

MISSING SOLAR ULTRAVIOLET OPACITY AND DIATOMIC MOLECULES

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ABSTRACT

The band absorption coefficient of some of the molecules abundant in the solar photosphere has been compared with the total absorption coefficient of metals and hydrogen. It is found that the band absorptions considered are possibly large enough to account for the missing opacity in the solar ultraviolet spectrum, except in a small interval between 2500 and 3000 Å.

I. INTRODUCTION

The atmospheric model calculations incorporating absorption by hydrogen and metals (C, Mg, Al, Si, Ca, Cr, Fe, and Ni), as well as Rayleigh scattering by hydrogen, give larger specific intensity in the solar ultraviolet spectrum than that observed (cf. Matsushima 1968). Further, many of the edges seen in the calculated spectrum either are not observed or are present with reduced strength (Gingerich 1970). This difference between the observed and calculated intensities has been interpreted as due to some unknown source (or sources) of opacity in this spectral region (cf. Matsushima 1968; Gingerich 1970; Pottasch 1970). The variation of this unknown opacity with wavelength and temperature has been determined by Bonnet (1968), Matsushima (1968), and Linsky (1970). The unknown opacity may have a maximum at about 2500 Å (Linsky 1970) or at about 2800 Å (Matsushima 1968). Further, the analysis of Linsky (1970), based on the observations of Bonnet (1968), shows that the unknown opacity should also increase around 2000 Å. The extension of the observations toward wavelengths shorter than 2000 Å has revealed that the unknown opacity should extend up to at least 1700 Å (cf. Gingerich 1970). Several suggestions (Matsushima 1968; Cuny 1969; Gingerich 1970; Linsky 1970) have been made about the sources of this unknown opacity, but the search still continues. Here we have attempted to examine the extent to which band absorption by diatomic molecules can account for this unknown opacity.

II. CALCULATIONS AND RESULTS

The absorption cross-section σ_ω at wavenumber ω for an electronic vibrational band (v' , v'') of a diatomic molecule can be approximated by (Golden 1967)

$$\sigma_\omega = \frac{\pi e^2}{mc} \frac{h}{kT} Q_R'' F_e'' f_{v'v''} \frac{B_{v''}}{|B_{v'} - B_{v''}|} \left[1 - \exp\left(-\frac{hc\omega}{kT}\right) \right] \\ \times \exp\left[-\frac{hc}{kT} (R_{v'v''} + S_{v'v''}\omega)\right] \text{ cm}^2, \quad (1)$$

where

$$f_{v'v''} = \frac{\omega_{v'v''}}{\omega_{00}} q_{v'v''} f_a, \quad (2)$$

$$F_e'' = \frac{g_e''}{Q} \exp(-hcT_e''/kT), \quad (3)$$

$$R_{v'v''} = \omega_{v''} - \frac{B_{v''} |\Omega_{v'v''}|}{B_{v'} - B_{v''}} \text{ (Normal bands) ,} \quad (4)$$

$$= T_e' - T_e'' + \omega_{v'} + \frac{B_{v'} |\Omega_{v'v''}|}{B_{v'} - B_{v''}} \text{ (Reversed bands) ,} \quad (5)$$

$$S_{v'v''} = B_{v''}/(B_{v'} - B_{v''}) \text{ (Normal bands) ,} \quad (6)$$

$$= -B_{v'}/(B_{v'} - B_{v''}) \text{ (Reversed bands) ,} \quad (7)$$

$$\Omega_{v'v''} = \omega_{v'v''} - \frac{1}{4} \frac{(B_{v'} + B_{v''})^2}{(B_{v'} - B_{v''})} , \quad (8)$$

