

Astro2020 Science White Paper

Solar System Science with the James Webb Space Telescope

- Thematic Areas:**
- Planetary Systems
 - Star and Planet Formation
 - Formation and Evolution of Compact Objects
 - Cosmology and Fundamental Physics
 - Stars and Stellar Evolution
 - Resolved Stellar Populations and their Environments
 - Galaxy Evolution
 - Multi-Messenger Astronomy and Astrophysics

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Abstract: NASA's astrophysics assets have been invaluable to advance Solar System exploration in ways that complement *in situ* spacecraft. In this white paper, we provide as an example a review of Solar System science planned for the James Webb Space Telescope using Guaranteed Time Observations (led by H. Hammel, Interdisciplinary Scientist). We envision similar robust science cases for other future astrophysics flagships, particularly LUVOIR.



An imaginative depiction of James Webb Space Telescope with an array of Solar System bodies

Introduction

The launch of the James Webb Space Telescope (Webb), now planned for early 2021, will enable unique and groundbreaking science. The capabilities of Webb have been reviewed elsewhere (Gardner et al. 2006). This white paper specifically outlines Webb's science capabilities in the area of Solar System science as planned in the Guaranteed Time Observation (GTO) program led by H. B. Hammel; GTO observations details can be found at <https://jwst.stsci.edu/observing-programs/approved-gto-programs>. I. de Pater also plans an Early Release Science program of the Jupiter system with Webb, but we do not discuss this program; for details on that, see <https://jwst.stsci.edu/observing-programs/approved-ers-programs/program-1373>. Interested readers can find many more details about Webb's capabilities for Solar System observations in Milam et al. (2016) and references therein, as well as in the references provided in this paper.

Webb's Solar System GTO Program

In 2003, H. B. Hammel was selected as an Interdisciplinary Scientist for Webb, based on a proposal that outlined a broad program of science within our Solar System. A total of 110 hours were guaranteed for Hammel's Solar System program. In this white paper, we review the proposed observations and briefly outline some of the expected science return. In each science area, we cite more detailed assessments crafted by team members.

Asteroids. Webb will provide ground-breaking observations of asteroids, covering wavelength regions that are unavailable from the ground and doing so with unprecedented sensitivity. Main belt and Trojan asteroids are all observable at some point in JWST's lifetime. Rivkin et al. (2016) present an overview of how Webb capabilities apply to asteroids, as well as some representative science cases that take advantage of these capabilities. One science case focuses on NIRSpect image cubes of spatially-resolved

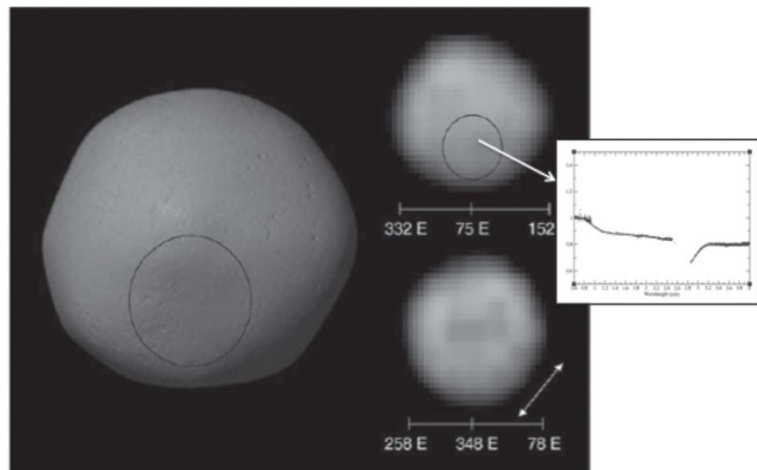


Figure 1. Illustrative figure from Schmidt et al. 2009 shows a Hubble image of 2 Pallas and indicates how Webb will obtain spatially-resolved spectra.

asteroids such as 10 Hygeia, where every pixel is associated with a near-infrared spectrum (e.g., see **Fig. 1**). Another science case involves observations of asteroid collisional family members. Observations in the 0.8–2.5 μm region have found asteroid family members to be remarkably similar to one another even when parent bodies are suspected to be differentiated. Using Webb, we can reach smaller targets in collisional families, and hence potentially determine the characteristic size of collisional fragments at which spectral diversity appears.

