Astrobiology and JWST

A report to NASA recommending addition or optimization of the James Webb Space Telescope capabilities to maximize astrobiology science return.

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Summary of Recommendations

JWST has many ‘nascent capabilities’ that could be developed to optimize their value for astrobiology at little cost or detriment to other JWST science. Here we summarize recommendations to the JWST project to ensure a wide variety of key astrobiological contributions.

Moving target software. JWST could determine the cometary D/H ratio to compare with the D/H value for Earth’s oceans, further testing the hypothesis that comets delivered water to Earth. The required accuracy is beyond the reach of current ground-based systems and other space-borne telescopes. In addition, moving target software will enable measurement of the reflection and rotation spectra of surfaces of Kuiper Belt Objects. This will help identify the composition of the Kuiper Belt Objects and hence their origin. The moving target software is being worked on now in the project and we urge its implementation.

Capability to observe bright stars with high cadence. JWST can measure transmission spectra from extrasolar giant planet atmospheres during planet transits around bright (7-14th mag) stars. Rapid readout time (on the order of 1 second) and high instrumental duty cycle are essential to enable high enough S/N from binned measurements over the course of the 2-12 hour transit durations. This recommendation is for NIRSpec, MIRI and NIRCam. Fast readout is being planned using subarrays for NIRSpec and we urge that this capability be retained. If Earth-sized planets are common and detected in transit about bright stars (brighter than 6th mag) JWST could detect atmospheric biomarker signatures with NIRSpec.

A set of filters or a tunable filter from 1 to 5 microns. NIRCam requires a selection of suitable filters. Near-infrared coronagraphy through narrow-band filters would allow JWST to detect and measure the distribution of ices and other molecules in a disk. In addition the narrow-band or tunable filters would allow detection of molecules present in a extrasolar planet atmosphere. The wavelength and bandwidth of filters needs to be determined. Although the narrow band filters or tunable filters could be in the guider instead of NIRCAM, it is important to have the filter in combination with a cornagraph.

Microshutter configurability flexibility. To keep scattered light from the primary star from contaminating circumstellar disk spectra will require 10^5 rejections (as for imaging) in the area around the shutter-occulted star. This puts a tighter requirement on the darkness of the microshutter boundaries than does spectroscopy in a basically empty extragalactic field. Microshutter configurability flexibility may also be important to design a “long-slit” which optimally occults the star and passes the light of the disk.

Stable PSF with a detailed characterization in terms of wavelength dependence, field dependence and temporal stability will enable observations of faint companions of stars such as planets and disks. It will also allow us to distinguish real objects from PSF artifacts, and remove PSF effects via subtraction or deconvolution.

Optimized pupil masks, in addition to a stable, well-characterized point spread function, would aid detections of planetary companions to relatively young (<1 Gyr) sub-solar-mass stars in the immediate Solar neighborhood with the coronagraphs on either NIRCam or MIRI.

Collection of 10^8 photons per image for NIRSpec, by spreading photons over 10^5 (spatial + spectral) pixels, would enable JWST to characterize terrestrial planet atmospheres if terrestrial planets can be found around bright stars. The large number of photons allows a high enough S/N over the duration of the terrestrial planet transit for a planet in the habitable zone of a solar-type star.

JWST has many capabilities that as currently designed are essential to astrobiology. We recommend that these capabilities not be descoped in any way. Below we describe these JWST capabilities that are of prime importance for astrobiology.

MIRI, JWST's mid-infrared camera/spectrometer. JWST is uniquely sensitive in the 5–27 micron region even when compared with potential future 30-meter ground-based telescopes. Specifically, spatially-resolved studies of protoplanetary disks will reveal astrobiologically relevant gases or ices.

NIRSpec, JWST's near-infrared spectrograph, is essential for characterizing transiting extrasolar planets. Many transiting extrasolar planets are expected to be found in the next several years with both ground-based and space-based telescopes (including Kepler). The short wavelength end is especially important for detecting scattered light and the planetary albedos. In particular, **NIRSpec's long slit** configuration is essential for these observations.

Coronagraphic capability. With NIRCam and MIRI's coronagraphic capability, JWST will be able to image young planets around nearby parent stars. In particular, finding young, 2 to 3 Jupiter-mass planets around young stars at 20-30 AU will help to settle the planet formation mechanism debate; only gravitational instabilities can form planets at 20-30 AU where there is not enough material for planetary accretion. In addition, the coronagraphic capability is necessary to study protoplanetary disks. The coronagraphic capability therefore is essential for astrobiology.

Careful control of stray and scattered light backgrounds. Stray and scattered light control at the level specified in the Science Requirements Documents will benefit investigations of dust disks, other circumstellar structures, faint extrasolar planets and substellar companions, and in general faint objects in crowded fields of brighter object, such as in Orion.

I Introduction

Astrobiology seeks to understand the origin, evolution, fate, and ubiquity of life in the cosmos. Astronomy plays a crucial role in addressing many of the scientific questions underpinning this formidable goal. The National Academy of Science and other advisory groups have emphasized astronomy's centrality in the growing field of astrobiology. In particular, some of the astrobiological questions that can be addressed through astronomical studies include:

Understand how life arose on the Earth: The origin of life on Earth represents the starting point for assessing the degree of commonality of life in the cosmos. Where did the raw materials for life on Earth come from? How were the elements manufactured in previous generations of stars, and in what sorts of molecular arrangements were these materials found in the nascent disk of gas and dust from which our planetary system formed? What were the chemical processes in various astrophysical environments and the resulting suites of organic compounds? How and from where was this material delivered to the planets of our solar system?

Determine what makes a planet habitable and how common those worlds are in the universe: The fundamental requirements for life on Earth are an adequate flow of energy, appropriate sources of carbon and other critical elements, and liquid water. Therefore, the simplest definition of a habitable world would be those that support these three fundamental requirements. Determining which planets have liquid water today, when and how much liquid water was present in the past, and whether adequate stores of biogenic elements and energy exist is key to addressing this goal.

Determine how to recognize the signature of life on other worlds beyond our solar system: The detection of planets orbiting stars that shine a billion or more times more brightly than the planets themselves is a daunting task, and as yet has been done indirectly with one exception. Even when large ground- and spaced-based telescopes become able to detect the light of a planet within the glare of its parent star, the daunting task of determining whether such planets are habitable remains unsolved—even if the biosphere one is looking for is Earth-like.

