ScienceCraft for Outer Planet Exploration (SCOPE)

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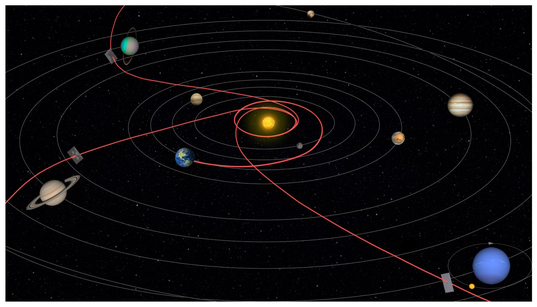
NIAC NASA Innovative Advanced Concepts

Motivation

- Exploring the outer planets and their moons will enable us to better understand Earth, as well as the formation and evolution of the solar system.[1]
- However, outer solar system exploration has been extremely limited due to high cost, long travel time and narrow window for mission implementation.
- The recent Planetary Decadal Study has identified outer planet missions as a gap in NASA's portfolio.[1]
- **We are developing a science mission architecture that addresses all of the key challenges of outer planet exploration and makes compelling scientific measurements.**

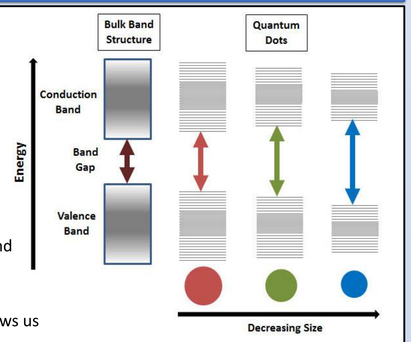


Multiple scienceCraft can be launched for different targets at the outer solar system for a relatively lower cost.

[1]*Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023 - 2032*, 2022

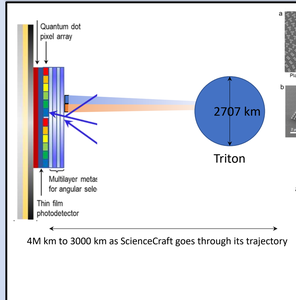
Quantum Dots

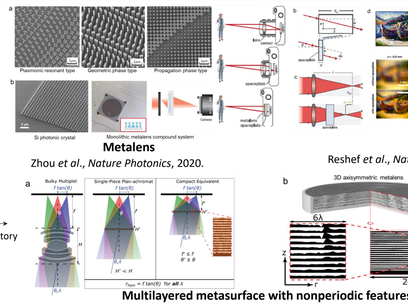
- Quantum dots are nanometer-sized crystals of semiconducting material.
- The size of quantum dots is smaller than twice its exciton Bohr radius, leading to:
  - Quantum confinement of electric charges
  - Discreet, quantized energy levels
  - A unique and well-defined emission and absorbance/transmission spectrum
- As the size of quantum dots decreases, the quantum confinement strengthens, increasing the bandgap, and shifting the absorbance/transmission spectrum in wavelength.
- The size dependency of the transmission spectra allows us to produce a well-defined, continuously tunable, yet distinct, set of absorptive filters.
- Quantum dots are printed using a suspension. When solvent evaporates, it leaves a solid layer of quantum dots called a quantum dot pixel. An array of quantum dot pixels are integrated with a detector to form an ultra-compact spectrometer



Quantum dots of gradually varied sizes

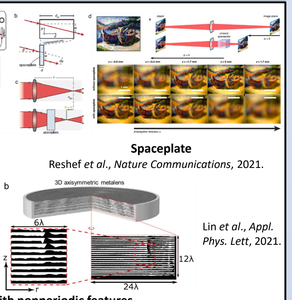
Enabling A Hyperspectral Imager





Metalens

Zhou *et al.*, *Nature Photonics*, 2020.



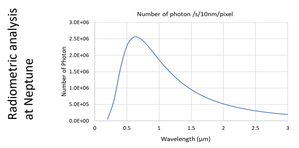
Spaceplate

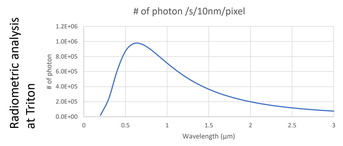
Reshef *et al.*, *Nature Communications*, 2021.