Near Earth Objects (NEOs). NEOs are a subset of asteroids and/or comets whose orbits bring them close to Earth's orbit. Thomas et al. (2016) report that the sensitivity of Webb's instruments, as well as the ability to reach wavelength regions that are unobservable from the ground, will add tremendously to our understanding of surface composition, alteration, and physical properties. Webb can observe approximately 75% of the NEO population over one year (**Fig. 2**). Analyses of calculated flux density suggest that both large and small NEOs can be observed if an observer waits for appropriate observing windows. Webb can easily execute photometric observations of meter-sized NEOs, which are difficult to observe with other facilities. Science cases discussed in Thomas et al. include: understanding the size frequency distribution of small NEOs; characterization of select individual objects; complementary observations of spacecraft targets; evolution of dead or dormant comets; and spectral changes between the Main Belt and near-Earth space.

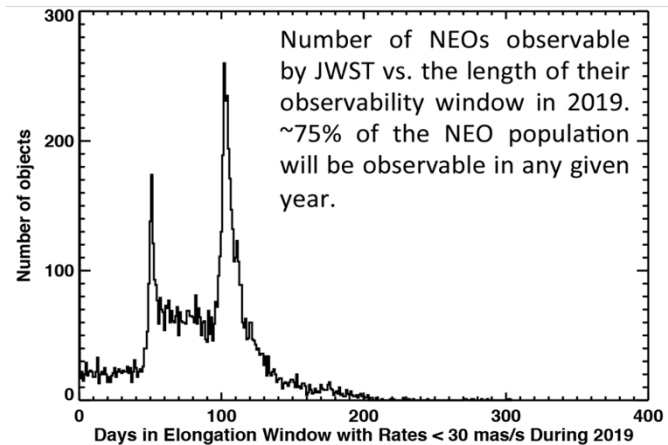


Figure 2. Observability of Near-Earth Objects with Webb.

Mars. Villanueva et al. (2016) assess Webb's capability for Mars observations. From Webb's distinctive vantage point at the Sun-Earth Lagrange 2 point, it samples the full observable disk, permitting the study of short-term phenomena, diurnal processes, and latitudinal processes between the hemispheres (including seasonal effects) with excellent spatial resolutions (0.07" at 2 μm). When Mars is

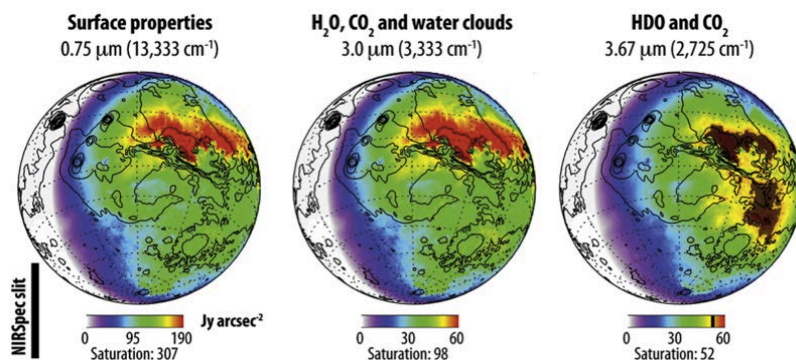


Figure 3. Simulated Mars continuum fluxes for select spectral regions, computed when Mars is 1.433 AU from the Sun and the season is $L_s = 306^\circ$ (southern summer). NIRSpec's 0.2×3.3 arcsec² slit is shown for comparison.

observable to Webb, its NIRSpec spectroscopic observations will be achievable from 0.7 to 5 μm at a maximum resolving power of 2700 (see **Fig. 3**); in later cycles, $R=8000$ in the 1–1.25 μm range may be achievable. NIRCcam imaging is attainable at 4.3 μm and with two narrow filters near 2 μm; the nightside will be accessible with several filters from 0.5 to 2 μm. Science cases include: mapping of the water D/H ratio; investigations of Mars' mesosphere via characterization of non-local thermodynamic equilibrium CO₂ emission at 4.3 μm; studies of chemical transport via observations of O₂ nightglow at 1.27 μm; high-cadence mapping of variability dust and water-ice clouds; and sensitive searches for trace species and hydrated features on the Martian surface.

