Space Telescopes for Solar System Science

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Value of Space Telescopes for Solar System Science

Astrophysics Telescopes have made critical contributions to Solar System Science
  • Captured High-resolution Snapshots and Short Movies

Next Revolutionary Advances:
  • Study Temporally Dynamic Phenomena
e.g. Plumes on Ocean Worlds, Volcanos on Venus and Io, Transient Atmospheric Phenomena, Aurora, Comets...
    → Need high-frequency, long-duration campaigns
  • Survey of Small-Body Surface Composition
    → Need HST-class sensitivity for many targets
  • Role of Astrophysics Telescopes:
    → Provide advanced observation capabilities
      (higher sensitivity, spectral resolution for high-value observations)

Space Telescopes have High Value for Solar System Science
Hubble’s Contributions to the Outer Solar System

Atmospheric Science (Storms on Jupiter)

Aurora Dynamics (Jupiter)

Ocean Worlds (Plumes on Europa)

Kuiper Belt (Discovery of 486958 Arrokoth)

Wong et al (2018)

Roth et al (2014)
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.


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:

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

**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 and surface evolution
- Cometary evolution
- Evolving ring phenomena

**Understand Origin and Evolution of Small Bodies**

Comprehensive Spectral Survey of Solar System Minor Bodies to:

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

Roberge et al., 2020 Mission Concept White Paper

LUVOIR-A
On-axis telescope
15 m aperture

LUVOIR-B
Off-axis telescope
8 m aperture

More information can be found at https://www.luvoirtelescope.org

ECLIPS
Extreme Coronagraph for Living Planetary Systems

HDI
High Definition Imager

LUMOS
LUVOIR Ultraviolet Multi-Object Spectrograph

POLLUX
UV spectropolarimeter (on LUVOIR-A only)
Future Space Telescopes: UV Coverage Gap

- **HST**
  - Diameter: 2.4 m
  - 0.1 to 2.5 um
  - Moderate resolution
  - Diverse inst. suite

- **TESS**
  - Diameter: 0.1 m
  - FOV 24 x 24 deg^2
  - Low resolution
  - Imaging only

- **JWST**
  - Diameter: 6.5 m
  - 0.6 to 28.5 um
  - Moderate resolution
  - Diverse inst. suite

- **Roman (WFIRST)**
  - Diameter: 2.4 m
  - 0.4 to 2 um
  - Moderate resolution
  - Wide-field imaging & coronagraphy

- **LUVOIR-A / -B**
  - Diameter: 15 m, 8 m
  - 0.1 to 2.5 um
  - High resolution
  - Diverse inst. suite

**Gap in UV Coverage**

- **2020**
  - Hubble (HST)
  - TESS

- **2030**
  - JWST

- **2040**
  - Roman (WFIRST)
  - LUVOIR-A / -B

**Future Space Telescopes: UV Coverage Gap**
CHARISMA: Caroline Herschel high-Angular Resolution Imaging & Spectroscopy Multi-Aperture Telescope

Sayanagi et al., 2020 Mission Concept White Paper

Address Requirements for Next Revolution in Solar System Observation:
- High Spatial Resolution
- High-Frequency, Long-Duration Observations

Notional Architecture
- ~10-meter Effective Aperture
- Sparse-Aperture Design
- Assembled and/or Deployed in Space
  (Assembly example shown)
- Create tech heritage for future astrophysics telescopes
Jupiter System L1 Observatory
A Time-Domain Science Mission for the Jovian System and Beyond
Hsu et al., 2020 Mission Concept White Paper

Why Time-Domain Science?

The two most powerful warriors are patience and time (Leo Tolstoy).
- To resolve time sequence of various phenomena in order to understand the cause-and-effect and interactions

Why at Sun-Jupiter L1?

