

## ON ULTRAVIOLET STELLAR FLUXES. III. IMPORTANCE OF H<sub>2</sub> LYMAN-BAND ABSORPTION IN THE SUN AND OTHER STARS

S. P. TARAFDAR AND M. S. VARDYA

Tata Institute of Fundamental Research, Bombay-5, India

Received 1972 April 21

### ABSTRACT

Lyman-band absorption of H<sub>2</sub>, when compared with the combined opacity of H, C I, Mg I, and Si I, has been found to contribute significantly to the total opacity in the range 912–1900 Å in the solar atmosphere. Inclusion of Lyman-band absorption in the solar model may reduce chromospheric temperature from that given by Gingerich *et al.* and improve agreement between observed and calculated extreme-ultraviolet and microwave intensities. The Lyman-band absorption may also be important in stars as hot as A0.

### I. INTRODUCTION

The molecular-band absorptions of CO, SiO, OH, and CH in the solar atmosphere (Tarafdar and Vardya 1972*a*, hereafter cited as Paper I) and of CO in stars, as hot as A5 (Tarafdar and Vardya 1972*b*, hereafter cited as Paper II) have been found to contribute significantly to opacity in  $\lambda\lambda 1400\text{--}4000$  Å. The absorption due to the Lyman band of H<sub>2</sub> operative longward of 912 Å may also be important in the Sun and other stars; here we have examined this possibility.

### II. DETAILS OF THE CALCULATION

The absorption due to the Lyman band has been calculated following Golden (1967), as discussed in Paper I. The oscillator strengths for different vibrational transitions have been taken from Allison and Dalgarno (1969); the molecular constants, from Herzberg (1950). The bound-free and free-free cross-sections of C I, Mg I, and Si I have been taken from Peach (1970). The opacity of H consists of bound-free absorption of H (Vardya 1964) and of H<sup>−</sup> (Doughty, Fraser, and McEachran 1966) and Rayleigh scattering by H which has been evaluated following Dalgarno (cf. Gingerich, Latham, and Linsky 1966) for  $\lambda > 1216$  Å and assumed to be the same as the electron-scattering cross-section for  $\lambda \leq 1216$  Å. The equilibrium number densities of different molecules, atoms, and ions have been determined following Vardya (1966) using solar photospheric composition (Paper II). It is hoped that the neglect of non-LTE effects, specially in the chromospheric region, will not sensibly vitiate our results.

### III. IMPORTANCE OF LYMAN-BAND ABSORPTION IN THE SOLAR ATMOSPHERE

Figures 1, 2, and 3 compare the Lyman-band absorption with the combined absorption coefficient of C I and Si I. Each figure contains two optical depths (defined at  $\lambda = 5000$  Å): one corresponding to the photosphere and the other to the chromosphere, having the same temperature. Temperature  $T$  and pressure  $P$  for these optical depths have been taken from Gingerich *et al.* (1971). Figure 1 compares the absorption coefficients at  $\theta (= 5040/T) = 1.0$  and gas pressure,  $P = 3.8 \times 10^4$  dyne cm<sup>−2</sup> (continuous curve) and  $1.35 \times 10^2$  dyne cm<sup>−2</sup> (dashed curve) corresponding to optical depths  $\tau = 0.07$  and  $1.58 \times 10^{-5}$ , respectively. The figure shows that at  $\tau = 0.07$ , the Lyman-band absorption is much larger than the combined opacity of C I and Si I

