The Phoenix Spectrograph at Gemini South

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ABSTRACT

Phoenix, a high resolution near-infrared spectrograph build by NOAO, was first used on the Gemini South telescope in December 2001. Previously on the Kitt Peak 2.1 and 4 meter telescopes, Phoenix received a new detector, as well as modified refrigeration, mounting, and handling equipment, prior to being sent to Gemini South. Using a two-pixel slit the resolution is ~75,000, making Phoenix the highest resolution infrared spectrograph available on a 6-10 meter class telescope at the current time. Modifications to and performance of the instrument are discussed. Some results on Magellanic cloud stars, brown dwarf stars, premain-sequence objects, and stellar exotica are reviewed briefly.

Keywords: infrared spectrograph, cryogenic instrumentation, high resolution spectroscopy, infrared array detectors, AGB stars, dwarf stars, T Tauri stars

1. INTRODUCTION

At the 1998 and 2000 SPIE meetings on astronomical instrumentation we described a cryogenic, high-resolution spectrograph (Phoenix) for use in the 1 – 5 μm region.[1,2] Phoenix was designed for the f/15 Cassegrain foci of NOAO telescopes, including the Kitt Peak 2.1 m and 4 m telescopes, the CTIO 4 m, the SOAR 4 m, and the Gemini 8 m telescopes. Our first report[1] was on the design, construction, and first light performance. Our second report[2] concentrated on improvements to the instrument reliability and enhancements to the optical quality. In late 2001 Phoenix was installed on Gemini South. We report here on modifications to Phoenix for use on the 8 m telescope and review some of the science from the first few months of observing.

To briefly summarize the basic features of Phoenix, a Ritchey-Chretien collimator illuminates a 31 line per mm echelle. The collimator optics also serve as the camera. The collimator/camera and grating form a compact assembly that is optimized to fit into a cryostat. The spectrograph is surrounded by fixed temperature and floating temperature radiation shields and is held in a vacuum vessel. Cooling is supplied by a pair of closed cycle refrigerators. No liquid cryogens are used during the cooling phase or normal operation. The detector is an InSb array which is sensitive to wavelengths as long as 5.6 μm, so the instrument must be cooled below liquid nitrogen temperature to eliminate thermal radiation from the instrument. The operating temperature is typically about

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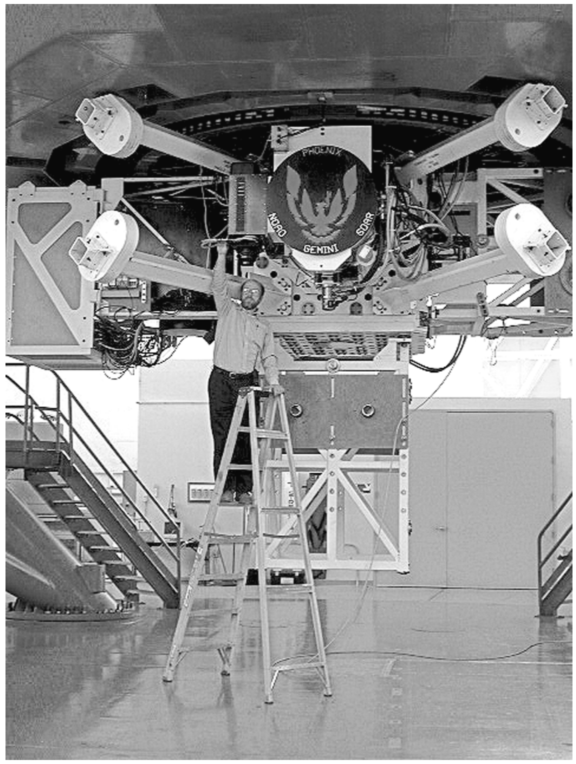

Figure 1. Phoenix mounted on the instrument support structure of Gemini South. K.H.H. is standing on the ladder under the instrument. Below his shoulder level is a standard Gemini instrument mounting frame for another instrument in the uplooking port. To his left, occupying a side looking port, is GCAL, the Gemini calibration unit. The end of the Phoenix dewar is prominent (behind the logo) with one cold head visible below the dewar. The four 'legs' are the balance weights required to match the weight and moment to the Gemini instrument specifications.

55 K. The instrument has seven operable mechanisms all of which are driven by externally mounted motors. Along with these motors, the motor controller, array electronics, and the cryogenic refrigerators are mounted to the outside of the cryostat.

In the following Section we discuss the modifications to Phoenix for use on Gemini South. In Section 3 the performance on the 8 m Gemini telescope is reviewed. A few scientific applications are reviewed in Sections 4 and 5.

