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The CO fundamental bands in the solar spectrum

by

C. MULLER and A.J. SAUVAL

B E L G I S C H I N S T I T U U T V O O R R U I M T E - A E R O N O M I E

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FOREWORD

This article entitled "The CO fundamental bands in the solar spectrum" has been accepted for publication in "Astronomy and Astrophysics."

AVANT-PROPOS

Cet article intitulé "The CO fundamental bands in the solar spectrum" a été accepté pour publication par "Astronomy and Astrophysics."

VOORWOORD

Deze tekst genaamd "The CO fundamental bands in the solar spectrum" werd voor publicatie door het tijdschrift "Astronomy and Astrophysics" aanvaard.

VORWORT

Dieser Text "The CO fundamental bands in the solar spectrum" wurde für Herausgabe in "Astronomy and Astrophysics" angenommen.

THE CO FUNDAMENTAL BANDS IN THE SOLAR SPECTRUM

by

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Summary

The results of a study of CO lines in the $\Delta v = 1$ bands in the solar disk spectrum are presented. Recently, the photospheric spectrum has been recorded using a balloon-borne spectrometer from 40 km altitude. From a comparison between the observed and synthetic solar spectra, an agreement is shown using the best available solar and molecular data. Our results are discussed and compared with other investigations and enable us to explain an apparent discrepancy between previous results.

Résumé

Les résultats d'une étude des raies de CO dans les bandes $\Delta v = 1$ du spectre du disque solaire sont présentés. Un spectre photosphérique enregistré récemment au moyen d'un spectromètre embarqué en ballon est également présenté. On montre un accord entre les spectres synthétiques et observés en utilisant les meilleures données solaires et moléculaires disponibles. Nos résultats sont discutés et comparés avec d'autres analyses; ils permettent d'expliquer un désaccord apparent entre de précédents résultats.

Samenvatting

De resultaten van een studie over de CO lijnen in de $\Delta v = 1$ banden van het zonneschijfspectrum worden voorgesteld. Onlangs werd aan boord van een ballon, vanop 40 km hoogte, een fotosferisch spectrum opgenomen. Een vergelijking van de waargenomen met de synthetische zonnenspectra vertoonde een overeenkomst wanneer we gebruik maakten van optimale gegevens over de zon en de CO molecule. Onze resultaten worden besproken en vergeleken met andere onderzoeken, en laten ons toe een klaarblijkelijke tegenstrijdigheid tussen vroegere resultaten uit te leggen.

Zusammenfassung

Die Resultaten eines Studium über die CO Linien in den $\Delta v = 1$ Banden der Sonnescheibe werden dargelegt. Vor kurzem wird am Bord eines Ballon, auf 40 km Höhe, ein photosphärischen Spektrum aufgenommen. Die Vergleichung zwischen experimentale und synthetische Sonnenspectra zeigt eine Übereinstimmung wenn wird die besserten verfügbaren Gegebene über die Sonne und die CO Molekül brauchen. Unsere Resultaten werden besprochen und verglichen mit andere Untersuchungen. Sie erlauben eine scheinbare Uneinigkeit zwischen frühere Resultaten deutlich zu machen.

I. INTRODUCTION

Carbon monoxide is the most stable of all the diatomic molecules and plays an important astrophysical role. Indeed, CO is present in all rather cold cosmic sources (interstellar medium, stellar and planetary atmospheres, infrared objects and galaxies).

The presence of CO in stellar atmosphere has been predicted a long time ago by Russell (1934) and CO plays a basic role in the equilibrium of carbon and oxygen compounds in stellar atmospheres. Only a few measurements of the solar CO abundance have yet been performed, such as the analysis of the first overtone bands made by Goldberg and Müller (1953) and a recent investigation of the $\Delta v = 1$ bands by Goldman *et al.* (1973). This last determination leads to a surprising low result concerning the CO abundance.

The present research, performed in the fundamental bands of carbon monoxide, enables to settle this case using higher resolution experimental data and a more accurate method of calculation of line profiles. The altitude of observation permits also to obtain, for the first time, an almost uncontaminated solar CO spectrum. Different sets of solar and molecular data will be tested for the interpretation of these spectra.

II. SOLAR OBSERVATIONS

The solar spectrum has been recorded on May 14 1973 using a balloon-borne equipment from 40 km altitude. The flight has been carried out from the CNES launching site at Aire-sur-l'Adour (France) jointly by the Institut d'Aéronomie Spatiale de Belgique and by the Office National d'Etudes et de Recherches Aérospatiales (France). The recorded solar spectrum in the region 1901.2 to 1915.2 cm^{-1} has been kindly put at our disposal.