$$\omega_{v'v''} = \omega_{00} + \omega_{v'} - \omega_{v''} , \quad (9)$$

$$B_v = B_e - \alpha_e(v + \frac{1}{2}) , \quad (10)$$

and

$$\omega_v = \omega_e v - \omega_e x_e v(v + 1) . \quad (11)$$

In equations (1)–(11), the different spectroscopic constants (ω_e , $\omega_e x_e$, ω_{00} , B_e , α_e , and T_e) have their usual meaning, Q is the total partition function, Q_R the rotational partition function, g_e'' the electronic statistical weight of the ground state, f_a the electronic oscillator strength, T the temperature, and the quantities e , m , k , h , and c have their usual meanings. For the (0, 0) transition from the ground electronic state one can approximately write equation (1) as

$$\sigma_\omega = \frac{\pi e^2}{m c k T} \frac{h}{f_{v'v''}} \frac{B_{v''}}{|B_{v'} - B_{v''}|} \text{ cm}^2 , \quad (12)$$

if ω is equal to ω_{00} , the wavenumber corresponding to the (0, 0) transition. The mass absorption coefficients for some of the bands of the eight abundant molecules, obtained from equation (12), and the equilibrium number densities, computed along the lines of Vardya (1966) for solar elemental abundances for two optical depths, have been listed in Table 1. The temperature and electron pressure corresponding to the optical depths have been taken from Matsushima (1968). Table 1 also contains the wavelengths and oscillator strengths of the (0, 0) transition for different bands and the number density of molecules relative to atomic hydrogen and the mass absorption coefficient of metals and hydrogen as given by Matsushima (1968). The table shows that the absorptions by all the molecules listed except NO are much larger than the combined absorption of metals and hydrogen.

To examine whether the band absorptions are broad enough to account for the unknown opacity, we have calculated absorption coefficients for the A - X band of CO, SiO, and OH molecules, and the B - X band of the CH molecule, from equation (1), using the number densities from Table 1. The various spectroscopic constants used are from Herzberg (1950). The values of $f_{v'v''}$ for CO are from Hesser (1968), and those for OH, CH, and SiO have been determined by equation (2). The values of $q_{v'v''}$ for OH are from Fraser, Jarman, and Nicholls (1955), for CH from Childs (1964), and for SiO from Nicholls (1962). The value of f_a for OH and CH has been taken from Wentink *et al.* (1964), and that for SiO has been determined from the f_{01} value of Czernichowski and Zyrnicki (1970) by using equation (2).

Figures 1 and 2 compare the molecular-band opacities with metal and hydrogen opacities at the two optical depths. Figures 1 and 2 also contain the unknown opacity (*dashed curve*) proposed by Matsushima (1968) to alleviate the discrepancy between theory and observation. Figure 1 shows clearly that at $\tau_{0.5\mu} = 0.08$ the absorption due to the A - X band of CO is much larger than the absorption by metals between 1400 and

