Mid-infrared molecular absorption in the atmospheres of K giants

Scientific Category:	Stellar Physics and Stellar Types
Scientific Keywords:	Late-Type Stars, Stellar Atmospheres
Instruments:	MIRI
Proposal Size:	SMALL
Exclusive Access Period:	12 months
Allocation Information (in hours):	
Science Time:	0.4
Charged Time:	5.3

Abstract

We will observe four K giants with the Medium-Resolution Spectrometer (MRS) on JWST in order to solve an enduring problem in stellar astrophysics. Stellar models consistently underpredict the strength of molecular absorption bands observed in the mid-infrared, including the CO fundamental at 5 um, the SiO fundamental at 8 um, and the OH bands from 14 to 18 um. This discrepancy impacts infrared photometric calibration and astrophysical fields well beyond stellar atmospheres, from stellar population models in galaxies to the cosmic distance ladder. Our MRS observations will resolve the line structure in the mid-infrared absorption bands with better spectral resolution and sensitivity than ever before possible. The resulting spectra will reveal the temperature and other physical properties of the absorbing molecular layer as a function of wavelength. With these measurements, we can build a better generation of more accurate models of late-type stellar atmospheres.

Target Summary:

Target	RA	Dec
HR6348	17 01 16.9261	+60 38 55.52
HR7341	19 18 37.8722	+49 34 10.04
HD166780	18 08 38.8451	+57 58 46.86
HD173511	18 41 40.5913	+61 32 47.09

Observing Summary:

Target	Observing Template	Flags	Allocation *
HR6348	MIRI Medium Resolution Spectroscopy		428 / 4,015
HR7341	MIRI Medium Resolution Spectroscopy		360 / 5,070
HD166780	MIRI Medium Resolution Spectroscopy		308 / 5,009
HD173511	MIRI Medium Resolution Spectroscopy		428 / 5,149

* Science duration / charged duration (sec)

Total Prime Science Time in Hours: 0.4

Total Charged Time in Hours: 5.3

Observing Description

The sample consists of 4 K giants, all close to the northern CVZ. Each star will be observed with the MRS, utilizing a self TA and in all three MRS grating settings. All TAs will use the neutral density filter. The observations consist of one or two short integrations with 5-8 groups in four dither positions in each grating setting.

This program does not have any special requirements, and it does not use simultaneous imaging.

Investigators:

Investigators and Team Expertise are included in this preview for your team to review. These will not appear in the version of the proposal given to the TAC, to allow for a dual anonymous review.

	Investigator	Institution	Country
*	B Aringer	Universita degli Studi di Padova	ITA
!	J Cami	The University of Western Ontario	CAN
*	M Garcia Marin	European Space Agency	ESP
	K Gordon	Space Telescope Science Institute	USA/MD
	K Kraemer	Boston College	USA/MA
	G Sloan	Space Telescope Science Institute	USA/MD

Number of investigators: 6
* ESA investigators: 2
! CSA investigators: 1

Team Expertise:

The PI (Sloan) is an infrared spectroscopist with decades of experience from ground-based and airborne observatories and infrared space telescopes. The team includes expertise in infrared stellar spectroscopy (Sloan, Kraemer), modeling stellar atmospheres (Aringer), molecular spectroscopy (Cami), and MIRI itself (Garcia Marin, Gordon, Sloan).

Scientific Justification

Observations of four K giants with the Medium Resolution Spectrometer (MRS) on MIRI will address an enduring unsolved problem in infrared astronomy. Theoretical spectra of K giants consistently underpredict the strength of the molecular bands in the mid-infrared. Spectra from the MRS will resolve the line structure within the bands. Fitting synthetic spectra to the observed data will determine the temperature and other physical conditions of the absorbing molecules, which will provide the constraints needed to correct the models.