The Girard grille spectrometer (Girard, 1963) used in this experiment (Ackerman *et al.*, 1973b) has a Littrow mounting with an off-axis parabolic mirror whose focal length is 60 cm. Its Jobin-Yvon grating is ruled at 60 grooves per mm over an area of 65 x 65 mm.

The Cassegrain telescope has a diameter of 32 cm and a focal length of 420 cm. The sun pointing system warrants an accuracy better than 30 arc seconds. The square grille (18 x 18 mm) was placed at the centre of the solar image of 37 mm diameter. The total half-width of the slightly asymmetric instrumental profile is about 0.09 cm^{-1} near 1900 cm^{-1} .

The main purpose of the experiment was the measurement of the stratospheric vertical distribution of nitric oxide (Ackerman *et al* 1973a, 1974). During the flight, the solar spectrum was recorded at different solar zenith angles during sunset starting from 86° . The obtained spectra above the horizon was of practically pure solar origin, those recorded at solar zenith angle larger than 90° show a continuous growth of telluric lines.

The solar lines of the measured spectral interval cannot be measured properly from the ground level because of the perturbing effects of strong telluric lines of H_2O and CO_2 . In that region, Migeotte *et al.* (1957) mention only 14 solar CO lines among 14 telluric H_2O and CO_2 lines. A solar atomic line of Ti I is also proposed at 1911.40 cm^{-1} but no gf value appears to be available.

III. GENERATION OF THE SYNTHETIC SOLAR SPECTRUM

The solar disk spectrum has been calculated in the region $1901 - 1916 \text{ cm}^{-1}$ with the help of a computer program (Sauval, 1972) assuming pure absorption as the only mechanism of line formation and local thermodynamic equilibrium (L.T.E.). Recent molecular data have been used in our calculations (see part IV).

Other contributors than CO have been searched for in the observed solar spectrum, telluric lines being quite negligible above 40 km as shown by computed telluric spectra. Intensities of solar lines of [CN], NO and SiH ($\Delta v = 1$) and Si O ($\Delta v = 2$) have been predicted to be unobservable in the solar disk spectrum (Sauval, 1972). Only one atomic line ought to be present in that region, Si I at 1909.396 cm^{-1} (theoretical gf-value of 1.4)

with a theoretical equivalent width of 0.008 cm^{-1} (Biémont and Grevesse, 1974a). Other atomic lines could also be present such as Sc I at 1909.14, Fe I at 1909.37 and at 1911.25 and Ti I at 1911.28 cm^{-1} , but there is no gf-value available (Biémont and Grevesse, 1974b).

First the system of equations representing the equilibrium for H, C, N, O and Si has been solved to give the variations with depth of the concentrations of CO and Si in the solar atmosphere. Then the line absorption coefficient has been calculated for each individual line using Voigt profiles. The solar intensity at each ω -value has been determined taking all contributing lines into account. The so obtained infinite resolution spectrum has been convolved with the measured instrumental profile in order to be compared with the observed spectrum.

The Harvard Smithsonian Reference Atmosphere, H.S.R.A., (Gingerich *et al.*, 1971) has been first adopted, but other photospheric models have also been used (see Discussion). The abundances of carbon and oxygen have been assumed to be 8.6 and 8.9 respectively in the usual scale where $\log N(\text{H}) = 12.0$. These values are based on Grevesse and Sauval (1973)'s compilation. More recent determinations of photospheric abundances (Mount *et al.*, 1973; Nicolaïdes and Sinanoglu, 1973; Upson, 1973; Mount and Linsky, 1974a, b) and of chromospheric and coronal abundances (Dupree, 1972) lead to somewhat smaller values : $\log [N(\text{C}), N(\text{O})]$ ranges from about 17 to 17.5. Furthermore, we have adopted the value 7.6 for the silicon abundance as derived from Engvold and Hauge (1974)'s review.

As a first approximation and in agreement with Hall (1973a), the terrestrial values of the isotopic CO ratios have been adopted.

Due to the questionable "microturbulence" ξ (Worrall and Wilson, 1973) and to the more recognized "macroturbulence", V_c , we have adopted constant, isotropic and depth independent velocities $\xi = 0.5 \text{ km sec}^{-1}$ and $V_c = 2.5 \text{ km sec}^{-1}$ (see also Discussion).

