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CO emission lines in the solar atmosphere

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Summary. New identifications of CO emission lines in the EUV spectrum of a sunspot are reported. The spectra were obtained with the Naval Research Laboratory's High Resolution Telescope and Spectrograph. The emission is from the CO fourth positive system and is excited by the strong lines of C IV, Si IV and O IV. Transitions in the 0–3 band which lie above 1700 Å and other lines at shorter wavelengths have been identified from the spectrum of the 1973 June 15 flare, obtained with the Naval Research Laboratory's normal incidence spectrograph on *Skylab*. The observed intensities in the sunspot are used to derive the CO column density.

1 Introduction

In a recent letter (Bartoe *et al.* 1978), we reported the detection of emission lines from the fourth positive system of CO, in the EUV spectrum of a sunspot, and showed that the lines are caused by fluorescence from the strong C IV transitions at 1548 and 1550 Å.

Further analysis of the spectra obtained from the first rocket flight of the Naval Research Laboratory's (NRL) high resolution telescope and spectrograph (HRTS I, 1975 July 21) has now been carried out. Most of the remaining lines of moderate intensity which appear enhanced over the sunspot have been identified as transitions in CO. The second HRTS flight (1978 February 13) also obtained spectra over an active region and sunspot, and the spatial distribution of the emission in the various lines was useful in deciding which lines were possibly due to CO.

Although the strongest CO lines are excited by the C IV transitions, there are also progressions excited by the lines of Si IV at 1393.8 and 1402.8 Å, and the O IV line at 1401.2 Å, which also excite H_2 fluorescence (Jordan *et al.* 1978). The new identifications involve both higher v' levels of the $A^1\Pi$ state and higher J'' values.

The CO emission is apparent in the spectrum of the 1973 June 15 flare observed from NRL's normal incidence spectrograph on *Skylab*. These spectra have allowed us to identify further lines including some in the strong 0–3 band which lies above 1700 Å, beyond the range of the HRTS instrument.

The measured emergent line profiles of the C IV, O IV and Si IV lines, combined with the observed intensities of the CO lines and oscillator strengths calculated by Kurucz (1976), have been used to find the column density of CO in the sunspot chromosphere.

Similar CO emission is likely to appear in the atmospheres of other late-type stars, and should provide a useful test of model chromospheres.

2 Identifications

Since the stronger of the lines discussed are visible in the HRTS I spectra published in the previous papers on H_2 and CO fluorescence (Bartoe *et al.* 1978; Jordan *et al.* 1977, 1978), the spectra are not reproduced here.

The new identifications are given in Table 1. Extensive use was made of the energy levels and oscillator strengths calculated by Kurucz (1976) for the CO fourth positive system. The oscillator strengths are listed in Table 1. For two progressions the oscillator strengths were calculated from the band strengths, Frank–Condon and Honl–London factors given by Kurucz. For the identification to be acceptable, a suitable excitation route must be found, in a transition of strength $gf \gtrsim 10^{-1}$, and all lines in the subsequent progression with $gf \gtrsim 10^{-1}$ should be observed. The table also gives the observed intensity and full width at half maximum of each line.

The transitions are listed in order of increasing v' and J', and are discussed below.

The 0–1, 2 Q21 lines cannot be distinguished from the lines with which they are blended, but are listed since they will contribute to the CO 1–0 R27 line and the C I line at 1656.93 Å. The intensity calculations show R27 to be the main contributor.

The 0–1, 1, 2 R34 and P36 lines are excited through 0–0 R34 which lies under C IV 1550.77 Å. This progression accounts for two moderately strong unblended lines at 1557.38 and 1610.55 Å. The 0–1 R34 line is blended with 0–1 Q28, giving a broad line at 1603.68 Å. Although difficult to see on the published prints, the 0–2 R34 line can be distinguished from the Fe II line at 1659.48 Å in short exposures, since Fe II has a different spatial distribution over the spot. The 0–2 P36 transition accounts for a strong line over the spot which is too intense to be due solely to S I at 1666.69 Å, although the latter will contribute most in the disk and limb spectra.

The next progression involves high J values in the 1–0 and 1–1 bands. The identifications were made on the basis of the v'' and J'' separations and the absolute position of the $v' = 1$, $J' = 63$ levels given by Kurucz. The 1–0 R62 line is the main contributor to the line at 1536.88 Å. The 'observed' value of the energy of the upper level differs from that given by Kurucz by 4 cm^{-1}.