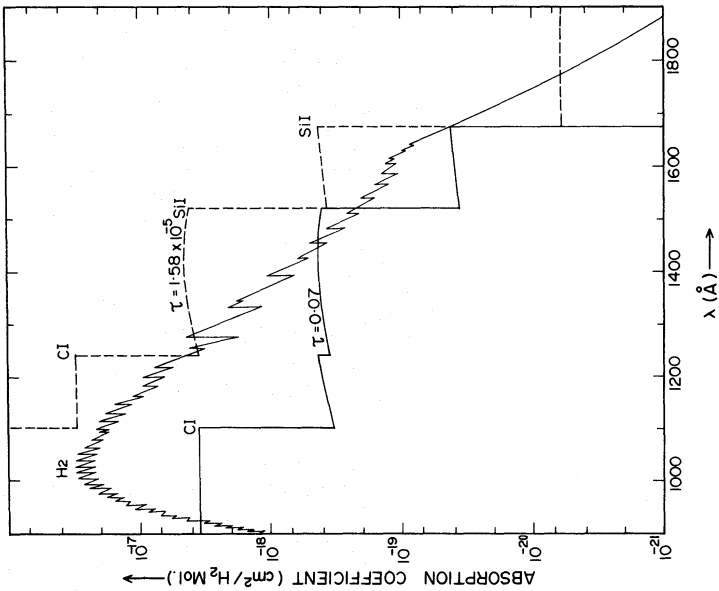


FIG. 1.—Variation of absorption coefficients in units of  $\text{cm}^2$  per hydrogen molecule with wavelength at  $\tau = 0.07$  (continuous curve) and  $1.58 \times 10^{-5}$  (dashed curve).

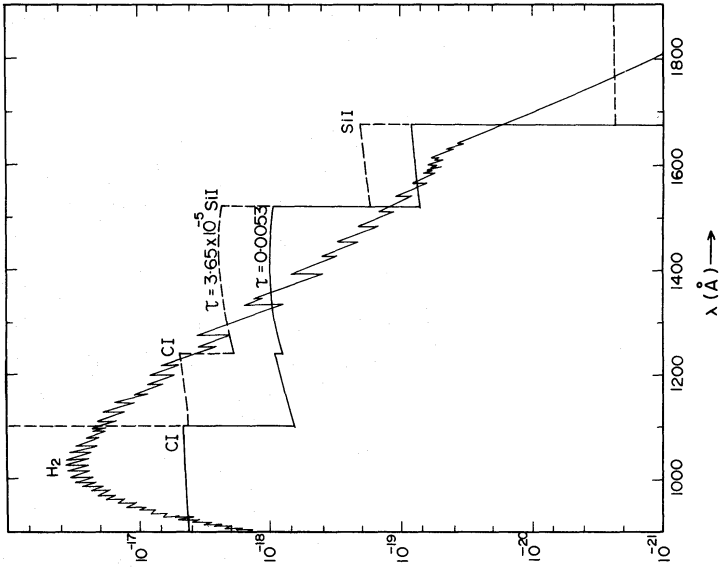


FIG. 2.—Same as fig. 1 at  $\tau = 0.0053$  (continuous curve) and  $3.65 \times 10^{-5}$  (dashed curve)

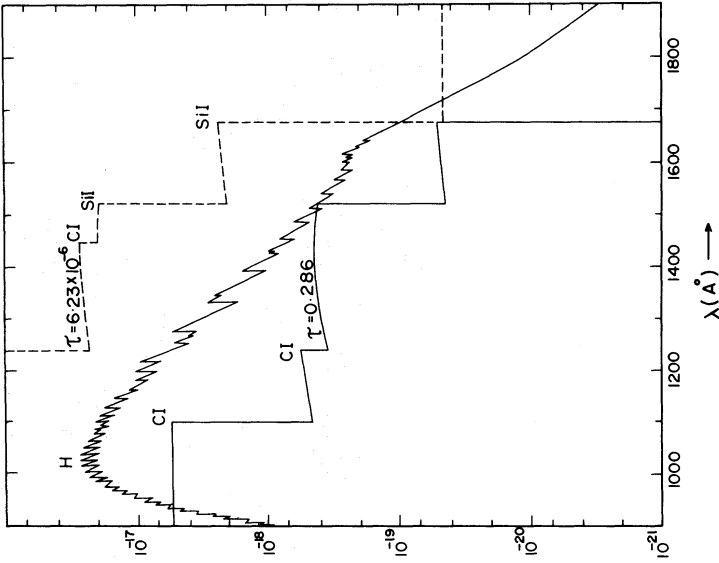


FIG. 3.—Same as fig. 1 at  $\tau = 0.286$  (continuous curve) and  $6.23 \times 10^{-6}$  (dashed curve).

from 925 to 1900 Å, except at two short intervals between 1450 and 1500 Å and around 1675 Å, where the Lyman-band absorption is almost equal to the total absorption of C I and Si I. At  $\tau = 1.58 \times 10^{-5}$ , the contribution of the Lyman-band absorption between 912 and 1900 Å varies from 5 to more than 100 percent of the combined opacity of C I and Si I, depending on wavelength.

