JWST/TMT synergy/complementarity for solar system observations

ELT Science in Light of JWST

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JWST Instruments Capabilities

- **Imaging**
  - NIRCam
  - NIRISS
  - MIRI
  - Coronagraphy
  - Aperture Masking Interferometry

- **Spectroscopy**
  - NIRSpec
  - NIRISS
  - MIRI
  - Single Slit
  - Multi-Object
  - Slitless

Wavelength (µm):
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1
- 1.5
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 15
- 20
- 30

Instrument Ranges:
- NIRCam: R ~ 1,000 - 2,700
- NIRISS: R ~ 700
- MIRI: R ~ 2,500
Instrument capabilities for solar system

- JWST wavelength coverage, sensitivity, and spatial resolution (+ stable PSF), enables breakthrough investigations about:
  - Conditions for life/habitability within solar system
  - Evolution of primitive planetesimals (building blocks of larger bodies)
  - Water and organics transport to inner regions of solar nebulae
- Gases, minerals, ices, have strong absorption features at these wavelengths

JWST wavelength coverage, sensitivity, and spatial resolution (+ stable PSF), enables breakthrough investigations about:

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Gases, minerals, ices, have strong absorption features at these wavelengths
The first ~1.5 years were prolific!
- Many programs already started or completed, and myriad of targets observed: Saturn, Enceladus, Titan, comets, asteroids, KBOs, Centaurs, Mars, Jupiter, Saturn, Neptune, Uranus, etc
- Follow-up of the DART target during impact showed capability for large tracking rates > 360”/hr (=100mas/sec, current limit is set to 75mas/sec).
Selected results (i)

**Villanueva et al., Science, 381, 1305 (2023)**

- **A** Europa NIRCam image
- **B** CO$_2$ at 2.7 microns
- **C** CO$_2$ at 4.27 microns
- **D** CO$_2$ at 4.25 microns

**Kelley et al., Nature, 619, 720 (2023)**

**Trumbo et al., Science 381, 1308 (2023)**
Selected results (ii)

Harrington Pinto et al., PSJ, 4:208 (2023)

depater et al., JGR, 128, e2023JE007872 (2023)

Villanueva et al., Nature, 7, 1056 (2023)

Fleitcher et al., JGR, 128, e2023JE007924 (2023)
JWST < ---- > TMT: complementarity
### Instrument Capabilities (first-light + first-decade)

<table>
<thead>
<tr>
<th>Instrument and Description</th>
<th>λ Range (µm)</th>
<th>Spectral Resolution</th>
<th>Modes</th>
<th>Field of View</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRIS/Diffraction-Limited NIR Imager and IFS</td>
<td>0.64–2.4</td>
<td>Z, Y, J, H, K, bandpass filters and multiple narrower in band filters. 4,000 and 8,000 (some modes to 10,000)</td>
<td>NGSAO, LGS MCAO</td>
<td>Imager: 34” x 34” @ 0.004”/pix IFU with two slicing techniques Lenslet: 0.512” x 0.512” @ 0.004”/spaxel Slicer: 2.25” x 4.4” @ 0.050”/spaxel</td>
</tr>
<tr>
<td>WFOS/Wide Field Optical Spectrometer</td>
<td>0.31–1.0</td>
<td>1,500 and 3,500 using 0.75” slits. Goal of 5,000 currently achieved and higher R available with narrower slits.</td>
<td>SL*</td>
<td>25 (8.3 x 3)-arcmin² 500” total slit length (up to 60 targets with 8” slits) Imaging: full field @ 0.05”/pixel</td>
</tr>
<tr>
<td>MODHIS/Multi-Objective Diffraction-Limited High-Resolution Infrared Spectrograph</td>
<td>0.95–2.4</td>
<td>&gt; 100,000 with 30 cm/s (goal 10 cm/s) Doppler velocity precision</td>
<td>NGSAO, LGS MCAO</td>
<td>4” diameter field of regard (possible that this will be slightly larger)</td>
</tr>
<tr>
<td>PSI/Planetary System Instrument</td>
<td>0.6–5.3</td>
<td>(fiber fed) High resolution R &gt; 100K (IFS) Medium resolution R &gt; 5,000 (IFS) Low resolution R &gt; 50</td>
<td>ExAO</td>
<td>2–5.3 µm only; 1.2” x 1.2” (low resolution) 0.15” x 0.15” (medium resolution)</td>
</tr>
<tr>
<td>MICHI/mid-IR Imager, IFU and Spectrometer</td>
<td>3.4–13.8</td>
<td>Imager &lt; 100, IFS 600–1,000, Spectrometer 120,000</td>
<td>MIRAO</td>
<td>Imager: 28.1” x 28.1” @ 0.027.5” mas/pix N band IFU: 0.175” x 0.07” (35 mas/spaxel)</td>
</tr>
<tr>
<td>HROS/High-Resolution Optical Spectrograph</td>
<td>0.31–1</td>
<td>Single Object: 100,000 &amp; 50,000 (fibers) 40,000 &amp; 20,000 (slits) Multi-Object: 25,000</td>
<td>SL, GLAO</td>
<td>&gt; 10” in diameter (single object mode) 10”–20” diameter (multi-object mode)</td>
</tr>
<tr>
<td>IRMOS/IR Multi-Object Spectrograph</td>
<td>0.8–2.5</td>
<td>2,000–10,000</td>
<td>MOAO</td>
<td>&gt; ten 3” IFUs deployable within a 5” diameter field</td>
</tr>
</tbody>
</table>
Science Capabilities

