Science with the Mid-Infrared Instrument on JWST

MIRI Science Team

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Summary

The James Webb Space Telescope combines low temperature operation in space and a large aperture to provide an immense potential gain in performance for the mid-infrared (5 – 27μm). The advance will be more than a thousand-fold in sensitivity over existing groundbased telescopes and nearly a hundred-fold over SIRTF or any plausible future groundbased telescopes. The "HST and Beyond" report strongly recommended including mid-infrared capability on JWST, so long as it did not drive the facility cost strongly. A number of studies, including the current JWST replanning effort, have now shown that the telescope can achieve phenomenal sensitivity levels without costly additional requirements on it. "HST and Beyond" and the decadal survey "Astronomy and Astrophysics for the New Millenium" have identified a large number of important investigations using this advance, and such programs appear prominently in the Origins Theme Roadmap. These studies show that the MIRI can advance nearly every field of astronomy, from the Kuiper Belt to the first light in the universe, as collected and described in this report.

See also the MIRI web page, http://ircamera.as.arizona.edu/MIRI, and the review of MIRI science by van Dishoeck (1999).

1. Introduction

> “Having NGST’s sensitivity extend to 27µm would add significantly to its scientific return.” – Astronomy and Astrophysics in the New Millenium (McKee-Taylor decadal survey), p. 9.
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> “Our recommended large-aperture, IR-optimized space telescope will be essential for the detailed studies of the early universe at λ ~ 1 – 5µm. However, we also recommend that it be operated as a powerful general-purpose observatory, serving a broad range of scientific programs over the wavelength range λ ~ 0.5 – 20µm, the exact coverage to be determined on the basis of future technical evaluation.” – HST and Beyond, p. 69.
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> “JWST is expected to … be celestial-background-limited between 0.6 and 10 micrometers, with imaging and spectroscopic instruments that will cover this entire wavelength regime.” – Origins Roadmap, p. 47.

The awesome power of JWST in the mid-infrared has been recognized uniformly by the astronomy advisory structure. The description of this capability has varied slightly from report to report because the engineering tradeoff between instrument performance and impact on facility cost and risk was incomplete. It is now known that an extremely powerful mid-infrared capability can be provided with no major impacts on the facility design.

The power of the MIRI derives directly from the huge gain it makes possible over any preceding method for studying the mid-infrared sky. This gain results from simple physics: 1.) the thermal background for any groundbased telescope blinds mid infrared detectors; and 2.) prior to JWST, cold telescopes in space have been limited in aperture to 0.85m (SIRTF). To illustrate this gain, in Figure 1 we compare relative integration time in surveys to equivalent point source detection limits.* The MIRI will be more than 10,000 times faster than even a 30-m infrared-optimized telescope on the ground. It will also be more than 10,000 times faster than SIRTF, with the accompanying gain of far higher angular resolution (with a beam a factor of 50 smaller in area than the one for SIRTF at the same wavelengths).

This unprecedented sensitivity allows the MIRI to make important contributions to all four defining science themes for JWST: 1.) Detection of the First Light; 2.) Assembly of Galaxies; 3.) Birth of Stars and Protoplanetary Systems; and 4.) Evolution of Planetary Systems and Conditions for Life. The gains achievable with JWST in the mid-infrared are central to NASA’s scientific program in astronomy and related fields, as has been recognized by a series of advisory committees. We highlight their statements as introductions to the discussions of the four defining science topics.

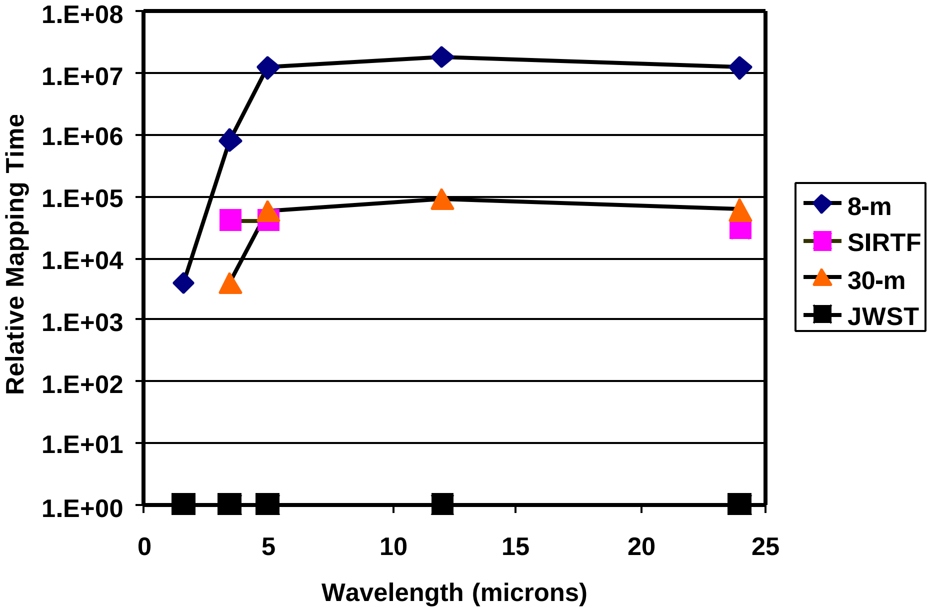

Figure 1. Gain in survey speed (astronomical capability) of MIRI on JWST over Gemini, SIRTF, and a 30-m diffraction limited groundbased telescope. For the latter telescope, the performance at the shorter wavelengths depends critically on Multi-Conjugate Adaptive Optics and hence has not been included in the figure.

* We have computed the imaging sensitivity for point sources for an infrared-optimized 8-m telescope operating at its diffraction limit. Based on the radiometric models for three state-of-the art mid-infrared cameras (MIRLIN, MIRAC, T-Recs, VISIR), and comparing with the radiometric model for the MIRI, we predict a sensitivity advantage for the MIRI by a factor of more than 1000 at 10µm broadband imaging and a similar factor for 20µm imaging (under excellent conditions from the ground). A similar comparison with a hypothetical 30-m telescope shows a factor of more than 100 gain for the MIRI, similar also to the gain over SIRTF. For the groundbased telescope, the calculated sensitivity depends critically on diffraction limited imaging, so the field of view with foreseeable arrays is small (e.g., about 20 arcsec for an 1024x1024 array critically sampled at 10µm). No bar is shown for SIRTF at 1.6 or 12µm because it has no detectors working at those wavelengths. For JWST and the groundbased telescopes we assume the same size array (1kx1k), while for SIRTF, we have multiplied by the relative number of pixels to retain the same meaning, relative integration time over a given number of pixels to a given detection limit. Our figure of merit is therefore equivalent to "astronomical capability" as used in both the Bahcall and McKee-Taylor decadal surveys.

2. First Light

"The unambiguous identification of nearly-normal galaxies in the process of formation has been one of the major efforts in extragalactic research. To date, no one has succeeded, perhaps in part because sufficiently sensitive observations are not yet possible at the long wavelengths where the bulk of the stellar radiation will be found. Such a study would require extremely high .. sensitivity to wavelengths as long as about 10μm (about the peak of the galaxian energy distribution for z ~ 10)." – HST and Beyond, p. 48.

"NGST is designed to have the sensitivity and wavelength coverage to detect light from the first generation of galaxies, out to a redshift of about 20. ….The ability of ground-based optical and infrared telescopes to address these questions is severely compromised by the opacity and thermal emission from the atmosphere at wavelengths longer than 2μm. NGST will cover the spectrum out to wavelengths of at least 5μm …extending the sensitivity of NGST farther into the thermal infrared would greatly increase its ability to study galaxies at high redshifts." – Astronomy and Astrophysics in the New Millenium (McKee-Taylor decadal survey), pp. 76-77.

"Because the prime science goals for JWST are to observe the formation and early evolution of galaxies, JWST's greatest sensitivity will be at mid- and near-infrared wavelengths, where the expansion of the universe causes the light from very young galaxies to appear most prominently." – Origins Roadmap, p. 47.

Expected Properties of First Light Candidates

Discovery of the "first light" is often described as the defining observation for JWST. Theoretical speculations for the nature of first light sources have a wide range, with large uncertainties in mass and redshift and even energy source (massive stars or perhaps accretion onto black holes). MIRI observations are critical if we are to be confident of identifying the first light objects. They are needed both to distinguish objects truly forming their first stars from ones with a longer history of star formation, and to distinguish stellar-powered and black-hole-powered sources. They are also needed to probe the properties of the first quasars, whenever they formed.

First light objects are expected to be at a redshift of $z > 8$, where the hot stellar continuum will lie in the NIRCam/NIRSpec spectral range. However, already by $z \sim 5$ features characteristic of red giants and supergiants, indicative of evolved stellar populations, shift out of the NIRCam and NIRSpec ranges. For $z \geq 12$, the Balmer limit is shifted out of the region accessible to these instruments. Thus, for $z > 12$, the photometric candidates will be detected at only a few NIRCam filter bands with no confirming detection of a second SED feature. Consequently, unless the first light sources have very specific characteristics (e.g., relatively low redshift, spectral energy distributions uncomplicated by additional energy sources such as AGNs), the near infrared instruments will have great difficulty confirming that they are bona fide first light objects.

> "It is possible that galaxy formation extends over a relatively long time, with important 'precursor' events at $z >> 5$. Such events may include the birth of the first generations of massive stars in the proto-spheroid,… An investigation into 'precursor' stellar systems would require very sensitive broadband imaging of stellar light .. at $\lambda \geq 10\mu m$, where the redshifted stellar light would be found." – HST and Beyond, p. 49.

This issue is illustrated in Figure 2. It shows continua of two model galaxies (from Bruzual and Charlot 1993) at $z = 15.0$. One is a bona fide first-light object, with all stars formed in a burst at $z = 15.2$ ($q_0 = 0.5$). The second has undergone two bursts of star formation, the first at $z \sim 20$ and the second at $z \sim 15.2$. Although this spectrum applies strictly to a specific model, it also illustrates the general tendency for older stellar populations to be much redder from rest UV to visible or infrared than true first light objects. The specific form of the "older galaxy" in the figure is approximately consistent with the star formation history suggested for the early Universe by Cen (2002).