Several progressions are observed from the $v' = 5$ levels. The 5–0, 1, 3 Q11 lines are excited not by C IV but by Si IV at 1393.76 Å. The 5–2, 5–4 and 5–6 bands are not observed, in accordance with their low calculated oscillator strengths. This is generally true of the other $v' = 5$ progressions.

Weak lines in the 5–0, 1, 3 R26, P28 and Q31 progressions are excited by O IV at 1401.16 Å.

The Si IV line at 1402.77 Å excites medium strength lines in the 5–1, 3 Q34 progression. The 5–1 Q34 line at 1445.78 Å lies under the Si VIII forbidden coronal line, but the two components are easily distinguished from their different width and appearance.

The 5–1, 3, 5 Q47 progression is unusual in that the excitation by C IV, at 1548.30 Å, arises not out of the $v'' = 0$ level, but from the $v'' = 3$ level. Although the wavelength coinci-

Table 1. Further CO $A^1\Pi-X^1\Sigma^+$ transitions in HRTS sunspot spectra.

v'	v''	Branch	λ (cal) (Kurucz) (Å)	λ (obs) (Å)	Log *gf* (Kurucz)	Intensity (erg cm^{-2} s^{-1} sr^{-1})	FWHM (Å)	Comments
0	0	Q21	1548.01		−0.80			Excited by C IV 1548.19
	1		1600.93	1600.94	−0.52	20	0.082	b1 CO 1–0 R27 F
	2		1656.86	1656.85	−0.57			b1 C I 1656.93 F
0	0	R34	1550.84		−0.87*			Excited by C IV 1550.77
		P36	1557.38	1557.38	−0.88	10	0.11	F
	1	R34	1603.62	1603.68	−0.59	23	0.10	b1 CO 0–1 Q28 F
		P36	1610.55	1610.55	−0.60	11	0.08	F
	2	R34	1659.40		−0.64			b1 Fe II 1659.48 F
		P36	1666.75	1666.69	−0.64			b1 S I 1666.69 F
1	0	R62	1536.87	1536.88	−0.31*	12		b1 CO 5–3 P28 F
		P64	1548.19		−0.31			Excited by C IV 1548.19
	1	R62	1587.49	1587.53	−0.56	13	0.11	
		P64	1599.46	1599.47	−0.57	11	0.08	
5	0	Q11	1393.70		−1.16			Excited by Si IV 1393.76
	1		1436.56	1436.55	−0.89	6.8	0.13	F
	3		1528.86	1528.88	−1.18	3.4	0.098	F
5	0	R26	1401.11		−1.09			Excited by O IV 1401.16
		P28	1396.99		−1.07			Very weak
	1	R26	1439.85	1439.85	−0.81	2.1		F
		P28	1444.19	1444.21	−0.82	1.8		
	3	R26	1532.12		−1.10			b1 H_2 very weak
		P28	1536.94		−1.12			Mainly CO 1–0 R62 F
5	0	Q31	1401.06		−0.72			Excited by O IV 1401.16
	1		1444.07	1444.05	−0.44	1.1		Very weak F
5	0	Q34	1402.74		−0.68			Excited by Si IV 1402.77
	1		1445.78	1445.78	−0.42	9.6	0.077	b1 Si VIII 1445.78 F
	3		1538.44	1538.44	−0.71	4.4	0.072	F
5	0	Q47	1412.05	1412.06	−0.54	3.4	0.080	F
	1		1455.28	1455.29	−0.28	5.2	0.078	F
	3		1548.30		−0.57			Excited by C IV 1548.19
	5		1651.14	1651.11	−0.71	2.0		Weak F
7	1	Q32	1393.63		−0.57			Excited by Si IV 1393.76
	2		1435.62	1435.59	−0.61	1.8		F b1 7–2 P29

* Calculated from band strengths, Frank–Condon and Honl–London factor given by Kurucz.
F Observed also in spectrum of 1973 June 15 flare.

dence with C IV is not close, the calculated oscillator strengths are large. Also, the lines are weak except where C IV is particularly broad.

Finally, Si IV at 1393.76 Å excites a 7–2 Q32 line at 1435.59 Å.

Since our earlier publication we have found that Swings & Swings (1970) first pointed out the close coincidence between the location of the C IV lines and the $A^1\Pi-X^1\Sigma^+$ 0–0 band head, and suggested that lines in comets might be excited from levels with $J \sim 32$.

