National Aeronautics and
Space Administration

Aerocapture for the Outer Planets

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International Planetary Probe Workshop
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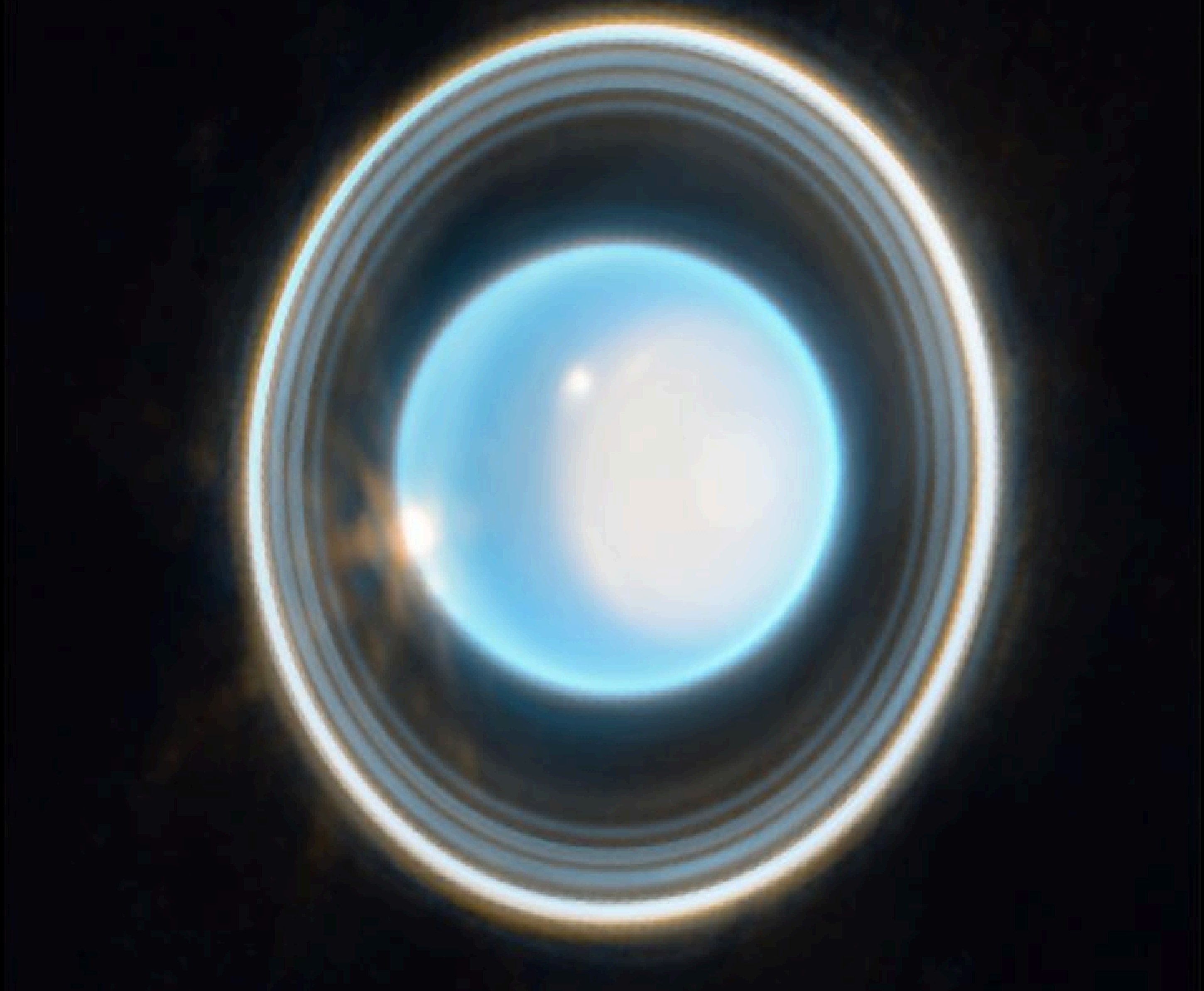
June 10,2024

