URANUS FLAGSHIP MISSION CONSTRAINTS

Marzia Parisi

Jet Propulsion Laboratory

California Institute Of Technology

DETERMINING THE INTERIOR STRUCTURE OF URANUS

KISS WORKSHOP

SEPTEMBER 11TH 2023

OUTLINE

- Past exploration of Uranus: Voyager 2
- The life cycle of a space mission
- Principles of mission design
  - Payload trade-offs
  - Trajectory trade-offs
- Uranus Orbiter and Probe (UOP): examples of trade-offs from gravity science
- The Uranus environment: risk mitigation strategies
- Probe science and release constraints
- UOP current recommendations and take-away message

Image credit: NASA/JPL

PAST EXPLORATION OF URANUS: VOYAGER 2

- Launch: August 20, 1977
- Flybys of the four giant planets and some of the moons
- Only spacecraft to ever visit Uranus (1986) and Neptune (1989)
- November 5, 2018 – Voyager 2 reaches interstellar space and joins its twin spacecraft (which had been there since 2012)
- From Stone (1987): ”…If there are no catastrophic failures, they should continue returning data well into the next century from distances beyond 100 AU…”
- … currently 160 AU away and counting

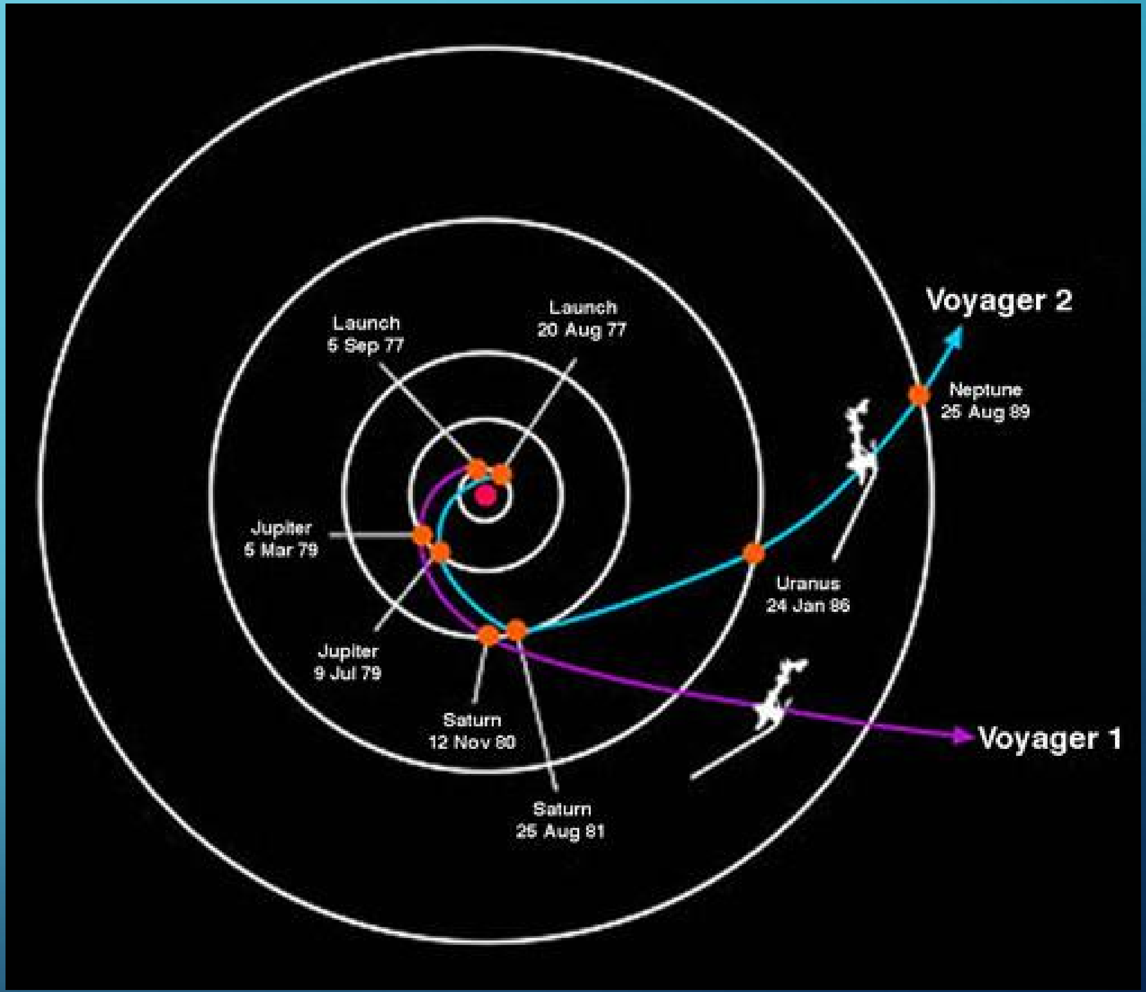


Image credits: NASA/JPL-Caltech

VOYAGER 2: ENCOUNTER WITH URANUS

- Closest approach altitude over Uranus's cloud tops of ~81,500 km (N)
- Deep Space Network (DSN) coverage was particularly problematic
- Voyager 2 is a flyby mission. After the Jupiter and Saturn exploration phases, continued scientific exploration to Uranus and Neptune were approved by NASA

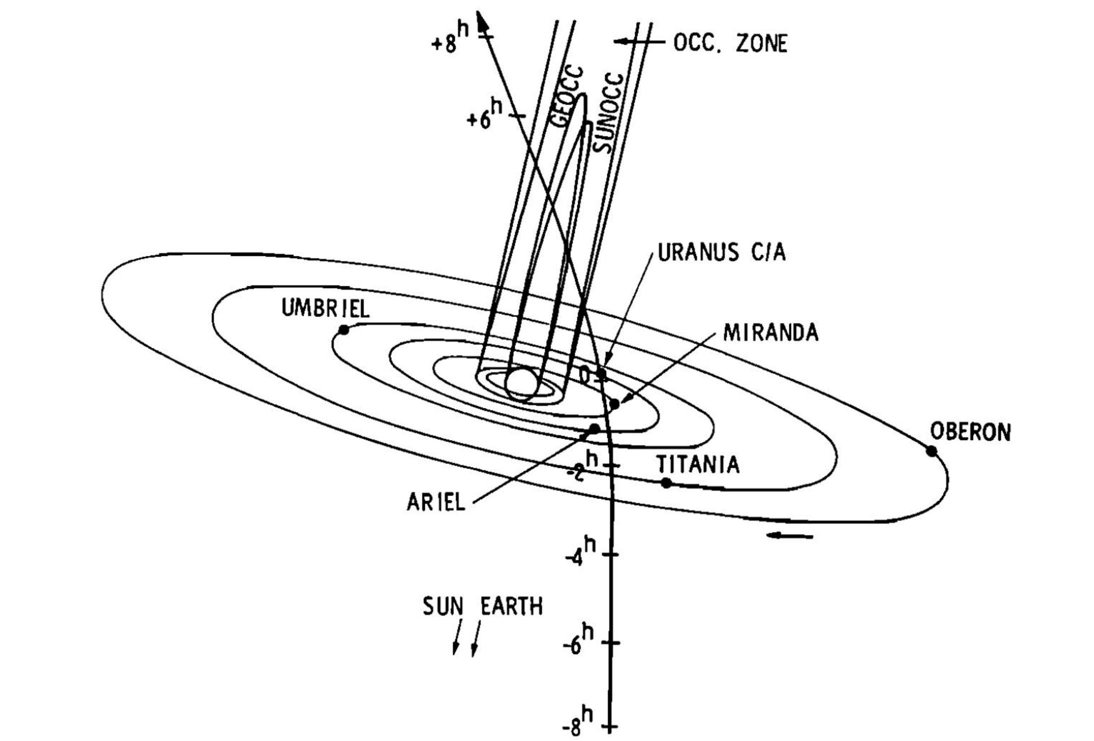


Fig. 3. A view normal to the trajectory plane of the Voyager 2 path through the Uranus system.

