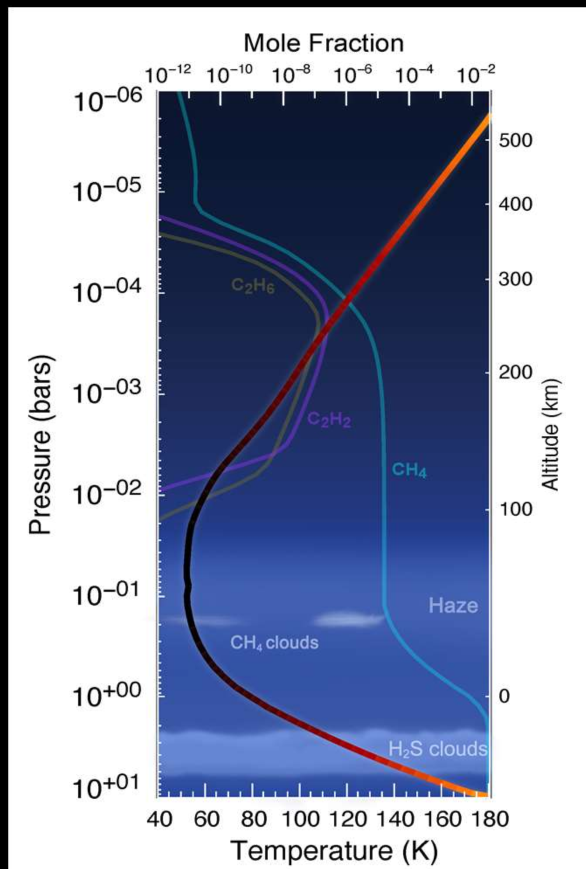
Theme II: Unique Atmosphere

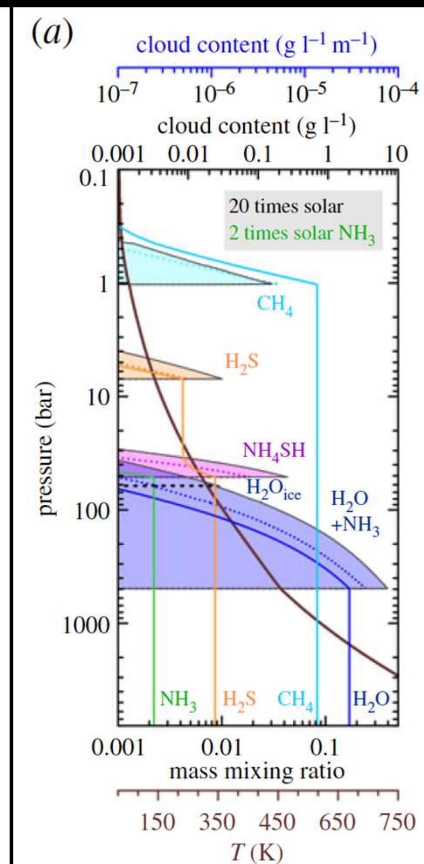




- Negligible internal heat – layered convection?
- Active storms, waves.
- Coldest troposphere/stratosphere.
- Seasonal chemistry & weak mixing.


(a)
(b)
(c)
(d)
(e)
(f)


Mole Fraction
10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2}
Pressure (bars)
10^{-06}
10^{-05}
10^{-04}
10^{-03}
10^{-02}
10^{-01}
10^{+00}
10^{+01}
C_2H_6
C_2H_2
CH_4
Haze
CH_4 clouds
H_2S clouds
Altitude (km)
500
400
300
200
100
0
40 60 80 100 120 140 160 180
Temperature (K)


(a)
cloud content (g l^{-1} m^{-1})
10^{-7} 10^{-6} 10^{-5} 10^{-4}
cloud content (g l^{-1})
0.001 0.01 0.1 1 10
pressure (bar)
0.1
1
10
100
1000
20 times solar
2 times solar NH_3
CH_4
H_2S
NH_4SH
H_2O_{ice}
H_2O $+NH_3$
NH_3 H_2S CH_4 H_2O
0.001 0.01 0.1
mass mixing ratio
150 350 450 650 750
T (K)