Uranus

Captured by Webb’s Near-Infrared Camera (NIRCam) Feb. 6, 2023

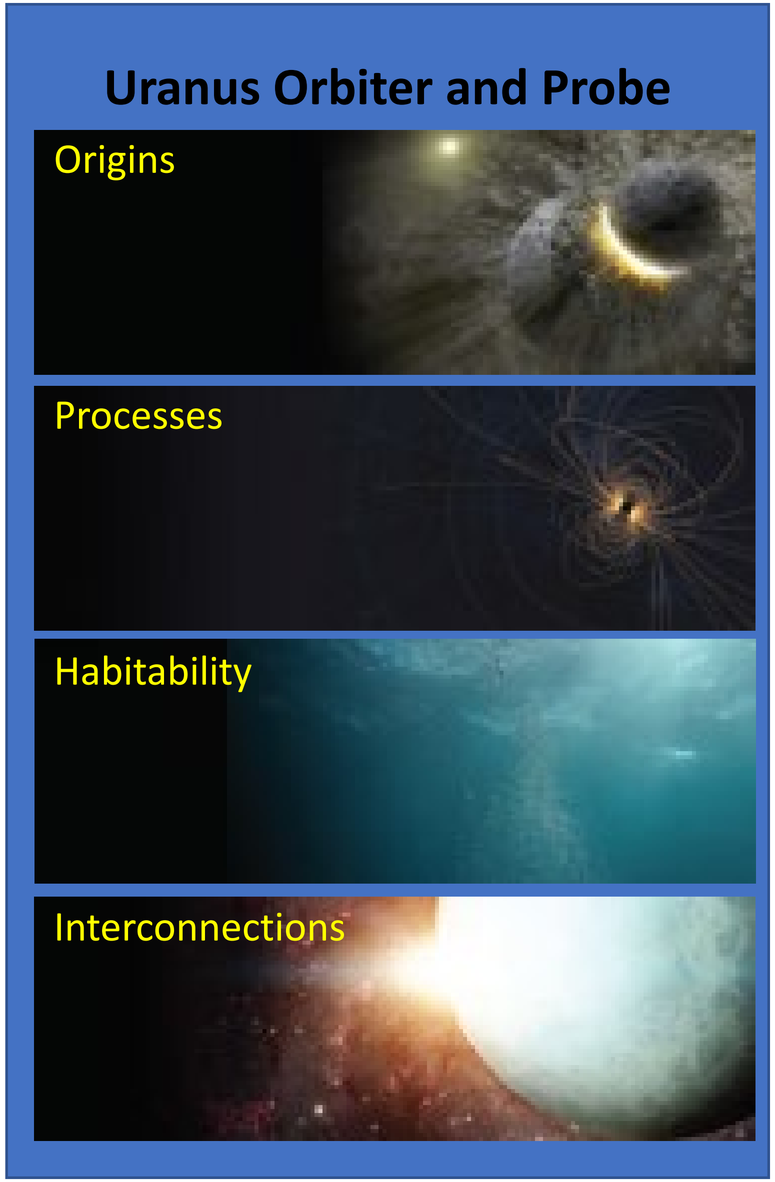


Credits: NASA, ESA, CSA, STScI. Image processing: J. DePasquale (STScI)

Flagship Priorities for Planetary Science

1. Uranus Orbiter and Probe
2. Enceladus Orbilander

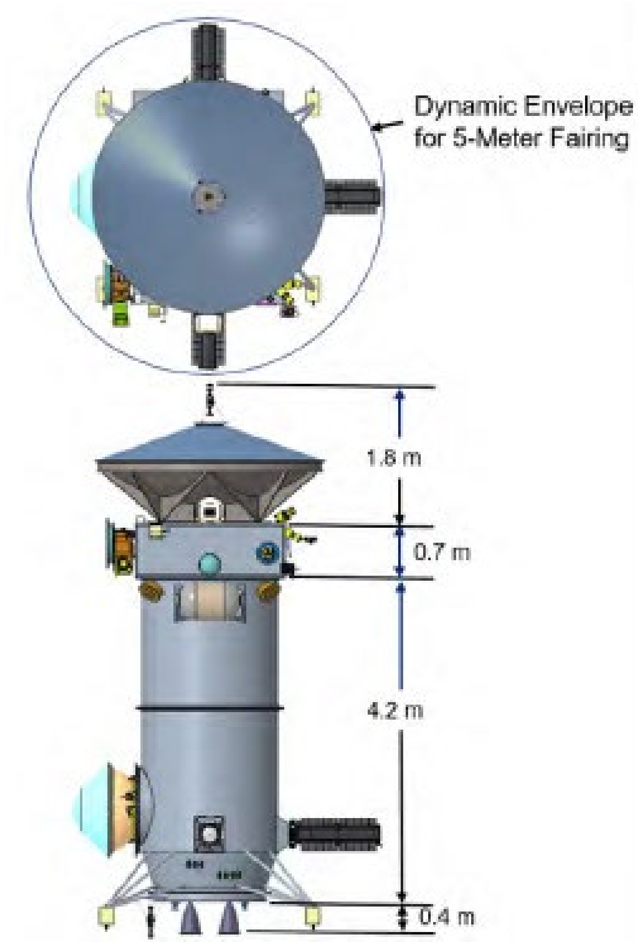
Europa Lander
Mercury Lander
Neptune-Triton Odyssey
Venus Flagship