Figure 3 from Stone (1987), Journal of Geophysical Research, 92, A13, 14873-14876.

NASA'S SPACE MISSIONS LIFE CYCLE

Uranus Orbiter and Probe (UOP) is currently in this phase

NASA Life-Cycle Phases	Approval for Formulation	FORMULATION		Approval for Implementation		IMPLEMENTATION		
Project Life-Cycle Phases	**Pre-Phase A:** Concept Studies	**Phase A:** Concept and Technology Development	**Phase B:** Preliminary Design and Technology Completion	**Phase C:** Final Design and Fabrication	**Phase D:** System Assembly, Integration & Test, Launch & Checkout	**Phase E:** Operations and Sustainment	**Phase F:** Closeout	

NASA Space Flight Project Life Cycle from NPR 7120 5E

NASA Program/Project Life Cycle (https://www.nasa.gov/seh/3-project-life-cycle):

- Pre-Phase A produces ideas for several mission architectures that address the science questions.
- Phase A develops a mission/system architecture that is credible and responsive to program expectations.
- Phase B completes the preliminary design and technology development.
- Phase C completes and documents the detailed design of the mission/systems that meet the detailed requirements.
- Phase D includes assembly, integration, verification, validation, and finally the launch of the mission/systems.
- Phase E conducts and supports the prime mission to meet the initially identified objectives.
- Phase F implements the systems decommissioning and disposal planning and analyze returned data and/or samples.

TRADE-OFF PARAMETERS FOR MISSION DESIGN

Resources are very limited in space:

- Cost
- Mass
- Power
- Data volume
- ΔV
- Type of orbits
- Number of flybys/orbits

It is an iterative process the starts from a set of ground rules, including:

- Cost cap
- Launch vehicle and launch window
- International partnership

SCIENCE →

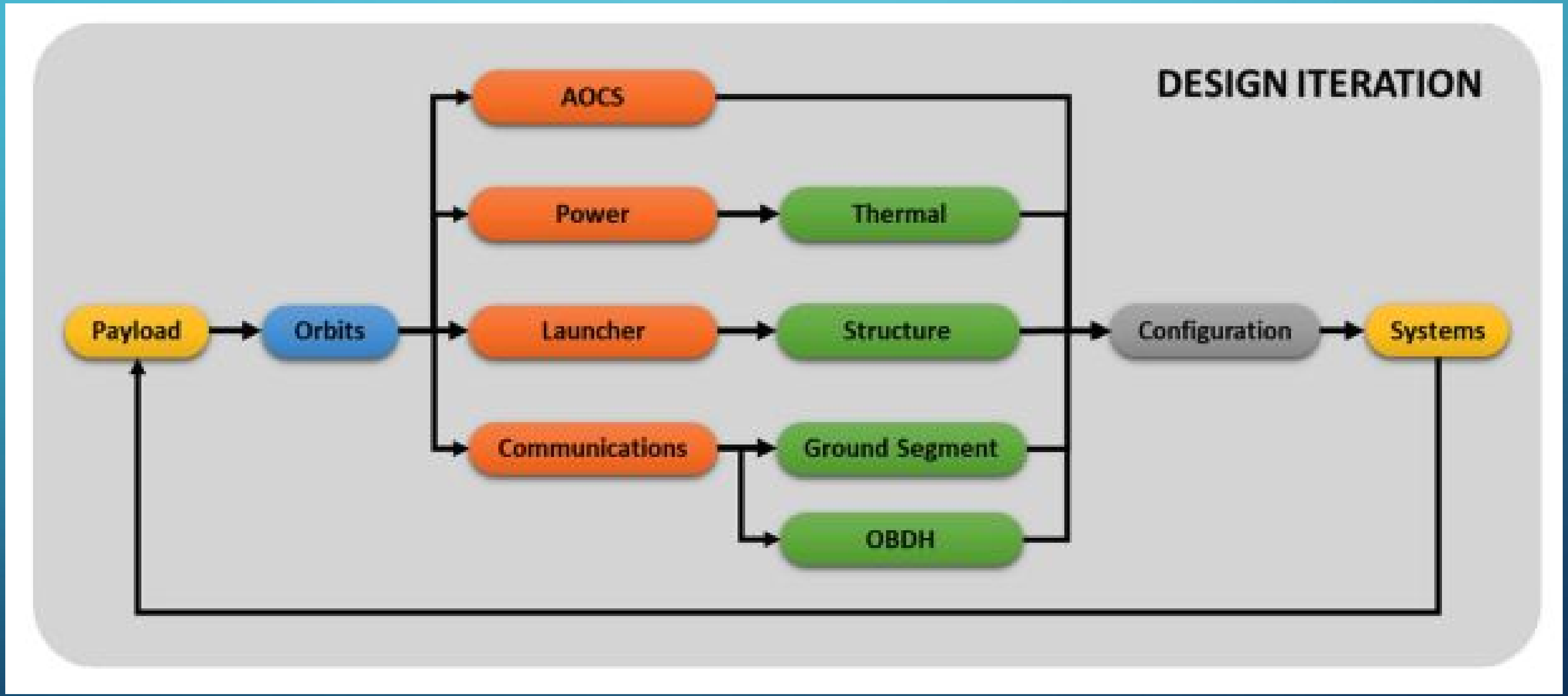


Figure 6 from Álvarez, J.M., Roibás-Millán, E. Agile methodologies applied to Integrated Concurrent Engineering for spacecraft design. *Res Eng Design* **32**, 431–450 (2021). https://doi.org/10.1007/s00163-021-00371-y

HOW DO WE CHOOSE THE PAYLOAD OF A MISSION?

"…the Cassini Resource Exchange [was]. a 'market-based' economic system, it permitted the varied instrument teams to 'trade resources' rather than being limited to a fixed allocation …"