Giant Planets. Norwood et al. (2016) describes Webb’s unprecedented observing opportunities in the near- and mid-infrared for Jupiter, Saturn, Uranus (**Fig. 4**), and Neptune. Webb can take advantage of methane’s wavelength-dependent absorption to probe to different depths in their atmospheres and to engage in myriad investigations: mapping vertical and horizontal cloud structures, including major storm systems and their evolution; mapping of latitudinal variation in methane abundance on Uranus and Neptune to explore implications for global circulation; and comparing near-simultaneous reflected-light and thermal imagery to study thermo-chemical processes behind different features. Other stratospheric investigations on these planets include: detection of (or improving the upper limits for) new hydro-carbons on these planets (e.g., ethylene and the CH₃ radical have been detected on Neptune, but not on Uranus; and benzene may be detectable on Neptune); mapping distributions of oxygen-bearing species such as CO₂, CO, and H₂O to constrain the influx rates and sources of external oxygen (sources may include infalling ring particles, dust from satellites, Kuiper Belt objects, or cometary impacts).

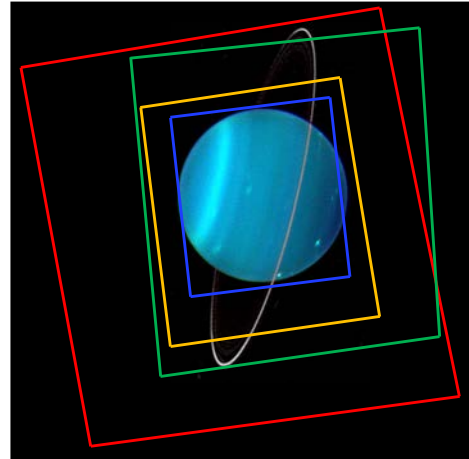


Figure 4. Uranus with Webb’s four MIRI medium-resolution IFUs. Different optical elements and light paths for each channel result in fields of view that are offset and rotated with respect to each other. The IFUs will produce spectral maps with high efficiency for Uranus, even at R=3000. Keck image courtesy L. Sromovsky.

Titan. Nixon et al. (2016) report on Webb’s significant potential for advancing Titan science (**Fig. 5**); at near-infrared wavelengths, its spectral resolution exceeds that of the Cassini spacecraft and its spatial resolution exceeds that of Hubble. In particular, Webb’s 5-10 yr lifetime will be valuable for time-domain monitoring of Titan. Nixon et al. assess science return in 5 key regimes: (1) surface: Webb can spectrally characterize Titan’s surface to provide new discriminants of surface solid and liquid composition, and to monitor changes in albedo that are due to rainfall; (2) clouds: Webb can monitor the apparition and frequency of lower atmosphere clouds, providing information not only on latitudinal and temporal distribution necessary to constrain climate models, but also potentially on cloud altitude and chemical composition; (3) lower atmospheric composition: Webb will search for spatial and temporal variation in the relative humidity of methane to give insights into meteorological and/or chemical sources and sinks of this key species; (4) middle-atmosphere composition: MIRI will search for new gas species using high spectral resolution, and NIRSpec will measure dayside gas fluorescence of HCN, CO, C₂H₂, CH₄, and other species; and (5) middle-atmosphere hazes and clouds: Webb can monitor the large-scale distribution of Titan’s haze, as it switches in appearance between hemispheres in response to annual circulation and insolation.

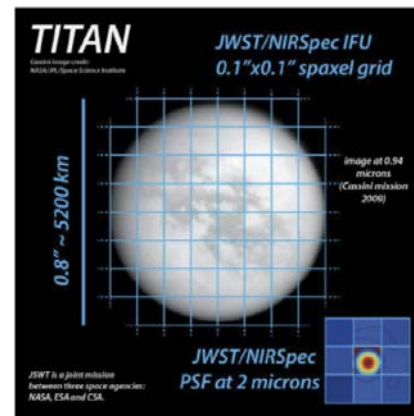


Figure 5. Titan with Webb’s NIRSpec.

