CARBON MONOXIDE FUNDAMENTAL BANDS IN LATE-TYPE STARS.
III. CHROMOSPHERE OR CO-MOSPHERE?

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ABSTRACT

The strong vibration-rotation lines of CO at 4.6 μm (Δν = 1) are unique diagnostics for the thermal conditions in the atmospheric altitude range of late-type stars near and above the temperature minimum in chromospheric models. Exploiting recent improvements in IR instrumentation, we observed a number of cool stars with high spectral resolution (R ≈ 100,000). The analysis of the spectra was based on an earlier theoretical study which had established CO Δν = 1 non-LTE spectra as useful probes for stars of spectral type F, G, and K with log g ≥ 1.

No direct chromospheric indicators were detected in the CO spectra. Stellar boundary (CO) temperatures were determined for the program stars and temperature profiles were constructed for α Tau, α Boo, β Gem and β Dra. The CO-based models feature a steady decrease in temperature at the height where the temperature increases in chromospheric models. Further comparison with chromospheric indicators shows an increasing discrepancy between the temperatures determined from CO measurements and those predicted from radiative equilibrium models, respectively, with increasing chromospheric activity. Thermal bifurcation of the stellar surfaces is proposed to reconcile the contradicting scenarios derived based on different spectral diagnostics.

Subject headings: infrared: stars — line: formation — stars: chromospheres — stars: late-type

1. INTRODUCTION

The infrared (IR) vibration-rotation bands of carbon monoxide are powerful diagnostics for the physical conditions in late-type stellar atmospheres. Several studies have used the Δν = 2 lines of CO at 2.3 μm and higher overtones in the near-IR, which are more easily accessible from a technical standpoint than the fundamental Δν = 1 bands near 4.6 μm. The weaker overtone lines—used predominantly in abundance studies—form deeper in the stellar atmospheres, where LTE generally is valid. The Δν = 1 lines are unique diagnostics for the thermal conditions in the higher altitude range. The strongest Δν = 1 lines occur at or above the temperature minimum in chromospheric solar and stellar models. Observations of CO Δν = 1 bands in the Sun by Ayres & Testerman (1981) revealed large amounts of cool material at an altitude where previous studies based on observations in the visible and ultraviolet (UV), e.g., by Vernazza, Avrett, & Loeser (1981) and Ayres & Linsky (1975, hereafter AL), inferred chromospheric gas at temperatures about 1000 K higher. A similar, yet more qualitative dichotomy was found in Arcturus by Heasley et al. (1978). Although these studies clearly indicated the important role of CO in apparently inhomogeneous late-type stellar atmospheres, quantitative analysis of red giant spectra has been limited by the uncertain magnitude of non-LTE effects in the formation of the Δν = 1 bands at low temperatures and densities.

We began a new study of cool stellar atmospheres based on the measurement and analysis of CO fundamental spectra. Recent improvements in IR instrumentation increased the number of cool stars accessible to high-resolution spectroscopic observations (Wiedemann et al. 1989). A formalism was developed to treat departures from LTE in the CO Δν = 1 bands of cool stellar atmospheres (Ayres & Wiedemann 1989, hereafter Paper I). The spectrum synthesis code permits a more accurate interpretation of observed CO spectra. In a previous paper (Wiedemann & Ayres 1991, hereafter Paper II) we applied the procedure of Paper I to a range of stellar atmosphere models to study the CO spectrum and establish its use as a remote sensor of thermal conditions in late-type stars. We computed spectra for a series of radiative-equilibrium (RE) and semiempirical models to examine the sensitivity of CO Δν = 1 bands to several stellar parameters and assess the errors caused by their uncertainties. That investigation constitutes the basis for the analysis of observed CO spectra presented here.

2. OBSERVATIONS
2.1. Observing Runs

All stellar CO spectra in this study were acquired with the Fourier transform spectrometer (FTS) at the NOAO Mayall 4 m telescope on Kitt Peak (Hall et al. 1979). A summary of the observations is given in Table I. The first CO spectra were...
taken with the Goddard Postdispenser (PD) at one FTS output. The PD (Wiedemann et al. 1989) is a liquid-helium-cooled grating monochromator used as a narrow spectral lator behind large Fourier spectrometers. It increases the sensitivity of observations in the thermal IR by reducing background radiation noise. The PD bandpass was centered at 2142 cm\(^{-1}\) and extended from 2139 cm\(^{-1}\) to 2145 cm\(^{-1}\). This region contains a number of \(\Delta v = 1\) lines from many excitation states and of all CO isotopes. It is largely free of atmospheric contamination, with two strong telluric absorption features just outside the PD bandpass. Frequency calibration of the grating monochromator is provided by the FTS. The grating with 79.35 lines per millimeter operated in third order at 4.67 \(\mu\)m. A cold optical low-pass filter blocked the radiation from higher grating orders. Because of the InSb detector's long-wavelength cutoff at 5.5 \(\mu\)m, no radiation noise was contributed from the first and second orders. We operated the FTS at 0.03 cm\(^{-1}\) spectral resolution with an entrance aperture equivalent to a 2.7' field of view, slightly larger than the average seeing disk for most of the observing run.

A facility broad-band detector at the second FTS output served two purposes. First, the total signal in the narrow spectral band of a postdispenser is in many cases not sufficient to guide on the IR image of the source, whereas a broadband signal, usually from a shorter wavelength region, can often be used. Second, the broad-band signal is very helpful in locating the zero path difference position for the FTS mirror carriage, as well as later in the interferogram. The central fringe of a narrow-band signal is extended in interferogram space, and it can be impossible to distinguish the real white-light fringe from secondary fringes. To overcome this problem, the signals from the 2 \(\mu\)m broad-band detector and from the PD were coadded into one interferogram, after both signals went through separate, nonoverlapping electronic bandpass filters. This ensured that no noise from the broad-band channel would deteriorate the primary channel. The well defined central fringe then facilitates the computation of the spectrum in the narrow band in the Fourier transform. The lower signal level from the narrow band also required a higher preamplifier gain to avoid digitization noise in the A/D converter.

In this survey 13 stars of spectral type F5 to K5 were observed. Sirius (\(\alpha\) CMa, A0 V) served as a high-temperature reference star without spectral features in this frequency range. Available quick-look routines did not work satisfactorily on the narrow PD spectra; therefore, no real-time control of the spectra was possible during the observing run. For several of the fainter stars, the achieved signal-to-noise (S/N) ratios were not sufficient for a reasonable analysis of the CO spectra.

CO fundamental bands in the Sun are known to be subject to 5 minute oscillations as a result of global pressure waves in the outer atmosphere (Noyes & Hall 1972). To assess the feasibility of a search for stellar p-mode oscillations, the bright red giant Arcturus (\(\alpha\) Boo, K2 III) was observed in seven consecutive scans. Owing to the larger scale length in the atmosphere of this giant star, the expected period is longer than in the Sun and S/N considerations suggested 30 minute integration time per scan. Continuing the stellar oscillation program, we observed Arcturus again over three nights, 1988 May 6–8, in a series of 20 minute exposures to search for temporal changes in the CO fundamental spectrum. For this project the PD was used simultaneously with a facility 5 \(\mu\)m broad-band detector with separately stored signals. The results of this investigation will be reported elsewhere.

For further stellar observations with the PD in July 1987 we used a 2\(^{\prime}\) aperture and a smaller detector for a 3 cm\(^{-1}\) bandpass. We eliminated the optical blocking filter after identifying it as the source of fringe modulation. (Isolation of grating orders is not necessary with an FTS; higher system throughput usually compensates for the additional radiation noise contributed by secondary orders.) The Moon provided a celestial reference source for atmospheric correction.

