

JWST Planetary Observations within the Solar System

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Abstract

JWST provides capabilities unmatched by other telescopic facilities in the near to mid infrared part of the electromagnetic spectrum. Its combination of broad wavelength range, high sensitivity and near diffraction-limited imaging around two microns wavelength make it a high value facility for a variety of Solar System targets. Beyond Neptune, a class of cold, large bodies that include Pluto, Triton and Eris exhibits surface deposits of nitrogen, methane, and other molecules that are poorly observed from the ground, but for which JWST might provide spectral mapping at high sensitivity and spatial resolution difficult to match with the current generation of ground-based observatories. The observatory will also provide unique sensitivity in a variety of near and mid infrared windows for observing relatively deep into the atmospheres of Uranus and Neptune, searching there for minor species. It will examine the Jovian aurora in a wavelength regime where the background atmosphere is dark. Special provision of a sub-array observing strategy may allow observation of Jupiter and Saturn over a larger wavelength range despite their large surface brightnesses, allowing for detailed observation of transient phenomena including large scale storms and impact-generation disturbances. JWST's observations of Saturn's moon Titan will overlap with and go beyond the 2017 end-of-mission for Cassini, providing an important extension to the time-series of meteorological studies for much of northern hemisphere summer. It will overlap with a number of other planetary missions to targets for which JWST can make unique types of observations. JWST provides a platform for linking solar system and extrasolar planet studies through its unique observational capabilities in both arenas.

Introduction

The James Webb Space Telescope continues the legacy of Hubble Space Telescope in observing solar system objects with the unique wavelength coverage and image quality available to space-borne observatories (Gardner et al., 2006). JWST brings much higher sensitivity and wavelength range to observing such targets. The moving target capability being implemented for the observatory will enable tracking and study of a wide range of interesting solar system objects (Balzano et al., 2008). JWST also will have capabilities for observing exoplanets that extend beyond what can be done from the Earth, and particularly for M dwarfs will permit characterization of exoplanets down to sizes a few times that of the Earth. In this white paper we highlight selected examples of solar system observations which JWST can do, in some cases uniquely, by virtue of its high sensitivity and broad wavelength coverage. Many of these objects are very bright, and special techniques to enable their observation are detailed in a separate report by Meixner et al. (2008). A separate white paper is being prepared by Clampin et al. on extrasolar planet observations, and hence is not covered here. The material presented here is derived largely from a workshop conducted at the 40th DPS meeting in Ithaca New York, on October 10, 2008.

In this paper we do not cover the inferior planets, simply because JWST is unable to observe them. Because of its architecture, especially the size and shape of the sunshield, sight lines from JWST may be no closer than 85 degrees from a line from the sun to the observatory axis (figure 1).

The importance of studying the solar system

With over 420 planets and 41 multiple planet systems in the nearby regions of the Galaxy, our solar system has become a kind of ground truth for what is a common cosmic phenomenon. Study of the planets of our solar system provides detailed information on atmospheric and surface processes that has already provided dividends in interpreting observations of extrasolar planets. For example, fluid dynamical models of atmospheric circulation in extrasolar planets derive from models constrained by the dynamical

phenomena observed on the solar system's giant planets (Showman et al. 2010). Observations of the terrestrial planets with atmospheres and of Titan, whose dense nitrogen-dominant atmosphere is part of an active hydrologic cycle involving methane, provide information on the range of potential terrestrial-type planets that will be observed around Sun-like stars and M-dwarfs. Studies of the most distant and primitive bodies in the solar system, including comets and Kuiper Belt objects, provide clues to the original inventory of material from which the solar system formed, and this information can be compared with and placed in the context of compositional studies of molecular clouds and the interstellar medium to better constrain the cycle of matter in the galaxy (Gardner et al., 2006) (figure 2). Finally, selected bodies may reveal spectroscopic features potentially indicative of biological or interesting prebiotic organic processes, so that telescopic observations become remote sensing searches for life.

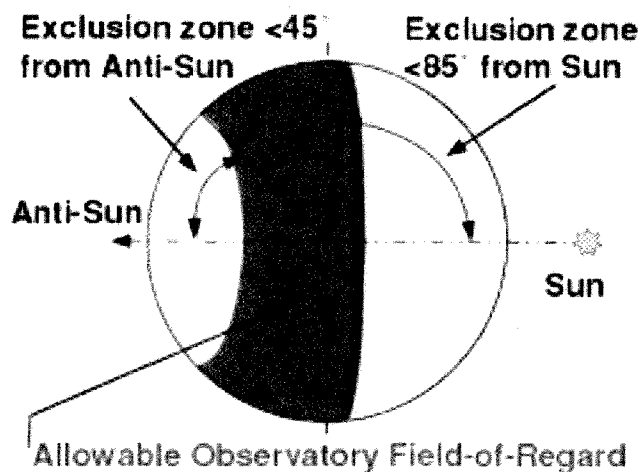


Figure 1. Allowable field-of-regard for JWST, showing the exclusion zones in the solar and antisolar directions. From Gardner et al (2006).