The progressions discussed above were identified from the HRTS spectra, where the differences between the sunspot, quiet Sun and active region can be systematically examined. Recently Cohen, Feldman & Doschek (1978) have compiled a list of lines observed in the spectrum of the 1973 June 15 flare, obtained with the NRL normal incidence spectrograph on *Skylab*. All the lines reported in our previous letter are present in the flare list. Several are blended with atomic lines but the CO lines account for seven unidentified features. Of the new lines reported in Table 1, the majority are present in the flare, and are indicated by F, in the comment column. Again, although real blends will occur, the new lines account for a further 11 previously unidentified lines. To check that coincidences with atomic lines were not responsible, prints of the original plates have been examined. The CO lines are present in the early phase of the flare, but become weaker as the flare progresses. Although it is possible that the CO emission occurs in the flaring region, it could also be caused in the non-flaring chromosphere by the intense flare radiation field in the transition region lines. The slit of the *Skylab* spectrograph has an equivalent area of 2 × 60 arcsec and the emission observed includes contributions from all this area.

Plate 1 shows a section of the flare spectra, including Si IV and CO lines in the region 1430–1460 Å. The group around 1440 Å is particularly striking and originates from the 5–v'' bands listed in Table 1, the excitations taking place mainly in the *blue* wings of the Si IV lines at 1393.76 and 1402.77 Å. The strength of these lines compared with the HRTS spectra is due to the strong blue wing of the Si IV lines in the early part of the flare. The CO lines weaken when the blue wing weakens. Four further lines of CO apparent in the flare

Table 2. CO lines in 1973 June 15 flare spectrum.

Band v'	v''	Branch	λ (cal) (Kurucz) (Å)	λ (obs) (CFD) (Å)	Log *gf* (Kurucz)	Intensity (erg cm^{-2} s^{-1} sr^{-1} Å^{-1})
0	3	Q21	1716.06	1716.07	−0.83	180
0	3	Q22	1716.42	1716.42	−0.81	270
0	3	R27	1715.78	1715.78	−1.00	160
		P29	1722.05	1722.05	−1.02	180
0	3	Q28	1718.85	1718.85	−0.71	280
7	1	R27	1389.37	1394.38	−0.92	10
		P29	1393.55	(1393.76)*	−0.94	
	2	R27	1431.20	1431.18	−0.96	10
		P29	1435.60	1435.59	−0.97	10
5	0	Q10	1393.51	(1393.76)	−1.20	
	1	Q10	1436.37	1436.36	−0.93	10
8	1	Q13	1362.42	1362.45	−1.14	10
	2	Q13	1402.81	(1402.77)	−0.91	
7	1	P42	1402.81	(1407.77)	−0.77	
		R40	1396.73	1396.74	−0.76	10
3	0	Q30	1455.04	1455.01	−0.35	30
	2	Q30	1550.41	(1550.77)	−0.68	
3	0	P21	1452.56	1452.54	−0.81	10
		R19	1449.23	1449.17?	−0.81	10
	2	P21	1547.97	(1548.19)	−1.16	
		R19	1544.28	(1544.26)	−1.16	50
3	0	Q25	1452.74	1452.73	−0.43	40
	2	Q25	1548.03	(1548.19)	−0.76	
	4	Q25	1653.80	1653.79	−0.95	120 bl

* Wavelengths of exciting lines are given in parentheses.