TABLE 1
COMPARISON OF THE ABSORPTION COEFFICIENTS OF MOLECULAR BANDS AND ATOMIC OPACITIES IN THE ULTRAVIOLET

MOLECULE	TRANSITION	WAVELENGTH FOR (0, 0) TRANSITION (Å)	OSCILLATOR STRENGTH FOR (0, 0) TRANSITION	$\tau_{0.5\mu} = 0.08; \theta = 1.0; \log p_e = 0.5$		$\tau_{0.5\mu} = 0.4; \theta = 0.9; \log p_e = 1.0$			
				Absorption Coefficient ($\text{cm}^2 \text{g}^{-1}$)		Absorption Coefficient ($\text{cm}^2 \text{g}^{-1}$)			
				Molecular	Atomic	Molecular	Atomic		
H ₂	$B(^1\Sigma_u^+) - X(^1\Sigma_g^+)$	1109	0.00196 ^a	1.41-3*	4.47+2	1.26+2	6.92-4	1.98+2	7.94 +1
	$C(^1\Pi_u) - X(^1\Sigma_g^+)$	1009	0.04437 ^a	1.41-3	1.35+4	6.76+2	6.92-4	5.96+3	6.310+2
CO	$A(^1\Pi) - X(^1\Sigma^+)$	1545	0.011 ^a	1.0-4	5.93+2	1.85+1	1.78-5	9.50+1	9.26 +0
	$B(^1\Sigma^+) - X(^1\Sigma^+)$	1151	0.007 ^a	1.0-4	4.83+3	1.47+2	1.78-5	7.73+2	8.58 +1
	$C(^1\Sigma^+) - X(^1\Sigma^+)$	1088	0.12 ^a	1.0-4	2.28+5	1.00+3	1.78-5	3.45+4	7.94 +2
OH	$A(^2\Sigma^+) - X(^2\Pi)$	3086	0.00066 ^b	2.0-6	1.85+0	2.71-2	1.35-6	1.12+0	7.36 -2
CH	$A(^2\Delta) - X(^2\Pi)$	4315	0.0049 ^c	1.41-7	2.39+0	5.41-2	1.12-7	1.71+0	1.17 -1
	$B(^2\Sigma^-) - X(^2\Pi)$	3889	0.016 ^c	1.41-7	2.19+0	4.65-2	1.12-7	1.57+0	9.26 -2
NH	$A(^3\Pi) - X(^3\Sigma^-)$	3359	0.008 ^d	7.08-6	5.09+1	3.42-2	6.40-8	4.14+1	7.94 -2
SiO	$A(^1\Pi) - X(^1\Sigma^+)$	2345	0.057 ^e	1.46-8	6.28-1	1.47-1	2.21-9	8.56-2	6.31 -2
CN	$B(^2\Sigma^+) - X(^2\Pi)$	3876	0.0234 ^f	1.59-8	4.01-1	4.65-2	6.87-9	1.56-1	9.26 -2
NO	$A(^2\Sigma) - X(^2\Pi)$	2269	0.00084 ^g	9.12-9	5.78-3	1.36-1	3.74-9	2.14-3	6.31 -2
	$B(^2\Pi) - X(^2\Pi)$	2204	0.0003 ^g	9.12-9	8.85-4	1.26-1	3.74-9	3.27-4	6.31 -2

* The number a - n denotes a X 10⁻ⁿ.

SOURCES.—^aHesser (1968). ^bFraser *et al.* (1955); Wentink *et al.* (1964). ^cChilds (1964). ^dBennett and Dalby (1960). ^eNicholls (1962); Czernichowski and Zyrnucki (1970). ^fNicholls (1964a); Wentink *et al.* (1964). ^gNicholls (1964b); Wentink *et al.* (1964).

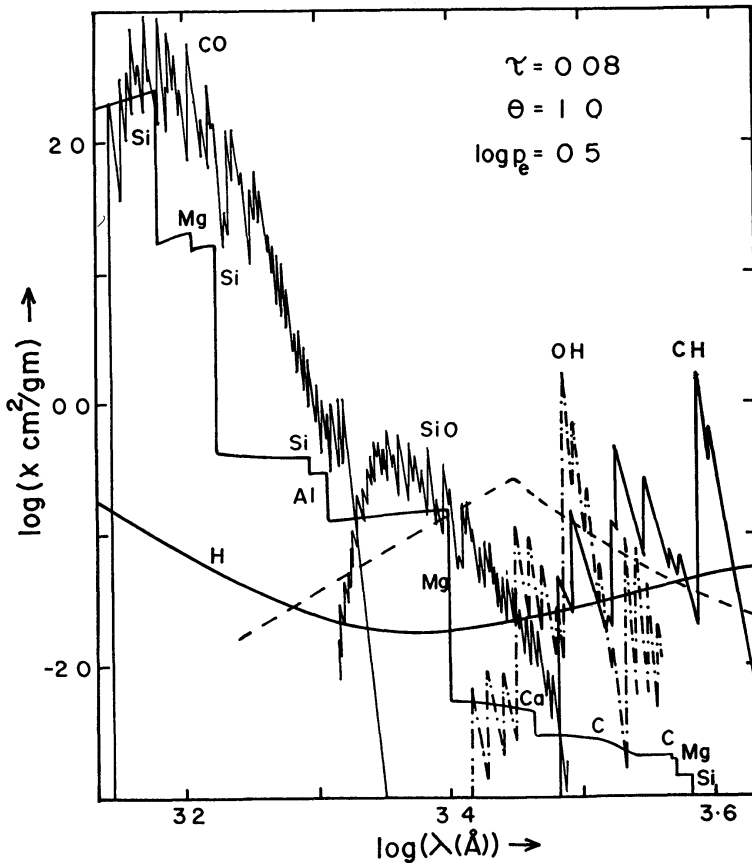


FIG. 1.—Variation of mass absorption coefficients with wavelength. Dashed curve shows the required absorption coefficient over and above that of metals and hydrogen to satisfy observed flux (Matsushima 1968).

