THE ASTROPHYSICAL JOURNAL, 177:L27–L32, 1972 October 1

OBSERVATIONS OF CARBON MONOXIDE IN COOL STARS AT 4.7 MICRONS

T. R. GEBALLE AND E. R. WOLLMAN*
Department of Physics, University of California, Berkeley
AND
D. M. RANK
Lick Observatory, Board of Studies in Astronomy and Astrophysics,
University of California, Santa Cruz
Received 1972 August 3

ABSTRACT

Spectra of six stars with high infrared luminosities have been obtained, with spectral resolution of 0.18 cm^{-1}, near the fundamental vibration-rotation band origin of $^{12}C^{16}O$ at 2140 cm^{-1}. They have been analyzed for rotational and vibrational temperatures, isotopic abundances, and column densities, the latter being in all cases substantially lower than theoretical predictions. For all six stars, the isotopic ratio $^{12}C/^{13}C$ is less than 10. The presence of $^{12}C^{18}O$ in W Hya, α Boo, and α Her is indicated.

I. INTRODUCTION

High-resolution spectra of six stars with high infrared luminosities have been obtained near the fundamental vibration-rotation band center of carbon monoxide at 2140 cm^{-1} (4.7μ). Almost all spectral features observed in these stars can be attributed to absorption by $^{12}C^{16}O$, $^{13}C^{16}O$, and $^{12}C^{18}O$. Some parameters describing the state of the CO observed are given in table 1.

All observations were made during the spring of 1972 with a tandem scanning Fabry-Perot interferometer mounted at the coudé focus of the 120-inch (305-cm) telescope at Lick Observatory. The basic optical system and associated electronic equipment have been described in detail by Holtz (1971). Spectra of six stars were obtained with integration times of approximately 1 hour per star. For these observations, a resolution of about 0.18 cm^{-1} and a scanning distance of about 5 cm^{-1} were used. This resolution is an order of magnitude higher than has been used previously for stellar spectroscopy in the region 4–5μ. Detailed analysis of stellar atmospheres in this spectral region requires comparable or perhaps higher resolution, as evidenced by the complex nature of the spectra shown in figure 1.

A spectral region near 2140 cm^{-1}, which is relatively free from atmospheric contamination, was chosen for the scans. This region is bounded by two strong terrestrial lines: an H_2O line at about 2144.8 cm^{-1} and the 1–0 $P1$ line of $^{12}C^{16}O$ at 2139.4 cm^{-1}. Numerous CO lines which should be excited in stellar atmospheres fall in this frequency interval. The strongest of these are listed in table 2. The line frequencies have been calculated using molecular constants given by Rosen (1970). The lower rotational lines of the 1–0 $^{12}C^{16}O$ band in the Earth's atmosphere are saturated and prevent observation of the same lines in the stellar spectra without Doppler shifts greater than about 60 km sec^{-1}. Nonetheless, the CO lines which were observed in the stellar spectra cover a wide range of vibrational and rotational quantum numbers for the most common isotopic species of the molecule and are suitable for measurement of excitation temperatures, column density, and isotopic ratios.

---

* National Science Foundation Fellow.

TABLE 1

PARAMETERS FOR BEST-FITTING SIMULATIONS TO OBSERVED SPECTRA

	α Boo (K2 III)	α Sco (M2 Iab)	α Ori (M2 Iab)	α Her (M5 Ib–II)	R Leo (M7 e [var])	W Hya (M8 e [var])
Assumed T_{eff} (° K) ..	4000	3500	3500	2950	2650	2500
T_R(° K)	3000	3000	3000	2950	2650	2500
T_V(° K)	2400	2200	2200	1900	1900	2000
N (^{12}C^{16}O)(cm^{-2}) ..	$10^{19.7}$	$10^{20.2}$	$10^{20.4}$	$10^{20.2}$	$10^{20.2}$	$10^{20.3}$
σ (cm^{-1})	0.025	0.043	0.043	0.027	0.030	0.035
^{12}C/^{13}C	7	5	8	7	5	3
^{16}O/^{18}O	40	>100	>100	50	>100	25
		(150)	(200)		(200)	
^{16}O/^{17}O	>100	>100	>100	>100	>100	>100

The spectra were processed to remove variations in the transmission of the infrared filter which is used to suppress the transmission sidebands of the Fabry-Perot interferometer. Terrestrial absorption features were removed by dividing each stellar spectrum by a lunar spectrum adjusted to the same zenith distance. This procedure is accurate only for terrestrial lines with small optical depths, several of which are present in the frequency interval observed.