Location, Location, Location!
1. Trade distance with resolution/telescope aperture (aperture equivalence: 50 cm at Jupiter L1 ~ 7.4 m around Earth)
2. Unique position for irregular satellites and other minor bodies observation (e.g., Hilda asteroids)
3. Near-Jupiter environment characterization, including both exogenous (e.g., upstream solar wind, interplanetary and interstellar dust) and endogenous (e.g., logenic energetic neutral atoms and nanodust, and radio emission) components
LightBeam Mission Concept

- Interferometric Observations of Small Bodies
- Under development by Made In Space and Lowell Observatory
- Small, space-based interferometer mission (SIMPLEx-class)
- 50-meter Baseline / Angular resolution ~2 milliarcseconds
- Demonstrate technologies needed for a larger mission
Take-home Messages

Space Telescopes enable new high-priority solar system investigations
  → Fill gap in UV coverage after the end of HST.
  → High-Frequency, Long-Duration Campaigns for Time Domain Science Survey
  → High Spatial Resolution would be essential for next revolutionary progress

Space Telescopes have Synergy with Visiting Missions
  → Enhance science return of visiting missions with complementary obs.
  → Identify targets and hazards for visiting missions
  → Extend studies of variability beyond mission lifetimes

Limitations of Astrophysics Telescopes
  → Have not supported high-frequency, long-duration campaigns
  → Difficult to schedule small-body surveys w/ large number of targets
  → General Oversubscription

Cost of a dedicated solar system telescope is unknown

Concept Study Needed to Assess Value of a Space Telescope Dedicated to Solar System Science
Backup Materials

Back-up Section contains:
1. The Science Enabled by a Dedicated Solar System Space Telescope
2. Solar System Objectives considered for the LUVOIR concept
3. Architectures and Technologies for a Space Telescope for Solar System Science
4. Jupiter L1 Observatory Concept
5. LightBeam telescope concept
The Science Enabled by a Dedicated Solar System Space Telescope

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Priority Science Questions to be addressed by a Space Telescope Dedicated to Solar System Science

Science Themes:
1. Active Plumes and Volcanism
2. Outer Solar System Minor Body and Irregular Satellite Survey
3. Dynamic Atmospheres
4. Magnetospheric Interactions
5. Planetary Ring Systems
6. Cometary Evolution, Morphology and Processes
Active Plumes and Volcanism

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.
Priority Questions

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].

Dynamic Atmospheres

**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].

Magnetospheric Interactions

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

[Image: HST far-UV images of Saturn’s aurora and changes during an auroral storm, and 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).
Planetary Ring Systems

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 $\epsilon$ and $\zeta$ rings. Such edge-on observations enable detecting and characterizing dusty rings. [9]

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) [10]
Right: Transmission during stellar occultation can determine associations between species such as O$_2$ and H$_2$O, as shown in these examples from Rosetta/Alice data [11].

OBSERVING THE SOLAR SYSTEM WITH LUVOIR

Study Scientist: Aki Roberge (Aki.Roberge@nasa.gov)
Science Support Lead: Giada Arney (giada.n.arney@nasa.gov)
NASA Goddard Space Flight Center
The Large UV / Optical / Infrared Surveyor

LUVOIR-A
On-axis telescope
15 m aperture

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LUVOIR in context

- **Hubble (HST)**
  - Diameter: 2.4 m
  - 0.1 to 2.5 um
  - Moderate resolution
  - Diverse inst. suite

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- **LUVOIR-A / -B**
  - Diameter: 15 m, 8 m
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  - High resolution
  - Diverse inst. suite
### Key features of LUVOIR for Solar System

#### Table 1: Summary of the LUVOIR space telescope concepts

<table>
<thead>
<tr>
<th>Feature</th>
<th>LUVOIR-A</th>
<th>LUVOIR-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope diameter</td>
<td>15-m</td>
<td>8-m</td>
</tr>
<tr>
<td>Location</td>
<td>Earth-Sun Lagrange 2</td>
<td></td>
</tr>
<tr>
<td>Telescope properties</td>
<td>Diffraction limited at 500 nm; 270 K telescope operating temperature</td>
<td></td>
</tr>
<tr>
<td>Lifetimes &amp; launch date</td>
<td>5-year prime mission; 10 years of consumables; 25-year lifetime goal for non-serviceable components; proposed launch date in late 2030s</td>
<td></td>
</tr>
<tr>
<td>Instantaneous field of regard</td>
<td>Sun-Telescope-Target angles ≥ 45°</td>
<td></td>
</tr>
<tr>
<td>Moving target tracking speed</td>
<td>≤ 60 milliarcsec/second (2x speed of JWST)</td>
<td></td>
</tr>
<tr>
<td>Total wavelength range of candidate instrument suite</td>
<td>100 nm – 2500 nm</td>
<td></td>
</tr>
<tr>
<td>Current candidate instrument capabilities</td>
<td>High-contrast near-UV/optical/ NIR imaging &amp; low-resolution spatially resolved spectroscopy</td>
<td>Wide-field near-UV/optical/NIR imaging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UV optical multi-resolution, multi-object spectroscopy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UV spectropolarimetry</td>
</tr>
<tr>
<td>Max spatial resolution at 1 μm</td>
<td>15 km, 50 km, 102 km; 28 km, 94 km, 193 km</td>
<td>28 km, 94 km, 193 km; 217 km, 346 km, 464 km; 409 km, 653 km, 875 km</td>
</tr>
</tbody>
</table>