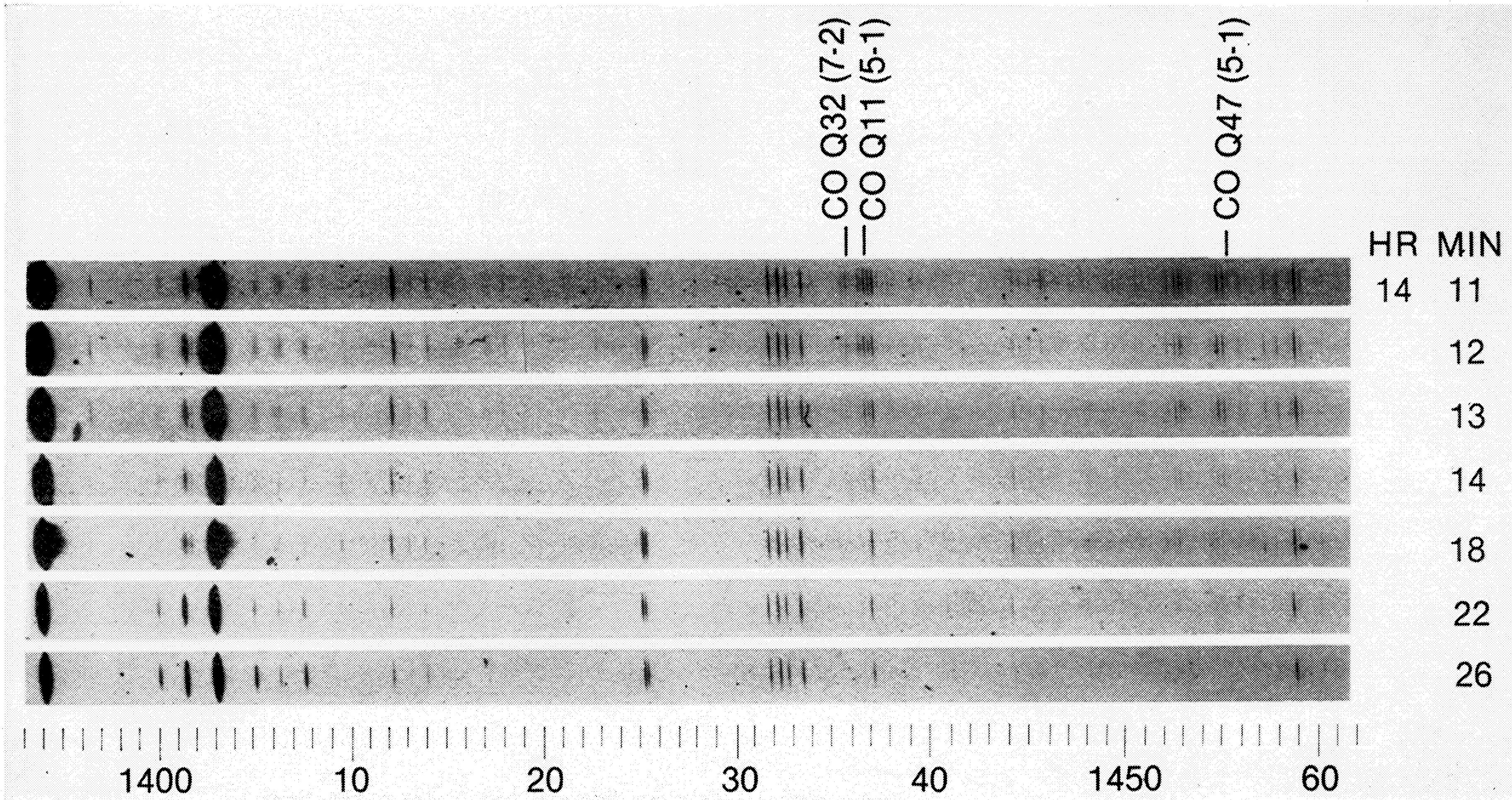


Plate 1. Section of spectra taken during the 1973 June 15 flare with the NRL spectrograph on *Skylab*.

[*facing page* 476

spectra but not in the HRTS spectra can be identified in this region, and are also due to excitation in the far blue wing of 1393.76 Å, in the 5–v'', 7–v'' and 8–v'' bands. These are listed in Table 2.

The second group around 1450 Å originates from excitations by the C IV lines in the 5–1 band and 3–0 bands, as given in Tables 1 and 2. Lines of H_2 also occur throughout this region (Bartoe *et al.* 1979).

This flare spectrum also provides a useful supplement to the HRTS spectra, which end at ~ 1700 Å. In particular we have identified several unblended lines in the 0–3 band which lies at $\lambda \gtrsim 1713$ Å. These lines are also listed in Table 2, together with Kurucz's *gf* values and the observed flare intensities. Unfortunately the C IV lines are overexposed in the flare data published by Cohen *et al.*, and the CO lines cannot be used immediately to derive column densities. However, the CO lines provide a new means of investigating the response of the chromosphere to flares.

About 30 lines, mostly weak, remain unidentified in the HRTS I sunspot spectra. Some of these coincide with lines in the CO fourth positive system, but not in a systematic manner. Excitation routes from all strong transition region lines between 1335 Å (C II) and 1670 Å, (Al II) have been investigated. The lines remaining unidentified may be from even higher *J* levels in bands at shorter wavelengths, or from CO bands not in the fourth positive system. A limited search of other bands using molecular constants given by Tilford & Simmons (1972) has not led to any definite identifications. In particular the $v' = 1$ to $v'' = 1$ band of the $e^3\Sigma^- - X^1\Sigma^+$ system lies near to, and perturbs, the 0–1 band of the $A^1\Pi - X^1\Sigma^+$ system. Simmons, Bass & Tilford (1969) point out that this perturbing band is exceptionally strong. Although 'extra lines' may occur, it has not been possible to identify any transitions responsible.