Lin *et al.*, *Appl. Phys. Lett*, 2021.

Multilayered metasurface with nonperiodic features

- Optics is not necessary for spectroscopy, but for imaging. The SCOPE team is currently working towards the demonstration of an integrated metasurface with QDS to achieve angular selectivity.





Neptune-Triton Mission: A Case in Point

- Triton has been identified as the highest priority ocean world by the NASA Outer Planets Assessment Group (OPAG) Roadmap to Ocean Worlds.[2]
  - Largest moon of Neptune
  - A Kuiper Belt Object captured by Neptune
  - One of the youngest surfaces in our solar system
  - Geologically active - plumes, geysers
  - Predicted oceans
  - Energetic ionosphere
  - ~60% of the surface is left unexplored[3]

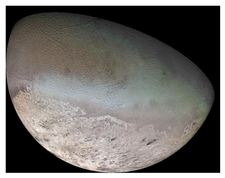
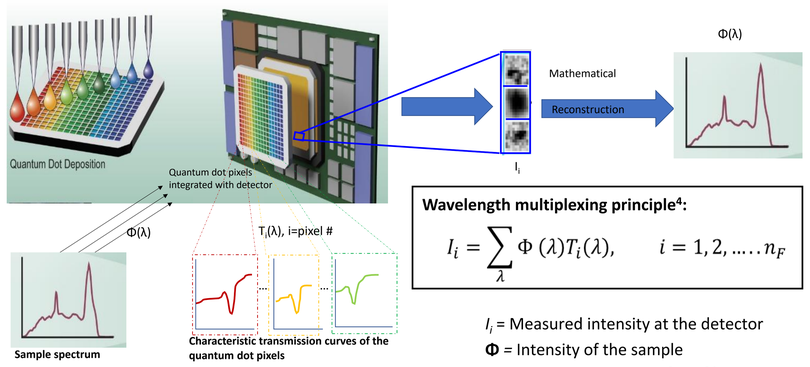


Image of Triton taken by Voyager 2 in 1989 during its flyby of the Neptune system

- However, Triton has a narrow window for a traditional propulsion-based mission that closes around 2045 and does not repeat for at least another century.[2]
- Planetary Decadal 2023-2032 named Uranus Orbiter and Probe (UOP) as the highest-priority new Flagship mission for initiation in the decade 2023-2032. The main reason for targeting Uranus instead of Neptune-Triton system is the lack of launch opportunity for Neptune in the target window.
- Conventional propulsion would take a 12+ year travel time to Triton, making it less and less likely to meet the narrow window.

[2]Hendrix *et al.*, *Astrobiology*, 2019
[3]Frazier *et al.*, *IEEE Aerospace Conference*, 2020

Quantum Dot Spectrometer



Wavelength multiplexing principle[4]:

$$I_i = \sum_{\lambda} \Phi(\lambda) T_i(\lambda), \qquad i = 1, 2, \ldots . n_F$$

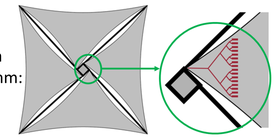
I_i = Measured intensity at the detector
Φ = Intensity of the sample
T_i = Transmission curve of QD filter *i*
n_F= Number of QD filters

Quantum dot spectrometer eliminates optical elements such as gratings and prisms, used in traditional spectrometers, that require a long pathlength to achieve high spectral resolution, and

[4]Bao *et al.*, *Nature*, 2015

End-to-End Mission Design that Closes

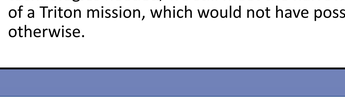
- The current baseline solution budgets for both RF and laser comm with OTS components, but ongoing developments in both should decrease mass budget for comm:
  - 2-dimensional RF antenna structurally integrated with the solar sail.[10]
  - Miniaturized laser comm currently under development by Fibertek is customized for the Neptune-Triton mission.[11]



An integrated RF antenna (indicated in red) on the solar sail.[10]

1x2U lasercom system consisting of electronics (left) and optical module (right).[11]