The James Webb Space Telescope (JWST) is a 6-meter aperture cooled space telescope with a wavelength range from 0.7 microns to 27 microns, and with imaging and spectroscopic capability. Planned for launch around 2011-2013, JWST will revolutionize broad areas of astronomy from cosmology through planetary system formation in ways that go beyond its predecessors (IRAS, Spitzer, and HST). The remarkable capabilities of JWST are well suited to addressing a broad range of problems in astrobiology, and NASA recognized this by selecting an Interdisciplinary Scientist (IDS) for astrobiology as a member of the Science Working Group, and establishing one of the themes within the Science Requirements Document as "Planetary Systems and Life".

To ensure that astrobiology, as a new discipline, takes full advantage of JWST and informs the development of the telescope in a timely fashion, NASA requested a workshop be organized to address astrobiological investigations that could be done with JWST. “Astrobiology and JWST” was hosted by the Carnegie Institution of Washington in May 2003, organized by S. Seager (CIW) and J. Lunine (University of Arizona; JWST Science Working Group), with an attendee list given in the Appendix. The purpose was to discuss key areas of astrobiological investigation that could be performed with JWST. This report is a summary of those deliberations. The report is organized as follows. Section II summarizes JWST capabilities important to astrobiology. Sections III through VI detail important scientific problems in astrobiology that can be addressed by JWST. Section VII concludes the report with summary findings and recommendations.

II Summary of JWST Capabilities Relevant to Astrobiology

JWST is a large, infrared-optimized space telescope. It will have an 18-segment, 6.5-meter primary mirror and will reside in an L2 halo orbit. JWST is scheduled for launch in 2011.

The capabilities of JWST have been defined to address scientific issues related to first generations of luminous objects in the early universe, assembly and evolution of galaxies, and processes of star and planetary system formation. The sensitivity, angular resolution and wavelength coverage offer the potential for exciting advances in the field of astrobiology, such as:

- Observations of circumstellar dust disks in both scattered and emitted light;
- Detection of dust disks around solar type stars;
- Studies of ices, mineral and PAH features;
- Studies of molecular species such as CO, H_2, H_2O and many others;
- Studies of water and prebiotic organics in comets;
- Detection of young Jovian planets 20–30 AU from their stars.

The capabilities that enable these include:

- Large aperture, area = 25 m^2, total circumscribed diameter = 6.5 m (from 18 1.3 m segments);
- Cryogenic telescope and instruments;
- Careful control of thermal background;
- Excellent image quality;
- Wide wavelength range 0.7 μm to 27 μm;
- Sophisticated state-of-the-art instruments and detectors:
    - Imaging with bandpass filters;
    - Spectroscopy of R=1000 with fixed slits, programmable slit masks and Integral Field Unit (IFU);
    - Coronography for high contrast imaging very near bright objects;
- High precision guiding on both stationary and moving targets.

MIRI is the "Mid-infrared instrument", a combined imager and spectrometer that will work from 5 to 28 microns at spectral resolution up to R of 3000, and with coronagraphic capability. The **NIRSpec**, or near-infrared spectragraph, will be capable of multiple objects with R up to 3000 at wavelengths from 0.7-5 microns. The **NIRCam** will image, with coronagraphic capability, from 0.7 to 5 microns and will feature tunable and fixed filters.

Below we detail selected problems or areas in astrobiology that JWST is well suited to address. Rather than being an exhaustive list, it is based on the interests of the participants who came to the workshop and reflects but does not fully encompass the breadth of astronomical astrobiology accessible through JWST. In particular, solar system studies beyond those of comets are well covered in the project Science Requirements Document and are not repeated here.

III Comet Isotopic Ratios

Comets represent the remnants of the ice-rich planetesimals that supplied many tens of Earth masses of heavy-element material to the giant planets and their moons during the planet-forming epoch of our solar system. As such, their chemical and isotopic composition should be of very high value in constraining the history of planet formation in the outer solar system. Comets have their origin in the belts of material within the region of giant planet formation and beyond. The equivalents of these belts are observable through the dusty debris of collisions among such bodies observed as disks around other stars. The ability to compare the composition of the debris disks around other stars to that of comets provides a powerful link between our own solar system and planetary systems around other stars, allowing the detailed clues to planet formation contained in our own solar system to be used to generalize and deepen our understanding of planet formation as a universal process.

Clues in comets to planetary formation processes include elemental, molecular, and isotopic abundances of major elements such as hydrogen, carbon, oxygen, nitrogen, and sulfur. 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 CH_4 ν_4 band at 7.7 μm and the CH_3D ν_6 band can be used. For gas components, H_2 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. ***Key to JWST's ability to perform such observations will be implementation of target tracking sufficiently capable to keep up with the large proper motions of typical comets.*** The astrobiology workshop participants were very pleased to see that NASA is working to implement the needed capability. Also important for cometary observations, especially long-period comets, is the ability to react quickly to the detection of new comets so that they can be observed during their brief apparitions.

IV Circumstellar Disks

JWST should be able to make outstanding contributions to the study of circumstellar disks because of two key advantages over HST and ground-based telescopes: outstanding sensitivity in the near to mid-infrared and capability for high dynamic range, near infrared imaging. To set the scale, the nearest sites of ongoing low-mass star formation in the Taurus and Ophiuchus molecular clouds are 150 pc away, so a diffraction limited 6 m telescope provides a resolution at 2 μm of 10 AU. This is sufficient to distinguish between the processes that formed the majority of the Solar System planets (out to and including Saturn) from those at work in the Kuiper Belt and beyond.

In the design of JWST's instruments, there is the opportunity to ensure that it will be excellent for disk science by careful attention to a few key areas.