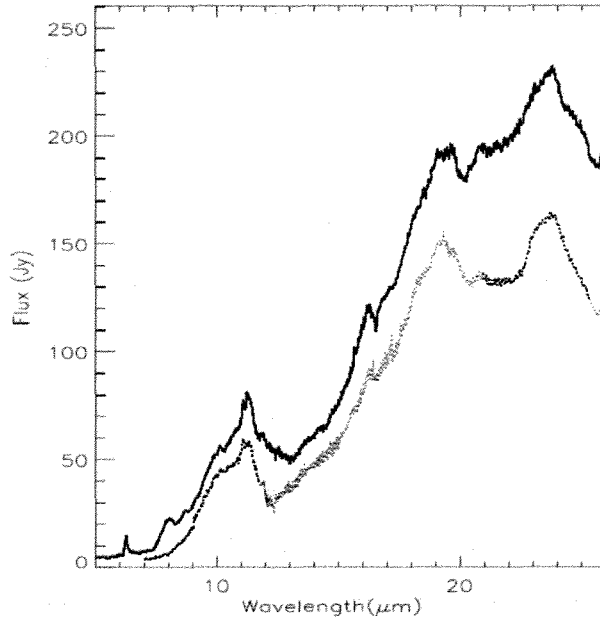


Figure 2. Comets and circumstellar disks. An ISO-SWS spectrum (speed 4, corresponding to a spectral resolution of approximately 1000) of the Herbig Ae/Be star HD 100546 (*upper curve*) shows emission features in the star's circumstellar disk as predicted if the disk is heated by radiation from the central source. The particle composition in the circumstellar disk appears to be remarkably similar to that of comet Hale-Bopp (*lower curve*). The wavelength range shown here corresponds to that which will be covered by JWST. (Figure modified from Malfait *et al.*, 1998).

Selected solar system objects

In this paper we move outward from the Earth to the edge of the solar system and examine selected objects and classes of objects for which JWST can make useful scientific contributions. All of these objects have angular rates that, for at least part of their orbit, will be within the capability of moving target tracking software being developed for JWST. Table 1 shows these rates (Anandakrishnan *et al.*, 2007). Comets are a special case in which rates vary greatly from object to object, and many comets exceed JWST's capability.

Table 1: Tracking rates for various solar system objects

Object	Minimum rate (mas/sec)	Maximum rate (mas/sec)	Distance moved in 10 hrs at min rate (arcsec)	Time to move 1 arcmin at max rate (hours)
Mars	2.5	28.6	90	0.6
Jupiter	0.070	4.5	2.5	3.7
Io	0.004	10.2	0.14	1.6
Saturn/Titan	0.040	2.9	1.4	5.7
Uranus	0.020	1.4	0.7	12
Neptune	0.004	1.0	0.14	17
Pluto/KBO's	0.160	1.0	5.7	17

By commanding the pointing control system to force the guide star to move opposite the motion of the solar system target, the Webb will hold the target steady in its IR cameras or spectrographs (1-28 microns). These observations must finish before the guide star moves out of the FGS field of view: imposing a limit on the product of the duration and the apparent angular speed of the target. Another important factor in assessing the utility of JWST is spatial resolution on the surface of a particular solar system body. In table 2 we take the diffraction limit at 2 microns as the criterion for calculating effective spatial resolution on various solar system objects.

Table 2: JWST spatial resolution for a 2 micron diffraction limit of 0.07 arcsec

Object	<u>Diameter, arcsec</u>	<u>Diameter, km</u>	<u>Spatial resolution, km</u>
Mars	4-25	6800	66
Jupiter/IO	30-49/.77-1.3	140,000/3600	230
Saturn/Titan	15-20/.65-.87	120,000/5200	420
Uranus	3-4	51,000	840
Neptune/Triton	2/0.11	50,000/2700	1300
Pluto @ 35 AU	0.1	2400	1500

Finally, JWST will overlap with a number of missions to important outer solar system and main belt asteroid targets (we do not include Mars missions as these are almost continuous now). Complementary observations by JWST during and after these missions will permit extension in wavelength range and time baseline of the mission targets. Table 3 lists these missions, their targets, and anticipated operating periods relevant to JWST.

Table 3: Main belt and outer solar system missions operating during JWST

<u>Object</u>	<u>Mission</u>	<u>Operating period</u>
Ceres	Dawn	2015
Jupiter	Juno	2016-2017
Saturn/Titan	Cassini Solstice	2010-2017
Comet 67P/ Churyumov- Gerasimenko	Rosetta	2014-2015
Pluto	New Horizons	2015

Mars

Continued studies of Mars with JWST offer the promise of unique and important new contributions to Mars science and to NASA's future mission goals. Specifically, global-scale near-IR observations can: (1) determine the variability of major and secondary atmospheric species like CO₂, CO, and H₂O, providing data for photochemical and dynamical modeling of the present Martian climate; (2) constrain the near-IR radiative and absorptive properties of airborne dust, another key component of the present Martian climate system; (3) assess the magnitude and scale of diurnal, seasonal, and interannual volatile transport through direct near-IR detection and discrimination of surface and atmospheric H₂O and CO₂ ices/clouds, especially in the polar regions; and (4) help to quantify the surface volatile budget and resource potential by detecting and mapping the distribution of H₂O-bearing or OH-bearing surface minerals like clays and hydrates.

Mars has a very high surface brightness in the near and mid infrared. NIRCam can only observe Mars at the longest wavelength, narrow band filter. MIRI cannot observe Mars in any imaging or spectroscopic configuration. Use of the FGS-TFI requires the sub-array mode through the neutral density filter. The photometric calibration of this mode is part of the baseline calibration plan of the FGS team.

Mapping of methane plumes on Mars

Beginning in 2003, ground-based telescopes and orbiting spacecraft detected methane in the Martian atmosphere (Formisano et al., 2004; Mumma et al. 2009), at levels as high as 33 parts per billion (ppb); were this spread uniformly over the planet's atmosphere this would be equivalent to 6 ppb. By 2006 the equivalent mixing ratio over the whole planet had dropped by a factor of two. The surprising aspect of this discovery, aside from the potential biological significance of methane itself (either generated by organisms or if produced geologically, indicative of subsurface water-rock reactions), is the short decay time of the methane. Although it is unstable in the predominantly CO₂-rich atmosphere, the photochemical loss timescale is centuries, and indeed a continuously emitted source over that time would have led to a uniform mixing ratio of methane throughout the Martian atmosphere over a much shorter timescale. The methane is definitely localized in latitude and longitude, and hence what is observed is material that has been recently emitted with a residence time in the atmosphere significantly less than a martian year, lost through oxidative reactions with the soil.

