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MEDIUM-RESOLUTION SPECTRA OF NORMAL STARS IN THE *K* BAND

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ABSTRACT

An Atlas of 115 medium-resolution *K*-band (2.0–2.4 μm) stellar spectra, spanning spectral types O–M and luminosity types I–V, is presented. *K*-band spectra are also presented for one N- and one J-type carbon star. A time series of spectra is presented for an S-type Mira variable. All the spectra are at a resolution of ∼3000 (1.4 cm^{-1}) and have had the terrestrial absorption removed by dividing by a featureless spectrum. The spectra are plotted with the major spectral features identified and are available digitally.

Subject headings: atlases — infrared: stars — stars: carbon — stars: early-type — stars: late-type — stars: variables: other (Mira)

1. INTRODUCTION

A brief review of recent literature shows widespread application of low- to moderate-resolution infrared spectra in the 1–2.5 μm region, and especially in the 2.0–2.5 μm *K* band. This is arguably the result of the recent development and application of highly sensitive infrared arrays. These arrays not only provide many more pixels (currently up to 10^6) than the single-element detectors they replace but are also much more sensitive. The combined increase in the number of pixels and in the sensitivity has been a great boon to spectroscopy (Ridgway & Hinkle 1988).

With this use of infrared spectra there naturally arises a need to understand the infrared spectra of normal stars. The first attempt at an infrared spectral atlas was made by Johnson & Mendez (1970), who presented $R(\equiv \sigma/\Delta\sigma) = 550$ spectra of 32 bright A–M stars in the 1.2–2.5 μm region. The next significant advance was an atlas of standard stars in the *K* band by Kleinmann & Hall (1986; hereafter KH86). The KH86 atlas covered the luminosity range from dwarfs to supergiants but was limited in temperature class to F8–M7.

Following this work, and with the advent of infrared array detectors, a number of papers have appeared on specialized topics. Hanson, Conti, and collaborators (Hanson & Conti 1994; Conti et al. 1995; Hanson, Conti, & Rieke 1996; Morris et al. 1996) have investigated the *K*-band spectra of O, B, and other hot, luminous stars. Hanson et al. (1996) have developed a spectral classification system in the *K* band for the hot, luminous end of the H-R diagram. This classification should prove useful in highly reddened star-forming regions. Figer, McLean, & Morris (1995) and Tamblyn et al. (1996) have applied *K*-band spectra in classifying hot stars in the Galactic center region. The 30 mag of visual extinction to the Galactic center requires the application of infrared techniques. Everall et al. (1993) used $R = 350$ *K*-band spectroscopy to study Be/X-ray binaries.

At the other end of the H-R diagram, Ali et al. (1995) have presented $R = 1380$ *K*-band spectra of 33 F3–M6 dwarf stars. Ali et al. measured equivalent widths and compared these to models to derive a temperature calibration to ±350 K. Their intent was to derive a temperature calibration for future spectroscopy of highly reddened pre–main-sequence stars. Jones, Longmore, & Jameson (1994), Davidge & Boeshaar (1993), and Steele et al. (1995) have undertaken investigations of moderate-resolution *K*-band spectra of M dwarfs in order to search for brown dwarfs. In an investigation of near–Galactic center regions, Terndrup, Frogel, & Whitford (1991) produced spectral energy distributions at $R = 1000$ for a selection of M giants with wavelengths in the range 0.45–2.45 μm. Greene & Meyer (1995) reported on *K*-band $R = 500$ spectroscopy of young stellar objects in the ρ Oph cloud. They find that *K*-band spectra can be used to find spectral types that agree with traditional optical techniques.

There are also a number of papers in which moderate-resolution *K*-band spectroscopy has been used to investigate peculiar stars. For instance, Tanaka et al. (1990) presented an atlas of 33 cool carbon stars in the 1.5–2.5 μm region at a resolution of 2000. Tanaka et al. proposed spectral indices for classification in the infrared. Lazaro et al. (1994) have presented $R = 500$ observations of 15 N-type carbon stars in the *J*, *H*, *K*, and *L* bands. They note the advantages to classification of these stars in the infrared: the presence of continuum regions, CNO group molecular bands, and the flux peak. These properties are also favorable for comparisons with models. Oudmaijer et al. (1995) reported on medium-resolution *K*-band spectroscopy of post–asymptotic giant branch (AGB) stars. Of particular interest is the CO first overtone in emission that results from post-AGB mass loss. McGregor, Hyland, & Hillier (1988) have reported on 1–2.5 μm $R = 500$ spectroscopy of emission-line A and B supergiants. Features include CO, Brγ, He I, Mg II, and Na I emission.

Other than KH86, the only other broad survey of *K*-band spectra in the H-R diagram is that of Lancon & Rocca-Volmerange (1992), who observed 1.4–2.5 μm spectra covering dwarfs through giants and temperature classes O–M. Lancon & Rocca-Volmerange used the Canada-France-Hawaii Telescope Fourier transform spectrometer (FTS) at $R = 390$ (unapodized resolution of 11.5 cm^{-1}). The spectra have only modest resolution and signal-to-noise ratio (S/N). They were intended for use in stellar population synthesis and are not of the same quality as those of KH86. The applications of low to medium-resolution infrared spectroscopy are much broader.

KH86 were interested in obtaining a sample of cool stars to use in the spectral synthesis of galactic nuclei but did