1. High dynamic range imaging in the near-infrared

The HST imaging instruments with coronagraphs, NICMOS, STIS, and ACS, currently demonstrate the most successful imaging of faint disk reflected light in the presence of tremendous glares of the parent stars. None of these instruments was designed primarily with coronagraphic imaging in mind, so they are not ideal systems, but the stability of HST compared to even AO-corrected ground-based telescopes makes PSF subtraction possible. JWST should have even greater stability and thus the potential for very high dynamic range imaging. For comparison, the NICMOS coronagraph imaging through a broadband 1.1 μm filter achieves a factor of 10^5 reduction in stellar background (surface brightness) over unocculted imaging integrated at 2–3". This translates into the ability to detect a surface brightness of 1 mJy arcsec^{-2} at 2" from a 6th magnitude star or 0.3 mJy arcsec^{-2} at 1" from a 7th magnitude star (Schneider 2003; Weinberger et al. 1999; Schneider et al. 2001). This improvement in contrast allows reliable imaging of disks with $F_{Scat}/F_* \approx 0.01$. However, some of the nearest, most tantalizing disks to Earth have yet to be imaged in scattered light. If we assume that, like the disks already known, circumstellar dust has a bulk albedo of approximately 0.5, then the infrared excess,

L_{IR}/L_*, is approximately equal to the integrated scattered light. The disks around Vega and Fomalhaut, both well known from submillimeter imaging (Holland et al. 1998) have L_{IR}/L_* of 10^{-4} to 10^{-5}. Spitzer will likely discover a large number of disks around nearby stars with this dust fraction. Obviously, there is large scope for improvement in disk imaging.

There is science of astrobiological importance to be done with high-resolution images of disks around main sequence stars. Just as the planets of our own solar system betray themselves by the structure they impart to our Zodiacal dust, planets may make themselves known by warps, rings, and clumps evident in their disks. This may be the only practical way to infer the presence of low mass planets, smaller than a Neptune mass, at Neptune-like distances from stars (Quillen & Thorndike 2002). Neither radial velocity, astrometric, nor transit techniques can find such small planets so far from their stars. Furthermore, imaging in narrow band filters can act as low-resolution spectroscopy and establish some of the basic dust chemistry in disks as a function of location, showing the location of the ice-line, for example. ***To do this science, filters should have bandwidths of 0.1-0.2 μm (~10%) and be usable with the coronagraph. A tunable filter in NIRCam would be of significant value for choosing in- and out-of feature wavelengths. This filter could either be in NIRCam or guider, but needs to be in combination with a coronagraph.***

2. Spatially resolved spectroscopy in the near infrared

Beyond imaging in narrow filters, there is the opportunity to do true spatially resolved spectroscopy of disks with NIRSpec. The main science drivers in this area are the search for biogenically useful molecules such as water in various locations in disks. Water ice has broad absorption bands at 1.5 and 2 μm. Steam and CO have features in the 5 micron region. Here, an important parameter will be the stray light rejection of the microshutters. ***To keep scattered light from the primary star from contaminating the spectra will require 10^5 rejections (as for imaging) in the area around the shutter-occulted star.*** This puts a tighter requirement on the darkness of the shutter boundaries than does spectroscopy in a basically empty extragalactic field. Shutter configurability flexibility may also be important to design a "long-slit" which optimally occults the star and passes the light of the disk.

3. High angular resolution mid-infrared imaging

Mid-infrared imaging is likely to be the best way to search for structure in the very inner parts of disks. While the contrast problems noted above plague near-infrared imaging, disks usually dominate their stars at wavelengths of 10 μm and beyond (for example, at 12 μm, the photosphere and integrated disk of Beta Pic are of equal luminosity). Structure in the innermost part of the Beta Pic disk was thus discovered using mid-infrared imaging (Weinberger et al. 2003, Wahhaj et al. 2003).

The combination of high angular resolution near- and mid-infrared imaging allows the determination of a number of important disk parameters. Dust albedo can be calculated as a function of location and used to indicate where chemical changes might be occurring. When structure in a disk is seen, the mid-infrared is a much better indicator of optical depth, especially where the disk might be optically thick at shorter wavelengths. Although ground-based telescopes and coming interferometers have higher angular resolution than JWST, the tremendous sensitivity provided by JWST will allow disks to be traced further from the stars where the temperatures are colder.

V Interstellar and Circumstellar Grains and Ices

1. Organics

One of the key objectives of astrobiology is to understand and characterize organic and inorganic matter needed to create habitable environments. JWST can play a significant role in this by conducting observations to investigate the formation of molecules and grains and to follow their evolution toward complexity in different cosmic environments. IR spectra have revealed that creation of astrobiologically significant molecules begins with the formation of relatively large hydrocarbon molecule chains and rings in the envelopes of dying stars which are then ejected into the ISM via circumstellar winds. These grains are composed of mostly C and H atoms because the weaker bonds of other species are destroyed in the harsh radiation environments of planetary nebulae and the ISM. These hydrocarbon chains and rings are eventually swept up with other material into dark molecular clouds, which harbor active sites of star formation. Approximately 10% of the accessible carbon in the universe may be found in polycyclic aromatic hydrocarbons (PAHs; aromatic hydrocarbon rings) alone.

Hydrocarbons such as PAHs have strong spectral features over the 3.3–16 μm range, and these are commonly seen in regions of star formation (in emission and sometimes in absorption). Furthermore, spectral absorption signatures of silicates and simple molecules such as H_2O, CH_4, and NH_3 are also frequently seen along lines of sight towards luminous protostars embedded in molecular clouds (see the ISO spectrum of W33A in Figure 1). Most of these molecules are in icy mantles on dust grains, while most PAHs are in the gas phase (i.e., when seen in emission from UV excitation). Laboratory simulations have recently shown that when PAHs freeze onto grains they can react with molecular ices in grain mantles if exposed to UV or other ionizing radiation (e.g., Bernstein et al. 1999). O, H, and other elements and radicals from the ices become incorporated in the PAH structures, producing significant amounts of new biologically important compounds, including alcohols, quinones, and ethers (see Figure 2). For example, ketones are needed for energy transport in cells and include compounds which are needed for blood to clot. Amino acids have also been produced in similar laboratory experiments.

JWST MIRI spectra are needed in order to determine whether the physical and chemical pathways for the assembly of prebiotic molecules actually occur in interstellar environments as the experiments noted above suggest. Many molecules are also detectable (and uniquely identifiable) via their millimeter wavelength rotational spectra, but the vast majority of prebiotic molecules either have very weak rotational dipole moments or else may be frozen in ices and thus not free to rotate. However, hydrocarbons and (prebiotic) organic compounds have many mid-IR spectral features which are diagnostic of their composition, structures, and types of bonds (see Figure 3). Real ISM environments contain many different individual molecules; this can create complex spectra instead of the relatively few, distinct features seen in Figure 4. Individual features of many different species are seen in many objects at sufficiently high spectral resolution (R ~ 2000; e.g., CRL 618 in Figure 5). However, some objects show blends of features, including common broad ones such as the 6.2 μm, 7.7 μm, 8.6 μm, 11.2 μm, and longer wavelength PAH emissions (see Figure 5). The exact wavelength positions, widths, and relative intensities of broad PAH features indicate the sizes and ionization fraction of the PAHs present. Likewise, the central locations and shapes of other features, such as those due to the stretching or bending of double C bonds, vary slightly when they occur in different types of molecules. The MIRI spectrograph has more than adequate (R=2000) resolution to measure these subtle features and shifts.

