CO FUNDAMENTAL LINES: INDICATORS FOR INHOMOGENEOUS ATMOSPHERES IN COOL STARS

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ABSTRACT: Carbon monoxide fundamental lines near 4.7 μm are employed to probe the thermal structure of the atmospheres of cool stars. We use a new non-LTE radiation transfer code to analyze high-resolution infrared CO line spectra and derive observation-based stellar atmosphere models. The main results of this investigation are: 1) The CO-based models developed here deviate strongly from previously published models based on UV/visible observations. 2) We find varying degrees of agreement between our CO-empirical models and predictions based on theoretical radiative-equilibrium (RE) atmosphere models. 3) The parameter used to quantify this agreement is anti-correlated with the magnitude of 'chromospheric activity' in the observed stars. These results suggest thermally bifurcated upper atmospheres as the standard case for cool stars.

OBSERVATIONS

The observational part of this investigation was triggered by the development of sensitive detection systems for high-resolution spectroscopy in the thermal infrared. All spectra used here were acquired with the Kitt Peak 4m Fourier transform spectrometer. The Goddard postdisperser (Wiedemann et al., 1989) was employed in several observing runs to reduce the thermal radiation noise and increase the sensitivity of the FTS.

ANALYSIS

A sensitivity study first examines the CO Δν = 1 lines as sensors for upper atmospheric conditions (Wiedemann, 1989). The fundamental lines can be used best to 'measure' the vertical temperature structure, provided the errors due to non-LTE effects are small. These errors are caused by uncertain collisional cross sections for vibrational excitation of CO by atomic hydrogen. Quantitative study has become possible with the recently improved laboratory results for this crucial parameter (Glass and Kirdge, 1982). The 'non-LTE errors' become reasonably small in stars with surface gravity g > 10 cm/sec².

A non-LTE synthesis program for molecular spectra (Ayres and Wiedemann, 1989) was then used to simulate CO Δν = 1 spectra. Theoretical RE atmosphere models (Bell et al., 1976) were adapted and extended on the 'chromospheric' side, in order to match computed and observed spectra. CO-based models were derived for stars observed with sufficient signal/noise ratios. To characterize a particular atmosphere, we use the ratio of boundary temperature $T_b$ and effective temperature $T_{\text{eff}}$. (The boundary temperature in an observation-based model is the lowest in CO observable temperature).
RESULTS

Chromospheric indicators in CO spectra: Line core emission reversals, indicative of a chromosphere in cool stars (Carbon et al., 1976) are not found in any of the observed stars.

Comparison with radiative-equilibrium (RE) models: Column 1 in Tab. 1 compares the 'observed' temperature ratios $T_{B/E}$ (defined as $T_b / T_{eff}$) with those of the corresponding theoretical RE models. There is a trend of increasing discrepancy $T_{B/E}$ (obs.) - $T_{B/E}$ (theor.) with increasing $T_{eff}$.

Comparison with semi-empirical models: The atmosphere models derived from the CO observations clearly contradict previously published (UV/visible line observation-based) models (Fig. 1). The temperatures decrease outwardly and the 'chromospheric' temperature rise cannot be seen in the IR-based models.

![Graphs for β Gem and α Tau](image)

**Fig. 1:** Atmosphere profiles derived from CO Δν = 1 spectra compared with UV/visible observation-based models. Left: βGem: upper curve: semi-empirical model by Basri et al., (1981), lower curve: CO model (this work). Right: αTau, upper curve: semi-empirical model by Kelch et al., (1978), lower curve: CO model (this work).

Correlation with chromospheric activity: The temperature discrepancy between CO based and theoretical RE-models mentioned above follows the same trend as the chromospheric activity (col. 2-4, Tab. 1) reported for all observed stars (indicated by He I, Si II, and Mg II).

INTERPRETATION

These results suggest a thermally bifurcated atmosphere (proposed first for the Sun by Ayres (1981) as the rule for late type stars: the stellar surface is covered mostly with cool material, whose temperature is determined by radiative cooling in optically thin CO lines. 'Hot' gas, visible in UV and optical lines is interspersed in the cool material. Observed at these frequencies, a star shows the chromospheric temperature rise. One can attempt to estimate filling factors for the cool component as follows: We assume the boundary temperature fixed by CO cooling, and given by a theoretical model. Higher boundary temperatures, observed in the cores of the strongest CO lines, may then be interpreted as spatial average, if the cool material fills only a fraction of the stellar surface. First rough estimates for the surface coverage thus range from ~99% for inactive stars like α Boo to ~50% for the active β Dra. (A qualitatively similar result can be obtained if the observed He I intensity variations (Tab. 1.) are ascribed to changes in the size of the total emitting area, as large fractional variations occur in stars with low total intensity (α Boo) and vice versa (β Dra)).
CONCLUSIONS

CO $\Delta v=1$ line observations in cool stars lead to atmospheric models incompatible with previous semi-empirical models, indicating 'bifurcation' of cool atmospheres into two distinct thermal components. These results demonstrate the importance of including molecular line (CO) observations in the analysis of cool stellar atmospheres. Yet, more work is necessary, to improve the molecular diagnostic as a valuable tool: Theoretical RE - models need to be extended to greater heights for better comparison with observed spectra. The sensitivity of measurements must be increased, in order to extend the observational data base. Large cryogenic infrared echelle spectrometers (currently under development at several institutions) will greatly increase the range of stars observable with the spectral resolution necessary for CO line studies. More experimental work is desirable to determine more accurately CO-H collisional de- excitation rates, especially their vibration state dependence, since the uncertainties caused by non-LTE effects still preclude accurate analysis of CO spectra in very low-gravity stars.

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|}
\hline
star & $\delta$ & $W_{\lambda}$ (10$^{-3}$Å) & Mg II (2800Å) \\
\hline
$\alpha$ Tau (K5 III) & 0.0 ±0.04 & 30 x 10$^{-7}$ & 60 x 10$^{-7}$ \\
$\gamma$ Draco (K3 III) & 0.0 ±0.05 & 54E-235A & 0.4 \\
$\alpha$ Hya (K3 III) & -0.06±0.05 & 255 & 0.5 \\
$\alpha$ Boo (K2 III) & -0.06±0.03 & 41E-145A & 0.6 \\
$\beta$ Gem (K0 III) & 0.04 ±0.04 & 120 & 1.2 \\
$\beta$ Corvi (G5 II) & 0.09 ±0.08 & 1.3 & \\
$\epsilon$ Vir (G8 II-III) & 0.13 ±0.1 & 230 & 1.4 \\
$\beta$ Draco (G2 II) & 0.21±0.13 & 935-1285 & 120 & 120 \\
\hline
\end{tabular}
\caption{Comparison of CO results with chromospheric activity}
\end{table}

col. 1: difference between observed (CO) and expected (RE) boundary/effective temperature ratios, $\delta = T_J/T_{\text{eff}}$ (observed) - $T_J/T_{\text{eff}}$ (predicted). col. 2: He I line equivalent widths (O'Brien and Lambert, 1986), A = absorption, E = emission, col. 3-4: chromospheric line flux ratios: fluxes divided by bolometric flux of the stars, ($f_{\text{line}}/f_{\text{bol}}$). (Ayres et al., 1981)

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