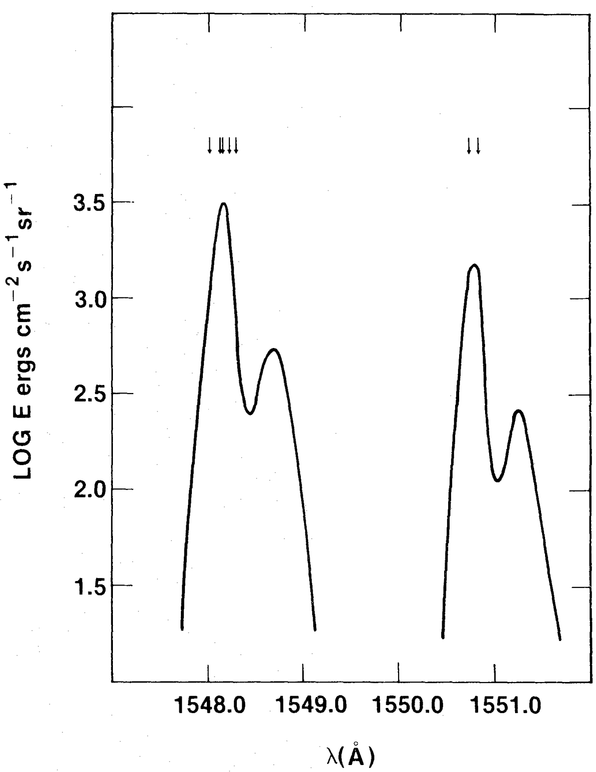


Figure 1. The profiles of the C IV lines over the sunspot. The arrows mark the wavelengths at which excitation takes place.

The fourth positive system of the isotopic molecule $C^{13}O^{16}$ has also been examined, but no identifications were found. (The molecular constants for $C^{13}O^{16}$ were provided by C. M. Brown, private communication.) Although fluorescent excitation by C IV can in principle occur, the natural abundance of C^{13} is 10^{-2} that of C^{14}, so the lines are not observable.

3 Determination of column density

The formulation given in the paper on H_2 fluorescence can be applied to CO.

Consider a level $v'J'$, excited by photo-excitation from a lower level $v''=v_n$, $J''=J_n$, and

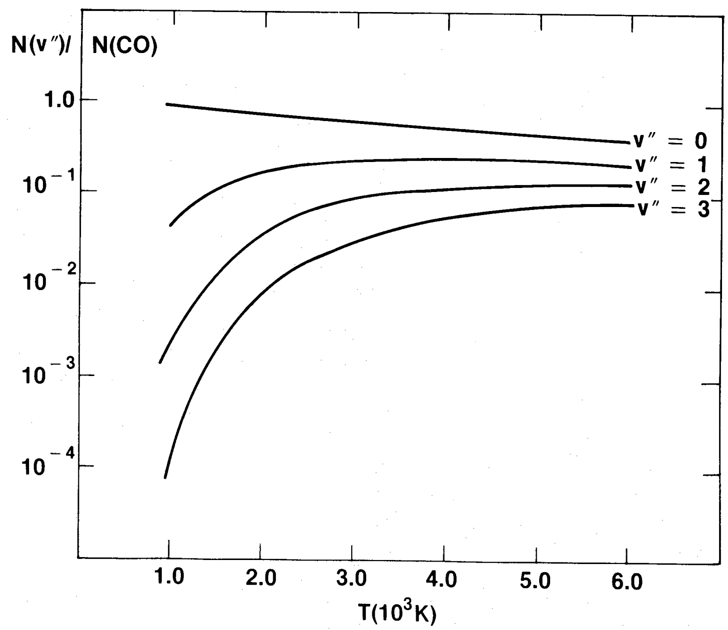


Figure 2. Variation of $N(v'')/N(\mathrm{CO})$ as a function of temperature.