While ground-based observations were made with spectral resolutions of 30,000, for Planetary Fourier Spectrometer aboard Mars Express in orbit around Mars had a spectral resolution of 3,000 at 3.3 microns, where methane was detected (figure 3). Other bands of sufficient strength within JWST's wavelength span are at 2.3 microns and 7 microns wavelength, though both are weaker than the 3.3 micron band, and the inability to use MIRI would rule out the longer wavelength band. While JWST's large distance from Mars and lack of a very high resolution spectrometer militate against it being a

useful way to find the ambient background level of methane, it might catch a large

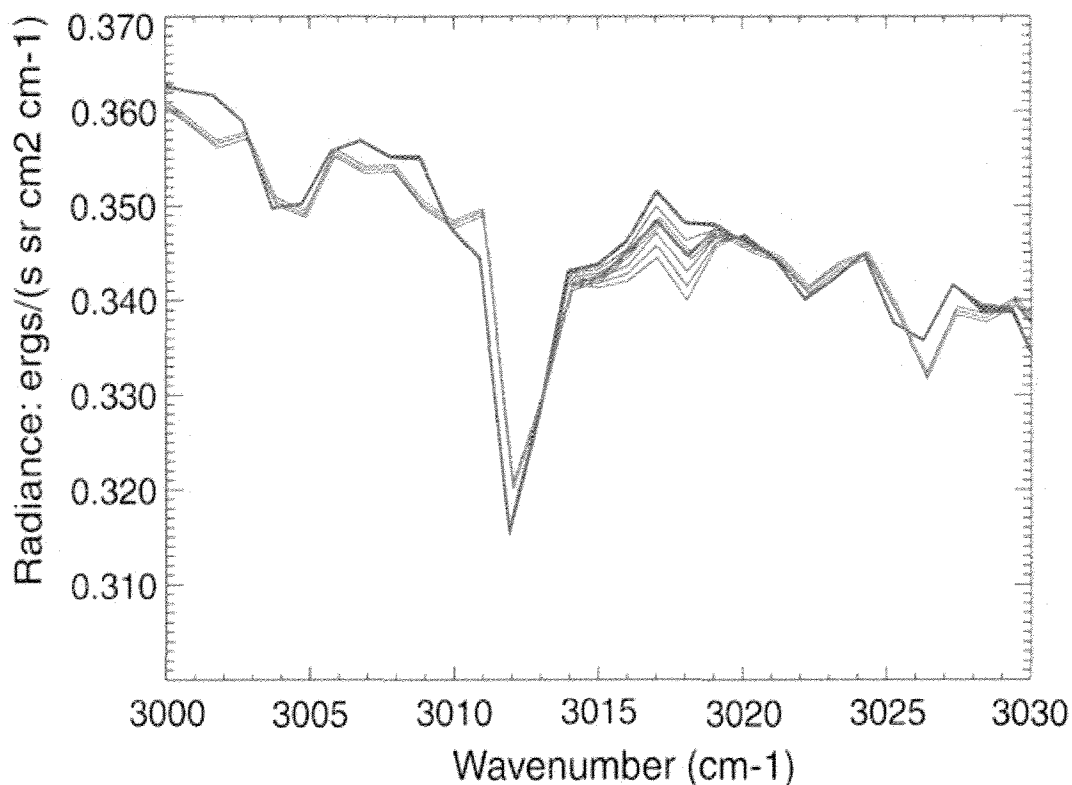


Figure 3. Synthetic spectra designed to simulate data from the Planetary Fourier Spectrometer (PFS) observing the Martian atmosphere from the Mars Express orbiting platform with spectral resolution of 3000. Visible is the methane ν_3 feature at 3018 cm^{-1} computed for 0 ppb (green curve) and 10, 20, 30, 40, and 50 ppb (violet curves) of methane, compared with the PFS average spectrum (black curve). Results are consistent with between 10-20 ppb of CH_4 in the atmosphere. The synthetic spectra have been computed for 6.7 millibars of CO_2 , including 350 ppm of H_2O , along with dust and water ice clouds. From Formisano et al. (2004).

outburst if these occur with a frequency higher than once per decade.

Io

Io's allure is its very unusual nature as the most volcanically active body in the solar system, and its direct links to both the Jovian magnetosphere (through its associated plasma torus) and the Jovian atmosphere (via the strong current system that links the two). Detection of SO_2 gas absorption at $7.4 \mu\text{m}$ —seen by Voyager IRIS but not recorded since—will be of great interest because it records gas abundance directly above hot spots. This band cannot be observed from the ground due to telluric absorption, and while

SOFIA can detect the band, it is unable to spatially resolve Io's disk. The mid infrared spectroscopic capabilities of JWST would also be very useful for exploring subtle 10-20 μm spectroscopic features seen by Voyager IRIS. Furthermore, detection of faint, very high temperature hot spots at 0.6 - 1.4 μm would be of some importance, as would detections of neutral S emissions at 1 μm . Roll stability in target tracking and cosmic ray constraints on the detectors limit exposure times to 1000 seconds; the effect of this on sensing of hot spots should be evaluated.

Titan

Titan is a target of the very highest astrobiological interest in our own solar system. It is the second largest moon in the solar system, has a nitrogen atmosphere several times denser at its surface than that of the Earth at sea level, and boasts an active equivalent of the Earth's hydrological cycle in which two hydrocarbons, methane and ethane, take the place of water--each cycling on different timescales (Lunine and Lorenz, 2009; Aharonson et al. 2009).