A. Simon, F. Nimmo, R. Anderson
Planetary Mission Concept Study for the 2023-2032 Decadal Survey, June 7, 2021

UOP Nominal Configuration

A. Simon et al. (2021)



18.9 AU average heliocentric distance

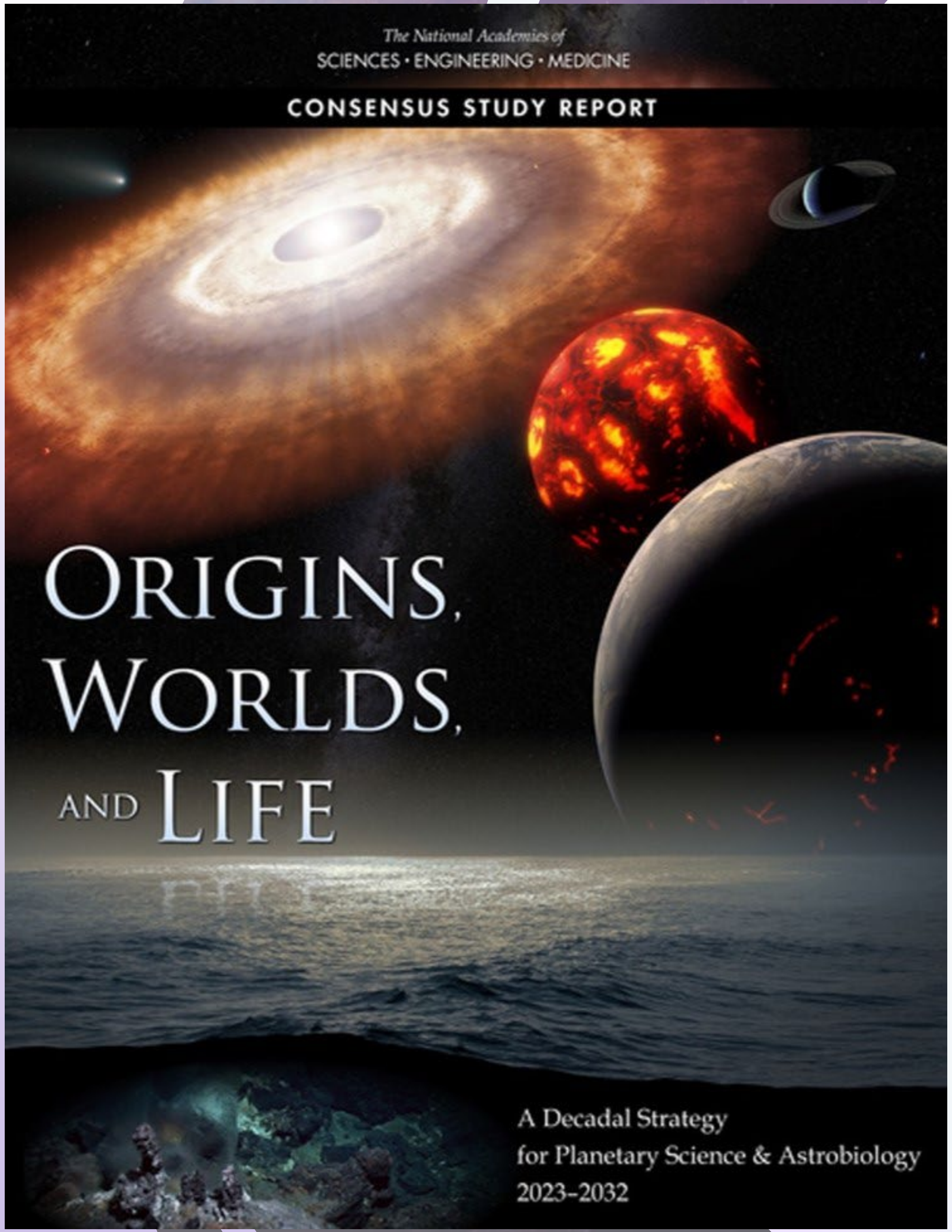
June 2031 launch date: 13.4 years (12-15 yr range through 2038 launch)

- 2.8 t dry mass (includes probe)
- 7.2 t wet mass (4.5 t propellant and oxidizer – 60%)
- 2.3 km/s total Δ V for Orbiter – 1.0 km/s of that for Uranus orbit insertion
- Payload: 85.5 kg, 95 W (includes probe)

Aerocapture: Transit to Uranus in 7-9 years, save 1 t fuel for orbit insertion
– S. Dutta, "Aerocapture as an Enabling Technology for Ice Giants" Nov 2023

Nuclear Electric Propulsion: Transit to Uranus in ~10 years (50 kg payload) plus additional on-board power for science and communications at Uranus
-- GRC, JPL, LANL: "Kilopower–Nuclear Electric Propulsion for Outer Solar System Exploration," JPL D-103385, April 24, 2019

Earth Launch	Deep Space Maneuver	Earth Flyby	Jupiter Flyby	**Uranus Approach**	Capture	Probe Deployment	Satellite Tour
	L+ ~ 1 year	L+ ~2 year	L+ ~4.5 year	**L+ ~13.4 year**	~77 min	~13-60 days from entry	2-4 year



Aerocapture

"Aerocapture is an orbital insertion technique which uses a single pass through a planetary atmosphere to dissipate enough orbital energy for planetary capture. It can deliver large orbit insertion ΔVs with minimum fuel, resulting in significant reductions in transit time and/or increases in science payload mass."