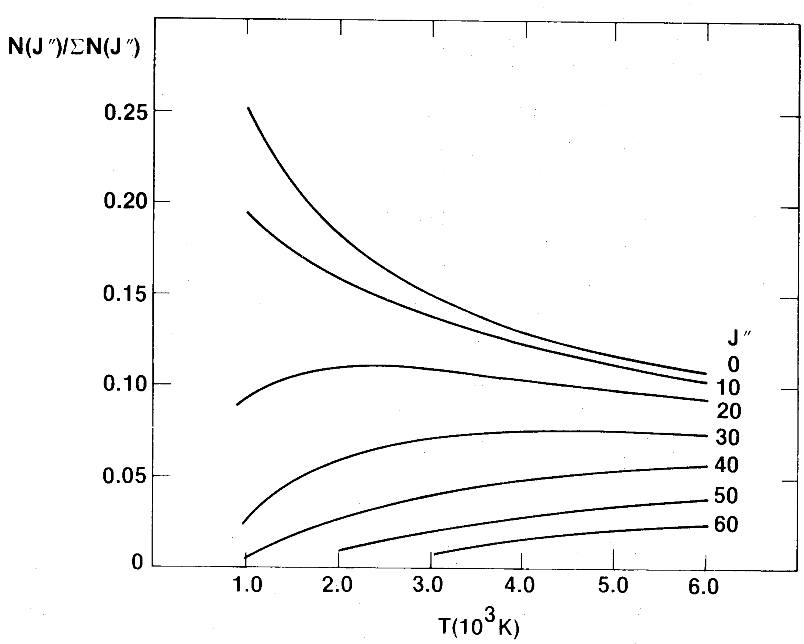


Figure 3. Variation of $N(J'')/\Sigma N(J'')$ as a function of temperature.

which can decay to levels $v'' = v_i$, $J'' = J_i$. The intensity of a particular transition $v'J'-v''J''$ can be expressed as

$$E_{J'J''} = \frac{c^3}{8\pi\lambda_{J'J''}} \frac{1}{\nu^3_{J'J_n}} \frac{g_{v'J'}}{g_{v''J''}} \int_L N_{v_nJ_n} I_\nu \frac{A_{v'J'\to v''J''}}{\sum_i A_{v'J'\to v_i''J_i''}} A_{v'J'\to v_nJ_n}\, dl \quad \text{erg cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1} \tag{1}$$

where g is the statistical weight, A is the spontaneous decay probability, $N_{v_nJ_n}$ is the number density of the lower level, and I_ν is the mean intensity of the radiation field at the frequency in which excitation takes place. $\lambda_{J'J''}$ is in centimetres.

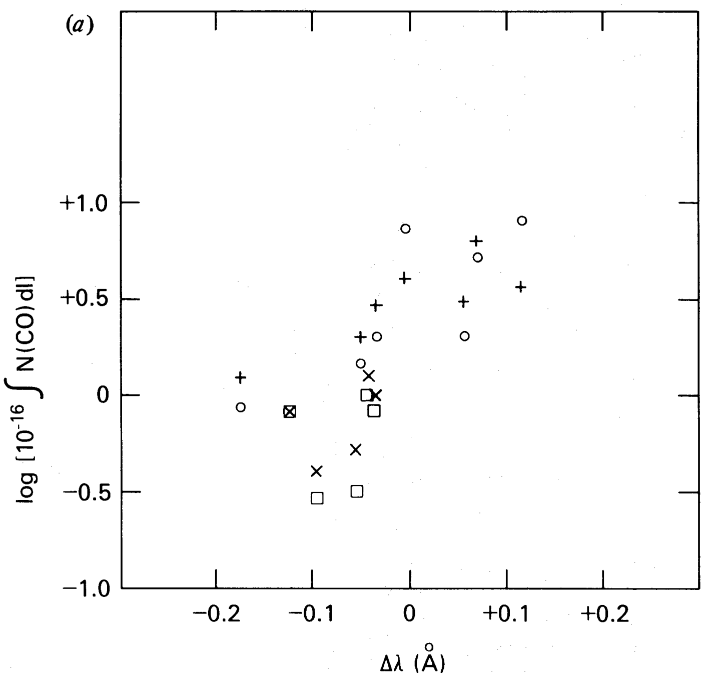
The necessary transition probabilities have been taken from Kurucz (1976).

The level populations have been calculated as a function of temperature using the usual molecular partition functions (e.g. Herzberg 1950).

The intensities and profiles of the C IV, O IV and Si IV lines over the spot have been measured from the HRTS I spectra, and I_ν has been found assuming the atmosphere to be optically thin to the exciting radiation.