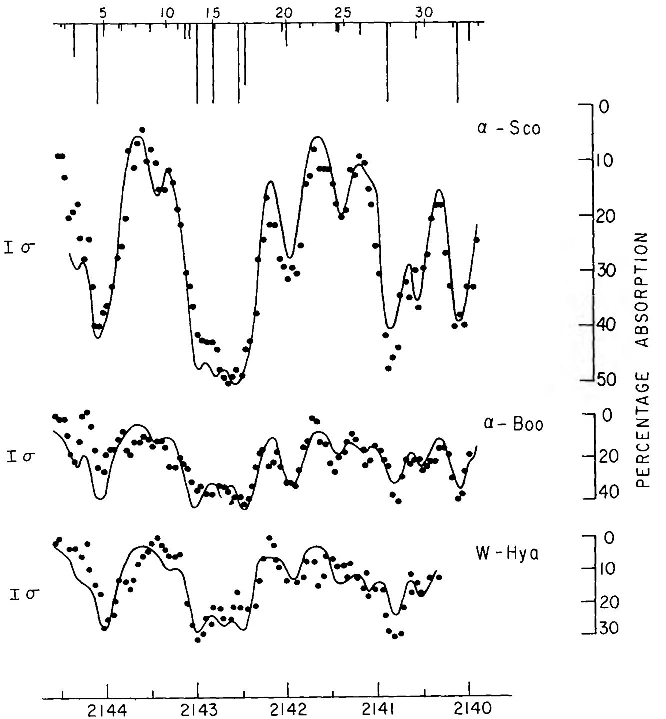

FIG. 1.—Infrared spectra of α Sco, α Boo, and W Hya. Dots, observed spectra. Solid lines, synthetic spectra computed using the values for the parameters listed in table 1. Positions and approximate relative intensities of the lines used in the synthetic spectra are shown at the top of the figure. σ, probable error for a single data point.

1972ApJ...177L..27G

TABLE

CO ROTATION-VIBRATION LINES IN THE SCANNED FREQUENCY INTERVAL

Line No.	Rest Frequency (cm^{-1})	Molecule	Transition
1	2144.45	$^{13}\mathrm{C}^{16}\mathrm{O}$	5–4 *R*60
2	2144.41	$^{12}\mathrm{C}^{16}\mathrm{O}$	7–6 *R*69
3	2144.31	$^{12}\mathrm{C}^{16}\mathrm{O}$	5–4 *R*34
4	2144.04	$^{13}\mathrm{C}^{16}\mathrm{O}$	1–0 *R*13
5	2143.93	$^{12}\mathrm{C}^{18}\mathrm{O}$	2–1 *R*23
6	2143.80	$^{12}\mathrm{C}^{16}\mathrm{O}$	6–5 *R*47
7	2143.79	$^{12}\mathrm{C}^{18}\mathrm{O}$	3–2 *R*33
8	2143.58	$^{12}\mathrm{C}^{16}\mathrm{O}$	7–6 *R*68
9	2143.42	$^{13}\mathrm{C}^{16}\mathrm{O}$	4–3 *R*43
10	2143.26	$^{12}\mathrm{C}^{18}\mathrm{O}$	4–3 *R*45
11	2143.15	$^{13}\mathrm{C}^{16}\mathrm{O}$	4–4 *R*59
12	2143.07	$^{12}\mathrm{C}^{18}\mathrm{O}$	1–0 *R*14
13	2143.02	$^{13}\mathrm{C}^{16}\mathrm{O}$	3–2 *R*31
14	2143.94	$^{12}\mathrm{C}^{16}\mathrm{O}$	4–3 *R*23
15	2142.71	$^{12}\mathrm{C}^{16}\mathrm{O}$	3–2 *R*14
16	2142.71	$^{12}\mathrm{C}^{16}\mathrm{O}$	7–6 *R*67
	2142.63	$^{12}\mathrm{C}^{17}\mathrm{O}$	3–2 *R*23
17	2142.47	$^{12}\mathrm{C}^{16}\mathrm{O}$	2–1 *R*6
18	2142.38	$^{13}\mathrm{C}^{16}\mathrm{O}$	2–1 *R*21
	2142.07	$^{12}\mathrm{C}^{17}\mathrm{O}$	2–1 *R*14
19	2141.98	$^{12}\mathrm{C}^{16}\mathrm{O}$	6–5 *R*46
20	2141.92	$^{12}\mathrm{C}^{16}\mathrm{O}$	5–4 *R*33
21	2141.80	$^{13}\mathrm{C}^{16}\mathrm{O}$	5–4 *R*58
22	2141.66	$^{12}\mathrm{C}^{16}\mathrm{O}$	7–6 *R*66
	2141.58	$^{12}\mathrm{C}^{17}\mathrm{O}$	1–0 *R*6
23	2141.41	$^{13}\mathrm{C}^{16}\mathrm{O}$	4–3 *R*32
24	2141.38	$^{12}\mathrm{C}^{18}\mathrm{O}$	3–2 *R*32
25	2141.32	$^{12}\mathrm{C}^{18}\mathrm{O}$	4–3 *R*44
26	2141.12	$^{12}\mathrm{C}^{18}\mathrm{O}$	2–1 *R*22
27	2140.83	$^{13}\mathrm{C}^{16}\mathrm{O}$	1–0 *R*12
28	2140.82	$^{12}\mathrm{C}^{16}\mathrm{O}$	7–6 *R*65
29	2140.52	$^{13}\mathrm{C}^{16}\mathrm{O}$	3–2 *R*30
30	2140.42	$^{13}\mathrm{C}^{16}\mathrm{O}$	5–4 *R*57
31	2140.11	$^{12}\mathrm{C}^{16}\mathrm{O}$	6–5 *R*45
32	2140.08	$^{12}\mathrm{C}^{16}\mathrm{O}$	4–3 *R*23
33	2139.91	$^{12}\mathrm{C}^{18}\mathrm{O}$	1–0 *R*13
34	2139.82	$^{12}\mathrm{C}^{16}\mathrm{O}$	7–6 *R*64