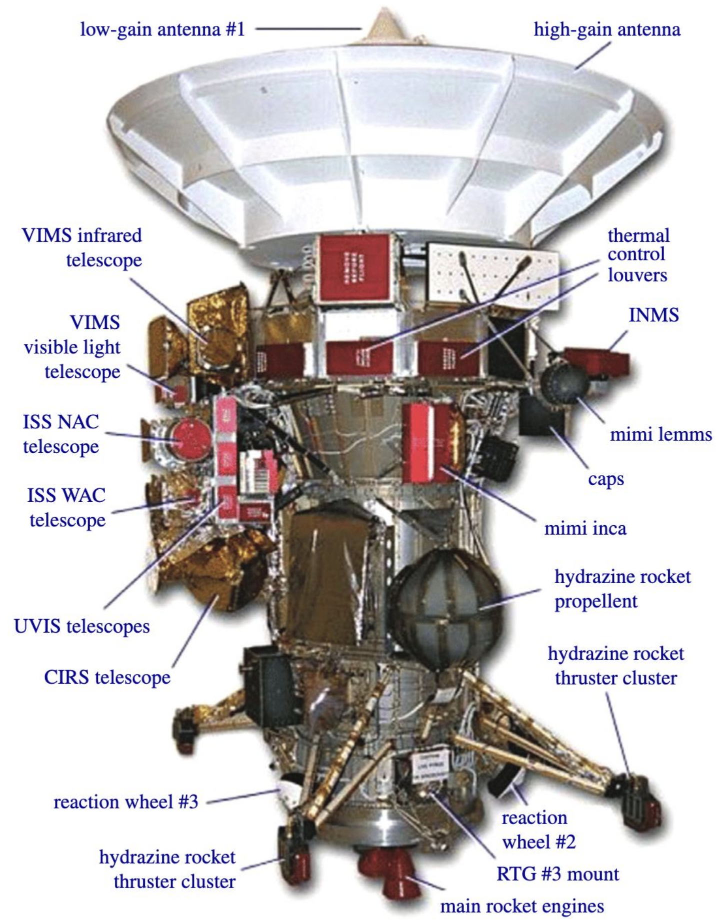


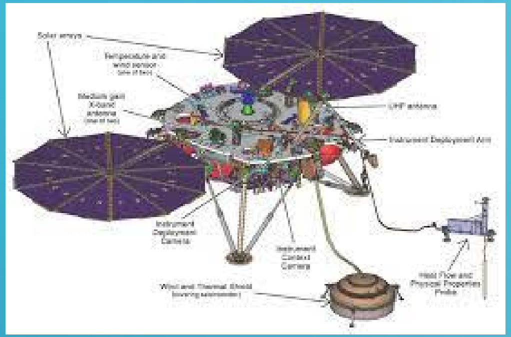
Figure 3. Cassini Mission to Saturn. The Cassini programme used an innovative 'Resource Exchange' to facilitate the development of its science payload. Image source: https://solarsystem.nasa.gov/basics/cassini. (Online version in colour.)

Hammel H.B. (2020) Lessons learned from (and since) the Voyager 2 flybys of Uranus and Neptune Phil.Trans.R.Soc.A378: 20190485.http://dx.doi.org/10.1098/rsta.2019.0485

PAYLOAD EXAMPLES FROM OTHER MISSIONS

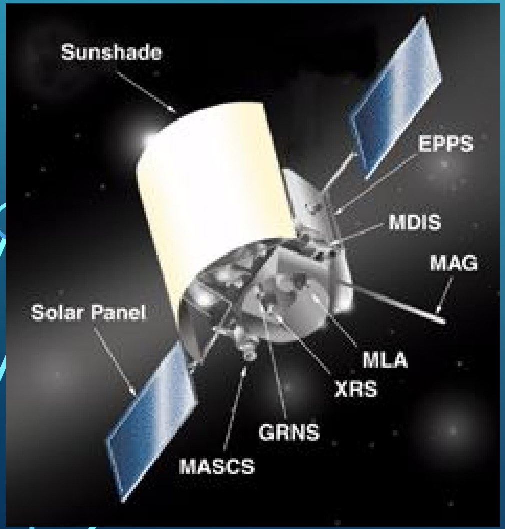
DISCOVERY

Insight: (4) or ~(50 kg)



Credit: NASA/JPL-Caltech

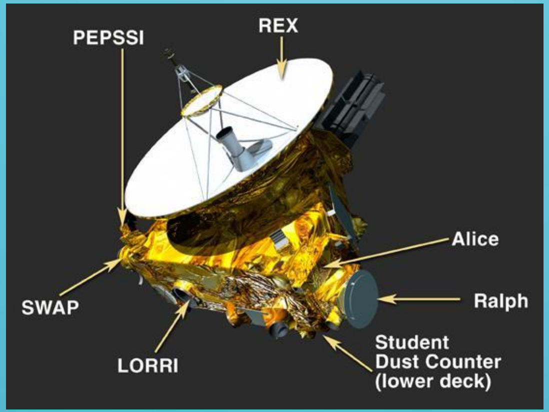
MESSENGER: (7) or ~(50 kg)



Credit: JHU/APL

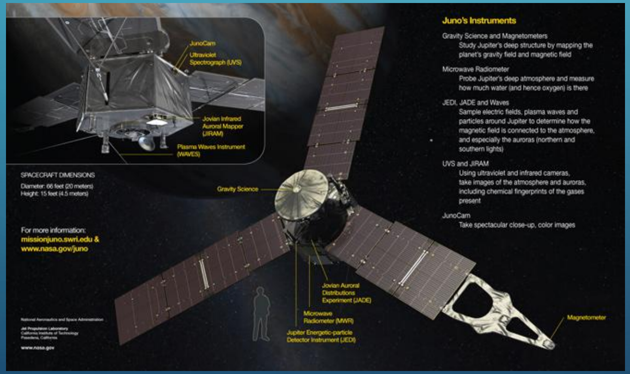
NEW FRONTIERS

New Horizons: (7) or ~(30 kg)



Credit: NASA/JPL-Caltech

Juno: (8+1) or ~(175 kg)



Credit: NASA/JPL-Caltech

FLAGSHIPS

Cassini-Huygens: (12+6) or ~(270+49 kg)

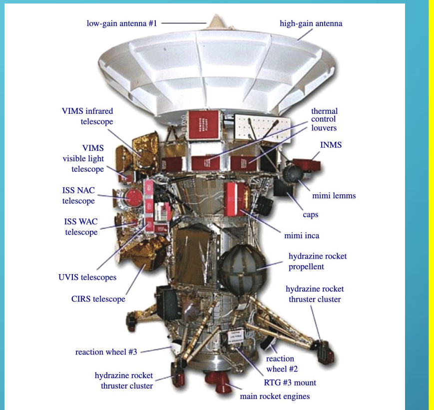


Figure 3. Cassini Mission to Saturn. The Cassini programme used an innovative 'Resource Exchange' to facilitate the development of its science payload. Image source: https://solarsystem.nasa.gov/basics/cassini. (Online version in colour.)

Hammel H.B. (2020)