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TABLE 1

List of Objects Observed

Object Designation	Other Name	Spectral Type	Date Observed	Reference Spectrum	Notes
HR 21	β Cas	F2 III	1994 Jun 7	α Cyg	1
HR 39	γ Peg	B2 IV	1994 Jun 8	α Cyg	1
HR 45	χ Peg	M2 + III	1981 Jun 11	α Lyr	2
HR 382	ϕ Cas	F0 Ia	1995 Mar 16	α CMa	1
HR 403	δ Cas	A5 III–IV	1994 Jun 7	α Cyg	1
HR 483	...	G1.5 V	1994 Jun 8	α Cyg	2
HR 969	...	G6 Ib–IIa	1995 Mar 15	α CMa	2
HR 1017	α Per	F5 Ib	1994 Jun 8	α Cyg	1
HR 1084	ϵ Eri	K2 V	1995 Mar 15	α CMa	2
HR 1155	BE Cam	M2+ IIab	1994 Jun 8	α Cyg	2
HR 1412	θ^2 Tau	A7 III	1995 Mar 14	α Leo	1
HR 1457	α Tau	K5+ III	1994 Sep 14	α CMa	2
HR 1713	β Ori	B8 Ia	1994 Sep 14	α CMa	1
HR 1791	β Tau	B7 III	1995 Mar 15	α Leo	1
HR 1903	ϵ Ori	B0 Ia	1995 Mar 15	α CMa	1
HR 2294	β CMa	B1 II–III	1995 Mar 14	α CMa	1
HR 2456	15 Mon	O7 V	1995 Mar 14/15	α Leo	1
HR 2473	ϵ Gem	G8 Ib	1994 Sep 14	α CMa	2
HR 2491	α CMa	A1 V	1994 Oct 21	α Leo	3
HR 2508	...	M1+ Ib–IIa	1994 Oct 21	α Leo	2
HR 2763	λ Gem	A3 V	1984 Apr 16	α Lyr	3
HR 2828	ϵ CMi	G6 II	1994 Sep 14	α CMa	2
HR 2943	α CMi	F5 IV–V	1995 Mar 14	α Leo	1
HR 2985	κ Gem	G8 III	1994 Sep 14	α CMa	2
HR 3003	81 Gem	K4 III	1994 Sep 14	α CMa	2
HR 3212	...	G7 III	1994 Oct 20	α Leo	2
HR 3275	31 Lyn	K4.5 III	1994 May 26	α Lyr	2
HR 3323	o UMa	G5 IIIa	1981 Jun 10	α Lyr	3
HR 3975	η Leo	A0 Ib	1994 Oct 20	α Leo	1
HR 3982	α Leo	B7 V	1994 Dec 8	β Leo	3
HR 4031	ζ Leo	F0 III	1994 May 27	α Lyr	1
HR 4033	λ UMa	A2 IV	1994 Oct 20	α Leo	1
HR 4069	μ UMa	M0 III	1994 May 27	α Lyr	2
HR 4166	37 LMi	G2.5 IIa	1994 Dec 9	β Leo	2
HR 4195	VY UMa	C6, 3	1994 Nov 17	α Leo	4
HR 4255	...	G4 III	1994 Dec 9	β Leo	2
HR 4295	β UMa	A1 V	1981 Jun 11	α Lyr	3
HR 4357	δ Leo	A4 V	1994 Nov 17	α Leo	3
HR 4362	72 Leo	M3 IIb	1994 Nov 17	α Leo	2
HR 4375	ξ UMa	F8.5 V	1994 Nov 17	α Leo	2
HR 4496	61 UMa	G8 V	1994 Dec 9	β Leo	2
HR 4517	ν Vir	M1 III	1994 Nov 18	α Leo	2
HR 4534	β Leo	A3 V	1994 Nov 17	α Leo	3
HR 4846	Y CVn	C5, 5J	1994 Dec 8	β Leo	4
HR 4883	31 Com	G0 IIIp	1981 Jun 9	α Lyr	2
HR 4931	78 UMa	F2 V	1995 Mar 14	α Leo	1
HR 4932	ϵ Vir	G8 IIIab	1981 Feb 18	β Leo and α Lyr	2, 5
HR 4963	θ Vir	A1 IV:	1981 Feb 18	β Leo and α Lyr	3
HR 5017	20 CVn	F3 III	1995 Mar 14	α Leo	1
HR 5054	ζ UMa	A1 Vp	1981 Jun 9	α Lyr	3
HR 5191	η UMa	B3 V	1994 Oct 21	α Leo	3
HR 5291	α Dra	A0 III	1994 Oct 21	α Leo	1
HR 5340	α Boo	K1.5 IIIp	1984 Apr 15	α Lyr	2
HR 5793	α CrB	A0 V	1981 Feb 17	α Lyr	3
HR 6165	τ Sco	B0 V	1995 Mar 14–15	α CMa	1
HR 6299	κ Oph	K2 III	1981 Feb 16	α Lyr	2
HR 6378	η Oph	A2 V	1981 Jun 10	α Lyr	3
HR 6406	α^1 Her	M5 Ib–II	1994 Jul 19	α Lyr	2
HR 6608	84 Her	G2 IIIb	1981 Feb 16	α Lyr	2
HR 6685	89 Her	F2 Ib	1994 May 1	α Lyr	1, 6, 7
HR 6703	ξ Her	G8.5 III	1994 Apr 7	α Lyr	2
HR 6705	γ Dra	K5 III	1981 Feb 16	α Lyr	2
HR 6714	67 Oph	B5 Ib	1995 Mar 15	α Leo	1
HR 6927	χ Dra	F7 V	1995 Jun 16	α Leo	3
HR 7001	α Lyr	A0 Va	1994 Oct 20	α Leo	1
HR 7009	XY Lyr	M4.5+ II	1994 Apr 7	α Lyr	2
HR 7157	R Lyr	M5 III	1981 Feb 16	α Lyr	3
HR 7236	λ Aql	B9 V	1995 May 18	α Cyg	3
HR 7314	θ Lyr	K0 II	1994 May 1	α Lyr	2, 6
HR 7373	31 Aql	G7 IV	1994 Jun 8	α Cyg	2
HR 7387	ν Aql	F2 Ib	1995 Mar 16	α Leo	3
HR 7462	σ Dra	K0 V	1982 Apr 11	α Lyr	2

TABLE 1—*Continued*

Object Designation	Other Name	Spectral Type	Date Observed	Reference Spectrum	Notes
HR 7495	...	F5 II–III	1995 Mar 15/16	α Lyr	1
HR 7503	16 Cyg A	G1.5 Vb	1982 Apr 10	α Lyr	2
HR 7504	16 Cyg B	G3 V	1982 Apr 15	α Lyr	2
HR 7557	α Aql	A7 V	1995 Apr 18	α Lyr	3
HR 7564	χ Cyg	S6+/le	1994 Apr 30, 1994 May 27, 1994 Jul 19	α Lyr	8
HR 7564	χ Cyg	S6+/le	1994 Sep 14	α CMa	
HR 7564	χ Cyg	S6+/le	1994 Oct 20, 1994 Nov 17, 1995 Mar 14	α Leo	
HR 7564	χ Cyg	S6+/le	1994 Dec 9	β Leo	
HR 7654	χ Cyg	S6 + /le	1995 Apr 18	α Lyr	
HR 7635	γ Sge	M0–III	1981 Jun 9	α Lyr	2
HR 7796	γ Cyg	F8 Ib	1994 Apr 6	α Lyr	1
HR 7806	39 Cyg	K2.5 III	1981 Jun 9	α Lyr	2
HR 7886	EU Del	M6 III	1994 May 1	α Lyr	2
HR 7924	α Cyg	A2 Ia	1994 Apr 6	α Lyr	1
HR 7957	η Cep	K0 IV	1994 Apr 6	α Lyr	2
HR 7977	55 Cyg	B3 Ia	1994 May 1	α Lyr	1
HR 8079	ξ Cyg	K4.5 Ib–II	1994 Apr 30	α Lyr	2
HR 8085	61 Cyg A	K5 V	1981 Jun 11	α Lyr	2
HR 8089	63 Cyg	K4 Ib–IIa	1994 Apr 30	α Lyr	2
HR 8232	β Aqr	G0 Ib	1994 May 1	α Lyr	2
HR 8284	75 Cyg	M1 IIIab	1981 Jun 9	α Lyr	2
HR 8313	9 Peg	G5 Ib	1994 May 1	α Lyr	2
HR 8316	μ Cep	M2–Ia	1981 Jun 10	α Lyr	2
HR 8317	11 Cep	K0.5 III	1994 Apr 30	α Lyr	2
HR 8465	ζ Cep	K1.5 Ib	1994 May 27	α Lyr	2
HR 8469	λ Cep	O6 I	1995 Mar 14, 16	α Lyr	1
HR 8530	...	M6 III	1981 Jun 10	α Lyr	3
HR 8621	...	M4+ III	1994 Apr 30	α Lyr	2
HR 8626	...	G3 Ib–II:	1994 Jun 7	α Cyg	2
HR 8634	ζ Peg	B8 V	1995 Apr 18	α Lyr	3
HR 8694	ι Cep	K0–III	1981 Jun 9	α Lyr	2
HR 8726	...	K5 Ib	1981 Jun 10	α Lyr	2
HR 8752	V509 Cas	G5var O	1981 Jun 10	α Lyr	2, 9
HR 8832	Gliese λ 892	K3 V	1994 Jun 7	α Cyg	2
HR 8905	υ Peg	F8 III	1981 Jun 9	α Lyr	1
HR 8989	...	M2 III	1994 Jun 7	α Cyg	2
HD 114961	SW Vir	M7 III:	1981 Feb 18	β Leo and α Lyr	2
HD 108849	BK Vir	M7–III:	1981 Jun 11	α Lyr	2
HD 95735................	Gliese 411	M2+ V	1981 Jun 11	α Lyr	2
HD 212466	RW Cep	K2 0–Ia	1981 Jun 11	α Lyr	2
HD 14469................	SU Per	M3–4 Iab	1981 Jun 11	α Lyr	2
Gliese λ 406.............	Wolf 359	M6 V	1995 Mar 15–16	α Leo	10
IRAS 22069+5918......	AZ Cep	M2 Ia	1984 Apr 15	α Lyr	11
HD 213758	Case 75	M1 Ia	1984 Apr 16	α Lyr	12
HD 339034	NR Vul	M1 Ia:	1984 Apr 15	α Lyr	2
IRAS 20241+3811......	KY Cyg	M3.5 Ia	1984 Apr 15	α Lyr	11
IRAS 23416+6130......	PZ Cas	M3var Ia	1984 Apr 16	α Lyr	2
IRAS 01051+6319......	HS Cas	M4 Ia	1984 Apr 16	α Lyr	11
HD 173739	Gliese 725A	M3 V	1994 Jun 8	α Cyg	10
HD 126327	RX Boo	M7.5–8 III	1994 Jul 15	α Lyr	2
HD 46223................	...	O4 V	1995 Mar 17	α Leo	1

NOTES: 1, Spectral type from Morgan, Abt, & Tapscott (1978); 2, spectral type from Keenan & McNeil (1989); 3, spectral type from Hoffleit & Jaschek (1982); 4, spectral type from Tanaka et al. (1990); 5, Spectrum dissimilar to other stars of similar spectral type; 6, continuum variation different from other stars of similar spectral type; 7, CO in emission; 8, spectral type at maximum light from Keenan & Boeshaar (1980); 9, emission lines; 10, spectral type from Kirkpatrick, Henry, & McCarthy (1991); 11, spectral type from Kholopov et al. (1985); 12, same as BD +58 2450, reddened (Nassau, Blanco, & Morgan 1954).

acknowledge the wider application of the spectra. The emphasis on cool stars came about because the flux of such stars peaks in the infrared, making them dominant in the Galactic infrared light. The value of KH86 was enhanced by the identifications of spectral features.