A critical question is the amount of reddening that should be applied to the intrinsic spectra of these objects. There is a possibility of significant reddening due to dust at very high redshift (e.g., Loeb and Haiman 1997). We have not included this effect but instead have only considered reddening due to foreground damped Ly α systems. These systems have been modeled by Fall and Pei (1993), who show that they may cover a substantial fraction of the sky. They will introduce a patchy reddening for objects behind them. We have approximated Model B of Fall and Pei (model B is their favored case) with a single reddening system at $z = 3$. We assume reddening of $A_V = 0.4$ in front of the object that formed all its stars at $z = 15.2$, and $A_V = 0.6$ in front of the older galaxy, corresponding to two damped Ly α systems of slightly different characteristics (as expected for two separate sources).

The NIRCam and MIRI filters convolved with the galaxy spectra are shown by the horizontal brown and orange bars, along with $\pm$ 10% error bars. NIRCam would reliably identify both objects as very young galaxies and would allow estimates of their redshifts, but it would have great difficulty distinguishing their differing histories. As shown in the figure, high sensitivity imaging between 5 and 8μm with the MIRI will detect the older stellar population and thus unambiguously identify objects with a longer star forming history than just a few million years. With slight adjustments in the reddening, first light and older galaxies can be made to appear virtually identical to NIRCam for any redshift above $z = 12$. A variety of reddening models is possible, but the basic conclusion is that we cannot be confident that JWST will accurately identify first light objects without MIRI observations.

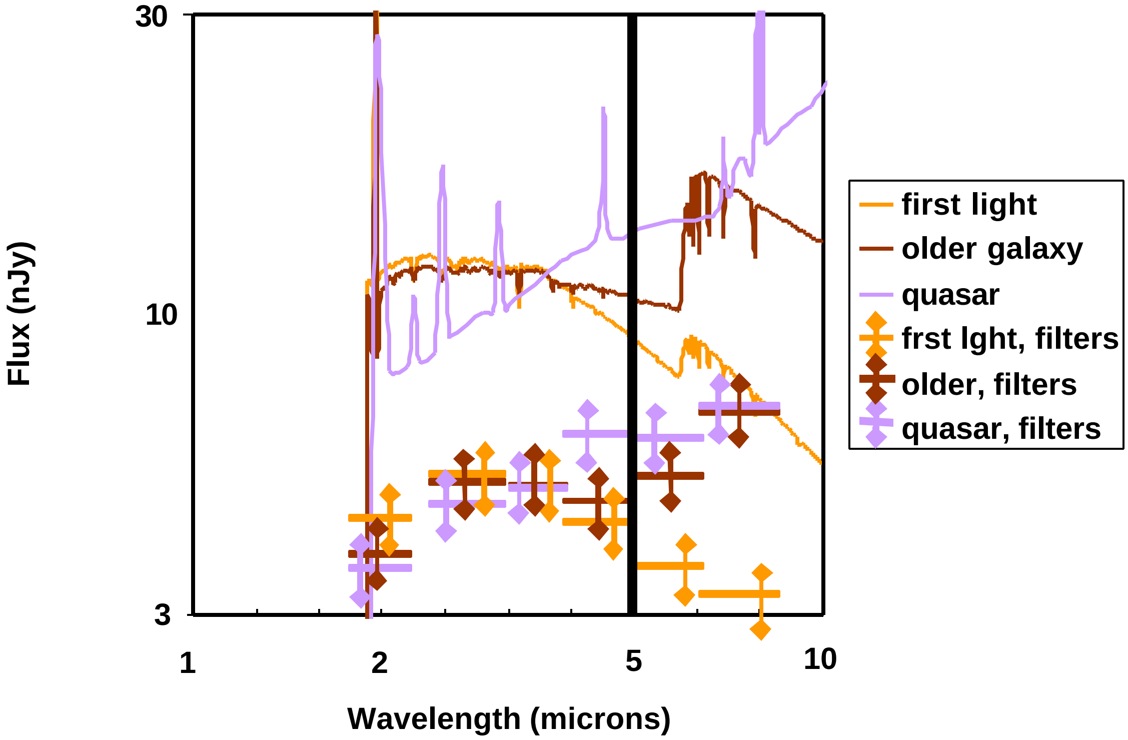

Figure 2. Modeled young galaxies and a typical quasar. All the sources are at a redshift of z = 15, and it has been assumed that the Lyman a forest strongly attenuates their outputs short of Ly a . It is assumed that there is a foreground damped Lyman a system that causes reddening of $A_V = 0.6$ for the first light object and $A_V = 0.4$ for the older galaxy. The horizontal bars indicate the NIRCam and MIRI filter bands and the relative signal levels that would be detected through them, offset for clarity. Error bars of ± 10% are also shown.

> “Distinguishing starbursts from supermassive black holes is complicated by the fact that AGNs are often shrouded in dust, so that much of the direct emission is hidden from view. Long wavelengths penetrate the dust more readily, so the EVLA, SAFIR, and NGST with an extension into the thermal infrared are all suitable for separating the two phenomena.” – Astronomy and Astrophysics in the New Millenium (McKee-Taylor decadal survey), p. 85.

Figure 2 also shows an average quasar spectrum, at the same redshift (where models suggest such objects may have formed: e.g., Haiman and Loeb 2001). A "first light" AGN may show differences in emission line spectrum and or in continuum shape (due to effects such as lower black hole mass, luminosity close to the Eddington limit, and low metallicity). In general, these effects would tend to make the continuum bluer than in the figure and hence even more difficult for NIRCam to distinguish from young galaxies. In any case, because of the large equivalent width of the Ly α emission line, early quasars are likely also to have similar colors to young galaxies in the NIRCam bands (despite differences in continuum shape). With the longer spectral baseline provided by MIRI, differences should become apparent between accreting massive black holes and stellar objects due to the fundamentally different physics of energy generation and radiative transfer in the quasar compared with galaxies (just as in the case for quasars at $z < 7$).

> "The release of highly energetic photons from these first stars and quasars heated the gas and ionized it. We seek to understand how this happened, in detail, and how it affected the formation of later generations of stars and black holes….The optical and ultraviolet light from these earliest quasars will be redshifted into the near infrared. Quasars can be distinguished from star forming regions because they produce relatively greater quantities of X-rays. Deep imaging surveys across the electromagnetic spectrum are therefore the best way to search for and interpret these early sources. This is already being done with HST and Chandra, but to push to earlier epochs we will require high-sensitivity detections in the near-to-mid-IR. The next generation of surveys will begin with the Space Infrared Telescope Facility (SIRTF) and be carried to unprecedented depths by JWST."– Origins Roadmap, p. 3, 6-7.

The SED and emission-line properties of quasars have shown a remarkable uniformity to beyond $z = 6$ (Fan et al. 2001), indicating virtually no evolution in the properties of these sources. Should significant differences be found in quasar SEDs at extreme redshifts through combined NIRCam and MIRI observations, it will open a new and important field of research (see for example Haiman and Loeb 1998). Given a possible formation epoch of $z \sim 10 - 15$ (e.g., Haiman and Loeb 2001), and the strong Lyman forest absorption, the accessible spectral range for studying the first quasars will be limited to the rest-frame ultraviolet for NIRCam and NIRSpec. The emission line properties of these sources in the MIRI wavelength range (rest-frame near UV, visible, and near-infrared) will help substantially in the comparisons with quasars at lower redshift.

Star Formation Rates in Very Early Galaxies

> “NGST will cover the spectrum out to wavelengths of at least 5µm, so that, for example, it can observe the hydrogen-alpha line produced in regions of massive star formation to a redshift of about 6 …. Extending the sensitivity of NGST farther into the thermal infrared would greatly increase its ability to study galaxies at high redshifts.” – Astronomy and Astrophysics in the New Millenium (McKee-Taylor decadal survey), pp. 76-77.

A variety of indicators are used to estimate star formation rates – ultraviolet, Hα, and far infrared luminosity being the most useful (Bell and Kennicutt 2001 and references therein). The lowest metallicity galaxies in the solar neighborhood are strongly affected by reddening, even at metallicity levels of 2% of solar (Thuan et al. 1999). We have little understanding of the extinction or emission properties of the dust that might lie within an extremely young galaxy. Changes in either ultraviolet absorption or far infrared emission properties will change the calibration of the star formation rates, potentially substantially. It is likely that Hα luminosity will be the most reliable indicator of star forming rates under these conditions. At $z > 6.5$, Hα moves out of the NIRCam spectral range. Although Lα is available, it is not a reliable star formation indicator because of optical depth effects and absorption connected with its status as a ground state transition. $z > 6.5$ corresponds to the period prior to reionization, and is the critical era in the Universe for judging the development and assembly of the first star forming galaxies. At the expected performance level of the MIRI, the Hα line will be one among only two or three of the most detectable (by JWST) emission lines in these objects (Panagia and Stiavelli, private communication).

Unexpected Discoveries in Deep Surveys

> “Improvements in sensitivity and angular resolution make NGST roughly 1000 times more capable than HST and SIRTF; its low temperature makes it up to a million times more capable than similar-size ground-based telescopes. The discovery potential of NGST is enormous. Having NGST’s sensitivity extend to 27µm would substantially improve its ability…Not only would this extension take full advantage of the effort to cool the instrument, but NGST would gain its greatest advantage over any ground-based telescope at the longer infrared wavelengths.” – Astronomy and Astrophysics in the New Millenium (McKee-Taylor decadal survey), pp. 100-101.

JWST will be the most sensitive instrument for surveying in the mid infrared by orders of magnitude over any other telescopes conceivably available in the same time frame (see Figure 1). It provides an immense discovery space for JWST

2.2 Assembly of Galaxies

Formation of Active Galactic Nuclei

> " A larger [than SIRTF] long-lived space observatory optimized for λ ~ 3 – 20μm will be the single most important facility for the study of Active Galactic Nuclei." – HST and Beyond, p. 76.