IV. MOLECULAR DATA

Since the first observation of the fundamental bands of carbon monoxide near $4.66 \mu\text{m}$ by Burmeister (1913), a large number of investigations have been devoted to the analysis of the $\Delta v = 1$ bands and are reviewed by Krupenie (1966). However, a lack of accurate measurements of line positions and intensities still remains, particularly for high excitation lines and for isotopic molecules.

As far as the 1-0 band is concerned, the existing rotational analysis is limited to $J < 51$ (Plyler *et al.*, 1955a; Rao, 1972). The lines with $J < 30$, which have an absolute accuracy of at least $\pm 0.002 \text{ cm}^{-1}$, have been proposed as wavelength standards (Rao *et al.*, 1966). Rotational lines of higher excitation energy have also been observed up to J values equal to 72 (Dowling *et al.*, 1971) but no measurement is known to the authors.

The hot bands, $(v + 1) - (v)$ with $v > 0$ which are only observed in high temperature sources have been measured up to $v = 4$ at moderate J- values (Weinberg *et al.*, 1965). Since the pioneering work of Patel and Kerl (1964) using a CO gas laser, the hot bands have been intensively investigated. Laser emission lines of bands with $3 < v < 36$ have been measured with a high accuracy ($\pm 0.005 \text{ cm}^{-1}$) (see Rao and Mantz, 1972, Roh and Rao, 1974). However, we must note that this new technique is restricted to P(J) lines of rather small rotational energy ($4 < J < 22$). Moreover, Roh and Rao (1974) have determined a new set of spectroscopic constants (from their measured 220 laser lines) which better predicts the line positions than the earlier sets of molecular data.

The $\Delta v = 1$ bands of the isotopic species of carbon monoxide have been much less investigated. To our knowledge, only low excitation lines of the 1 - 0 band for each isotopic molecule ($^{13}\text{C}^{16}\text{O}$, $^{12}\text{C}^{17}\text{O}$, $^{12}\text{C}^{18}\text{O}$, $^{13}\text{C}^{17}\text{O}$ and $^{13}\text{C}^{18}\text{O}$) have been measured (Mills and Thompson, 1953; Plyler *et al.*, 1955b; Benedict *et al.*, 1962). Very recently, Johns *et al.* (1974) have measured 160 $^{13}\text{C}^{16}\text{O}$ lines of hot bands ($v'' = 6$ to 22) with an accuracy of about $\pm 0.003 \text{ cm}^{-1}$.

In our calculations, the measured line positions have been used whenever possible (practically, only in a few cases). Predicted positions based on Roh and Rao's (1974) molecular data have been used in all other cases. It must be noted here that lines of the fundamental and first overtone bands have been measured in the sunspot spectrum with higher rotational energies (J around 100) than in experimental sources (Hall, 1973a, b). The position of these lines which cannot be accurately predicted from Roh and Rao's (1974) data will be used to improve the rotational constants (Hall, 1973a) as already performed from solar photospheric lines (Goldberg and Müller, 1953). For lines of the isotopic species (i), the approximate relations of Dunham (1932) have been used :

$${}^i Y_{jk} = Y_{jk} \rho^{(j+2k)}$$

where the Y_{jk} 's are the Dunham coefficients and ρ is the square root of the ratio of the reduced masses. Table 1 shows the 118 selected lines of the CO fundamental bands in the solar spectral region 1901 - 1916 cm^{-1} . Other isotopic species lead to undetectable solar lines at our spectral resolution. We note here that Kunde's (1967) detailed tables are limited to ${}^{12}\text{C} {}^{16}\text{O}$ lines (up to 13-12 bands) and to ${}^{13}\text{C} {}^{16}\text{O}$ lines and are based on Goldberg and Müller's (1953) set of data.

Most of the determinations of the intensity of the fundamental bands are related to absolute measurements of the 1-0 band and to relative theoretical transition probabilities for the hot bands.

According to Herman and Wallis (1955), the complete matrix element of a transition is the product of a vibrational (rotationless) matrix element and a rotational factor :

$$|R_{v, J'', J'}^{v+1, J'}|^2 = |R_v^{v+1}|^2 \cdot F_{v, J'', J'}^{v+1, J'}$$

where $F_{v, J'', J'}^{v+1, J'}$ is the Herman-Wallis factor.

TABLE 1 : Selected lines of the fundamental bands of CO in the spectral interval 1901 - 1916 cm^{-1} .