Three factors motivated us to extend the KH86 atlas. First, after the production of our atlases of resolution 60,000–100,000 (e.g., Hinkle, Wallace, & Livingston 1995) we were asked to extend our line identification work to other spectral types. Second, Meyer (1996) produced a spectral atlas of temperature classes O–M and luminosity classes V–I in the *H* (1.5–1.8 μm) and *J* (1.1–1.3 μm) bands. Meyer and collaborators suggested that their atlas would be of greater use if the existing KH86 *K*-band atlas were similarly extended in temperature and luminosity range. Last, the high-quality broadband spectra used by KH86 and by Meyer were observed with the KPNO 4 m FTS. Because of financial stress at NOAO, this instrument was slated for closure. Since no other instrument currently available can obtain data of similar wavelength coverage, resolution, and signal-to-noise ratio, we felt obligated to proceed with the current survey.

Spectra of 80 objects were observed, in addition to 39 already by other observers, including KH86. We have corrected these spectra for atmospheric absorption by dividing by various reference stellar spectra observed with the same instrument used for the program objects. All of the primary atomic and molecular absorbers are identified and their development is tracked for luminosity classes I, III, and V and from late O through mid-to-late M spectral type. The spectra are available in computer-readable form in the AAS CD-ROM Series, Volume 9.

2. THE SAMPLE

The spectra were gathered over the period 1981 February through 1995 June. Most of the spectra obtained before 1984 were observed and published by KH86. KH86 was limited to 26 stars of spectral types G, K, and M. We expanded this sample during the interval 1994 April through 1995 June, in an attempt to obtain good coverage of temperature range O–M and luminosity range 1–V. As in KH86, observations were obtained with the KPNO 4 m telescope and FTS. The same observing procedure, filter, and detectors were used as in KH86. Observations were terminated in the fall of 1995 because of the deactivation of the FTS. While the FTS produced high-quality, large-wavelength spectra for bright stars, the observing technique required making many samples with a single-element detector. The detector was read out rapidly, and as a result the technique was not very sensitive to sources fainter (for the 4 m FTS) than $K \sim +5$ mag. For the hot stars our sample is rather limited because of the small number of bright hot stars and pressures on observing time caused by bad weather. However, the sample is sufficient to provide overlap with surveys that deal exclusively with these stars by using other observing techniques (e.g., Hanson et al. 1996).

A list of the objects observed, ordered, where possible, according to HR number, is given in Table 1.

3. DATA REDUCTION

All of the spectra were reduced using the same technique, including those previously reduced by KH86. Although we approached the reduction with the idea of developing an independent method, we converged to a process almost identical to that used by KH86, but extended to remove certain artifacts.

All of the reductions were performed with the program DECOMP, written by J. W. Brault. Some of the spectra obtained at resolution higher than the standard 0.8 cm^{-1} were first reduced to that resolution. Wherever possible, the telluric absorptions were cancelled out by taking the ratio of the program star spectrum to a reference spectrum obtained on the same night and interpolated to the same air mass as the program star. The reference stars used were α Lyr (A0 Va), α Leo (B7 V), β Leo (A3 V), α Cyg (A2 Ia), and α CMa (A1 V). These stars were believed to be free of significant absorption except at 4616.6 cm^{-1} H Brγ. This H line was compensated for by division by the line profile constructed by the division of the reference spectrum by IRC +10216, which does not show the H line. Finally, the spectra were shifted to zero heliocentric velocity using published radial velocities and interpolated onto a common scale at a dispersion of 0.5 cm^{-1} per point. At a subsequent stage the spectra were filtered with a Gaussian of full width at half-maximum (FWHM) 1.4 cm^{-1}, again following KH86, and then normalized to unity at 4500 cm^{-1}.

Occasional complications required modifications of this scheme. Sometimes bad weather prevented the observation of the needed reference stars, requiring that stars from other dates be used. These other stars did not always give good compensation and some trial and error with stars from different dates was needed to achieve good results. One such observing run, made 1985 March 13, proved unreducible for that reason. Another, made 1996 June 16, yielded ratios for τ Sco and χ Dra with peculiar continuum variation.

The use of reference spectra obtained on the same night as the program star, and interpolated to the same air mass, usually gave good compensation for both of the major atmospheric absorbers in the K band, namely CH_4 and H_2O. However, as we have noted at higher resolution (Wallace & Hinkle 1996), in some cases the H_2O amount changes rapidly during the night and is not well compensated in the ratio. To overcome this defect, a H_2O spectrum was constructed from ratios of spectra of α Lyr taken on different days (1994 April 6 and May 27) but at the same air mass. This H_2O spectrum was then stretched logarithmically to fit the residual H_2O in the spectrum after the ratio was taken and was then divided out. The fine details of the H_2O spectrum do vary with temperature and vertical distribution, but these effects are not apparent in these spectra.

Some artifacts appear in the processed spectra, particularly in the spectra gathered after 1994 June. One artifact is ringing, which appears in the spectra at a frequency of 3.4 cm^{-1} $cycle^{-1}$ and is caused by fringing in either the dewar window or filter. In any case, we removed it with an appropriate notch Fourier filter. As noted above, we have followed this notch filter with a Gaussian apodizing filter of FWHM 1.4 cm^{-1}.

In addition, the shape of the transmission function of the blocking filter does not cancel out as it should in some of the ratios of spectra gathered in 1994 and 1995. This may have to do with the differing illumination of the FTS and filter or the lack of frequent beam switching. Automatic beam switching was no longer available by 1994 because of changes in the telescope operating system. We compensated by taking short integrations in alternating apertures and combining these after the observation. In any case, we have taken the measured shape of the filter transmission, and, where necessary and appropriate, stretched it logarithmically to match the continuum peculiarities of the spectrum, and corrected for it.

One more artifact was the result of 60 Hz interference caused by an unintentional connection between clean and dirty building power by other users of the 4 m telescope. This interference first appeared in the run of 1994 September and continued through 1994 December before it was eliminated. In the spectra it shows primarily as a spike at $\sim$4857.5 cm^{-1}. This is an unfortunate circumstance since the spike coincides with the position of a He I line that is present in the spectra of some of the early-type stars. In the cases for which we can cope with this spike, we have simply substituted a "-1" in the place of the spike in the filtered data files and used that value as a flag to signal a gap in the data. In the more severe cases of very strong primary spikes or secondary spikes, we have not attempted to salvage the spectra.