Can point to Venus at max elongation and planets at opposition
Key goals for LUVOIR include …

1. Find dozens of potentially habitable exoplanets and search them for signs of life

2. Observe a wide range of exotic exoplanets to place the Solar System in context

3. Study the Solar System in detail to better understand what we’ll see far more coarsely in exoplanet systems

Expected yields of directly imaged exoplanets

LUVOIR Final Report, Figure 1-6
LUVOIR’s wide-field optical imaging resolution is near-flyby quality

**JunoCAM** image: 30 km/pixel

**LUVOIR** (15 m): 24 km resolution

Credit: NASA, Juno, SwRI, MSSS, Gerald Eichstädt & Seán Doran
**UV / optical / NIR Imaging**

- **JunoCam** image: 30 km/pixel
- **LUVOIR** (15 m): 24 km resolution

**UV Imaging and Spatially Resolved Spectroscopy**

- **HST** provided the first detailed imaging of the Jovian UV aurora.
- **LUVOIR** can monitor at higher resolution.
UV Hydrogen Lyman-α emission from HST
Roth et al. (2014)

Credit: G. Ballester (LPL) / R. Juanola-Parramon (GSFC)
LUVOIR Lyman-α images assume 16-exposure dither pattern
Enceladus

Sun  Mercury  Venus  Earth  Mars  Jupiter  Saturn  Uranus  Neptune  Pluto

Ceres  Enceladus  Europa  Triton

2.4 m
LUVOIR-B (8 m)
LUVOIR-A (15 m)

Cassini (April 2013)
ISS – Narrow angle camera
Blue filter
Distance: 832000 km
Resolution: 5 km/pixel
NASA/JPL-Caltech/Space Science Institute
Neptune

Voyager 2 (1989)
ISS - Narrow angle camera
Green (530-640 nm) and clear (280-640 nm) filters
NASA/JPL
Triton

Voyager 2 (1989)
ISS - Narrow angle camera
Green (530-640 nm) and clear (280-640 nm) filters
NASA/JPL
Pluto + TNOs

New Horizons (July 2015) MVIC camera:
- 400 – 550 nm (blue)
- 540 – 700 nm (red)
- 780 – 975 nm (NIR)

Resolution 1.3 km/pixel
NASA/JHUAPL

LUVOIR-A can survey for ~2 km diameter bodies at 40 AU
(~4 km diameter for LUVOIR-B)
What’s been happening

NASA Astrophysics initiated four large mission concept studies in 2016, in preparation for the 2020 Astrophysics Decadal Survey (Astro2020).

- HabEx (UV / optical / NIR), LUVOIR (UV / optical / NIR), Lynx (x-ray), Origins (infrared)

Over 3.5 years, we did the following and more …

- Defined science goals
- Matured architectures, created designs, & executed trade studies
- Produced mission lifecycle schedules and technology development plans with cost & schedule
- Calculated mission lifecycle cost estimates (in several ways)

All mission concepts reached Concept Maturity Level 4. Our very long Final Reports are publicly available for download.

Concepts are currently being evaluated by Astro2020. Results in early 2021.
Summary
The LUVOIR mission concept has been studied in detail for 3.5 years and builds upon extensive earlier work on similar concepts.

LUVOIR’s high resolution can deliver near-flyby quality imaging throughout most of the Solar System.

LUVOIR’s sensitivity makes currently daunting projects routine and impossible ones feasible.