Galaxy interactions can trigger powerful episodes of star formation and also can activate accretion onto nuclear supermassive black holes, producing an AGN. In the initial stages, these processes are deeply shrouded in the interstellar medium of the colliding galaxies. This material obscures our view nearly completely in the optical and near infrared, and the activity is most easily studied through the strong re-radiated emission and emission line spectra in mid-infrared and accessible to the MIRI.

> "Ultimately, we want to know how all the relevant processes worked together .. to form the first galaxies. This means tracing the growth of dark matter halos, the distribution of gas space and time, the synthesis of the heavy elements, and the buildup of stars and their remnants as the Universe ages. A particularly important epoch lies between redshifts of 1 and 3 (from 7 to 10 billion years ago), when the present-day universe began to take shape." – Origins Roadmap, p. 3.
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> "JWST can measure even heavily dust enshrouded star formation out to redshift z = 3.5 by detecting rest frame 3.3-micron polyaromatic hydrocarbon (PAH) emission. In addition, JWST can exploit numerous mid-IR spectroscopic diagnostics to distinguish star formation from hidden AGN. These include coronal lines of silicon, sulfur, and calcium as well as rotation-vibration emission of molecular hydrogen." – Origins Roadmap, p. 8.

A much higher merger rate prevailed in the past, and the space density of luminous AGNs appears to peak between z = 2 and 2.5. Observations in the mm- and submm-wave have discovered a class of extremely luminous infrared-emitting galaxies at redshift roughly 2, which contribute a substantial fraction of the star formation at this epoch. Although they have been very difficult to identify because of the relatively large beams used in the submm, ALMA should provide accurate positions to allow investigations of them in other wavelength regions. Perhaps 90% of AGNs at this redshift range were also heavily absorbed (e.g., Gilli et al. 2001). We must understand this population to learn the role they play in the evolution of galaxies and the integrated light of the Universe. Explorations of both these source types must be concentrated in the MIRI wavelength bands because of the strong extinction. Although it has taken 30 years to gain a reasonable understanding of the mid-infrared properties of local Ultraluminous Infrared Galaxies and Type 2 AGNs, the power of JWST lets us extend many key observations all the way back to the quasar heyday at z ~ 2 – 2.5.

> " The best diagnostic lines for study of AGNs are found from the UV to mid-IR (λ ~ 20μm) in the rest frame. … Because it is possible that many of the earliest quasars are obscured by gas and dust, the near- to mid-IR lines are particularly valuable indicators of their nuclear activity." – HST and Beyond, p. 50.

For example, the black hole accretion sources produce hard ultraviolet fluxes that can be identified by high excitation mid-infrared fine structure lines. A key line is [NeVI] at 7.65μm rest wavelength; it is the shortest wavelength bright high excitation line (see Figure 3). In addition, its rest wavelength lies in a region of exceptional transparency of the interstellar medium, $A_{7.6\mu m} < 0.02\ A_V$. Thus, sources where the rest optical line emission is totally inaccessible can be studied with this line using MIRI up to z ~ 2.5, determining key parameters such as the true AGN hard UV energetics. Studies can be extended to even higher redshifts using the "coronal" high excitation lines. There are a number of strong lines of this type at 2 to 4μm rest wavelengths (e.g., Greenhouse et al. 1993, Moorwood et al. 1997), such as the lines of [MgVIII] and [SiIX] in Figure 3. The sensitivity of the MIRI, combined with the absence of terrestrial atmospheric absorptions, can access these lines even for AGNs of modest luminosity.

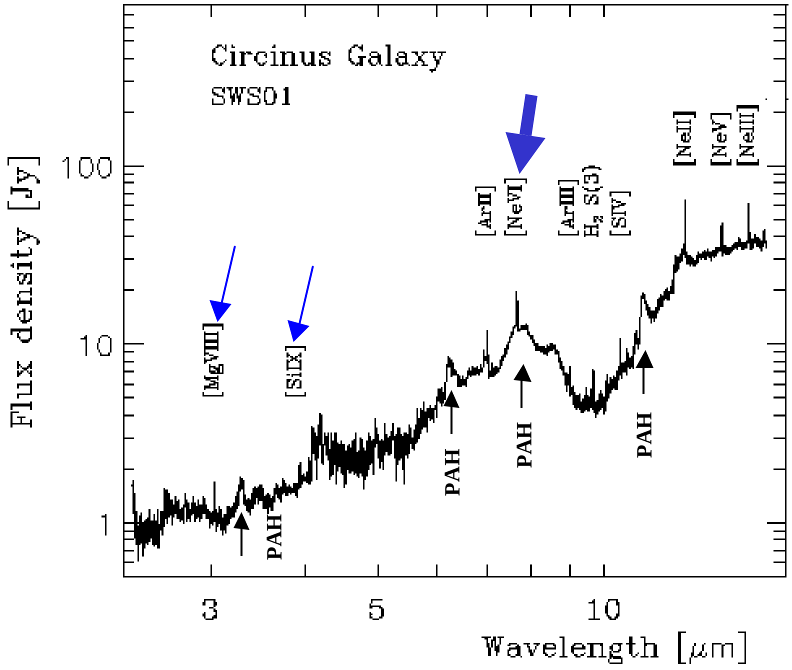

Figure 3. ISO spectrum of the Circinus galaxy (Sturm et al. 2000) showing the strong NeVI line.

Dark Matter

> "A quantitative study of the distribution of dark matter might be undertaken by investigating the kinematics of the visible matter using prominent near-IR photospheric features (e.g., H_2O, CO). These strong photospheric features are found at 4.6, 2.3, 1.8, and 1.6μm, so are shifted well into the mid-infrared at even moderate redshift. … As a baseline, we will assume that the CO first-overtone band (2.3μm) will be a prime target, which will mean extremely sensitive operation of an observatory at $\lambda \geq 10\mu m$ for $z \geq 3$." – HST and Beyond, p. 49.

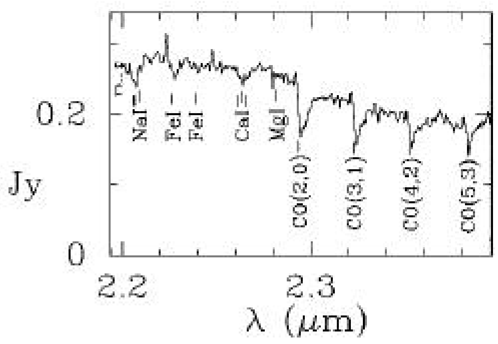

Figure 4. CO first overtone bands in NGC 253 (Engelbracht et al. 1998)

The CO first-overtone bandhead at 2.3μm (Figure 4) is a sharp feature of very large equivalent width, characteristics that have made it extremely useful for determining dynamical masses in heavily obscured galaxies (e.g., Engelbracht et al. 1998). MIRI provides the sensitivity and spectral resolution to study dynamics in this band at high redshift. For example, it will provide unique insight to the dynamics of dark matter in high redshift ULIRGs and obscured AGNs.

> "The morphology of today's mature galaxies is described by the Hubble sequence – a variety of distinct morphological types including irregulars, spirals, and ellipticals – and these morphologies consist of basic structural components such as disks, bulges, bars, and spiral arms. There is now good evidence that the Hubble sequence arose between $1 < z < 3$, but as yet there are no observations to guide modeling of how the morphology and structures of galaxies arose and evolved. The high angular resolution and sensitivity of JWST will permit direct observations of the morphological evolution of galaxies as well as the history of galaxy collisions and mergers over this crucial epoch." – Origins Roadmap, p 8.

Formation of the Hubble Sequence

Once galaxies have aged beyond 10-20 million years, they emit strongly at rest wavelengths near 1.6μm due to the populations of red giant and supergiant stars, which generally represent most of the stellar mass. However, given the high optical and ultraviolet luminosities of forming massive stars, the light in the rest frame optical and near ultraviolet often is dominated by young objects, and as a result it can mis-represent the intrinsic nature of the galaxy. As a result, galaxy morphologies are often significantly different at rest wavelengths beyond 1μm compared with short of this wavelength (see Figure 5). Tracing the development of the Hubble sequence of galaxies to $z \geq 3$ will therefore require high

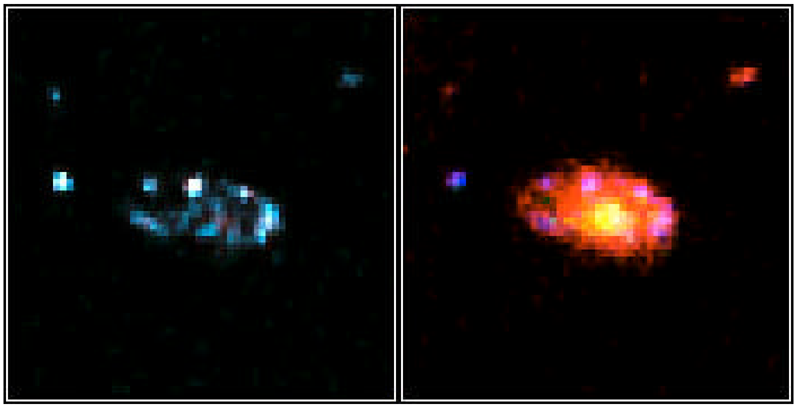

Figure 5. Comparison of visible (WFPC2, left) with near infrared image (NICMOS, right) of a distant galaxy from http://oposite.stsci.edu/pubinfo/pr/1998/32/b.html

sensitivity MIRI imaging at 5 – 10µm to access the red giant light.

Formation of Heavy Elements

> " One of the most important events in the evolution of the universe was the transformation of the star-forming gas from the nearly pure H and He of the Big Bang to the heavy-element-bearing material of the modern ISM. Diagnostic absorption lines from heavy elements are found in the UV and visual, emission lines are found at visual and infrared wavelengths, and broad solid-state features are found at many wavelengths beyond about 3µm. Consequently, an inventory of the heavy element composition of the high-z universe will require a space observatory.. with wavelength coverage extgending from the visible to as far as possible into the mid- or even far-infrared." – HST and Beyond, p. 49.