2. INSTRUMENT MODIFICATIONS

In order to use Phoenix on the Gemini telescopes it was necessary to make a number of relatively minor alterations. The most significant of these had to do with the instrument to telescope coupling. The axial dimension of the coupling had to be shortened since the Gemini telescope focus is closer to the instrument mounting surface than was the case at Kitt Peak. A new coupling was fabricated. Two lamps (hollow cathode and flat field) had been mounted in the Kitt Peak coupling. The hollow cathode lamp was remounted in the new coupling. The flat field lamp was removed in favor of the flat field system provided at the telescope. A remotely operated window cover also was installed.

Phoenix is mounted at the Gemini telescope with the window facing to the side. At Kitt Peak the window looked up. It was necessary to design hardware for holding and moving the instrument on its side and for installing the instrument on the telescope. Counter weights had to be designed to bring the instrument mass and moment into the Gemini specifications.

A limited set of instrument improvements was also undertaken. Modifications were made to the refrigeration system and the detector was upgraded from an Aladdin I to an Aladdin II InSb array. A number of small modifications were made to the electronics and software. The refrigeration system, which consists of two closed cycle coolers mounted on opposite sides of the dewar, had been the main cause of instrument down time at Kitt Peak. Through experience at Kitt Peak backed up by laboratory tests, we discovered that the cold heads are dependent on the temperature of the input helium gas. If the helium temperature drops below a critical value, which depends on the cold-head design and materials, the sealing gasket will not remain flexible, allowing gas to pass through the expansion cylinder without removing heat. For the Leybold model 5/100-2 cold heads used in Phoenix we found that the input gas temperature must be at least 10 C. At the 8 m telescope the helium is delivered through long lines with the compressor hundreds of meters away from the cold heads. These lines run through cold areas of the dome and the temperature of the delivered helium can be below 10 C. To preheat the helium for the cold heads we installed a slightly customized Watlow circulation heater (part number CBLNA17G3). The thermostat is set to maintain 10 C helium.

The upgrade to an Aladdin II InSb array was a straight forward replacement of the chip. The pixels in the Aladdin I chip had large, pixel-to-pixel variable dark current. This resulted in much poorer signal-to-noise on long exposures than expected. The Aladdin II array has both low read noise, 40 e^-, and low dark current, 0.15 e^- s^{-1}. There are few hot pixels. The signal-to-noise ratio as a function of integration time and magnitude with the Aladdin II array is predictable with standard expressions. Fowler sampling typically reduces the read noise to 15 e^- for long exposures.

Among the electronic modifications, a heater servo-system was added to keep the instrument temperature above the equilibrium value for the refrigerators. The natural equilibrium temperature had two problems. First, it was not a constant temperature over a long period but depended among other input on the dewar shell temperature. This resulted in optical focus changes. Second, the equilibrium temperature was near the point where the light sensitive diodes, used as position sensors, cease functioning. We have selected to stabilize the temperature in the mid-50 K range. A number of switches were also installed which are remotely operable under computer control. This allows control of cold heads, main instrument power, etc. without the need to go to the dome.

3. INSTRUMENT PERFORMANCE

In December 2001 a week of telescope time was devoted to integration and testing Phoenix on the 8 m telescope. A considerable fraction of the time was used for tasks such as alignment of the instrument and pupil, tracking and acquisition of sources, and rotation of the instrument to desired slit angles. Phoenix is normally mounted with the slit E-W. The instrument support structure on Gemini (ISS) rotates to keep the slit position on the sky fixed E-W. Rotation to other slit position angles is possible but tests showed that this can not be done quickly due to the fact that Phoenix is mounted slightly off axis. Instrument related tests were concerned with the spectral resolution, flexure, and signal-to-noise performance. Flat fields generated by the Gemini Calibration Unit (GCAL) were tested and found to be uniformly illuminated and, although brighter than our previous flat fields, the exposure times are acceptable.

As described by Hinkle et al. (2000),[2] the maximum resolution achievable with Phoenix is ~75000, with the two pixel wide slit. The resolution is determined from the full width at half maximum of hollow cathode emission lines. The limiting factor in the resolution is a small amount of astigmatism in the collimator/camera optics. Astigmatism is a feature of the off-axis, centrally obstructed collimator/camera design. With the two pixel slit small (a few percent) changes in the resolution can be found as a function of position along the slit as a result of field curvature. The most frequently used slit width at Gemini is the four pixel (0.35") slit. The resolution with this slit is 50000. The delivered image quality at Gemini South during the 2001–2002 Phoenix runs averaged about 0.4 arcsecond and was an excellent match to the four pixel wide slit.