The LUVOIR team appreciates the need for long-duration monitoring of Solar System bodies, which is entirely possible with LUVOIR (see the Final Report for details).

https://www.luvoirtelescope.org
Architectures and Technologies for a Space Telescope for Solar System Science


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8 SETI Institute, Mountain View, CA
9 New Mexico State University, Las Cruces, NM
10 Boston University, Boston, MA
11 University of Central Florida, Orlando, CA
12 University of California, Berkeley, CA
13 University of Maryland, College Park, MD
14 University of Leicester, Leicester, UK
15 Planetary Science Institute, Tucson, AZ
16 Space Telescope Science Institute, Baltimore, MD
17 University of Colorado, Boulder, CO
18 Southwest Research Institute, Boulder, CO
19 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
20 Japan Aerospace Exploration Agency, Sagamihara, Japan
21 University of Colorado Laboratory for Atmospheric and Space Physics, Boulder, CO
22 Johns Hopkins Applied Physics Laboratory, Laurel, MD
Planetary Dynamics Explorer (PDX) Concept

PDX: 2-meter Monolithic Aperture Telescope, Ritchey-Chretien (RC) optical design
Design Goal: Maximize Filled Aperture Size

PDX Notional Performance

<table>
<thead>
<tr>
<th>Measurement Performance</th>
<th>Sensitivity</th>
<th>Diffraction Limit</th>
<th>Instrument FoV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging Limiting Mag = 31 Spec. Limiting Mag = 24</td>
<td>63 mas at 500 nm</td>
<td>110 arcsec 4.2 arcsec/mm Plate Scale</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Baseline Design</th>
<th>Sensitivity</th>
<th>Diffraction Limit</th>
<th>Instrument FoV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-meter circular aperture</td>
<td>2-meter circular aperture</td>
<td>58 m Focal Length</td>
<td></td>
</tr>
</tbody>
</table>

Launch Vehicle Constraints for a 2-meter class Telescope

<table>
<thead>
<tr>
<th>Parameters</th>
<th>HST</th>
<th>PDX (Notional)</th>
<th>Atlas V 400</th>
<th>Atlas V 500</th>
<th>Delta IV Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>13.2 m</td>
<td>11.0 m (Extra Extended)</td>
<td>5.8 m</td>
<td>7.6 m (Medium)</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>4.2 m</td>
<td>3.5 m</td>
<td>3.8 m</td>
<td>4.6 m</td>
<td>3.8 m</td>
</tr>
<tr>
<td>Mass</td>
<td>12,000 kg</td>
<td>6,900 kg?</td>
<td>15,718 kg (LEO)</td>
<td>18,814 kg (LEO)</td>
<td>13,140 kg (LEO)</td>
</tr>
</tbody>
</table>
CHARISMA: Caroline Herschel high-Angular Resolution Imaging & Spectroscopy Multi-Aperture Telescope

Sayanagi et al., 2020 Mission Concept White Paper

Requirements for Next Revolution in Solar System Observation:
- High Spatial Resolution
- High-Frequency, Long-Duration Observations

Notional Architecture
- ~10-meter Effective Aperture
- Sparse-Aperture Design
  (HST-like Light-collecting area)
- Assembled and/or Deployed in Space
  (Assembly example shown)
- Create tech heritage for future astrophys. telescopes
Sparse-Aperture Telescope

Solar system observation requirements:
- High-Angular Resolution
- HST-class sensitivity is sufficient
- No coronagraph is needed

→ Sparse Aperture Telescope is uniquely suitable for solar system observations

Lockheed-Martin Tri-Arm sparse aperture telescope prototype
Enabling Technologies for Large Space Telescopes: Deployable vs. in-Space Assembly

Deployable Structures:
→ Transform from launch to operation config using joints and actuators
  Pro: James Webb Space Telescope (JWST) matured the technology
  Con: Joints and Actuators must withstand the launch load
    ... even though they are needed for a one-time deployment in zero-G
    ... drives up cost

In-Space Assembly (iSA)
→ Components are rigidly mounted
→ Use a Robotic Servicing Arm (RSA) to manipulate modularized components to assemble in Space
  Pro: All joints and actuators are concentrated on RSA
    Modularized components can be mounted rigidly for launch
  Con: Technology needs to be matured

Common Challenges – Technologies need to be matured in:
(1) Component Modularization
(2) Robotic Deployment/Assembly Mechanisms
(3) Supervised Autonomy Software/Algorithm for Deployment/Assembly
(4) Verification and Validation
Connection to Astrophysics Telescope Studies

Future Astrophysics telescopes require deployable structures and in-Space Assembly technologies.