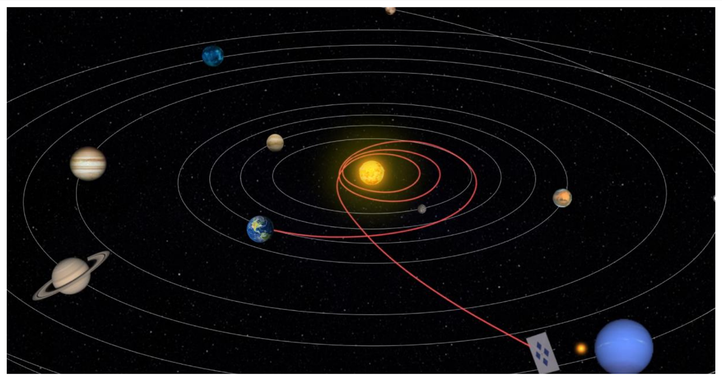
- Sail and boom architecture trade studies are being performed in partnership with Opterus to optimize the sail size.
- The ADCS solution leverages all commercially available components.
- The current baseline for power uses betavoltaic using Strontium-90, with Americium based Atomic Planar Power for Lightweight Exploration (APPLE) (NIAC 2021) as a backup option.



Lightweight Single sided APPLE consisting of a 2-D RTG and rad hard battery can be integrated with ScienceCraft to provide high specific power.[9]

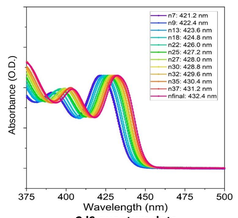
[9]Nemanik, E.J. *et al.*, *NIAC Phase I Study Report*, 2022.
[10]Appel, N., *IEEE Aerospace Conference*, 2022.
[11]Mathason et al., *Small Satellite Conference*, 2019

Solar Sail for Outer Planet Exploration

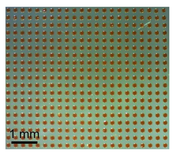


- Swinging around the Sun at a close proximity allows solar sails to reach outer solar system in a few years.
- Recent developments of small satellite components are enabling or solar sails.
- However, solar sails have extremely limited mass allocations for science payloads.

Advantages of Quantum Dot Spectrometer



CdS quantum dots



Quantum dot pixels printed at GSFC

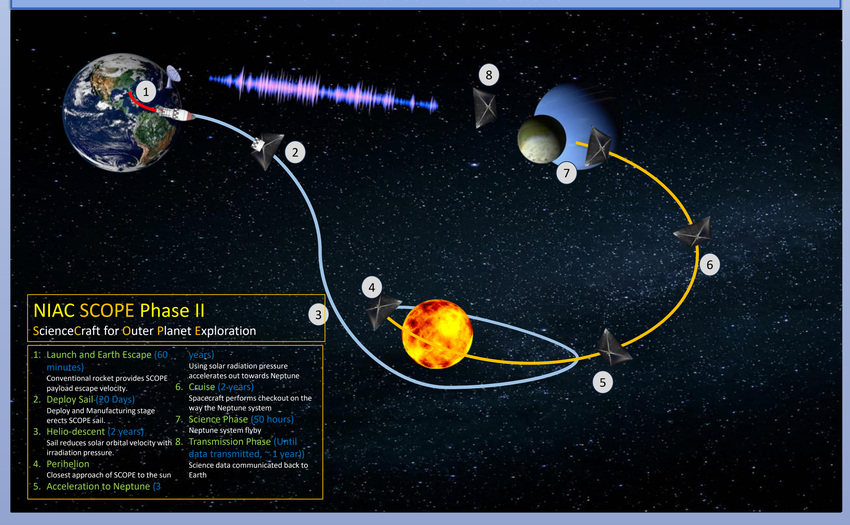
Spectroscopy	Wavelength	Quantum Dot Composition
Ultraviolet	300 -400 nm	Zinc Oxide, Zinc Sulfide, Zinc Selenide
Visible	400 -700 nm	Cadmium Sulfide, Cadmium Selenide, Cadmium Telluride
Near Infrared – Mid Infrared	700-3000 nm	Lead Sulfide, Lead Selenide, Indium Arsenide, Mercury Telluride

Composition of nanocrystals to cover different ranges of wavelength

- Printed on flexible substrates and directly on the detector pixels, eliminating any alignment issues
- Provides the ability to customize the wavelength and bandwidth of only the spectral features of interest in order to maximize the signal-to-noise