Molecule	Band designation ($v' - v''$)	Line designation*	References for laboratory line positions
$^{12}\text{C}^{16}\text{O}$	1 - 0	P(50 to 51)	(1)
	2 - 1	P(45 to 47)	-
	3 - 2	P(40 to 42)	-
	4 - 3	P(35 to 37)	-
	5 - 4	P(30 to 32)	-
	6 - 5	P(24 to 26)	-
	7 - 6	P(18 to 21)	(2)
	8 - 7	P(12 to 15)	(3)
	9 - 8	P(5 to 8)	(2)(3)
	10 - 9	P(1), R(0, 1)	-
	11 - 10	R(5 to 9)	-
	12 - 11	R(14 to 18)	-
	13 - 12	R(23 to 29)	-
	14 - 13	R(35 to 42)	-
	15 - 14	R(51 to 64, 98, 99)	-
$^{13}\text{C}^{16}\text{O}$	1 - 0	P(42 to 44)	-
	2 - 1	P(37 to 39)	-
	3 - 2	P(32 to 34)	-
	4 - 3	P(27 to 29)	-
	5 - 4	P(21 to 24)	-
	6 - 5	P(15 to 18)	-
	7 - 6	P(9 to 12)	-
$^{12}\text{C}^{18}\text{O}$	1 - 0	P(42 to 44)	-
	2 - 1	P(37 to 39)	-
	3 - 2	P(31 to 34)	-
	4 - 3	P(26 to 28)	-
	5 - 4	P(20 to 23)	-
	6 - 5	P(14 to 17)	-

(1) Plyler *et al.* (1955a)

(2) Rao and Mantz (1972)

(3) Roh and Rao (1974)

- no laboratory data available

* the line positions are available from the authors

About ten experimental determinations of the vibrational matrix element, $|R_0^1|$, are now available [see table V in Penner and Weber (1951) for results prior to 1951 and Toth *et al* (1969) for all recent measurements]. There remains a small scattering of the experimental results and Toth *et al* (1969)'s adopted value is $|R_0^1| = 0.014 \pm 0.002$ Debye. Recently, Weisbach and Chackerian (1973) have suggested a slight increase for the band intensity of the 1-0 band, $|R_0^1| = 0.106$ Debye, adopted in our calculation. The first absolute measurements of the intensity of hot bands, R_v^{v+1} with $4 < v < 10$, are also due to these authors.

As far as relative transition probabilities are concerned, various methods have been used to calculate the ratio $(|R_v^{v+1}|^2 / |R_0^1|^2)$ (see Penner, 1959, Cashion, 1963; Young and Eachus, 1966; Bell, 1970). Recently, the ratios of the successive square matrix elements $(|R_v^{v+1}|^2 / |R_{v-1}^v|^2)$ have been measured for $v = 6$ to 11 using a CO laser (Djeu and Searles, 1972). There appears to be a very good agreement between all various results and the classical following approximation has been proved to be quite correct :

$$\frac{|R_v^{v+1}|^2}{|R_0^1|^2} = v + 1$$

As first pointed out by Herman and Wallis (1955), the $F_{v,J'',J'}^{v+1,1,J'}$ factor does not differ much from unity for lines with moderate J-values of the 1-0 CO band. This can be explained by the smallness of the characteristic vibration-rotation interaction parameter, $|M_0/M_1 r_e|$ (0.032 for CO). The constants M_j are the coefficients of the development of the electric dipole moment : $M(r) = \sum_j M_j (r - r_e)^j$. That important result has received experimental confirmation (Benedict *et al.*, 1962) and more elaborate calculations (Penner, 1959; Young, 1966) also show a very small v -dependence of $F_{v,J'',J'}^{v+1,1,J'}$. Therefore, due to other uncertainties, the Herman-Wallis factors have been taken equal to unity for all lines.

Owing to the absence of similar data for the isotopic species (i) of CO, we have calculated $|R_v^{v+1}|^2$ using the relations recommended by Cashion (1963) [Eq. (31)]. It

follows that $|{}^1R_v^{v+1}|^2 / |R_v^{v+1}|^2$ is practically equal to ρ . Here too, we have adopted the same matrix elements for all isotopic molecules since ρ is always larger than 0.975.

