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ON ULTRAVIOLET STELLAR FLUXES. IV. IMPORTANCE OF BOUND-FREE ABSORPTION OF S I IN B TO K STARS

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ABSTRACT

The bound-free absorption of S I has been found to be an important source of opacity in the spectral region $\lambda\lambda$1000–1197 Å in stars as early as B5.

Subject headings: early-type stars — opacities — spectra, ultraviolet — stellar atmospheres

I. INTRODUCTION

The bound-free absorption of S I has been found to be important in the solar atmosphere around λ1100 Å (Gingerich *et al.* 1971). Here we have examined its importance in stars of spectral type earlier than the Sun, especially in view of the need felt for extra source(s) of opacity in this spectral region by some authors (Byram, Chubb, and Werner 1965; Adams and Morton 1968; Carruthers 1968), though not all (Carruthers 1970).

II. COMPARISON BETWEEN OBSERVED AND CALCULATED FLUXES AT 1115 Å

Figure 1 gives the variation of the observed and calculated color difference, $m_{1115} - V$ with $B - V$. The observed color differences have been determined from the fluxes at λ1115 Å given by Byram *et al.* (1965), Yamashita (1968), and Carruthers (1970) and at λ1200 Å by Stecher (1970). The observed fluxes have been corrected, whenever necessary, for interstellar reddening, following Carruthers (1971); note, however, the wide range of correction factors used (Yamashita 1968; Adams and Morton 1968; Carruthers 1971; Bless and Savage 1972). The observed values of $B - V$ and V magnitudes are from Iriarte *et al.* (1965) and from Hoffleit (1964), and the intrinsic values of $B - V$ are from Johnson (1963). The ($B - V$, effective temperature) relation of Wolf, Kuhi, and Hayes (1968) and of Hanbury Brown *et al.* (1967) has been used to calculate the ($m_{1115} - V$, $B - V$) relation from atmospheric models of Mihalas (1966), Adams and Morton (1968), and Hickok and Morton (1968) (*dashed curve*) and of Carbon and Gingerich (1969) (*continuous curves*, one for $\lambda < 1100$ Å and the other for $\lambda > 1100$ Å).

The figure shows that the observed fluxes given by Yamashita (1968) and Carruthers (1970) agree with those calculated by Adams and Morton (1968) and Hickok and Morton (1968) for stars B3 and earlier (i.e., $B - V \leq -0.2$). However, the observed fluxes of Byram *et al.* (1965) are much smaller than calculated. There are very few observations at this wavelength for stars of spectral type later than B3, except those of Byram *et al.* (1965); these give fluxes smaller than calculated. The observed flux of 32 Ori (B5 IV) (Carruthers 1970), though slightly smaller, agrees reasonably well with the calculated flux (Adams and Morton 1968; Mihalas 1966); the inclusion of carbon opacity may possibly improve the agreement. The observed flux of α Leo (B7 V) (Yamashita 1968) is in better accord with the calculated flux with carbon opacity included (Carbon and Gingerich 1969) than without it (Mihalas 1966). This implies that the models of Carbon and Gingerich (1969) are more realistic than those of

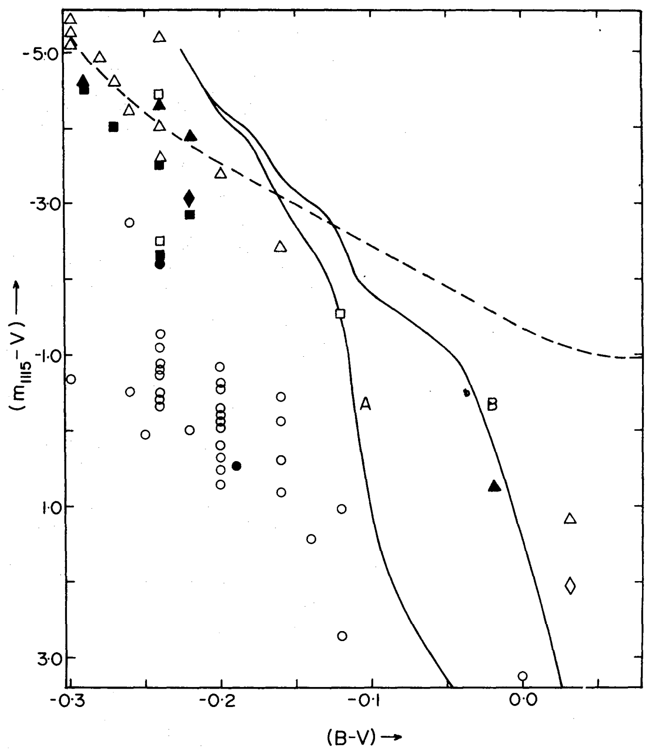

FIG. 1.—The observed and theoretical color difference, $m_{1115} - V$, as a function of $B - V$. The observed values of Carruthers (1970) are represented by △ (V, IV, III) and ▲ (II, Ia, Ib), of Yamashita (1968) by □ (V, IV, III) and ■ (II, Ia, Ib), of Stecher (1970) by ◇ (V, IV, III) and ♦ (IIa, Ia, Ib) and of Byram *et al.* (1965) by ○ (V, IV, III) and ● (II, Ia, Ib); Ia, Ib, II, etc., inside the parentheses refer to the luminosity class. The dashed curve corresponds to the models of Mihalas (1966), Adams and Morton (1968), and Hickok and Morton (1968). The continuous curves correspond to the models of Carbon and Gingerich (1968); *A* refers to $\lambda <$ 1100 Å, and *B* to $\lambda >$ 1100 Å. All the theoretical models are for $\log g = 4.0$.