Finding: "Aerocapture is a technology that is ready for infusion and that can enhance/enable a large set of missions, but that will require special incentives to be proposed and used in a science mission."

-- Origins, Worlds and Life: A Decadal Strategy for Planetary Science and Astrobiology (2022)

Could a small spacecraft
using aerocapture in Earth orbit
buy down risks for an Outer Planet Mission?

Aerocapture Demonstration Relevance Team (ADRAT)

Determine the potential relevance of a small spacecraft performing aerocapture in Earth orbit to reduce risks for large spacecraft to the outer planets and other solar system destinations by answering the following questions:

1. What are the top risks associated with using aerocapture on future NASA missions to the outer planets?
2. What architecture(s) and requirements are necessary for a tech demo to retire identified risks for various aerocapture techniques?
3. Would a demonstration of aerocapture using a small spacecraft in Earth's atmosphere buy down any of those risks? If so, what data would be most beneficial to collect?
4. There are at least two fundamental concepts to control a spacecraft during aerocapture: drag modulation and lift modulation. Is one of these clearly more beneficial to demonstrate as risk reduction to the outer planets?

ADRAT Team

Carolyn Mercer, Chief Technologist SMD	Sponsor
Florence Tan, Deputy Chief Technologist SDM	Sponsor
Eileen Dukes (Systems Engineering, GNC)	Chair
Brian Sutter (Mission Design, EDL)	Member
Tom Spilker (Aerocapture Systems)	Member
Hilary Justh (Atmospheric Modeling)	Member
Robert West (Science and Instruments)	Member
Jeff Elbel (Mission Operations)	Technical Editor
Rich Burns	Project Management
Lori Wang	CTS Task Manager

Many thanks to Michelle Munk for organizing the speakers and providing the research bibliography

Outer Planet Aerocapture Risk List

-ANDRAT Nov 2022

Risk	Type	Level
If the atmospheric density profile uncertainty is too large, then trajectory of flight-path calculations based on the blunt-body heritage would be in error	Development	High
If the aerocapture implementation heat shield TPS performance and sizing requires more mass than studies assumed, then the dry mass will exceed the allocation	Development	Low
If the aerocapture implementation requires more mass for ancillary systems (e.g. g-load mitigation, separation mechanisms, packaging, heat dissipation), then the dry mass will exceed the allocation	Development	Medium
If the aerocapture uncertainties are too high, then the cost ($, mass) of implementation with sufficient capability will be too high	Development	High
If the aerothermodynamics of the target body are not well understood/modeled, then heat shield performance will be compromised	Mission	High
If the aerothermodynamics of the target body are not well understood/modeled, then the control actuators may not have sufficient control authority to maintain the flight path angle and the lift vector orientation	Mission	Medium
If the entry heating (integrated heat flux and soak-back) can not be accommodated, then components may overheat resulting in failures	Mission	Medium
If autonomous optical navigation cannot correctly correlate the atmosphere altitude to the planet barycenter, then the density will not be as expected and may exceed the ability of the spacecraft to compensate	Mission	Low

Outer Planet Aerocapture Risk List

-ANDRAT Nov 2022

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If the aerocapture implementation requires more mass for ancillary systems (e.g. g-load mitigation, separation mechanisms, packaging, heat dissipation), then the dry mass will exceed the allocation	Development	Medium
If the aerocapture uncertainties are too high, then the cost ($, mass) of implementation with sufficient capability will be too high	Development	High
If the aerothermodynamics of the target body are not well understood/modeled, then heat shield performance will be compromised	**Mission**	**High**
If the aerothermodynamics of the target body are not well understood/modeled, then the control actuators may not have sufficient control authority to maintain the flight path angle and the lift vector orientation	**Mission**	**Medium**
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Atmospheric Uncertainties create the highest risks and can not be addressed by an aerocapture technology demonstration at Earth