Heavy elements form and are ejected into the interstellar medium over a time scale of 10 – 100 million years after the first major episode of massive star formation. Much of the mass of the heavy elements will be locked up in dust. The MIRI can study this component in two ways. First, through measurement of interstellar spectral features, such as the PAH bands (indicated in Figure 3), it can observe directly the nature of the dust component of the heavy elements. Although the bands can be detected at low resolution, probing changes in the composition responsible for them and using the features as diagnostics of physical conditions requires spectral resolution of 1000 or higher. Second, identification and estimation of reddening will have large uncertainties due to the degeneracy of colors due to aging and reddening effects, if the wavelength baseline is not large enough. By combining MIRI and NIRCam photometry of high redshift galaxies, we can remove this degeneracy and quantify the growth of reddening with galaxy age in the early Universe.

2.3 Formation of Stars & Protoplanetary Systems

Structure of Protostars

> "A 4m [IR-optimized] telescope would be a powerful tool for general studies related to important problems in star formation. Spectroscopy over the wavelength range of about 10 – 30µm includes the pure-rotational lines of H_2, emission from Fe, Si, and other elements near regions of mass outflow,…unobscured IR diagnostic lines will allow determination of density, excitation, and stellar temperature, and elemental abundances." – HST and Beyond, p. 72.
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> "In order to provide clues concerning the earliest phases of star formation, .. continuum and spectral line observations must be conducted at angular resolutions of 0.1 – 1.0 arcsec (10 – 100 astronomical units in the nearest star-forming regions). JWST will be able to probe the most central regions of protostars." – Origins Roadmap, p. 17.

Mid-infrared imaging and spectroscopy of very young protostars will provide a breakthrough in studies of the earliest stages of star formation. Figure 6 shows observations and a theoretical spectrum of a protostar from André et al. (1993). The submillimeter and millimeter wave spectrum is consistent with a cold blackbody (solid line), indicating that the millimeter observations only probe the accretion disks and

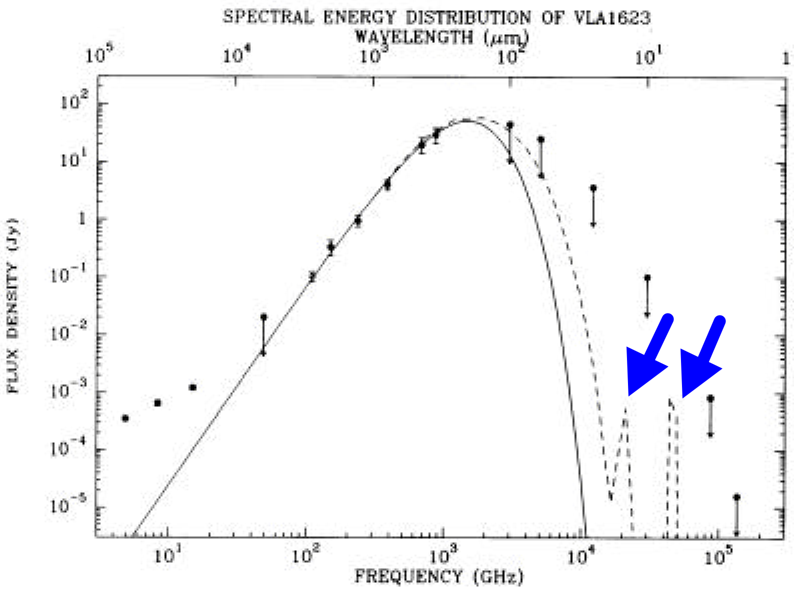

Figure 6. The spectral energy distribution of the Class 0 protostar VLA 1623 and a projection into the mid infrared based on a radiative transfer code (André et al. 1993). The MIRI detection limit is below the bottom of the figure.

extended envelopes. The actual protostars (i.e., the first and second hydrostatic cores) are accessible through their mid (and far) infrared emission. The spectral energy distribution of a first protostellar core rises steeply longwards of 10µm, but is already dominated by the surrounding cloud at wavelengths longer than about 60µm.

The features on either side of 10µm (indicated by blue arrows) lie in wavelength regimes where the interstellar dust is particularly transparent. They therefore provide the opportunity to probe deeply into the cloud, to warmer regions. The capability of MIRI to image these sources to sensitivity levels of 1µJy or even fainter is the key to determining the structure of the warm interior of protostars. Along with this unprecedented sensitivity, the angular resolution of MIRI is critical for these studies. There are five forming clusters or T-associations within 200 pc, in each of which observations at a physical resolution of ~ 30AU can be obtained.

Protoplanetary Disks

> "The initial steps toward planet formation occur in the surrounding disk of material that avoids either falling into a forming star or being ejected in outflows. These steps are now occurring around young stars in nearby molecular clouds. They should be apparent through their effects on the structures of the disks, but are hidden from view by a combination of obscuration due to the surrounding dust and limitations in resolution that mask the details in those young disks we can observe… JWST will penetrate the obscuration to image these disks … With these images, we will fit disk model parameters, such as disk scale height (flaring), outer radius, and grain optical properties. These constraints provide the initial conditions necessary for studying the origin of planetary systems" – Origins Roadmap, p. 20.

As shown in Figures 6 and 7, the MIRI will let us image protoplanetary disks at exquisite resolution. Such observations will be virtually impossible from the ground both because of sensitivity limitations and because much of the interstellar spectral window for these observations lies at wavelengths that are obscured by the terrestrial atmosphere. The MIRI beam at 6µm corresponds to only 30 - 35 AU for nearby protostars, compared with estimated sizes for hundreds of AU for protoplanetary disks, so it will be possible to obtain many resolution elements across these structures. Spectroscopic measurements will allow us to probe the mineralogy and the state of the gas in protoplanetary disks, including the molecular hydrogen as well as raw materials for life such as water and hydrocarbons. These topics are discussed in more detail below under "Mineralogy of Debris Disks" and "Precursors to Life."

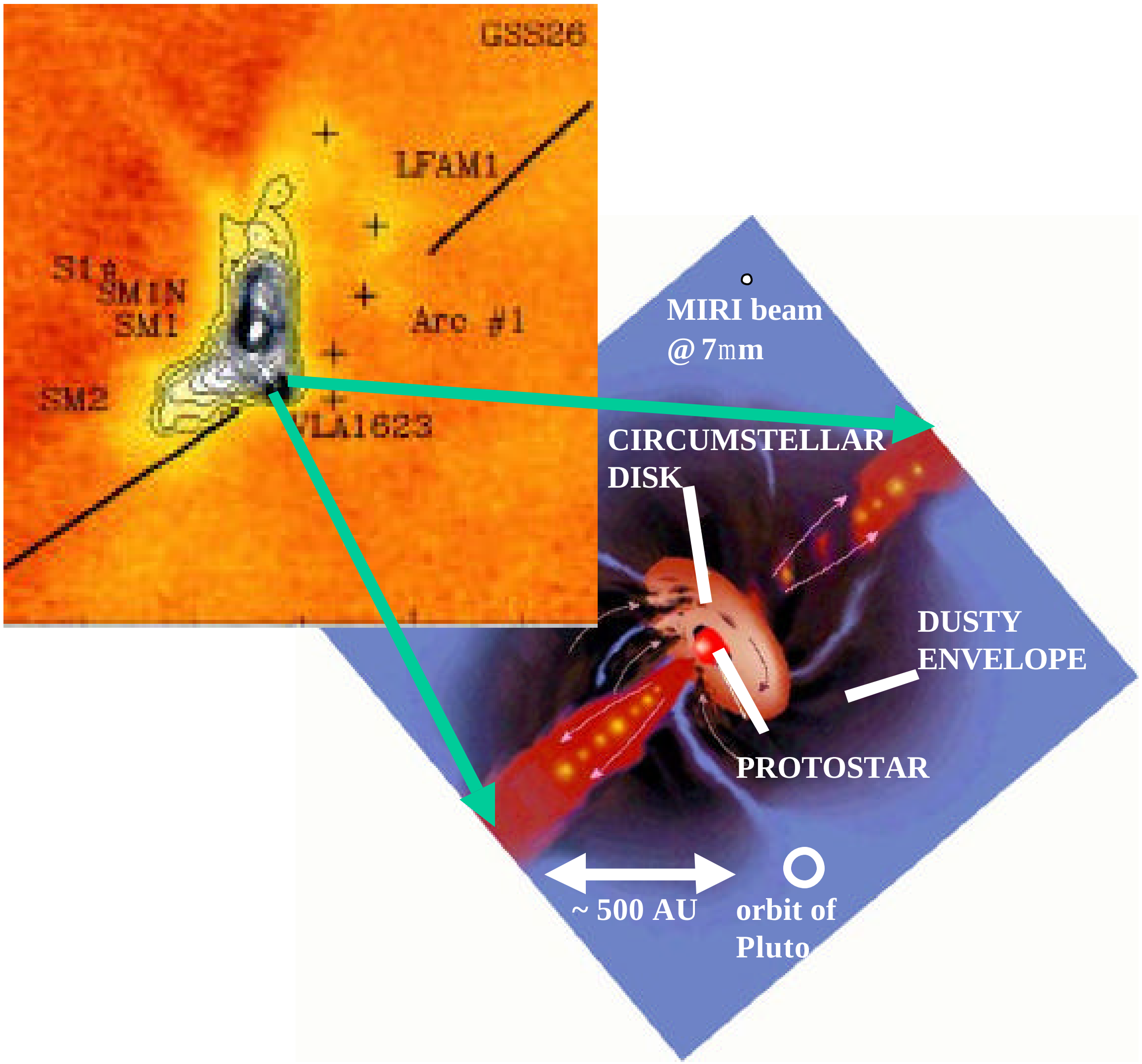

Figure 7. VLA 1623 in the submm (left; Wilson et al. 1999), and artist's concept (right, Greene, private communication). The MIRI beam at 7mm is indicated at the top of the artist's concept.

