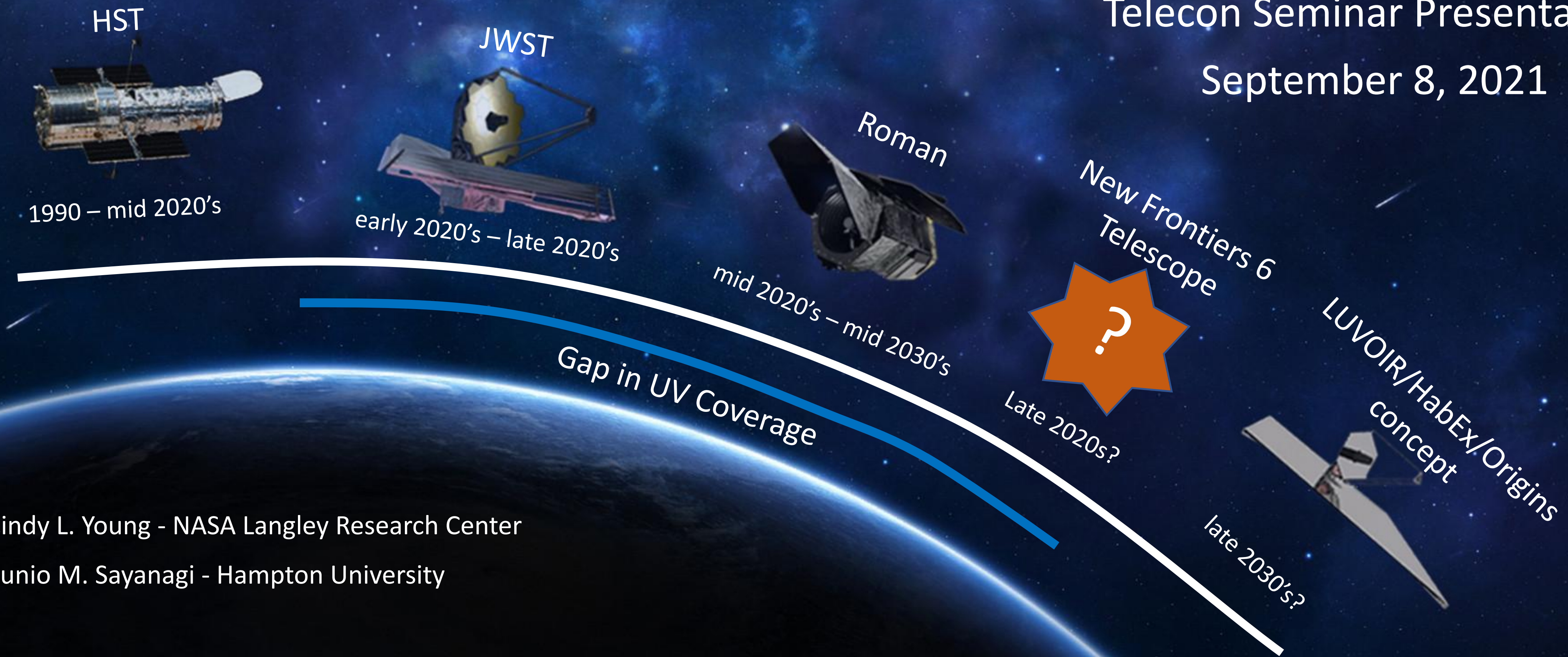
CHARISMA: A Concept for an in-Space Assembled Telescope Dedicated to Solar System Science

Future In-Space Operations (FISO)
Telecon Seminar Presentation
September 8, 2021



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Solar System
Space Telescope Team

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Summary

- Unique science only enabled by UV observation
  - Time-domain science (high frequency, long-duration)
  - New, wide-ranging small bodies surveys
- Urgent need: preserve UV observation capabilities
- Mission targets
  - A focused space telescope mission is viable
  - Can potentially serve broad planetary science community
- Telescope Architecture options; optimized for:
  - Spatial resolution
  - Photometric sensitivity
  - Balance of both
- Concept study needed as recommended by CAPS
  - Survey of technology options
  - Examine benefits of Deployment and in-Space Assembly
  - Point design to demonstrate viable options for the next decade
- We advocate to add a solar system space telescope to the NF6 list

The time for a solar system space telescope is NOW!

Recommendations by Recent National Academies Reports

Getting Ready for the Next Planetary Science Decadal Survey (2017):

"Synoptic observations of solar system bodies are limited by two factors, the availability of telescope time and resolution. First, while current (e.g., Hubble Space Telescope and Spitzer Space Telescope) and future (e.g., James Webb Space Telescope and Wide-Field Infrared Space Telescope) space observatories are available to the planetary astronomy community and are not resolution constrained, such assets are in great demand for other astronomical studies. Therefore, the availability of telescope time for long-term monitoring of, for example, Titan, Europa, and Io or for surveys is highly limited. Second, the resolution of such observations is primarily dictated by telescope aperture (the larger the aperture the greater the cost of the mission). Hence, *studies to determine the potential scientific return of a space telescope dedicated to the monitoring and studies of solar system bodies that can be achieved within the scope of either the Discovery or the New Frontiers programs would benefit the next planetary science decadal survey.*

Visions into Voyages for Planetary Sciences in the Decade 2013-2022: A Midterm Review (2018):

NASA should conduct an assessment of the role and value of space-based astronomy, including newly emerging facilities, for planetary science.
This assessment should be finished before the next decadal survey is significantly under way.

NASA Response to the Midterm Review Recommendation (2018):

NASA agrees that it is important to continue to explore the role that space-based astronomy plays in planetary science and will seek community input for an assessment through a mechanism such as a community workshop or study, the planning for which will begin in 2019. Further, NASA recognizes that space-based astronomy has already proven its value for planetary science such as observing the Comet F2 D/1993 Shoemaker-Levy 9 impacts with Jupiter using the HST; discovering approximately fifty of the potentially hazardous asteroids with NEOWISE and characterizing many more with NEOWISE and Spitzer; discovering the New Horizons follow-on target 2014 MU69 in the Kuiper Belt with HST; and assessing the potential hazard to the Mars orbiters posed by Comet C/2013 A1 (Siding Spring) using HST, NEOWISE, Spitzer and Swift.

Science Needs

Young et al., 2020 Science White Paper

Understand Temporally Dynamic Phenomena

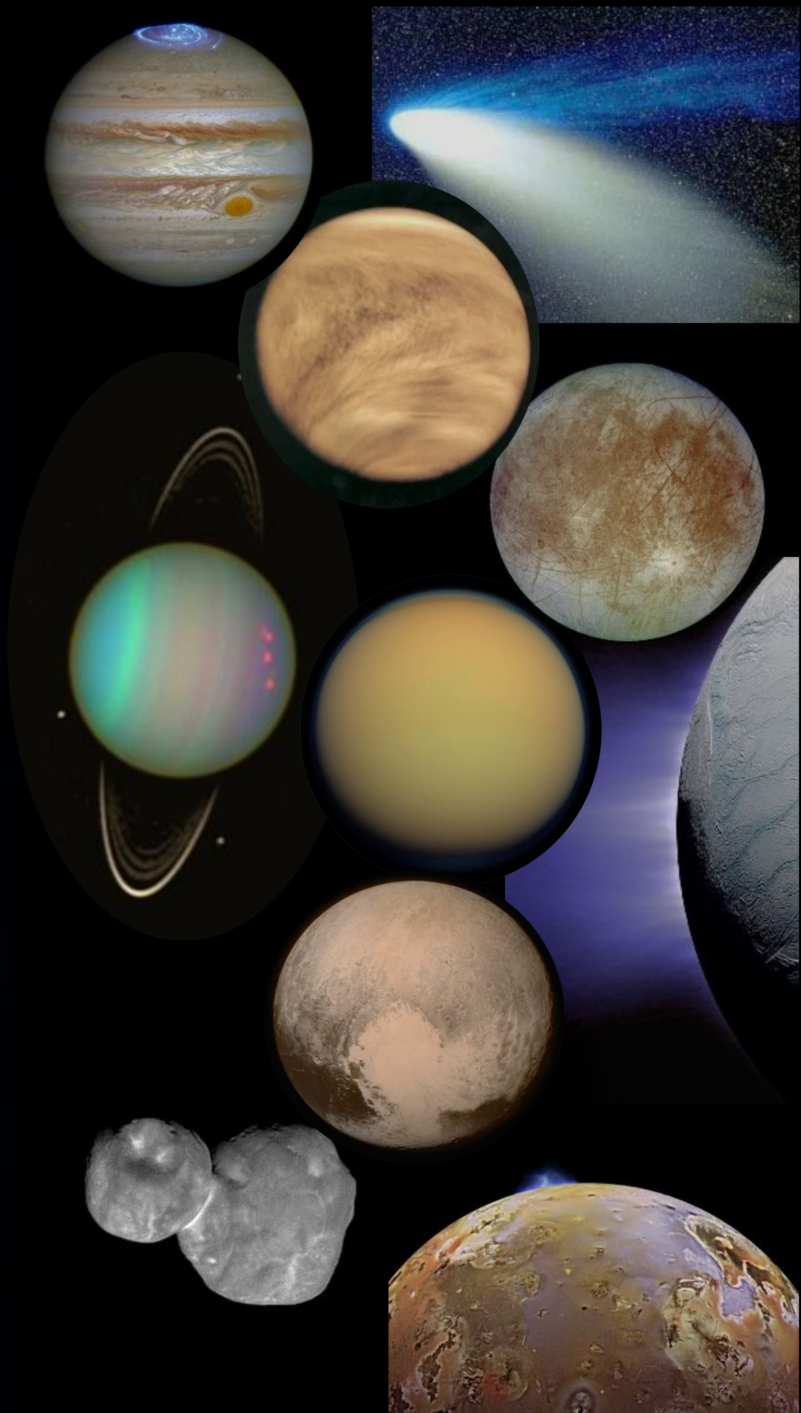
High-Frequency, Long-Duration Campaigns to understand:

- Interaction of planetary magnetospheres with the solar wind
- Venus and giant planet atmospheric dynamics
- Icy satellite geologic activity (e.g., plume searches) and surface evolution
- Evolving ring phenomena
- Cometary evolution & outgassing asteroids

Understand Origin and Evolution of Small Bodies

Comprehensive Spectral Survey of Solar System Minor Bodies to:

- Characterize Surface Properties and Composition
- Understand the overall physical properties including:
  size, shape, mass, density, porosity, and spin rate.



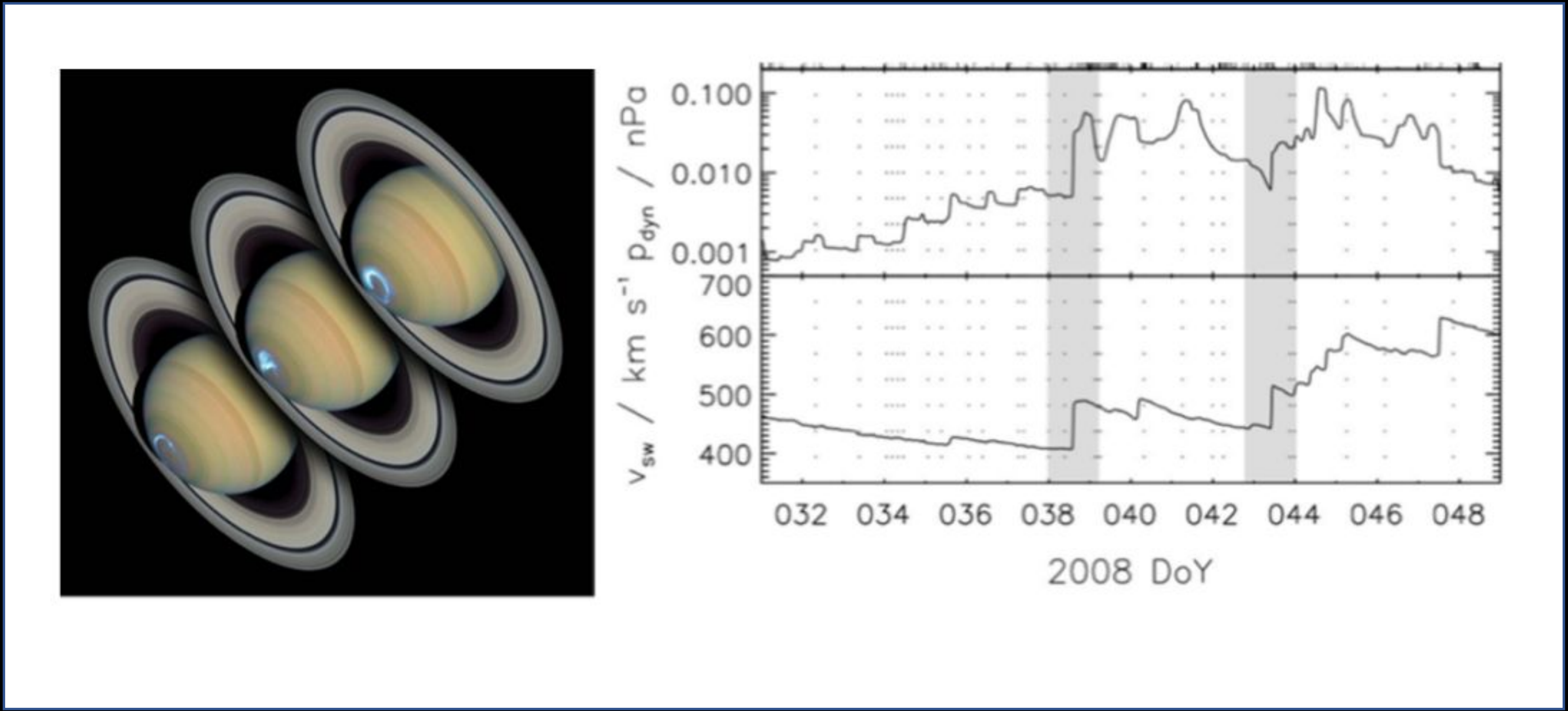
Magnetospheric Interactions

Must be in space to observe UV auroras!