Outer Planet Aerocapture Risk List

-ANDRAT Nov 2022

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If the **aerocapture uncertainties** are too high, then the cost ($, mass) of implementation with sufficient capability will be too high	Development	High
If the aerothermodynamics of the target body are not well performance will be compromised		
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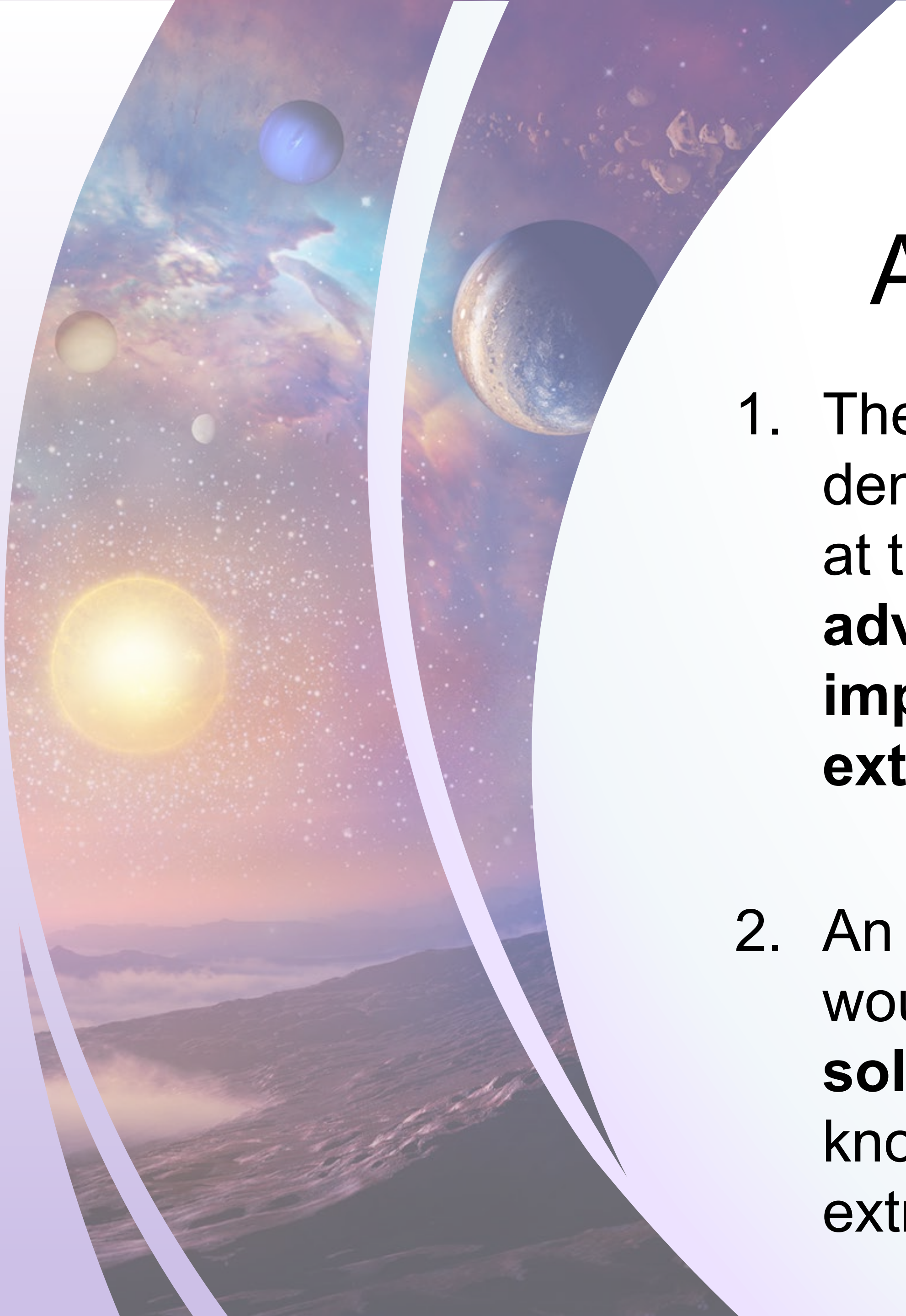
If **autonomous optical navigation** cannot correctly correlate the atmosphere altitude to the planet barycenter, then the density will not be as expected and may exceed the ability of the spacecraft to compensate	Mission	Low

But an aerocapture technology demonstration at Earth can reduce spacecraft risks

ADRAT Findings

- The greatest barrier to infusing aerocapture in an outer planet mission is the **inability to sufficiently characterize the environment** to produce a mission with an acceptable level of risk