Additional CO data were available from a previous stellar observing run in Dec. 1985, during which a 5 \(\mu\)m broadband detector was used at the second FTS output. The PD output was tuned to 12.32 \(\mu\)m for measurements of the solar Mg \(\iota\) emission lines in the giant stars \(\alpha\) Ori, \(\alpha\) Tau, \(\alpha\) Ari, and \(\alpha\) Boo (Jennings et al. 1986). The spectral resolution was 0.017 cm\(^{-1}\) and several hours integration time were necessary to reduce the thermal noise level sufficiently. The broadband detector at the second output was primarily used to provide a strong guiding signal. The detector signal, containing the range of the CO fundamental bands was electronically separated and coadded into the 12 \(\mu\)m interferogram. The NaCl long-wavelength beam splitter used in this experiment has a reduced modulation efficiency at 5 \(\mu\)m, but strong signal levels were obtained nonetheless due to the long integration times. 5 \(\mu\)m FTS spectra of some bright late-type stars are available from the Kitt Peak archives. For these data no reference spectra for atmospheric transmission exist. (Many of the interferograms were taken during bright time, but before the Moon was recognized as a sufficiently strong reference.) The spectra are also strongly contaminated by etalon effects, caused by a beam splitter without antireflection coated surfaces.

### 2.2. Data Reduction and Calibration

The raw interferograms were transformed into spectra using the NOAO facility Fourier transform program "Grammy." Additional phase corrections and calibration of the data were conducted at NASA/Goddard, using the FORTAN program.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Detectors</th>
<th>Spectral Resolution (cm(^{-1}))</th>
<th>Observed Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985 Dec 26–1986 Jan 1</td>
<td>10 (\mu)m PD/5 (\mu)m BB</td>
<td>0.017</td>
<td>(\alpha) Boo, (\alpha) Tau, (\alpha) Ori, (\alpha) Aur *</td>
</tr>
<tr>
<td>1986 Feb 22–1986 Feb 26</td>
<td>5 (\mu)m PD/2 (\mu)m PD</td>
<td>0.030</td>
<td>(\alpha) Boo, (\alpha) Tau, (\alpha) Aur, (\beta) Gem, (\beta) Dra*, (\epsilon) Vir*, (\beta) Crv, (\alpha) Cmi, (\alpha) Cma*</td>
</tr>
<tr>
<td>1987 Jul 4–1987 Jul 6</td>
<td>5 (\mu)m PD</td>
<td>0.030</td>
<td>(\beta) Dra*, (\beta) And, (\alpha) Boo, Moon*</td>
</tr>
<tr>
<td>1988 May 5–1988 May 7</td>
<td>5 (\mu)m PD/5 (\mu)m BB</td>
<td>0.010</td>
<td>(\alpha) Boo, Moon*</td>
</tr>
</tbody>
</table>

DECOMP, also originally developed at NOAO. The phase corrections are more critical in a narrow-band system, since the low-resolution transform of the central fringe area cannot resolve the narrow bandpass. It can therefore not correct for the asymmetries of long one-sided interferograms.

The instrument profiles were recorded with a featureless “calibration lamp” (hot soldering iron), placed in front of the FTS. Different beam-filling geometries were responsible for the occasionally different bandpass shapes for stellar and lab sources. Different paths traveled through the FTS by the infrared signal and the reference laser light result in a distortion of the length scale in the interferogram, causing a shift of the spectrum in velocity space. This effect is noticeable in broadband spectra, but emphasized only with steep features in the instrument profile (narrow fringes or steep filter). Fringing of any kind was carefully examined (via Fourier transform) for excess modulation at the fringing frequency, indicating incomplete removal of the instrument profile. Improperly removed wide filter fringes affect the determination of the true continuum level. This uncertainty can be reduced with a broadband spectrum of the same source: the observations of 1988 May were conducted with the PD at the first and a broadband detector at the second FTS output. Ratiointo the narrowband and broadband spectrum (corrected for instrument effects) yielded the true transmission function for the narrow-band detector.

Narrow fringes were caused by reflections at the back side of the long wavelength (12 μm) NaCl beam splitter used for the observations in 1986 December. The uncoated back surface acted as a second beam splitter and produced ghost interferograms, displaced from the “real” one by the optical thickness of the 2 cm thick beam splitter body. The beam splitter fringes are much narrower than the filter fringes and the numerical correction is more critical. The beam splitter fringes (0.155 cm^{-1} at 4.7 μm) are comparable in width to CO features and can, if not properly removed, affect line shapes and center frequencies, especially of weak lines in high-resolution spectra. The uncertainties introduced by channeling were in general less than or comparable to those due to the photon statistics. In 1986 February and 1987 July an AR-coated CaF2 beam splitter for 5 μm was used and channel spectra were detected only below the 1% level in very high S/N lamp scans.

Ratiointo a stellar spectrum and the air mass–corrected spectrum of a source without spectral features in the region of interest directly yields the “true” source spectrum, corrected for both instrument response and atmospheric transmission. During the 1986 February observation, Sirius (x CMa) was observed as a celestial reference source. The signal/noise of the reference spectra were not sufficient to ratio the high S/N stellar spectra without increasing the noise levels. However, the telluric lines in the PD bandpass could be identified and modeled in the stellar scans. The atmospheric conditions were excellent during the observing run, and the correction for water vapor lines was not critical. No celestial reference sources were observed during the 1986 December observing run, which was aimed at the detection of the Mg i lines, at 12.32 μm in a clean atmospheric region. Here the following procedure for the correction of CO spectra was employed: broadband high-resolution FTS spectra were obtained from the McMath archives, covering the region from 1.7 to 5 μm. Ratiointo two spectra taken at different air masses on the same day produces a spectrum free of lines of solar origin (a G2 star has an abundance of CO Aν = 1 lines), and corrected for instrument effects. The ratio spectrum then is scaled to the air mass of the stellar observation and used to identify or eliminate atmospheric contamination in stellar CO spectra. The limits of this procedure are set by different atmospheric conditions (water vapor) during the respective observations. Telluric lines were accounted for line by line where clearly identifiable in the stellar spectra. During the 1988 May observations of Arcturus, the Moon was available as a celestial reference source. The close examination of a high S/N lunar spectrum revealed only telluric lines: no reflected sunlight could be detected at 4.7 μm. Since the apparent diameter of the Moon (0.5) is much larger than the 50” separation of the FTS input apertures, a spot near the limb had to be observed with one aperture off the Moon. For beam switching, a spot on the opposite limb with similar brightness was observed.

The uncertainties in the derivation of line parameters from an observed spectrum due to atmospheric or instrumental effects can greatly be reduced if, as in the case of CO, several lines from from adjacent excitation states and almost identical line-forming conditions are accessible.

The noise in a postdisperser spectrum can be judged directly from the spectral region outside the bandpass, since the FTS distributes radiation noise evenly among all frequencies. In broad-band observations this information may not be available. The radiation noise can then be determined from the difference between separately stored forward and backward scans of a longer exposure.

While the frequency calibration of the FTS is in principle determined to a very high accuracy by the 6328 Å He-Ne reference laser, systematic shifts of the frequency scale of up to 1.7 km s^{-1} occurred in stellar spectra. These deviations were determined from the frequencies of unsaturated atmospheric lines (H2O, CO 1-0, O2, etc.) in stellar and reference spectra, compared to their rest frequencies. A shift of the velocity scale is caused by a multiplicative error in the length scale of the interferogram, for example, as a result of errors in the wavelength correction for the refractive index of air or by different optical paths traveled through the instrument by the infrared and the laser reference signal. It can be treated like an additional Doppler shift in the spectrum.