Therefore, the gf- value for an individual rotational line is given by

$$[gf]_{v,J}^{v+1, J \pm 1} = f_o^1 (v+1) |m| \frac{\omega_{v,J}^{v+1, J \pm 1}}{\omega_o^1}$$

where $f_o^1 = 1.13 \times 10^{-5}$ (with $\omega_o^1 = 2143 \text{ cm}^{-1}$)

$|m| = J + 1$ for R(J) and J for P(J)

ω_u^1 is the wavenumber of the transition $u - 1$

The CO dissociation energy is now well known : $11.09 \pm 0.02 \text{ eV}$ (Gaydon, 1968). The value has been adopted for all isotopic species since, according to Gaydon (1968), the difference

$$D_o^0 ({}^1\text{CO}) - D_o^0 (\text{CO}) = \frac{1}{2} \omega_e (1 - \rho)$$

is at most equal to 0.003 eV.

The logarithmic values of the partition function Q and the equilibrium constant, pK , of CO have been calculated at different temperatures using the selected molecular constants. Using the least squares method the numerical results have been fitted to a polynomial development which gives the best accuracy with the smallest number of coefficients (Sauval, 1972).

$$\log {}^pK (\text{CO}) = 13.528 - 11.3226 \theta + 0.0399 \theta^2 - 0.411 \log \theta \text{ (CGS)}$$

$$\log Q (\text{CO}) = 3.543 + 0.0416 \theta - 1.950 \log \theta$$

where θ , equal to $5040/T$, ranges from 0.6 to 5. The same numerical values have been adopted for all isotopic molecules because the molecular partition function vanishes in the calculation of the absolute population of a given state and since

$$\log \frac{P_K(\text{CO})}{P_K(^i\text{CO})} = [D_0^0(^i\text{CO}) - D_0^0] \theta < 0.003 \theta$$

which is negligible at photospheric temperatures.

V. DISCUSSION OF THE RESULTS

Figure 1 shows the observed and synthetic solar spectra in the $1910 - 1915 \text{ cm}^{-1}$ interval. The five spectra shown are first at the top the computed synthetic spectrum at the disk's center, using the data set of Roh and Rao (1974), the second is the corresponding convolved spectrum, the third is a convolved spectrum using the older data set of Goldberg and Müller (1953). The two last spectra are observations of the solar spectrum shown in order to check the accuracy of the observations.

The comparison between the convolved spectra permits to note that the influence of the adopted set of molecular constants is not negligible. We must expect that the positions of lines with high vibrational excitation are better predicted by Roh and Rao's (1974) constants. Figure 1 shows a not too bad agreement between observed and synthetic spectra obtained with the best solar and molecular data available.

The line profiles have been computed at some different positions on the solar disk and we can conclude that only the equivalent widths of the weakest CO lines vary much from center to limb.

The influence of the solar parameters such as temperature distribution, velocity field, carbon and oxygen abundances, has been investigated. In addition to the H.S.R.A. model,