Figure 2 compares the Lyman-band absorption with the combined absorption of C I and Si I at  $\tau = 0.0053$  (*continuous curve*) and  $3.65 \times 10^{-5}$  (*dashed curve*) corresponding to  $\theta = 1.1$ , and  $P = 8.95 \times 10^3$  and  $3.938 \times 10^2$  dyne cm<sup>-2</sup>, respectively. The figure shows that at  $\tau = 0.0053$ , the band absorption is larger than the combined absorption of C I and Si I between 925 and 1325 Å, contributes 10–100 percent between 1325 and 1675 Å, and is larger again between 1675 and 1800 Å. At  $\tau = 3.65 \times 10^{-5}$ , the Lyman-band absorption contributes from 5 to more than 100 percent between 1100 and 1800 Å. A perusal of figures 1, 2, and 3 reveals that the contribution of the Lyman-band absorption to the combined opacity starts at around  $\tau = 6.0 \times 10^{-6}$  (fig. 3, *dashed curve*) and increases with increasing optical depths up to at least around  $\tau = 0.286$  (fig. 3, *continuous curve*). The Lyman-band absorption, therefore, appears to be an important source of opacity in the solar photosphere, in the photosphere-chromosphere transition zone, and in the chromosphere. As the major contribution to the emergent intensity between 912 and 1900 Å comes from these layers, which includes the region where temperature increases with decreasing  $\tau$ , the inclusion of the Lyman-band absorption in the solar model calculation will possibly increase the specific intensity in the short-wavelength region and decrease in the long-wavelength side. If it does, then the agreement of the calculated intensity with observation (cf. Gingerich *et al.* 1971) will improve. Further, some of the edges expected in theoretical intensity (Gingerich *et al.* 1971) will be reduced or washed out, in agreement with the observation.

The radiation around 1100 Å possibly originates in the chromosphere. Gingerich *et al.* (1971) have found an approximate agreement between the calculated and observed (Parkinson and Reeves 1970) specific intensities around 1100 Å. Therefore, inclusion of Lyman-band absorption in the solar model may imply a temperature lower than that in the model of Gingerich *et al.* (1971) for this chromospheric region. If this proves to be the case, then the specific intensity in the infrared and microwave spectral regions, where Gingerich *et al.* (1971) have found intensity larger than that observed (Tolbert and Straiton 1961; Salomonovich and Losovskii 1962; Bastin *et al.* 1964; Staelin, Barrett, and Kusse 1964; Buhl and Tlamicha 1968; Low and Gillespie 1969; Eddy, Lena, and McQueen 1969), will be reduced, and will be in better accord with the observations. Note that the chromospheric model of Linsky and Avrett (1970), in agreement with these observations, gives temperatures lower than the model of Gingerich *et al.* (1971).

#### IV IMPORTANCE OF THE LYMAN BAND ABSORPTION IN A TO K STARS

Table 1 gives the ratios of absorption due to the Lyman band to H, C I, Mg I, and Si I at several  $\lambda$ ,  $\theta$ , and  $P$  to examine the importance of the Lyman-band absorption in other stars. The table shows that the contribution of the Lyman band not only is significant but can also exceed the combined opacity of H, C I, Mg I, and Si I in the range 1000–2200 Å,  $\theta \geq 0.6$ , and  $P \geq 10^2$  dyne cm<sup>-2</sup>. For a given ( $\theta$ ,  $P$ ), the Lyman-band absorption varies from 30 percent to less than 1 percent of the combined opacity of H, C I, Mg I, and Si I at 2200 Å, normally increases with decreasing wavelength, attains maximum around 1100 Å at low temperature and high pressure, and decreases thereafter with decreasing wavelength. However, even at 1000 Å, depending on ( $\theta$ ,  $P$ ), the Lyman band contributes from more than 100 *times* to a few percent relative to the combined opacity of H, C I, Mg I, and Si I. For a given ( $\lambda$ ,  $\theta$ ), the effect of the Lyman