Line intensities and positions in the observed spectra were determined by least-squares fitting of theoretical profiles. The data analysis program DECOMP generates Voigt profiles with continuum level and damping coefficient as variable parameters. Since the CO lines in stellar atmospheres are turbulent velocity-broadened, both extremes of the Voigt convolution, the symmetric Gaussian and Lorentz functions reproduce the line center position with the same accuracy. For the determination of a line core intensity and position, the continuum levels were artificially fixed in the wings of the line below the level where blending with adjacent lines and possibly systematic velocity shifts occur. The main errors in the frequency and intensity determination are due to the correction of the spectra for atmospheric and instrument effects, (especially weaker lines in the wings of a telluric absorption feature or near a steep part of an instrument fringe) and not due to the line-fitting procedures.

The determination of the true continuum level is a fundamental problem in any astronomical absorption spectrum and is particularly acute in spectra of molecular bands with many overlapping lines. Wherever possible, the continuum level derived from broad-band observations (with line free-regions) was used in a consistent manner for the narrow-band spectra.
3. RESULTS AND DISCUSSION

3.1. Occurrence of CO Fundamental Bands in Stars of Spectral Type Later than F5

The spectrum of Procyon (F5, 1V–V, $T_{\text{eff}} = 6500$ K) (Ayres 1975) shows no CO lines above the noise. All clearly identifiable lines can be attributed to terrestrial absorption while none of the usually strong 0–1 lines occur at the correct Doppler-shifted position. The search for overtone lines in the 2 $\mu$m spectrum of Procyon also was negative. This supports the conjecture that no stable CO forming regions exist in stellar atmospheres with effective temperatures $\geq 6500$ K where not enough CO can be created to initiate molecular line cooling and overcome chromospheric heating.

In the Sun (G2 V, $T_{\text{eff}} = 5770$ K), CO lines have extensively been studied, e.g., by Noyes & Hall (1972) and Ayres & Testerman (1981). The warmest stars in our sample with observed $\Delta v = 1$ lines are $\beta$ Dra ($T_{\text{eff}} = 5373$ K, from Basri, Linsky, & Eriksson 1981) and the G5 giant $\beta$ Crv. The S/N ratio in the spectrum of $\beta$ Vir (F8 V) was insufficient for an identification of the expected weak CO lines. The theoretically predicted temperature instabilities (e.g., Johnson 1973; Ayres 1981) are supported by the detection of strong CO absorption spectra, but the investigation of CO-induced cooling requires more detailed modeling of the stars. Observed CO spectra of stars of spectral type F5 to K5 are shown in Figure 1.

Several M giants were also observed during this investigation. These IR-bright stars are easy observing targets, yet we exclude them from the discussion for several reasons: 1) The strong spectral lines are heavily broadened and blended, making the spectrum interpretation very difficult; 2) circumstellar material can contribute substantially to the observed photospheric spectra; 3) uncertainties due to departure from LTE caused by the very low surface gravities are large (see Paper II).

A large number of isotopic lines occur in the spectra of the red giants. The lines of $^{13}$C, $^{17}$O, and $^{18}$O are much stronger in most evolved stars than in the Sun (Fig. 1), as expected from the associated deep convective mixing of nuclear-processed material from their interior to the stellar envelopes. $^{13}$C/$^{12}$C ratios 5 to 10 times greater than solar have been determined for red giant stars, e.g., by Lambert & Ris (1981, hereafter LR) and Tsuji (1986), using, among other diagnostics, the CO $\Delta v = 2$ lines. The overtone lines are formed in LTE deeper in the atmospheres, whereas uncertainties in the non-LTE treatment of the strongest fundamental lines would strongly affect the accuracy of $^{13}$C/$^{12}$C abundance determinations. However, in an Arcturus-type atmosphere, the high-excitation $\Delta v = 1$ lines, as well as the $^{17}$O and $^{18}$O lines, are also largely unaffected by departures from LTE and can be used to determine isotopic ratios or verify the results derived from other spectral diagnostics.

Low-$v$ lines of $^{12}$C$^{17}$O, $^{12}$C$^{18}$O occur in $\alpha$ Boo, $\alpha$ Tau, $\beta$ Gem, $\alpha$ Hya, $\alpha$ Ari, and $\gamma$ Dra, e.g., 1–0 R6 of $^{12}$C$^{17}$O at 2141.5797 cm$^{-1}$ in $\alpha$ Hya, $\gamma$ Dra, and $\alpha$ Tau, all of which have nearly solar metal abundances and $\alpha$ Boo, a slightly metal-deficient ([Fe/H] = −0.5) giant. In this study we did not attempt to derive abundances and isotopic ratios. The abundance ratios reported by LR and Tsuji (1986) reproduce the isotopic lines in all of the observed fundamental spectra fairly well. There is no indication of vertical abundance gradients in the atmosphere. One aspect of CO fundamental band observations should be mentioned, however: lines from double-isotopic molecules provide a consistency test for observationally determined $^{16}$O/$^{18}$O and $^{13}$C/$^{12}$C ratios. These lines will not be detectable at 2 $\mu$m in most cases. In evolved, isotope-rich red giants, $^{13}$C$^{18}$O lines from low vibrational states can be identified, although many lines are affected by atmospheric contamination or blending with stronger lines. In the 2140–2145 cm$^{-1}$ window, the least-blended lines are 1–0 R33 at 2143.629 cm$^{-1}$ and 1–0 R32 at 2141.234 cm$^{-1}$. Again, the $^{13}$C$^{18}$O lines in Arcturus are weaker due to its reduced metal abundances.

Double-isotope CO line observations with a FTS/postdispersion system could be demonstrated; yet accurate analyses and abundance determinations need to include more lines than observable in the narrow spectral window of the single-detector postdisperser.

3.2. Velocity Measurements

Precision line profile measurements can be used to study the vertical velocity distribution in stellar atmospheres (Gray 1980) Ridgway & Friel (1981) report measurements of CO $\Delta v = 2$ bands in an investigation of convection and stellar
winds in red giant stars. The often used bisector method reveals asymmetries in spectral lines indicating the vertical gas velocity distribution. It is important that no instrumental and atmospheric effects or blending with other lines introduce asymmetries in the line profiles. The CO fundamental bands offer an alternative for vertical velocity studies in cool stars. The center frequencies of optically thick lines are representative of the relative velocity of the line forming region, which is well confined in altitude due to the LTE and near-LTE CO line formation. Fundamental and overtone bands probe the altitude range from the opacity minimum near 1.6 μm (in G and K stars) to the classical chromosphere.

The technique was applied to two sets of observations of Arcturus (K2 III). The results are summarized in Table 2. The CO rest frequencies, calculated from the Dunham coefficients given by Guellachvili et al. (1983), are much more accurate than required for the excitation states considered here. The lines were grouped into "weak" and "strong" lines according to their observed depths. The 2.3 μm and 4.7 μm spectra of the first set were recorded simultaneously with the PD and a broad-band detector, respectively. This allows a direct comparison of relative Doppler velocities since no errors are introduced by heliocentric velocity, instrument and atmospheric conditions. A frequency calibration using narrow laboratory lines in a gas cell was not performed during the observing run, which was aimed at a different scientific goal. The FTS/PD spectrum was calibrated using atmospheric lines in featureless stellar spectra taken on the same day and lamp scans containing the signature of water vapor in the FTS room. These lines are shifted by 1.7 km s⁻¹ with respect to their rest frequencies. The error in this number is large due to the weakness of the observed lines, but the shift is identical to the one determined during an earlier observing run for both the 12 μm and 5 μm region. Stronger atmospheric lines served to calibrate the 2.3 μm spectra, but indicates almost no difference between the observed atmospheric lines and their laboratory frequencies. We have no straightforward explanation for the large calibration effect. The correction of the frequency scale has a great impact on the result of the measurement. Adopting only the high S/N correction of the 2 μm lines, there is a clear trend of increasing redshift of line cores with increasing altitude of the line forming region, the strongest Δv = 1 lines being shifted by 400 m s⁻¹ with respect to the weaker Δv = 2 lines. The same trend can be seen, if the bands are considered individually, eliminating the uncertain frequency calibrations. The strong lines in both Δv = 1 bands and the overtone band are redshifted by 200 m s⁻¹ compared to the weaker lines in these bands. The relatively larger errors in the Δv = 1 spectra are due to the small number of weak lines in the PD bandpass and their lower S/N ratio.