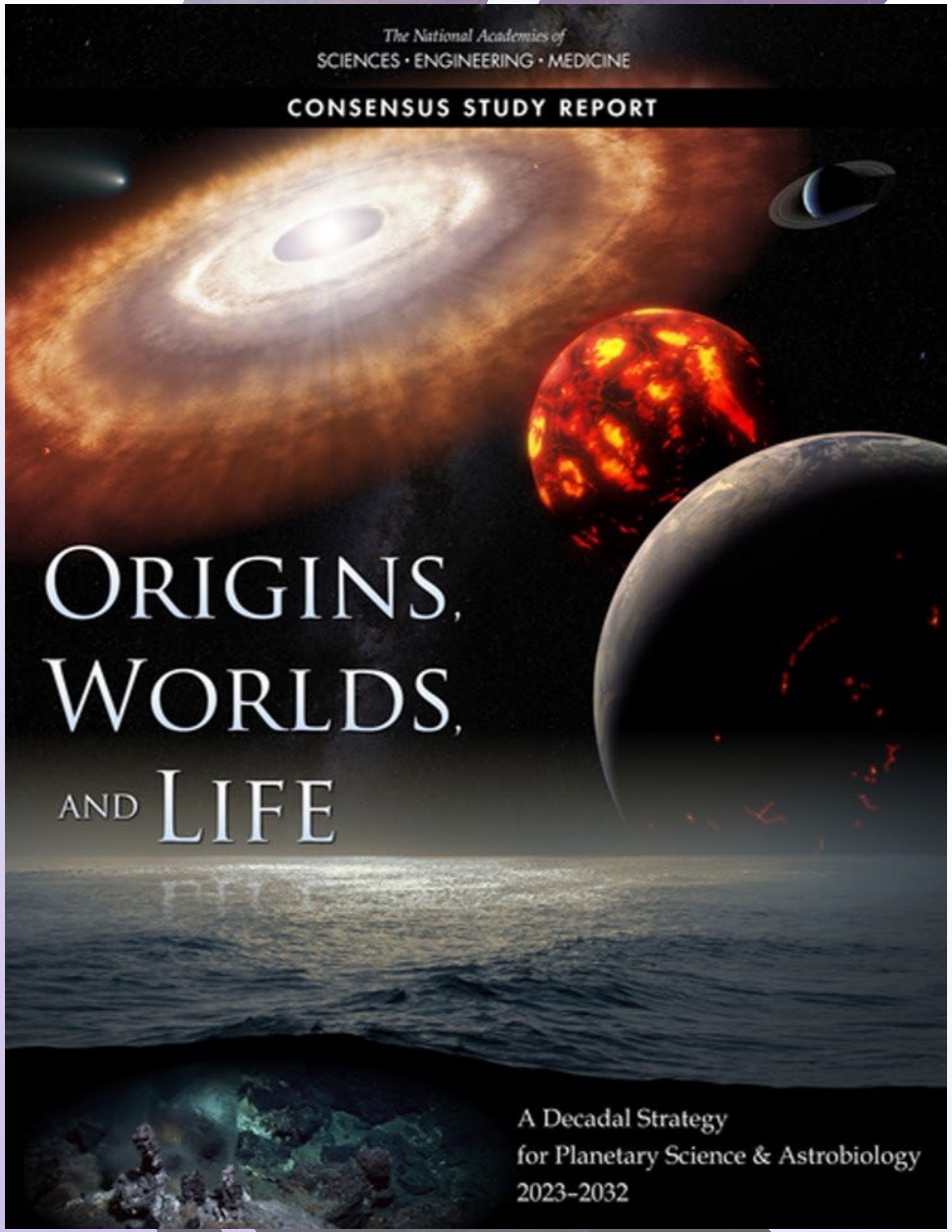
- **However, an Earth demonstration could improve the integrated system TRL for lift modulated direct force modulation and/or drag modulation and provide valuable data for model correlation**
    - **Aerothermal response modeling** including TPS surface and flow-field chemistry and coupled TPS material response modeling
    - **TPS development** of rigid body and 3-D woven dependent on mission implementation (e.g. higher heating rates, larger structure, integrated system)
    - **Control actuator development** and performance assessment
    - TRL advancement of **Numerical Predictor-Corrector algorithms** for this application
        - Density estimation algorithms for control and/or jettison timing
        - Verification that these algorithms can be supported by current platforms (e.g. for C&DH computational resources and timing, sensor accuracy and noise)
    - **Autonomous Optical Navigation** is needed to target outer planets to compensate for poor ephemeris



ADRAT Conclusions

1. The relevance of Earth aerocapture demonstration missions to potential aerocapture at the outer planets is limited to **technology advancement and model correlation that can improve confidence in models for extrapolation and scaling**

2. An Earth aerocapture demonstration mission would **reduce the risk of aerocapture to other solar system destinations** that have a well-known atmosphere where scaling and model extrapolation have high confidence



Nuclear Propulsion

“Fission power systems can …offer new possibilities for more capable missions and access to the farthest reaches of the solar system and beyond. NTP and NEP …can significantly lower costs while enabling heavier science payloads and more frequent missions, and more importantly, open up exciting new science concepts.”