A large number of tests were performed to look for mechanical flexures. Phoenix was designed to be used at the Cassegrain focus of a equatorial telescope. On Gemini Phoenix is mounted on a side looking port (Figure 1) of an alt-azimuth telescope. Since the slit position angle on the sky is fixed, the instrument can be at any orientation relative to gravity during the night. The orientation relative to the gravity vector is not known to

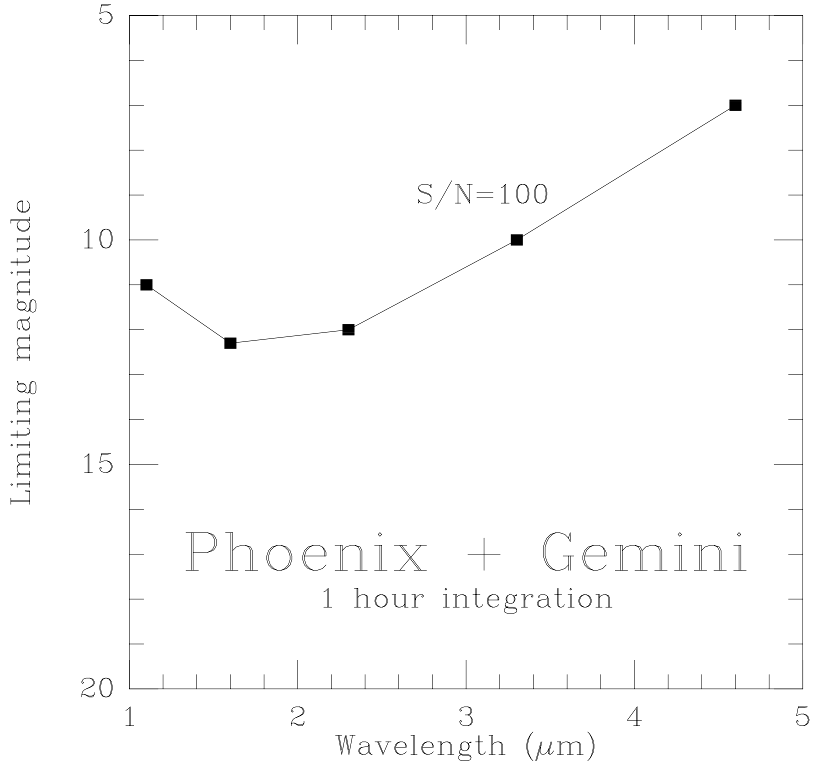

Figure 2. Approximate limiting magnitudes for signal-to-noise ratio 100 in a 1 hour integration for Phoenix on Gemini South. The values are based on sample spectra taken under good observing conditions at resolution 50000. This figure omits degradations to the signal-to-noise ratio due to blaze efficiency, seeing, cosmic rays, bad pixels, etc. In the thermal infrared the maximum exposure time for a single integration will be much less than 1 hour due to the contribution from the thermal background radiation. For instance, at 4.6 μm the maximum integration time for an individual exposure is about 2 minutes.

the observer. The cryogenic section of the instrument is supported in the dewar by a fiberglass ring. This ring was not specified for all the instrument orientations experienced on the Gemini telescope. Flexure of the slit plane relative to the Gemini guide probes was observed. However, flexure is also seen relative to the Phoenix on-axis acquisition TV. It seems likely that the observed flexure is not in the mounting ring but takes place in the foreoptics assembly. For most positions of the instrument the flexure is a few tenths of an arcsecond per hour. The operational fix has been to use Phoenix in imaging mode to peak up the star in the slit before each exposure. This typically works well for the longest exposures taken with Phoenix at Gemini ($\sim$30 minutes).

A number of test spectra were taken over the entire 1 to 5 μm range of the instrument to gauge performance. In the non-thermal near-infrared infrared, i.e. at λ <2.5 μm, sources brighter than 10^{th} magnitude were trivial to observe, yielding high signal-to-noise spectra in integration times of minutes. In the range brighter than 12^{th} magnitude good results were possible with total integration times of up to 1 hour. Observation of objects fainter than 12^{th} magnitude became challenging. Part of the difficulty with objects this faint is that best results come from long integration times and over long integration times some motion of the source in the slit is likely. We also confirmed that the efficiency of the spectrograph degrades near 1 μm, presumably as a result of the visual/infrared dichroic and/or the antireflection coatings on the foreoptics lenses.

The performance in the thermal infrared is much harder to characterize than in the near infrared. Individual spectral images in the thermal infrared are dominated by telluric lines in emission. A continuous thermal contribution is also present. By differencing multiple exposures along the slit it is possible to cancel this emission in individual extracted spectra, but the noise contribution from both the telluric line emission and the thermal background emission remains. To date the only part of the thermal infrared observed extensively with Phoenix at Gemini South has been the 4.6 – 4.9 μm region. In this wavelength interval observations of sources fainter than about M=7 become difficult. However, the thermal infrared is very sensitive to conditions. It is possible that Phoenix will perform significantly better in cold winter conditions. We also look forward to improved performance when the Gemini South mirrors have coatings matching specifications.