Priority Questions

Telescope in Earth Orbit offers stable vantage point outside of planetary systems

1. What controls auroral processes on different timescales?
2. What is the balance between internal/external control of magnetospheric variability?



(left) HST far-UV images of Saturn's aurora and changes during an auroral storm, and (right) total auroral power at Saturn vs arriving solar wind speed. The shaded regions indicate the arrival of solar wind shocks at Saturn[8].

[8] Clarke et al., 2009 JGR (Space Physics).

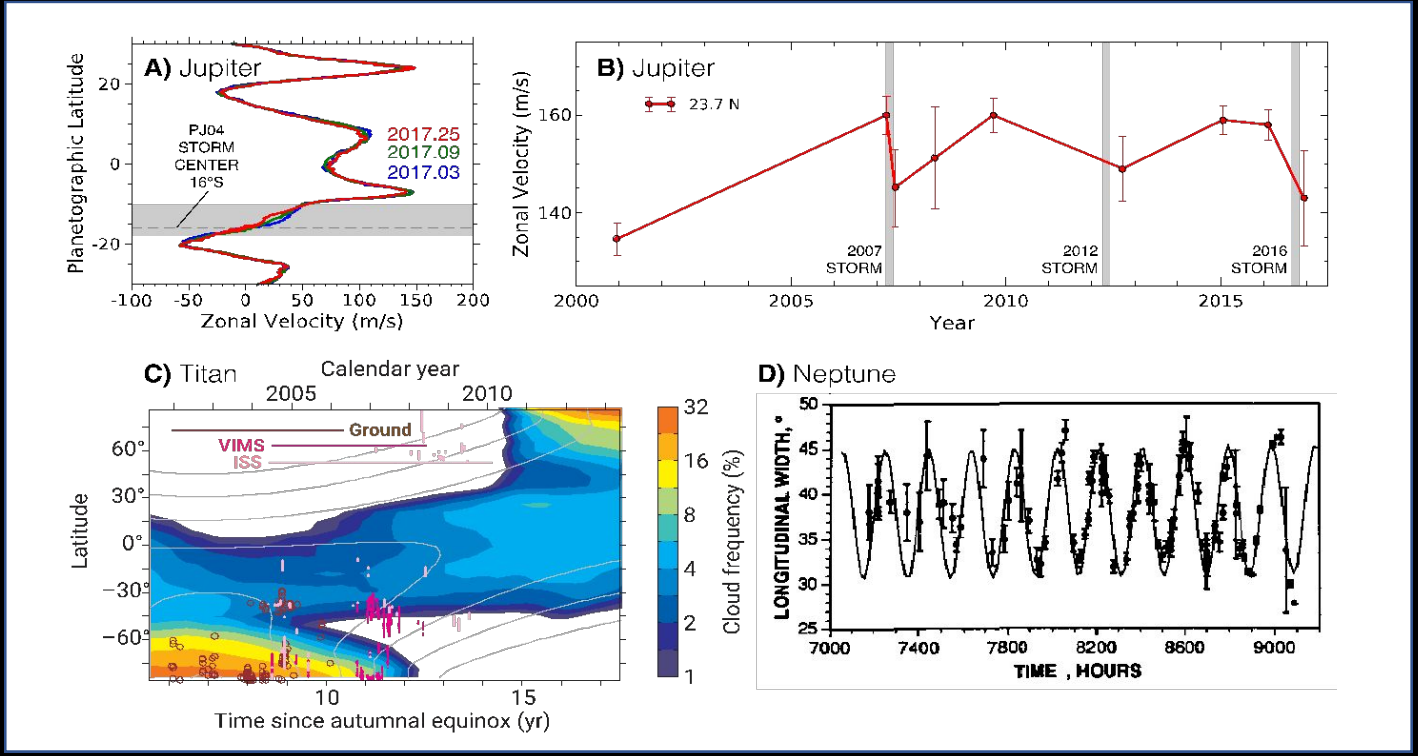
Dynamic Atmospheres

UV to provide unique information about atmospheric processes

UV capability is needed to observe atmospheres during stellar occultations

Priority Questions

1. How does energy/momentum transport vary temporally and spatially in dense planetary atmospheres?
2. How is vertical energy transport modulated by chemical and thermodynamic processes?
3. What is the current impactor flux and size distribution in the outer solar system?



Gaps exist in our understanding of storm/cloud activity, jets, and vortices of all planets with atmospheres due to the limited temporal coverage currently available. Major storm eruptions in Jupiter's southern (A) and northern (B) hemisphere alter zonal winds[5]. Models[6] duplicate storm activity at Titan's pole but not at mid- latitudes (C). Oscillations in the shape of Neptune's Great Dark Spot (D) from Voyager's Neptune approach give insights into deep stratification, wind shear, and chemistry[7].

[5] Tollefson et al., 2017 Icarus. [6] Schneider et al., 2012 Nature. [7] Sromovsky et al., 1993 Icarus.

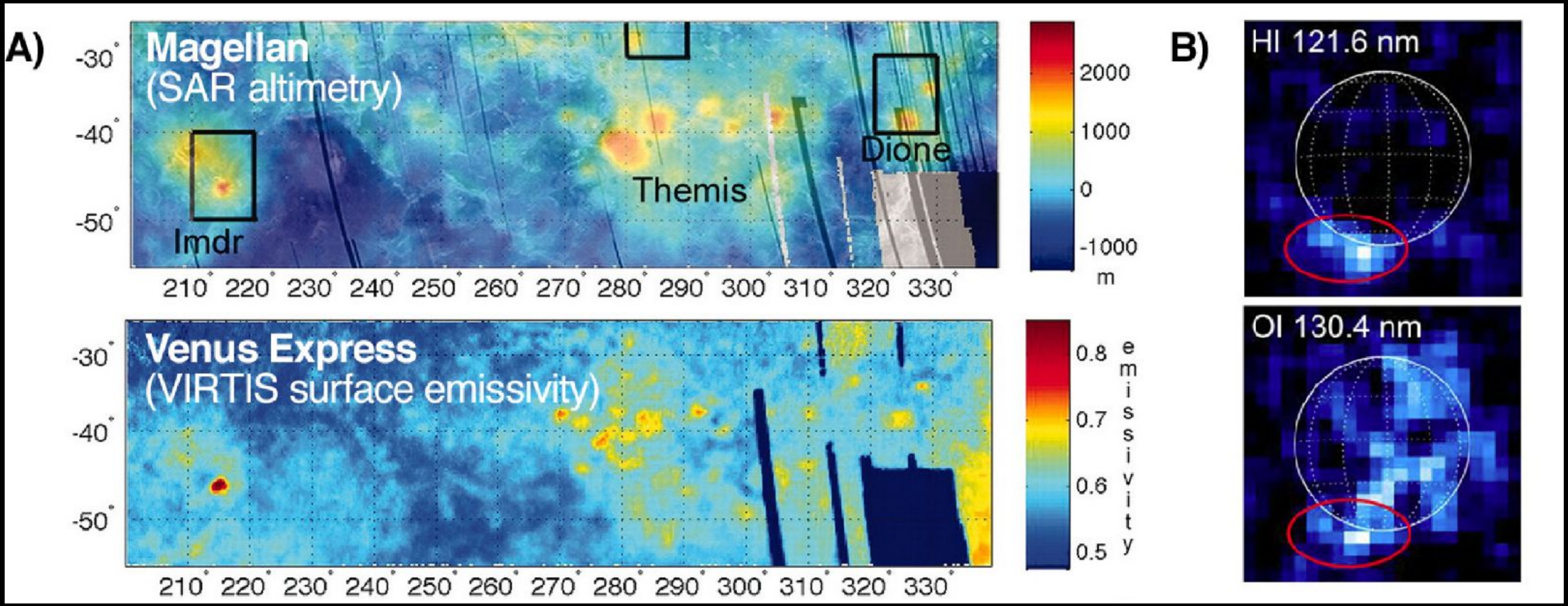
Active Plumes and Volcanism

UV needed for high-resolution detection of transient plumes

Complementary measurements of deposits and thermal anomalies in VNIR

Priority Questions

1. Are Venus and Titan volcanically active today?
2. What drives variability in volcanic and cryovolcanic activity?
3. What is the composition of magma and cryomagma reservoirs?



(A) Surface emissivity (bottom) reveals areas of recent lava flow on Venus that are less weathered than their surroundings. Surface emissivity is derived from spectral data in the 1.02 µm region[1].

(B) Plume activity on Europa is suggested by HST UV observations of transient signals[2].

[1] Smrekar et al., 2010 Science.

[2] Roth et al., 2014 Science.

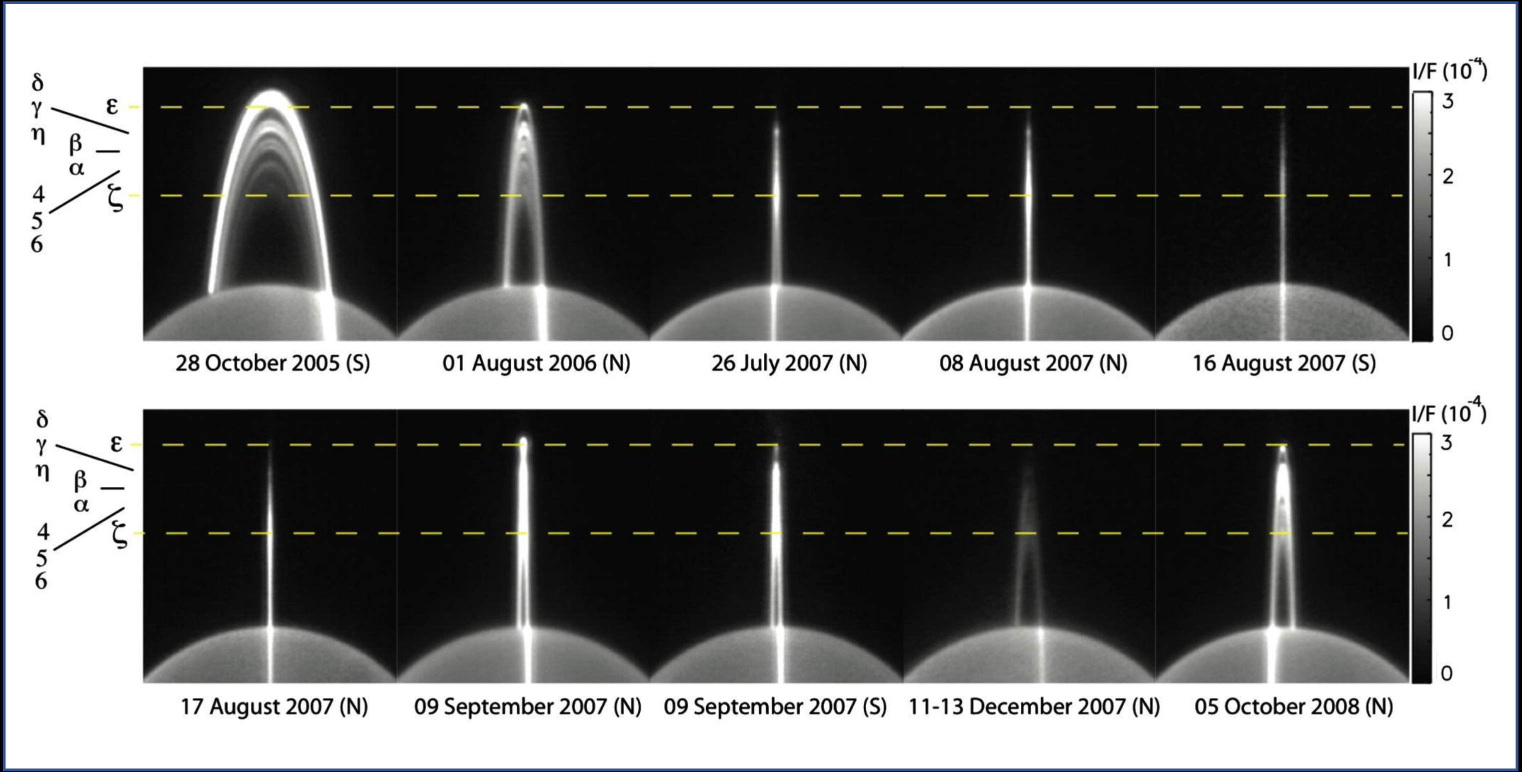
Planetary Ring Systems

Far-UV particularly sensitive to water ice

UV beneficial for studying collisional activity in the rings

Priority Questions

1. What are the current and past environments of planetary rings across the solar system?
2. How do ring structures evolve and interact with nearby and embedded moons?