Binary Protostars

> "Gravitationally bound multiple star systems (e.g., binaries) are thought to form by fragmentation, induced by rotational effects during the collapse of a single molecular cloud core. In order to explain the diversity in orbital periods, eccentricities, and mass ratios observed in binary star systems, an understanding of the physics of fragmentation is needed…. In order to achieve the scientific goals listed in this investigation, deep imaging and spectroscopic surveys from the ground, in the air with SOFIA, and from space with SIRTF and the James Webb Space Telescope (JWST) will be crucial." – Origins Roadmap, p. 17-18.

Although there is growing evidence that the majority of stars form in binary and multiple systems, a major gap in our understanding of star formation concerns the origins of binary stars. While some theoretical predictions of fragmentation models are indirectly supported by statistical studies of evolved binary systems at optical and near-infrared wavelengths, direct observations of the formation phase itself became possible only very recently with the advance of large and sensitive millimeter interferometers. As discussed above, millimeter wave observations only probe the extended envelopes, not the protostellar cores. JWST will be able to test binary star formation and fragmentation models by using the MIRI near 10μm to observe the actual hydrostatic cores in a turbulent, rotating, fragmenting, collapsing protostellar cloud. To constrain formation process further, the mid-infrared data can be combined with kinematic information on the circumstellar material provided by mm/submm interferometers.

2.4 Planetary System Evolution and Conditions for Life

> "Near the end of the evolution of a mature disk-planet system, the remnant disk gas is dispersed, leaving behind planets and the rubble of many smaller bodies. Dust produced in collisions of asteroid-like debris is thought to form the low-mass disks that have been detected around more mature stars, such as Vega. SIRTF will give us our first hints concerning gas and dust dispersal, but follow-on large space-based telescopes such as JWST and SAFIR are ideally suited to track the evolution and map the structure of vestigial debris disks around nearby main-sequence stars." – Origins Roadmap, p. 18.

Debris disks are the most visible manifestation of a planetary system because they dominate its surface area. MIRI provides the capabilities to image the nearest examples in detail, revealing the composition and structure of the dust and gas. Such images are inaccessible from the ground because of the low surface brightnesses of these relatively faint, extended structures. Dynamical models for debris disks predict that massive planets will have a dominant effect on their structures. MIRI can not only deduce the presence of these planets indirectly from the debris disks, but in many cases will image them directly.

Debris Disk Structure

Figure 8 shows a sampling of the variety of structures that can be induced in a debris disk by a massive planet, depending on the details of its orbit around the primary star. Similar results have also been reported by Liou and Zook (1999), who show that external observations of the Kuiper Belt debris disk would show that the solar system has at least two massive planets.

As Figure 9 shows, the MIRI can probe these structures well (although the model in Figure 9 is nominally for the mm-wave region, we use it as a surrogate for models with appropriate parameters for 24μm).

Vega and β Pictoris are the two prototypes, but as Figure 8 shows, we need to image a number of these systems to probe their structures and the planets that shape them.

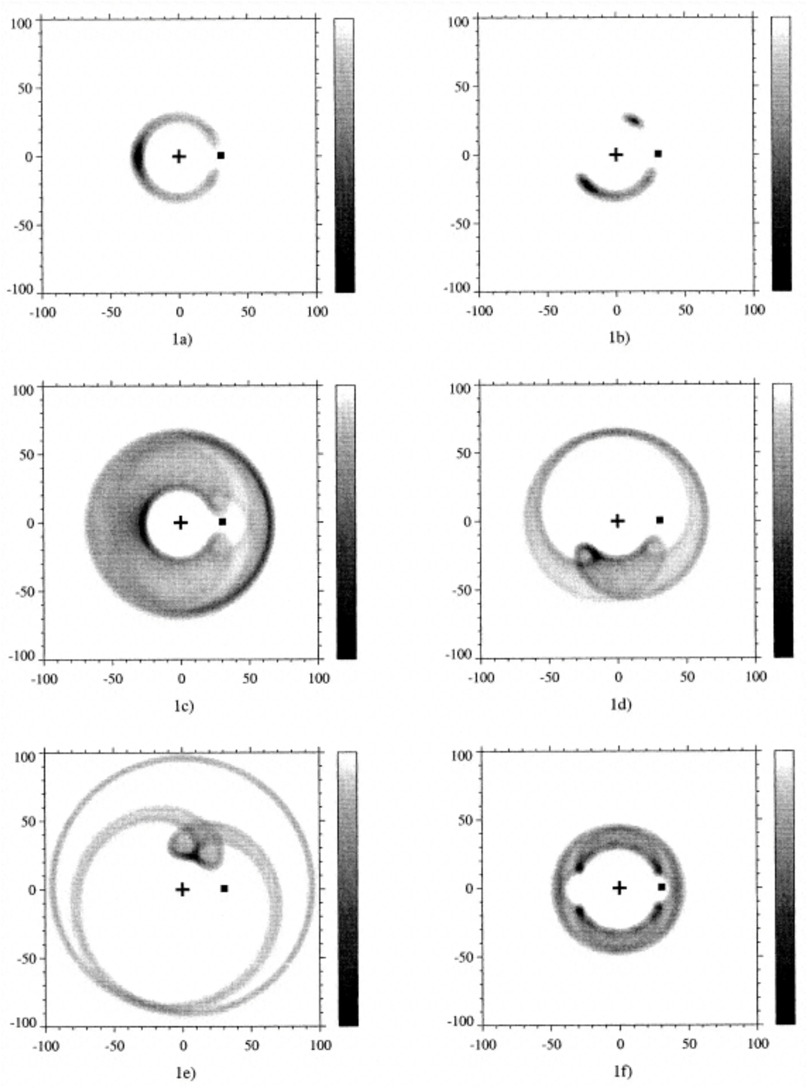

Figure 8. Possible structures for debris disks as a function of planetary mass and orbital resonance properties (Ozernoy et al. 2000). The boxes correspond roughly to 200AU.

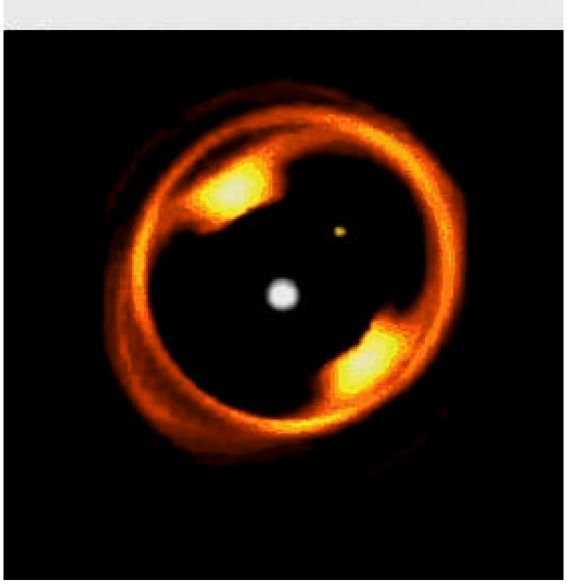

Figure 9. Simulated MIRI image of the Vega debris disk. The model is from Wilner et al. (2002). The massive planet responsible for the structure is shown to the upper right of Vega itself (the white object). The ring is 25 arcsec in diameter.

A minimal list of 10 stars can be deduced from IRAS and ISO data. Additional candidates will be discovered by SIRTF, and/or can be added by going to fainter excesses. If we use the IRAS data to deduce the relative brightnesses of the systems in these ten stars, they range down to about 1/6 that of the Vega system, to an integrated brightness of 200 mJy at 25µm. Even on this restricted list, the stars range in distance up to about 6 times further than Vega, so their disks would scale to about 4 arcsec in diameter. Figure 10 shows how the Vega disk would appear to MIRI at this distance, still revealing enough information to constrain models.

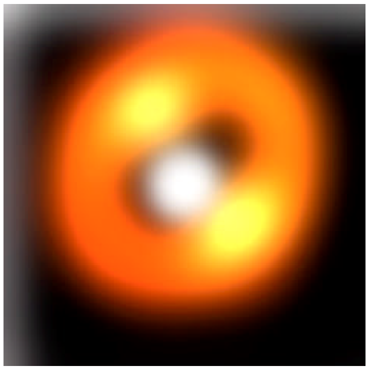

Figure 10. Simulation of the same Vega model as imaged from a distance 5 times greater (40 pc).

Mineralogy of Debris Disks

"The most likely chemical constituents of the [protoplanetary] disks, including simple organic compounds that are the raw material for life, have characteristic absorption features accessible to JWST." – Origins Roadmap, p. 20.

"A large-aperture IR-optimized mission could undertake an extremely deep survey…searching for circumstellar dust emission at λ ~ 5 – 50µm – the 'Vega phenomenon' – around main sequence stars similar to the Sun…. a next-generation observatory would also possess sufficient sensitivity to undertake spectroscopic mineralogy and petrology of the dusty material. This undertaking would include study of the composition as a function of position in the target system." – HST and Beyond, p. 71.

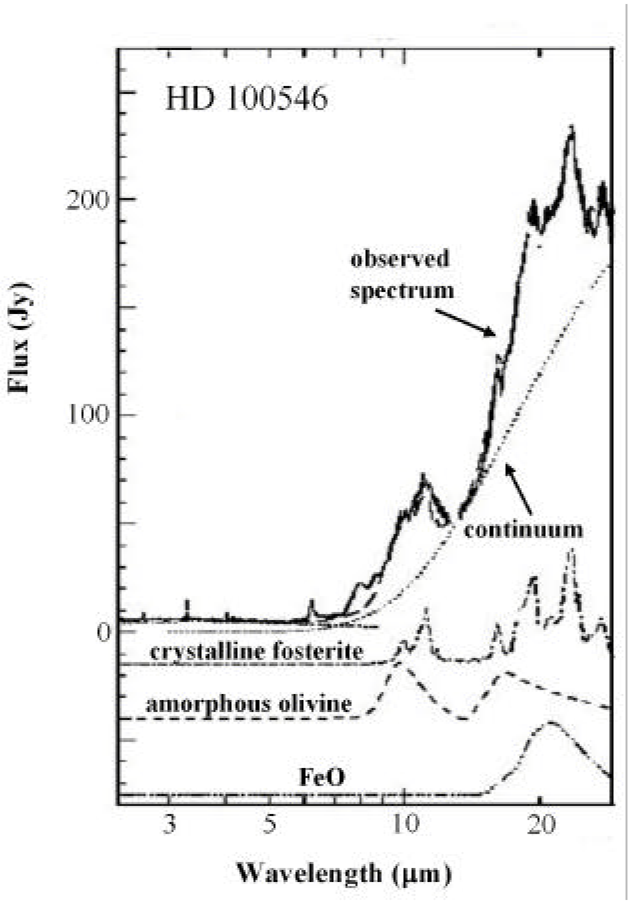

Figure 11. Spectrum of HD 100546 by Malfait et al (1998).; we show only the region accessible to MIRI. The observed spectrum is fitted by a combination of featureless continuum, crystalline fosterite, amorphous olivine, and FeO, as shown in the individual spectra at the bottom.