The relative velocity shifts of the CO lines are small compared to the apparent collective blueshift of all CO Δv = 1 lines with respect to the stellar standard velocity: the lines in Arcturus show a systematic blueshift of 1.1 km s⁻¹ and 1.5 km s⁻¹ relative to the star in the spectra taken in 1986 February and 1985 December, respectively.

A different result was found for α Tau: here the velocities measured from CO Δv = 1 lines agree with the calculated relative velocity to within 100 m s⁻¹ for both observing runs. The apparent relative redshift of lines formed at greater altitudes contradicts the results previously reported for Arcturus by other groups. Because of our (for this purpose) inadequate observing procedures, we made no attempts to resolve these discrepancies. A remark seems appropriate, however: disagreement between the results of CO observations and atomic line measurements is not surprising in the context of spatially inhomogeneous models. Stellar winds likely originate in active regions, whose higher temperatures tend to suppress the molecular spectra. Precision velocity measurements of CO lines, which are representative of cool areas, may well develop into a powerful probe for the cool component of horizontal thermal inhomogeneities.

3.3. Chromospheric Indicators in CO Fundamental Spectra

CO fundamental line cores in cool giants can become optically thick above the altitude of the chromospheric temperature minimum. The strongest lines, as first predicted by Heasley & Milkey (1976), should exhibit central emission reversals if the chromospheric profile is similar to those derived for many late-type stars from the analysis of Ca II and Mg II lines. Heasley et al. (1978) did not detect core inversions in strong CO lines in their Arcturus observations conducted with 0.06 cm⁻¹ spectral resolution. Emission cores, if present, should have been clearly detectable with the higher instrument resolution of our 1986 February survey (0.03 cm⁻¹) and the 1986 December and 1988 May observations (0.017 cm⁻¹). However, in none of the observed late-type giants were line inversions actually observed.

Microturbulent velocities increasing in the chromosphere and non-LTE effects are possible explanations for the suppression of emission cores. A study of non-LTE effects in fundamental CO spectra by Carbon, Milkey, & Heasley (1976) qualitatively predicted considerable deepening of strong CO line cores in red giants. The magnitude of the line darkening

<table>
<thead>
<tr>
<th>Δv</th>
<th>Observed Shift</th>
<th>FTS Correction</th>
<th>Corrected Shift</th>
<th>Stellar Radial Velocity σ*</th>
<th>v_{CO-σ*}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986 Feb:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δv = 1</td>
<td>−24.79 ± 0.03</td>
<td>−1.72 ± 0.64</td>
<td>−26.51 ± 0.67</td>
<td>−25.4</td>
<td>−1.11</td>
</tr>
<tr>
<td>Δv = 2</td>
<td>−25.16 ± 0.10</td>
<td>+0.30 ± 0.10</td>
<td>−24.86 ± 0.20</td>
<td>−25.4</td>
<td>+0.54</td>
</tr>
<tr>
<td>1985 Dec:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δv = 1</td>
<td>−30.00 ± 0.47</td>
<td>−1.72 ± 0.64</td>
<td>−31.72 ± 0.45</td>
<td>−30.2</td>
<td>−1.52</td>
</tr>
<tr>
<td>Δv = 2</td>
<td>−30.25 ± 0.82</td>
<td>−1.72 ± 0.64</td>
<td>−31.97 ± 1.46</td>
<td>−30.2</td>
<td>−1.77</td>
</tr>
</tbody>
</table>

Notes.—Measured Doppler shifts (km s⁻¹) of CO lines in Arcturus. Observations of 1986 February were taken with 5 μm PD Δv = 1 and 2 μm broad-band detector Δv = 2, 1985 December spectra with 5 μm broad-band detector.
depends critically on the CO-H collisional cross sections, which were poorly known at the time. The impact of departures from LTE on the observability of emission cores is not discussed in their paper. Synthetic spectra computed from chromospheric models with new CO-H collision rates (discussed by Ayres & Wiedemann 1989) demonstrate that emission cores cannot be negated by non-LTE effects in typical K giants (Wiedemann & Ayres 1991): The departure coefficients in the CO spectrum computed from the chromospheric AL model for Arcturus are close to unity in the line-forming regions. The resulting quasi LTE lines clearly reflect the temperature inversion in their emission cores. Non-LTE effects are stronger at the lower temperatures and densities of the Kelch et al. (1978) Aldebaran model and sufficient to deepen the cores of some vibrational lines below the inversion point. However, near-LTE still prevails above the temperature minimum for many lines. No realistic choice of CO-H cross sections caused the disappearance of all line core inversions in the synthetic spectra. It is possible, however, to explain the lack of observed core inversions in CO fundamental lines by increasing microturbulences, \( \xi \), at chromospheric heights. In a synthesized spectrum with \( \xi = 2 \, \text{km s}^{-1} \) below the temperature minimum and increasing to 10 km s\(^{-1} \) in the higher chromosphere, all the emission cores are broadened and indiscernible. An increase of \( \xi \), with height has been suggested (e.g., AL) to improve the agreement between theoretical and observed UV/visible spectra. The turbulent velocity as a function of altitude, however, need not be similar in hot chromospheric and cool CO regions in a bifurcated atmosphere model and a turbulent velocity profile which negates the line emission cores in the hot regions could easily be constructed. While the lack of observed emission cores in CO lines by itself does not contradict the existence of chromosphers, the large depths of CO \( \Delta v = 1 \) lines in observed spectra indicate that the assumption of spatial homogeneity of the Ca \( \mathrm{II} \)–Mg \( \mathrm{II} \) emitting regions is severely violated.

3.4. Stellar Boundary Temperatures

Stellar boundary temperatures can be determined from atmospheric models that reproduce the observed CO spectra. To begin with, these models assume homogeneous surface coverage and are not designed to match any of the observed chromospheric diagnostics.

The effect of CO opacity on the temperature structure of the outer atmospheres of cool stars was investigated theoretically by Johnson (1973). Cooling in optically thin CO fundamental and overtone lines lowers the stellar boundary temperature, \( T_b \), by several hundred K compared to the models without CO opacity. The observational deduction of \( T_b \) is somewhat ambiguous, since the location of the line formation depends on several critical stellar parameters and varies substantially for different models. For consistency we take for the boundary temperature of the theoretical models that value of \( T \) at optical depth unity of the strongest line [\( T_{\text{CO}}(\max) = 1 \)] in the observation-based model. The choice of the exact location of \( T_b \) on the mass column density scale, \( n(T_b) \), is uncertain since \( T \) is approximately constant in the outer layers of the radiative equilibrium models.

Molecular opacity effects are also included in the RE models of Bell et al. (1976, hereafter BEGN), which, with respect to the effect of CO cooling, are in good agreement with Johnson's results. These models, like the Johnson models, naturally differ greatly from the semiempirical chromosphere models, which exhibit dramatic temperature increases above the photosphere, presumably as a consequence of non-radiative heating.