Rings of Uranus observed by the Keck telescope. The Greek letters and numbers to the left identify the rings. The yellow lines mark the radii of the ∈ and ζ rings. Such edge-on observations enable detecting and characterizing dusty rings. [9]

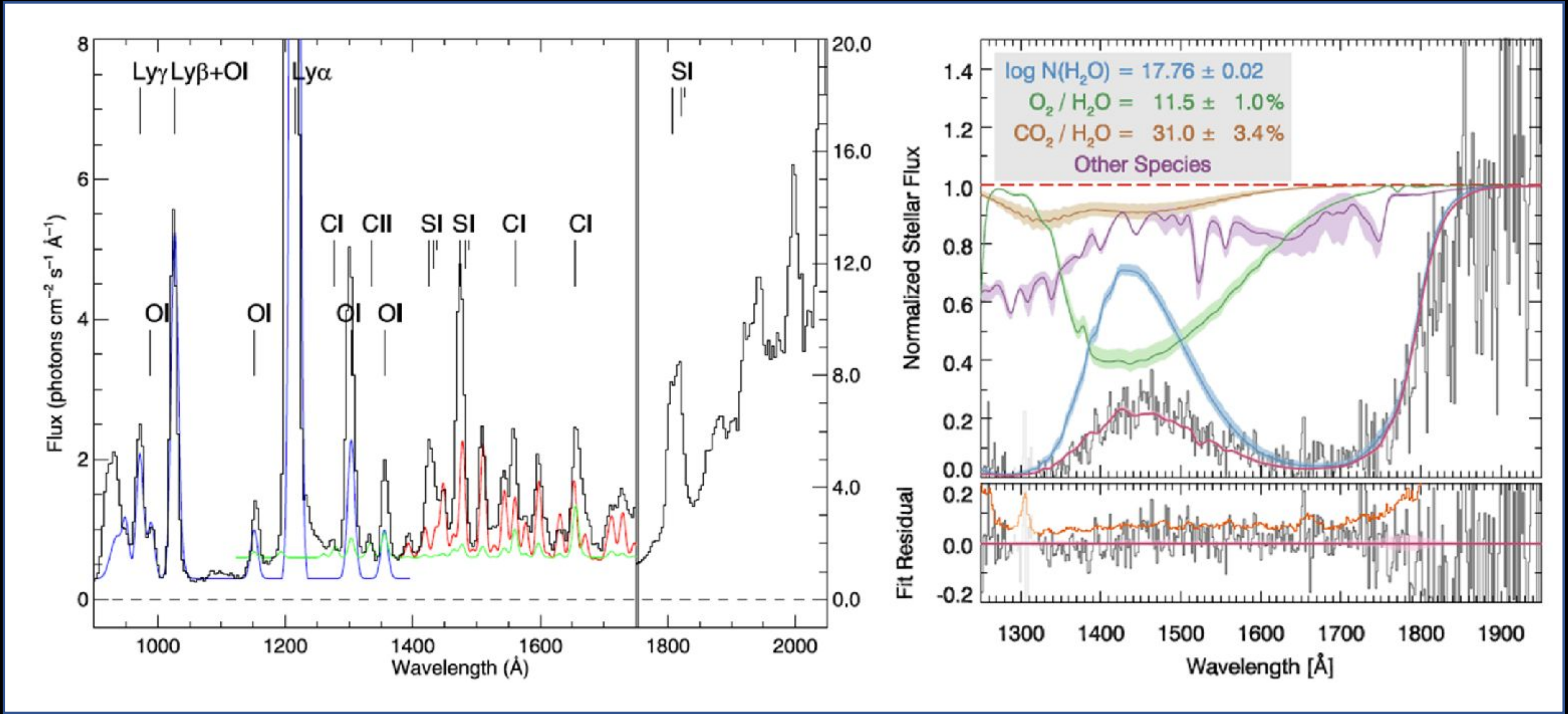
[9] I. de Pater, D. E. Dunn, D. M. Stam, et al. 2013, Icarus, 226

Cometary Evolution, Morphology, and Processes

Critical lines in UV are observable only from space!

Priority Questions

1. How do the coma and nucleus evolve with heliocentric distance (Rh)?
2. What drives outbursts and their frequency and how often is water ice expelled?
3. What processes dominate in the coma?



Left: atomic and molecular UV emission can distinguish coma processes such as electron impact (blue, green) and fluorescence (red) [1]

Right: Transmission during stellar occultation can determine associations between species such as O_2 and H_2O, as shown in these examples from Rosetta/Alice data [2].

[1] Feldman et al., 2018 Astronomical Journal.

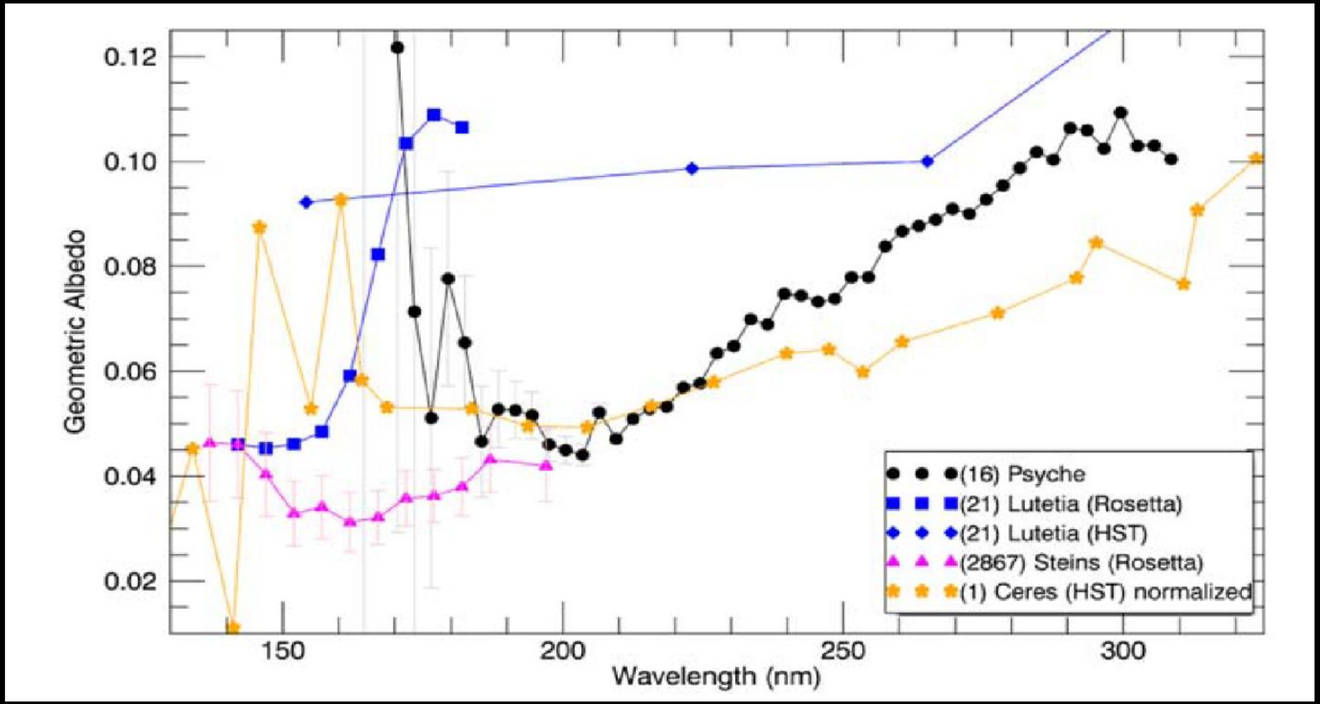
[2] Keeney et al., 2019 Astronomical Journal.

Main Belt and Near-Earth Asteroids

Priority Questions

1. What are the spectral characteristics of asteroids in the far UV? UV provides an important constraint for characterization

2. What is the composition and spatial extent of outgassing produced by active comet-like asteroids? UV instrumental in searching for gases



[5] Becker et al., 2020 Planetary Science Journal.

Left: Comparison of the geometric albedos for Psyche with Rosetta Alice observations of (2867) Šteins (purple triangles) and (21) Lutetia (blue squares), HST observations of (21) Lutetia (blue diamonds), and HST STIS observations of (1) Ceres (orange stars). These are the only four asteroids studied at wavelengths <220 nm, and their spectra appear very different from one another at these wavelengths [5].

UV provides brand new information!!!

Main Belt and Near-Earth Asteroids

Priority Questions

UV wavelengths are particularly sensitive to space weathering effects, allowing for the study of space weathering at relatively very low levels.

3. Can we constrain surface exposure to space weathering by measuring its effects on asteroids' UV reflectance spectra?

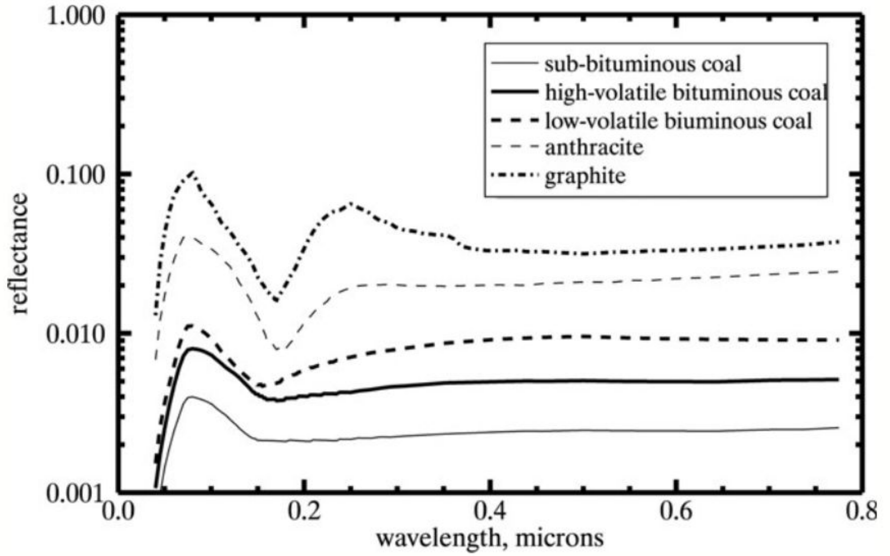
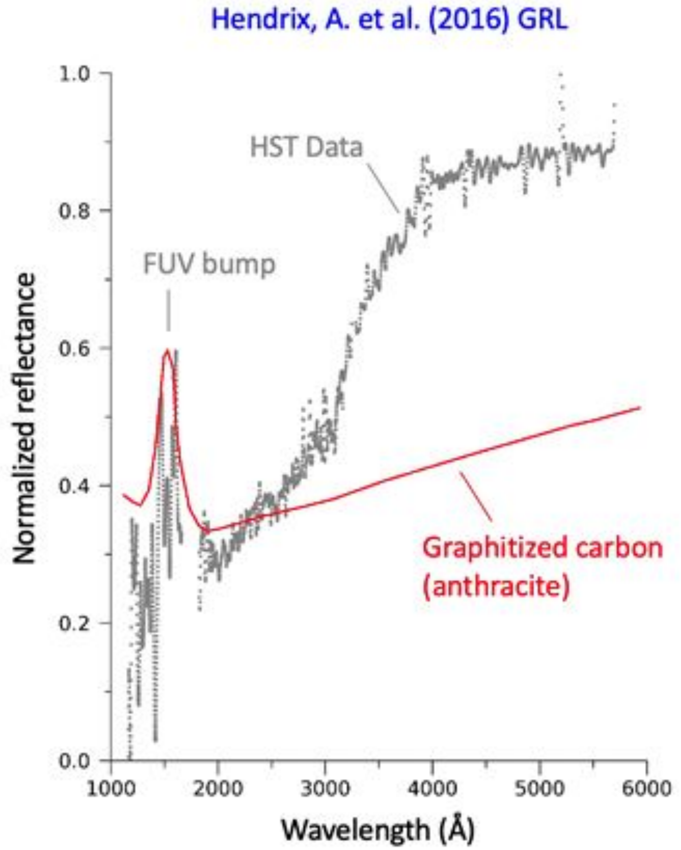


Fig. 1. Coals with increasing graphitization, showing that the absorption feature near 200 nm becomes stronger and narrower and shifted to the red; after Papoular et al. (1995) (their fig. 1); spectra are offset.


Hendrix, A. et al. (2016) GRL

Primitive, outer main belt low-albedo class asteroids are critical to studying links to the early solar system, but these targets have few features at VNIR wavelengths. Carbon compounds are spectrally active in the UV, unlike at other wavelengths.

Left: Coal is relatively featureless at VNIR wavelengths

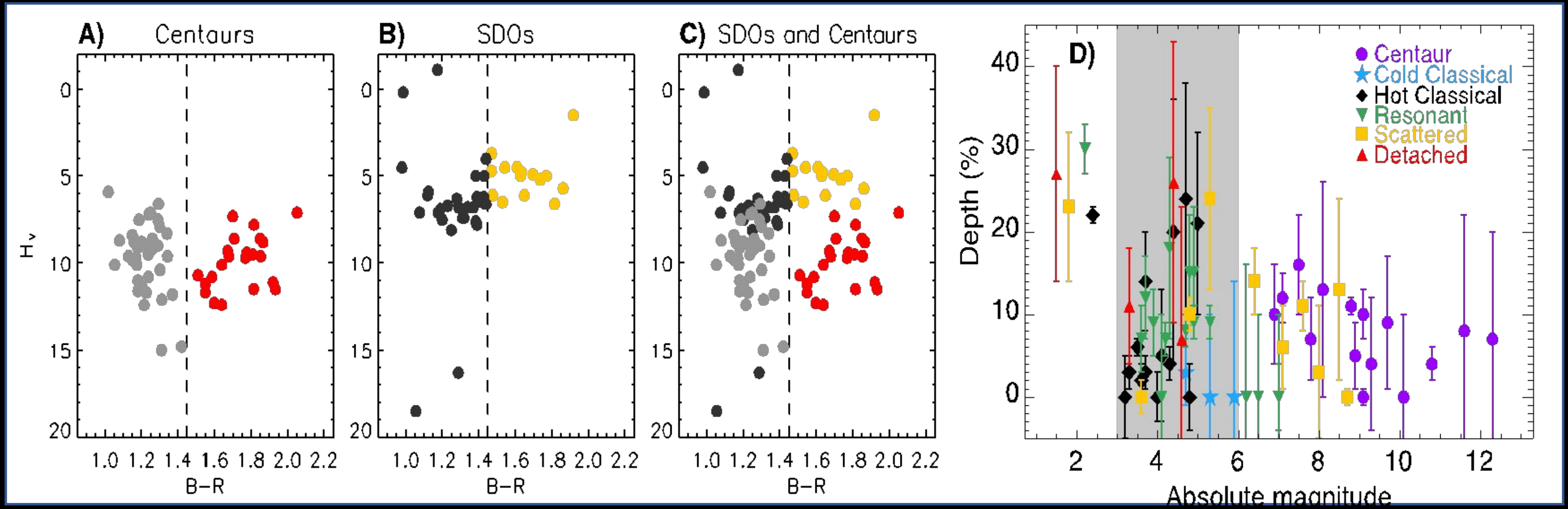
Right: FUV bump in HST spectrum of CERES matched to Graphitized carbon (anthracite spectrum).