The overall performance of Phoenix as a function of wavelength is shown in Figure 2.

4. GEMINI DEMONSTRATION SCIENCE

The Gemini Observatory undertook a competition for a "demonstration science project" with Phoenix. This project was intended both to demonstrate the capabilities of Phoenix on Gemini South and to verify the system performance by executing a specific scientific program. An other aspect of the project is that it provided a sample data base on objects that were challenging to observe with Gemini. Enough telescope time was provided (about one week) so that a large body of data could be collected. The project was also designed to have collaborators in all the Gemini member countries. The proposal selected was "Determining the O/Fe ratio in the Large Magellanic Cloud." These data are now available on the Gemini web site.

Smith et al (2002)[3] discuss the principal scientific results of the demonstration science project. High-resolution infrared spectra ($\lambda/\Delta\lambda$= 50,000) were obtained for twelve red-giant members of the Large Magellanic Cloud (LMC). Two wavelength regions, at 15540Å and 23400Å, were observed. Sample spectra are shown in Figure 3. The program stars were early M giants in the K magnitude range 10.8 to 12.6, although one supergiant with K=8.5 was observed. The integration times per star per wavelength region were on the order of 1 hour.

Quantitative chemical abundances of carbon (both ^{12}C and ^{13}C), nitrogen, and oxygen were derived from molecular lines of CO, CN, and OH, while sodium, scandium, titanium, and iron abundances were obtained from neutral atomic lines. The twelve LMC red giants span a metallicity range from [Fe/H]= -1.1 to -0.3. It is found that values for both [Na/Fe] and [Ti/Fe] in the LMC giants fall below their corresponding Galactic values at the same [Fe/H] abundances by about $\sim$ 0.1 to 0.5 dex. This effect is similar to abundance patterns found in the few dwarf spheroidal galaxies with published abundances. The program red giants all show evidence of first dredge-up mixing of material exposed to the CN-cycle, i.e. low ^{12}C/^{13}C ratios, and lower ^{12}C-abundances with higher ^{14}N-abundances. The carbon and nitrogen trends are similar to what is observed in samples of Galactic red giants, although the LMC red giants seem to show smaller ^{12}C/^{13}C ratios for a given stellar mass. This relatively small difference in the carbon isotope ratios between LMC and Galactic red giants could be due to increased extra mixing in stars of lower metallicity. Comparisons of the oxygen to iron ratios in the LMC and the Galaxy indicate that the trend of [O/Fe] versus [Fe/H] in the LMC falls about 0.2 dex below the Galactic trend. Such an offset can be modeled as due to an overall lower rate of supernovae per unit mass in the LMC relative to the Galaxy, as well as a slightly lower ratio of supernovae of type II to supernovae of type Ia.

5. FIRST SEMESTER SCIENCE

We briefly discuss four projects below that were undertaken in 2002A (February – June 2002), the first semester Phoenix projects were scheduled on Gemini South. Three of these projects demonstrate the performance of Phoenix in three widely separated wavelength regions, 1.08 μm, 2.31 μm, and 4.6 μm. The fourth project discusses capabilities for observations of bright objects.

5.1. He I 10830 Å in Metal Poor Giants

The He I line at 10830 Å falls at the extreme limit of CCD performance but is sufficiently near the visible that many IR instruments also omit this wavelength region. Formation of the He I 10830 Å line requires temperatures $\sim$20000 K so the line is a probe of stellar chromospheres and high temperature flows. He I 10830 Å acts as a probe of stellar atmospheric regions that are otherwise mainly accessible from the ultraviolet.

While the throughput of Phoenix is not optimal at 10830 Å, the spectrograph still performs well at this wavelength. As part of a project started at Kitt Peak, we obtained spectra of a few metal poor giants at 10830 Å. Metal poor stars present an astrophysical quandary because the evolution of stars with mass several times