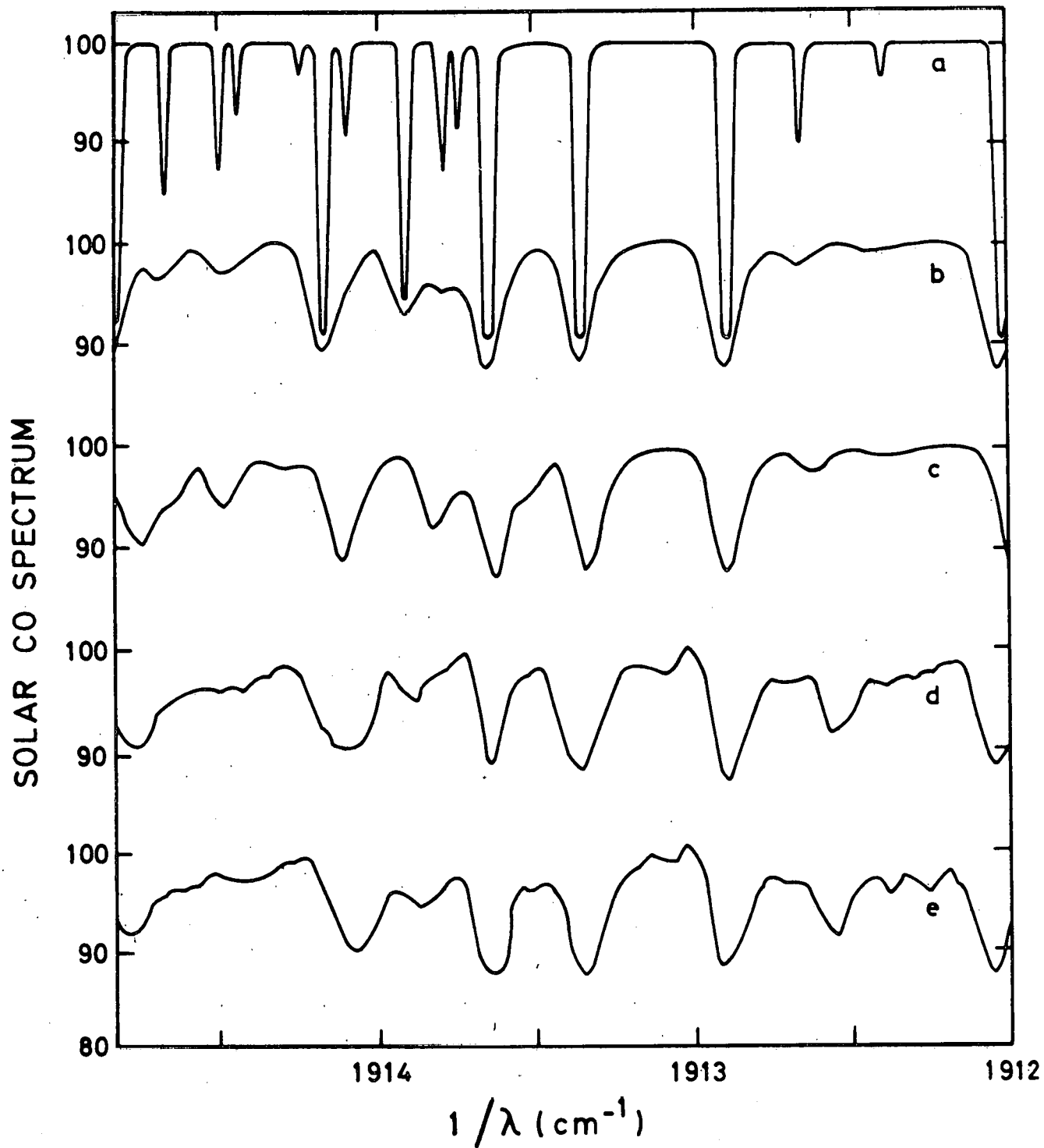


Fig. 1.- Comparison of computed and observed spectra
 a) unconvoluted (Roh and Rao, 1974)
 b) convoluted (Roh and Rao, 1974)
 c) convoluted (Goldberg and Müller, 1953)
 d and e) experimental spectra.

two other photospheric models have been used in our calculations : B.C.A.'s (Gingerich and De Jager, 1968) and Holweger (1967)'s distributions. As expected, weak and moderate lines do not give much different profiles whatever the adopted model may be. In the other hand, for strong lines, the B.C.A. model predicts about 25% smaller equivalent widths than the two other models. The effect of a variation of the macroturbulent velocity on the observed spectra is small : this line broadening is much smaller than the instrumental blurring. Recent calculations of Berger and Léna (1972) show a strong dependence of the equivalent width on the adopted microturbulent velocity (1 to 3 km/sec). As mentioned before, in our calculations, we choose a constant and small ξ -value equal to 0.5 km/sec.

The influence of the abundances of carbon and oxygen on the line profiles has been particularly investigated. As first noted by Locke and Herzberg (1953), the strongest lines of the fundamental bands of CO appear to be in the flat portion of the curve of growth. This important result implies that the equivalent width of strong lines are nearly insensitive to the CO abundance. The logarithmic values of the column density (molecules cm^{-2}) calculated with the three different solar models and our adopted C and O abundances, 20.0 for H.S.R.A.; 20.1 for BCA and 19.9 for Holweger, show a good agreement between the three models. The CO distribution with optical depth is very similar for the three models and shows a maximum near $\log \tau_0 = -1.6$. On the contrary, the relative concentration to hydrogen, $n(\text{CO})/n(\text{H})$, presents a very flat distribution and depends more strongly on the adopted model.

We note here that the center of the strongest CO lines are formed near the temperature minimum ($T \sim 4200$ K) of the HSRA model ($\log \tau_0 = -4$); in that region, a variation of the temperature of 300 K changes the CO concentration by a factor 9 (since the dissociation energy is very large).

In the observed spectra, two unidentified and rather strong lines are present at 1908.0 cm^{-1} and at 1911.0 cm^{-1} . The second line could be due to Fe I (1911.25 cm^{-1}) and Ti I (1911.284 cm^{-1}) lines. A determination of the transition probability for these lines is needed before any conclusion. At the calculated position of the Si I line at 1909.4 cm^{-1} , we

predict a rather strong line which is not visible on the recorded spectra. This disagreement could be due to inaccuracies in the position or more probably in the gf -value.