Europa Clipper (9) or 352 kg

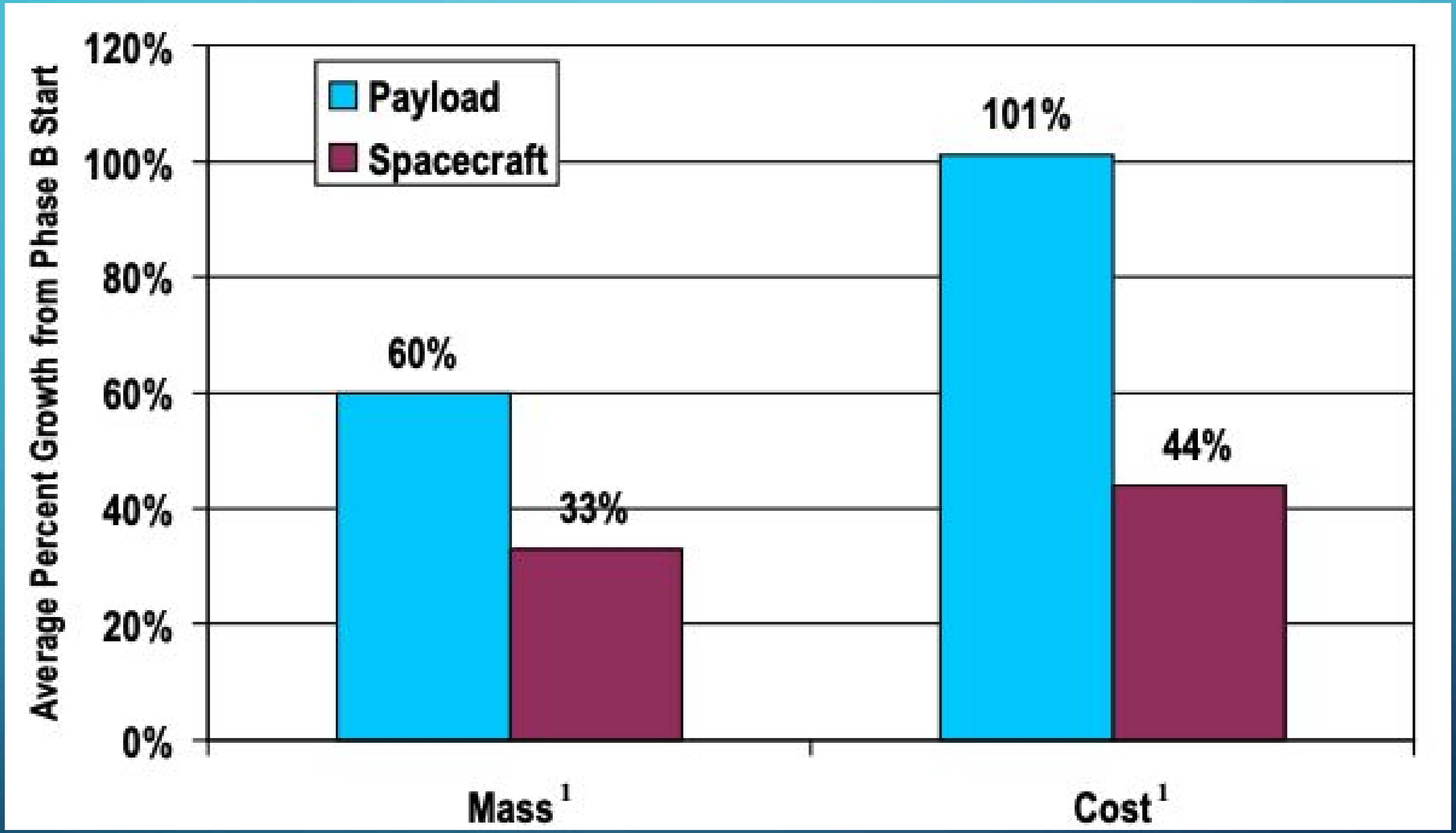
Bayern et al. 2019

URANUS ORBITER AND PROBE (UOP)?

~70-150 kg?
6-9 instruments?

PAYLOAD: HISTORICAL DATA FOR MASS AND COST

Payload resources are characterized by greater uncertainty than the spacecraft



Taken from “Inherent Optimism In Early Conceptual Designs and Its Effect On Cost and Schedule Growth: An Update”, Freaner C., Bitten R., Emmons D., 2010 NASA PM Challenge, Houston, Texas, 9-10 February 2010

AKIN'S LAWS OF SPACECRAFT DESIGN

….

2) To design a spacecraft right takes an infinite amount of effort. This is why it's a good idea to design them to operate when some things are wrong .

3) Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.

4) Your best design efforts will inevitably wind up being useless in the final design. Learn to live with the disappointment.

…

12) There is never a single right solution. There are always multiple wrong ones, though.

…

14) (Edison's Law) "Better" is the enemy of "good".

…

17) The fact that an analysis appears in print has no relationship to the likelihood of its being correct.

…

19) The odds are greatly against you being immensely smarter than everyone else in the field.

20) A bad design with a good presentation is doomed eventually. A good design with a bad presentation is doomed immediately.

…

22) When in doubt, document.

…

28) (Ranger's Law) There ain't no such thing as a free launch.

29) (von Tiesenhausen's Law of Program Management) To get an accurate estimate of final program requirements, multiply the initial time estimates by pi, and slide the decimal point on the cost estimates one place to the right

…

32) (Atkin's Law of Demonstrations) When the hardware is working perfectly, the really important visitors don't show up.

…

37) (Henshaw's Law) One key to success in a mission is establishing clear lines of blame.

45) Space is a completely unforgiving environment. If you screw up the engineering, somebody dies (and there's no partial credit because *most* of the analysis was right...)

UOP CONSTRAINTS: POWER AND DATA RATE

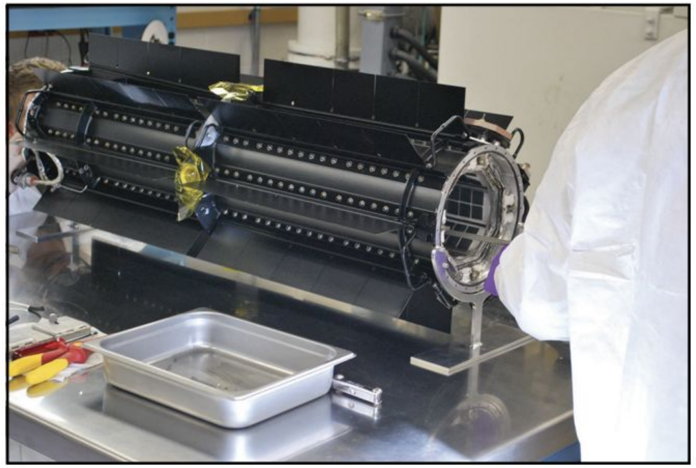
Power is a very limited resource at Uranus distances.

The onboard power system must power:

- Payload
- Spacecraft subsystems
- Deep-space communications (downlink)

Recent estimates for the required power are in the 350-450 W ballpark.

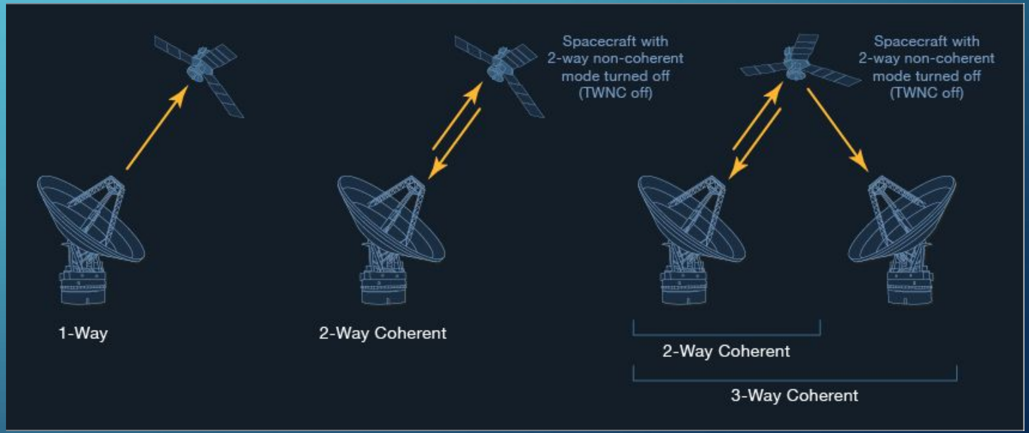
For instance, "3 Mod-1 Next- Generation Radioisotope Thermoelectric Generators (NGRTG)" were assumed by the Uranus Orbiter and Probe, Planetary Mission Concept Study for the 2023-2032 Decadal Survey (7 June 2021).



Next Gen RTG Mod-0 Inspection. *Credits: DOE/INL*

The spacecraft needs to relay back the data.

- Data volume/rate are also very limited resources onboard a space mission.
- They depend on many factors, such as power and frequency/bandwidth of the radio carrier.
- Instruments can be at the extremes of possibilities when it comes to data volume requirements.