Solar System Minor Body and Irregular Satellite Survey

Priority Questions

UV observations are an important part of the full picture!

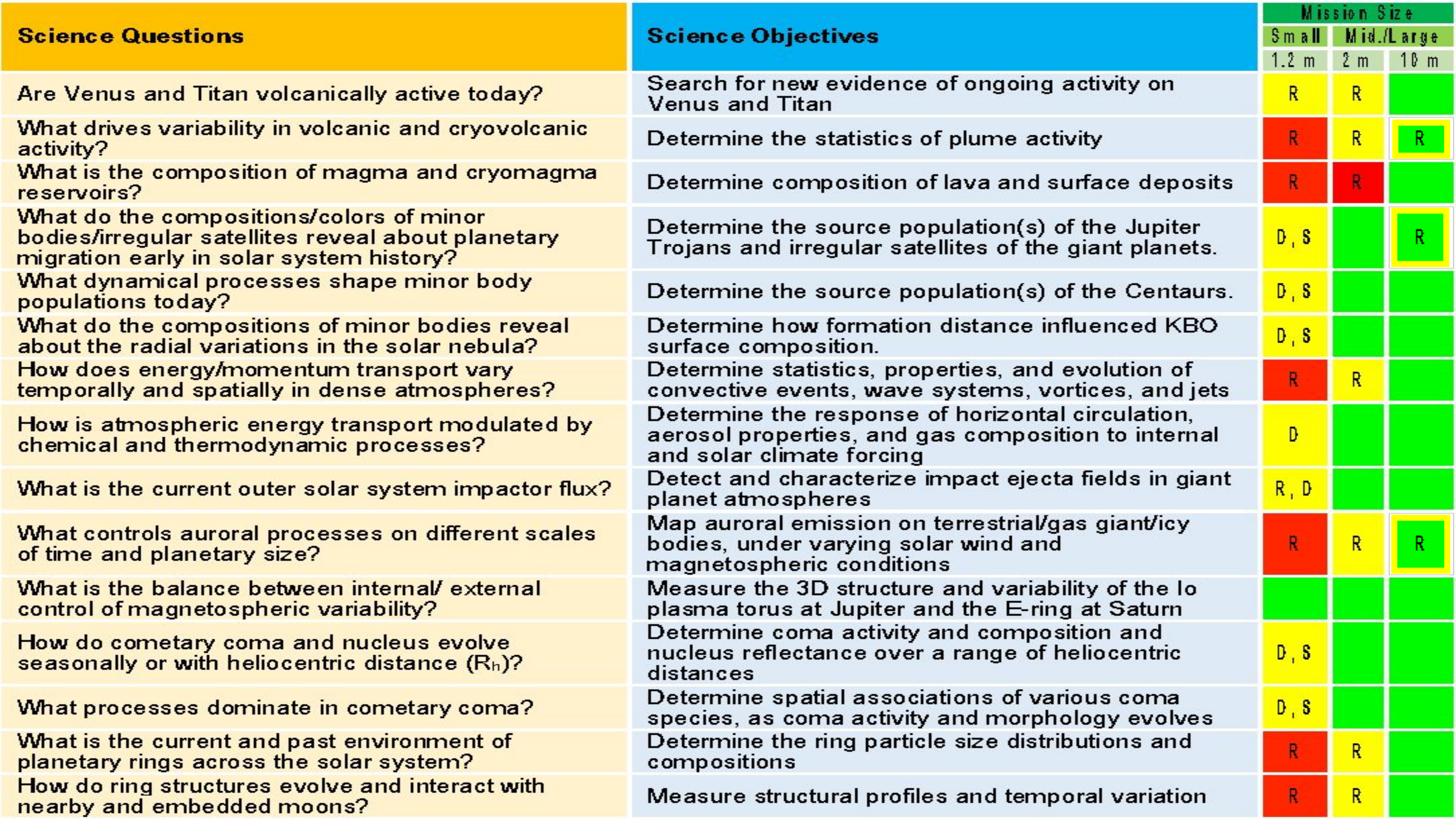
1. What do the compositions/colors of minor bodies/irregular satellites reveal about planetary migration early in solar system history?
2. What dynamical processes are shaping minor body populations today?
3. What do the compositions of minor bodies reveal about the radial variations in the solar nebula?



Broadband color data [3] (for (a) Centaurs, (b) Scattered Disk Objects (SDOs), and (c) both overplotted) cannot conclusively validate the dynamically-based hypothesis that Centaurs originate from the SDOs, requiring a spectroscopic sample from each population. (d) The transition region from water-rich to water-poor surfaces is shown in grey, in a plot of water ice feature strength vs. absolute magnitude [4].

[3] Hainaut et al., 2012 Astronomy and Astrophysics.

[4] Barucci et al., 2011 Icarus.



Science Questions	Science Objectives	Mission Size		
		Small	Mid./Large	
		1.2 m	2 m	10 m
Are Venus and Titan volcanically active today?	Search for new evidence of ongoing activity on Venus and Titan	🟨 R	🟨 R	🟩
What drives variability in volcanic and cryovolcanic activity?	Determine the statistics of plume activity	🟥 R	🟨 R	🟩 R
What is the composition of magma and cryomagma reservoirs?	Determine composition of lava and surface deposits	🟥 R	🟥 R	🟩
What do the compositions/colors of minor bodies/irregular satellites reveal about planetary migration early in solar system history?	Determine the source population(s) of the Jupiter Trojans and irregular satellites of the giant planets.	🟨 D, S	🟩	🟩 R
What dynamical processes shape minor body populations today?	Determine the source population(s) of the Centaurs.	🟨 D, S	🟩	🟩
What do the compositions of minor bodies reveal about the radial variations in the solar nebula?	Determine how formation distance influenced KBO surface composition.	🟨 D, S	🟩	🟩
How does energy/momentum transport vary temporally and spatially in dense atmospheres?	Determine statistics, properties, and evolution of convective events, wave systems, vortices, and jets	🟥 R	🟨 R	🟩
How is atmospheric energy transport modulated by chemical and thermodynamic processes?	Determine the response of horizontal circulation, aerosol properties, and gas composition to internal and solar climate forcing	🟨 D	🟩	🟩
What is the current outer solar system impactor flux?	Detect and characterize impact ejecta fields in giant planet atmospheres	🟨 R, D	🟩	🟩
What controls auroral processes on different scales of time and planetary size?	Map auroral emission on terrestrial/gas giant/icy bodies, under varying solar wind and magnetospheric conditions	🟥 R	🟨 R	🟩 R
What is the balance between internal/ external control of magnetospheric variability?	Measure the 3D structure and variability of the Io plasma torus at Jupiter and the E-ring at Saturn	🟩	🟩	🟩
How do cometary coma and nucleus evolve seasonally or with heliocentric distance (R_h)?	Determine coma activity and composition and nucleus reflectance over a range of heliocentric distances	🟨 D, S	🟩	🟩
What processes dominate in cometary coma?	Determine spatial associations of various coma species, as coma activity and morphology evolves	🟨 D, S	🟩	🟩
What is the current and past environment of planetary rings across the solar system?	Determine the ring particle size distributions and compositions	🟥 R	🟨 R	🟩
How do ring structures evolve and interact with nearby and embedded moons?	Measure structural profiles and temporal variation	🟥 R	🟨 R	🟩

Performance Requirements for Solar System Observations

1. Diffraction-limited imaging with resolution of up to 13 milli-arcsec at 500 nm wavelength

   Adaptive Optics not yet available for visible-UV wavelengths;
   could enable required resolution from the ground in the future?

2. Light-collecting area greater than that of a 2-meter filled aperture
3. Imaging and Spectroscopic capability between 100 nm – 2 µm

   UV wavelengths can be observed only from space

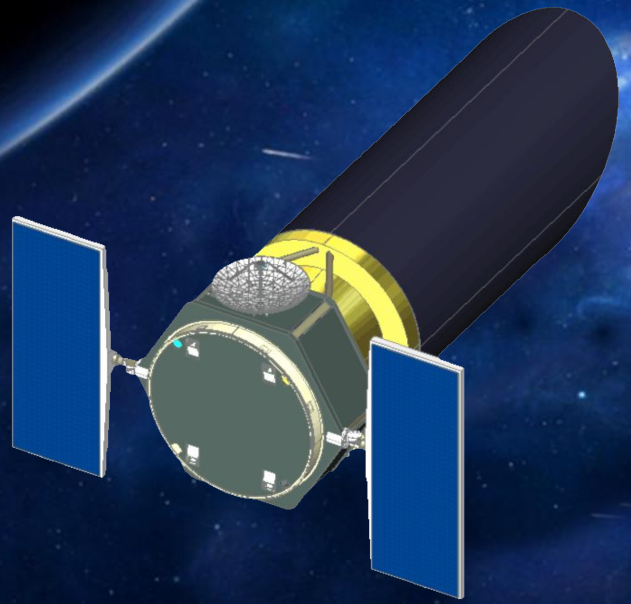
4. High-cadence, long temporal baseline observations

   Cadence of ground-based telescope is constrained by 24-hour Earth rotation

Need for a Space Telescope

Telescope Design Examples

Kuiper Space Telescope Discovery 2015

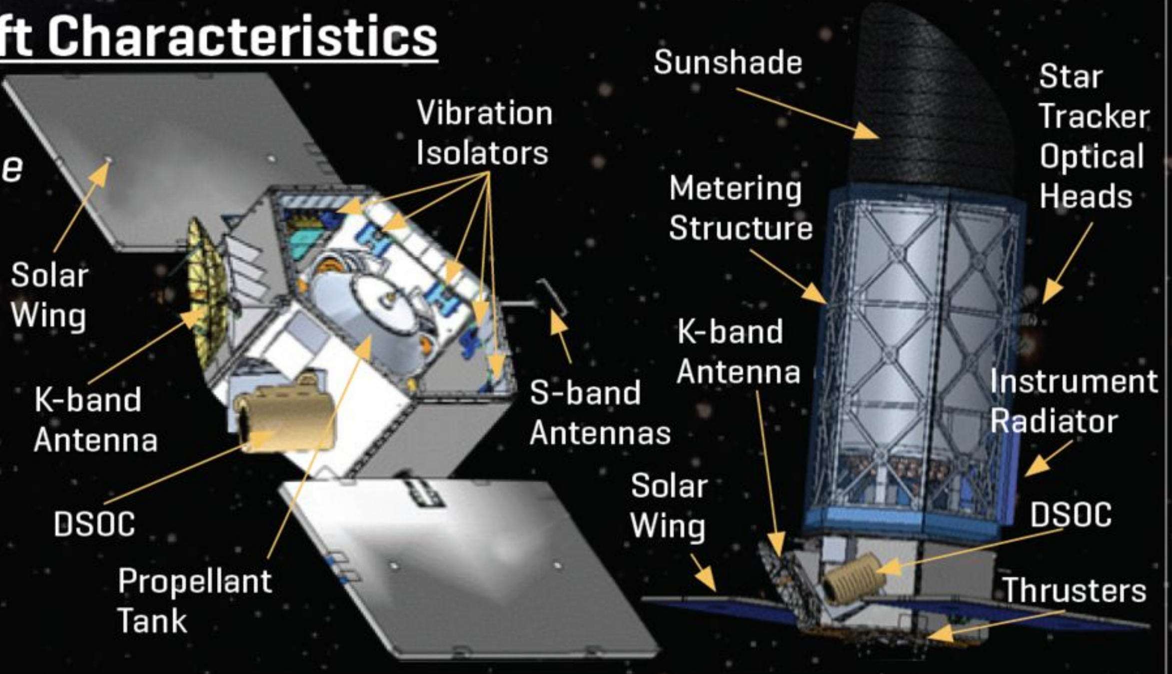


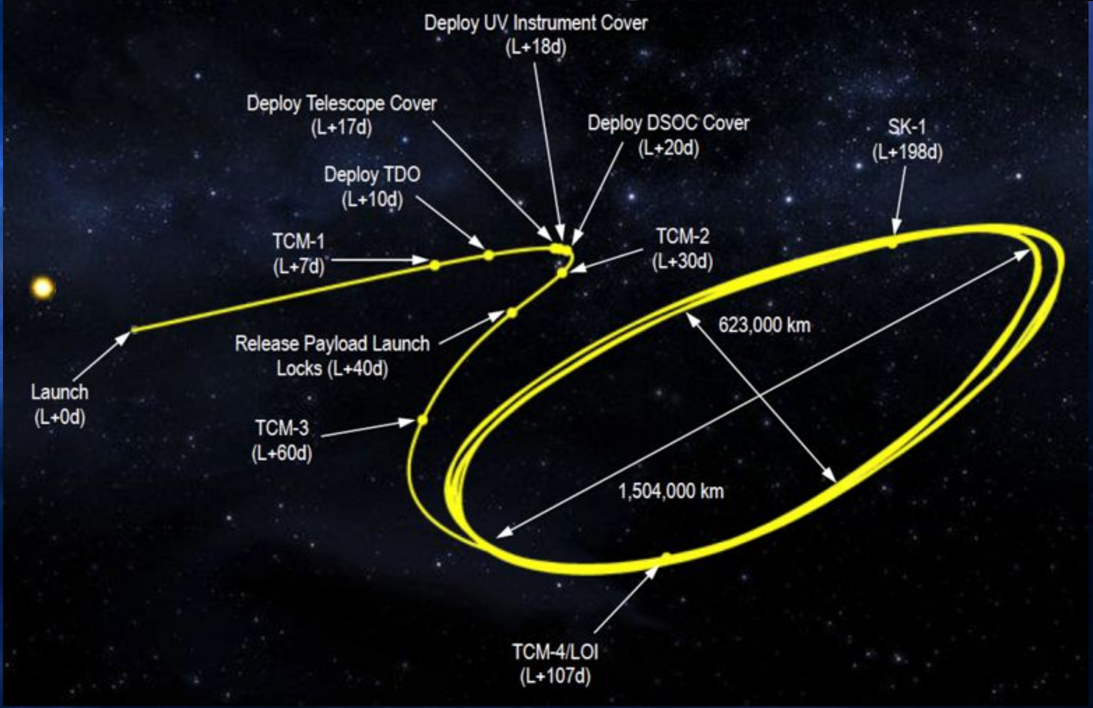
Key Telescope & Spacecraft Characteristics