NOTE.—Line-identification list for CO transitions in the frequency interval 2140–2145 cm^{-1}. Lines included in the synthetic spectra have been numbered according to the legend at the top of figs. 1 and 2.

II. DESCRIPTION OF SPECTRA

Spectra of three stars (α Sco, α Boo, and W Hya) are shown in figure 1. The spectra have been shifted to zero radial velocity to allow direct comparison of stellar features. Shown at the top of the figure are the positions and approximate relative strengths of the lines enumerated in table 2. An absorption scale and the rms noise for a single data point are given for each star. The solid lines represent computer-generated synthetic spectra whose parameters, shown in table 1, have been chosen to give a best fit to the data.

Each stellar spectrum in figure 1 shows strong $^{13}\mathrm{C}^{16}\mathrm{O}$ 1–0 *R*12 and *R*13 lines at 2140.8 and 2144.0 cm^{-1}. The approximately 0.7 cm^{-1} broad absorption centered at 2142.6 cm^{-1} is the strongest feature in each spectrum and is due to a number of $^{12}\mathrm{C}^{16}\mathrm{O}$ and $^{13}\mathrm{C}^{16}\mathrm{O}$ lines from low vibrational states. The strength of the absorption at 2141.9 cm^{-1} (due to the 5–4 *R*33 and 6–5 *R*46 lines of $^{12}\mathrm{C}^{16}\mathrm{O}$) relative to this feature indicates that the $^{12}\mathrm{C}^{16}\mathrm{O}$ transitions in the 2142.6 cm^{-1} absorption are strongly saturated. Likewise, the strength of the 3–2 *R*30 transition of $^{13}\mathrm{C}^{16}\mathrm{O}$ at 2140.5 cm^{-1} relative to the 1–0 lines of $^{13}\mathrm{C}^{16}\mathrm{O}$ mentioned above suggests that the 1–0 lines of $^{13}\mathrm{C}^{16}\mathrm{O}$ are saturated as well.

The most easily resolved $^{12}\mathrm{C}^{18}\mathrm{O}$ line in these spectra is the 2–1 *R*22 transition at 2141.1 cm^{-1}. A significant absorption at this frequency occurs in α Boo, W Hya, and α Her. With the exception of the 1–0 *R*6 transition at 2141.6 cm^{-1}, none of the strongest $^{12}\mathrm{C}^{17}\mathrm{O}$ lines would be clearly resolved from other absorption features in these spectra. In α Sco, there is some indication that this line of $^{12}\mathrm{C}^{17}\mathrm{O}$ is present. In none of the other stars studied is there evidence for the presence of $^{12}\mathrm{C}^{17}\mathrm{O}$.