Figure 6 shows the differentiation of molecular ices and gases expected in protostellar environments. It is likely that the highest column density lines of sight will be dominated by molecular absorptions of frozen materials (as in Figure 1), but inner protostellar regions may show emission lines arising in warmer molecules, such as H_2O lines detected in Orion (Figure 7). The MIRI IFU has adequate field (several arcseconds) and spatial resolution (~ 0.5 arcsecond) for obtaining spectra at many spatial locations so that reactions such as those in Figure 2 can be investigated. Although many central protostellar objects will have point source fluxes of 1 mJy or more at 10 μm, their spatially resolved disks and envelopes 1 – 2 arcsec away may easily be 100 times fainter. Therefore the full sensitivity of JWST is needed for these investigations.

Hydrocarbons (PAH), molecular ice, and silicates give rise to some of the strongest IR spectral features in other galaxies. JWST spectra will produce a thorough inventory of these organic and inorganic materials in nearby and distant galaxies, allowing the first studies ever of how these materials are distributed in the Universe out to z=1 and beyond. JWST NIRSpec and MIRI will be sensitive enough to acquire spectra of hundreds of galaxies with modest exposure times. These data will promote analyses of how organic and grain content varies with galactic morphological type, luminosity, metallicity, interactivity, nuclear activity, and age.

2. Silicates

Silicate dust has little direct relevance to astrobiology. However, it can serve two interesting functions that are relevant and that may be tracked using JWST. First, silicate dust can serve as a catalyst for the synthesis of complex organic materials in nebular environments via a generalized Fischer-Tropsch synthesis. This synthesis ($nCO + [n+1]H_2 \Rightarrow C_nH_{2n+2}$) inevitably results in the deposition of an organic coating on the grains that might be detectable as a change in the ratio of the 3.4 μm solid state organic absorption feature (due to C-H stretching vibrations) compared to the 9.7 μm SiO stretching vibration. Because the organic coating itself also seems to act as a catalyst, it is possible to deposit a thick organic coating on silicate grains in protostellar nebulae that could potentially obscure the silicate stretch completely. High spatial resolution studies of nearby protostellar systems might reveal a difference in the 3.4 to 9.7 μm ratio between the outer and inner portions of the disk. Alternatively, there may be a correlation between the age of the disk system and a reduction in the 9.7/3.4 micron ratio in the disk if we assume that the organic coating builds up uniformly with time on nebular materials.

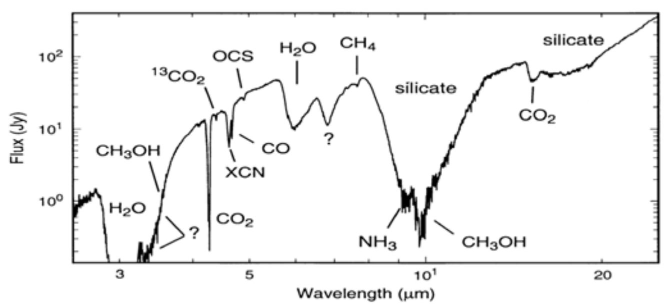

Figure 1. ISO spectrum of W33A, from Gibbs et al. (2000)

Silicate dust might also serve as a tracer for the activity of high-temperature dust processing in nebular environments. Dust in the ISM is amorphous whereas some dust in both comets and in modern protostellar nebulae has been observed to be crystalline. As the dust is intimately mixed with the gas, such processing would also imply the potential for high temperature chemical processes to occur in such environments, thus greatly increasing the expected complexity of chemistry in protostellar systems. There are currently two different models for crystallization of silicate grains in protostellar nebulae. The most direct method is via shock heating as large masses accrete into the giant planets. This generally occurs about once every 100,000 years and would not be expected to cause large-scale perturbations in our models of nebular chemistry.

A more interesting scenario for astrobiology is that crystalline grains are made in the innermost regions of the nebulae via thermal annealing at temperatures above about 1000K, then are transported out to regions of comet formation. The reason this becomes interesting is that gas in this relatively high-temperature, high-pressure environment would also be transported with the grains, thus spreading complex organic materials throughout the nebula. JWST can look for the faint signature of the outward flow of material both above and below protostellar disks. It can also observe the infrared signature of the silicate dust itself. If shock heating produces the crystalline silicates, then both magnesium and iron silicate crystals should be observed. If thermal processing in the nebula is responsible, then only magnesium silicate minerals should be observed as iron silicates require much higher temperatures for crystallization. When shock heated, these temperatures are achieved for only a very brief time, but when enveloped in a long-term high temperature environment, such temperatures cause small grains to evaporate.

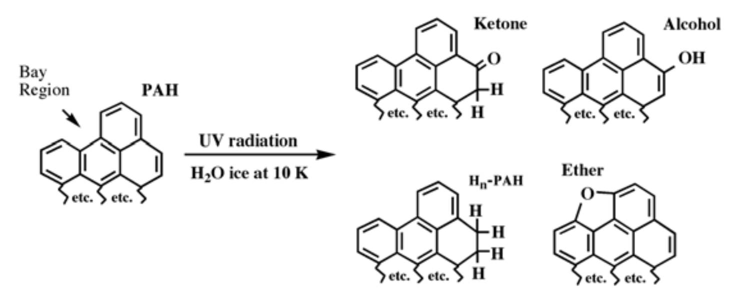

Figure 2. Chemical reactions between PAHs and H_2Omolecules on dust grains, from Bernstein et al. (1999).

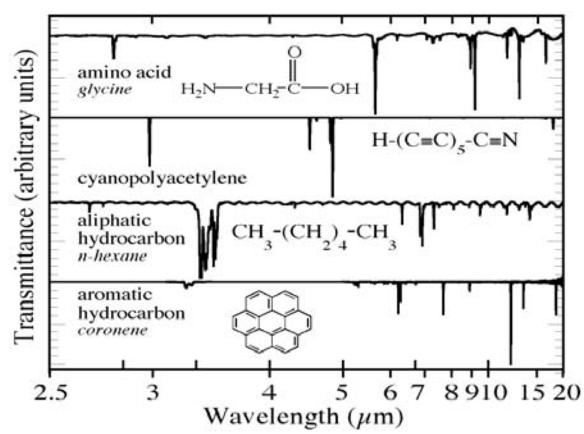

Figure 3. Spectral variations of different organic molecules.