Titan is richly endowed in organic molecules on the surface; a series of lakes and seas at polar latitudes hold more hydrocarbon material than the known oil reserves on the Earth (Lorenz et al., 2008). Its nitrogen-methane atmosphere, by virtue of continuous loss of hydrogen liberated from photolyzed methane in the upper atmosphere, is not strongly reducing, and hence is comparable to the pre-biotic Earth's atmosphere in net redox propensity for synthesizing organic polymers. While the chemistry of the atmosphere is well known, that of the surface is not. However, the atmospheric chemistry liberates hydrogen from methane to create a suite of higher carbon number hydrocarbons and nitriles, whose fate in the extraordinarily cold atmosphere (94 K at the equatorial surface, 90 K at the poles) must be to condense and fall to the surface. Some of this material falls directly into the lakes and seas or is transported there by winds; other aerosols agglomerate to form sand-sized particles comprising the equatorial dunes.

Impacts melt the water ice crust and internally-generated volcanism might as well, leading to locations on the surface where the organics react with water over significant

timescales to produce amino and carboxylic acids, as well as other precursors to biomolecules. Thus, while the low temperatures rule out continuous surface liquid water and hence life, Titan is a Mercury-sized world upon which some of the steps associated with the pre-biotic synthesis of polymers essential to life are played out--over and over again with every impact.

The US-European mission "Cassini-Huygens" entered Saturn orbit in 2004 to begin an exploration that continues beyond the four-year prime mission into the present "equinox mission" (2008-2010) (referring to the present seasonal phase of Saturn and Titan) and the "solstice mission" (2010-2017) after which it will be directed into a destructive entry of Saturn's atmosphere to avoid contaminating Titan or Enceladus. In 2005 the instrumented Huygens probe descended through the atmosphere to the surface, relaying images of valley networks evidently carved by liquid methane. In total the mission has told us that organic deposits are indeed widespread across the surface, and hints of variations in the organic composition can be seen in the medium-resolution (R~150 at 2 microns) near-infrared spectroscopy done by Cassini.

However, gaps will remain in our knowledge when final observations of Titan by Cassini are made in 2017. These gaps are the result of several limitations of Cassini. First, geometric constraints associated with the fixed-pallet placement of instruments on the Cassini orbiter (a compromise due to cost) dictate that each of the close flybys will be devoted to only a subset of the instrument techniques. In the end, radar will cover only 40% of the surface at its best spatial resolutions of hundreds of meters. Second, the VIMS near-infrared spectrometer has a lower spectral resolution and sensitivity compared to JWST. The limited spectral resolution is particularly frustrating because Titan's atmosphere must be viewed through a scattering haze of photochemical aerosols and at wavelengths in between the deep absorbing atmospheric methane bands. The VIMS wavelength bands are such that residual methane absorption remains a problem, and atmospheric models must be used to remove this residuum. Finally, there was no possibility for Cassini to cover a full Titan year, 29.5 Earth years. Because of the axial tilt of Titan (essentially coaligned with the spin axis of Saturn), Titan experiences seasonal

shifts of sunlight similar in amplitude to that of the Earth. Spacecraft missions to date, and those planned, will cover a portion of Titan's year corresponding to northern late fall through the first "day" of northern summer (figure 4). JWST's period of operation is unique in that it will cover the portion of Titan's year corresponding to the late northern spring and almost all of the northern summer.

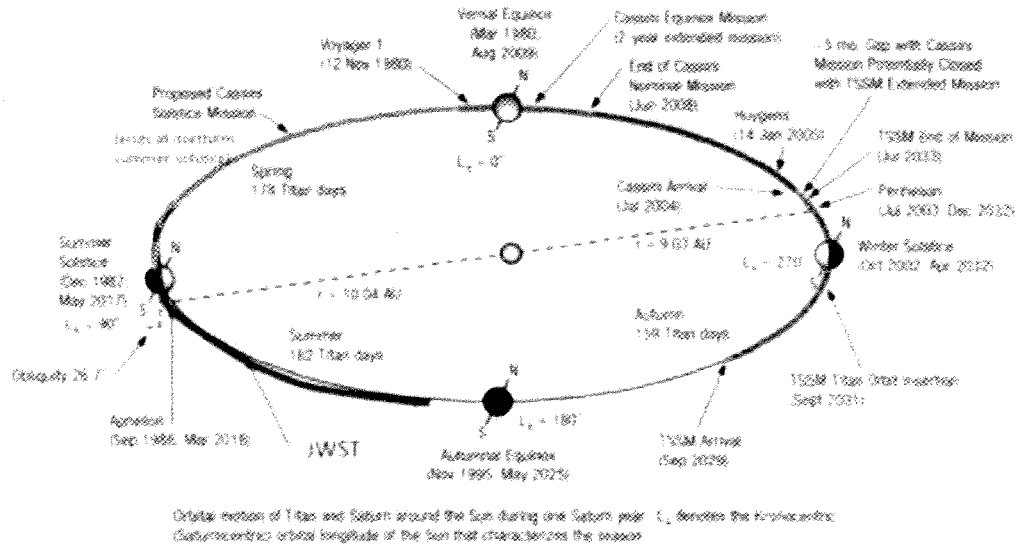


Figure 4: The seasonal configuration of Titan (identical to that of Saturn) is shown. Designations "Vernal", "Summer" etc. are for Titan's northern hemisphere. The seasonal phases for various spacecraft missions in the past, present and future are shown. JWST's period of operation, assumed here to be ten years from launch in 2014, occupies a unique time during northern summer not probed by other space missions. Note the approximately two-year overlap between Cassini (orange) and JWST (purple) observations. Saturn's orbit around the Sun has an eccentricity of 0.05; "r" indicates the Saturn (Titan) perihelion and aphelion. A proposed Discovery-class mission, Titan Mare Explorer, would arrive in 2023 (not marked on the figure).