III. ANALYSIS

The values of the parameters listed in table 1 were determined by fitting a computer-generated synthetic spectrum to each observed spectrum. The synthetic spectra are calculated for an isothermal shell model, in which case the optical depth for a Gaussian line, centered at frequency ν_0 is given by

$$\tau(\nu,\nu_0) = \frac{(2\pi)^{5/2}\nu_0 N}{3hc\sigma Z}(v+1)(j+1)|\mu|^2 \times e^{-(E_V-E_0)/kT_V}\, e^{-E_R/kT_R}\,[1-e^{-h\nu_0 kT_V}]\, e^{-(\nu-\nu_0)^2/2\sigma^2},$$

where N = molecular column density, $|\mu| = 0.104\ D$ (Young and Eachus 1966), σ = turbulent linewidth parameter, Z = vibration-rotation partition function, v and j = lower-state vibrational and rotational quantum numbers, E_V and E_R = lower-state vibrational and rotational energies, E_0 = ground-state energy, and T_V and T_R = vibrational and rotational temperatures. Since the change in rotational energy is much less than the change in vibrational energy for these transitions, we have made the approximation that

$$1 - e^{-(\Delta E_V/kT_V + \Delta E_R/kT_R)} \simeq 1 - e^{(-\mathrm{h}\nu_0/kT_v)}.$$

Then the normalized intensity spectrum is

$$\frac{I(\nu)}{I_0} = e^{-\tau(\nu)} + \frac{B(T_V,\nu)}{B(T_e,\nu)}[1-e^{-\tau(\nu)}]$$

where

$$\tau(\nu) = \sum_{\text{all lines}} \tau(\nu,\nu_0),$$

T_e = effective continuum 5 μ temperature, and $B(T,\ \nu)$ = Planck function. The approximation stated above has again been used in order to characterize the CO radiation by the vibrational temperature.

The $I(\nu)$ is computed using various selections for the parameters T_V, T_R, σ, N ($^{12}C^{16}O$), and the isotopic ratios $^{16}O/^{18}O$ and $^{12}C/^{13}C$. The stellar spectrum thus generated is convolved with the Fabry-Perot instrumental transmission function to yield the spectrum as we observe it. A sample synthetic spectrum and the convolved (instrumental) spectrum are shown in figure 2.

Several synthetic spectra were generated for each star. A best fit was chosen on the basis of a visual comparison. The parameters of the best-fitting simulation for each star are listed in table 1. It was found possible to vary one parameter and recover a good fit to the stellar spectrum by varying other parameters. The maximum variation of each parameter which allows recovery of a good fit differs from star to star, but is about ± 150° K in T_V, ± 700° K in T_R, ± 30% in σ, and a factor of 2 in N ($^{12}C^{16}O$), $^{12}C/^{13}C$, and $^{16}O/^{18}O$.

IV. DISCUSSION

The stars in table 1 are listed in the order of spectral classification and assumed effective temperature. Except for the decrease in T_V and T_R as T_e decreases, no systematic variation of any parameter with T_e is apparent. In all the stars, $T_V < T_R \leqq T_e$.

The derived CO column densities in these stars are all approximately two orders of magnitude lower than the predictions of Goon and Auman (1970) for stars of these spectral types. Our value of the column density of CO in α Ori is a factor of 4 less than the value 1.3×10^{21} cm^{-2} given by Spinrad *et al.* (1970), who used high-resolution observations of the ($\Delta v = 2$) bands of CO in this star.

The isotopic ratio $^{12}C/^{13}C$ has been measured to be about 3 in α Ori (Spinrad

1972ApJ...177L..27G

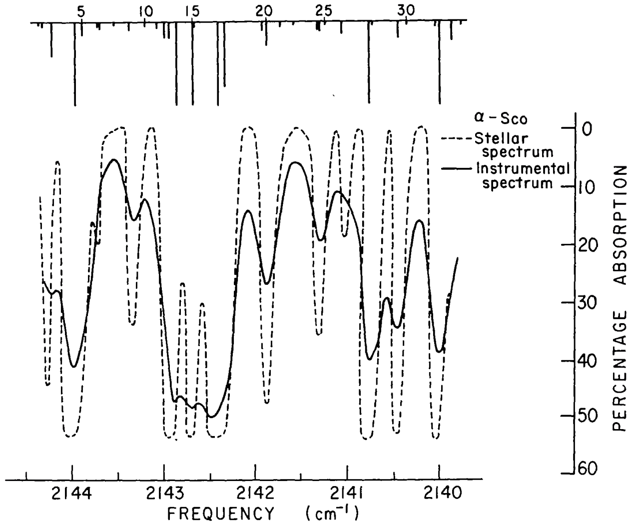

FIG. 2.—Computer-generated synthetic spectrum of α Sco. Predicted stellar spectrum (*dashed line*) is convolved with the instrumental transmission function to produce the predicted instrumental spectrum (*solid line*). Positions and approximate relative intensities of the lines used in the synthetic spectra are shown at the top of the figure.

et al. 1970) and 5.5 ± 1.5 in α Boo (Lambert and Dearborn 1971), the latter value in good agreement with our value. A low value of the ratio ^{12}C/^{13}C is a common feature of all six stars observed by us and suggests that in late-type giants and supergiants not only has the CNO cycle been a dominant process for hydrogen burning, but there has also been substantial mixing of the core with the outer layers of these stars.