Telescope: 1.2 m diameter light-weighted primary; 0.1 arsec image resolution at 425 nm

Spacecraft:

- Ball RS-300 product line
- 1008 kg (wet) launch mass
- Two-stage vibration isolation
- Average of 5.2 GB/day of science data downloaded via K-band to DSN



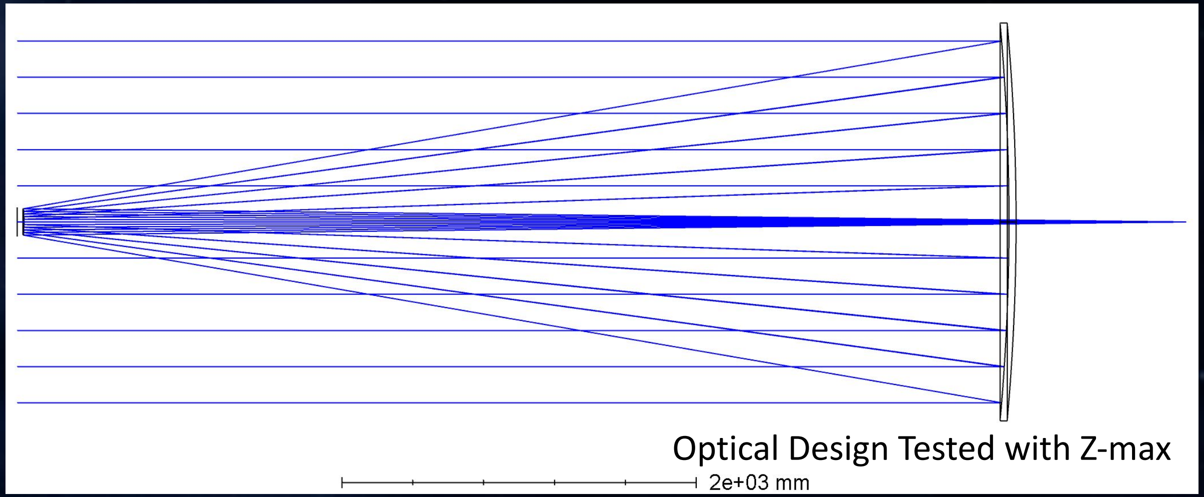


L2 orbit enables rapid commencement of science observations (L + 30d), and is well above the UV background induced by the Earth's geocorona

Planetary Dynamix Explorer Concept

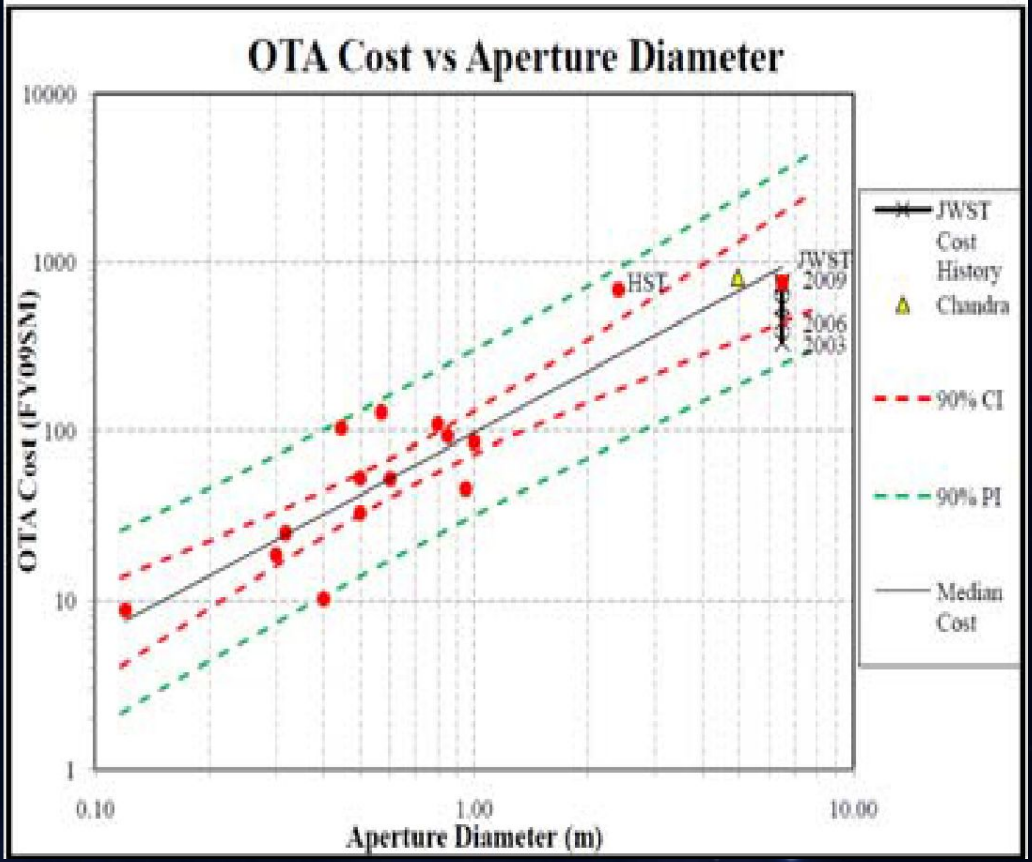
Notional PDX Design: Mature Optical Design Approach

	Sensitivity	Diffraction Limit	Instrument FoV
Measurement Performance	Imaging Limiting Mag = 31 Spec. Limiting Mag = 24	63 mas at 500 nm	110 arcsec 4.2 arcsec/mm Plate Scale
Baseline Design	2-meter circular aperture	2-meter circular aperture	58 m Focal Length



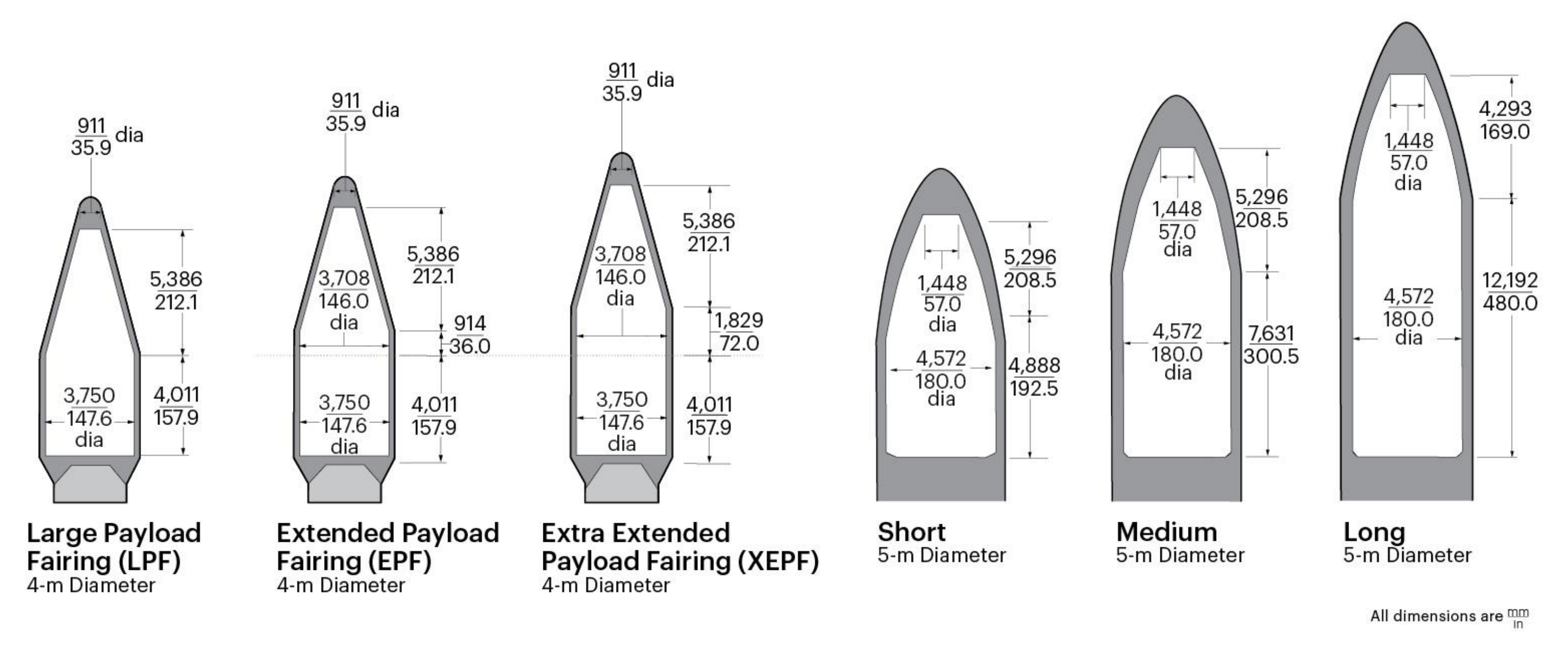
Optical Design Tested with Z-max

Stahl et al. (2017) parametric cost model suggests HST’s OTA could be built for <$1B

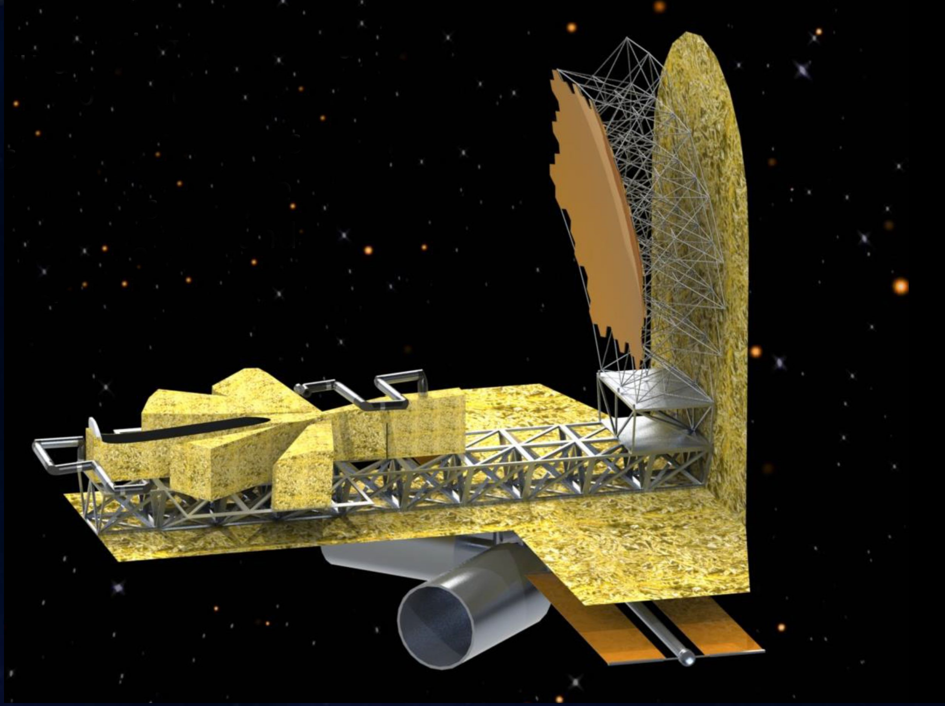


Launch Vehicle Constraints

Parameters	HST	PDX	Atlas V 400	Atlas V 500	Delta IV Medium
Length	13.2 m	11.0 m	5.8 m (Extra Extended)	7.6 m (Medium)	6.5 m
Diameter	4.2 m	3.5 m	3.8 m	4.6 m	3.8 m
Mass	12,000 kg	6,900 kg ?	15,718 kg (LEO) 5,860 kg (GTO)	18,814 kg (LEO) 6,860 kg (GTO)	13,140 kg (LEO) 4,490 kg (GTO)



Filled-Aperture in-Space Assembled:
iSAT Concept



Astro2020 in-Space Assembled Telescope (iSAT) study:

- Examined feasibility of a 5, 10, 15 and 20-meter telescope assembled in space
  - Optimized for sensitivity: Filled Aperture design
  - Optical surfaces: actively controlled to maintain mirror shape

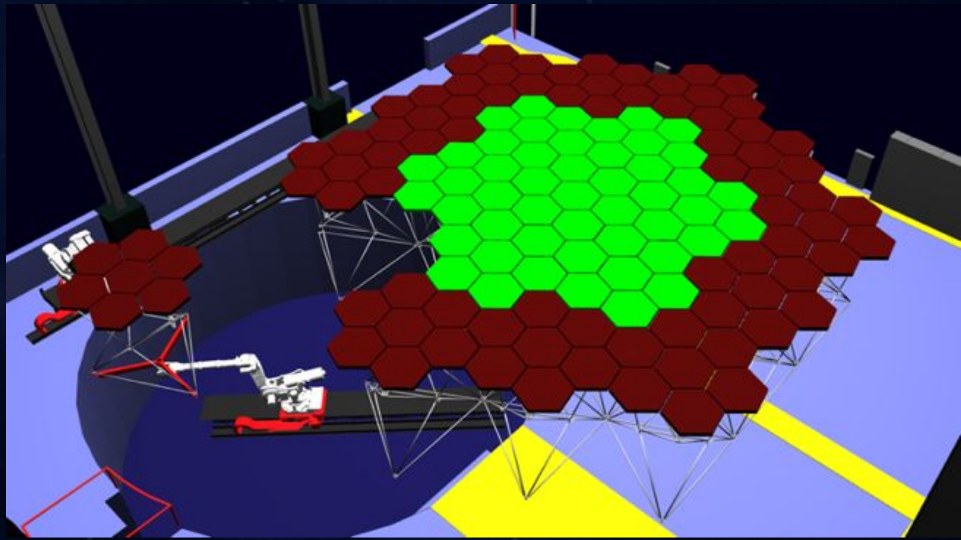
Solar System Telescope Trade Study Objective:

- Use iSAT design as a point of departure
- Examine the cost impact of relaxing the mirror shape precision
- Determine the Diameter, Imaging Quality vs. Cost

On-going Relevant Project:

- Precision Assembled Space Structures (PASS)
  - Laboratory Demonstration to build a 20-meter parabolic aperture
  - Robotic Autonomous Assembly
- Effort is applicable to future Solar System Telescope
- See whitepaper by J. Dorsey

https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/



LaRC RAMSES Lab
Robotic Assembly of Modular Space Exploration Systems

Sparse Aperture Telescope Architecture

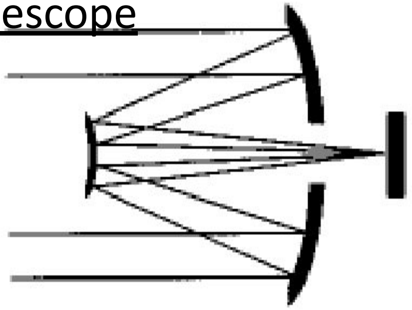
Common Secondary Mirror:

- Advantage: Simpler Optical Design
- Disadvantage: Larger volume

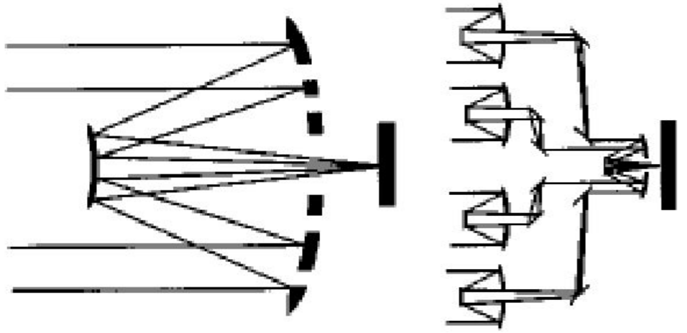
Multiple Telescopes:

- Disadvantage: Complicated Optical Design
- Advantage: Compact Volume
- Advantage: Can work as a Fourier-Transform Spectrometer

Filled Aperture Telescope

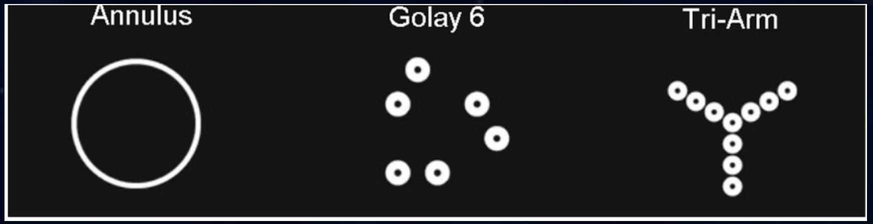


Sparse Aperture Telescope

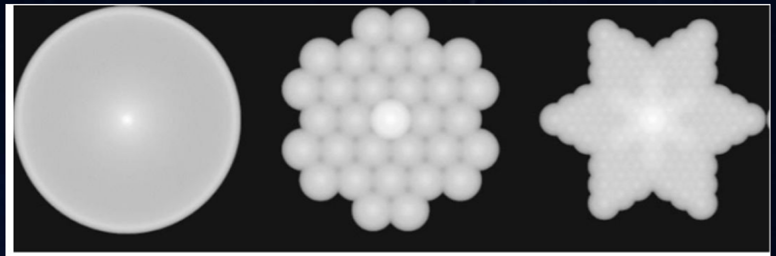


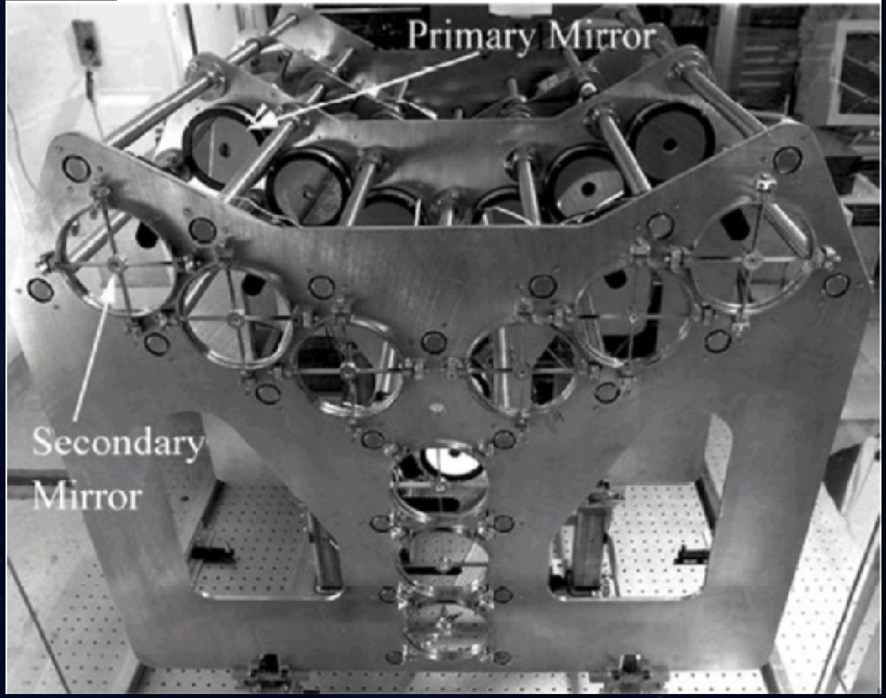
Fiete et al. (2002, Opt. Eng)

Aperture Arrangement Options



Modulation Transfer Function (MTF)

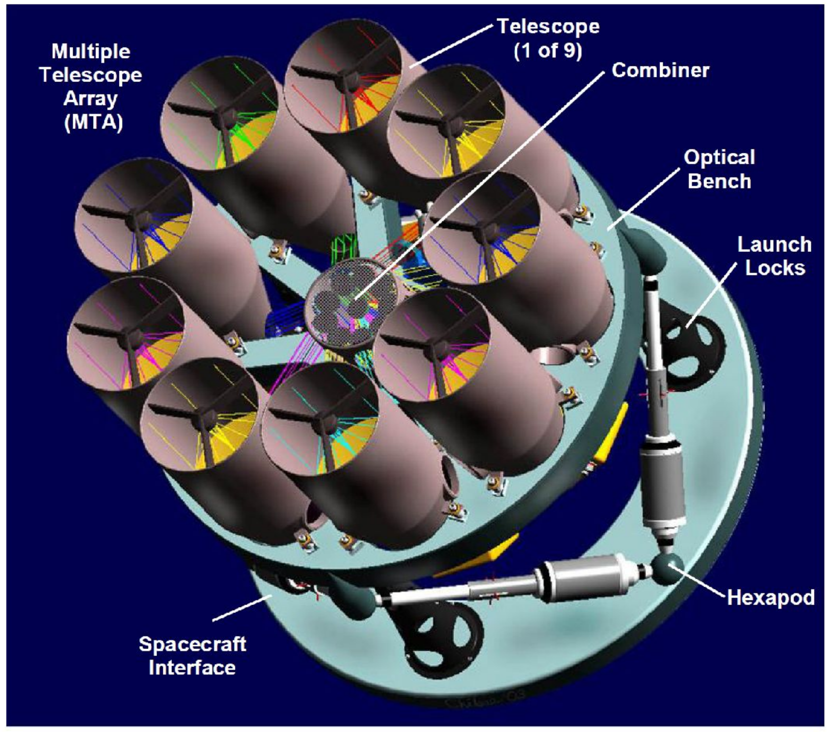


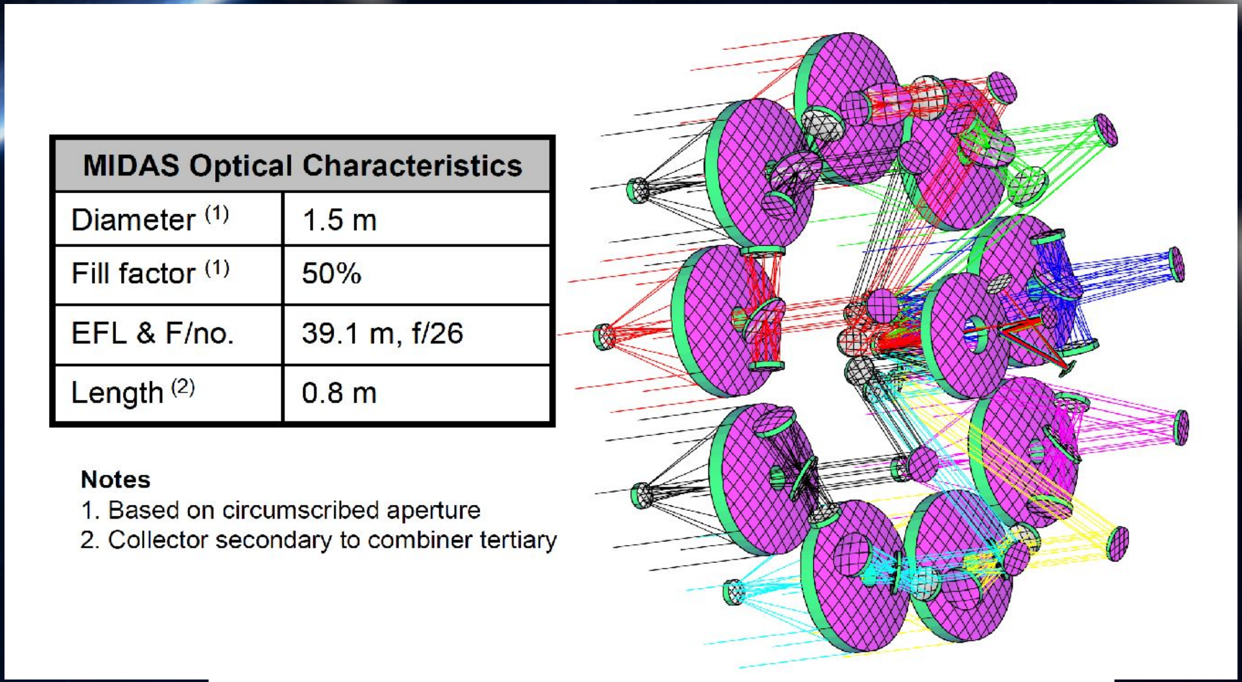


Lockheed Martin Tri-Arm Prototype

Sparse Aperture Design Example: Multiple Instrument Distributed Aperture Sensor (MIDAS) Concept

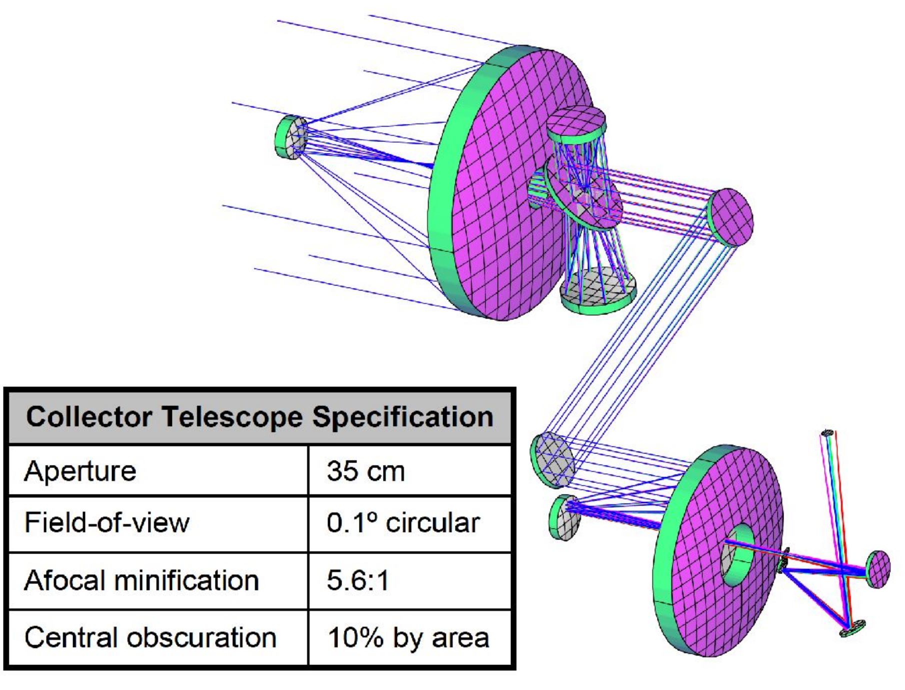
Considered for the Jupiter Icy Moon Orbiter (JIMO) mission in the early 2000s.