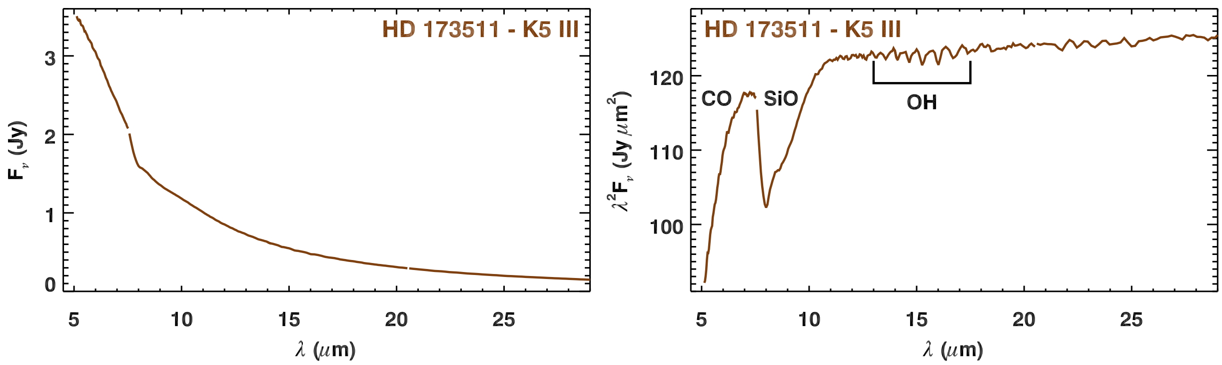

Figure 1: Two views of the *Spitzer*/IRS spectrum of the late K giant HD 173511, with flux density plotted in F_ν units (*left*) and Rayleigh-Jeans units ($\lambda^2 F_\nu$, *right*). The right-hand panel shows more clearly the strong absorption bands from CO at 5 μm and SiO at 8 μm and the weaker bands from OH.

Background

For decades, K giants have served as calibrators for infrared spectroscopy. They are stable, bright, and plentiful in the infrared sky, making them a common choice, but they present significant challenges. Infrared space telescopes orbit above the Earth's atmosphere, so that their photometric calibration simplifies to the following equation:

$$S_{true} = S_{obs} \frac{C_{true}}{C_{obs}}, \tag{1}$$

where S is the science target, C is the calibration standard, the subscript "true" refers to the true values after calibration, and the subscript "obs" refers to the values as observed. For spectra, all of the above quantities are vectors. The devil lies in the details of the term C_{true}, the assumed true spectrum of the calibration standard. Any errors in this spectrum will propagate into the entire database of spectra calibrated with that standard, and that has happened on multiple occasions.

The original plan to calibrate the photometric and spectral data from the *Infrared Astronomical Satellite* (*IRAS*) was to use the standard of all standards, α Lyr (A0 V), but *IRAS* revealed that the star had a debris disk which gave it a significant excess past the 12 μm filter [1]. Consequently, K giants were pressed into duty to calibrate the atlas of 7.7–23 μm spectra from the

Low-Resolution Spectrometer (LRS) on *IRAS* [2]. The assumption that K giants could be modeled with a simple Rayleigh-Jeans tail proved to be incorrect, and it introduced an emission artifact with a peak strength of ∼15% at 8 μm that stretched past 10 μm [3].

Fig. 1 shows the spectrum of a typical K giant observed with the Infrared Spectrograph (IRS) on the *Spitzer Space Telescope*. These spectra are much more than just Rayleigh-Jeans tails and have multiple molecular absorption bands. To use them as standard stars, one must account for those bands. Fig. 1 also introduces Rayleigh-Jeans units ($\lambda^2 F_\nu$). When plotted in these units, a Rayleigh-Jeans tail will appear as a horizontal line, and the absorption bands will stand out much more clearly.

The question of how to use K giants to calibrate infrared spectral databases came up again with the launch of the *Infrared Space Observatory* (*ISO*) in 1996. The K giant γ Dra (K5 III) was the primary standard for the Short-Wavelength Spectrometer (SWS), which covered the 2.4–45.2 μm wavelength range [4]. The decision to base the truth spectrum of this star on synthetic spectra derived from atmospheric models led to artifacts in the SWS database [5]. They appeared at the positions of the fundamental bands from CO at 5 μm and SiO at 8 μm because the synthetic spectra underpredicted the strength of those bands. Interestingly, the synthetic spectra fitted the overtone CO band at 2.4 μm remarkably well in the spectra of several K giants [6]. The issues with the synthetic spectra are confined to longer wavelengths and do not appear in the near-infrared.