HST and adaptive optics ground-based telescopes have achieved diffraction limited imaging of Titan from Earth. HST NICMOS observations of Titan demonstrated

spatial resolution of roughly 200-300 km resolution near the Titan equator and sufficient signal-to-noise to identify the darkest areas as having near-infrared albedos consistent with hydrocarbons (Meier et al., 2000). Ground-based telescopic studies can do what Cassini cannot: provide frequent if not continuous coverage of changes in the atmosphere and on the surface. Ground-based observations suggested short-term changes in the 1-2 micron region of the spectrum associated with the formation of clouds even prior to Cassini (Griffith, 2000). In 2008 a major outburst of mid-latitude clouds was observed from the IRTF (Schaller et al., 2009).

By 2017 we will be left with the following questions:

1. What does the surface look like in higher ($R \sim 3000$ vs. 200) near-IR spectroscopy?
2. What time-variable phenomena might occur due to seasonal (decadal) variations or stochastic surface events in the near-infrared and in that part of the mid-infrared (640 cm^{-1}) where the atmosphere is once again optically thin enough to see the surface?

JWST can make NIRCams images, and NIRSpec spectra of Titan to build on the 2004-2017 Cassini mission survey, creating a potentially long (10 year +) baseline of spaceborne near-infrared observations of Titan's surface and atmosphere during a seasonal configuration hitherto unexplored in the infrared. The pixel size on NIRCams gives about the same spatial resolution on Titan as Hubble (table 2), but the signal-to-noise is much higher. Spectral resolution a factor of 6 better than on Cassini can be accomplished using the NIRSpec, allowing for spectra far more diagnostic of the types of organic species present on the surface. Thus while Cassini gets better spatial resolution, JWST will achieve higher spectral resolution with useful spatial resolution over the mid-latitude regions of Titan. Of interest is whether surface changes or secular atmospheric changes are in evidence over a decadal timescale. With NIRSpec, the ability to probe the atmosphere over several levels down to the surface provides a unique long-term capability that is unavailable from Hubble and will cease to be available from

Cassini after 2017. Thus JWST provides long-time baseline continuity throughout the infrared.

One approach is to take NIRCcam, NIRSpec and MIRI data on Titan over three equally spaced intervals during the 16-day orbit of Titan, which is phase-locked to Saturn. This provides images and spectra centered approximately 120 degrees apart from each other, and hence global coverage. Cloud movement in the stratosphere, based on our understanding of Titan's winds, occurs with a velocity of 100 m/sec and hence it requires many hours to track cloud movement in detail. Cloud tracking with HST was very difficult because of the telescope's 90-minute orbit around the Earth; with JWST at L2 it will be much easier. Beyond the initial cloud campaign, revisits to Titan once per year should be done to map in imaging and spectroscopy each of the hemispheres to look for longer-term changes.

Of additional interest is whether surface changes or secular atmospheric changes are in evidence over a decadal timescale. The year 2009 corresponds to the onset of northern hemisphere spring equinox, and the polar regions where large numbers of lakes and one Caspian-sized sea are present will be experiencing sunlight for the first time in almost 15 years. Dramatic changes are expected in the atmosphere above the lakes region and on the surface itself. JWST will be able to monitor these changes beyond the hard cutoff for detailed observations of Titan by the Cassini mission of 2016. Observations prior to that will allow correlation between Cassini and JWST data, allowing a better understanding of what the JWST observations mean when Cassini is no longer available. Should JWST's mission last for a decade, that is, into 2024, it will carry Titan seasonal observations into northern summer solstice, and connect Cassini with the next potential mission to Titan, the Titan Mare Explorer, proposed to arrive in 2023.

Giant planets

The giant planets make up most of the mass of the solar system with the exception of the Sun, and represent natural laboratories for fluid dynamical, including meteorological processes, distinct from that of the Earth and from each other as well. The

foundational goal to understanding these systems is to quantify how energy, momentum and gaseous composition are connected/transported between various layers in the atmosphere (thermosphere, mesosphere, stratosphere, upper and lower troposphere, and their connection to the charged environment of aurorae/magnetospheres).

The evolution of discrete features such as storms, convective instabilities, waves, polar vortices and seasonal phenomena should be observed at a variety of wavelengths. Regular coverage across the spectrum of winds (of jets and vortices) to see how they change, particularly in response to changes in the thermal and cloud profiles observed in the IR and visible, is of particular value as well. Center-to-limb studies over multiple wavelengths and comparison of clouds and hazes from planet-to-planet are important to understanding formation of clouds and particle size distributions: a particular problem for modeling the atmospheres of extrasolar giant planets.

Jupiter and Saturn

Jupiter is the archetypal giant planet that provides a “ground truth” for the hundreds of giant planets seen around other stars. Much of what we know of Jupiter comes from Earth- and space-based telescopic observations, including the spectacular set of results obtained during and after the impact of the Shoemaker-Levy comet fragments into the Jovian atmosphere. The Galileo mission in the 1990’s provided the first close-up near-infrared spectra of the Jovian atmosphere, revealing a variety of meteorological phenomenon in the deeper water cloud layer beneath the surface ammonia clouds, some of which could be tied to optical lightning flashes seen in CCD images from the Galileo camera. Moist convection—convective activity enhanced and shaped by the condensation of water and ammonia, may be the dominant process by which energy is transported vertically through the atmospheres of Jupiter and Saturn. Higher in the atmosphere, the distributions of hydrocarbons and stratospheric hazes are complex and serve as tracers of stratospheric dynamics and chemistry.

Juno, a polar orbiting mission that will arrive in 2016 for a one-year mission, will make near-infrared spectra and images from very close range (within 10,000 km of the

visible cloud surface), thereby providing extremely high-resolution detail (tens of kilometers) on convective storm activity. However, the highly elliptical orbit of the spacecraft means these visits will be brief, and they will lack global context, which JWST can provide overlapping wavelengths to the Juno infrared mapper via MIRI and possibly NIRCams (but see below on brightness constraints for JWST constraints regarding bright objects.).