More than one spectrum was obtained for a number of the objects. In all of these cases except for χ Cyg, only the best spectra, in terms of S/N or unwanted artifacts were retained and are listed in Table 1. Nine spectra are included

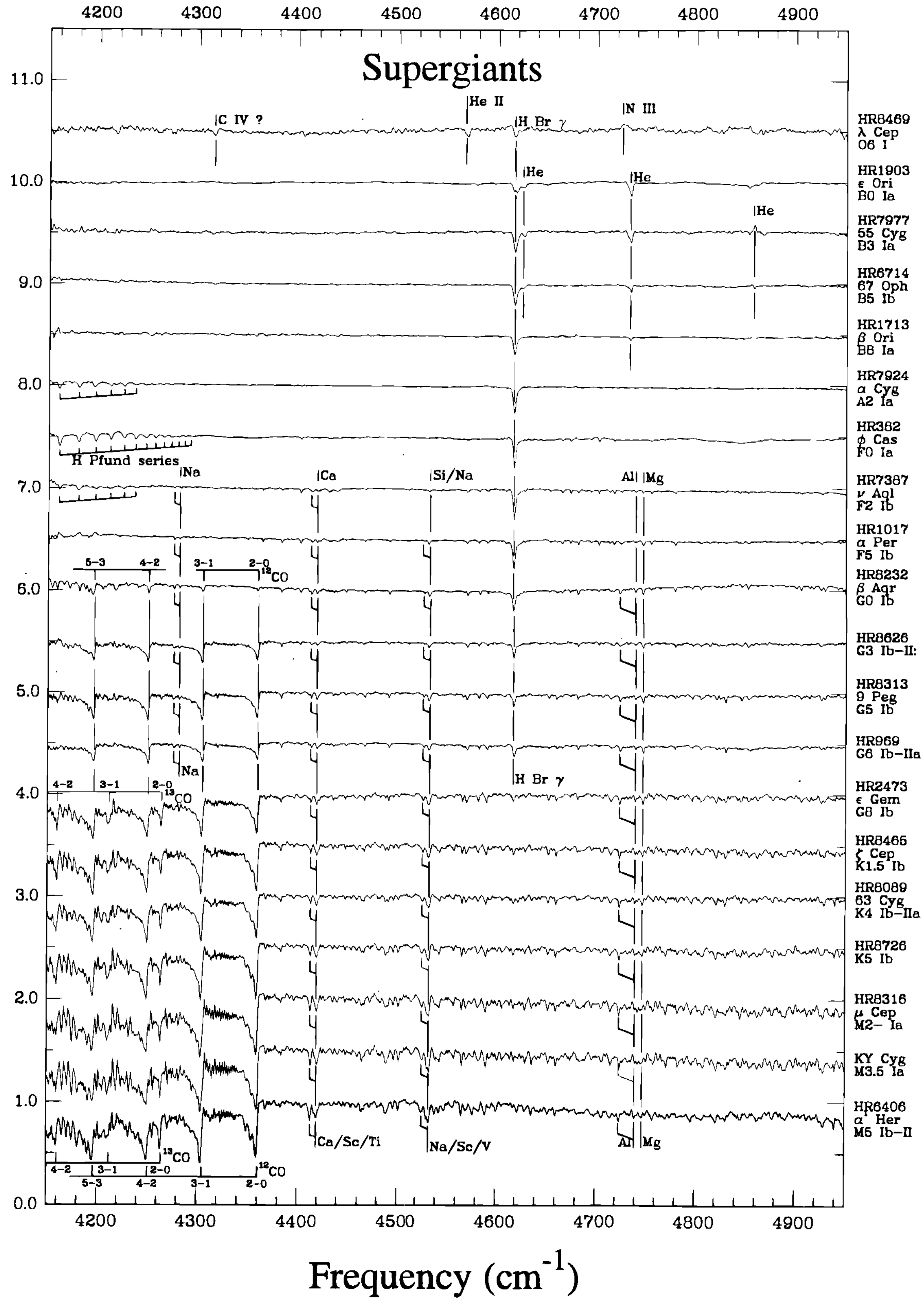

FIG. 1.—Spectra of supergiants in the *K* band, corrected for atmospheric absorption and normalized to unity at 4500 cm^{-1}. Each successive spectrum has been shifted vertically by 0.5 to avoid overlap. Only the more prominent features are labeled. The labels using slashes, e.g., Ca/Fe, are meant to indicate blends.