Comets. Kelley et al. (2016) summarize four cometary science cases especially suited for Webb: the drivers of cometary activity; comet nucleus heterogeneity; water ice in comae and on surfaces; and activity in faint comets and main belt asteroids. With Webb, we can expect the most distant detections of gas, especially CO₂, even for only moderately bright comets (Fig. 6). For nearby comets, coma dust properties can be simultaneously studied with their driving gases. For comets in the distant solar system, studies of water ice and gas will help elucidate our understanding of cometary interiors and coma evolution. Activity in main belt comets will be explored with the possibility of the first direct detection of coma gas. The figure (from Milam et al. 2016; see references therein) illustrates simulated NIRSpectra with R~3000 for major cometary constituents compared to the NASA Deep Impact spectra towards comet 9P/Tempel 1 (dark green line; molecular emissions arbitrarily scaled). The GTO program includes a Target-of-Opportunity observation of a new dynamic comet, a main-belt comet, and a known periodic target.

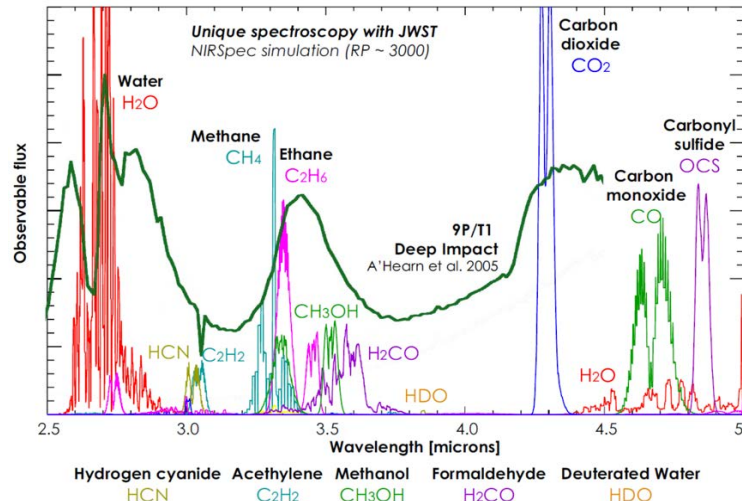


Fig. 6. Webb’s spectroscopic capabilities are well matched to explore comet composition.

Trans-Neptunian Objects. Parker et al. (2016) report that Webb will bring about a new era in physical characterization of TNOs. Specific areas explored include: temperatures, diameters, albedos, and thermal properties; binary discovery and characterization; and TNO surface compositions. TNOs are highly diverse (e.g., in size, color, albedo, surface composition, binarity, and orbit), but many previous studies were limited by these targets’ faintness. NIRSpect’s sensitivity will enable near-infrared spectral observations for the first time over the full near-infrared range (1-5 μm) for many TNOs. Spectral observations across different dynamical classes will probe the chemical composition of the primordial Kuiper Belt as a function of heliocentric distance and provide the first information on the surface compositions of small TNOs (see, e.g., Fig. 7). Near-infrared images will enable color measurements for TNOs too small to observe with NIRSpect and has sufficient spatial resolution for resolving binary TNOs in tight orbits. NIRCcam can also provide near-IR color measurements of

