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ON ULTRAVIOLET STELLAR FLUXES. II. IMPORTANCE OF CO BAND ABSORPTION AND BOUND-FREE ABSORPTION OF Al I IN A, F, G, AND K STARS

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ABSTRACT

The discrepancy between observed and calculated ultraviolet fluxes of A to G stars can be largely alleviated between λλ1376–2400 Å, if absorption coefficients of the *A–X* band of CO and bound-free transitions of Al I are incorporated in the model calculations. However, the discrepancy around λ2800 needs further investigation.

I. INTRODUCTION

The computed ultraviolet fluxes (Mihalas 1966) for late B to F main-sequence stars with continuous sources of opacity from bound-free absorption of H, H^-, H_2^+, He I, and He II, scattering of H and e^-, and line blanketing from the Balmer series of hydrogen give larger values than those observed (Davis and Webb 1970; Bless 1970). This may be due to the neglect of important absorptions due to metals like Si I (Strom and Strom 1969) and C I (Gingerich and Latham 1970). Recently, a grid of atmospheric models, including convection and opacities due to bound-free absorptions of H, H^-, H_2^+, C I, Mg I, and Si I, scattering by H, H_2, and e^-, and blanketing by hydrogen lines have become available (Carbon and Gingerich 1969). Our aim here is to compare the fluxes of these models with observations, to examine how far the discrepancies between previous models and observations have been accounted for, and to suggest other possible sources of opacity which, if included in the model calculations, may remove the disagreement, if any.

II. COMPARISON BETWEEN OBSERVED AND THEORETICAL ULTRAVIOLET FLUXES

Figures 1, 2, and 3 compare the observed and calculated fluxes at λλ2800, 2100, and 1376 Å, respectively. The observational points are the same as in Davis and Webb (1970). The continuous and dashed curves represent the theoretical fluxes from the set of models by Carbon and Gingerich (1969) and by Mihalas (1966), respectively with $\log g = 4.0$, and the effective-temperature scale from Wolff, Kuhi, and Hayes (1968), and Hanbury Brown *et al.* (1967). Figures 1 and 2 show that the fluxes obtained from the two sets of models do not differ very much at 2800 and 2100 Å. This is understandable for 2800 Å, where the sources of opacity (mainly H) is same in both the models. However, the reason of having almost the same fluxes at 2100 Å in the two sets of the models is not very clear, as the models of Carbon and Gingerich (1969) include opacity due to bound-free absorption of Mg I operative shortward of 2510 Å. This may be because Mg I opacity is not large enough compared with that of hydrogen in the overlapping temperature region of these two sets of models to affect the emergent flux significantly. Further, inclusion of opacities due to bound-free absorptions of C I and Si I operative at $\lambda < 2100$ Å in the models of Carbon and Gingerich (1969) reduces the flux in the spectral region $\lambda < 2100$ Å but enhances it in the longward region of spectra, thus nullifying, at least in part, the absorption by Mg I. However,