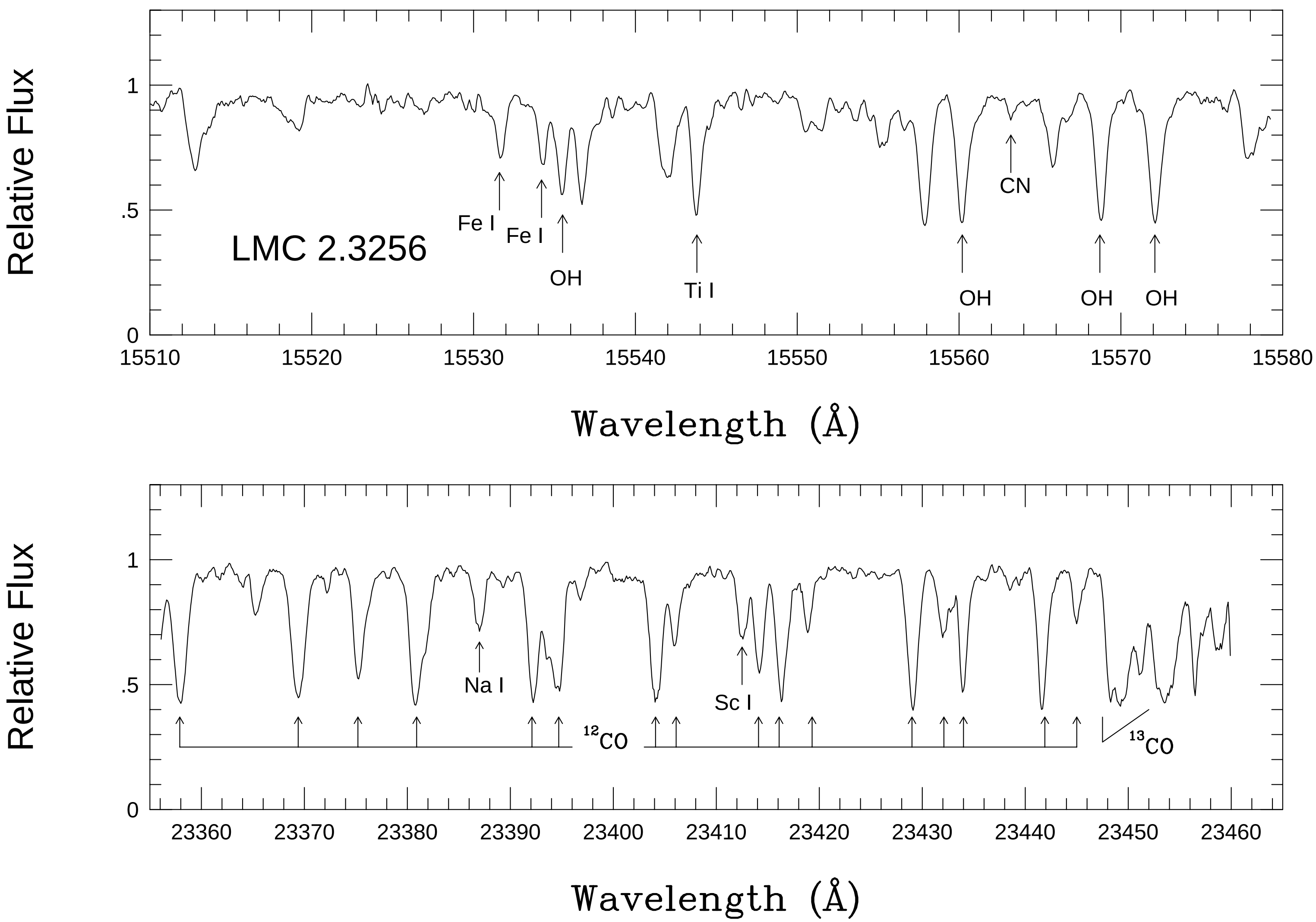

Figure 3. Sample spectra for the LMC red giant 2.3256 (K=12.0; see Smith et al.[3]) showing two different wavelength regions. Some stronger lines are identified. Each spectrum consists of a combination of three 30 minute integrations and the signal-to-noise in each spectrum is a bit more than 100.

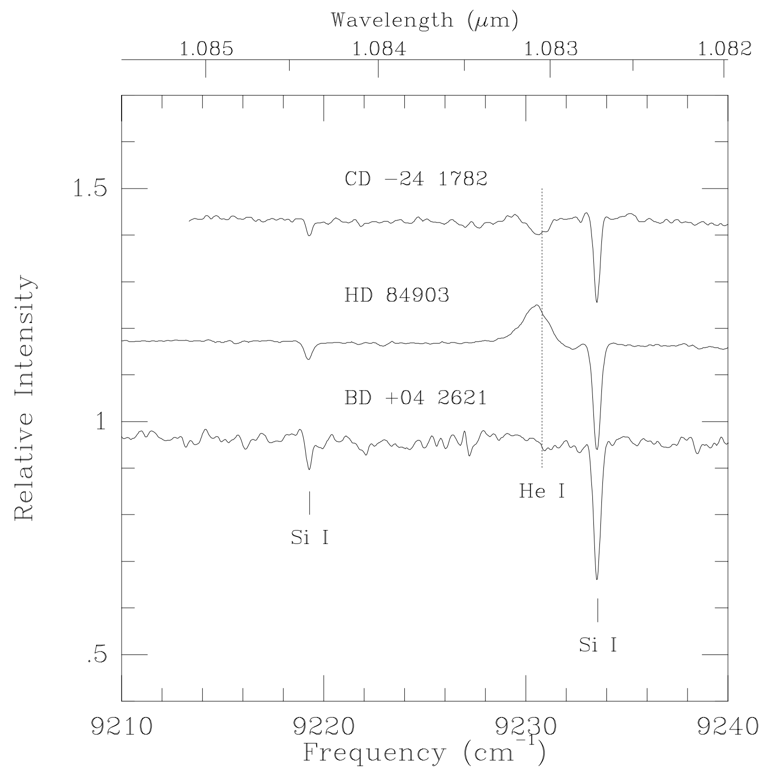

Figure 4. Spectra of three metal poor giant stars ([Fe/H]∼-2.5) at the He I 10830 Å line.