Mihalas (1966) for spectral type later than B5. The observed flux of α CMa (A1 V) (Stecher 1970) agrees, within observational uncertainties, with that by Carruthers (1970), but is larger than that calculated with carbon opacity. However, Gingerich and Latham (1970) have concluded that this star has a flux deficiency for $\lambda >$ 1100 Å. The difference mainly arises due to the uncertainties in the effective temperature of α CMa; spectral classification implies an effective temperature ~9670° K, whereas the continuous energy distribution suggests ~10,000° K (Hanbury Brown *et al.* 1967; Gingerich and Latham 1970). In other words, the uncertainties in the temperature scale, spectral classification, observation, and model calculation do not permit a better comparison between observed and calculated fluxes in this spectral region at present. Moreover, there is no observation at this wavelength for stars cooler than A1 V. Hence the improvement of models depends on the comparison between possible sources of opacities and the used ones and on inclusion of them in the models, if found important.

III. IMPORTANCE OF S I ABSORPTION IN B TO K STARS

Table 1 gives the ratios of absorption coefficients of S I to the combined opacity of *e*, H, C I, and Si I for various values of wavelength λ, temperature *T*, and pressure *P* to examine the importance of S I opacity. The bound-free cross-sections for C I and Si I have been taken from Peach (1970), and for S I from Chapman and Henry (1971).

TABLE 1

RATIOS OF ABSORPTION COEFFICIENTS OF S I TO THE COMBINED OPACITY OF *e*, H, C I, AND Si I

θ	log P	1197 Å	1101 Å	1000 Å	θ	log P	1197 Å	1101 Å	1000 Å
1.2......	2	1.63	1.96	0.17	0.8....	4	0.80	1.00	0.14
	3	0.51	0.68	0.25		5	0.72	0.94	0.16
	4	0.26	0.36	0.55	0.6....	2	0.27	0.36	0.08
	5	0.22	0.30	0.97		3	0.30	0.41	0.09
1.0......	2	1.36	1.53	0.12		4	0.35	0.48	0.10
	3	1.44	1.68	0.15		5	0.42	0.58	0.14
	4	1.08	1.19	0.17	0.4....	2	0.10	0.05	0.02
	5	0.36	0.53	0.21		3	0.15	0.09	0.03
0.8......	2	0.48	0.59	0.08		4	0.19	0.11	0.03
	3	0.66	0.81	0.11		5	0.29	0.16	0.04

The total opacity of H consists of bound-free absorption of H (Vardya 1964) and H^- (Doughty, Fraser, and McEachran 1966) and Rayleigh scattering which has been assumed equal to electron-scattering cross-section. The equilibrium number densities for various atoms and ions have been computed for solar photospheric composition (Tarafdar and Vardya 1972*a*).

The table shows that S I contributes significantly to the total opacity for $\lambda \leq 1197$ Å (the threshold wavelength), θ ($\equiv 5040/T$) ≥ 0.4 and $P \geq 10^2$ dyne cm^{-2}. For a given (θ, P), in the domain $0.6 \leq \theta \leq 1.0$, $P \leq 10^5$ dyne cm^{-2}, the effect of S I absorption starts from a finite value at its threshold wavelength, increases with decreasing λ, attains maximum at around λ1100 Å, and decreases hereafter, with decreasing λ, contributing as much as 21 percent of the combined opacity of *e*, H, C I, and Si I at λ1000 Å. For $\theta = 1.2$, $P \geq 10^4$ dyne cm^{-2}, the effect of S I absorption increases monotonically with decreasing wavelength. At a given λ, the importance of S I absorption relative to the combined opacity of *e*, H, C I, and Si I increases with increasing P (or θ) for given θ (or P), except at low temperature and $\lambda\lambda$1100–1197 Å. However, even at $\theta = 0.4$, $P = 10^2$ dyne cm^{-2}, the bound-free absorption of S I contributes as much as 10 percent of the combined opacity of *e*, H, C I, and Si I between $\lambda\lambda$1000 and 1197 Å; note that even though most of the sulfur at this (θ, P) is in the form of S II, its contribution to the opacity in this spectral region is negligible.

The Lyman band absorption has also been found to be important in this spectral region for stars as hot as A0 (Tarafdar and Vardya 1972*b*). It has been found that S I absorption relative to the Lyman band is large at high temperature and/or low pressure, decreases with decrease in temperature and/or increase in pressure, and is small at very low temperature and/or high pressure.

In conclusion, S I absorption may be an important source of opacity in stars as hot as B5. If the abundance of sulfur, which is rather uncertain (see, e.g., Vardya 1967), is higher in hot stars (Traving 1966) than the solar value, the contribution of sulfur opacity will be higher than found above.

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