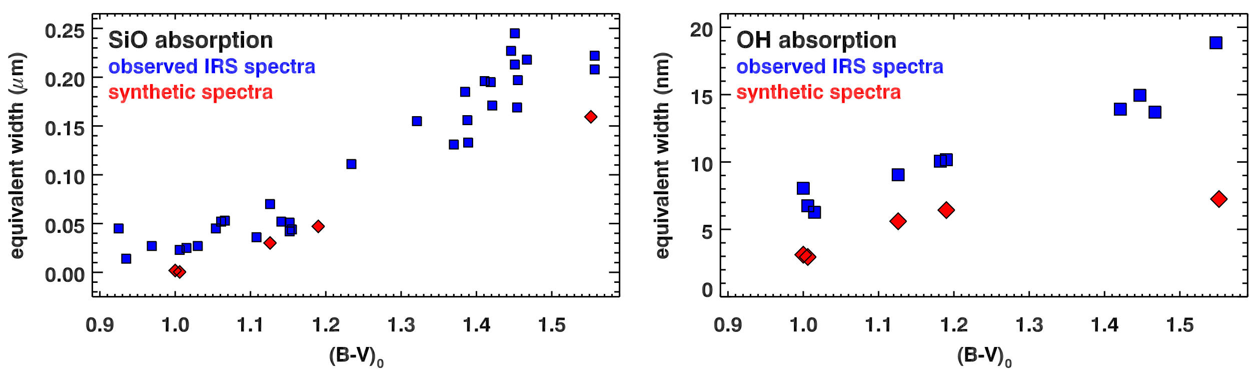

Figure 2: The equivalent width of the SiO fundamental (*left*) and the sum of the equivalent widths of the four strongest OH bands (at 14.7, 15.3, 16.0, and 16.7 μm, *right*). The K giants observed by the IRS on *Spitzer* are plotted in blue, and the synthetic spectra are plotted in red. (Data from [7].)

The IRS on *Spitzer* observed a sample of over 30 K giants and revealed that the synthetic spectra consistently underpredicted the strength of the SiO band at 8 μm and the weaker OH bands at ∼14–18 μm [7]. Fig. 2 illustrates the discrepancies, which are greater in the OH bands than in the SiO band, suggesting that the problem grows worse at longer wavelengths.

One of the enduring challenges in infrared spectroscopy is determining why synthetic spectra based on atmospheric models do not accurately predict the strengths of absorption bands from CO, SiO, and OH at 5, 8, and ∼14–18 μm, respectively.

While it was a focus on calibration that uncovered the limitations of atmospheric models of K giants, the problem has far-reaching consequences. Red giants dominate the emission from entire galaxies in the infrared [e.g., 8, 9], and we need to model their contribution to the total spectrum accurately to isolate other populations of interest. Underestimating the absorption bands at 5 and 8 μm will lead to underestimates of the emergent emission in the near-infrared. These errors will affect the calibration of standard candles in the near-infrared like the tip of the red giant branch [e.g., 10, 11] and the period-luminosity relation for Mira variables [e.g., 12, 13]. Both methods offer near-infrared alternatives to using Cepheids to calibrate Type Ia supernovae. JWST will be a powerful infrared telescope, and it will make these infrared methods increasingly important. If we don't understand the atmospheres of red giants, we're only adding to the error budgets as we address fundamental questions in cosmology like the tension between values for the Hubble constant determined in the local Universe and from the cosmic microwave background [e.g. 14, 15, 11].

The MRS on MIRI offers a solution. It will produce spectra with a spectral resolving power of ~2000–3000 ($R \equiv \lambda/\Delta\lambda$), which will resolve the line structure within the CO, SiO and OH bands.