The boundary temperatures in the BEGN models are taken from their highest layers, which for the cooler models are much deeper than \( \log m(\text{g cm}^{-2}) = -2 \). Using the temperature of the highest layer of the BEGN models as boundary temperature seems justified if, as indicated by many of Johnson's models, the temperature is approximately constant in the higher layers. Increasing non-LTE effects are likely to reduce the cooling efficiency of the strongest fundamental lines above \( \log m = -1 \) and should, in addition to the decreasing number of optically thin lines contributing to the cooling, prevent a drastic temperature decrease. (A temperature drop in very cool stars can result from the onset of molecular cooling mediated by other species [SO, H\(_2\)O] at very low temperatures [Muchmore, Nuth, & Stencil 1987].)

One can define a ratio \( T_{B/E} = T_b/T_{\text{eff}} \),

which is useful in a comparison of the various theoretical and empirical models. The discrepancies between the Johnson and BEGN boundary/effective temperature ratios are small.

3.5. The Stellar Models

Temperature-mass column density \( (T, m) \) profiles were derived for \( \alpha \) Boo, \( \alpha \) Tau, \( \beta \) Gem, and \( \beta \) Dra by fitting synthetic to observed CO spectra. Starting from the available chromospheric models, the temperature profiles were iteratively modified until a good match with the observed spectra was obtained at all altitudes. For \( \alpha \) Hya, \( \epsilon \) Vir, \( \beta \) Crv, and \( \gamma \) Dra boundary temperatures were extracted from the core intensities of the strongest fundamental lines, using the results of the sensitivity study of Paper II. The full non-LTE code was used for most of the stellar models, because departures from LTE in the cooler stars can be considerable.

1. \( \alpha \) Tauri (K5 III). — The atmospheric profile in Figure 2 was obtained from matching synthetic spectra to the observed postdisperser and broad band spectra of \( \alpha \) Tau. It is based on the semiempirical model of Kelch et al. (1978) for the photosphere below the temperature minimum, with \( T_{\text{eff}} = 3800 \) K and \( \log g = 1.4 \). The atomic carbon abundances determined for \( \alpha \) Tau by (LR) and Tsuji (1986) agree to within 0.1 dex.

![Fig. 2.—\( \alpha \) Tau: CO-based model (this work, dotted line) and chromospheric (solid line) model (Ayres & Linsky 1975).](image-url)
Tsuji's result \([\text{C/H} = -0.30 \pm 0.14]\) was adopted since it was directly derived from measurements of LTE CO lines. The C/O and the \(^{12}\text{C}/^{13}\text{C}\) ratios as well as the microturbulence (2 km s\(^{-1}\)) were taken from LR. The lowest temperature determined from the intensities of the strongest lines (2-1 R6, 2-1 R7, 3-2 R14, 3-2 R15) was 2350 K near log \(m = -2\). The deduced \(T_{\text{BB}}\) of 0.62 agrees with the theoretical values of 0.62 interpolated from Johnson's models and 0.63 from BEGN. The temperatures observed in CO are clearly lower than \(T_{\text{min}}\) in the chromospheric model and the disagreement between the CO empirical and chromospheric models is striking at high altitudes.

Errors in the determination of \(T_{\text{BB}}\) are caused by uncertainties in \(T_{\text{eff}}\), abundances, \(g\), and non-LTE effects in the strongest lines. Errors in \(T_{\text{eff}}\) have almost no consequences for the determination of \(T_{\text{BB}}\) from the observed spectrum, because of: 1) the nearly linear temperature dependence of the Planck curve at 4.7 \(\mu\)m; and 2) the weak temperature dependence of the collisional CO-H cross sections which determine the magnitude of non-LTE line deepening. LR use \(T_{\text{eff}} = 4140\) K in their analysis of CNO abundances in \(z\) Tau. The temperature ratio \(T_{\text{BB}}\) is barely affected by the 340 K temperature difference for the line-to-continuum ratio dictated by the observed spectrum.

Uncertain abundances also minimally affect the interpretation of line intensities in terms of boundary temperatures: due to the flat temperature structure above log \(m = -1.0\), errors in the carbon or (to a lesser extent) oxygen abundances affect primarily the location of CO line formation but not the brightness temperature. The errors for the C/H ratio in \(z\) Tau are 0.2 dex or less (Tsuji 1986; LR). The corresponding effects on the line intensities are equivalent to a temperature uncertainty of \(\pm 30\) K.

The main error sources are uncertain surface gravity and CO-H collisional cross sections. Reported values for \(g\) in \(z\) Tau were discussed by Kelch et al. (1978). More recently determined values include log \(g = 1.25\) (Bonnell & Bell 1993) and log \(g = 1.2\) (Bell & Gustafsson 1989). These are less than our adopted value but still within the error of \(\pm 0.2\) for log \(g\) given by Kelch et al. (1978). Their quoted error corresponds to an uncertain density scale of \(\pm 50\)%. A density decrease of 50% in the CO line-forming region would cause deeper non-LTE lines. This would have to be balanced by a temperature increase of 50 K to reproduce the observed intensities.

Due to the low gravity and temperature of \(z\) Tau, errors in the collisional CO-H cross sections translates into considerable uncertainties for the non-LTE portion of observed line intensities. Reducing the Glass & Kirden rates (Glass & Kirden 1982, hereafter GK) by a factor of 3 increases the boundary temperature indicated by the observed line depths by \(\approx 150\) K. A detailed comparison of theoretical and observed spectra could reduce this uncertainty, because line intensity ratios are affected in different ways by changes in temperature and collisional cross sections (provided their \(v\)-dependence is known). However, such a computationally intensive effort is beyond the scope of the present work. In addition, the critical \(v\)-dependence of the CO-H reaction rate is uncertain. Nevertheless, the error in the derived boundary temperature is small enough not to alter our ultimate conclusions.

2. \(\gamma\) Draconis (K5 III).—\(\gamma\) Dra is a red giant similar to \(z\) Tau. Its surface gravity (log \(g = 1.55\)) and effective temperature \((T_{\text{eff}} = 4280\) K) are given by LR. The CO spectrum of \(\gamma\) Dra was obtained from the Kitt Peak archives. It is compatible with a spectrum generated from an interpolated BEGN RE model. The depths of the strongest lines, corrected for non-LTE effects, indicate \(T_{\text{BB}} = 0.6\), which is in agreement with the predicted value. The errors are somewhat larger than in \(z\) Tau due to the lower S/N in the spectrum.

3. \(\alpha\) Hydrea (K3 III).—The broad band spectrum of \(\alpha\) Hya (from the Kitt Peak archives) also is very similar to the spectra of \(z\) Tau and \(\gamma\) Dra. Again, the S/N in the observed spectrum is lower, and detailed spectrum synthesis was not performed here. The boundary temperature is estimated from the depths of the strongest lines relative to the continuum. The adopted gravity of log \(g = 1.86\), taken from LR, leads to an estimated non-LTE contribution of 10% to the observed line depth. This yields a \(T_{\text{BB}}\) of 0.54, lower than expected from the Johnson value of 0.60. The discussion of the uncertainties follows the arguments used for \(z\) Tau and \(\gamma\) Boo, with errors due to non-LTE effects slightly smaller as a result of the higher gravity, but overall greater due to the lower quality of the observations. Adopting the lower gravity of log \(g = 1.6\) (Bonnell & Bell 1993) increases \(T_{\text{BB}}\) as a greater portion of the observed line depths is attributable to non-LTE effects. The discrepancy with the Johnson value of 0.60 is therefore reduced.