Conceptual Payload: Orbiter and Probe

Instrument Suite

Orbiter Instrument Suite

Magnetometer

Narrow Angle Camera

Wide Angle Camera

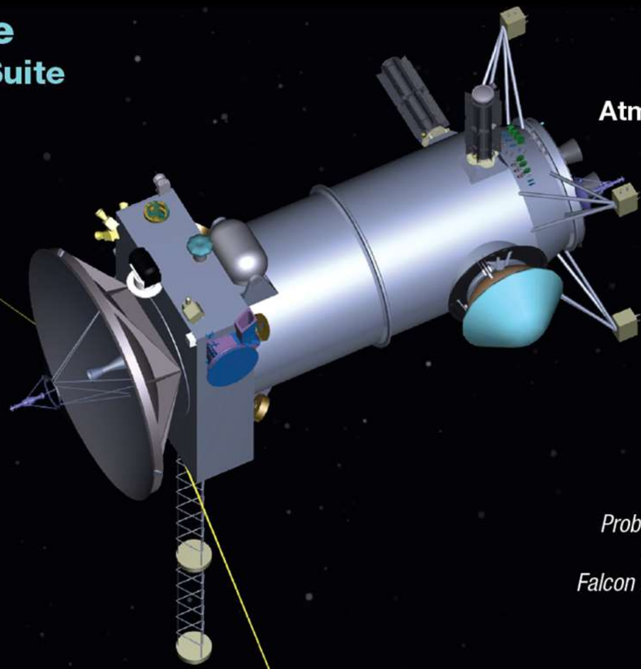
Thermal IR Camera

Visible-Near IR Imaging

Spectrometer
Comprehensive Fields
& Particle Suite

Radio Science +
UltraStable Oscillator

+Microwave, UV, Mid-IR Spectrometer; ENA; Doppler Imager



Probe Instrument Suite

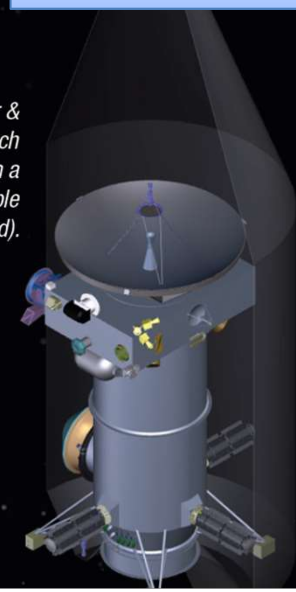
Atmospheric Structure Instrument

Mass Spectrometer

UltraStable Oscillator

Ortho-Para Hydrogen Sensor

+Nephelometer; Net Flux Radiometer; Helium Detector



Uranus Orbiter & Probe shown in launch configuration on a Falcon Heavy Expendable (baselined).

Spacecraft Characteristics

- Total flight system mass (including probe): 2756 kg (dry), 7235 kg (wet)
- 30% dry mass and power margins
- 3-axis stabilized, except for passive spin during cruise hibernation
- Uses 3 Next-Gen Mod 1 Radioisotope Thermal Generators
- Planned mission data volume return: 51.9 GB