that of the sun into white dwarfs demands substantial mass loss. Mass loss is required as well to reconcile observed colors of evolved cluster stars with theory. However, there is meager direct evidence for mass loss from metal poor stars. He I 10830 Å would allow the detection of a hot wind.

The spectra obtained (Figure 4) show that there is activity detectable in He I in metal poor stars. However, there is no evidence for He I near the escape velocity of these stars. The He I emission and absorption in these spectra can be attributed to chromospheric activity rather than mass loss. Similar He I 10830 Å line profiles have been seen in field G and K giants.[4]

5.2. 2.3 μm Spectra of L dwarfs

An observing program undertake by coauthors Hinkle and Valenti in collaboration with P. Bernath (Univ. of Waterloo) focused on the atmospheric chemistry of very cool dwarfs. With the Aladdin I detector spectroscopy of the coolest M dwarfs had been a challenge at Kitt Peak.[5] With the Aladdin II detector and the collecting power of Gemini South, the cool, faint, very late M dwarfs proved easy targets. A reasonable sample of L-dwarfs can be observed with Phoenix on Gemini South. A sample of spectra spanning the L dwarf temperature range are plotted in Figure 5. The region illustrated proved to be dominated by CO first overtone lines. Note the CO lines are strong through the entire L dwarf sequence, although they seem to weaken in the mid-L temperature range. Water is also a major contributor to the spectrum. A surprising aspect of the spectra is the relative sharpness of the lines. The broadest CO lines correspond to rotational broadening of at most 44 km s^{-1}. The L dwarfs are believed to be young objects and the naive expectation was to observe many spectra with highly rotationally broadened lines.

5.3. 4.6 μm Spectroscopy of Premain Sequence Stars

The thermal near-infrared provides access to a wealth of fundamental carbon monoxide (CO) lines. In emission, these lines are an excellent diagnostic of low density, relatively cool (300 − 1000 K) gas, and because they