2140 Å, the absorption due to the A - X band of SiO dominates the absorption of metals and hydrogen between 2140 and 2818 Å, and the absorption due to the A - X band of OH and the B - X band of CH is comparable to the absorption by hydrogen between 2818 and 4000 Å. With increase in optical depth (Fig. 2) the relative importance of molecular-band absorption decreases compared with the absorption by metals and hydrogen. However, even at $\theta = 0.9$, $\log p_e = 1.0$ corresponding to $\tau_{0.5\mu} = 0.4$, the absorption due to the A - X bands of CO, SiO, and OH and the B - X band of CH are large enough to contribute significantly to the total opacity. According to Schadee (1968), the optical depth of formation $\langle\tau\rangle$ of the $2.3\text{-}\mu$ rotation-vibration band of CO is 0.04. Since the absorption coefficient at 1550 Å around which the A - X band of CO is formed is larger than that at $2.3\ \mu$, one expects the depth of formation of the A - X band of CO to be less than 0.04. This implies that in the solar atmosphere, in reality, the relative importance of A - X band absorption of CO compared with metals is even more than what appears from Figure 1, and the edges due to Si I at 1518 and 1674 Å may be washed out as the observations reveal (cf. Gingerich 1970).

The value of $\langle\tau\rangle$ for the A - X bands of SiO and OH may be assumed to be about 0.16, corresponding to the B - X band of CH (Schadee 1968), since the absorption coefficients of these bands are not very much different. This will result in the reduction of the edges of Al I at 2100 Å and of Mg I at 2515 Å.

Figure 3 compares the absorption due to the A - X bands of CO, SiO, and OH and the B - X band of CH with the empirically determined opacity (*dashed curve*) between 2000