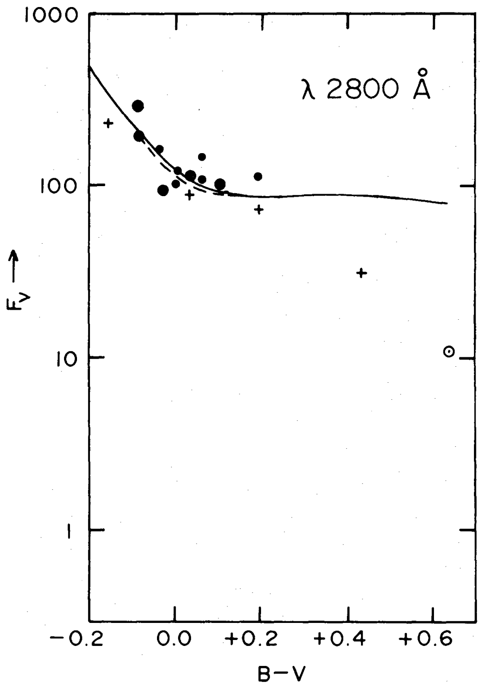

FIG. 1

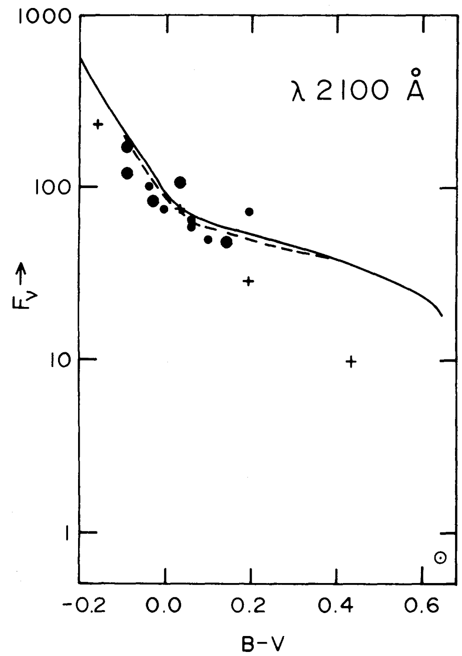

FIG. 2

FIG. 1.—Observed (Davis and Webb, 1970) and theoretical (---, Mihalas 1966; ——, Carbon and Gingerich 1969) ultraviolet fluxes, F_ν, for main-sequence stars at λ2800 Å. F_ν is in units of 10^{-22} ergs cm^{-2} s^{-1} Hz^{-1}.

FIG. 2.—Same as in fig. 1 at λ2100 Å.

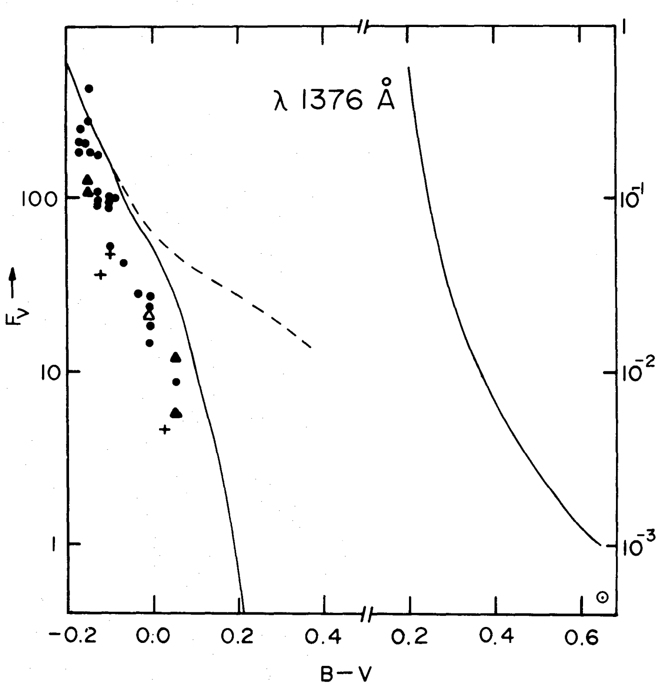

FIG. 3.—Same as in fig. 1 at λ1376 Å

the need of extra opacity around 2800 and 2100 Å increases as one goes from spectral type around F0 to later-type stars.

Figure 3 shows that at high temperatures, models with (Carbon and Gingerich 1969) and without (Mihalas 1966) opacities due to C I, Mg I, and Si I are similar and in agreement with observations. However, as the temperature decreases, the agreement between observations and models of Mihalas (1966) worsens. But the fact that the models of Carbon and Gingerich (1969) are in better accord with observations shows that the opacities due to C I, Mg I, and Si I play increasingly important role with decrease in temperature. In spite of it, the theoretical fluxes are still larger than the observed fluxes by about a magnitude. Whether this difference between models and observations is real is not certain, as the observational error in this spectral region is large (cf. Bless 1970). However, the calculated fluxes are always larger than the observed ones. As no observations are available for stars later than A3 in this wavelength region, it is not certain whether this difference persists for stars cooler than A3 or not, except that the model of Carbon and Gingerich (1969) gives fluxes larger than that observed for the Sun by about 0.75 mag.