We also note that two CO lines at 1909.9 and 1912.6 cm^{-1} present calculated equivalent widths much smaller than the observed ones; other contributions may be expected at these positions.

VI. COMPARISON WITH PREVIOUS RESULTS

The solar fundamental bands of CO have been much less investigated in the past than the weaker first overtone bands near 2.4 μm . The main reason is the contamination at ground level of spectra by telluric CO_2 , H_2O and N_2O lines. The telluric low J -values of the 1-0 band CO lines do not interfere seriously with solar CO lines which have usually much higher excitation energies. Therefore, the first observations of the solar fundamental bands by Locke and Herzberg (1953) and Migeotte *et al.* (1956, 1957) were not followed quickly by other researches. Only recently, CO photospheric lines have been obtained by balloon-borne experiments near 4.66 μm by Murcray *et al.* (1969) and Goldman *et al.* (1973). The sunspot spectrum, which offers stronger CO fundamental bands than the disk spectrum, has been recently investigated by Hall (1973a); that research leads to the first determination of solar isotopic ratios of ^{18}O and ^{17}O from measured lines of carbon monoxide.

Among the various papers related to the solar first overtone CO bands, many of them are devoted to the study of the formation and loss processes of the CO molecules. The excitation temperatures and CO column densities are also sometimes determined. The logarithm of the CO amount as deduced experimentally is about 19.3 for Goldberg and Müller (1953); 19.6 for Locke and Herzberg (1959), 19.0 - 19.5 for Livshits and Polonskii (1968) and Kozhenikov and Polonskii (1969). We must note here that no determination of the CO amount has been reported from the strong solar ultraviolet bands of the $A^1\Pi - X^1\Sigma^+$ transition; observed relative intensities of various bands have only been compared with theoretical results (Porter *et al.*, 1967).

Recently, Goldman *et al.* (1973) have observed the solar spectrum on the region 2130 - 2230 cm^{-1} with a smaller spectral resolution (0.3 cm^{-1}). In order to interpret the recorded CO lines, they assume a one-layer solar model at 4500 K and derive a CO column density of about 10^{18} molecules cm^{-2} . Furthermore, using the weak line approximation they obtain this same CO abundance from three strong lines, such as the R(30) line of the 2-1 band. Their result, which completely disagrees with all other previous investigations, is examined here in detail.

The very rough approximation of an isothermal layer for the solar photosphere leads to quite different results than ours. For example, for the [R(30), 2-1] line at 2217 cm^{-1} , Goldman *et al.* (1973) show "at infinite resolution" a central depression of about 80% and a total half width of 0.023 cm^{-1} . Our calculation of that line leads to 33% depression and 0.056 cm^{-1} half width. The equivalent width in the isothermal calculation is 0.03 cm^{-1} for about 10^{18} molecule cm^{-2} and ours is 0.02 cm^{-1} for 10^{20} molecule cm^{-2} . Results identical to Goldman's value had been first obtained in a preliminary analysis of our spectra also based on the isothermal approximation. The large difference between the two methods can be explained by our adopted temperature distribution and the saturation effect.

We also note that with the exception of Goldberg and Müller's (1953) low value of 4300 K, all other determinations of the rotational and vibrational excitation temperature of the first overtone bands are in very good agreement $T = 4850 \pm 50 \text{ K}$ (Newkirk, 1957; Pande, 1967; Sitnik and Pande, 1967; Polonskii, 1972). We recall that the excitation temperature, as deduced from the $[\log W_{\omega}, \chi]$ diagram, has only a physical meaning for the weak lines of the first overtone bands and cannot be used for most of the lines of the fundamental bands. The CO lines at $2.3 \mu\text{m}$ are formed deeper in the photosphere ($\log \tau_0$ around - 1.5) than the strong lines of the $\Delta v = 1$ bands. Lambert's (1968) interpretation of Newkirk's (1957) observations leads to an empirical determination of $\log [N(\text{C}) N(\text{O})]$ equal to 17.28. Recent results, derived by Livshits and Polonskii (1968), Kozhenikov and Polonskii (1969) and Noyes and Hall (1972), suggest that the CO molecules are not uniformly distributed in the solar atmosphere; that might be due to the presence of granulation in the high photosphere. Our calculations of lines of the first overtone bands show that

all lines are practically on the linear part of the curve of growth as already noted in the past (Goldberg and Müller, 1953; Pande and Sitnik, 1966). However, the isothermal layer approximation always predicts larger equivalent widths than the rigorous method using a real distribution of temperature; that is due to the weighting factor, wavelength dependent and always smaller than unity.