Baseline and Threshold Mission Requirements

Category	Baseline Requirement	Threshold Requirement	Goal
Orbital Tour	4 Years	2 Years	Adequate sampling of magnetosphere, satellite flybys, rings, atmospheric observations, satellite gravity
	Polar phase, followed by low inclination phase	Polar only	Obtain Uranus gravitational moments
Satellite Flybys	3 targeted, 2 non-targeted, flybys of each of the major moons @ <10 km/s	2 targeted,1 non-targeted, flybys of each of the major moons @ <10 km/s	80% surface coverage (incl. w/ Uranus-shine)
	Targeted and non-targeted flybys of small moons	Non-targeted flybys only	Inventory and characterize small moons
	Polar and low inclination passes	Polar only	Gravitational moments and coverage
Uranus Orbits	Close (1.1 R_u) polar & low inclination dayside passes	Polar only	Gravitational moments and coverage
Probe Depth Range	From 0.1 to 5 bars (10 bars preferred, but not a driver)	From 0.1 to > 1 bar	Reach depths past certain condensation levels
Payload	Full Complement	Remove WAC from orbiter and ortho-para sensor from probe	

Orbiter Configuration [APL Study, 2022]

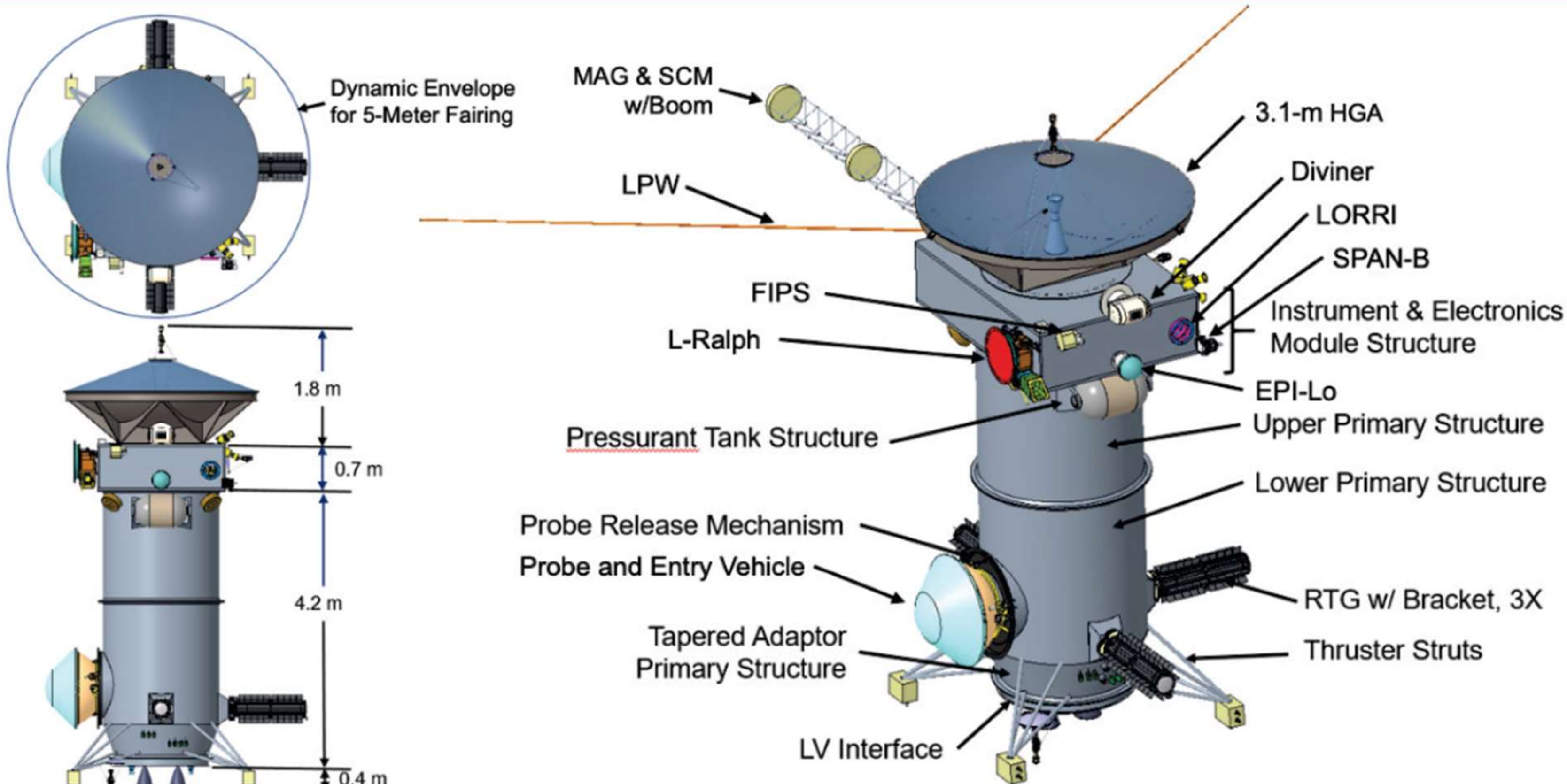