4. \(\alpha\) Bootis (K2 III).—The model that best matches the observed CO spectrum (Fig. 3) of Arcturus is shown in Figure 4. The model is identical to the AL model for the upper photosphere. The parameters for the AL model are \(T_{\text{eff}} = 4250\) K and log \(g = 1.7\). The temperature minimum of 2700 K, derived from the UV/visible observations, occurs at log \(m = 0\). The weaker CO lines in the observed spectra can be well reproduced with the AL model for the photosphere. The intensities of the strongest CO lines, forming near log \(m = -1.5\) require a boundary temperature of 2400 K, with no indication for an outward temperature increase at any altitude. The CO based model begins to deviate from the AL model near the onset of the chromospheric temperature rise.

The boundary temperature in the empirical CO model is considerably cooler than predicted for Arcturus by Johnson (1973). This difference does not affect the bifurcation model for Arcturus, but ways to improve the agreement and the errors in the empirical (and theoretical) models should be examined nonetheless. The arguments are similar to those used for \(z\) Tau. The errors introduced by non-LTE effects are smaller, however, at the higher temperature and gravity of Arcturus. It is virtually impossible to explain the deeper absorption lines in

![Fig. 3.—\(\alpha\) Boo: observed and computed CO spectra](image)
terms of an error in the atomic carbon abundance. The C/H ratio would have to be increased by a factor of at least 3 in the near-LTE atmosphere of Arcturus in order to produce the observed line depths with $T_e = 2780$ K. This is much larger than the errors for the carbon abundance (Tsuji 1986; Kjærgaard et al. 1982) and would also degrade the match between observed and predicted weak lines. Similarly, as can be seen from the theoretical analysis, the uncertainty in surface gravity of $\pm 0.2$ on log $g$ (Ayres & Johnson 1977; Kelch et al. 1978; Bonnell & Bell 1993; Bell & Gustafsson 1989) is too small to sufficiently alter the line intensities through stronger non-LTE line deepening and stronger CO cooling of the atmosphere under reduced gravity.

There is still some scatter in the values for the effective temperature of Arcturus published by different authors. AL adopt 4250 K in their semiequilibrium model. Other values include 4375 K (Frisk et al. 1982) 4490 K (LR), and 4321 K (Bell & Gustafsson 1989). For further discussion see Peterson, Dalle Ore, & Kurucz (1993). Again, the exact value of $T_{\text{eff}}$ is not critical, because the parameter $T_{\text{eff}}$ was used to quantify the agreement between semiequilibrium and theoretical models and can be derived almost directly from the ratio of the line core intensity to that of the continuum and thus is nearly independent of $T_{\text{eff}}$.

Line depths similar to those in the ($T_e = 2400$ K) model are obtained with a boundary temperature of 2700 K, if the ($v$-independent) collisional CO-H cross sections are reduced by a factor of 3. These cross sections would be similar to the lower experimental limit of GK, but significantly lower than those derived from Wight & Leone (1983). The $^{13}$CO 1–0 lines, formed closest to LTE, then appear too shallow, however, and the higher boundary temperature causes 3–2 R14 to be stronger than 2–1 R6, clearly in conflict with the observations. One has to keep in mind, however, that arguments of this kind rely on assumptions about the $v$-dependence of CO-H relaxation rates, which must be tested directly in future laboratory work. Possible explanations for the discrepancy can also be sought in the Johnson model for Arcturus, which does not allow for atmospheric cooling by other molecular species, as suggested by Muchmore et al. (1987) and also possibly overestimates the effect of atomic line blanketing which (like CO) was treated in LTE. Furthermore, the Johnson model (and all of the other stellar RE models) are hydrostatic: it is possible that hydrodynamical effects like convective overshooting might produce localized regions cooled by adiabatic expansion, which are temporarily much cooler than the RE boundary temperature, particularly in the outermost layers where the radiative heating (and cooling) timescales are long.

The fact that the boundary temperature of Arcturus is apparently lower than predicted by previous numerical simulations should not be overrated. The empirical model derived from CO observations is clearly compatible with a radiative equilibrium-type atmosphere with a very low boundary temperature.

5. $\beta$ Gemini (K0, III).—The observed $\beta$ Gem spectrum can best be reproduced with the $T$, $m$ profile of Figure 5 which is based on the model constructed by Kelch et al. (1978). The chromospheric temperatures were lowered until a reasonable match with the observed spectrum was obtained. Carbon abundance relative to hydrogen (3 x 10$^{-4}$) and $^{12}$C/$^{13}$C ratio (18) were taken from a compilation by Harris, Lambert, & Smith (1988). Owing to the relatively high gravity of log $g = 2.9 \pm 0.2$ (Kelch et al. 1978), non-LTE effects barely affect the strongest lines which form at log $m \approx -1.5$ g cm$^{-2}$. The temperature here is 3320 K, considerably cooler than in the Kelch et al. (1978) model, but approximately 200 K above the value expected from an RE atmosphere. The largest uncertainty in $T_e$ arises from the S/N in the observed spectrum. The estimated boundary temperature error is $\pm 140$ K. Adopting $T_{\text{eff}} = 4898$ K and log $g = 2.8$ (Bell & Gustafsson 1989) leads to virtually the same result.

6. $\varepsilon$ Virginis (G8 II–III).—The observed spectrum of $\varepsilon$ Vir is strongly affected by noise. However, the 65% deep CO absorption lines, expected from a red giant with $T_{\text{eff}} = 5300$ K and log $g = 3.2$ (LR) are not observed. The derived $T_{\text{eff}}$ is $0.82 \pm 0.1$; the estimated error is largely due to the S/N in the observed spectrum. Adopting $T_{\text{eff}} = 5052$ K and log $g = 2.7$ (Bell & Gustafsson 1989) increases the portion of the line depth attributable to non-LTE effects and therefore increases the derived temperature as well as the discrepancy with a RE model, but because of the higher gravity the effect is much smaller than in the case of $\alpha$ Hya and stays well within the error limits. Unlike the cooler giants, $\varepsilon$ Vir thus is very poorly represented by a homogeneous atmospheric model in radiative equilibrium.

7. $\beta$ Coron (G5 II).—The S/N in the observed spectrum did not justify extensive modeling of the atmosphere of $\beta$ Crv. No values for $g$ are reported in the literature. The gravity was therefore estimated using the tables by Allen (1983).
adopted log \( g \) of 2.3 together with the relatively high stellar temperature result in minor non-LTE effects. The main uncertainties are again due to the low S/N in the spectrum. \( T_{\text{eff}} \) is derived as 0.77 ± 0.08, which is higher than the RE value of 0.69.

8. \( \beta \) Draconis (G2 II).—The greatest discrepancy between the theoretical RE model and the CO empirical model is found for the supergiant \( \beta \) Dra. The chromospheric model derived by Basri et al. (1981) was used to estimate the temperature in the highest CO line-forming region in \( \beta \) Dra. The S/N in the observed CO spectra was too low to analyze the weaker lines in the spectrum. The strongest lines reach an average depth of 75% of the continuum level. The spectrum synthesis calculation uses the log \( g \) = 1.35 of Basri et al. (1981) and solar carbon abundance. The non-LTE calculation with these parameters indicates \( T = 4500 \) K at log \( m = 0.9 \), where \( \tau = 1 \) occurs for the strongest lines. The line cores thus form at the altitude of the chromospheric temperature minimum; consequently, no information is available concerning higher layers. Since the errors due to the low S/N ratio in the observed spectrum are considerable, a detailed investigation of other sources of error is futile.