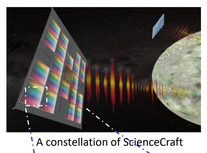
With a single instrument, we can perform several scientific measurements, including infrared spectroscopy for atmospheric chemistry, visible imaging and ultraviolet spectroscopy

Power and Communications

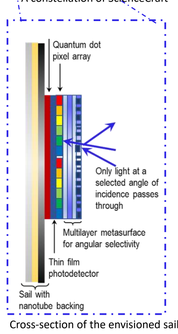


ScienceCraft

- ScienceCraft integrates a science instrument, a quantum dot-based spectrometer, with a solar sail into one monolithic and lightweight structure
- Quantum dot spectrometer is a unique high throughput spectrometer that can be printed as a thin film directly on the solar sail
- The key advantages of ScienceCraft include:
  - Fast transit missions with shorter lead time
  - Relatively lower cost -> targeting SIMPLEX/Discovery cost cap
  - **Relatively lower power need that can be met with non-plutonium options**
    - **The current administration plans to stop plutonium production past the Dragonfly mission**
  - Can be a secondary payload, increasing launch opportunities
  - Does not use techniques like gravity assist, significantly expanding mission implementation window
  - Offers a scalable and low resource platform for science missions -> can use constellation for greater coverage and greater science return



A constellation of ScienceCraft

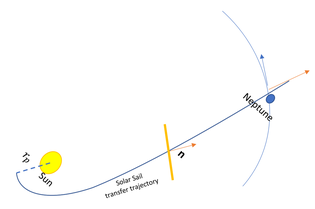


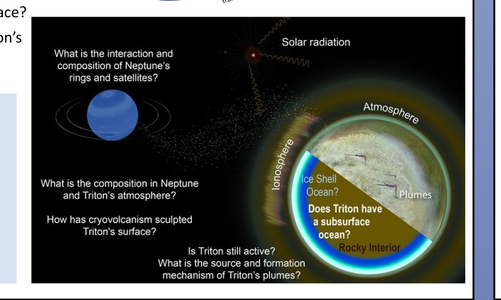
Cross-section of the envisioned sail

Mission Concept Based on Phase I Study

- End-to-end mission feasibility study confirms no show-stopper for a flyby mission
- SCOPE will address several high priority science questions outlined in the Planetary Decadal Survey[1]:
  - Does Triton have a subsurface ocean?
  - Is Triton still active?
  - What is the source and formation mechanism of Triton's plumes?
  - How has cryovolcanism sculpted Triton's surface?
  - What is the composition of Neptune and Triton's atmosphere?

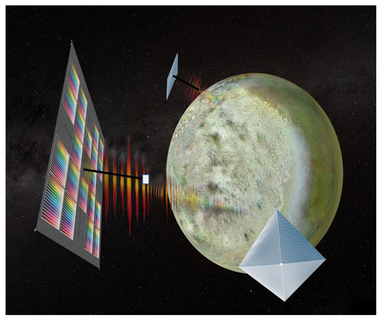
SCOPE can perform most of the science measurements that Trident, a Discovery mission proposal for the Neptune-Triton system, was targeting but at a significantly reduced cost and with much better launch opportunities and broader mission implementation window.





Summary

- ScienceCraft is a game changing concept that offers a new mission architecture for the outer solar system at a relatively low cost.
- By using several cutting-edge technologies, including quantum dots, precision nanoprinting techniques, metasurface, integrated sciencecraft and miniaturized laser comm system, it addresses all the major challenges of outer solar system missions.
- The proposed methodology of SCOPE makes ScienceCraft scalable and low cost, allowing us to fly a constellation of ScienceCraft for a great coverage of the planetary target, or to multiple targets.
- While we are working on a Neptune-Triton mission concept, ScienceCraft can be used for other targets in the solar system.
- The Triton mission concept highlights one of the biggest advantages of the proposed mission architecture, which is that even if it takes 5-10 years to develop all the technologies needed, we still meet the narrow window of a Triton mission, which would not have possible otherwise.



SCOPE will investigate the use of a constellation of ScienceCraft to image Neptune-Triton system