***Exhibit 3-17**. Orbiter Layout with Dimensions and Instrument Configuration.*

UOP Cost

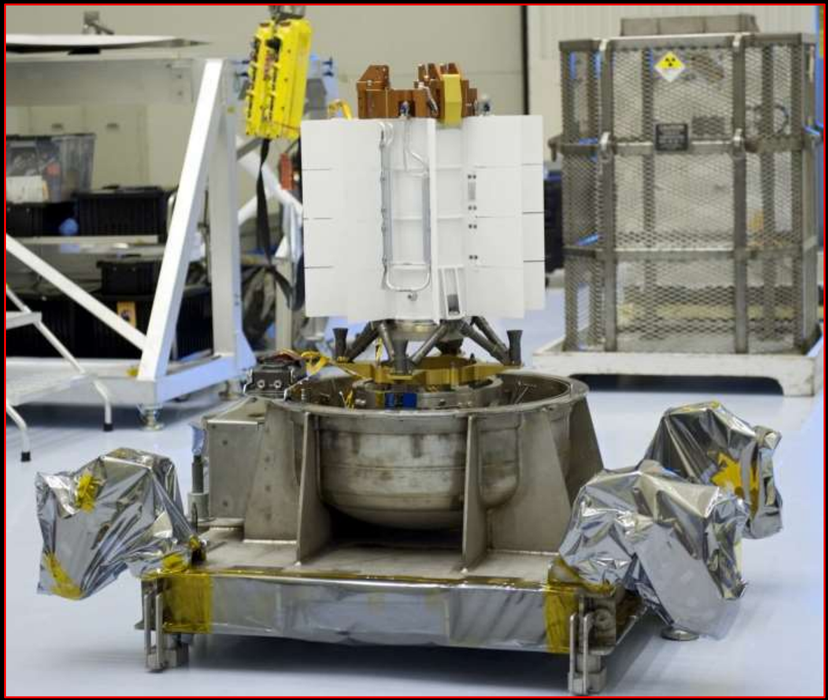
WBS		Uranus Orbiter & Probe Cost Estimate: Cost in FY25$K Ph A-D	Ph E-F	Total	Notes
	Phase A	$ 7,628	$ -	$ 7,628	Assumption based on previous studies
1	PM	$ 162,077	$ -	$ 162,077	A-D: Wrap factor based recent NFs and APL missions E-F: Bookkept with WBS 7
2	SE				
3	MA				
4	Science	$ 27,192	$ 223,668	$ 250,860	Average $13.3M per year during Phase E
5	Payload	$ 180,247	$ -	$ 180,247	Hardware estimated via parametric models (NICM, SEER Space)
6	SC	$ 724,234	$ -	$ 724,234	Estimated via parametric models
7	MOps	$ 41,121	$ 299,053	$ 340,174	Ph E: DSN $21.3M, Average Ph E MOps based on APL historical costs
8	LV	$ 236,000	$ -	$ 236,000	Falcon Heavy Expendable ($210M) + $26M NEPA
9	Ground	$ 18,573	$ 19,313	$ 37,886	BOE
10	I&T	$ 114,869	$ -	$ 114,869	Based on APL historical I&T %, includes testbeds
	Reserves	$ 634,157	$ 135,508	$ 769,665	Per Decadal guidelines: 50% A-D, 25% E-F. LV excluded
	Total	$ 2,146,097	$ 677,542	$ 2,823,640	
	Total w/o LV	$ 1,910,097	$ 677,542	$ 2,587,640	