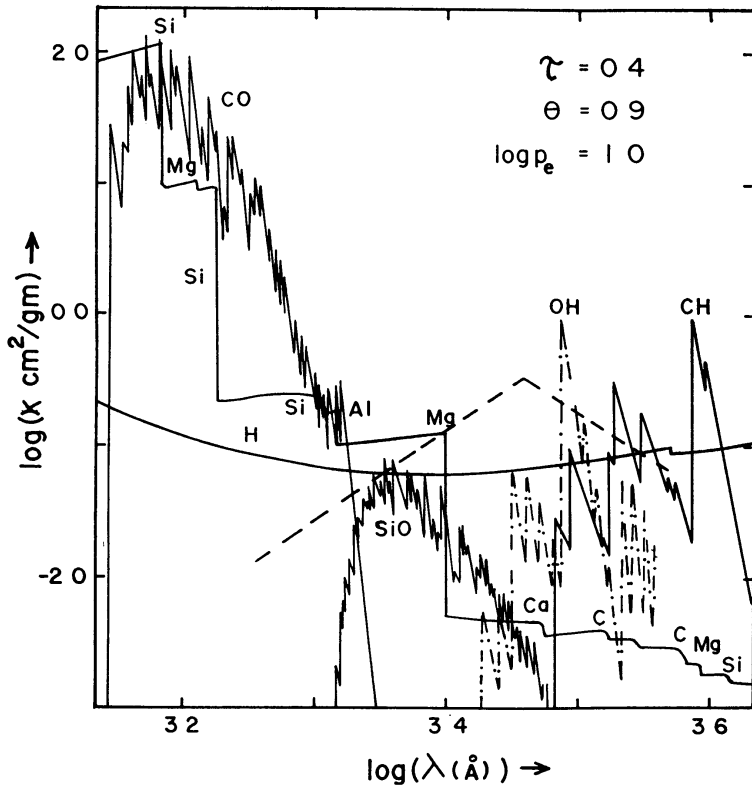


FIG. 2.—Same as Fig. 1, for different values of τ , θ , and $\log p_e$

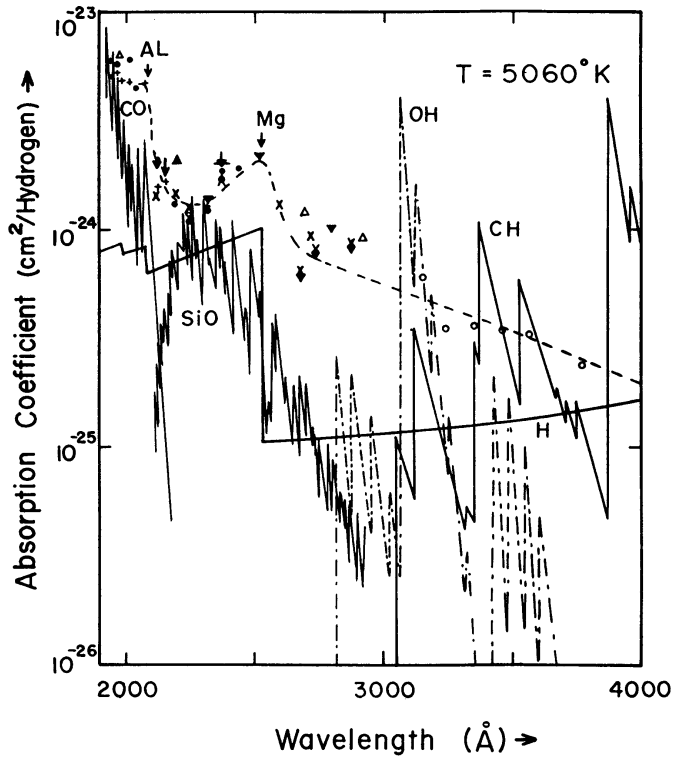


FIG. 3.—Variation of absorption coefficients with wavelength. The dashed curve shows the empirically determined solar ultraviolet opacity. Symbols for different observational points follow Bonnet (1968).

and 3750 Å at 5060° K (Bonnet 1968). It also contains the total absorption due to metals and hydrogen (Bonnet 1968). This figure shows that the total opacity due to metals, hydrogen, and molecules is sufficient to account for the required opacity except between 2500 and 3000 Å.

The $b(^3\Sigma^+)-a(^3\Pi)$ band of CO having (0, 0) transition at 2828 Å with violet shading and the $A(^1\Pi)-X(^1\Sigma)$ band of CS having a (0, 0) transition at 2577 Å with shading to the red are possible candidates to explain the discrepancy in the 2500–3000 Å interval. The available spectroscopic constants (Herzberg 1950) and the oscillator strengths (Wentink *et al.* 1964; Smith 1969) give too small an absorption coefficient from these two bands to have any significant effect on the solar ultraviolet opacity. However, these bands may contribute not insignificantly, if the dissociation energy of CS and excitation energy of the level a of CO, which are somewhat uncertain (cf. Gaydon 1968; Herzberg 1950), are revised upward and/or the oscillator strength is found to be larger than the presently assumed value.

III. CONCLUSIONS

The absorption coefficient due to bands of the abundant diatomic molecules in the solar photosphere has been compared with that of metals and hydrogen in the ultraviolet spectral region. The molecular-band absorption due to the $A-X$ bands of CO, SiO, and OH and to the $B-X$ band of CH has been found to be larger than or equal to the total absorption by metals and hydrogen below 4000 Å and large enough to account for the unknown opacity in the region except possibly between 2500 and 3000 Å. Whether absorption due to some other molecular band or bands is responsible for the opacity in this wavelength interval is not certain. It is hoped that these molecular opacities, when incorporated into the model calculation, will go a long way toward mitigating the problem of the missing opacity of the solar ultraviolet spectrum.

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