As noted by Basri et al. (1981), lowering \( T_{\text{min}} \) (4800 K) in the chromospheric model for \( \beta \) Dra by 300 K has little effect on their analysis; the observed CO spectrum can be reproduced with the chromospheric model atmosphere with a slightly lower \( T_{\text{min}} \) and therefore does not contradict the results inferred from UV diagnostics. Unlike for the red giants, the existence of cool regions without a chromosphere cannot be claimed based on these observations. The coolest temperature indicated by CO observations of \( \beta \) Dra, (assuming a homogeneous atmosphere), is clearly much higher than expected from a RE model with \( T_{\text{eff}} \) = 5375 K and log \( g \) = 1.4.

9. Summary.—The attempt to model stellar atmospheres based on CO observations can be summarized as follows. The atmospheres of one group of stars (\( \alpha \) Boo, \( \alpha \) Tau, \( \alpha \) Hya, and \( \gamma \) Dra) are well described by homogeneous radiative equilibrium models if they are extended into the CO fundamental line-forming regions. A second group, consisting of earlier spectral types G5–K0 (\( \beta \) Gem, \( \beta \) Crv, \( \epsilon \) Vir, and \( \beta \) Dra), is poorly represented by RE models. Their apparent boundary temperatures are too high for homogeneous RE atmospheres.

Accurate quantitative investigations of low-gravity stars suffer mostly from uncertainties in the molecular parameters (collisional cross sections). In addition, the sensitivity of available instrumentation limits accessible stars to a rather small sample. With these limitations in mind, we define a parameter \( \delta \) to quantify the difference between observed and expected (CO-induced) temperature depression in the outer atmosphere:

\[
\delta = \frac{T_{\text{d}}(\text{observed}) - T_{\text{d}}(\text{predicted})}{T_{\text{eff}}}
\]

The parameter \( \delta \) is useful in demonstrating the connection between a lack of CO activity and chromospheric activity, which will be examined next.

3.6. Comparison with Chromospheric Diagnostics

Table 3 compares the deltas, \( \delta \), determined from the CO observations with results from observations of spectral diagnostics representative of chromospheres and higher excitation conditions. Chromospheric indicators include the He i line at 10830 Å and the Mg ii 2800 Å doublet. Spectral indicators for chromospheric and other high-atmosphere activity and the correlations between them have been discussed by Ayres, Marstad, & Linsky (1981). The He i line at 10830 Å was analyzed in a large sample of stars, containing most of the stars of this program, by O'Brien & Lambert (1986). The flux ratios \( f_{\text{Halpha}}/f_{\text{bol}} \) for Mg ii, other high temperature lines, and X-rays were taken from a compilation by Ayres et al. (1981). A detailed analysis of the various chromospheric diagnostics and their relation to CO is not warranted here, but a clear trend is visible if \( \delta \) is compared with the average chromospheric activity for each star: Stars that have CO boundary temperatures equal to or less than expected from RE models (\( \alpha \) Boo, \( \alpha \) Tau, \( \alpha \) Hya, and \( \gamma \) Dra) show little chromospheric activity.

The CO-based models clearly are incompatible with the existing semiempirical chromospheres for the low-activity red giants. The formation of CO lines and chromospheric indicators at similar altitudes is confirmed by the models. The dilemma posed by the different temperature profiles cannot be resolved within the severe constraints of a laterally homogeneous model.

In \( \beta \) Dra, the prototype of a chromospherically active star with a large chromospheric line flux/total luminosity ratio, the molecular component is far less pronounced than in the appropriate RE atmosphere. \( \beta \) Gem, \( \beta \) Crv, and \( \epsilon \) Vir follow the overall trend with a modest but clear CO cooling deficit \( \delta \) and moderate chromospheric activity. Interestingly, the reported temporal He i flux fluctuations are much stronger in \( \alpha \) Boo, where the relatively weak absorption/emission line equivalent

<table>
<thead>
<tr>
<th>Star</th>
<th>( \delta )</th>
<th>( W_{4} ) (10830 Å)</th>
<th>( C^{4} ) (1550 Å)</th>
<th>( Si^{4} ) (1815 Å)</th>
<th>( Mg^{2+} ) (2800 Å)</th>
<th>0.25 keV X-Rays</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
</tr>
<tr>
<td>( \alpha ) Boo</td>
<td>0</td>
<td>41E–145A</td>
<td>0.04</td>
<td>0.6</td>
<td>95</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>( \alpha ) Tau</td>
<td>0</td>
<td>30</td>
<td>&lt;0.01</td>
<td>0.4</td>
<td>60</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>( \alpha ) Hya</td>
<td>0</td>
<td>255</td>
<td>&lt;0.08</td>
<td>0.5</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>( \gamma ) Dra</td>
<td>0</td>
<td>54E–235A</td>
<td>&lt;0.04</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta ) Gem</td>
<td>0.04</td>
<td>120</td>
<td>0.2</td>
<td>1.2</td>
<td>93</td>
<td>0.4</td>
</tr>
<tr>
<td>( \beta ) Crv</td>
<td>0.09</td>
<td>120</td>
<td>0.2</td>
<td>1.3</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>( \epsilon ) Vir</td>
<td>0.13</td>
<td>230</td>
<td>0.4</td>
<td>1.4</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>( \beta ) Dra</td>
<td>0.21</td>
<td>935–1285</td>
<td>9</td>
<td>12</td>
<td>660</td>
<td>30</td>
</tr>
</tbody>
</table>

Notes.—Col. (2) CO "cooling deficit" \( \delta = T_{\text{d}}/T_{\text{eff}} \) (observed) – \( T_{\text{d}}/T_{\text{eff}} \) (predicted); \( \delta \) is set equal to 0 if difference < 0; col. (3) \( H_{\alpha} \) line equivalent widths (O'Brien & Lambert 1986); A = absorption, E = emission. Cols. (3)–(6) Fluxes divided by total flux of the stars (\( f_{\text{Halpha}}/f_{\text{bol}} \) (Ayres et al. 1981). Cols. (2)–(5) represent chromospheric activity indicators. The difference between \( \delta \) and zero is a measure for the deviation of the observation-based CO model from a radiative-equilibrium atmosphere.
width changes by a factor $\approx 15$ over several months, than in $\beta$ Dra, where the flux ratios are 10–100 times greater, but the variations are only of the order of 30%. In the proposed bifurcation model for cool stellar atmospheres this result can be used to place limits on the geometrical filling factor for cold and hot areas, under the additional assumption of a nearly constant temperature of the molecular gas, fixed by temperature instabilities similar to those predicted for the Sun (Kneer 1983). A test of the bifurcation theory and the interpretation of stellar spectra in terms of fractional surface coverage by hot and cold atmosphere components could be provided by simultaneous observations of intensity fluctuations of diagnostics representative of the different thermal profiles. Such observations do not exist yet. In fact, only in the case of Arcturus is even the temporally uncorrelated magnitude of fluctuations of CO and He I spectra approximately known.