MIDAS Optical Characteristics	
Diameter [(1)]	1.5 m
Fill factor [(1)]	50%
EFL & F/no.	39.1 m, f/26
Length [(2)]	0.8 m

Notes
1. Based on circumscribed aperture
2. Collector secondary to combiner tertiary



Collector Telescope Specification	
Aperture	35 cm
Field-of-view	0.1° circular
Afocal minification	5.6:1
Central obscuration	10% by area

Figure 7 MIDAS Concept Collector Optical Design

Stubbs et al (2004) Optical, Infrared, and Millimeter Space Telescopes, edited by John C. Mather, Proceedings of SPIE Vol. 5487

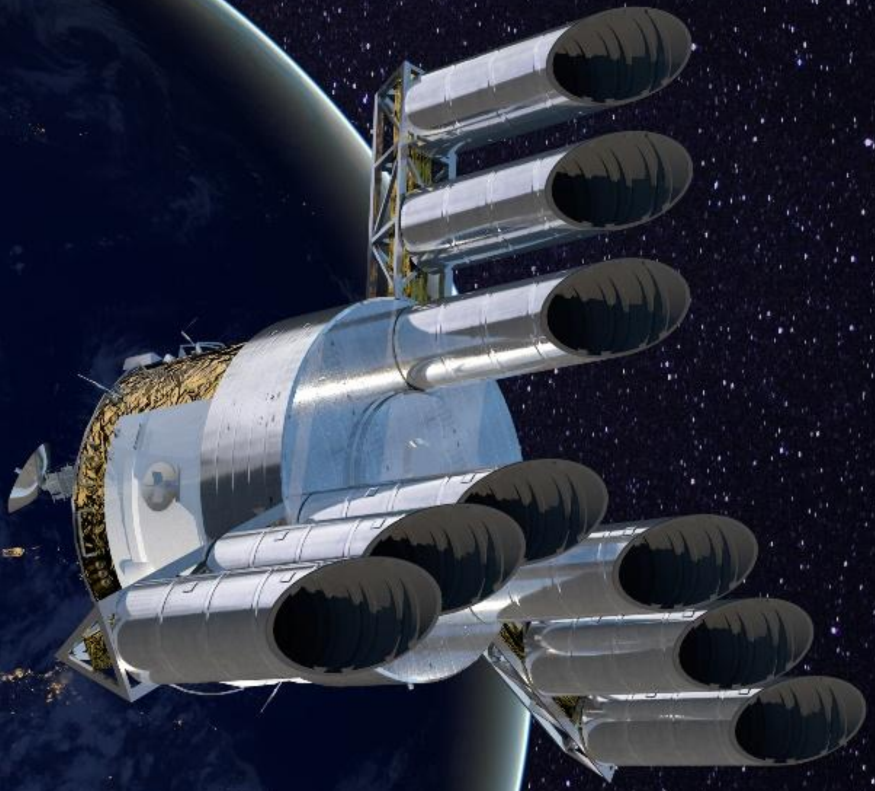
CHARISMA: Caroline Herschel high-Angular Resolution Imaging & Spectroscopy Multi-Aperture Telescope

Sayanagi et al., 2020 Mission Concept White Paper Submitted to the 2020 Planetary Science and Astrobiology Decadal Survey

Designed to balance sensitivity and resolution

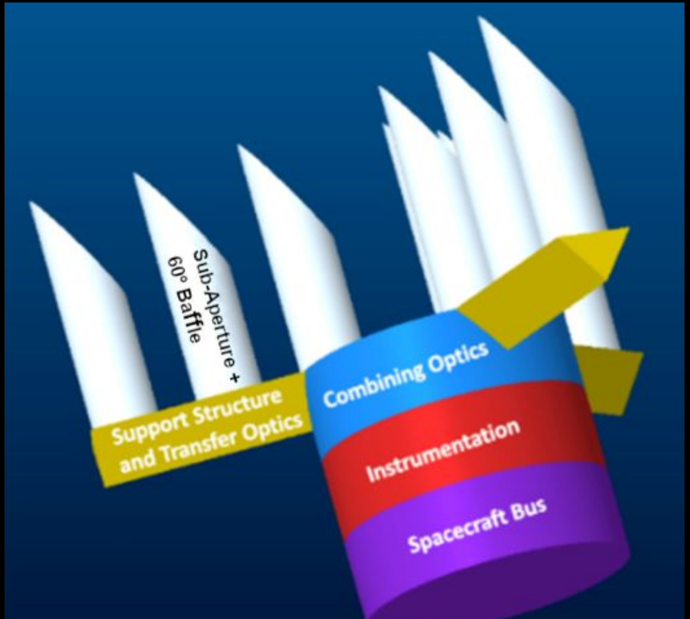
Notional Architecture

- ~10-meter Effective Aperture
- Equivalent of 2-meter circular aperture area
- Sparse-Aperture Design
- Assembled and/or Deployed in Space
- 30-deg Solar Exclusion Zone
- Create tech heritage for future astrophysics telescopes



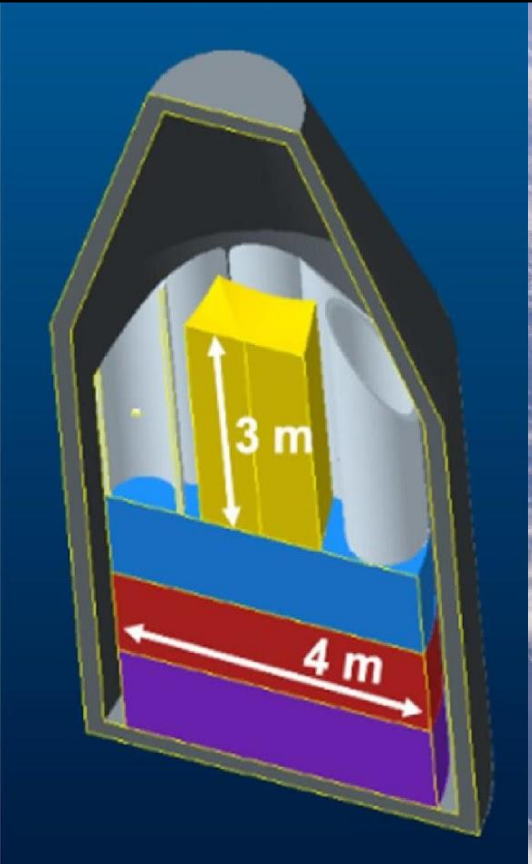
Sparse Aperture Telescope Assembly/Deployment

Modularized nature of a Sparse Aperture design is conducive to in-Space Assembly or Deployment



CHARISMA Notional Design

CHARISMA Launch Configuration

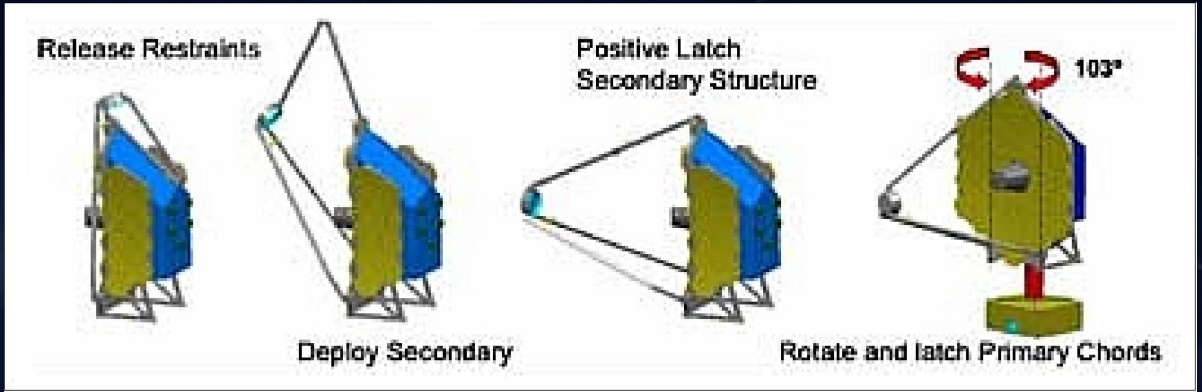


Notional Assembly Sequence of CHARISMA telescope

Deployment and in-Space Assembly (iSA) Comparison

Deployment

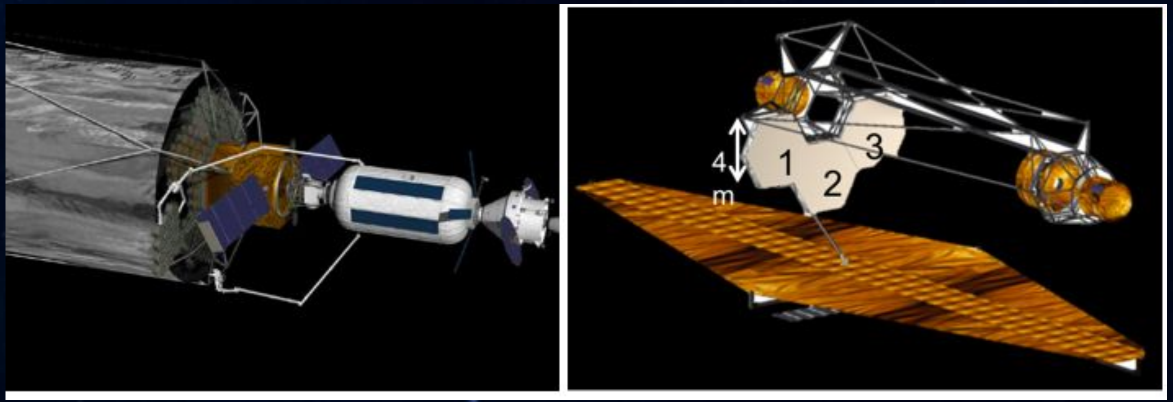
Example: James Webb Space Telescope (JWST)

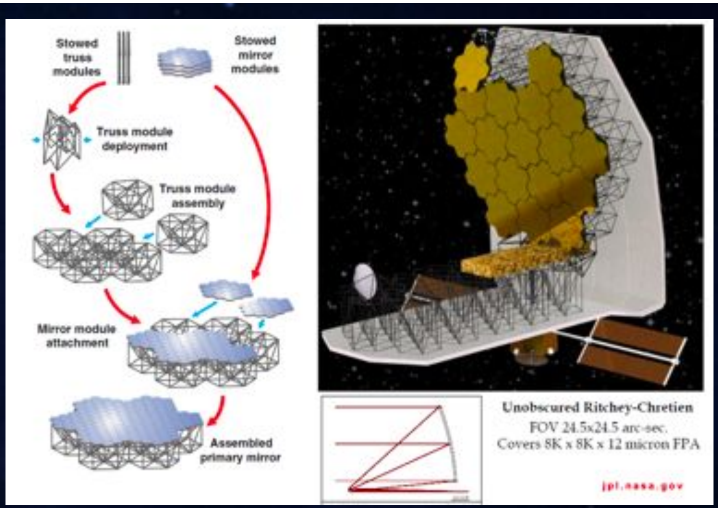


- Structure is unfurled using joints and actuators
- Extension of existing technologies (e.g. solar panels).
- Joints and actuators must be built to withstand launch loads even though they are only needed for one-time deployment in zero-G.