Figure 2 shows a theoretical curve of growth for a solar CO line, (R(30), 1-0 band) giving $\log W_\omega$ as a function of $\log [\int N(\text{CO})dz]$. Clearly, the saturation effect already appears at $\log [N(\text{CO}) dz] = 18$ for this line. Also shown in figure 2 is Goldman *et al.* (1973)'s representative point for that line situated on the straight line corresponding to a 4500 K isothermal layer :

$$W_\omega (\text{cm}^{-1}) = 4.5 \times 10^{-20} \int N(\text{CO}) dz$$

The position of that straight line higher than the linear part of the real curve of growth may be explained by the omission of the induced emission term and of the weighting function relative to the solar model at 2200 cm^{-1} . It is clear from the curve of growth that a very precise value of the CO amount cannot be deduced from the medium and strong CO lines. The weak lines alone could be used but our spectral resolution is not high enough to perform this work. We note that Noyes and Hall (1972) also claim a good agreement between observed and calculated profiles of CO fundamental lines at the disk's center adopting L.T.E. and a temperature distribution similar to that of the H.S.R.A. model.

VII. CONCLUSIONS

From a comparison of observed and calculated solar spectra, we find a rather good agreement using recent solar and molecular data for CO infrared lines. Our rigorous method of calculation is compared with previous approximations.

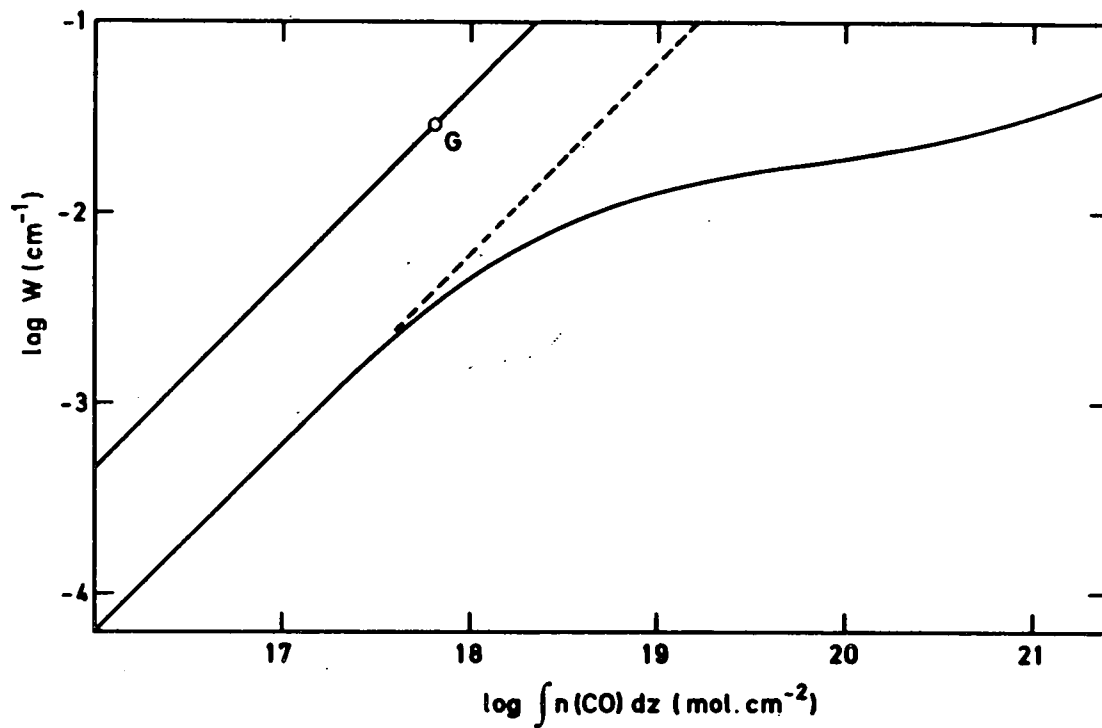


Fig. 2.- Curve of growth of the 2217 cm^{-1} CO line (R(30), 2-1), G indicates the representative point of Goldman *et al* (1973).

An agreement is also found between the results from the first and second overtones. The present research has enabled us to remove some disagreements found earlier about the CO amount in the solar atmosphere.

New solar spectra at higher resolution are needed in order to identify more individual lines of carbon monoxide and its isotopic species. Experimental determinations of positions and transition probabilities of atomic lines in the infrared are also necessary to confirm further identification of atomic lines.

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