MIRI spectroscopy of protoplanetary disks and of their descendents, the debris disks, will reveal the mineralogy of the dust and the physical conditions of the gas. An ISO spectrum in Figure 11 shows these features around a bright Ae star. The infrared diagnostic spectral features for the dust mineralogy extend to the long wavelength cutoff of MIRI, and can be detected by smoothing MIRI spectroscopy to a final resolution of R = 100.

To explore the mineralogy of grain materials requires higher spectral resolution. As an illustration, the laboratory work reported for example by Fabian et al. (2001) and the ISO spectroscopy summarized by Tielens et al. (1997) show complex features as a function of mineral state; see Figure 12.

The mineralogy and particularly the presence of crystalline featrures are also potential indicators of disk processing and evolution, as well as indirect tracers of the formation of large planetary bodies (e.g., Bouwman et al. 2001)

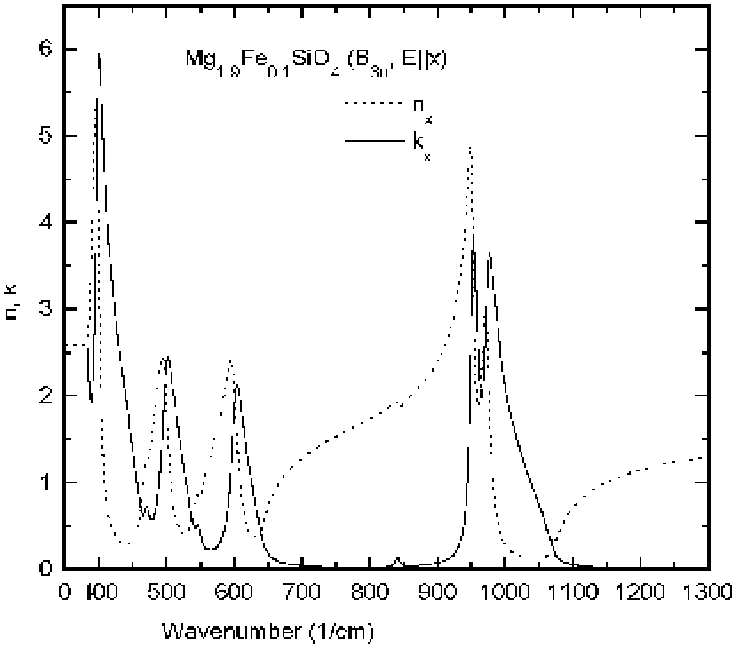

Figure 12. Complex refractive index of single-crystal olivine, from Fabian et al. (2001).

> “The most abundant species in protostellar disks is molecular hydrogen. However, its quantity until now has largely been inferred from trace species such as carbon monoxide, which may not be a proper tracer of total gas throughout the lifetime of the disk. Hence, direct measurements of molecular hydrogen, via infrared spectroscopy with SIRTF, SOFIA, and … SAFIR are needed to directly probe gas disks.” – Origins Roadmap, p. 18. [the OS assumed a MIRI operating only to 10µm, hence did not mention it explicitly]

In addition to the dust, warm (~100 K) molecular gas located 1-50 AU from the central star in these nearby debris disks can be traced using the pure rotational lines of H_2: J=5-3 S(3) at 9.662 µm, J=4-2 S(2) at 12.278 µm, and J=3-1 S(1) 17.035 µm. The H_2 S(1) lines at 17 and 28 µm have been tentatively detected by ISO in two nearby debris disks shown in Figure 13 (from Thi et al. 2001).

Simultaneous measurements of these rotational lines would provide a profile of the temperature and mass of the gas as a function of radius. Dust-to-gas mass ratios can be derived by comparing the H_2 results with dust measurements. These H_2 measurements in different-age disks will constrain the age at which gas giants can form because they will be sensitive to small masses of molecular gas. The measurements can also show how gas is cleared from the disks, and on what time scale.

The expected MIRI line flux sensitivity would readily detect ~0.5 Earth mass of 100K molecular gas in a debris disk at 30 pc.

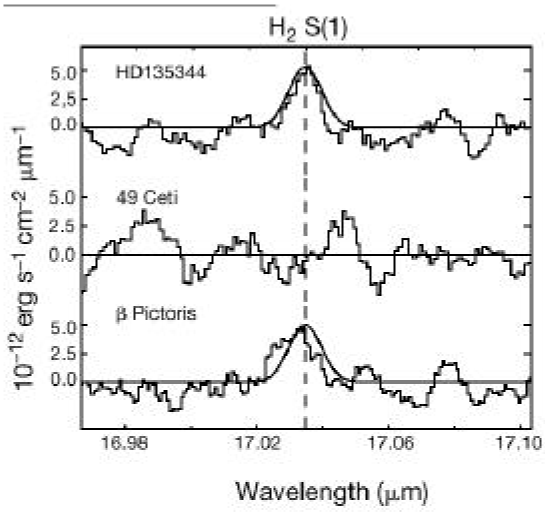

Figure 13. Possible detections of H_2 at 17mm in the debris disks around HD135344 and b Pic, from Thi et al. (2001).

Planet Detection

> "Future observations and theoretical investigations within the Origins program will address such questions as how the presence of terrestrial and giant planets is related to stellar mass and age, magnetic activity in the star, binarity and/or the presence of surrounding stars in a cluster, and the overall galactic environment in which the star formed. For example, SIRTF, JWST, and eventually next-generation near-to-far-IR space telescopes will be able to observe planet formation in a wide range of environments." – Origins Roadmap, p. 11.

JWST will bring the comparative study of extrasolar giant planets to a mature level. Figure 9 shows the 3 M_J planet hypothesized to account for the debris disk structure around Vega. In addition to direct imaging detections, MIRI images of debris disks can also be used as signposts for the presence of giant planets at large radii from the primary star. Current radial velocity techniques are not sensitive to this population of giant planets. Their identification is extremely important because their relatively large separations from the much brighter primary stars means that we can study their properties in far more detail than is possible with planets detected through radial velocity measurements.

Giant planets and brown dwarfs have an atmospheric window near 4.6μm where energy can emerge from deep in their atmospheres. They are therefore relatively bright at this wavelength, making them accessible to initial searches with NIRCam. However, this effect is dependent on the amount of cloud cover as well as the structure of the atmosphere (through the temperature structure under the cloud deck) and potentially also the orientation of the object (the windows in the Jovian cloud deck are primarily in the equatorial zones). Thus, the fluxes are strongly model-dependent and cannot be used for a robust determination of the full nature of a detected object, i.e., its thermal balance or mass. To obtain this information requires detection near the peak of the thermal output. The sensitivity of MIRI would allow a solid detection of Jupiter at 24μm from a distance of 10pc. Systems with such planets should be common, perhaps found in 10% of the nearby stars of roughly solar type (Trilling et al. 2002).

> " Near or mid-infrared spectra, even at low spectral resolution (R ~ 20 – 50), will yield the abundance of key chemical species like water, methane, or ammonia, in giant planet atmospheres." – Origins Roadmap, p. 27.

Spectra in the near-to-mid infrared are also important to constrain the atmospheric models. Figure 14 shows a suite of models for an age of 1 GYr and for masses ranging from 1 to 40 M_J, all at 10 pc distance.

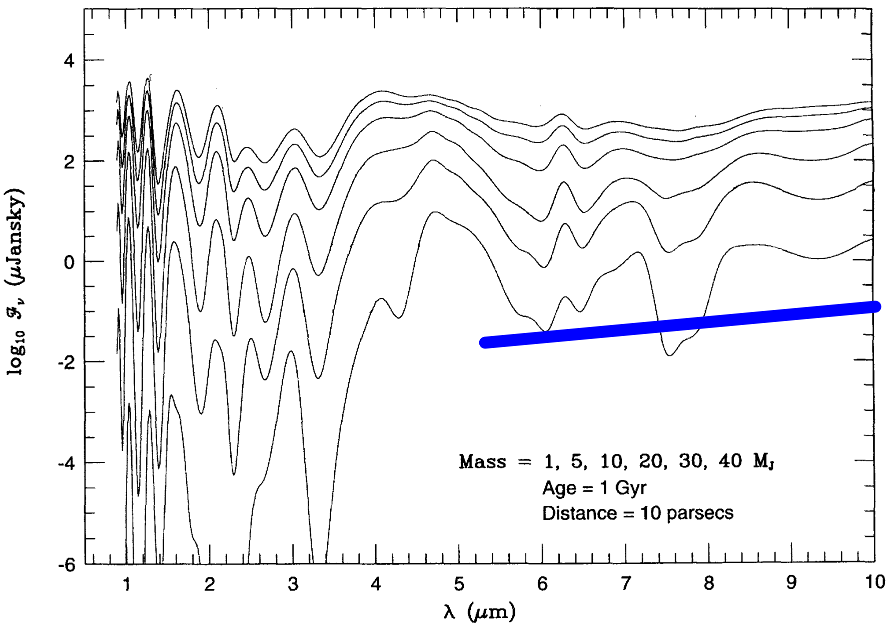

Figure 14. Spectra of giant planets at an age of 1 GYr (Burrows et al. 1997),. The heavy line shows the 1-sigma detection limit for MIRI at a spectral resolution of R = 100 after 10,000 seconds.