- Cost estimates are reported in Fiscal Year 2025 (FY25) dollars
- The NASA New Start inflation index was used to adjust to FY25 dollars
- Major cost drivers: spacecraft complexity, long mission duration, RTGs (3)

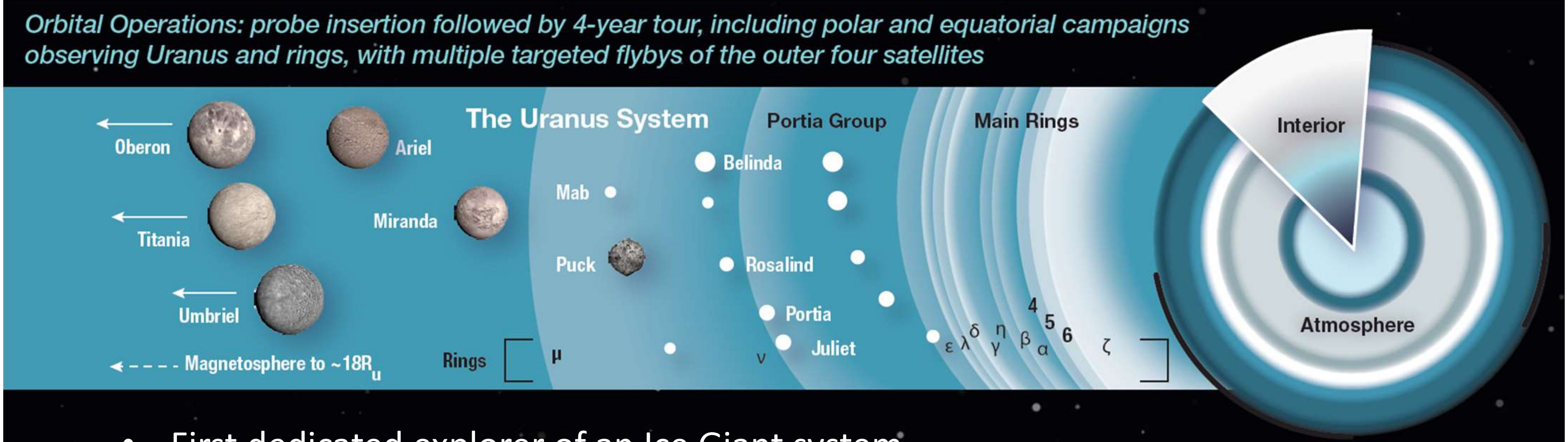
$3M in Presidential budget for FY25
Compare to MSR wanting wanting an extra $500M in FY24 and 25

Plutonium

- NASA is working with the Department of Energy to ensure it has sufficient plutonium-238 for missions projected to launch through the end of the decade.
  - Single Multi-Mission RTG (MMRTG) and up to 24 RHUs for the Dragonfly mission to Saturn's moon Titan in 2027.
  - 40 RHUs for Rosalind Franklin Mars rover, slated for launch in 2028.
  - Two MMRTGs and 20 RHUs for potential use on a New Frontiers mission in the early 2030s.
- UOP needs 3 units of a new Next-Gen RTG design under development by NASA, which each use twice the plutonium of an MMRTG. 1st Mod-1 PDR in 2024.
  - Constant-rate Pu production not enough, mid-to-late 2030s more reasonable.