The wavelength dependence of the differences between synthetic and observed spectra suggest that the H^- ion may be involved [16, 17, 7]. This ion was first proposed as a continuous opacity source in stellar atmospheres in 1939 [18]. Its opacity increases steadily with increasing wavelength, and its impact on the infrared continuum from late-type stars can be modeled analytically by making the effective temperature (T_{eff}) a function of wavelength [19]. As the wavelength increases, the H^- ion pushes the stellar photosphere (as defined by an optical depth of 1) higher into the atmosphere. The molecular absorbing layer must be above the photosphere, and it must move outward with increasing wavelength as the photosphere does.

Stellar atmospheric models account for the presence of H^- [e.g., 17, 20], but something must be happening that they do not account for. One hypothesis is that at greater distances from the star, departures from the local thermodynamic equilibrium (LTE) affect the accuracy of the models [e.g., 21, 22]. Other possibilities to consider are turbulence and clouds.

Approach

Our objective is to find out what is happening in the molecular absorbing layer around K giants by using the MRS to resolve the line structure in the bands and using those lines to measure the temperature and other physical conditions of the gas. Our targets are four K giants that were used as standard stars by the IRS on *Spitzer*. They were observed dozens of times and are well measured (at much lower resolution) and well vetted for any surprises [7]. They span the range of K giants, with spectral classes of K0, K1, K4, and K5 III.

The traditional approach to fitting models to stars has been to start with the star, use the ancillary data to determine its basic properties: T_{eff}, surface gravity, and luminosity, and fit models consistent with these values. We will reverse this process and determine the temperature and

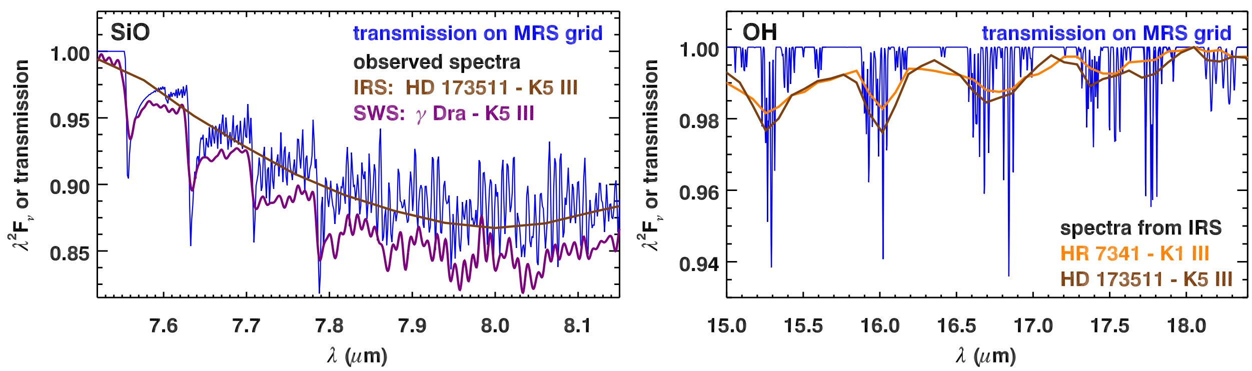

Figure 3: Transmission spectra of SiO (*left*) and OH (*right*) from synthetic spectra from an atmospheric model with T_{eff} = 3800 K. The transmission data are on the wavelength grid and resolution of the MRS. In the SiO panel, the resolving powers of the three instruments at 8 μm are: IRS $\sim$100, SWS $\sim$700, MRS $\sim$3000.

pressure that best fits the spectrum, treating each wavelength region separately.

We will analyze the spectra from the MRS using synthetic spectra from models of stellar atmospheres. Our models are based on MARCS models, which are designed for late-type stars [26, 27], supplemented with code to address molecular opacity and utilize lines lists such as HITRAN 2008 [28]. We will adjust the parameters in the models by fitting the synthetic spectra to the observed spectra and explore the dependencies in parameter space. Fig. 3 illustrates what the models can produce. It also demonstrates the power of the MRS to resolve the detailed line structure within the bands. As a check, we will also generate synthetic spectra independently of the atmospheric models by considering test volumes of gas at adjustable temperatures and pressures. This second approach may be particularly important when non-LTE conditions prevail.