Credit: NASA/JPL-Caltech

UOP PAYLOAD FOR PROBING URANUS'S INTERIOR

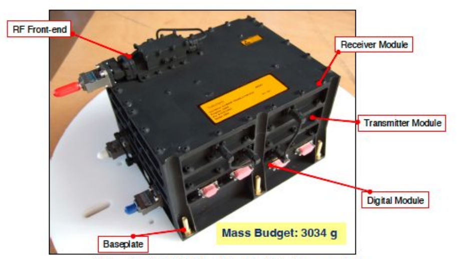
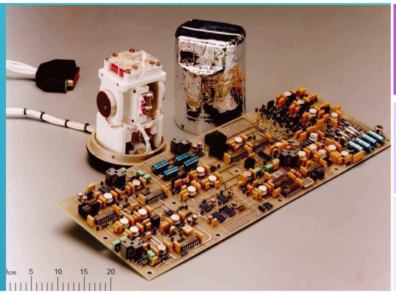
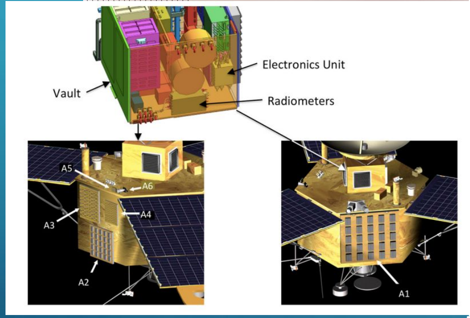


Fig. 1. JUNO's KaT: flight model

GRAVITY SCIENCE (e.g. JUNO KaT, Ciarcia et al. 2013)		
MASS	POWER	DIMENSIONS
~6 kg	< 60 W	215x140x175 mm



MAGNETOMETER (e.g. Cassini/MAG, Dougherty et al. 2004)		
MASS	POWER	LENGTH
~9 kg	~13 W	~11 m



MICROWAVE SOUNDER (e.g. Juno/MWR, Janssen et al. 2017)		
MASS	POWER	DIMENSIONS
~42 kg	~33 W	Tab. 4 Janssen 2017

DOPPLER IMAGER (Hofstadter et al. 2019)		
MASS	POWER	DIMENSIONS
~20 kg	~20 W	?

UOP
~80 kg, 4 instruments?
Out of 70-150 kg and 6-9 instruments.

INTERNATIONAL PARTICIPATION

One way to reduce payload costs and maximize the scientific return of a space mission is to encourage international participation, where one (or more) space agency (other than NASA) provides one (or more) science instruments or engineering components. It is still necessary do budget for power consumption, as well as total mass and volume occupancy.

ESA's HUYGENS PROBE

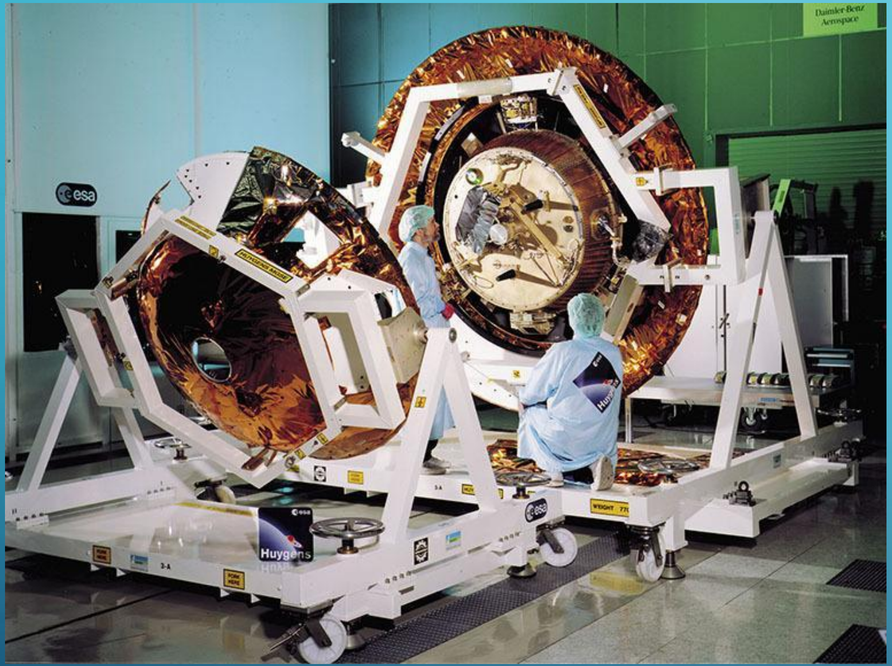


Image Credit and Copyright: European Space Agency

ASI/TASI JUNO's KaT

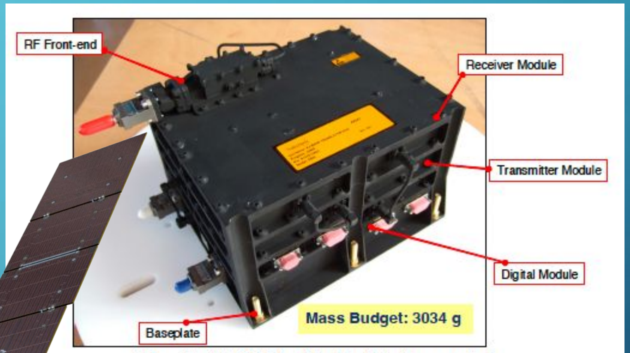
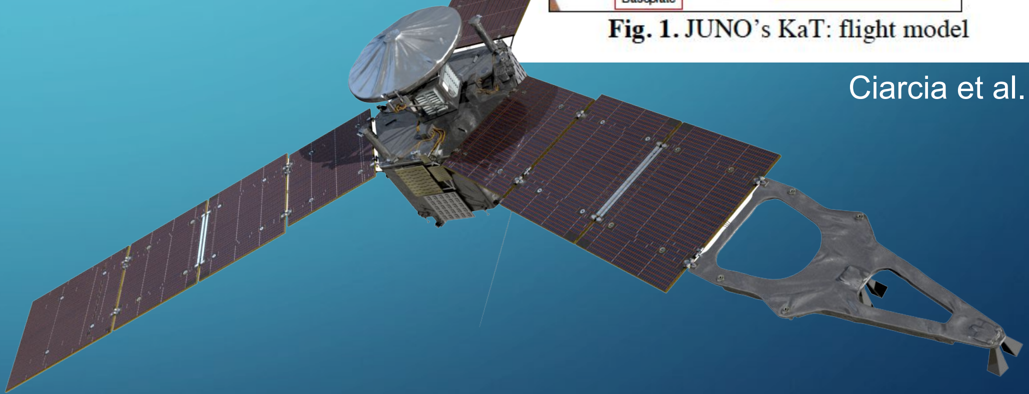