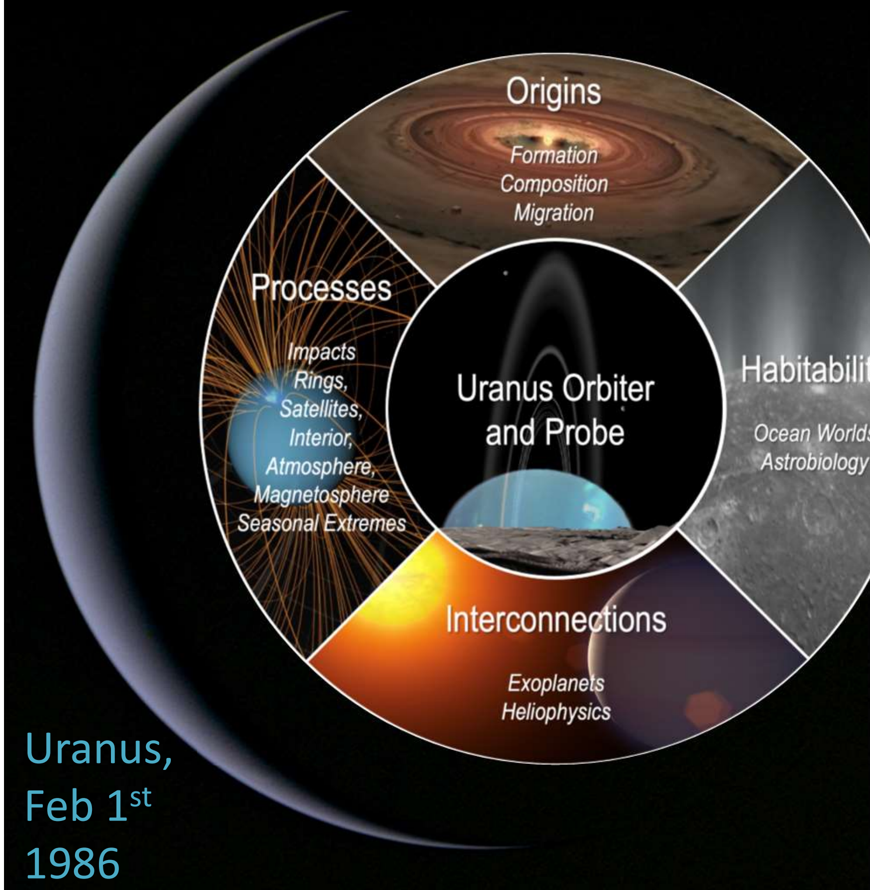


System-Level Explorer



- First dedicated explorer of an Ice Giant system.
- Provides a balanced programme within decadal survey, alongside target-specific (Mars, Europa, Titan) missions.
- International participation supported by ESA Voyage 2050.
- Robust science & architecture, hope to begin in 2023-24.

Summary: Onwards to Uranus

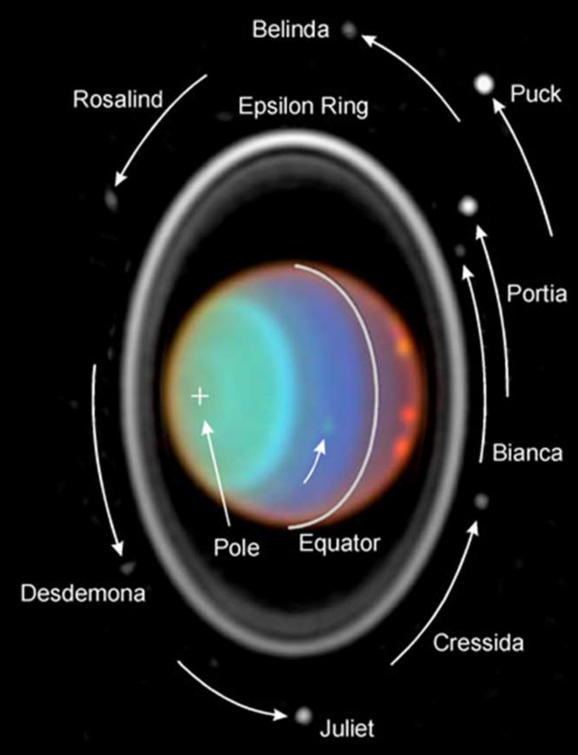


Uranus,
Feb 1st
1986

- Uranus mission top priority flagship.
  - Optimal launches: 2031-32.
  - *No time to lose!*
- System-level science.
- Recommendations under consideration by NASA; programme requires budget lift.
- International participation supported by ESA Voyage 2050 (CMIN22 v. important!).
- ***Can we make this a reality?***