A 10-meter Solar System Telescope could be an opportunity to mature technologies needed for >>10-meter astrophysics telescopes of future decades.

Solar System Telescope can serve to create heritage for astrophysics telescopes

Mature Technologies:

(1) Deployment/Assembly mechanisms
   ... precision latches, bolts
   ... enable large structures and yet stable under on-orbit disturbances

(2) Verification and Validation
   ... advanced metrology methods for in-space pre-assembly
   ... inspection and post assembly Verification and Validation.
Recommendations for Solar System Space Telescope Concept Study

1. Examine the benefits of a large sparse-aperture telescope for solar system science

2. Determine the optimal method to deploy/assemble a sparse aperture telescope in space to enable large aperture and minimize cost
Jupiter System L1 Observatory
A Time-Domain Science Mission for the Jovian System and Beyond

Jupiter System L1 Observatory
A Time-Domain Science Mission for the Jovian System and Beyond

Hsu et al., 2020 Mission Concept White Paper

**Why Time-Domain Science?**

*The two most powerful warriors are patience and time (Leo Tolstoy).*

- To resolve time sequence of various phenomena in order to understand the cause-and-effect and interactions

- To extend temporal baseline to study sporadic events

**Why at Sun-Jupiter L1?**

*Location, Location, Location!*

1. Trade distance with resolution/telescope aperture (aperture equivalence: 50 cm at Jupiter L1 ~ 7.4 m around Earth)
2. Unique position for irregular satellites and other minor bodies observation (e.g., Hilda asteroids)
3. Near-Jupiter environment characterization, including both exogenous (e.g., upstream solar wind, interplanetary and interstellar dust) and endogenous (e.g., logenic energetic neutral atoms and nanodust, and radio emission) components

- Irregular satellites
- Io nanodust
- Radio emission (Juno WAVES)

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Science Themes
1. Jupiter, the Exoplanet at the Front Door
2. A Song of Ice and Fire - Geological Activities of Io and Europa
3. Time Capsules of the Solar System - Irregular Satellites and Minor Bodies

Timely, Advantageous, & Synergistic
- Astrophysics: Exoplanet & brown dwarfs
- Heliophysics: Solar wind monitor @ 5 AU Space weather @ Jupiter
- Continuous bird-eye’s view on Galilean moons complimenting future orbiter/lander missions
- Best Europa plume hunter & irregular satellite explorer

Preliminary Mission Architecture
- Remote sensing + field-and-particle instruments
- Feasible with existing technology
- Robust mission design: reasonable launch C3 ($43\text{km}^2\text{s}^{-2}$), $\Delta V$ ($\sim1800\text{m/s}$), and cruise time (launch-JOI: 3.8 yr)
LightBeam Mission Concept

- Under development by Made In Space and Lowell Observatory
- Simple, space-based interferometer
- Angular resolution ~2 milliarcseconds
Enabling Technologies

- In-space manufacture of booms holding simple outboard optics
  - 50-meter interferometer in a 1 m³ ESPA Grande smallsat package
  - Booms do not need to be hardened for launch, packaged for payload shroud
- Space vs. ground: 10ms coherence time $\rightarrow$ 10-1000sec: significant gain in sensitivity
  - Apply techniques well-developed on ground for stellar surface imaging, binary orbits $\rightarrow$ asteroids
Current Status of *LightBeam*

- Made In Space, Lowell completing NASA SBIR Phase II on *Optimast-SCI* concept
  - Lab testing of representative manufacturing units, beam combiners
- *LightBeam* mission from O-SCI technology to be sized for SIMPLEx call

- SIMPLEx concept
  - Earth-Sun L1 observing of $m_V < 16$ targets down to 2 milliarcseconds
  - Resolved observations of NEOs, main belt asteroids, Jupiter Trojans

*Test booms 3D printed on ISS*