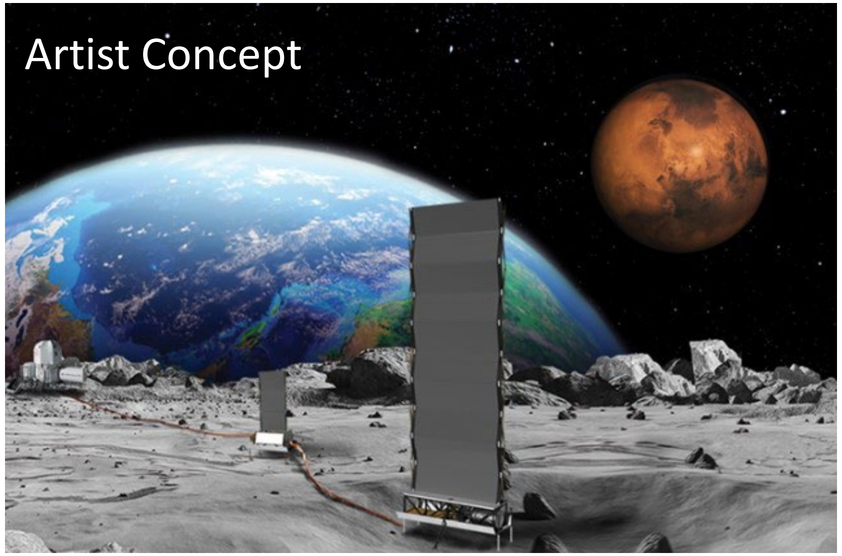
-- Origins, Worlds and Life: A Decadal Strategy for Planetary Science and Astrobiology (2022)

“Flight times to Saturn with 10 kW NEP can be as short as 5 years with 50 kg of science payload and 500 kbps of downlink data rate compared to 10 years with solar panels or RTGs”

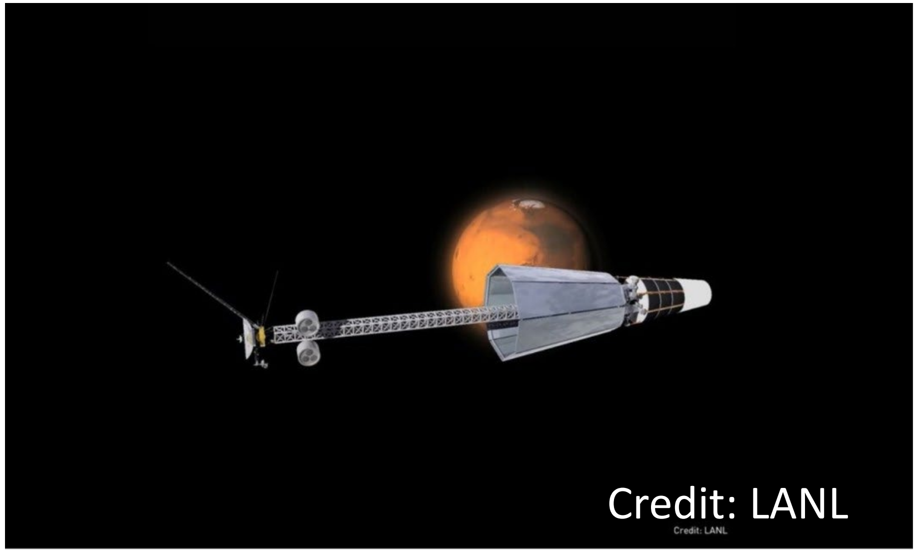
“Outer solar system exploration missions having a Cassini-class science payload within short mission lifetimes (8 to 15 years)”

-- J.R. Casani et al: “Enabling a New Generation of Outer Solar System Missions: Engineering Design Studies for Nuclear Electric Propulsion” White Paper to Planetary Decadal Survey Report

Major Contracts Relevant to Future Nuclear Propulsion for the Outer Planets



Fission Surface Power
NASA STMD
(Lockheed Martin, Westinghouse, Intuitive Machines)
$5M design studies



JETSON
Nuclear Electric Propulsion
USSF/AFRL
Lockheed Martin, $33M through CDR
Westinghouse $17M tech maturation
Intuitive Machines $10M low-power design
PDRs in 2026

DRACO Nuclear Thermal Propulsion
NASA and DARPA
(Lockheed Martin)

Summary

- Outer planet missions that do more than fly-bys are a high priority for science exploration

- Conventional chemical propulsion with radioisotope power results in very long trip times

- Aerocapture can substantially reduce those trip times
  - Uncertainties in knowledge of outer planet atmospheres is the largest risk to the successful use of aerocapture
  - An Earth-based technology demonstration:
    - would NOT retire risks associated with atmospheric uncertainty.
    - COULD retire GN&C risks, validate critical models, and provide direct benefit for the use of aerocapture at destinations with well understood atmospheres

- Nuclear propulsion can also reduce trip times and development is underway

- SMD is requesting that STMD develop an Earth-based, small spacecraft aerocapture technology demonstration

Backup

Aerocapture Demonstration Relevance Team (ADRAT)