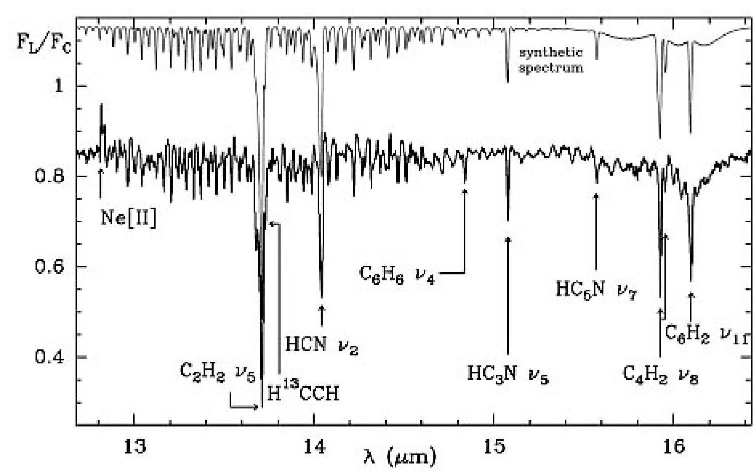

Figure 4. Spectrum of CRL 618, from Cernicharo et al. (2001).

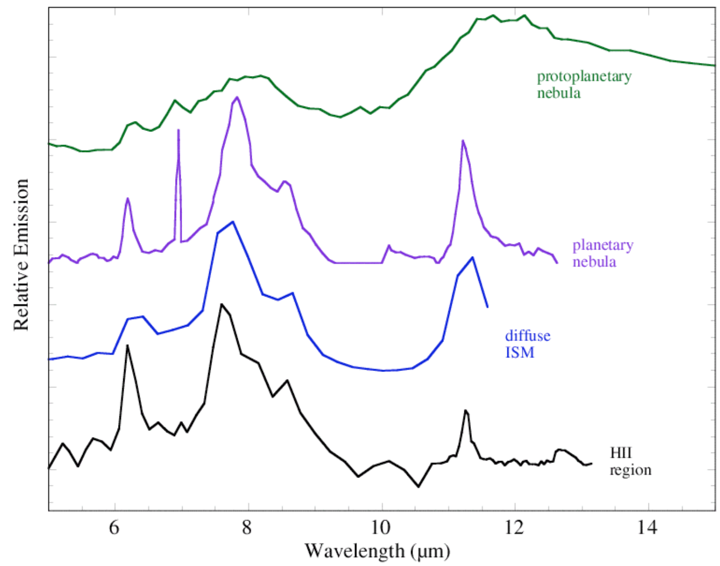

Figure 5. Low resolution mid-IR spectra of different astrophysical environments.

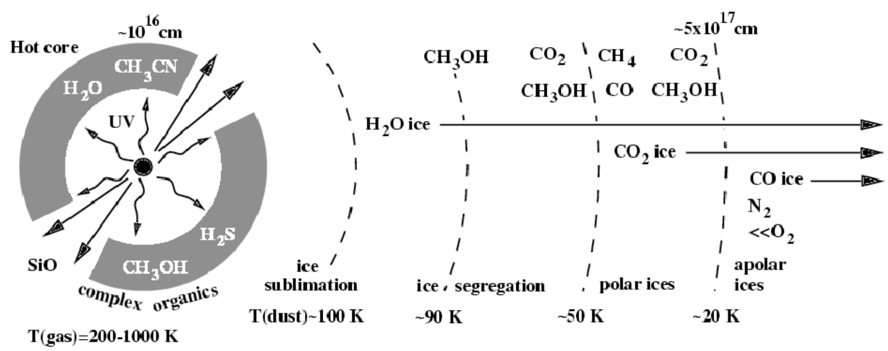

Figure 6. Temperature structure and phases of organic matter in protostellar envelopes, from van Dishoeck & Hogerheijde 1999.

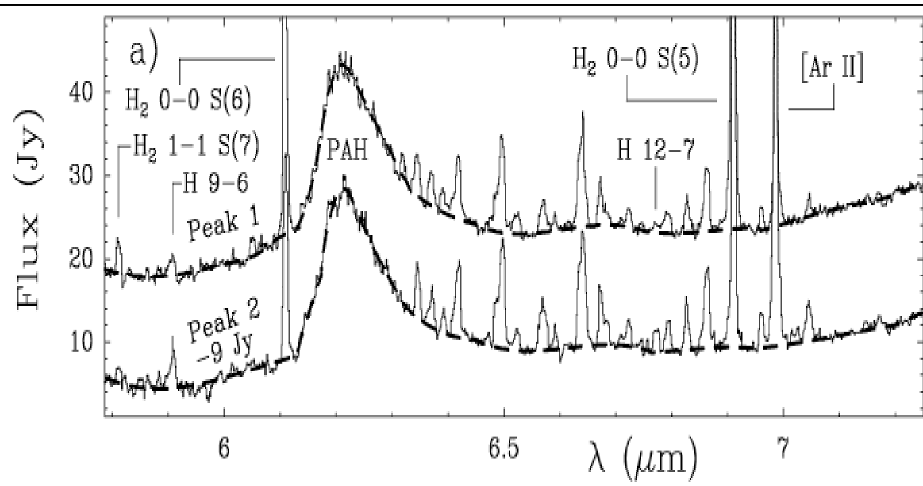

Figure 7. Water emission in Orion, from Gonzalez-Alfonso et al. 2002.

VI Imaging And Spectra Of Brown Dwarfs, Sub-Brown Dwarfs, And Extrasolar Giant Planets

What do sub-brown dwarfs look like? JWST will have unique capabilities for studying the detailed properties of sub-brown dwarfs, isolated star-like objects with masses too low to allow the burning of deuterium (roughly 13 Jupiter masses). By the time of the launch of JWST, we expect numerous detections of extremely cool (T < 500K) brown dwarfs and sub-brown dwarfs, through deep imaging by Spitzer and perhaps by the WISE mid-infrared survey. At the same time, deep ground- and space-based near-infrared imaging of star-forming regions will have identified sub-brown dwarfs with masses of 1 M_{Jup} or less, if they exist. JWST will have the only instrumentation with sufficient sensitivity and spectral resolution to study sub-brown dwarfs at mid-infrared wavelengths, probing their detailed atmospheric structure. In particular, monitoring observations with wavelength-tunable filters will permit study of the development and evolution of cloud structure within their upper atmospheres.