Fig. 1. JUNO's KaT: flight model

Ciarcia et al. 2013

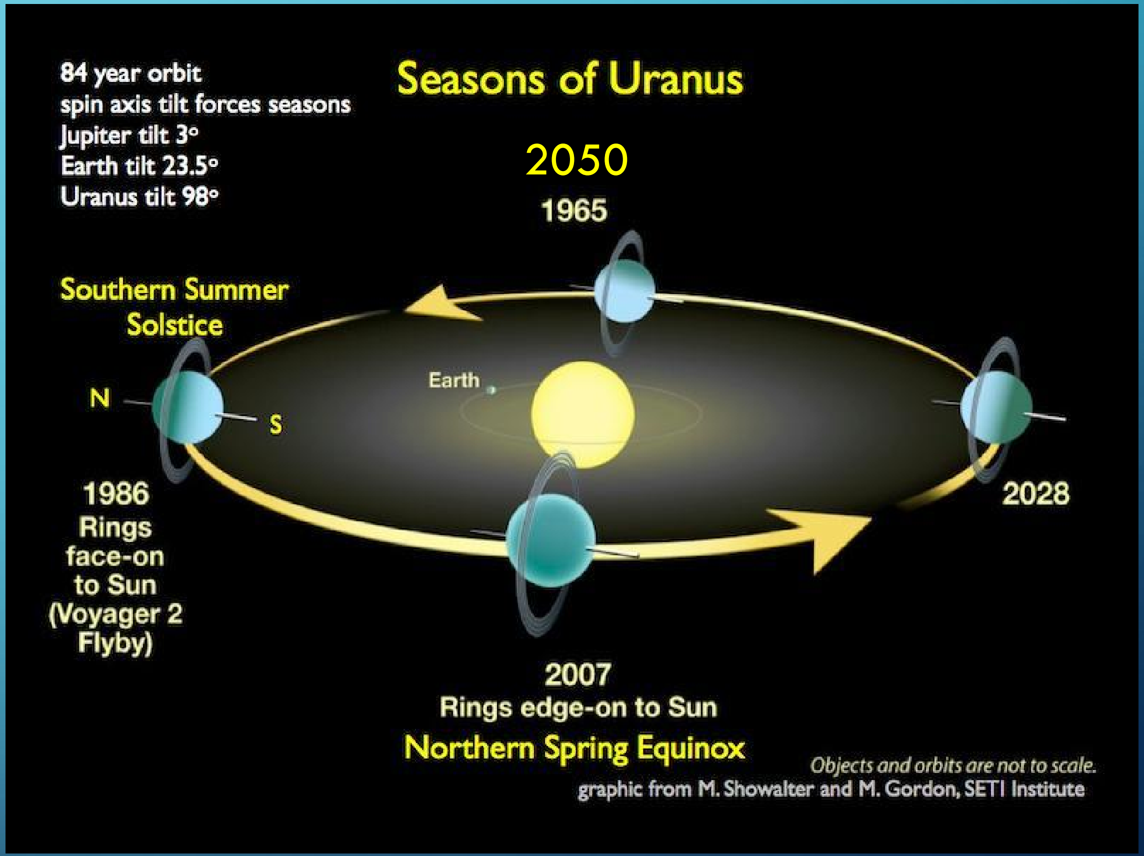


"…it is highly advantageous for mission teams to engage early and often with industry counterparts. Avoid waiting until NASA has defined mission criteria or puts out a call; rather reach out to potential partners very early in the development process. …"

Hammel H.B. (2020)

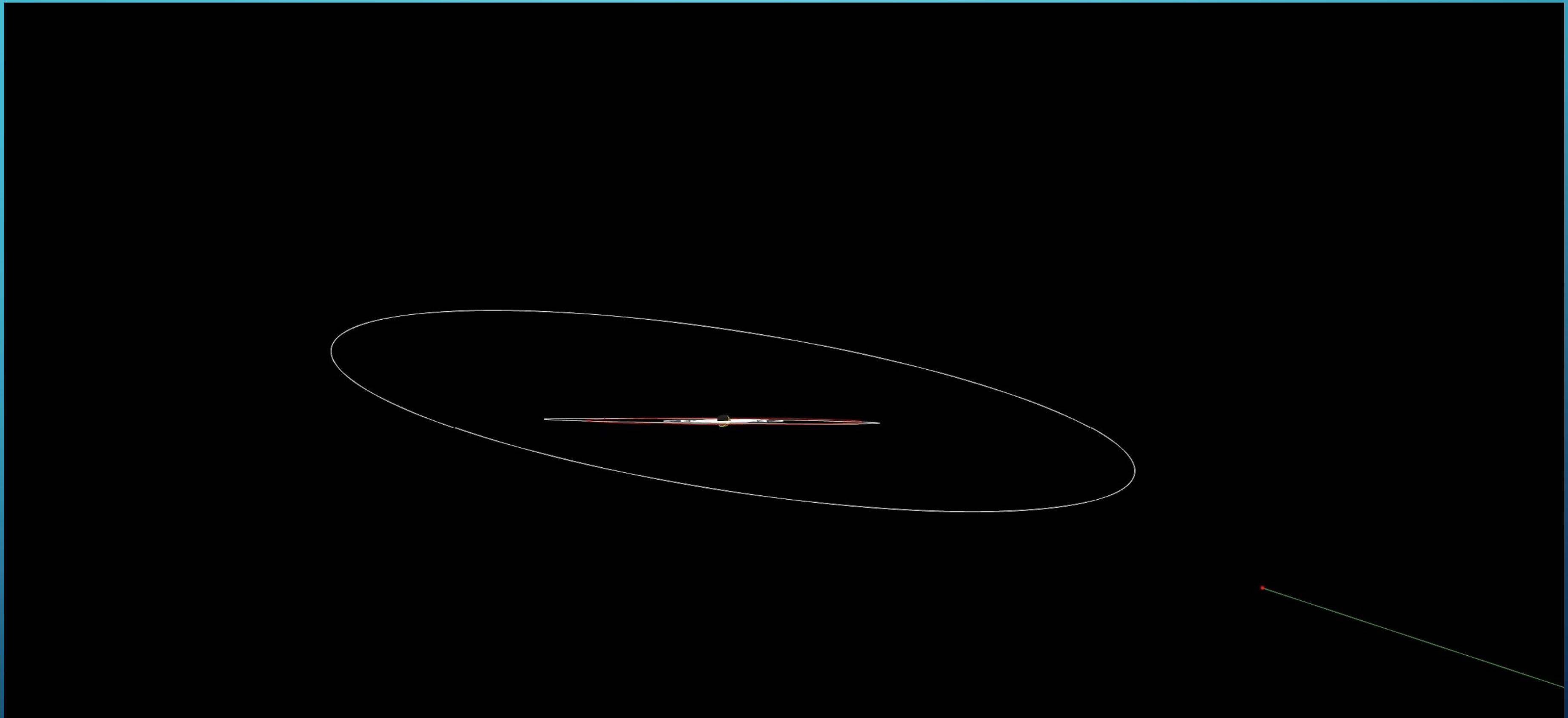
LAUNCH, CRUISE AND URANUS'S SEASON

- At the time of Voyager 2's flyby of Uranus, the planet was near southern solstice. Only the southern hemispheres of its moons were illuminated and available for imaging.
- We ideally want to get there before the next equinox in early 2050.
- Previous studies identified UOP trajectories that used a Jupiter gravity assist (launch 2029-2032) as the most favorable.
- However, with the current timeline, we are looking at a launch in the mid to late-2030s.
- Launches after the late-2030's will not allow for the imaging of the northern hemispheres of the satellites.



UOI, PROBE RELEASE, URANUS AND MOON SCIENCE: THE CASSINI ANALOGUE

There’s a limited available ΔV and multiple goals to accomplish. What is a feasible tour for a Uranus orbiter mission?