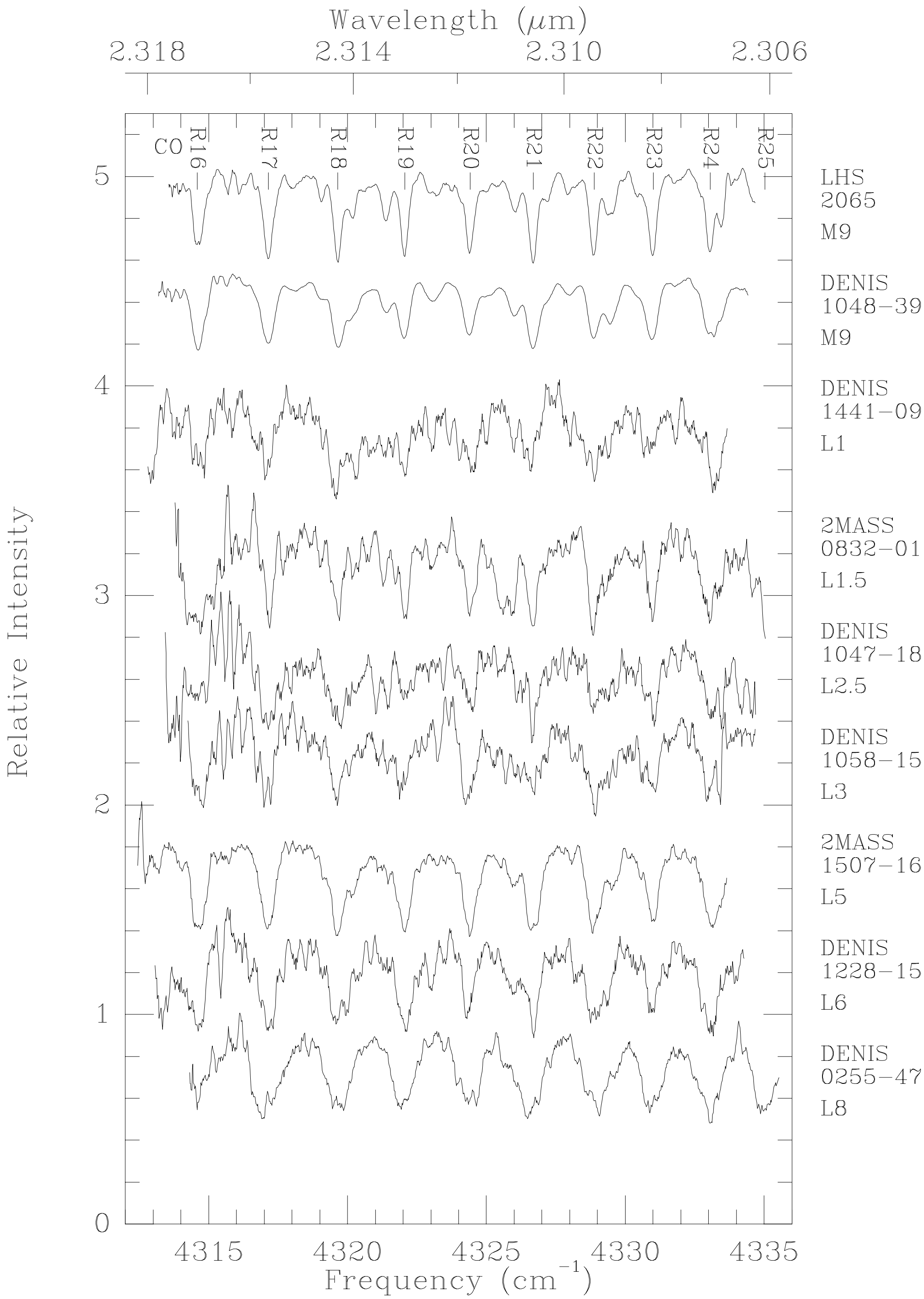

Figure 5. Spectra of a selection of very late M and L dwarfs spanning the L dwarf temperature range to L8.