Because the MRS spectra resolve so much structure in the bands, many tests become possible. As one example, we can measure turbulence because it affects strong lines more than weak ones. The strong lines are saturated, and the greater spread in Doppler shifts within the line allows their equivalent widths to increase in more turbulent environments. The equivalent widths of the weak lines won't change; they just get spread out. Temperature has the opposite effect. Lowering the temperature will strengthen the weak lines, but the strong lines are already saturated. As another example, resolving the lines enables accurate measurements of isotopic ratios by disentangling contributions from ^{12}CO and ^{13}CO at 5 μm, or Si^{16}O and Si^{18}O at 8 μm. These ratios will help us estimate the initial metallicity of the star, which will in turn better constrain our modeling efforts.

The H^{-} ion and its increasing opacity with wavelength mean that by looking at molecular absorption at different wavelengths, we can sample different altitudes in the stellar atmosphere. The wavelength coverage of the MRS will allow us to build an observational radial profile, which we can then compare to the models to identify where they work, and where they don't.

With this knowledge, we can then improve the models and finally correct a problem that has remained unsolved for too long.

■ Technical Justification

Sample

K giants in sample

Target	RA	Dec.	Spectral class	F_{22} (mJy)	groups ×integrations for grating setting A	B	C
HR 6348	255.320525	+60.648756	K0 III	235	6×2	6×2	7×2
HR 7341	289.657801	+49.569456	K1 III	293	5×2	5×2	6×2
HD 166780	272.161855	+57.979683	K4 III	237	6×2	7×1	8×1
HD 173511	280.419130	+61.546414	K5 III	247	6×2	6×2	7×2