Table 3. Values of $\int N(\mathrm{CO})\, dl$.

Band		Line	E (erg cm^{-2} s^{-1} sr^{-1})	$10^{-16} \int N(\mathrm{CO})\, dl$ (cm^{-2}) T(K) 4000	6000
0	0	R15	16	2.2	2.7
0	1	R15	21	1.6	2.5
		P17	20	1.6	2.5
0	2	R15	31	2.8	4.2
0	0	Q21	8	0.84	1.2
0	0	P29	11	1.5	2.2
	1	R27	12	2.3	3.3
		P29	14	1.0	1.4
	2	R27	32	2.7	3.8
		P29	25	2.2	3.0
0	1	Q28	23	0.96	1.3
		Q28	37	1.8	2.5
0	0	P36	10	4.8	5.8
	1	R34	23	7.2	8.9
		P36	11	3.0	3.7
1	0	R62	12	4.3	2.3
	1	R62	13	9.3	5.0
		P64	11	7.9	4.2
5	1	Q11	6.8	0.30	0.47
	3	Q11	3.4	0.31	0.49
5	1	R26	2.1	1.0	1.3
		P28	1.8	0.9	1.2
5	1	Q31	1.1	0.28	0.38
5	1	Q34	9.6	0.85	1.0
	3	Q34	4.5	0.83	1.0
5	0	Q47	3.4	7.8	3.6
	1	Q47	5.2	7.1	3.3
	5	Q47	2.0	8.3	3.9
7	2	Q32	1.8	0.80	0.79



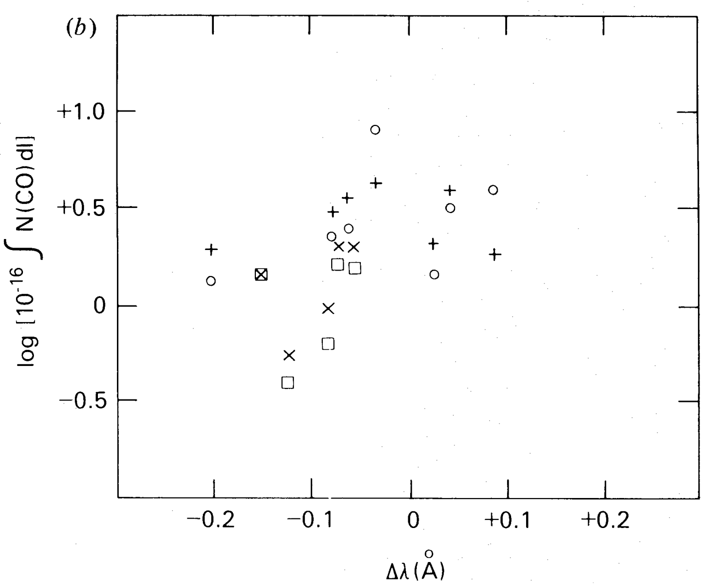


Figure 4. Column densities as a function of the distance of the wavelength of molecular excitation from the line centre of the transition region lines. (a) As calculated. (b) With wavelength shift of + 0.03 Å.

Fig. 1 shows the C IV profiles in the central region of the spot, with some positions of the CO lines in which excitation takes place indicated. The redshifted component is limited to the centre of the umbra and does not excite fluorescence.

Figs 2 and 3 illustrate the dependence of the vibrational and rotational level populations on temperature. It can be seen that over the range of temperatures likely to be of interest in the spot chromosphere, $T_e \sim 4000$ K to 6000 K, the populations of the $v'' = 0$ and 1 levels are insensitive to temperature. Only the excitation route from $v'' = 3$, in Q47 and from $v'' = 0, J'' = 64$ can provide limited information on the temperature.