What do the youngest sub-brown dwarfs look like? JWST will offer the most effective means of studying the detailed atmospheric structure of isolated planetary-mass objects in the nearest star-forming regions, notably the low-density Taurus clouds and the high-density Orion cluster. Mid-infrared imaging with MIRI will provide a unique perspective on disk formation in those systems.

A key step towards characterizing the distribution of habitable planetary systems is determining the extent to which planet formation depends on the mass of the parent star. ***While JWST will not be capable of direct detection of terrestrial-mass planets, extrasolar giant planet (EGP) companions to relatively young (<1 Gyr) sub-solar-mass stars in the immediate Solar neighborhood could be resolved through deep imaging with the coronagraphs on either NIRCam or MIRI. Those observations will require a stable, well-characterized point-spread function, and would profit from the inclusion of optimized pupil masks.*** Spectroscopy of any detected very low mass companions can probe the similarity of their atmospheric structure to that of the Solar System's gas giants.

The detection of young, multiple-Jupiter-mass planets at orbital distances of 20 AU to 30 AU around young stars in Taurus and Ophiuchus may be possible with JWST's coronagraphic imagers. If such objects are detected, they would be a strong indicator that gas giant planets can form by the disk instability mechanism, one of two competing mechanisms for the formation of giant planets. The competing mechanism, core accretion, is unlikely to be able to form gas giant planets *in situ* at such great distances from the central protostar.

JWST's spectral capabilities may allow the detection of evidence of disk gaps in the protoplanetary disks orbiting young stars in nearby star-forming regions. While not a unique interpretation, the detection of dips in the spectral energy distribution (SED) of such disks may imply the presence of giant planets massive enough to open gaps in the disk's gas and dust distribution. As a result, JWST's measurements of disk SEDs could help determine the epoch of gas giant planet formation, by determining the age at which protoplanetary disks begin to show evidence for giant planet formation. The formation epoch is another key determinant for the formation mechanism of giant planets, as the two alternative mechanisms vary greatly in the time required – disk instability proceeds on a time scale of thousands of years, while core accretion requires millions of years. The formation of a planetary system's giant planets is expected to have a major influence on the formation of any habitable planets, making the question of the dominant mechanism of giant planet formation an important one in the search for habitable worlds.

VII Detection of Planetary Transits with JWST

1. Requirements

JWST will have the capabilities to make significant, early progress in extrasolar planet studies. In this section we discuss four general areas associated with planet transits:
(1) Quantification of atmospheric properties of extrasolar giant planets and extrasolar ice giants via differential spectroscopic comparisons in and out of transit.
(2) Potential observations relevant to detecting life signs on extrasolar terrestrial planets.
(3) Searches for moons and/or ring systems around extrasolar giant planets.
(4) Providing confirmation of the best Kepler terrestrial planet candidates.

While a subset of the desired science (some of (1) and all of (4) above) could likely be accomplished with instruments designed according to the JWST primary goals related to evolution of the early universe, much larger scientific payoffs will follow with several minor modifications of instrument capabilities. First, transit studies with JWST will require support for time-series observations to be executed at specific times. Transits discovered by other programs will have very precisely known windows in which observations should be obtained. Second, transits will in some cases be associated with nearby stars (e.g., the edge-on system HD 209458b with host star V = 7.6, H = 6.1), and ***JWST will need to allow observations of such bright objects. Third, the detection of transiting Earths or giant planet moons, and the characterization of giant planet atmospheres, will be possible if the cycle time between successive integrations is kept very short (~1 second). Finally, JWST can characterize terrestrial planet atmospheres if photons can be spread over 10^5 pixels (spatial + spectral), thereby allowing collection of 10^8 photons per image.***

The studies to be discussed here rely on high signal-to-noise (S/N) time-series observations that span about three times the length of known transits, to be started one transit width before and end one transit length after the transit proper. In some cases such photometry could be done with NIRCam. In others for which evidence of specific atmospheric features is sought, the time series would be of spectra obtained with either NIRSpec or MIRI. We have assumed for our simulations a total throughput of 10%, a collecting area of 25 square meters, and a 1-5 micron bandpass for NIRSpec.

Transit signals, in terms of overall light blocked (ratio of planet to host star area), will vary from some 2% (HD 209458b is 1.6%) down to only 85 parts per million for a true analogue of the Earth-Sun system. Transit timescales will range from 1-2 hours for the shortest period systems (HD 209458b has a 3.1 hour transit every 3.52 days) to 10-15 hours for planets in Earth-like systems repeating on timescale of about a year. The truly exciting application possible now for transiting planets is to probe atmospheric conditions, e.g., as was successfully done using the Space Telescope Imaging Spectrograph on the Hubble Space Telescope to detect two constituents in HD 209458b. In this case, sodium was detected with optical spectroscopy where the relative signal (comparing in- and out-of-transit spectra) within the Na D lines was a few parts in 10^{-4}.

2. Probing atmospheric properties of extrasolar giant planets with JWST.

The technique for detecting spectroscopic features of transiting planet atmospheres is simple in concept. During transit, a planet atmosphere will allow some wavelengths to pass through relatively deep layers, while other wavelengths will be blocked at smaller optical depths. This is the case for the resonance line of sodium, where there is extra blockage (compared to the continuum) during the occultation event of HD 209458b.

Detailed discussion of diagnostics that are possible with transmission spectra of extrasolar giant planet atmospheres have been provided in Brown (2001a). In particular, EGPs like HD 209458b will present many molecular features (H_2, CO, H_2O, CH_4), strong atomic lines (Na, K), and a spectral shape (due to Rayleigh scattering) that leave distinct imprints on transmission spectra. Brown (2001a, esp. Section 5.1 and Figure 22) provided direct simulations of JWST/NIRSpec observations at a resolution of 1000 over 1.65 - 2.5 μm for HD 209458 itself. For this bright star and a large space-based telescope the primary constraint likely to determine the quality of results is how quickly successive observations can be made. ***If overhead time can be kept to 1 second, then superlative results providing a S/N of ~35,000 per pixel can be obtained in one 10-hour observing block.*** If overheads of 300 seconds (acceptable perhaps for edge-of-universe studies) exist, then the S/N ratio drops below 2000, which is relatively uninteresting for atmospheric diagnostic purposes.