The Ball of Yarn: Cassini's Orbits
Source: NASA/Jet Propulsion Laboratory-Caltech

UOP: MISSION DESIGN CONSTRAINTS

A representative target for a Uranus mission is ΔV~3 km/s:

- ~1.6 km/s for Uranus Orbit Insertion (UOI)
- ~0.5 km/s for tour phase tour phase (Oberon, Titania, Umbriel, Ariel, Miranda) and disposal
- ~0.2 km/s probe phase (targeting and divert)
- ~0.4 km/s deep space maneuvers
- ~0.3 km/s for gravity/mag phase (rotate orbit 180°)

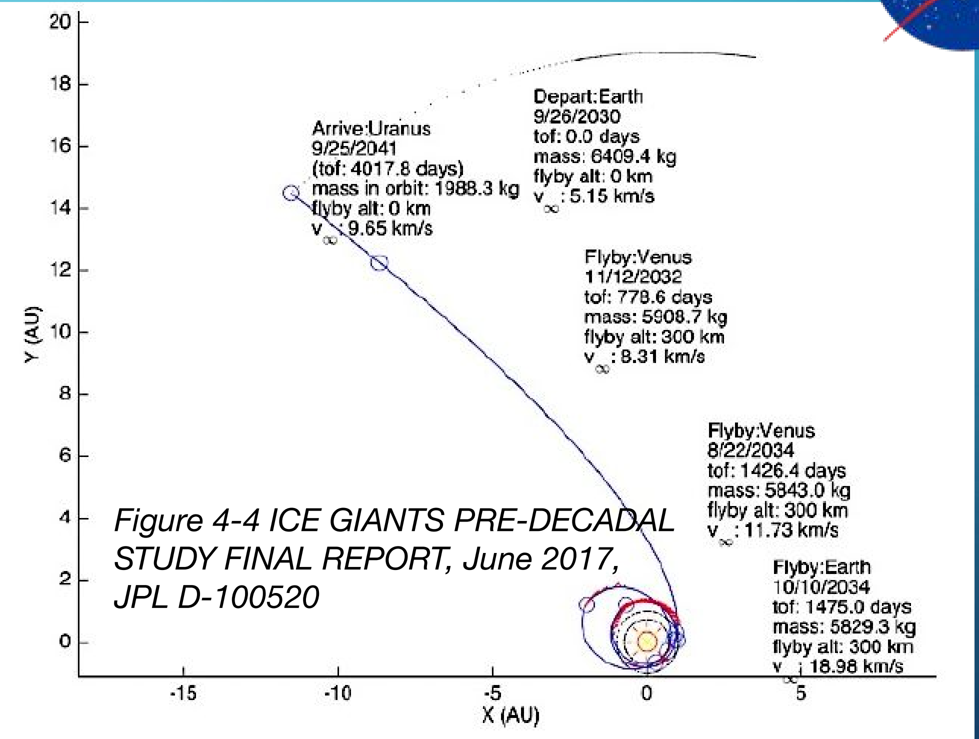


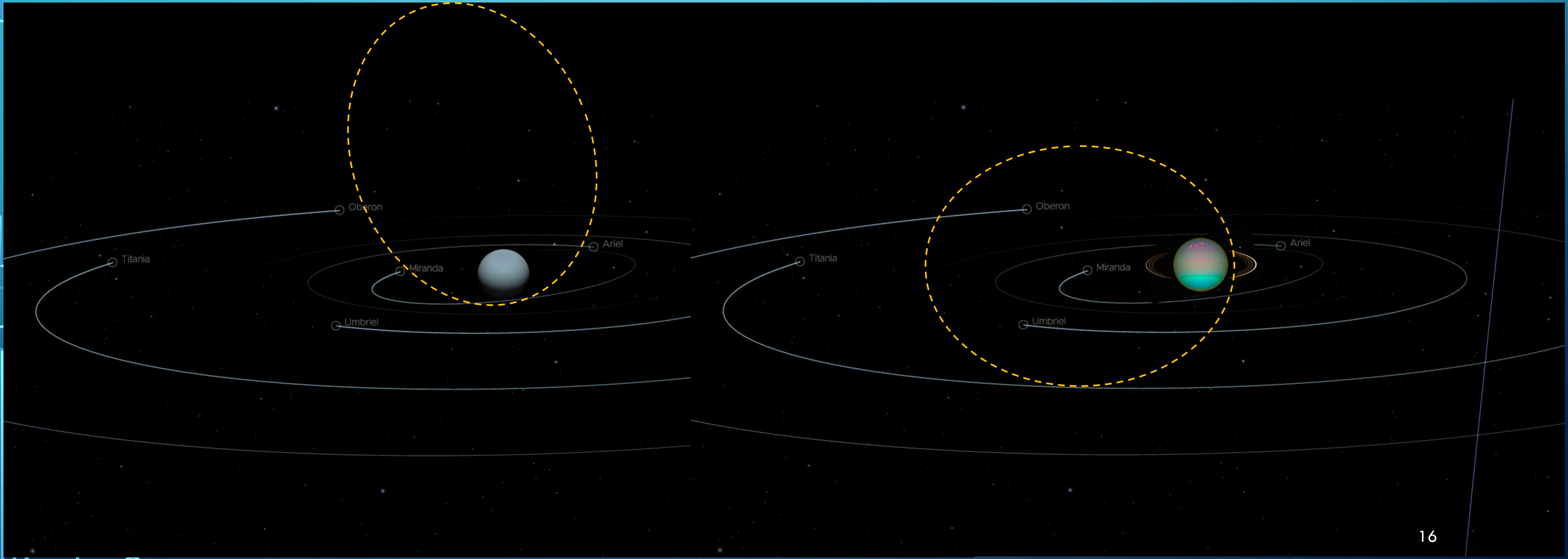
Figure 4-4 ICE GIANTS PRE-DECADAL STUDY FINAL REPORT, June 2017, JPL D-100520

Time is also a limited resource:

- The mission is designed for the prime mission (e.g. 2-4 years in Uranus orbit). All primary science objectives need to be met within that period.
- It's possible to use the outer satellites of Uranus to transition between equatorial and moderately inclined orbits, but it can take more than a year.
- Getting to Uranus quicker means a larger ΔV to get into orbit, or relying on new technology like aerocapture (considered a risk and increases cost).

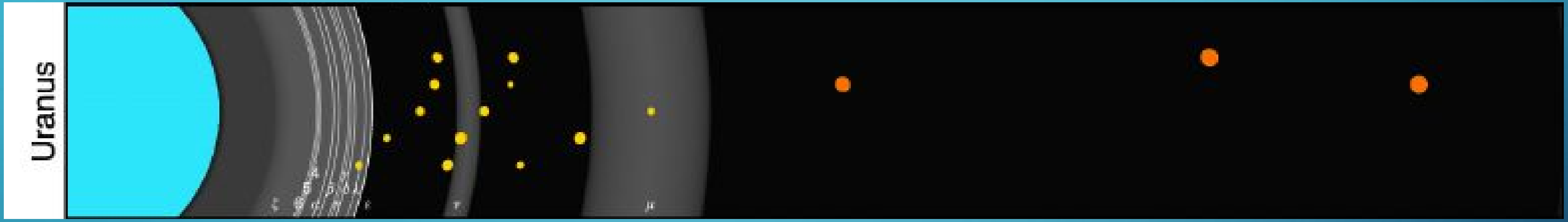
URANUS ORBITER AND PROBE: INCLINED ORBITS

The choice of the orbital parameters is also key to mission success. For instance, orbits that get very close to the planet represent a favorable scenario for some of the instruments: gravity science, magnetometer, microwave sounding and others.