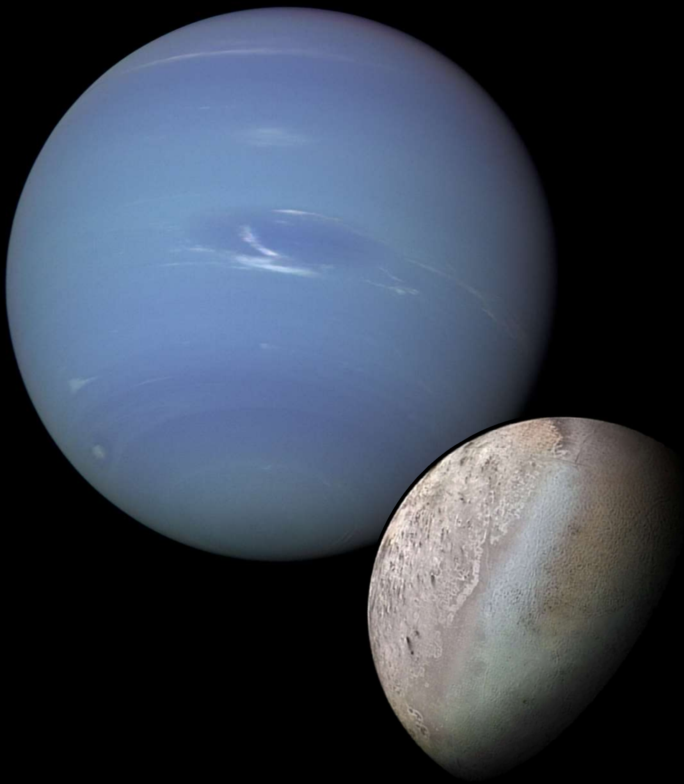
Concept of Operations

- Orbital period during tour ~34 days
  - Start in polar orbit, use Titania to pump down to equatorial
- General data strategy
  - Tour - Ka-band science downlink, one 8-hr pass /day
  - Possible additional passes for critical events and nav purposes
  - Compression assumption – average, assuming 2:1
- Onboard Storage of all science data and housekeeping
  - Some instruments also have their own storage
- Solar conjunction not a problem during any of the critical events
- Considered 4 orbit types, all have sufficient downlink to achieve science goals
  - Uranus/Rings Remote sensing focused
  - F&P and Mag focused
  - Satellite flyby w/ remote sensing focused
  - Multiple satellite flyby focused (equatorial phase)



Why Not Neptune?

- Equally compelling, both critical to understanding Ice Giant systems.
  - Triton: captured KBO with active processes & atmosphere.
- **Uranus:**
  - End-to-end viable mission concept on currently available launch vehicle
  - Flexible launch dates starting in 2031 through 2038+
  - No new technologies required; Low-Medium risk
- **Neptune:**
  - 2029 Jupiter gravity assist not viable; trajectory/fuel/power not adequately demonstrated; higher risk.
  - New gravity-assist window in 2040s.