During the next decade, it is likely that many gas giant planets will be found transiting relatively bright stars. Some of these will be at large orbital radii, allowing the science to begin quantifying atmospheric properties as a function of orbital scale. Missions such as Kepler are likely to discover gas giant and ice giant planets with orbital scales of 1 AU around other stars. For Kepler planet discoveries around brighter stars, JWST will be able to perform atmospheric diagnostics sufficient to establish basic strengths of the primary molecular features and probable height of atmospheric cloud decks.

3. Detecting terrestrial planets and giant planet moons around EGPs.

The original HST observations of HD 209458b transits were already sufficient to set an upper limit to moons (not a full phase space search) slightly larger than Earth, as well as ring systems comparable to Saturn's but scaled up by the relative planetary radii. JWST, with four times the collecting area, could make comparable observations to systems up to

4 magnitudes fainter and could thus make similar observations of edge-on systems found by Kepler (the distances of which will typically be about 300 pc).

The two central issues for detecting Earth-sized moons orbiting known giant planets are that of (a) the maximum total number of counts that can be collected per frame with the MIRI/NIRSpec detectors and (b) the cycle time between frames. For example, in the NIRSpec 1-5 micron bandpass, JWST will collect 2×10^8 photons per second from a Sun-like star at 50 pc. If these photons are spread over 10^4 total pixels on the detector, then integration times must be limited to 0.15 seconds in order to avoid saturation of the pixels at the short-wavelength end of the spectrum. ***Given a cycle time between successive integrations of 1 second, we can obtain 35-sigma transit detections for the two cases of (1) an Earth-sized moon orbiting HD209458b (transit time 3 hours, d = 47pc), and (2) an Earth-sized planet orbiting the Sun at 1 AU at 300 pc distance (transit time 13 hours). If cycle time is as long as 300 seconds, then the transit detection level for both these cases drops to a less compelling value (in terms of telescope time allocation) of 3-sigma.***

4. Can we study extrasolar terrestrial planet atmospheres with JWST?

Being able to study the atmosphere of an Earth-like planet with sufficient fidelity to determine if life is likely present (e.g., existence of free oxygen, molecules out of equilibrium without life) is one of the grand long-term NASA goals. JWST was not envisioned to address this, but neither was HST envisioned to provide the first evidence of atmospheric constituents on an extrasolar planet. Could JWST provide early (relative to TPF and other missions directed at this) observations relevant to life's existence on other planets? Surprisingly, the answer may be yes. What would it take to enable this?

Assuming that terrestrial planets are common, then the brightest star with such a transiting planet will be V = 6 - 7th mag. (Finding such a planet is a separate issue that JWST will not address. If an 8 - 10 times Earth mass planet exists in the habitable zone of a K star, then such a planet is likely to be detected by ongoing radial velocity surveys over the next decade.)

Brown (2001b) has simulated transmission spectra for Earth, Venus and Mars (see Figure 8), degraded to the R = 1000 spectral resolution of NIRSpec. A transit detection level of ~500-sigma would be necessary to detect water and CO_2 features in a terrestrial planet atmosphere, and this could distinguish Earth and Venus-like atmospheres. Such a strong detection is achievable with JWST for planets slightly larger than Earth, if: (1) de-focusing is allowed in order to spread incident photons over a factor of 10 more pixels, and (2) down time is kept to less than 1 second. ***For a 1.5 Earth-radius planet orbiting the Sun at 1 AU at 20 pc distance, JWST could achieve a 500-sigma detection with 0.25 sec exposures, 0.5 second down time, and 3×10^8 photons per integration (i.e., 10^5 pixels for 50k electrons in the brightest pixel)***.

In this scenario, Earth- and Venus-like atmospheres can indeed be distinguished, and the observations required for such a 4-sigma discrimination in this case would span only 30 hours centered on a 10-hour transit. The chance of such an optimistic scenario (a V=6 dwarf with a transiting terrestrial planet, plus a JWST capable of efficiently recording these high photon fluxes) unfolding is not high; however, it is hard to imagine a higher payoff from the JWST mission. ***If NIRSpec and/or MIRI can be operated in a manner which allows recording high photon fluxes, without compromising core science, the potentially high payoff certainly argues for a serious consideration of what would be required to enable such observations.***