![Science Capabilities Diagram]

- **HROS** (Fiber)
- **HROS** (Fiber Multi-object)
- **IRMOS**
- **IRIS** (IFS)
- **PSI-B** (IFS)
- **PSI-R** (IFS)
- **MODHIS** (Fiber)
- **MICHIS** (Fiber)
- **MICHIS** (IFU)

Pixel/Spaxel Size (mas) vs. Wavelength (μm)

- **1HROS** (Fiber IFU LR and Slit)
- **2WFOS** (spec)
- **IRMOS** (IFS)
- **IRIS** (Slicer IFS)
- **MODHIS** (spec)
- **MICHI** (IFS)
- **MICHI** (img / spec)
- **PSI-R** (img)
- **IRIS** (Lenslet IFS)
- **PSI-B** (img)

Diffraction limit vs. Wavelength (μm)
### TMT Spatial Resolution for Selected Solar System Bodies

<table>
<thead>
<tr>
<th>Target</th>
<th>Diameter (km)</th>
<th>Distance (in AU)</th>
<th>Angular diam. (&quot;)</th>
<th>Nb resolution elements across apparent diam.</th>
<th>Nb resolution elements across apparent surf.</th>
<th>Spatial resolution (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceres</td>
<td>952</td>
<td>1.63</td>
<td>0.81</td>
<td>130</td>
<td>17012</td>
<td>7</td>
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<tr>
<td>Pallas</td>
<td>545</td>
<td>1.29</td>
<td>0.58</td>
<td>94</td>
<td>8920</td>
<td>6</td>
</tr>
<tr>
<td>Io</td>
<td>3644</td>
<td>4.09</td>
<td>1.23</td>
<td>199</td>
<td>39442</td>
<td>18</td>
</tr>
<tr>
<td>Europa</td>
<td>3122</td>
<td>4.09</td>
<td>1.05</td>
<td>170</td>
<td>26951</td>
<td>18</td>
</tr>
<tr>
<td>Titan</td>
<td>5152</td>
<td>8.09</td>
<td>0.88</td>
<td>142</td>
<td>20156</td>
<td>36</td>
</tr>
<tr>
<td>Triton</td>
<td>2706</td>
<td>28.87</td>
<td>0.13</td>
<td>21</td>
<td>436</td>
<td>130</td>
</tr>
<tr>
<td>Chiron</td>
<td>220</td>
<td>15.96</td>
<td>0.02</td>
<td>3</td>
<td>9</td>
<td>72</td>
</tr>
<tr>
<td>Pluto</td>
<td>2390</td>
<td>34.05</td>
<td>0.10</td>
<td>16</td>
<td>245</td>
<td>153</td>
</tr>
<tr>
<td>Charon</td>
<td>1210</td>
<td>34.05</td>
<td>0.05</td>
<td>8</td>
<td>63</td>
<td>153</td>
</tr>
<tr>
<td>Mars</td>
<td>6780</td>
<td>0.64</td>
<td>14.55</td>
<td>2352</td>
<td>5531644</td>
<td>3</td>
</tr>
<tr>
<td>Jupiter</td>
<td>143000</td>
<td>4.09</td>
<td>48.23</td>
<td>7794</td>
<td>60740203</td>
<td>18</td>
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<tr>
<td>Saturn</td>
<td>120500</td>
<td>8.09</td>
<td>20.55</td>
<td>3321</td>
<td>11026150</td>
<td>36</td>
</tr>
<tr>
<td>Uranus</td>
<td>51120</td>
<td>18.24</td>
<td>3.86</td>
<td>624</td>
<td>389997</td>
<td>82</td>
</tr>
<tr>
<td>Neptune</td>
<td>49530</td>
<td>28.87</td>
<td>2.37</td>
<td>382</td>
<td>146085</td>
<td>130</td>
</tr>
</tbody>
</table>
On Instrument WaveFront Sensor (OIWFS) guide probe acquisitions

Sidereal tracking mode acquiring on different constellations

Non-Sidereal tracking mode for a single target
TMT: Solar System Applications

Enceladus Plume TMT Simulation

\[ 1'' = 620 \text{ km} \]

Keck AO H-band
TMT IRIS H-band
Galileo
Image credit: Tuan Do, UCLA

IFS
IRDIS
Yang et al. 2016

HST
Faint Object Camera 1994
183 pixels at 7.2mas
HST Advanced Camera for Surveys 2002
16 pixels at 25mas
TMT IRIS
595 pixels at 4mas
New Horizons 2015

Pluto

IFS 29-05-2015
Studying Active Volcanic Plumes

IO. IRIS/TMT – N. Rundquist
TMT prospects vs JWST

- Higher-spatial resolution will enable **detailed geological studies** of solar system objects, including **monitoring of their activities** (e.g. Enceladus, Triton, satellites of the giant planets, planetary rings, etc).
- Higher-spectral resolution, combined with high-spatial resolution, will enable measurements of the **temperature and distribution of atmospheric trace species** on Mars, Venus, gas giants and their moons, tracking spatial and temporal evolution.
- Visible spectroscopy will extend studies of small solar system bodies to include **spectral slope** measurements and effect of space weathering, but also detection of strong spectral lines, **like CN in comets**, etc.
Acknowledgments

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