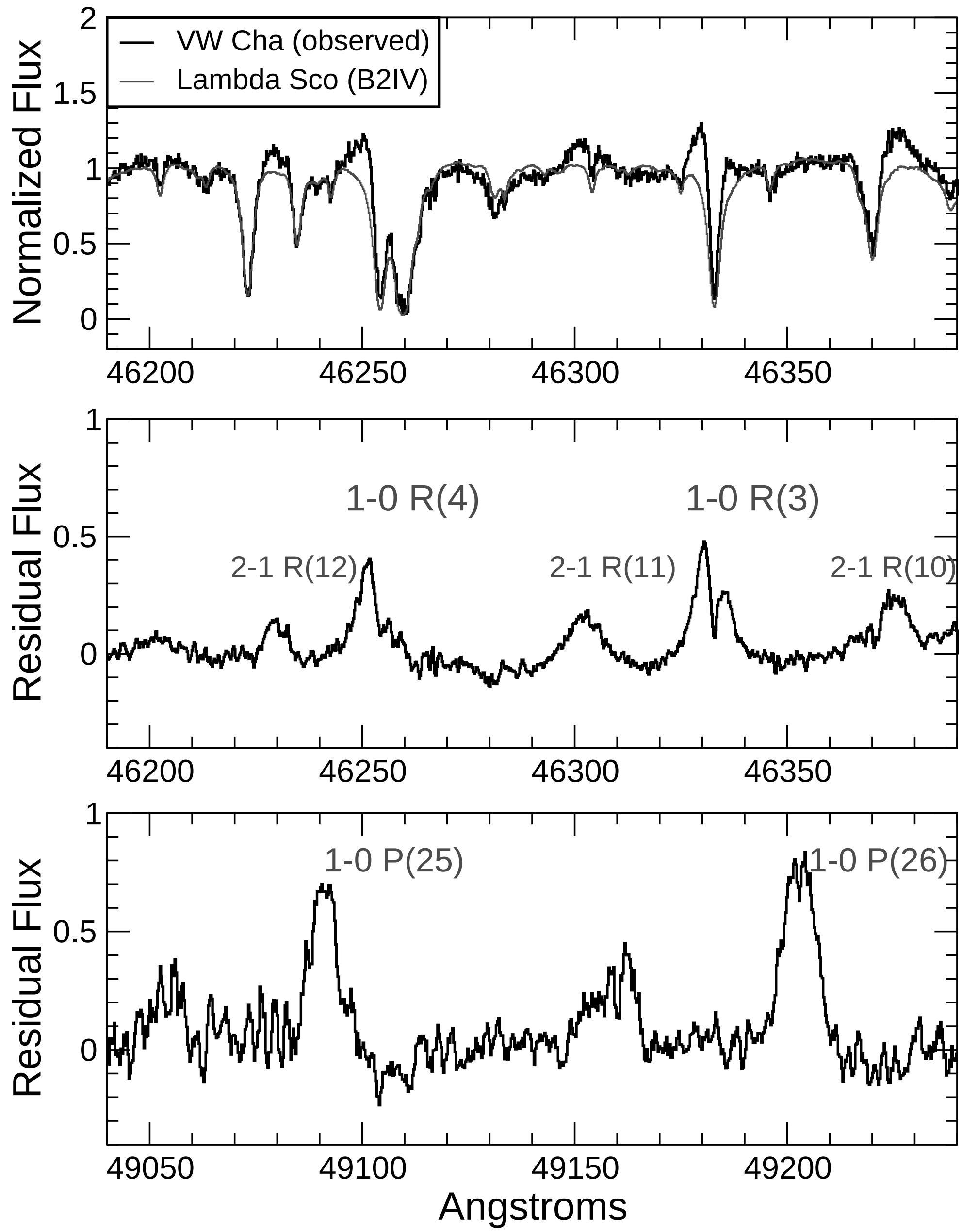

Figure 6. T Tauri star VW Cha observed 2002 Feb 10 and Feb 11 with Phoenix on Gemini-South. Top panel: Observed 4.6 μm spectrum with telluric standard overlaid (thin line); Middle: Residual spectrum after telluric subtraction; Bottom: Residual spectrum at 4.9 μm. Prominent CO lines are labeled. Exposure time was 48 minutes at 4.6 μm and 28 minutes at 4.9 μm.

originate in fundamental transitions (i.e., between adjacent levels) they can reveal the presence of even small amounts of this gas. This temperature regime probes the inner 1 – 5 AU of circumstellar disks around low and intermediate mass pre-main sequence stars, where planet formation is thought to take place. Planet formation theory suggests that accretion by large planets will leave essentially cleared annuli, or "disk gaps", that might harbor small quantities of low density gas such as CO. Therefore, analysis of fundamental CO emission in young stars provides an exciting new tool to investigate this largely unexplored environment.[6] However, pre-main sequence circumstellar environments are incredibly complex and dynamic places, and one of the challenges is to sort out contributions from a variety of sub-environments including an accretion flow, stellar and disk winds, and a disk atmosphere, as well as structure within the disk itself. High-resolution spectroscopy is needed to properly constrain the temperature, surface density and kinematics of the emitting gas in order to distinguish between these various physical regimes.

Co-author Rodgers, in collaboration with J. Najita and J. Carr are extending a program begun by Najita and Carr[7] to detect and model CO fundamental emission in young stars. During the 2002A semester, several low mass pre-main sequence stars were observed as part of two Gemini South queue programs. Fundamental CO emission was detected for the first time in at least 5 systems, one of which is the active T Tauri star VW Cha (Figure 6). At these wavelengths, care must be taken to remove the atmospheric water and CO absorption features from the observed spectrum (top panel). Once this is done, a number of fundamental CO emission lines are revealed within just two grating positions (middle and bottom panels). Line ratios and fluxes from several different transitions are essential to determining the temperature and surface density, which in turn give us an estimate of the total volume of gas present. The lines are clearly resolved, providing kinematic information that, when interpreted as Keplerian orbital velocities, translate directly into the radial distribution of the gas.

5.4. Extended Spectral Coverage of Bright Objects

For bright stars, the integration times are very short. We have observed a few stars over an extended spectral region by moving the telescope between the program star and a nearby hot reference star. After taking a flat field observation using GCAL, the grating angle is changed and the cycle repeated. While each step of the observation cycle goes rapidly, this mode of observing is an inefficient use of telescope time. For an integration time of a few seconds, many minutes are used moving the star and locking up the guide probes, centering the star on the slit, and obtaining the required flats at each grating position. However, this observing mode does allow extended spectral coverage on objects of special interest. This is of considerable importance since there is currently no other instrument capable of obtaining high-resolution infrared spectra in the southern hemisphere.

On 2002 February 13 we used this mode of observing on V838 Mon. At the time of the observations it was not known if V838 Mon was a slow nova, a final flash post-AGB star, or a new class of object.[8] Strong CO had been reported in IAU Circulars. A series of spectra at five different grating positions were taken to map ~500 Å of the 2.3 μm CO region to look for both circumstellar and photospheric ^{12}CO and ^{13}CO. As reported by Hinkle et al. (2002),[9] at the time of this observation the CO was much weaker than previously reported. It was possible to determine a CO line width (FWHM=50 km s^{-1}), velocity (-10 km s^{-1}), and approximate excitation temperature (cool star photosphere). The atomic line spectrum indicated a second velocity of +190 km s^{-1}. Phoenix has an imaging mode which is mainly used for acquisition. While the field of view is small on Gemini (15") images do give good magnitudes and colors of point sources. The filter is the spectrograph order sorting filter. From images of V838 Mon and comparison stars, a 2.32 μm magnitude was derived.

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