3.7. Thermal Bifurcation

To resolve the dilemma posed by observational results demanding different types of atmospheric structures at chromospheric altitudes, a two-component model with physically distinct areas of hot and cool material at the same altitude very likely would provide a better representation of cool stellar atmospheres than existing homogeneous one-component models of either type. Such a thermal bifurcation model for the Sun has been proposed and discussed in detail by Ayres (1981) and Ayres, Testerman, & Brault (1986). The numerical simulations by Kneer (1983), Muchmore (1986), and Anderson & Athay (1989) for the solar case suggest that two physically distinct states of a stellar atmosphere can coexist if molecular cooling and nonradiative energy dissipation govern the atmospheric temperature structure. Simulations for stars other than the Sun have not yet been performed, by similar thermal instabilities mediated by CO or other molecules (Muchmore et al. 1987) can be expected under different gravity and effective temperature. The empirical stellar bifurcation model assumes a division of the stellar atmosphere into two distinct types of areas: one which is controlled by molecular cooling, represented by a radiative equilibrium model atmosphere with CO-induced temperature depression, and a second component that features a temperature inversion produced by the deposition of “mechanical” energy. In the bifurcation model, the observed disk-averaged spectrum must be interpreted as the spatial sum over the two types of thermal regions with appropriate geometrical weighting factors. The interpretation is straightforward only if one component contributes substantially to the particular spectrum and it occupies the majority of the stellar surface. This may be the case, for instance, for CO in the stars for which the cool component occupies the majority of the stellar surface. On the other hand, even if the temperatures in the cool areas are such that they do not contribute to the line spectrum of the chromospheric indicators, the observed spectrum will still be spatially diluted if the hot component occupies only a small area. If cool and hot areas are comparable in area, both the IR and UV/visible spectra will be affected by spatial dilution, and the properties of the two components must be derived carefully in order to reproduce the composite spectra. Fortunately, two factors facilitate the task: 1) RE models contribute little to the UV line flux; 2) the temperature structure of chromospheric areas must be altered from the spatially homogeneous case if the fractional area is reduced, in order to reproduce the total observed flux. The necessary temperature increase can be substantial if the hot component occupies a small fraction of the total area. A temperature increase of considerable magnitude reduces the abundance of CO at chromospheric heights. CO therefore contributes little in the “enhanced” chromospheric areas.

The program stars can now be arranged in groups of increasing chromospheric and decreasing cool area dominance.

1. $a$ Boo.—The CO observations confirm the picture of Arcturus as a “quiet star.” The deduced temperature profile imposes severe limits on the role of chromospheric areas. This result is further supported by the observed magnitude of temporal fluctuations in the He 10830 Å line flux, which is known to vary by a factor $>15$ over several months (O'Brien & Lambert 1986). In a simple two-temperature model where the flux is only proportional to the area covered by the respective component, $f_{\text{hot}}$ could therefore not exceed a few percent. The geometrical interpretation must of course be used with great caution. Fluctuations in the chromospheric line fluxes can also be triggered by temperature changes as a result of temporarily varying energy deposition. If cool areas are transformed into hot areas and vice versa, a decrease in chromospheric flux must be accompanied by an increase in CO absorption. Synchronously observed chromospheric line and CO absorption variations would be very valuable in determining accurate filling factors for stellar surfaces and testing the geometrical bifurcation interpretation. Indications of variations in the CO line intensities of $\approx 2\%$ can be seen in the Arcturus spectra taken in 1986 February and 1987 July. If a flux change of this magnitude were correlated with the observed He I line flux change, it would imply a “cool” filling factor for Arcturus in excess of 99%. This would have considerable impact on the temperature structure of the hot areas, since the area-reduced model must produce the same total flux as the previously assumed homogeneous chromosphere.

In order to estimate the necessary changes in a homogeneous chromosphere, we synthesized a series of Ca II K line profiles with the AL model atmosphere of Arcturus. This was done with a modified version of the partial redistribution code (PRD) (AL) for a three-level continuum model Ca I line. The chromosphere was assumed to occupy 10% of the total surface. An atmosphere profile derived from the CO observations represented the remaining fraction. The chromospheric temperatures were increased until the spatially averaged line profile was identical to the one generated by the homogeneous, cooler chromosphere (AL). The cool portion of the surface was found not to contribute to the Ca II emission line. The chromospheric temperature increase necessary to preserve the total flux with a smaller emitting area is only a few hundred degrees because of the strong temperature sensitivity of the short-wavelength flux on the Wien side of the Planck curve. The radiation transfer in the Ca K line is largely controlled by the nonlocal radiation field. The spectral line profile is therefore not very sensitive to the detailed temperature structure of the chromosphere, which can likely be modified to accommodate other observational constraints. If chromospheric areas occupied a few percent or less of the stellar surface on Arcturus, then the contribution to the averaged CO spectrum is negligible. The required temperature increase in the area-reduced chromosphere furthermore leads to rapid destruction of CO through dissociation.

2. Other CO-dominated Stars ($\alpha$ Hyd., $\alpha$ Tau, $\gamma$ Draconis).—For the group of stars including $\alpha$ Hya, $\alpha$ Tau, and $\gamma$ Dra similar conclusions can be drawn as in the best investi-
gated case of Arcturus. The CO spectra indicate the dominance on the stellar surfaces of cool regions having large filling factors. No CO cooling deficit can be derived from the observations. The chromospheric activity, on the other hand, is comparatively weak.

γ Dra shows similar large variations in the observed He line flux as Arcturus. All these stars appear to have the largest portion of their surfaces occupied by radiatively cooled material. The observed chromospheres likely emerge from hot spots covering a very small fraction of the total surface area.

3. β Geminorum, ε Virginis, β Corvi.—The modest CO cooling deficit, derived in the preceding paragraph, interpreted in terms of a fractional surface coverage, leads to a geometrical filling factor of 90% for the cool chromosphereless areas on β Gem. Not neglecting the considerable margin for errors, this result is in good agreement with the 10% coverage derived by O'Brien & Lambert (1986) for hot areas on β Gem. Additional CO measurements with better altitude resolution are clearly desirable.

The two relatively warm stars β Crv and ε Vir are related to β Gem in their CO and chromospheric appearance: The moderate disagreement between CO spectra and theoretical models is accompanied by enhanced chromospheric activity as indicated by the He line and X-ray flux and other high-temperature line luminosity ratios.

4. β Draconis.—The observed CO spectrum of β Dra is compatible with a chromosphere covering the stellar surface homogeneously. The CO observations do not contradict the results gained from the high-excitation diagnostics, but they clearly rule out a homogeneous radiative equilibrium—e.g., BEGN-type—atmosphere. If one adopts the requirement that the CO spectrum emerges from a radiative equilibrium atmosphere occupying a fraction of the stellar surface, then the filling factor of cool material cannot exceed 50%. If, on the other hand, the fluctuations in the observed He line flux are interpreted as variations in the filling factor of hot areas, then the relative small change (30%) in He line equivalent widths (O'Brien & Lambert, 1986) compared to Arcturus, together with the large He line flux/total luminosity ratio, suggests a large $f_{H_\alpha}$ for β Dra. A realistic two-component model for β Dra would have to be constructed to reproduce the averaged spectrum from cool and hot regions, since owing to its much larger geometrical weight the chromospheric component must contribute substantially to the observed disk-averaged CO spectrum. The poor quality of the existing CO spectra of most active stars does not warrant such an effort yet. In addition, numerical simulations for the behavior of CO mediated temperature instabilities, as described by Kneller (1983) for the Sun, are necessary.

4. MOTIVATION FOR FUTURE WORK

The study of cool star upper atmospheres will greatly benefit from better observations. The development of large cryogenic grating spectrometers, now under way at several institutions, is an important step toward improving the sensitivity of infrared observations far beyond the limits of the present FTS/postdispersion system. The study of thermal bifurcation in stellar atmospheres requires a much broader observational basis, which includes fainter dwarf stars and stars of different activity levels. Coordinated observations at different wavelength as outlined would also be very valuable for a more rigorous determination of geometrical filling factors. Furthermore, more time-resolved observations are necessary to determine the role of acoustic waves in the heating of stellar atmospheres and the generation of a chromosphere.

More theoretical work is necessary in the field of molecular cooling of late-type stellar atmospheres, particularly the inclusion of non-LTE effects of molecule-dominated low-gravity atmospheres. The thermal bifurcation model itself eventually will have to be tested in three-dimensional simulations, allowing for the different pressure scale heights of the different temperature components.

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