1. What are the top risks associated with using aerocapture on future NASA missions to the outer planets?
   - **The largest risk is uncertainty in the environment**
     - Uncertainty in the vertical profiles of fundamental atmospheric conditions
     - Uncertainty in the aerothermodynamics of a hypersonic vehicle with the atmosphere it encounters at extreme hypersonic speeds
   - The greatest barrier to infusing aerocapture in an outer planet mission is the inability to sufficiently characterize the environment to produce a mission with an acceptable level of risk

Aerocapture Demonstration Relevance Team (ADRAT)

2. **What architecture(s) and requirements are necessary for a tech demo to retire identified risks for various aerocapture techniques?**
   - Improved atmospheric model fidelity
   - **Aerothermal response modeling** including TPS surface and flow-field chemistry and coupled TPS material response modeling
   - **TPS development** of rigid body and 3-D woven dependent on mission implementation (e.g. higher heating rates, larger structure, integrated system)
   - **Control actuator development** and performance assessment
   - TRL advancement of **Numerical Predictor-Corrector algorithms** for this application
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   - **Autonomous Optical Navigation** is needed to target outer planets to compensate for poor ephemeris

Aerocapture Demonstration Relevance Team (ADRAT)

3. **Would a demonstration of aerocapture using a small spacecraft in Earth's atmosphere buy down any of those risks? If so, what data would be most beneficial to collect?**
   - An Earth demonstration would not directly address the outer planet aerocapture risks that are dominated by environment uncertainty
   - An Earth demonstration can't meet the high heat fluxes or entry velocities (>20 km/s) to simulate the hypersonic conditions of an outer planet entry
   - **However, an Earth demonstration could improve the integrated system TRL for lift modulated direct force modulation and/or drag modulation and provide valuable data for model correlation**
     - Hypersonic flight test needed to mature ADEPT beyond TRL 5 since aeroheating and separation event can't be adequately tested on the ground
     - TRL advancement and model correlations would provide benefit to destinations with a well-understood atmosphere and approach velocities similar to demonstration velocity (e.g. Mars, Venus)
   - Other than data needed to address the overall aerocapture development, there is no additional specific data collection relative to an outer planet demonstration that would be beneficial

Aerocapture Demonstration Relevance Team (ADRAT)

4. **There are at least two fundamental concepts to control a spacecraft during aerocapture: drag modulation and lift modulation. Is one of these clearly more beneficial to demonstrate as risk reduction to the outer planets?**
   - No. Until a mission design is selected, the methods can't be directly compared as both have pluses and minuses
     - Optimization is destination dependent and time dependent. One size fits all isn't possible (e.g. Titan vs Uranus)
     - Both demonstrate GNC and density estimation with known Earth atmosphere
     - Both should continue to be pursued to provide more tools by improving the TRL of respective methods
     - Each would qualify different TPS materials
       - Drag modulation: ADEPT, woven carbon fiber TPS on the drag skirt
       - Lift modulation: conformal 3-D Mid-Density Carbon Phenolic (3MDCP)
   - Scaling would be needed in either case if demonstrated on SmallSats

ADRAT Results

1. Use of aerocapture at the outer planets provides potential mission benefits in mission duration and mass delivery to orbit
2. The risks are real, dominated by uncertainty in the destination’s atmosphere and environment, and need mitigation before an aerocapture mission to the outer planets can be undertaken
3. A mission design effort is needed to provide a frame of reference for an aerocapture technology trade study
4. Steps can be taken to advance the needed technologies and reduce uncertainty to relieve the implementation burden on the future project
5. **Earth aerocapture technology demonstrations are useful to raise the TRL of the various techniques and associated TPS materials, providing options for outer planet aerocapture missions**
6. There are many specific, high-risk aspects of aerocapture for an outer planet that cannot be addressed in an Earth demonstration
7. An Earth demonstration would provide benefits for an aerocapture mission at destinations with a well understood atmosphere

ADRAT Recommended Next Steps (1/2)

1. Invest in technology development now that would reduce the uncertainty and reduce the burden on the implementing project
2. Perform a relevant mission design study for the outer planets, including Titan, to address specific risks and enable a direct comparison of the various aerocapture methods

   Note: Aerocapture implementation will be destination dependent
3. Collect data on a precursor orbiter/probe mission specifically targeted to enabling subsequent aerocapture-based missions to reduce the atmospheric uncertainty and associated risk of a future aerocapture mission

ADRAT Recommended Next Steps (2/2)

4. Atmospheric Characterization
    - Continue efforts to update and improve the fidelity of GRAMs for the outer planets, including Titan
5. Entry Systems Modeling and Testing
    - Continue/accelerate ground testing and analysis of TPS behavior in an H2/He environment
    - Continue tool development for dynamic Computational Fluid Dynamics (CFD) analysis
    - Consider a study to characterize thruster performance in a relevant aerocapture (shock) environment
6. Continue to explore aerocapture technology enhancements in order to improve margin position