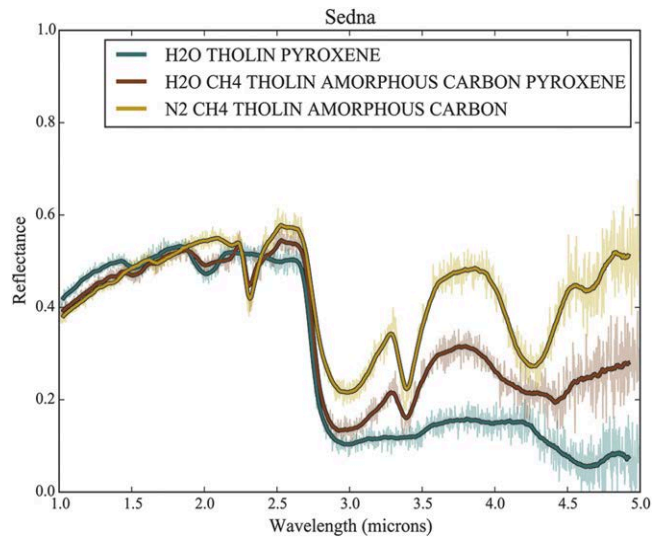


Fig 7. Simulated NIRSpectra of Sedna. the three model spectra are incompatible with each other at very high confidence at wavelengths accessible to Webb.

binary components, enabling tests of theories of binary formation through comparison of the colors of the individual components. MIRI's mid-infrared observations will enable observations of TNOs at the shortest wavelengths of the thermal regime. By combining MIRI and ALMA measurements (the latter on the red side of the thermal peak) very precise size and albedo measurements could be made for TNOs not already characterized using Herschel or Spitzer.

Occultations. Santos-Sanz et al. (2016; and references therein) describe the capabilities of Webb to observe stellar occultations by outer Solar System bodies, including detection of tenuous atmospheres (e.g., of Pluto or Triton) and monitoring of seasonal variations in atmospheric structure and surface pressure; determination of lower limits on sizes of smaller TNOs as well as constraints on size-frequency distribution; and the study of rings around planets and small bodies. NIRCarn is the preferred instrument to observe predictable stellar occultations due to its sensitivity and high time resolution. To examine the potential utility of Webb occultations by distant Solar System minor bodies, Santos-Sanz et al. (2016) searched for candidate events for 13 large and/or interesting TNOs and Centaurs over a period of 5 years. This yielded several dozen potential opportunities. Though this is just a notional list (actual events will depend crucially on knowledge of Webb's specific orbit), it indicates that such occultations are feasible.

Planetary Rings and Small Satellites. Webb will provide unprecedented opportunities to observe the rings and small satellites in our Solar System, accomplishing three primary objectives: discovering new rings and moons; unprecedented spectroscopy of such bodies; and time-domain observations, e.g., positions of Neptune's ring arcs or spokes in Saturn's rings (**Fig. 8**). Tiscareno et al. (2016) explore these cases in detail. Because faint rings and small moons are often in close proximity to the (bright) planet about which they orbit, it is important to characterize the stray light and extended point-spread function (EPSF) of Webb. In particular, the wavelength-dependent EPSFs need to be compiled for extended objects especially when the planet is off the edge of the field of view.

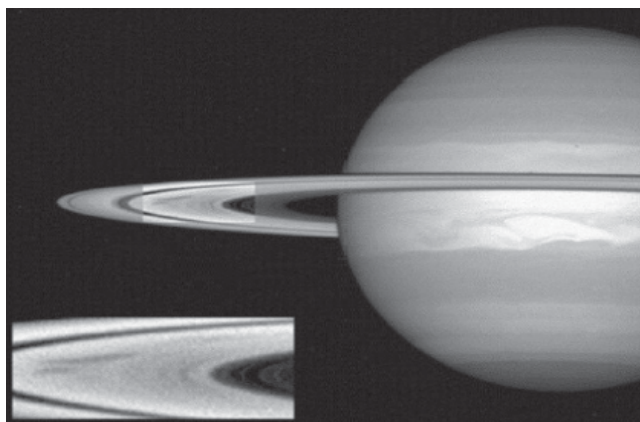


Fig. 8. Image of Saturn taken with Hubble Space Telescope in 1996 (McGhee et al. 2005); inset shows a zoom in on the ring spokes.

Summary

Webb will provide a rich and robust suite of scientific observations in our Solar System, complementing work done with other telescopic facilities as well as with *in situ* spacecraft at these bodies. The URLs below provide more information about Solar System science with Webb.

<https://jwst.stsci.edu/about-jwst/science-themes/solar-system>

https://jwst.nasa.gov/faq_solarsystem.html

<https://jwst-docs.stsci.edu/display/JPP/JWST+Moving+Target+Observations>

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