In-Space Assembly

Example: in-Space Assembled Telescope (iSAT)





- Structure is built by Robotic Servicing Arm (RSA)
- Joints and actuators are concentrated in RSA
  Optimal Configuration for launch
- Components can be delivered on multiple launches
- High-degree of autonomy and control required

Synergy with Astrophysics Missions

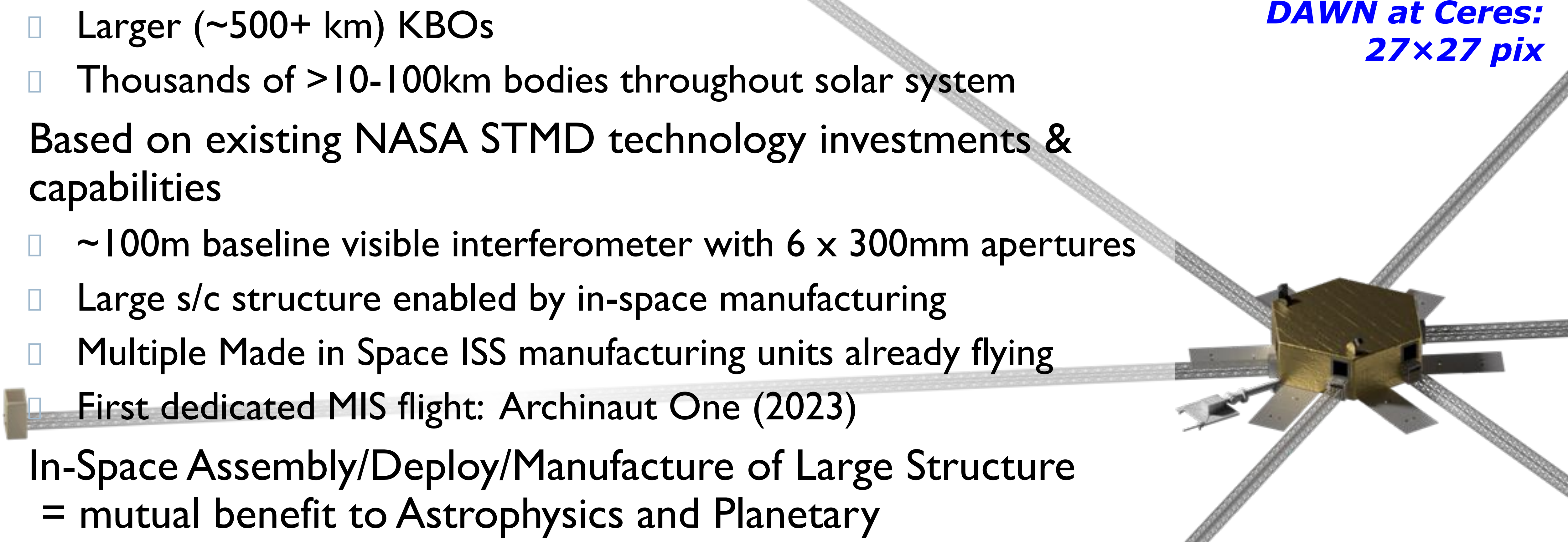
Solar System Science goals benefit more from increased angular resolution

- Sparse Aperture Design is Optimal for Science Objectives
- Sparse Aperture Design requires less optical surface than a filled-aperture – requires less mass to be launched.
- Solar System telescope like CHARISMA can open a path toward future large Astrophysics Missions.
- iSA will also benefit space-based interferometers

LightBeam:
Optical Interferometer Concept

van Belle et al., 2020 Planetary Decadal Whitepaper

DAWN at Ceres:
27×27 pix



- Optimized for Imaging Resolution
- Flyby-like snapshot imaging at ~10×10 to 100×100 pixels
  - Outer planet moons
  - Larger (~500+ km) KBOs
  - Thousands of >10-100km bodies throughout solar system
- Based on existing NASA STMD technology investments & capabilities
  - ~100m baseline visible interferometer with 6 x 300mm apertures
  - Large s/c structure enabled by in-space manufacturing
  - Multiple Made in Space ISS manufacturing units already flying
  - First dedicated MIS flight: Archinaut One (2023)
- In-Space Assembly/Deploy/Manufacture of Large Structure
  = mutual benefit to Astrophysics and Planetary

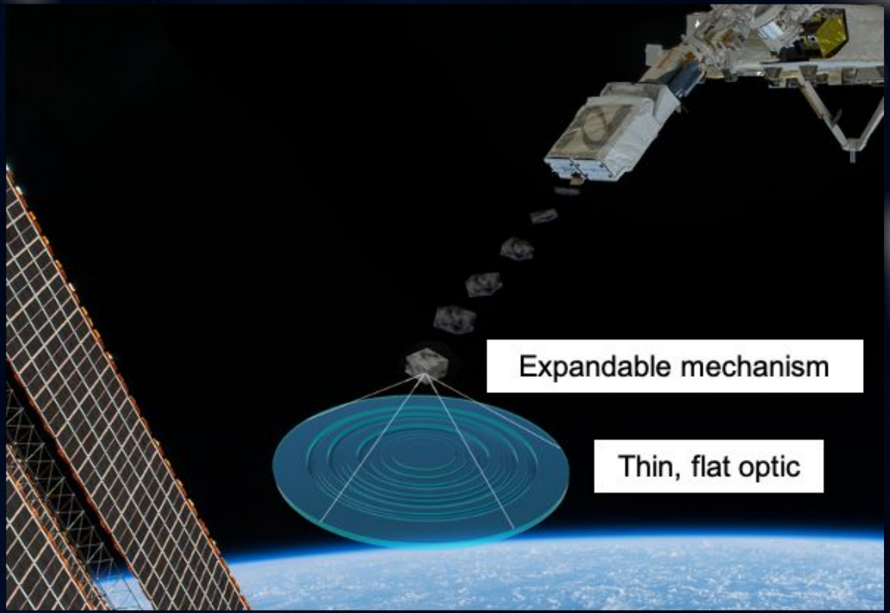
Diffraction Zone Plate Telescope

Under Development at NASA Langley

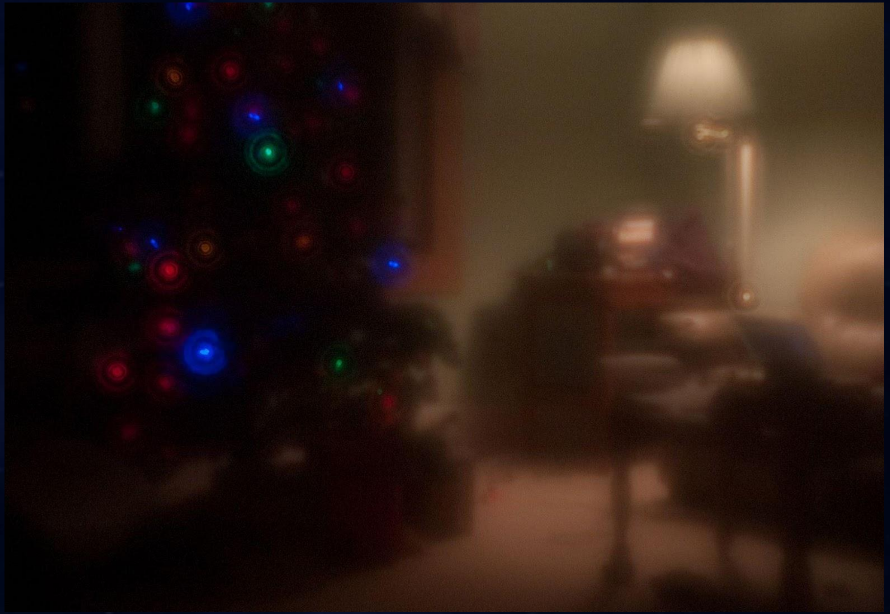
- -SPECIES Concept / PI: J. Leckey
- -Light-weight Membrane Diffraction Zone Plate
- -90% reduction in system mass compared to traditional optics
- -40% Optical Throughput
- -Design optimized for sensitivity (not for image quality)
- -Currently TRL =2, TRL = 4 expected by 2023

Concept Study Objective

- -Examine Technology Benefit for Planetary Science
- -Recommend Development Roadmap



Multi-layer Fresnel Zone Plate LIDAR Concept



Diffraction Zone Plate Image Example
(From Wikipedia)

Optical Tube Assembly (OTA) Design Trade

Measurement Req.

- Imaging Resolution
- Sensitivity
- Spectral Range
- Solar Exclusion Zone

Note: Spectral Resolution is an instrument parameter, not OTA

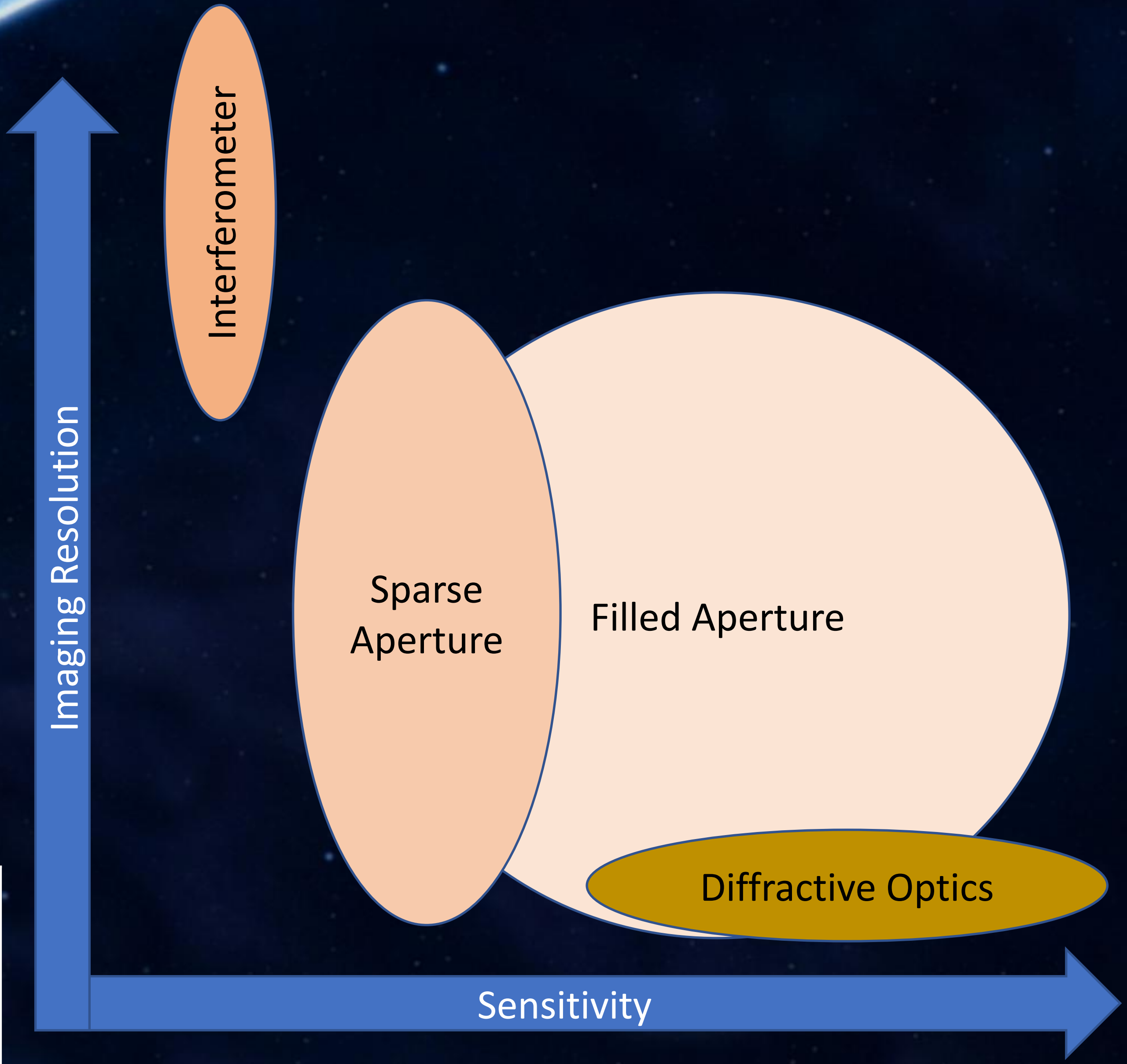
Assembly Approach

- Assembled on Ground
- Deployable Structure
- In-Space Assembly
- Any Combination of Above

Orbit
Affects temporal cadence

- Low-Earth Orbit
- High-Earth Orbit
- Earth-Trailing
- L2

OTA Architectures: Resolution & Sensitivity



Summary

- Unique science only enabled by UV observation
  - Time-domain science (high frequency, long-duration)
  - New, wide-ranging small bodies surveys
- Urgent need: preserve UV observation capabilities
- Mission targets
  - A focused space telescope mission is viable
  - Can potentially serve broad planetary science community
- Telescope Architecture options; optimized for:
  - Spatial resolution
  - Photometric sensitivity
  - Balance of both
- Concept study needed as recommended by CAPS
  - Survey of technology options
  - Examine benefits of Deployment and in-Space Assembly
  - Point design to demonstrate viable options for the next decade
- We advocate to add a solar system space telescope to the NF6 list

The time for a solar system space telescope is NOW!

Supporting Documents

OSAM: On-orbit Servicing, Assembly and Manufacturing:

- Hosted by NASA Office of the Chief Technologist Science and Technology Partnership Forum
- Multi-agency + commercial industry effort
- OSAM In-Space Assembly Activities Overview: https://www.nasa.gov/sites/default/files/atoms/files/st_partnership_isa_open_forum_presentations.pdf
- OSAM Website: https://nexis.gsfc.nasa.gov/osam/index.html
- GSFC In-Orbit Servising https://nexis.gsfc.nasa.gov/
- In-Space Assembled Telescope Project https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

Relevant Planetary & Astrobiology Whitepapers

- Young et al. “The science enabled by a dedicated solar system space telescope” http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5489366/252-f51fa816bdec93f9ab78348a5b800942_YoungCindyL.pdf
- Sayanagi et al. “Architectures and Technologies for a Space Telescope for Solar System Science” http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5489366/243-742a8a794f8326d15ef77fa570071e58_SayanagiKunioM_Telescope.pdf
- Roberge et al. “The Large UV / Optical / Infrared Surveyor (LUVOIR) Telling the Story of Life in the Universe” http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5489366/105-a55c230e6554ece5707470d3937e2ce9_RobergeAki.pdf
- Van Belle et al. “LightBeam: Flyby-Like Imaging Without The Flyby” http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5489366/140-4b806c5f42723adffe694d7829dd117a_vanBelleGerardT.pdf
- Dorsey et al. "NASA Langley Research Center Capabilities/Technologies for Autonomous In-Space Assembly and Modular Persistent Assets” http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5489366/84-1324fe88e1b6b31c428928122e4ccd65_DorseyJohnT.docx

Kuiper Space Telescope Presentation to OPAG:

- https://www.lpi.usra.edu/opag/meetings/feb2015/presentations/19_Bell_Kuiper_OPAG_Feb2015.pdf