III. IMPORTANCE OF CO BAND ABSORPTION AND BOUND-FREE ABSORPTION OF Al I

Recently bound-free absorption of Al I (Gingerich *et al.* 1971) and the *A–X* band absorption of CO (Tarafdar and Vardya 1972, referred hereafter as Paper I) have been found to be very important in the solar extreme-ultraviolet region. Therefore, in table 1 we have compared the absorption of Al I and of the CO (*A–X*) band to the combined absorption of Si I, Mg I, C I, H^-, and H including Rayleigh scattering by H at several wavelengths for values of temperature T and pressure P relevant to atmospheres of A to K stars. The band absorption coefficient of CO has been computed following Golden (1967) as described in Paper I, except that here we have included more transitions than those for which Hesser (1968) gave oscillator strengths; for these, the Franck-Condon factors have been taken from Nicholls (1962). Photoionization cross-sections for C I, Mg I, Al I, and Si I are from Peach (1970). Photoionization and Rayleigh scattering cross-sections of H have been determined following Vardya (1964). The photodetachment cross-section of H^- has been taken from Doughty, Fraser, and McEachran (1966). The equilibrium number densities of different atoms and molecules have been determined following Vardya (1966), with solar photospheric composition (Lambert 1968; Lambert and Mallia 1968; Lambert and Warner 1968*a*, *b*, *c*; Warner 1968) except Zr for which the value given by Goldberg, Müller, and Aller (1960) has been used.

Table 1 shows that the absorption by the *A–X* band of CO is important compared to the combined opacity of H, C I, Mg I, and Si I for $\theta(\equiv 5040/T) \geq 0.8$, $P \geq 10^2$ dyne cm^{-2}, and wavelengths between 1400 and 2400 Å. At 1400 Å, CO band absorption is ~180 percent of the combined opacity of H, C I, Mg I, and Si I at $\theta = 1.2$, and is only a few percent at $\theta = 0.8$. For a given (θ, P), the mean contribution of CO band absorption increases from its value at 1400 Å with increasing wavelength, attains maximum around 1800 Å, and decreases thereafter. However, it may contribute as much as 15 percent even at 2400 Å. At 1800 Å depending on pressure, CO band absorption is 157 to 75 *times* larger than the combined opacity of H, C I, Mg I, and Si I at $\theta = 1.2$, and 88 to 1 *times* at $\theta = 1.0$. For a given wavelength, the effect of CO opacity compared to the combined opacity of H, C I, Mg I, and Si I increases with increasing pressure for fixed values of $\theta \leq 1.0$. For $\theta \geq 1.1$, depending on wavelength, the effect of CO opacity, either remains almost independent of pressure (e.g., at $\lambda =$ 1400 Å, $\theta = 1.2$), or increases with increasing P (e.g., at $\lambda \leq 1800$ Å, $\theta = 1.1$), or passes through a maximum (e.g., for $\lambda \geq 1600$ Å, $\theta = 1.2$; and for $\lambda \geq 2000$ Å,