RING HAZARD AND ATMOSPHERIC TORQUE

- It is hard to predict the ring hazard faced by the spacecraft at Uranus.
- The Cassini spacecraft found a less harsh ring environment at Saturn than expected.
- Getting too close to the upper atmosphere comes with its own set of issues. The uncertainties on the Uranus atmospheric density are also very high.



GIANTS PRE-DECADAL STUDY FINAL REPORT, June 2017, JPL D-100520

- Some studies suggest significant cooling of the upper atmosphere, which could lead to higher densities, but also collapsing of the atmosphere, with consequent increase in the ring particle population.
- The sweet spot is distant enough from the rings to avoid dense regions but also distant enough from the upper atmosphere (for Uranus it is ~probably 1.08-1.11 R_U).
- We might keep these orbits for the end of the mission, but that has consequences for a possible extended mission.

RELEASING A PROBE INTO URANUS'S ATMOSPHERE

Requirements for releasing a probe and for Uranus Orbit Insertion can be at odds.

- Dropping the probe into Uranus's atmosphere before UOI (*deployment on hyperbolic*):
  - Pros: less mass to insert
  - Cons: entry speed of the probe
- Dropping the probe after UOI (*deployment on elliptic post capture*):
  - Pros: it reduces the mass of the thermal protection system (lower speeds); larger range of latitudes can be targeted; time for remote sensing before targeting.
  - Cons: higher ΔV.

ICE GIANTS PRE-DECADAL STUDY FINAL REPORT, June 2017, JPL D-100520

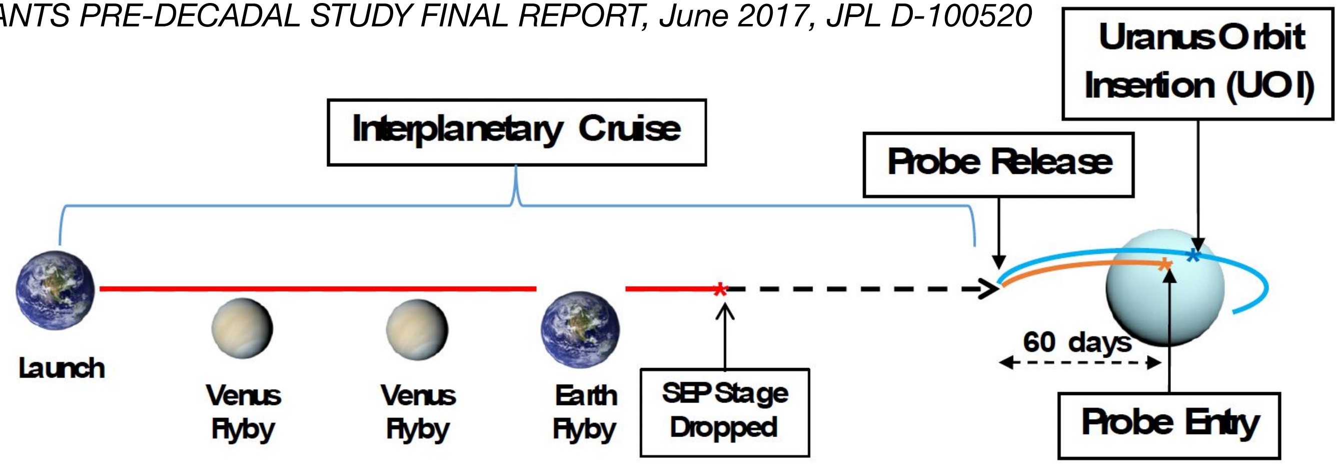
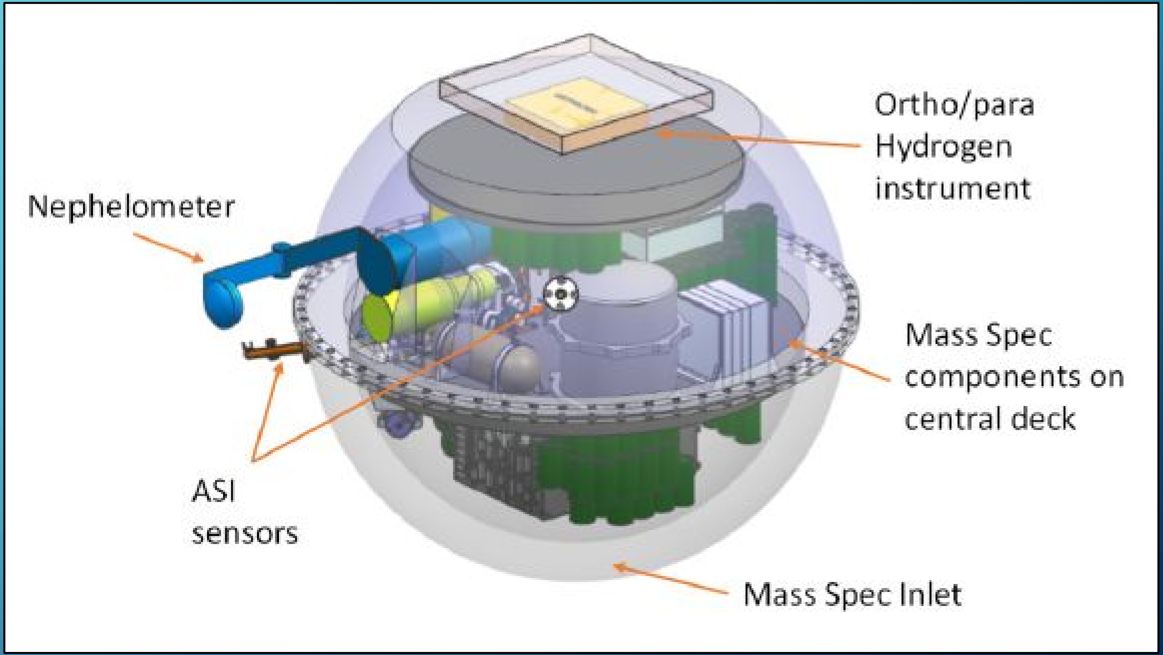


Figure 4-2. Mission Concept Option 1: SEP mission design overview.

RELEASING A PROBE INTO URANUS'S ATMOSPHERE

There are also trade-offs related to getting the probe's data to Earth:

- Direct Earth transmission of probe data is impractical: the orbiter is used as a relay station
- The orbiter must point its antenna at the probe for as long as possible.
- Most mission studies suggest there will be a single atmospheric probe, and it will take measurements in the ~100 mbar to ~20 bar pressure range.
- It is possible to go deeper. For example, down to 1 kbar pressure, but that will likely require significant amounts of resources, leaving not much space for other science goals!



ICE GIANTS PRE-DECADAL STUDY FINAL REPORT, June 2017, JPL D-100520

TAKE-AWAYS AND POSSIBLE UOP TIMELINE

- Science, payload, s/c, probe and orbital design are iterative processes where limited resources, such as mass, data volume, power, etc. are optimized
- International collaborations should be leveraged to maximize the science return while minimizing the cost to each partner
- There are several mission requirements for each science instruments (sometimes within the same instrument!). Trade-off studies are crucial
- Investment in research to better constrain the ring-crossing hazard and conditions in the upper atmosphere is necessary

Possible mission timeline:

- Selection of a few scientists to provide initial guidance: 2025
- New mission start: late 2020's
- Launch: late 2030's
- Arrival at Uranus: ~2050.

Image credit: NASA/JPL

We are going to Uranus!

Image credit: NASA, ESA, CSA, STScI. Image processing: J. DePasquale (STScI)