The column densities $\int N(\mathrm{CO})\, dl$ derived using equations (1) are given in Table 3, at 4000 and 6000 K. It can be seen that within each progression there is reasonable agreement between the various lines. Fig. 4(a) shows a plot of column density against $\Delta\lambda$, the distance of the molecular line in which excitation takes place, from the line centre (at rest) of the transition region line. The open symbols refer to $T_e = 4000$ K, and the crosses to $T_e = 6000$ K. Two systematic effects are apparent. The column densities derived from the lines excited by Si IV and O IV (open squares and diagonal crosses) are a factor of ~ 3 lower than those derived from lines excited by C IV (open circles and vertical crosses). The two lowest points are not very significant as they depend on lines which have intensity less than $2\,\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}}$. However, the other trend is that lines excited in the blue wings of transition region lines give lower column densities than those excited in the red wings. In determining I_ν, the intensity of the radiation field, it was assumed that all lines were at their rest wavelength, and the instrumental profile was not removed from the observed profile. This can be done to determine FWHM, but would not result in an accurate profile. Although the *average* column density is not sensitive to the details of the profile, the dependence on $\Delta\lambda$ is of course very sensitive to the profile. A narrower, symmetric profile will raise the values of column density found from points distant from line centre. But to remove the dependence on the sign of the shift, either an increase of 0.03 Å in the relative wavelengths of the molecular and transition region lines is required, or the true profile must have an asymmetry which raises the red wing. Fig. 4(b) shows, for example, the result of a 0.03 Å red shift in the transition region lines. Apart from the two low points mentioned above the scatter is distinctly reduced, and $T_e = 6000$ K gives a better fit to the data than does $T_e = 4000$ K. The actual appearance of the CO lines in the spectra – the spatial dependence of the emission – shows that they are very sensitive to the incident radiation field. The O IV and Si IV lines vary in both intensity and wavelength across the spot and this is reflected in the CO lines. This also shows that the molecules receive the radiation from a small solid angle.

The average column density derived is $2.2 \times 10^{16}\,\mathrm{cm^{-2}}$, for $4000\,\mathrm{K} \leqslant T_e \leqslant 6000\,\mathrm{K}$. The average column density does not depend critically on the assumptions made and is the most useful parameter to compare with the predictions of model atmospheres.

The only published model of a sunspot chromosphere which gives $N(\mathrm{H})$ and T_e as a function of height is that by Kneer & Mattig (1978), which is based on observations of the Ca II line intensities. The scale height of $N(\mathrm{H})$ near the temperature minimum of this model is $\sim 10^2$ km. This gives $N(\mathrm{CO}) = 2.2 \times 10^9\,\mathrm{cm^{-3}}$. Equilibrium calculations of $N(\mathrm{CO})/N(\mathrm{C})\,N(\mathrm{O})$, made assuming C and O to be only in the form of C, O or CO, and use of the abundances $N(\mathrm{C})/N(\mathrm{H}) = 2.5 \times 10^{-4}$, $N(\mathrm{O})/N(\mathrm{H}) = 6.3 \times 10^{-4}$, then lead to $T_e = 4000$ K for the region where the CO lines are formed.

The observed column density is difficult to explain at higher temperatures. All the assumptions made will tend to *underestimate* the column density and $N(\mathrm{CO})$, not overestimate it. However, it should be stressed that the step from column densities to finding T_e is highly model-dependent. Work is in progress on a self-consistent model of the spot chromosphere.

Acknowledgment

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References

Bartoe, J.-D. F., Brueckner, G. E., Nicolas, K. R., Sandlin, G. D., VanHoosier, M. E. & Jordan, C., 1979. *Mon. Not. R. astr. Soc.*, **187**, 463.

Bartoe, J.-D. F., Brueckner, G. E., Sandlin, G. D., VanHoosier, M. E. & Jordan, C., 1978. *Astrophys. J.*, **223**, L51.

Cohen, L., Feldman, U. & Doschek, G. A., 1978. *Astrophys. J. Suppl.*, **37**, 393.
Herzberg, G., 1950. *Spectra of Diatomic Molecules*, D. Van Nostrand Co., Inc., Princeton, New Jersey.
Jordan, C., Brueckner, G. E., Bartoe, J.-D. F., Sandlin, G. D. & VanHoosier, M. E., 1977. *Nature*, **270**, 326.
Jordan, C., Brueckner, G. E., Bartoe, J.-D. F., Sandlin, G. D. & VanHoosier, M. E., 1978. *Astrophys. J.*, **226**, 687.
Kneer, F. & Mattig, W., 1978. *Astrophys. J.*, **65**, 17.
Kurucz, R. L., 1976. *Smithson. Astrophys. Obs. Spec. Rep. 374.*
Simmons, J. D., Bass, A. M. & Tilford, S. G., 1969. *Astrophys. J.*, **155**, 345.
Swings, J. P. & Swings, P., 1970. IAU Symp. 36, *Ultraviolet Stellar Spectra and Related Ground-based Observations*, p. 226, eds Houziaux, L. & Butler, H. E.
Tilford, S. G. & Simmons, J. D., 1972. *J. Phys. Chem. Ref. Data*, **1**, 147.