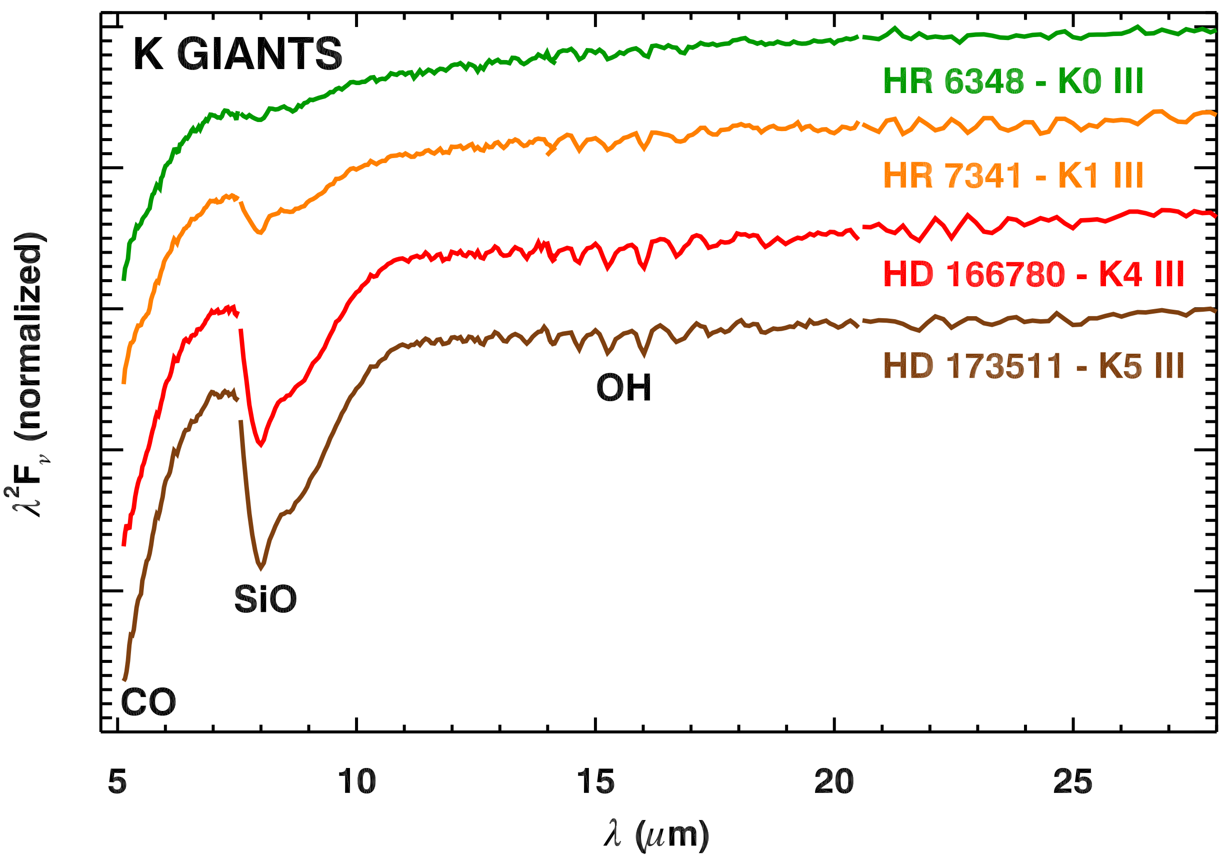

Figure 4: Spectra of the four targets in the sample from the IRS on *Spitzer*. The spectra are in Rayleigh-Jeans units, normalized, and shifted for clarity. Each small increment on the vertical axis is 1% of the continuum, so the SiO absorption band in HD 173511 is ∼12% deep at the minimum.

The table and figure on the preceding page present the targets in the sample and their low-resolution spectra from *Spitzer*, which are based on dozens of individual pointings (between 41 and 132 per target [7]). The flux density at 22 μm is from the red peak-up array on the IRS. In the spectra, the structure in the segment from 14 to 21 μm is real and from the OH band, but the structure past 21 μm is an artifact from residual fringing. (Plotting spectra of stars in Rayleigh-Jeans units in the mid-infrared hides no sins!)

The sample spans the full range of T_{eff} for K giants, from 4400 K for K0 III to 3800 K for K5 III. If the physical conditions of the molecular absorbing layers are well behaved, then this sample will give us a sequence of results for K giants. If not, then we will treat the sample as two pairs, of early and late K giants, and the differences in their properties will be our first assessment of how much how much stars of similar T_{eff} can vary.

Observations

The spectra will be observed in all three grating settings with the MRS in order to build continuous spectra from 4.9 to 28.3 μm. The targets are bright, and to minimize any calibration challenges, we have avoided even partial saturation by setting the integrations to between 5 and 8 groups, depending on the target. The exception is HR 7341, which has two partially saturated pixels in Channel 1A in the shortest advisable integration: 5 groups.

Our sensitivity objective is to achieve a 3-σ detection of OH lines with a 1% contrast with respect to the continuum. That will give us a sufficient number of lines to constrain our models, as can be seen in the OH spectrum in Fig. 3. Assuming that a line will be measured in three adjacent wavelength elements (which gives a $\sqrt{3}$ advantage), the minimum signal/noise ratio (SNR) needs to be 170 out to 18 μm. To reach that limit, we have obtained two integrations per dither position for the majority of the targets and grating settings. The target table provides the specifics.

The SNR depends strongly on wavelength due to the shape of the spectra, which means that the limit at 18 μm gives much higher SNRs at shorter wavelengths. All of the spectra will achieve a point-to-point SNR of 300 or better at wavelengths shorter than 12 μm, which will facilitate detailed analysis of the CO band at 5 μm and the SiO band at 8 μm.

The sensitivity of the MRS drops dramatically in Channel 4. Consequently, we have not considered wavelengths beyond 18 μm for our integration requirements. Some SNR can be recovered at these wavelengths in exchange for spectral resolution by smoothing.

All observations will use the 4-point dither pattern optimized for point sources. In addition to needed redundancy due to the short integrations, these PSFs will provide the best possible sampling of both the point-spread function (PSF) and the line-spread function (due to offsets in the dispersion direction). The spectral sampling will maximize our spectral resolution. Four pointings in each grating setting will also help mitigate for any possible residuals after correcting for fringes.