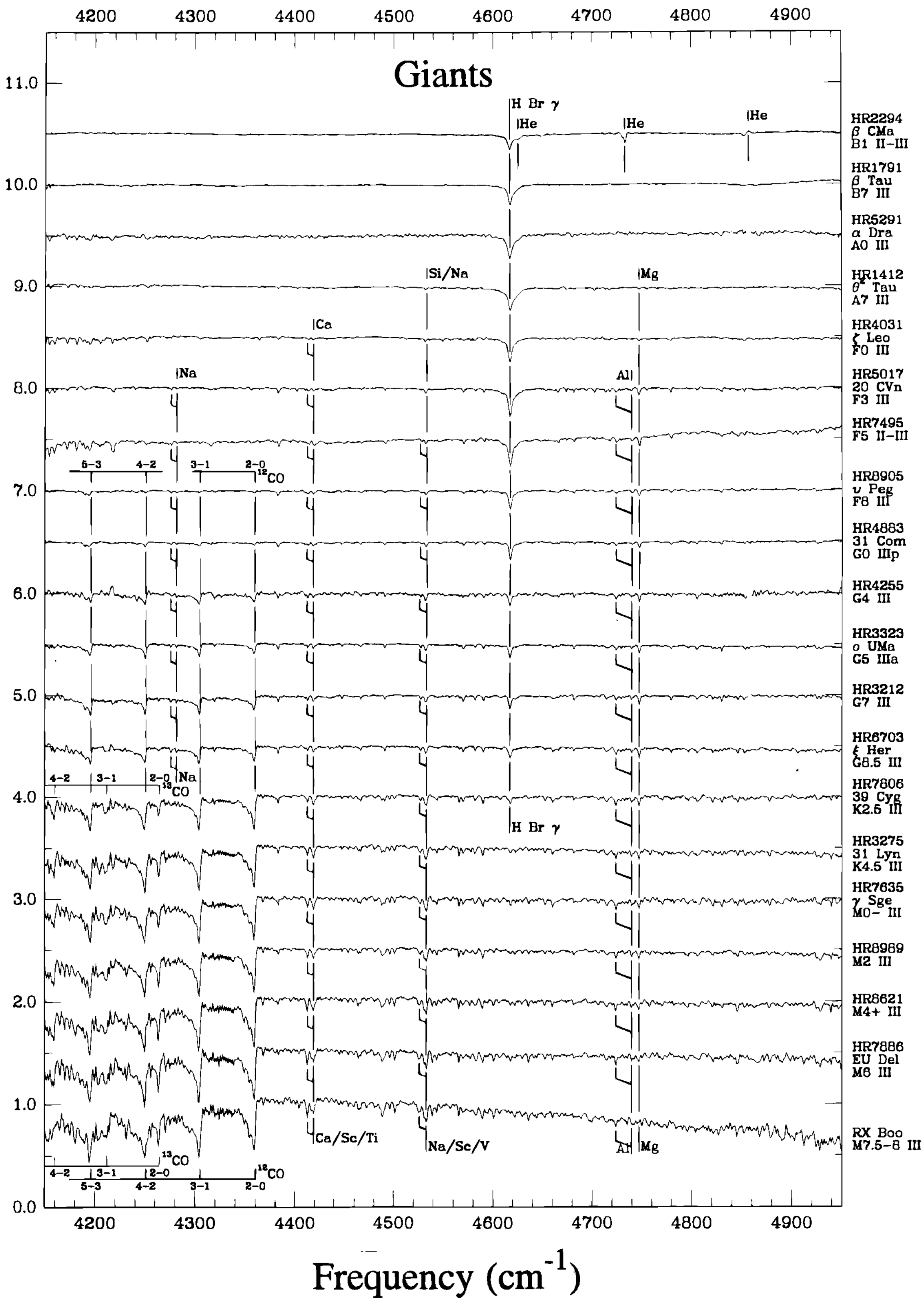

FIG. 2.—Same as Fig. 1, but for giants

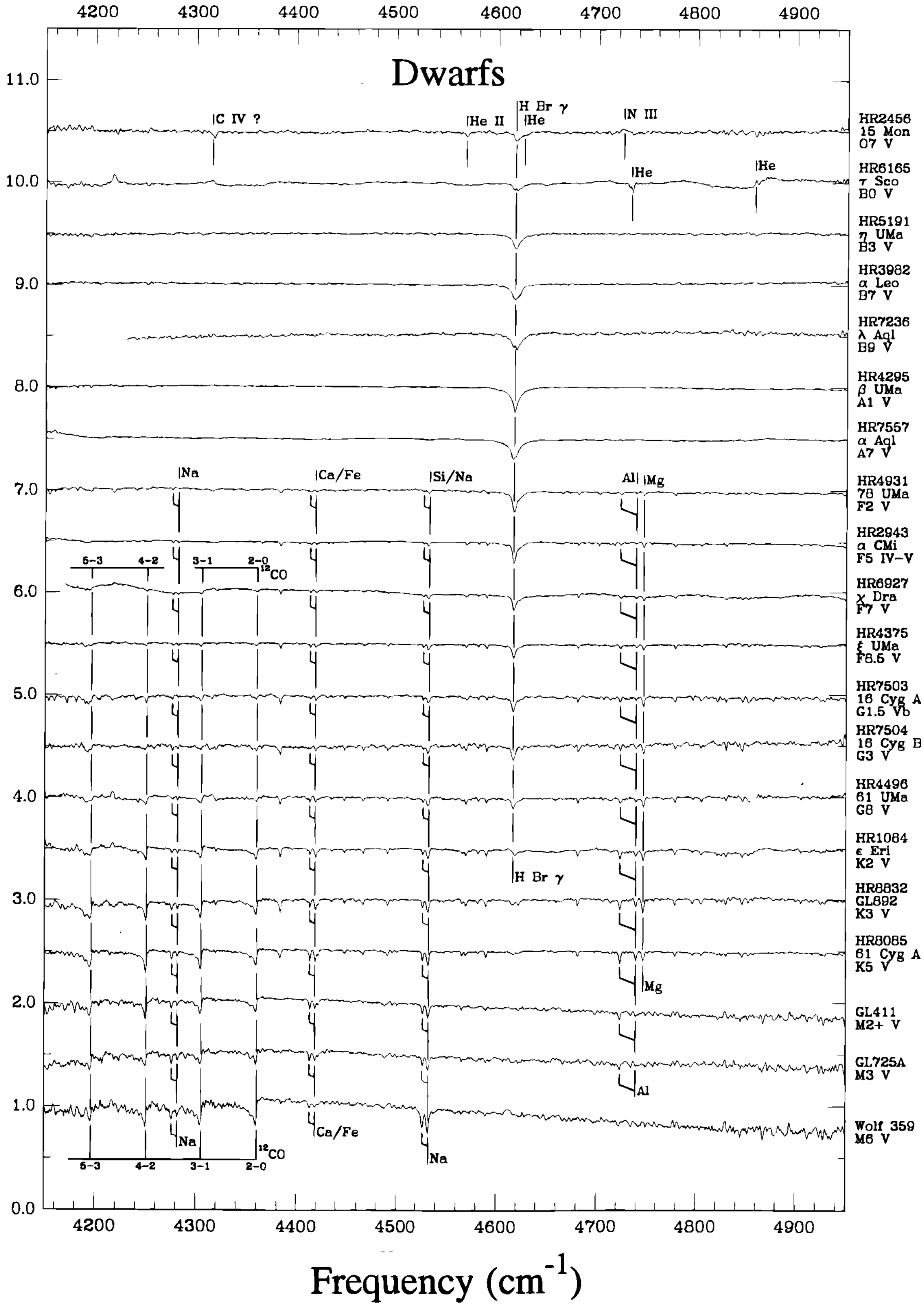

FIG. 3.—Same as Fig. 1, but for dwarfs

for χ Cyg, representing the phase variation through a full cycle. Two carbon stars, VY UMa (N-type) ad Y CVn (J-type), were also included in the observing list.

The details of retrieving digital versions of the spectra from the CD-ROM are given in the Appendix. All of the spectra listed in Table 1 are available.

4. APPEARANCE OF THE SPECTRA ORGANIZED BY LUMINOSITY AND SPECTRAL TYPE FOR SPECTRAL TYPES O THROUGH M

The observing program in 1994 and 1995 was initially targeted toward filling a grid of spectral types and luminosity in which the box widths were defined by the changes in the spectra as observed in the visible. As the spectra were gathered, we changed the division points to give more uniform changes in the appearance of the K-band spectra. The changes gave fewer boxes for spectral type A and more for type G. The boundaries of the boxes so adjusted were as follows: O6, O8, B0, B2, B4, B6, B8, A0, A5, F0, F2, F4, F6, F8, G0, G2, G4, G6, G8, K1, K3, K5, M1, M3, M5, and M7. Hence we had 27 boxes in spectral type; we only worked diligently at filling those for luminosity classes I, III, and V. By the time the instrument was decommissioned we had filled only 21 boxes for the supergiants, 19 for the giants, and 20 for the dwarfs.

We have examined plots of all of the spectra of the program stars of types O–M, reordered roughly first according to luminosity and second according to spectral type. From these we contructed displays, following the boxing cited in the previous paragraph with slight modifications, to give 20 stars per luminosity class. These displays are given in Figures 1, 2, and 3, with generally only the best spectrum in each box. The exceptions are the supergiant set, in which we dropped γ Cyg to reduce the set to 20 objects, and the giant set, where we added HR 4255 to increase the set to 20.

5. LINE IDENTIFICATIONS

5.1. *Spectral Types O through M*

The line identifications for the O and early B stars rely on the more extensive sample analyzed by Hanson & Conti (1994). The O stars in Figures 1 and 3 (HR 8469 and HR 2456) do not have very good S/N, and our tentative labeling of the C IV and N III features relied on Hanson & Conti. Our earliest dwarf, HD 46223, has too low an S/N to warrant inclusion in the figures.

The Pfund series lines (Fig. 1, spectral types A through early F) were identified for us by R. Joyce. The presence of these lines in α Cyg points to our error in using that star as a reference in the analysis of a number of stars (see Table 1). Spectra normalized to α Cyg should be used with caution between 4150 and 4260 cm^{-1} because a weak inverse signature of the Pfund lines will appear. One example of this appears in HR 8832 (Gl 892, K3 V) in Figure 3. In most of the others, this signature is masked by noise or by the CO bands.

A notable feature of the Brγ line is that it appears asymmetric in many of the B, A, and F stars. The high-frequency side is lower than the low-frequency side. We are not certain to what extent the nearby He I line at 4625 cm^{-1} produces this effect. The profile of Brγ depends on our determination of the Brγ profile in the comparison star, and while we have been very careful in these measurements, intensity errors at low levels are possible.

Reduction problems are no doubt the cause of the peculiar continuum variation of the dwarf τ Sco (B0 V), but the Brγ line of that star shows only a weak emission core, as opposed to the full-blown emission line seen by Waters et al. (1993) in 1992 July.

For spectral types F and later we have only labeled some of the more prominent features in Figures 1, 2, and 3. Outstanding, of course, is the CO first overtone extending from 4360 cm^{-1} to our limit of 4150 cm^{-1}. The bands are clearly stronger at the same spectral type for supergiants and giants than they are for dwarfs, and the ^{13}CO isotope, which is prominent in the supergiants and giants, is not apparent in the dwarfs.

A more detailed view of the cooler stars of spectral type F and later, but exclusive of the CO bands, is given in Figures 4, 5, and 6. The selection of stars here does not follow the boxing that we established for the observing program, but it does give a very good sampling of the rapidly changing spectral features. In these plots we have labeled all of the atomic features that we were able to identify on the basis of high-resolution spectra (Wallace & Hinkle 1996). Many of these are blends, and at this low resolution the identifications are not at all obvious, but we are confident that they are essentially correct. The more notable of these features are those involving Ca at $\sim$4415 cm^{-1} and Na at $\sim$4530 cm^{-1}, which are complex blends with Sc, Ti, V, and Fe. These blends have already been discussed in detail by Wallace & Hinkle. They have proven useful as empirical indicators of $T_{\rm eff}$ (KH86; Ali et al. 1995), and their blends with other features are only of concern when they are interpreted as unblended.

The almost featureless jumble of molecular lines in the supergiants and giants (Figs. 4 and 5) between the CO band head at 4360 cm^{-1} and our limit of 4950 cm^{-1} appears around the mid-G spectral type and strengthens toward the cooler types. Our work on high-resolution spectra of supergiants and giants in this region has shown that this "grass" is due to the CN red system alone through early M and that by α Her (M5 Ib–II) and RX Boo (M7.5–8 III) it comes from a blend of both CN red and H_2O. One prominent structure due to CN is indicated in Figure 4 at $\sim$4777 cm^{-1}. It is a set of three weak minima surrounded by two stronger minima, the latter at the tines of the fork. This feature persists through KY Cyg (M3.5 Ia) but loses its character by α Her because of H_2O blending. This feature is also indicated for the giants in Figure 5 but is not quite so clear. It is apparent at spectral type M4+ but is blended with H_2O at M7.5–8. It is also possible that in the band 4800–4950 cm^{-1}, H_2O might become important at a somewhat earlier spectral type.