Unresolved Debris Disks

> "Another promising way of studying planet formation in disks is to find evidence that small dust grains are being depleted by coagulation into larger grains and eventually into planetesimals. Observations must distinguish grain growth from effects caused by radiation blowout and Poynting-Robertson drag. Spectral and photometric studies using JWST and SAFIR, of the temporal development of the IR spectral energy distributions of the disks around young stars play central roles in this investigation." – Origins Roadmap, p. 20.

A critical step in understanding the formation of habitable planets is the clearing of small bodies from the inner regions of debris disks, as they are swept up by planets. Probing this process requires that debris disks be observed in stars of a range of ages 1 – 50 million years and in the 0.1 – 5 AU radial range, where the output of the debris disks is peaked in the 5 – 20µm range.

It is difficult to determine the ages of most of the nearby stars, since factors like rotational velocity as well as evolution affect their placement on the HR diagram and there are few spectral features with significant age dependence. The most reliable age determination is based on membership in associations, moving groups, or clusters, where ages can be determined from the stars with the greatest leverage – low mass objects that settle slowly onto the main sequence or high mass ones that leave it quickly. To include clusters with an adequate sampling of ages for a full understanding of debris disk evolution requires searches for debris disks to distances of about 1 – 1.5 kpc. At this distance, the 10 and 20µm magnitudes of a solar-type star are below the limits for high accuracy photometry by SIRTF or very large groundbased telescopes. SIRTF may find extreme examples of debris disks through large 24µm or 70µm excesses, but only the MIRI will be capable of systematic surveys to the level of systems similar to the most famous nearby examples such as Vega or eps Eridani.

Mineralogy and Debris Disk of the Solar System

> "The vast majority of Solar System sources are simply far too faint for detailed observations by observatories suffering the thermal background and obscuration of the Earth's atmosphere….. a space observatory will provide unimpeded access throughout the scientifically-crucial spectral regions, such as the 3 – 4µm and 6 – 8µm regions of carbonate signatures; 2.3, 4.5, and 9µm features of sulfates/bisulfates; as well as hydrated minerals with bands at 3 and 10[µm]. …Sensitive mid-IR band emission over λ ~ 8 – 30µm from solid surfaces can also indicate surface mineralogy, weathering, particulate structure, and the effects of photochemistry, all of which would qualitatively improve our understanding of the evolution of our own planetary system." – HST and Beyond, p. 70.

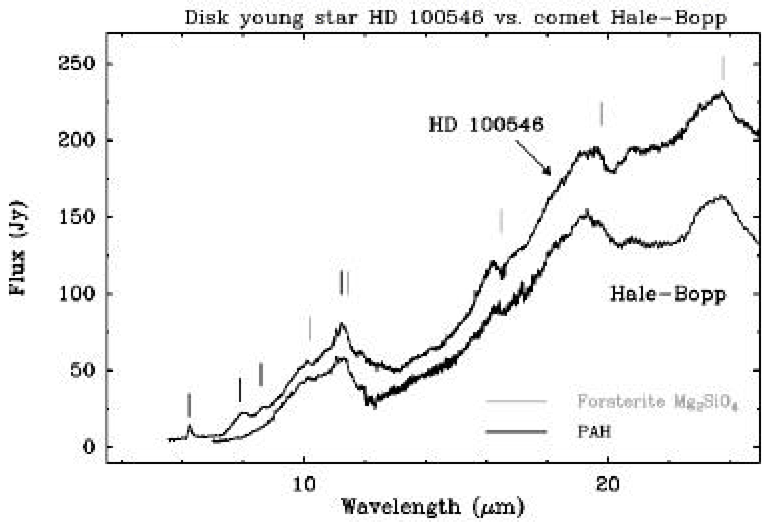

Figure 15. Comparison of Mid-Infrared Spectra of Comet Hale-Bopp and HD 100546, from Malfait et al. (1998).

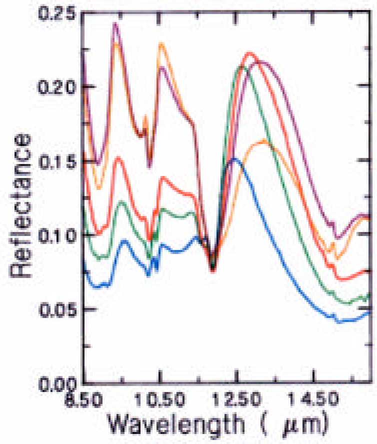

Figure 16. Olivine reflectance vs. wavelength, for particle sizes ranging from <5, 5 - 10, 10-15, 15-20, and 20-25μm (upward at 10.5μm). From Mustard and Hays (1997).

There may be a close correspondence of mineralogy between outer solar solar system objects and circumstellar disks, as indicated in Figure 15. The investigations described under "Mineralogy of Debris Disks," above, can be applied to small bodies in the outer solar system, such as faint comets. The MIRI spectra can also constrain the forms of material on the surfaces of solar system objects, such as particle size or the effects of weathering. See Figure 16. Finally, MIRI can also explore hydrocarbon prebiotic materials on small bodies, a subject that is discussed further in "Precursors to Life," below.

> "Having NGST's sensitivity extend to 27μm, would substantially improve its ability to study Kuiper Belt Objects (KBOs) in the solar system, ….." – Astronomy in the New Millenium (McKee-Taylor decadal survey), p. 100.

Kuiper Belt Objects (KBOs) are not only an important constituent of the solar system, but also represent the largest members of the debris system of the sun, analogous to the more dramatic debris systems around other stars. Although it is now known that KBOs have a range of colors in the visible, the albedos can only be guessed and hence the diameters and masses of the individual objects are very uncertain. Mid-infrared radiometry provides a measure of albedos when combined with measurements of reflected light. Figure 17 shows the predicted results for KBOs at the inner edge of the Kuiper Belt (~40AU) with various combinations of diameter and albedo that give identical signatures in reflected light. It also shows the predicted flux for a low albedo object in the middle of the Kuiper Belt. Fluxes are plotted as νF_ν to indicate where the maximum energy emerges. The different albedos are readily distinguished with the MIRI observations.

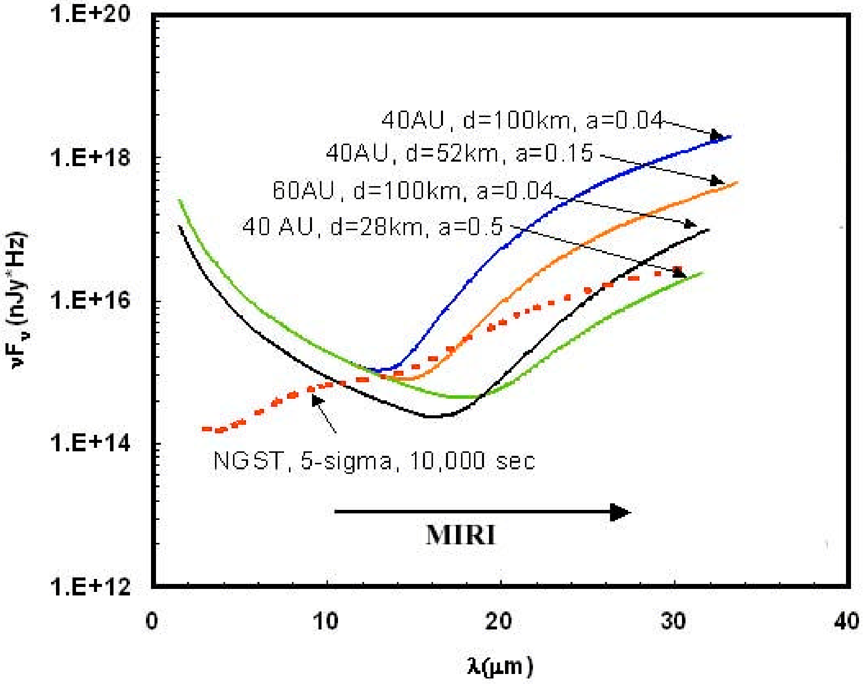

Figure 17. Fluxes from Kuiper Belt Objects

Precursors to Life

> "Prebiotic chemistry might begin in interstellar clouds. Laboratory simulations have recently demonstrated that key molecules can be synthesized in interstellar ices that are incorporated into nascent solar systems, and astronomical observations and analyses of extraterrestrial materials have shown that many compounds relevant to life processes are also present in meteorites, interplanetary dust particles and comets. It is likely that substantial amounts of such organic material were delivered to the Earth during late accretion, thereby providing organic compounds that could be directly incorporated into early forms of life or serve as feedstock for further chemical evolution. An important research objective …. is to establish sources of prebiotic organic compounds and to understand their history in terms of universal processes that would take place on any newly formed planet. This will require an integrated program of pan-spectral astronomical observations." -- Astrobiology Roadmap, p.8.

Volatile compounds, hydrocarbons, and simple organic ices have all been found in dark clouds and regions of star formation. There are a variety of complex organic materials that are important for conducting physical and chemical processes required for life as we know it, and several of these compounds may be discovered in different ISM environments with MIRI.

It is likely that the creation of these materials begins with the formation of relatively large hydrocarbon molecule chains and rings in the envelopes of dying stars. These materials are then ejected into the ISM via planetary nebulae (PNe) winds. They are composed of mostly C and H atoms because the weaker bonds of other species are destroyed in the harsh radiation environments of PNe. These hydrocarbon chains and rings are eventually swept up with other material into the dark molecular clouds that harbor active sites of star formation. 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. 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, ketones, and ethers (see Fig. 18). For example, ketones are needed for energy transport in cells and include compounds that are needed for blood to clot. Amino acids have also been produced in similar laboratory experiments.