TABLE 1

RATIOS OF ABSORPTION COEFFICIENTS OF CO AND OF Al I TO THE COMBINED ABSORPTION OF H, C I, Mg I, AND Si I

θ	LOG P	CO					Al I		
		1400 Å	1600 Å	1800 Å	2000 Å	2400 Å	1600 Å	1800 Å	2000 Å
1.2....	2	1.82	48.01	74.66	2.68	0.08	0.00	0.18	0.16
	3	1.88	50.38	157.33	8.60	0.13	0.01	0.54	2.77
	4	1.85	47.50	155.21	6.24	0.07	0.01	1.53	5.81
	5	1.87	43.75	122.65	3.04	0.03	0.05	4.61	10.82
1.1....	2	0.57	11.59	9.36	0.37	0.02	0.00	0.08	0.23
	3	1.01	22.14	50.41	2.74	0.09	0.01	0.28	1.10
	4	1.34	29.59	101.50	6.94	0.13	0.01	0.66	3.23
	5	1.62	34.25	106.88	4.45	0.07	0.02	1.66	4.97
1.0....	2	0.10	1.74	1.19	0.06	0.00	0.01	0.07	0.17
	3	0.34	6.12	13.14	0.75	0.03	0.01	0.26	0.79
	4	0.74	13.76	48.01	3.78	0.11	0.01	0.47	2.01
	5	1.33	24.52	88.08	6.24	0.15	0.01	0.76	2.98
0.9....	2	0.01	0.08	0.06	0.00	0.00	0.01	0.06	0.15
	3	0.03	0.41	0.74	0.05	0.00	0.01	0.22	0.53
	4	0.09	1.38	3.97	0.28	0.01	0.01	0.38	1.07
	5	0.25	3.75	11.73	0.92	0.04	0.01	0.47	1.45
0.8....	2	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.08
	3	0.00	0.03	0.04	0.00	0.00	0.01	0.15	0.24
	4	0.01	0.12	0.23	0.01	0.00	0.01	0.26	0.47
	5	0.03	0.41	0.92	0.06	0.00	0.01	0.31	0.64

$\theta = 1.1$). For a given (θ, P) the effect of CO band absorption decreases with increasing temperature except for $\lambda \geq 2000$ Å and $P \geq 10^4$ dyne cm^{-2}, where the effect of CO opacity passes through a maximum.

Table 1 also shows that Al I opacity is significant compared to the combined opacity of H, C I, Mg I, and Si I shortward of its threshold wavelength of 2077 Å for $\theta \geq 0.8$ and $P \geq 10^2$ dyne cm^{-2}. For a given (θ, P) the importance of Al I opacity is maximum at its threshold wavelength but decreases with decrease in wavelength. The absorption coefficient of Al I, depending on (θ, P), varies from 2 percent to more than 1000 percent of the combined opacity of H, C I, Mg I, and Si I at 2077 Å and is about a percent at 1600 Å. For given wavelength and θ (or pressure) the effect of Al I opacity increases with increasing pressure (or θ) compared with those considered in the models of Carbon and Gingerich (1969). However, even at $\theta = 0.8$ and $P = 10^3$ dyne cm^{-2}, Al I contributes as much as 24 percent of the combined opacity in the wavelength region of 1800 and 2077 Å.

Comparing the pressures and temperatures over which CO and Al I opacity is important with those in the models of Carbon and Gingerich (1969) with log $g = 4.0$, one finds that these sources of opacity are important not only in K and G main-sequence stars but possibly also in stars as hot as A5 V. The range of temperature and pressure over which these opacities have been found to contribute significantly, suggests that these opacities may be important even in late-type giants and supergiants. In fact, the discrepancy between the observed and calculated fluxes near 2100 Å for the F0 supergiant star Canopus (α Car) (cf. Kondo, Henize, and Kotila 1970) may be due to the neglect of these sources of opacities in the models of Parsons (1969).

Concluding, the discrepancy between observations and models, when CO and Al I opacities are incorporated, should decrease if not completely disappear in the spectral range 1400–2400 Å, though not at longer wavelengths. However, with the recent upward revision of iron abundance by an order of magnitude (Garz *et al.* 1969), the possibility of line blanketing due to Fe I and Fe II lines in the spectral region 2000–3000 Å has brightened up; if this is taken into account, it may alleviate the discrepancy, at least partially, at longer wavelengths.

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