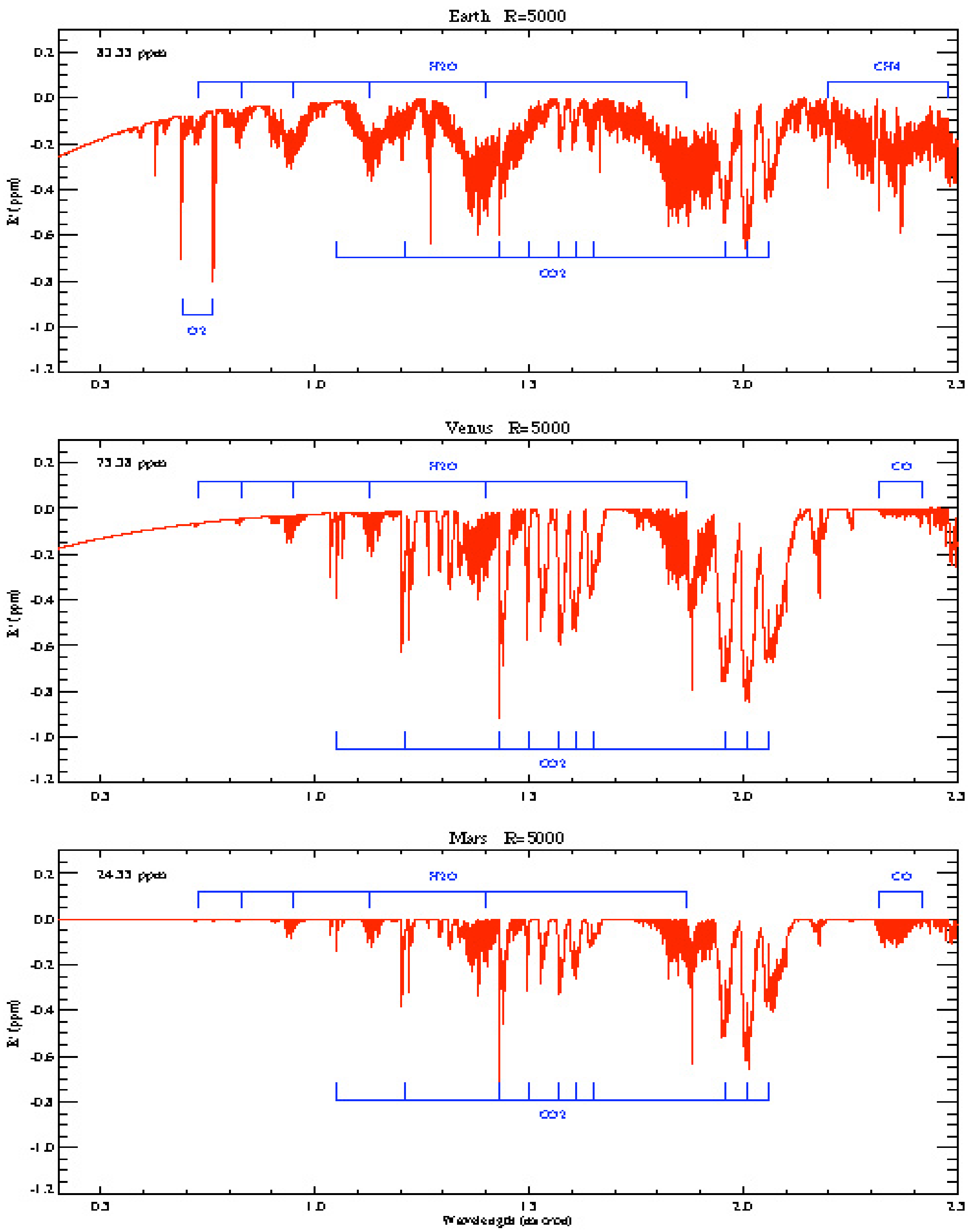

Figure 8. Predicted, relative transmission spectra for Earth, Venus and Mars calculated as the ratio of spectra observed during transit to the stellar spectrum out of transit. Continuum level offsets during transit (upper left number in panels) in parts per million have been suppressed. Note the significantly different balance between H_2O and CO_2 features in the transmission spectra of Earth and Venus. (Courtesy of T.M. Brown.)

5. Establishing Kepler terrestrial planet candidates as real.

If terrestrial planets are common in other systems, the Kepler Mission, scheduled for launch in 2007 will have detected many tens of such planets by 2011. The Kepler project has in place adequate procedures to eliminate most false positive detections through follow-up analysis of the Kepler data itself. Ground-based radial velocity observations will eliminate some fraction of the remaining false positives, and AO or high-resolution space imaging can largely eliminate the remaining possibilities. For the most reliable claims of Earth-like planet detections, especially for a few cases in which the planet seems to be in the habitable zone, JWST could provide invaluable confirmation and further study of such objects. With a collecting area some 50 times larger than Kepler, JWST can in principle return individual transit detections to a S/N seven times higher, thus enabling sensitive confirmation via transit light curve shape and color that the interpretation is secure. Since the stars of interest would be about 11-13th magnitude (typically at distances of 300 pc), these would not stress the capabilities on the bright, high S/N regime as much as other applications discussed above.

VIII Summary and Conclusion

In addition to JWST's baseline properties, there are many 'nascent capabilities' that could be developed to optimize their value for astrobiology at little cost or detriment to other JWST science. The control of stray and scattered light backgrounds, both in the optical and thermal parts of the spectrum will benefit investigations of dust disks, other circumstellar structures, faint extrasolar planets and substellar companions, and in general faint objects in crowded fields of brighter object, such as in Orion. The stability of the PSF and its detailed characterization in terms of wavelength dependence, field dependence and temporal stability will enable observations of faint companions of stars (planets, disks), the distinguishing of real objects from PSF artifacts, and removal of psf effects via subtraction or deconvolution.

At the same time that JWST seeks very faint objects, its ability to observe bright stars (6^{th} magnitude and fainter) is essential for certain high priority astrobiological observations such as transits of planets across stars, which require detector subarray rapid readout modes, and instrumental high duty cycle and low dead time. The ability to do both imaging and spectroscopy with such capabilities will benefit high precision studies of planetary transits, and hence follow-up of Kepler discoveries as well as spectroscopic investigations of extrasolar planet atmospheres.

JWST's broad wavelength range is essential to a range of studies of disk and extrasolar planet composition. This range includes a short wavelength cutoff of NIRCam and NIRSpec below 1 micron, the overlap of NIRSpec and MIRI, and the ability of MIRI to observe out to 27 microns. Spectroscopic capability as detailed in the project science requirements document is sufficient for studies of ices and minerals on surfaces of outer solar system bodies and of mineral grains and PAHs in interstellar clouds and dust disks.

Finally, moving target tracking is key to observing comets and other objects in our own solar system, for comparison with composition and properties of planet-forming or remnant disks around other stars and of extrasolar planets. This capability is being worked now in the project and we urge its implementation.

JWST is an astrobiology machine, in the sense that it will address a broad range of issues associated with the origin and evolution of planetary systems, the source material of life and life-sustaining water, and other primary goals of astrobiology. Most of the capabilities required to address these issues are already formal requirements within the project, with the Science Working Group being the caretakers ensuring that the goals are met. In particular several IDSs on the SWG, including the IDSs for astrobiology, for star formation, and for solar system studies, have primary roles in this regard for astrobiological studies. Additional capabilities required beyond those in the formal project documents include those associated with transit studies (listed above), and moving target capability for solar system bodies. ***A preliminary assessment suggests that these can be accommodated within the existing design at little or no cost, and we urge that the JWST project ensure that these are implemented.***

As with any major flight project, vigilance is required to ensure that capabilities do not change over time in such a way as to narrow the focus of a mission or make it difficult to implement key science goals. It is thus essential that the astrobiology community remain in touch with JWST as the project moves from Phase B (current) through Phase C/D and launch. To do so, the NASA Astrobiology Institute has initiated an astronomy focus group, and we urge that a major part of its effort be to keep contact with the JWST Science Working Group to ensure the implementation of astrobiologically important observations.

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