The situation with this jumble of lines in the dwarfs (Fig. 6) is much simpler. Judging from the high-resolution work, the jumble is entirely due to H_2O, with no evidence for CN. It appears not to set in until late K or early M.

5.2. χ Cyg *and Two Carbon Stars*

Our medium-resolution of χ Cyg (Fig. 7) show none of the complex profiles seen in CO at high resolution (Hinkle, Hall, & Ridgway 1982). The CO strength, however, clearly varies. We measured the average depth of the CO absorption in the region of the ^{12}CO 2–0 band head from 4357.0 to 4359.0 cm^{-1} relative to that in the high region from 4362.0

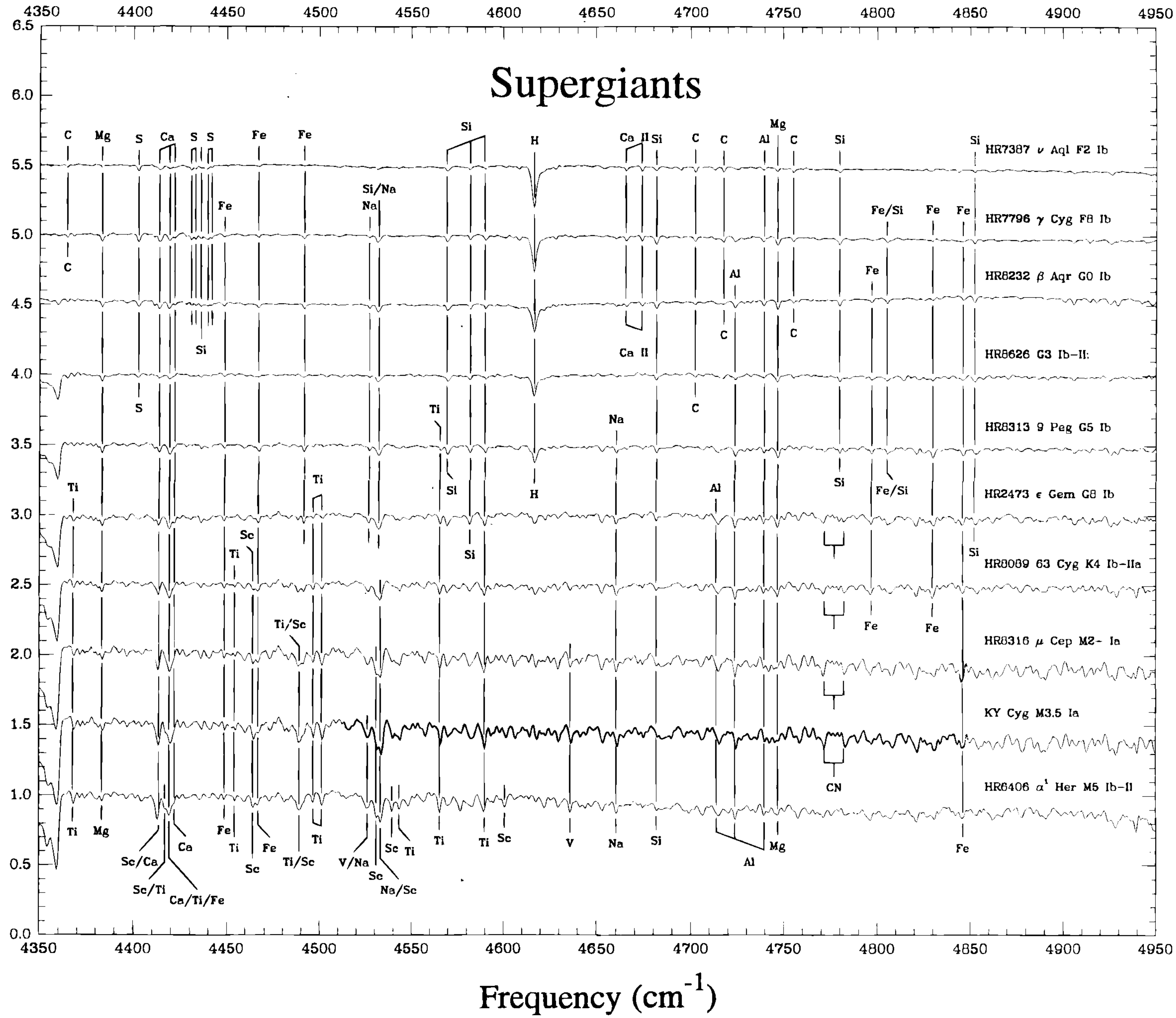

FIG. 4.—Expanded view of the supergiants of spectral types F–M in the spectral region 4350–4950 cm^{-1}. The spectra have been corrected for atmospheric absorption and normalized to unity at 4500 cm^{-1}. Each successive spectrum has been shifted vertically by 0.5 to avoid overlap. In this figure all of the identified atomic features are labeled. The jumble of weak features, which becomes more prominent at late spectral type, is molecular and is discussed in the text.