Saturn's disk appears bland relative to Jupiter in the optical, but is spectacular in the near infrared as revealed by the Cassini Visible and Near-Infrared Spectrometer (figure 5). Beginning in 2016, Cassini will be placed in a highly inclined, highly eccentric, polar orbit of Saturn that is akin to the orbit of Juno around Jupiter. Although the intent of this orbit is to eventually destroy Cassini in Saturn's atmosphere (in 2017) for purposes of planetary protection, these Juno-like orbits will allow high-resolution near-infrared images of the turbulent Saturn atmosphere revealed to be present below the haze. As in the Jupiter case, global context will be missing but is important for placing the detailed images into larger-scale weather systems. JWST will be capable of providing this information in overlapping wavelength regions via NIRCams and MIRI. A rich variety of features exist in the infrared diagnostic of various atmospheric processes (figure 6). These observations, in turn, will help greatly the interpretation of data on exoplanet weather systems, a newly emergent subfield of extrasolar planetary studies also enhanced by JWST.

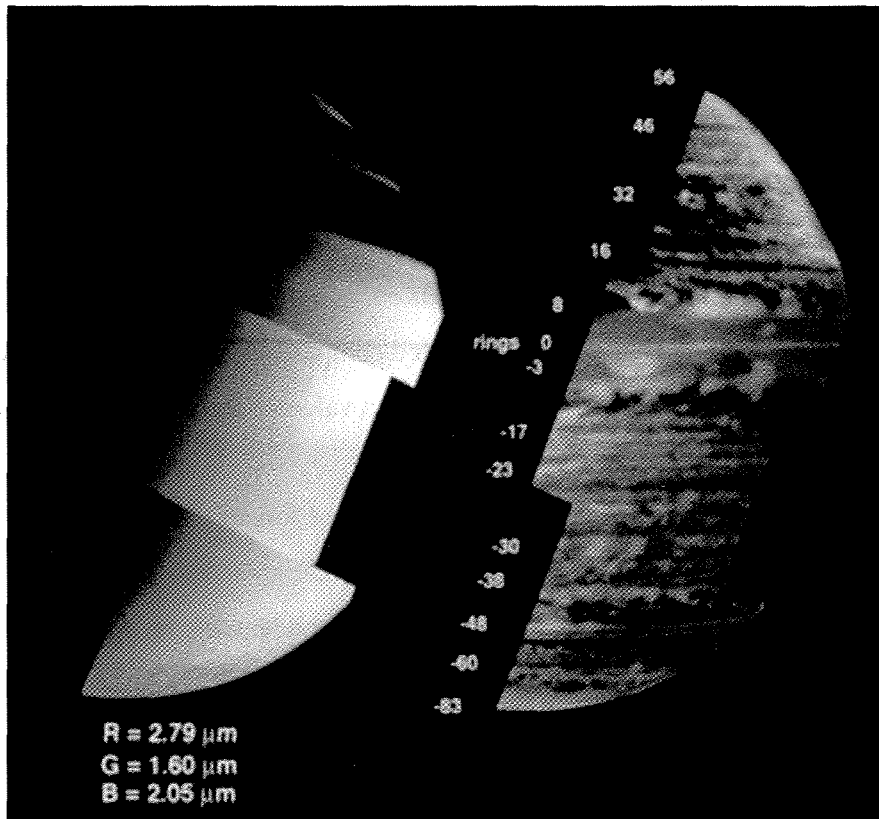


Figure 5: High spatial resolution thermal imaging of giant planets strips away the haze to reveal dynamical processes within the deeper atmosphere. Saturn seen from Cassini-VIMS in (left) reflected sunlight at 1.6 (green), 2.05 (blue) and 2.79 (red) microns wavelength presents a hazy, relatively featureless surface. In the thermal infrared at 5 microns, Saturn's deeper atmosphere (2 bars) exhibits dynamical processes resembling those seen on Jupiter.

NIRCam can only observe Saturn at the longest wavelength, narrow band filter. NIRCam cannot observe Jupiter, unless a highly specialized “strip mode” is adopted, which seems unlikely given that the bright planets are not science drivers for the mission. Jupiter and Saturn can be imaged in MIRI's neutral density filter, but this filter is not planned for calibration. The MIRI MRS/IFU can observe Jupiter and Saturn. The TFI can observe through its neutral density filter.

Uranus and Neptune

Much less is known about Uranus and Neptune-mass than about Jovian-mass objects, both within and beyond our solar system. There are important differences, tied to the proportionately larger effect of a heavy element core in the former relative to the latter. Neptune had significant influence on the early history, evolution, and development of the solar system, deflecting icy planetesimals containing water and other volatiles to inner solar system from the Kuiper Belt. Detailed comparisons of internal structures and compositions of gas giants with ice giants will yield valuable insights into processes that formed the solar system.

Uranus and Neptune are each a tenth the mass of Jupiter and Saturn, contain a higher proportion of heavy elements, and because of their greater distance from the Sun have different condensables in their atmospheres. The condensable responsible for moist convection in the upper atmosphere is methane, not water or ammonia, and rapid rotation plays an even larger role on these objects relative to vertical motions. Observations of Uranus and Neptune within our own solar system are sparse, and the ability to observe at a wide range of wavelengths with high sensitivity is of keen value. These two bodies do not pose saturation problems for JWST.

JWST can image spectral features formed at high altitudes in these atmospheres with extreme sensitivity. Moving target tracking software will allow exposures in principle of a day (other operational constraints will require that exposures longer than that be broken up). This allows mapping of clouds, spectral imaging of specific species such as H_3^+ (auroral emission), CO in fluorescence, and others. JWST's unique sensitivity will allow detailed mapping of the 5-micron window, search for minor species and measure the isotopic ratios of major elements in trace species.