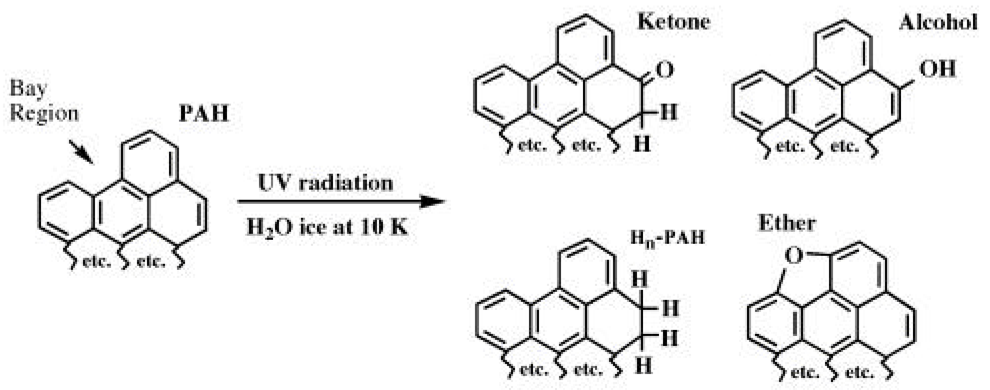

Figure 18. Chemical reactions between PAHs and H_2O molecules on dust grains, from Bernstein et al. (1999).

MIRI spectra are needed to determine whether these physical and chemical pathways for the assembly of pre-biotic molecules actually occur in interstellar environments. Many molecules are also detectable (and uniquely identifiable) via their millimeter wavelength rotational spectra, but the vast majority of pre-biotic molecules either have very weak rotational dipole moments or else are frozen in ices and thus not free to rotate. However, hydrocarbons and (prebiotic) organic compounds have many mid-IR spectral features that are diagnostic of their elements, structures, and types of bonds. Clues to prebiotic chemistry can also be obtained from spectra of the PAHs themselves. 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 windows in the interstellar extinction between 4.5 and 8µm and 13 and 17µm are the key to these studies. The ability of the MIRI to take very high sensitivity spectra in these ranges will let us look through these windows to witness the processes occurring in heavily obscured protostellar clouds where stars form. The coincidence of rich organic spectra and interstellar spectral windows make MIRI a uniquely powerful tool. For example, inner protostellar regions may show emission lines arising in warmer molecules, such as H_2O lines detected near 6.5µm in Orion (Figure 19). In addition, rich organic absorption spectra can be expected in the 13 to 17µm window (Figure 20).

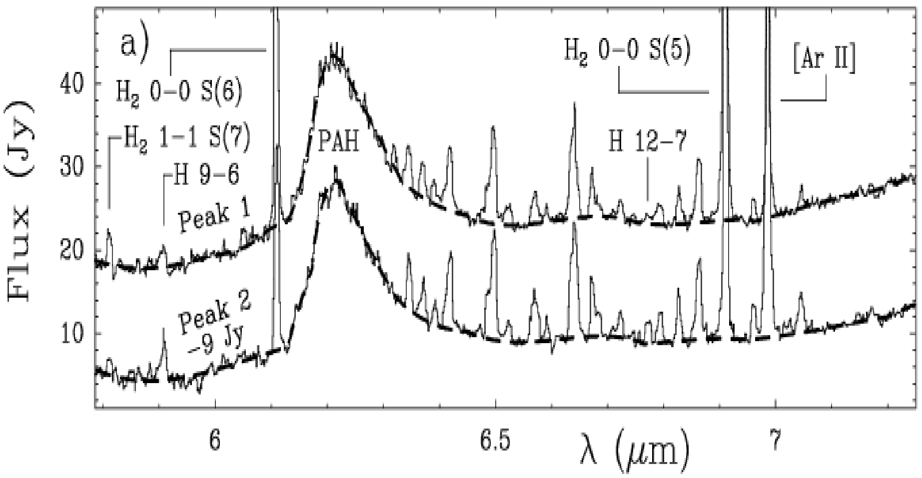

Figure 19. Water emission in Orion (the unidentified emission lines), from Gonzalez-Alfonso et al. 2002.

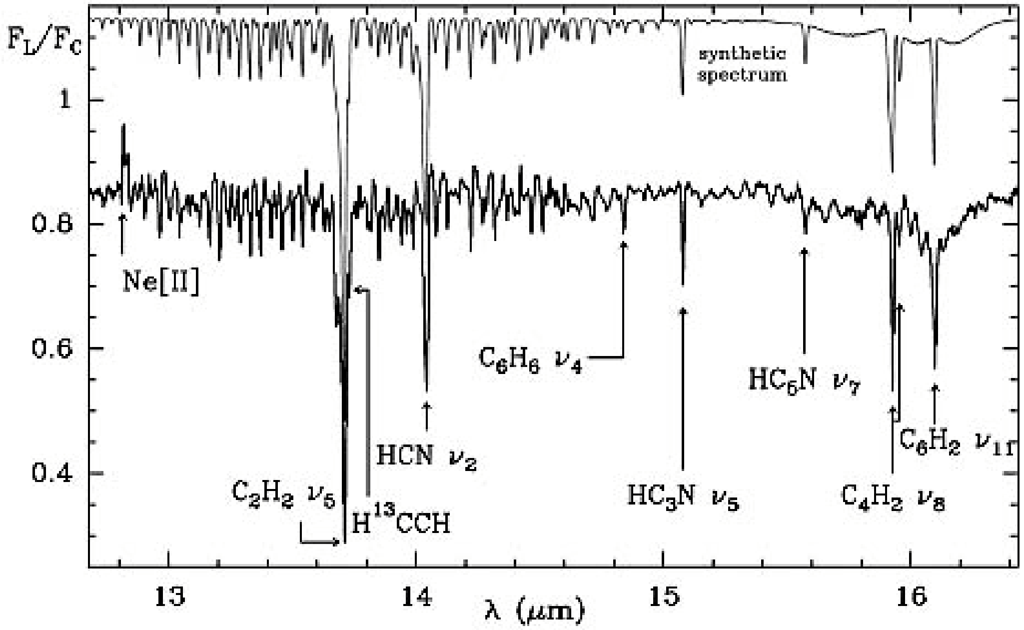

Figure 20. Spectrum of CRL 618, from Cernicharo et al. (2001). Although this object is an evolved and dying star, its spectrum illustrates the richness of this spectral region for study of organics.

Conclusion

> "Our recommended large-aperture, IR-optimized space telescope will be essential for the detailed studies of the early universe at λ ~ 1 – 5µm. However, we also recommend that it be operated as a powerful general-purpose observatory, serving a broad range of scientific programs over the wavelength range λ ~ 0.5 – 20µm, the exact coverage to be determined on the basis of future technical evaluation." – HST and Beyond, p. 69.

From the beginning, it was recognized that NGST has tremendous potential for the mid-infrared.

> "Extension of this telescope's wavelength range shortward to about 0.5µm and longward to at least 20µm would greatly increase its versatility and productivity. The Committee strongly recommends this course, if it can be done without a substantial increase in cost." – HST and Beyond, p. x.

It was recommended that the mid-infrared be included in the instrument complement, unless the facility costs were prohibitive.

> "the mid-infrared compatible concept…is the most advantageous solution for NGST, whether mid-infrared instrumentation is added or not. Such a solution is not significantly more costly and offers lower risk because of the possibility to passively cool the NIR detectors. This approach enables the mid-infrared, zodiacal light limited to 10µm, without increasing complexity, risk, or cost of the observatory." – Bély et al. 1998, p. 2.

A preliminary study (Bély et al. 1998) indicated that the facility costs were small. A project study to be completed in mid-January appears to confirm this conclusion, and the prime contractor, TRW, is also in agreement.

> "Having NGST's sensitivity extend to 27µm would add significantly to its scientific return." – Astronomy and Astrophysics in the New Millenium (McKee-Taylor decadal survey), P. 9.
>
> "JWST is expected to … be celestial-background-limited between 0.6 and 10 micrometers, with imaging and spectroscopic instruments that will cover this entire wavelength regime." – Origins Roadmap, p. 47.

Subsequent studies by the astronomy advisory structure have re-affirmed the high desirability of including the mid-infrared on JWST. Keying directly from statements made in these advisory reports, we have demonstrated that the mid-infrared is central to the goals of the Origins Theme and of NASA.

Appendix A

The Origins Theme Roadmap (published October, 2002) provides a comprehensive summary of all the missions planned under this science area. It therefore illustrates the science contributions of the MIRI in an overall context. It contains a large number of investigations requiring the MIRI, emphasizing the central role this instrument plays in achieving the goals of the Origins Theme. We trace the roadmap investigations into the features of the instrument in the table below.

Investigation	Imaging	R~3000 Spectroscopy	R~100 Spectroscopy	Coronagraphy
1. Pristine gas, the first stars, and the first heavy elements	**			
2. Black holes and structure in the early Universe	X*			
3. Formation and evolution of galaxies	X*	X*	X*	
4. Lifecycle of stars in the Milky Way and other galaxies	X*	X*	X*	
5. Habitats for life in the Milky Way and other galaxies		X*		X*
6. Molecular clouds as cradles for star and planet formation	X*	X*		
7. Emergence of stellar systems	X*	X*		
8. Evolution of protoplanetary dust and gas disks into planetary systems				X*
9. Evidence of planets in disks around young stars	X*		X*	
10.Census of planetary systems around stars of all ages				**
11. Chemical and physical properties of giant extrasolar planets				
12. Detect giant planets by direct imaging, and study their properties			X*	X*
13., 14., 15., 16. Not major JWST impact				

* Identified as a MIRI key investigation by the Origins Subcommittee

** JWST SWG has found MIRI has an important role

Additional investigations have been discussed in this document, such as:

- Under 8., evolution of protoplanetary dust and gas disks into planetary systems, we have shown how R=3000 spectroscopy with the MIRI can detect molecular hydrogen, and study the mineralogy in disks, and how R = 100 spectroscopy can identify the major constituents of disks.
- Under 11., chemical and physical properties of giant extrasolar planets, R=100 spectroscopy can help determine the properties of giant planet atmospheres and imaging at 24 microns is needed to constrain their thermal balance and, through models, their mass.

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