Technical readiness differs substantially

Uranus Orbiter and Probe

– End-to-end viable mission concept on currently available launch vehicle
– Flexible launch dates starting in 2031 through 2038+
– No new technologies required
– Low-Medium risk (only large mission TRACEd to receive this)

Neptune Odyssey

- Lacks demonstrated trajectory and launch date within the decade on currently available launch vehicle
- Uncertainties in power requirements and possible need for solar electric propulsion if neither SLS nor Jupiter gravity assist are available
- Accommodation on current launch vehicles unclear (faring size)

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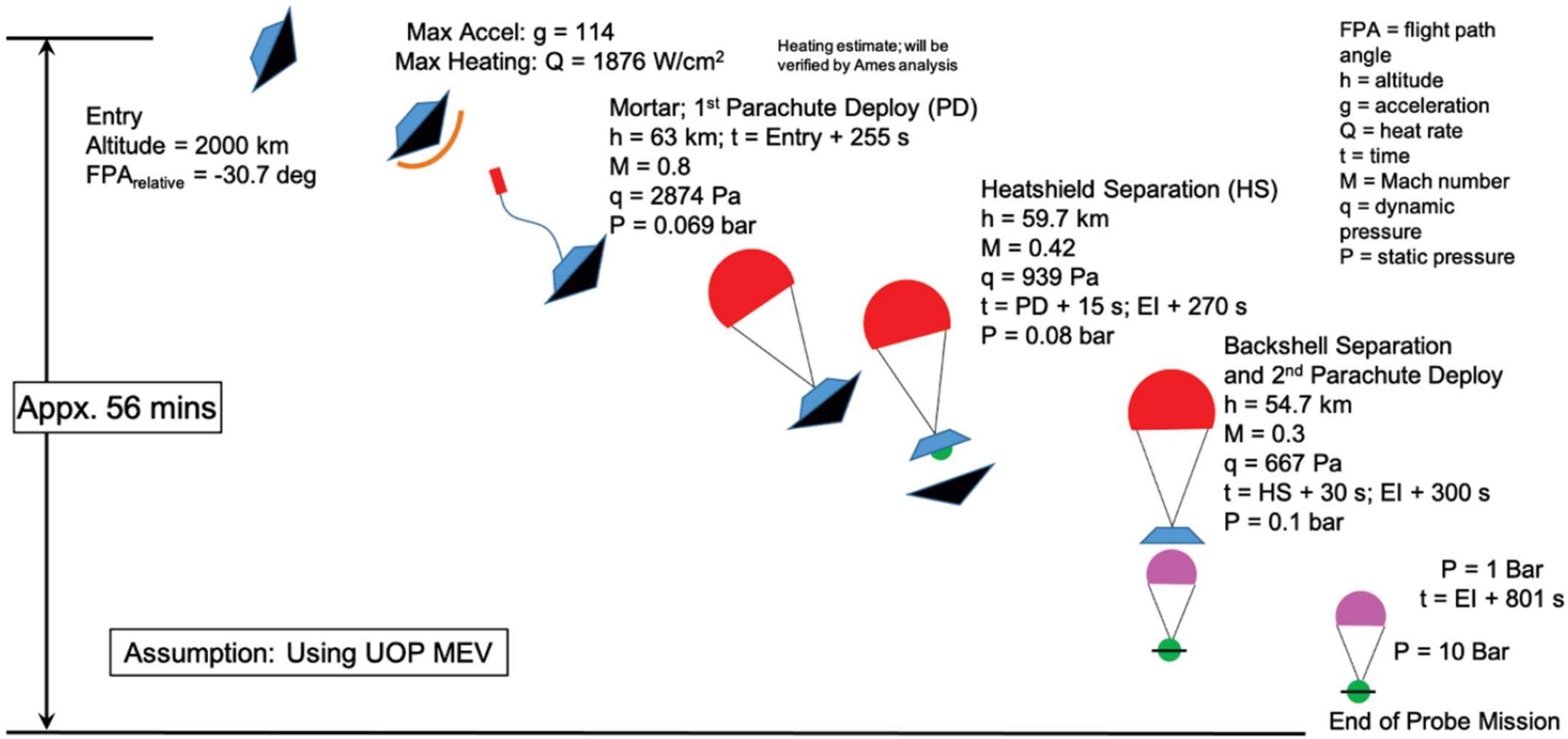

Exhibit 3-34. *Probe Trajectory Concept of Operations.*