The mid infrared is observable with JWST both for Uranus and Neptune, up to at least 22 μm wavelength in many modes. In the mid infrared it is possible to identify poorly resolved features in both planets (e.g., in the 5-7 micron region, and particularly deuterated species), track the variability of species with altitude using the $R=3000$ capability (for example CH_4), and determine the spatial distribution and time evolution of

Table 4. JWST Bright Object Capabilities
from Meixner et al. (2008)

Object	NIRCam	NIRSpec	MIRI	FGS
Mars	Longest λ	Highest $\lambda/\Delta\lambda$	No	TFI
Jupiter	Strip mode	Highest $\lambda/\Delta\lambda$	Neu. dens. filt and MRS/IFU	TFI
Saturn	Longest λ	Highest $\lambda/\Delta\lambda$	Neu. dens. filt and MRS/IFU	TFI
Uranus	Subarray mode	Highest $\lambda/\Delta\lambda$	Spectra and imaging	TFI
Neptune	Subarray mode	Highest $\lambda/\Delta\lambda$	Spectra and imaging	TFI

Comets

Comets are remnants of Solar System formation, and their current composition and physical properties provide a constraint on the conditions in the solar nebula 4.6 billion years ago. Comets were the building blocks of the giant planets' cores. Low resolution infrared spectroscopy of cometary dust will uncover mineralogical signatures, which can be compared with those seen in protostellar and planetary debris disks around nearby young stars and solar analogs, and potentially reveal the isotopic ratios of some major elements. Many comets fall within the maximum moving target rate studied for JWST (30 mas/sec). An important example is Comet 67P/Churyumov-Gerasimenko.

The International Rosetta Mission, the Planetary Cornerstone in ESA's long-term space science program, will rendezvous with Comet 67P/Churyumov-Gerasimenko (C67P/C-G) in mid 2014, making this object one of great scientific potential for JWST. Rosetta will study Comet 67P/C-G the nucleus and its environment in great detail for a period of nearly two years prior to the 2014 rendezvous. After reaching Comet 67P/C-G, the spacecraft will spend one year mapping and examining the surface using remote sensing, analyzing dust and vapors, and releasing a 100-kg lander equipped with a drill

and scientific instruments for in situ analyses. C67P/C-G belongs to the Jupiter family comets, which represents a large group of the short-period comets ($P < 20$ years) in the Solar System that are dynamically controlled by the giant planet. Analysis of the orbit of C67P shows that it is observable by JWST during key portions of the mission.

Observations of comets with JWST will enable investigations of the chemical composition of cometary ice and dust with unprecedented sensitivity. Near- and mid IR spectroscopy of cometary comae can be used to measure abundances of H_2O , CO , CO_2 , and CH_3OH in even relatively faint comets. Near-IR spectrometry with $R \sim 1000$ resolution will be used to measure the ratio of ortho-to-para H_2O (OPR) separately, possibly providing an indication of the comet's formation temperature. Likewise, mid-IR spectroscopy can determine the mineralogy of cometary dust grains. Finally, JWST's ability to image cometary nuclei at both mid and near-infrared wavelengths with high spatial resolution and sensitivity will allow high accuracy measurements of sizes and albedos of cometary nuclei. The results from cometary programs can be combined with those from programs investigating circumstellar disks and star formation regions to build a complete picture of planetary system formation and evolution.

JWST will measure the CO_2 abundance in comets that come within ~ 3 AU of the Earth and Sun. Such measurements cannot be done from the ground because of CO_2 in the Earth's atmosphere. Depending on the circumstances, JWST can measure CO_2 emission in either the ν_3 band near $4.3 \mu\text{m}$ or the ν_2 band near $15 \mu\text{m}$, both of which are exceptionally strong. The CO_2 molecule must be detected from space because strong absorption in the terrestrial atmosphere prevents ground-based IR observations, and its lack of a permanent electric dipole moment molecule precludes radio emission.

The deuterium-to-hydrogen ratio (D/H) is an extremely important indicator of the extent to which Earth's oceans could have been derived from comets. In this regard, the only three comets for which D/H has been measured are long-period (i.e., Oort cloud comets; Meier et al. 1995). Short-period comets (i.e., Kuiper Belt comets) which arose from a reservoir further out in the planet-forming realm than the Oort cloud comets, might have a different isotopic signature in hydrogen. A lower D/H in short-period

comets than long-period might permit a larger fraction of Earth's oceans to have been derived from comets than the 10% figure given by the Oort cloud D/H; a high D/H would more severely constrain dynamical models by forcing the fractional contribution of comets to Earth's oceans to be lower. The D/H ratio can be measured in any of the ice bands, for a variety of hydrogen-bearing molecules. For example, the CH₄ ν₄ band at 7.7 μm and the CH₃D ν₆ band can be used. For gas components, H₂ and HD can be used to determine the D/H ratio. For example, the S(0) quadrupolar lines at 17.1 μm can be observed with JWST.

There are many more issues that can be addressed by cometary spectra. For example, the spin state—para vs. ortho—of hydrogen is an important measure of the extent to which cometary grains were processed during formation, as is the ratio of amorphous to crystalline ice. The kinds of observations required to make progress on these abundances and ratios include high-sensitivity infrared spectroscopy at spectral resolutions exceeding 1000. While ground-based 30-meter telescopes will have very high sensitivity in the near infrared and can make key contributions there, JWST will be unparalleled in the region beyond 3 μm wavelength.