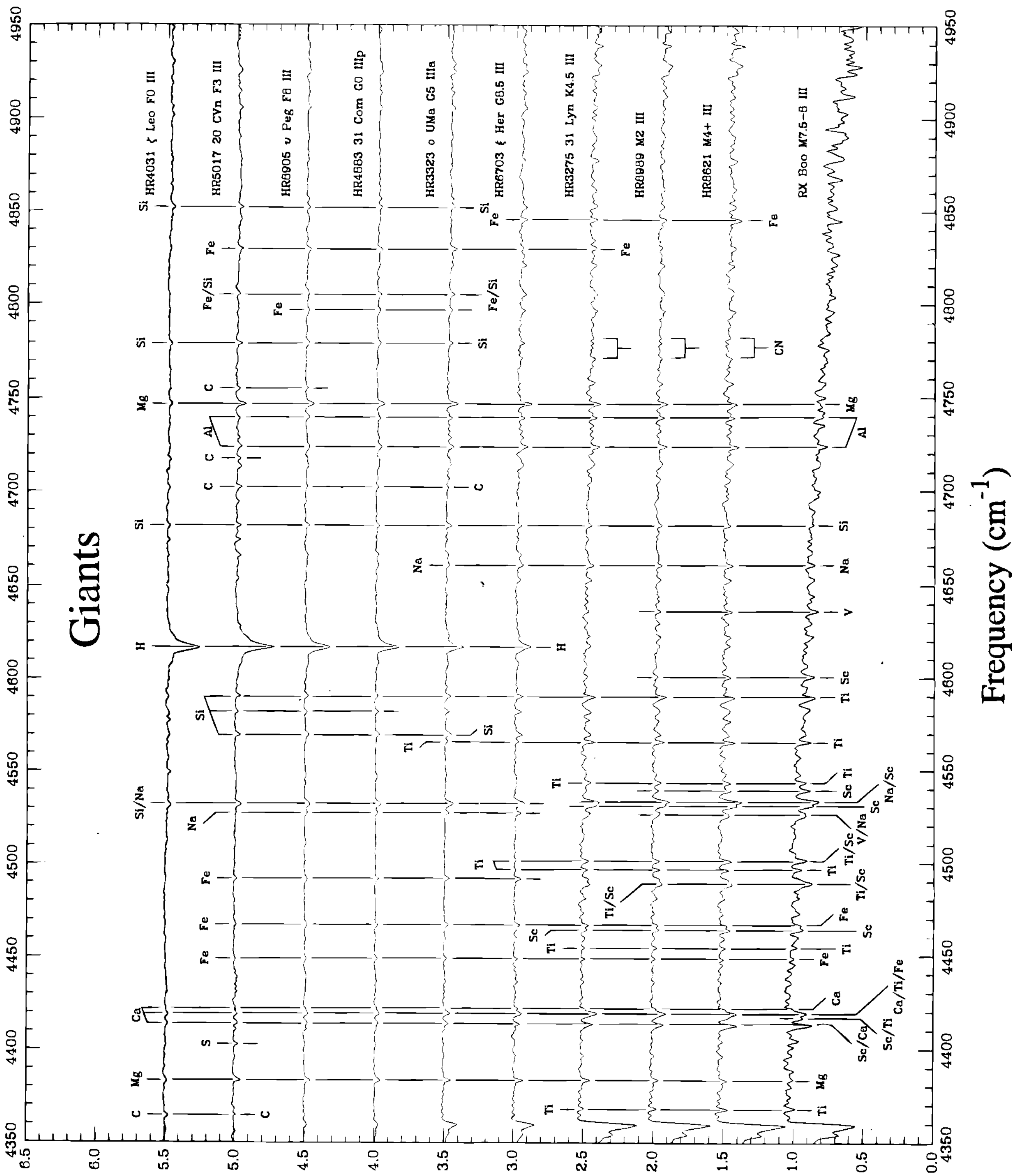

FIG. 5.—Same as Fig. 4, but for giants

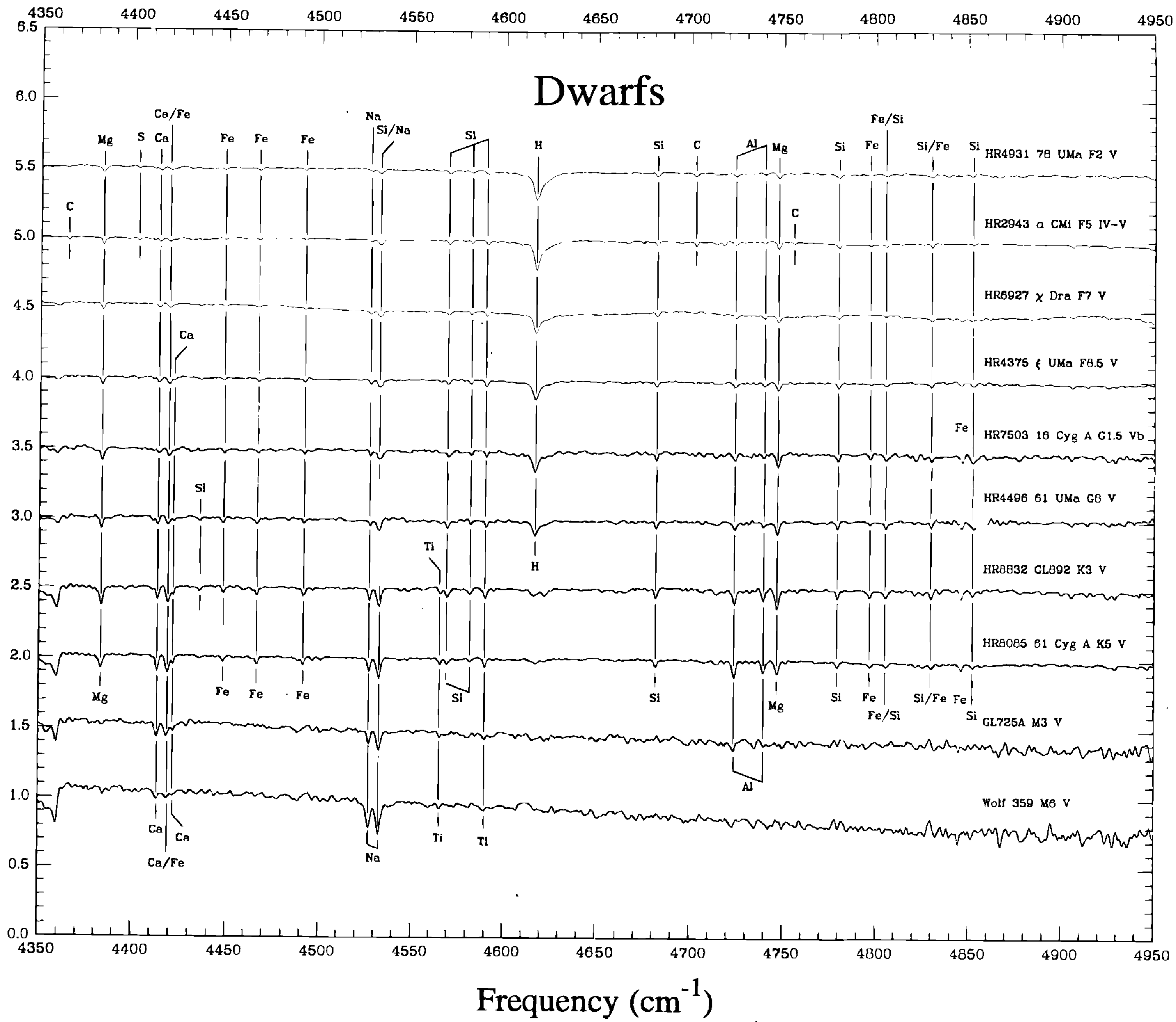

FIG. 6.—Same as Fig. 4, but for dwarfs

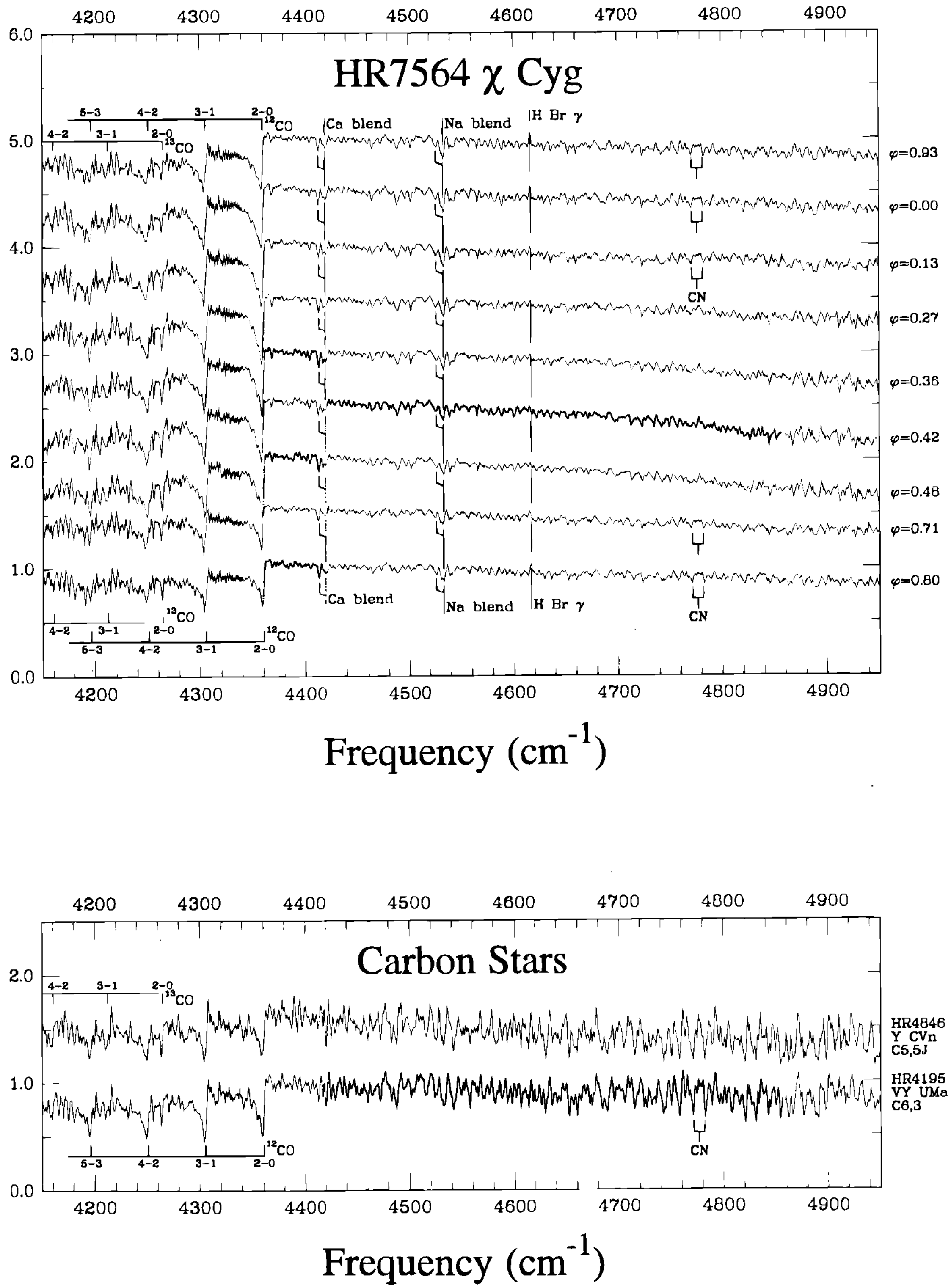

FIG. 7.—Same as Fig. 1, but for χ Cyg and two carbon stars

to 4364.0 cm^{-1}, just ahead of the band head. These measurements, given in the top panel of Figure 8, show a factor of 1.5 variation, peaking at a phase of ~0.8. There also appears to be variability in the Ca and Na blends near 4415 and 4530 cm^{-1}, respectively; these features are blends with Sc, Ti, V, and Fe (Wallace & Hinkle 1996).