The sampling of the PSF will give us options to the standard spectral extraction method of the pipeline, if it proves necessary. The pipeline will first rectify the data into a spectral/spatial data cube, from which the spectrum will be extracted. That process involves blending information from adjacent pixels, which will degrade the spectral resolution of the final spectrum. While the loss of resolution is small, we may still wish to recover it. We will develop algorithms to extract directly from the two-dimensional spectral images. The sampling of the PSF in four fractional pixel positions will enable the development and application of optimal extractions. We will provide our own work on extraction to STScI for distribution to the community.

The science targets will be used for self-target acquisition. Their brightness requires the use of the neutral-density filter. *Spitzer* peak-up images reveal that our target fields are clear of any confusing sources.

Analysis

As described in the Scientific Justification, we will analyze the observed spectra by fitting them with synthetic spectra and adjusting the input parameters to minimize the residual differences. The synthetic spectra will be based on both atmospheric models and simpler test volumes. The wavelength dependence of the H^- opacity means that the physical location of the absorbing molecules is moving outward with increasing wavelength. The absorption bands from the CO fundamental at 5 μm, the SiO fundamental at 8 μm and OH at longer wavelengths all probe different layers in the extended atmosphere. With the MRS, we can use the molecules to build observed profiles of temperature and pressure, which can then be used to better constrain and improve the models.

Our primary interest is the scientific question of why synthetic spectra from model atmospheres lead to underpredictions of the strength of the molecular bands in K giants, but this project also affects calibration in the infrared. Because the spectra of the four targets in this program were used to calibrate the IRS spectral database, any knowledge gained about them can be used to improve the calibration of the IRS and tie it directly to the calibration of JWST.

The absolute photometric calibration program for JWST reflects the past difficulties with K giants by not using them as standards [e.g., 23, 24]. Instead, the calibration will rely on three classes of standards: A dwarfs, solar analogs, and white dwarfs. If difficulties with the models of any one class arise, that class should stand out in a comparison with the other two. Unfortunately, white dwarfs are too faint to be used by the MRS, leaving it with just two classes of standards. In the event that they disagree, the four K giants in this program would serve as a contingency sample to help determine which of the other classes is discrepant.

The need for JWST

Ground-based observatories cannot obtain the spectra needed for this project because of telluric absorption, which eliminates all wavelengths below $\sim$8 μm due to water vapor, the $\sim$9.2–9.8 μm region due to ozone, and the $\sim$14–18 μm region due to CO_2. SOFIA flies above the water vapor, but not the ozone or CO_2. Bright nearby K giants like α Boo and α Tau could be observed at high spectral resolution with EXES (the Echelon-Cross- Echelle Spectrograph), but its resolution is so high, only exceedingly narrow wavelength regions are available in a given pointing. The objective of this project is to resolve the line structure in entire bands across a wide wavelength range in the mid-infrared, and the only instrument and telescope with that capability are the MRS and JWST.

The SiO panel in Fig. 3 includes a spectrum from the SWS on *ISO* of the K giant γ Dra. This spectrum represents the best spectral resolution of a K giant at these wavelengths available in the

SWS Atlas [25], and its resolving power is only ∼700. As Fig. 3 shows, while the spectrum reveals some sub-structure in the bands, the MRS is a dramatic improvement. Our line-matching analysis is not feasible with the existing SWS data at these wavelengths. The resolution of the SWS is better at shorter wavelengths, where this approach has been applied [e.g., 6]. However, as noted above, the problems we are addressing start in the CO band at 5 μm and continue to longer wavelengths, where the SWS has poorer resolution. Fig. 3 does not include SWS data in the OH panel because the spectra at those wavelengths show just noise and no band structure.

The MRS on JWST is the only instrument suited to solve a problem that has dogged infrared spectroscopy for four decades and has consequences well beyond immediate questions of calibration. As JWST shifts the attention of the astronomy community into the infrared, this problem is only going to grow more important.

Special Requirements (if any)

This proposal does not have any special requirements.

Justify Coordinated Parallel Observations (if any)

No coordinated parallel observations are requested.

Justify Duplications (if any)

No observations are duplicated.

Analysis Plan (AR only)

This section is not required for an observing proposal.

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