Main Belt Asteroids and Comets

The main belt asteroids are a set of remnants of the last stage of planet formation and, in some cases, the fragments of much larger planetary bodies which differentiated into iron cores and rocky mantles. They have tracking rates intermediate between those of Mars and Jupiter and hence are candidates for observation with JWST. Ceres is the one asteroid large enough (900 km diameter) to be classified as a dwarf planet along with Pluto and Eris of the Kuiper Belt, and is believed to have differentiated into a rocky core and an ice-rich mantle, covered in turn by a dusty outermost layer (Zolotov, 2008). It may also have a tenuous atmosphere (A'Hearn et al., 1992).

Astronomers have known for more than two centuries that comets can be split into two groups as defined by their orbits about the Sun. Long-period comets (P>200 years) originate from the Oort Cloud. Jupiter-family comets (P~20 years) originate from the region beyond Neptune. A new third dynamical class of comets, recognized only in

2006, orbit much closer to the Sun entirely within the main asteroid belt. These are referred to as the main belt comets – faint icy asteroids that have dusty eruptions producing cometary comae. These objects are of particular interest as they could have been an important source for terrestrial water delivered to the Earth early in its history. JWST is the only means to characterize the chemical properties (water, hydrocarbons, mineralogy) of this new class of comets. Their apparent rates of motion are intermediate between those of Mars and Jupiter.

Kuiper Belt Objects

Kuiper Belt Objects (KBOs) reside beyond the orbit of Neptune (30 AU) and have apparent rates of motion of <1 to 3 milli-arc seconds (mas) per second relative to the inertial reference frame (guide stars). The largest of these bodies, including Pluto, are known as dwarf planets. In addition to these large objects, over 1000 smaller KBOs are now known (down to $d \sim 30$ km) and an order of magnitude more are likely to be discovered over the next five years as large survey telescopes such as PanSTARRS and LSST begin their observations. JWST will have the ability to obtain $R=100$ near-IR spectra and 20–25 μm mid-IR photometry of all known KBOs. The small KBOs are the remnants of the icy building blocks that formed the giant planets and are analogous to the material in debris disks that are now being observed around other stars. Understanding the physical properties of these objects is key for determining the origins and subsequent evolution of the objects in our solar system and in other planetary systems.

Currently, the only physical property that has been measured for a large number of KBOs is object visible color. KBOs have a wide range of colors from neutral (solar-like) to extremely red. In addition, observations of only the brightest KBOs with Spitzer have found wide range of albedos from close to zero to in excess of 0.9. The wide range of optical colors and albedos of KBOs is likely a result of “nature” (formation location and compositional differences) and may also include the effects of “nurture” (weathering processes such as irradiation or collisions that have altered the surfaces over the past 4.5 billion years). This ambiguity may be resolved with near and mid-IR narrow band

imaging and spectroscopy of many KBOs with JWST. Unlike visible color, which does not provide any direct compositional information, near-IR spectroscopy of KBOs will record the reflected solar spectrum to identify absorption features from surface constituents, such as water ice, hydrocarbons (propane, ethane, etc), water hydration bands, and nitrile compounds. Mid-IR spectra and imaging of KBOs longward of ~20 microns will record the intrinsic thermal radiation from the object enabling the independent determination of its albedo, and hence its diameter. The compositions and sizes of large numbers of objects will allow us to understand how these properties relate to dynamical class in the Kuiper Belt. In addition, comparison of these properties with dynamically related populations such as centaurs (objects with perihelia between the giant planets) and short period comets will indicate how heating these objects changes their surface properties.²⁴²⁴

A large fraction of KBOs are binary which enables the mass of the system to be determined. Size information from JWST mid-IR photometry combined with the mass will enable the measurement of a large number of densities, a key physical property related to composition and porosity. In addition, near-IR spectroscopy of each object within a binary will determine if the compositions of the objects are indeed alike as is indicated by their similar visible colors (Benecchi et al 2009). If the surfaces of each pair within a binary are identical, it indicates that surface composition is likely primordial and provides a powerful constraint on the initial disk compositional architecture.

Near-IR spectroscopy and mid-IR photometry with JWST will likely reveal additional information about large-scale collisions in the Kuiper Belt. The Haumea collisional family was detected because of the unique spectral signature of the family members (nearly pure crystalline water ice on the surfaces of objects that were close to each other in orbital element space). Near IR spectroscopy of a large number of objects spread throughout the Kuiper Belt will help determine the extent of the spread of the fragments from this large collision (constraining physics of the impact) and may also find additional clusters of objects with similar surfaces that are fragments of other collisions.

Understanding the frequency and the physics of collisions in the outer solar system will help to determine the initial mass and dynamical excitation of the early Kuiper Belt.

$R = 3000$ spectroscopy of the largest and closest current and former members of the Kuiper Belt--Triton and Pluto-- will constrain isotopic ratios in the water ice and other components, as well as providing surface temperature monitoring through the nitrogen overtone band. While the near-IR is the most familiar territory in this regard, because of the ground-based spectra of Triton and Pluto, rotational features will appear in the mid IR and will provide compositional and isotopic data not attainable in the near-IR overtone region. Mid IR detection leading to the separation of the size and albedo of such objects is of fundamental importance, and requires the high mid-IR sensitivity that JWST provides.

Finally, JWST will allow for the detailed examination of the physical properties of a new population of objects with orbits that are detached from the Kuiper Belt. While most KBOs have perihelia within ~ 15 AU of Neptune and are thus dynamically controlled by it, Sedna, with a perihelion of 76 AU, is the harbinger of a new population of objects in the outer solar system. Sedna's faintness ($v_{\text{mag}}=21$) makes ground-based near-IR spectroscopy difficult and determination of the ices present on the surface has hampered by the low signal-to-noise of the spectrum. Sedna's surface is so cold that it should be able to retain ices too volatile to survive on the surfaces of most KBOs. Comparisons of the physical properties of Sedna to other KBOs and to debris disks around other stars will provide insight into the origin and evolution of these populations.

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