The values of ^{16}O/^{18}O in α Boo, α Her, and W Hya in table 2 are all about an order of magnitude lower than the terrestrial ratio of 489. It is interesting to note that in those three stars where ^{12}C^{18}O appears to be present, the ratio (^{16}O/^{18}O)/(^{12}C/^{13}C) is very close to the terrestrial ratio of 5.5.

V. UNIDENTIFIED LINES

Almost all of the spectral features observed in these stars can be attributed to CO. One exception is that in the spectra shown in figure 1 the absorption at 2140.8 cm^{-1} is substantially greater than that predicted for the 1–0 R12 line of ^{13}C^{16}O. While this unexplained absorption might be a systematic effect, it is not present in the remaining three observed spectra. Therefore, it is likely that the strength of this particular feature is due to a blend of the ^{13}C^{16}O line and an unidentified line.

In W Hya and R Leo, the absorptions at 2143.80 ± 0.05 and 2141.65 ± 0.05 cm^{-1} are also too strong to be produced by any of the isotopic species of CO. No identification of the 2143.80-cm^{-1} absorption has been found. The feature at 2141.65 cm^{-1} has at least two possible identifications. It corresponds within 0.1 cm^{-1} to the frequency of the 5_{-3}–4_{-1} line of the ν_1 hot band of H_2O (Benedict and Calfee 1967) and would indicate H_2O column densities of approximately 3×10^{21} cm^{-2} in W Hya and R Leo. Near-infrared measurements of H_2O in W Hya and R Leo have yielded column-density estimates of 2×10^{22} and 5×10^{21} cm^{-2}, respectively (Spinrad and Vardya 1966).

The 2141.65-cm^{-1} absorption also corresponds closely to the 1–0 R30 transition of ^{12}C^{14}N as calculated by Phillips (1972). This line should be the most easily detected

CN line in the spectral region observed. The strength of the feature corresponds to a column density and transition-matrix element such that

$$N(\mathrm{CN})\ |\mu_{\mathrm{CN}}|^2 \simeq .02\, N(^{12}\mathrm{C}^{16}\mathrm{O})\ |\mu_{\mathrm{CO}}|^2,$$

where $|\mu_{\mathrm{CN}}|$ is unknown but is thought to be substantially larger than $|\mu_{\mathrm{CO}}|$.

Spinrad and Vardya (1966) calculate the column density of CN in α Ori to be an order of magnitude greater than in R Leo and W Hya. Our results, on the other hand, do not indicate the presence of absorption at 2141.65 cm^{-1} in α Ori. Thus, identification of the 2141.65-cm^{-1} line as CN would be inconsistent with the results of Spinrad and Vardya (1966).

We wish to thank Dr. C. H. Townes for helpful discussions and assistance in the preparation of this paper. We are also grateful to Aurora L. Isaac for assisting with the observations and data reduction. We were partially supported by NASA grants NGL 05-003-272 and NGR 05-003-452.

REFERENCES

Benedict, W. S., and Calfee, R. F. 1967, *Line Parameters for the 1.9 and 6.3 Micron Water Vapor Bands*. ESSA Professional Paper No. 2 (Washington: U.S. Department of Commerce).

Goon, G., and Auman, J. R. 1970, *Ap. J.*, **161**, 533.

Holtz, J. Z. 1971, unpublished thesis, University of California, Berkeley.

Lambert, D. L., and Dearborn, D. S. 1971, paper delivered at the 17th International Astrophysics Symposium, Liège.

Phillips, J. G. 1972 (submitted for publication).

Rosen, B. 1970, *Spectroscopic Data Relative to Diatomic Molecules* (Oxford: Pergamon Press).

Spinrad, H., Kaplan, L. D., Connes, P., Connes, J., Kunde, V., and Maillard, J. 1970, *Proceedings of the Conference on Late-Type Stars*. Kitt Peak National Observatory Contribution 554.

Spinrad H., and Vardya, M. S. 1966, *Ap. J.*, **146**, 399.

Young, L. J., and Eachus, W. J. 1966, *J. Chem. Phys.*, **44**, 4195.