Brγ appears in emission for phases of ~0.7 to ~1.2 at about the same point at which the CN feature at ~4777 cm^{-1} is seen (Fig. 7). The details of the molecular "grass" certainly vary, but the cause of the variation is unclear. According to Wallace & Hinkle, the grass in χ Cyg is due to CN, at least at a phase of 0.24. It could be that CN is primarily responsible at all phases, but that the strength of the absorption and the excitation conditions vary. This

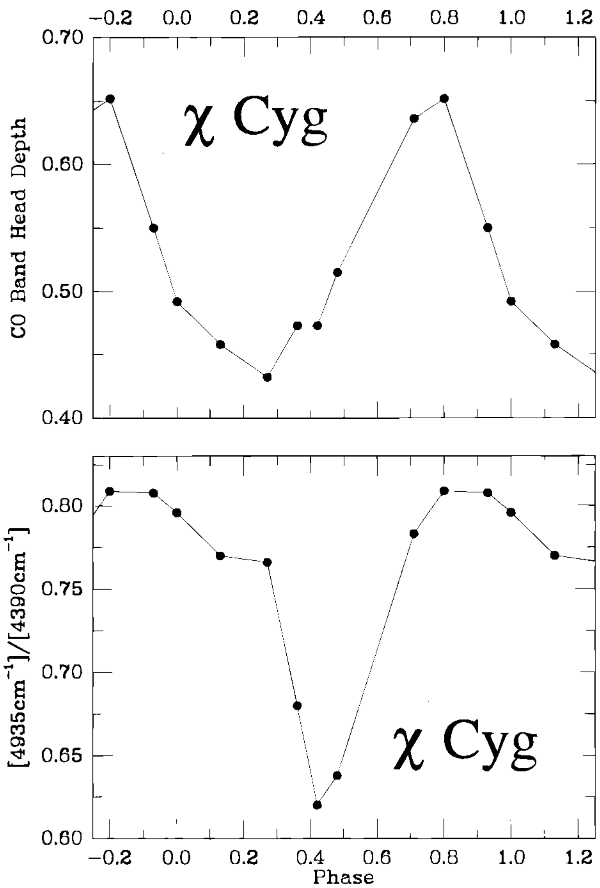

FIG. 8.—Variation of the CO 2–0 band head strength and the continuum slope of χ Cyg with phase.

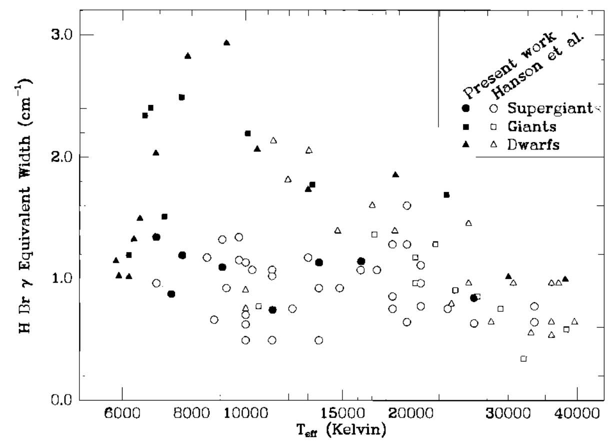

FIG. 9.—Brγ equivalent widths as a function of effective temperature for supergiants, giants, and dwarfs. The measurements by . Hanson et al. (1996) of the normal MK stars of spectral type O7 and later are shown for comparison.

variation is probably the cause of the difference in CN for supergiants and giants as well.

It is also apparent in Figure 7 that χ Cyg shows some variation in continuum slope. We have averaged the two bands from 4920 to 4950 cm^{-1} and from 4380 to 4400 cm^{-1} and taken the ratio to produce the bottom panel of Figure 8. We assume that changes in the effective temperature are the cause of this variation, but we cannot rule out changes in the molecular formation process.

The carbon stars are shown in Figure 7. The main difference between these two stars is that Y CVn is J-type, i.e., it has a small $^{12}C/^{13}C$ ratio, $\sim$3.5, as opposed to a $^{12}C/^{13}C$ ratio of $\sim$44 for the N-type star VY UMa (Lambert et al. 1986). The difference is clearly visible in the strengths of the ^{13}CO band heads. We also note the continuum depression because of the addition of isotopic CO and CN in Y CVn.

6. DISCUSSION AND CONCLUDING REMARKS

It is beyond the scope of this paper to delve into the use of these spectra for MK classification. As noted in the introduction, classification criteria in several regions of the H-R diagram using *K*-band spectra have been discussed in a number of other papers. A prominent feature in the *K*-band spectra of many types of stars is the H 4–7 line Brγ. Several groups have used this line or at least present measurements on it. Since the spectra in this atlas span the F-A-B spectral region, which has not been presented in atlas form previously, and since this spectral region is one in which Br γ is a dominant feature, we have measured this line and present the result in Figure 9. The continuum levels were set by linear interpolation between the two 10 cm^{-1} wide bands centered at 4550 and 4766 cm^{-1}, and the effective temperatures were taken from Schmidt-Kaler (1982). In comparing our equivalent widths to those of KH86, we note that at spectral type G and later the results depend critically on the adopted continuum levels. Since our continuum level was optimized for Brγ and theirs was not, some of our results are very different from theirs. The comparison with Hanson et al. (1996), shown in Figure 9, does not suffer from the continuum placement problem and the agreement for stars common to both studies is very satisfactory. For the hot stars, we have included the 4625 cm^{-1} He I line in the Brγ equivalent width. Hanson et al. separated the two in some cases.

We feel that the spectra presented in this paper approach the limit of results possible with the Fourier transform technique. For brighter stars the spectra are of very high quality because of the broad bandpass, the mathematically defined instrumental profile, and the absence of scattered light or contamination by background radiation that are instrumental features of the FTS used for the observations. However, this instrument was not competitive with instruments using modern array detectors on fainter sources, and as a result the less infrared bright ends of the HR diagram were not fully observed. We intend that the spectra presented here be used for calibration of other spectra taken with much more sensitive spectrometers.

We thank Michael Mayer for use of his lists of MK standards and both him and Richard Joyce for valuable discussions. We also thank Dave Stultz for assistance at the telescope, setting up the FTS, assisting with the observations, and especially for tracking down the cause of the 60 Hz interference.

APPENDIX

STRUCTURE OF THE SPECTRAL FILES ON THE CD-ROM

The results of the final data reduction were stored in a series of ASCII files from which our plots and measurements were made. These files are available in computer-readable form in the AAS CD-ROM Series, Volume 9.

The file names have the form spec.xxxxxxxx, where xxxxxxxx is the HR number if available, or the star name otherwise. The first row of the file repeats the star name in more detail, and the second gives the date observed, the FTS scan numbers, the reference star, and other details, such as water vapor correction. The next four rows give titles for the columns as follows. The first is the frequency scale, where all stars have been interpolated onto a scale from 4150.0 to 4950.0 cm^{-1} at intervals of 0.5 cm^{-1}. The second column is the fully processed version of the spectrum, as described in § 3 above. The third is the fully processed difference of the forward and backward scans, which gives an objective measure of the S/N in the processed spectrum. The last column is a version of the spectrum that is processed but not filtered. Specifically, the notch filter designed to remove the 3.4 cm^{-1} $cycle^{-1}$ ringing and the apodizing filter were not applied. This version is included because, for some purposes, filtering can obscure relevant data.

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