1972ApJ...178..509T

TABLE 1  
RATIOS OF ABSORPTION COEFFICIENT OF LYMAN BAND TO THE COMBINED OPACITY OF H, C I, Mg I, AND Si I

$\theta$	LOG $P$	H <sub>2</sub> LYMAN BAND						
		1000 Å	1101 Å	1200 Å	1400 Å	1600 Å	1800 Å	2200 Å
1.2.....	2	0.19	4.20	1.10	0.08	0.08	0.04	0.0
	3	2.69	14.3	4.14	0.15	0.15	0.15	0.0
	4	59.40	74.2	18.8	0.72	0.69	0.72	0.01
	5	983.0	599.0	152.0	5.92	5.12	4.58	0.04
1.0.....	2	0.02	0.47	0.20	0.17	0.21	0.06	0.0
	3	0.16	3.82	1.59	0.49	0.69	0.60	0.02
	4	1.60	23.9	10.7	1.16	1.61	1.28	0.08
	5	19.4	106.0	37.7	3.12	4.25	6.22	0.17
0.8.....	2	0.0	0.05	0.03	0.08	0.15	0.04	0.0
	3	0.02	0.32	0.19	0.33	0.67	0.41	0.01
	4	0.14	2.44	1.38	1.16	2.24	2.24	0.07
	5	1.29	18.5	10.0	3.87	7.25	8.34	0.27
0.6.....	2	0.00	0.01	0.01	0.01	0.01	0.0	0.0
	3	0.00	0.05	0.04	0.09	0.07	0.01	0.0
	4	0.01	0.25	0.10	0.45	0.57	0.10	0.0
	5	0.12	1.52	1.15	1.85	3.09	0.76	0.03

band increases with increasing pressure. For a given ( $\lambda, P$ ) the importance of the Lyman-band absorption compared to the combined opacity of H, C I, Mg I, and Si I generally decreases with decreasing  $\theta$ ; however, even at  $\theta = 0.6$  and  $P = 10^3$  dyne cm<sup>-2</sup>, the Lyman band contributes as much as 10 percent of the combined absorption in the interval 1000–2200 Å.

The range of temperature and pressure over which Lyman-band absorption relative to H, C I, Mg I, and Si I is not insignificant, vis-à-vis atmospheric models (Carbon and Gingerich 1969; Parsons 1969), shows that H<sub>2</sub> may be an important source of opacity for stars as early as A0 spectral type. It is hoped that the model atmospheres computed after incorporating the absorption by the Lyman band together with Al I and the A–X band of CO (Paper II) will better represent the real stars compared to the models so far computed.

REFERENCES

Allison, A. C., and Dalgarno, A. 1969, *J. Quant. Spectrosc. and Rad. Transf.*, **9**, 1543.  
Bastin, J. A., Gear, A. E., Jones, G. O., Smith, H. J. T., and Wright, P. J. 1964, *Proc. Roy. Soc., A*, **278**, 543.  
Buhl, D., and Tlamicha, A. 1968, *Ap. J. (Letters)*, **153**, L189.  
Carbon, D. F., and Gingerich, O. 1969, *Proceedings Third Harvard-Smithsonian Conference on Stellar Atmospheres*, ed. Owen Gingerich, p. 377.  
Doughty, N. A., Fraser, P. A., and McEachran, R. P. 1966, *M.N.R.A.S.*, **132**, 255.  
Eddy, J. A., Lena, P. J., and McQueen, R. M. 1969, *Solar Phys.*, **10**, 330.  
Gingerich, O., Latham, D. W., and Linsky, J. 1966, *Colloquium on Late-Type Stars*, ed. Margherita Hack, p. 291.  
Gingerich, O., Noyes, R. W., Kalkofen, W., and Cuny, Y. 1971, *Solar Phys.*, **18**, 347.  
Golden, S. A. 1967, *J. Quant. Spectrosc. and Rad. Transf.*, **7**, 225.  
Herzberg, G. 1950, *Molecular Spectra and Molecular Structure. I. Spectra of Diatomic Molecules* (New York: D. Van Nostrand Company, Inc.).  
Linsky, J. L., and Avrett, E. H. 1970, *Pub. A.S.P.*, **82**, 169.  
Low, F. J., and Gillespie, C. M. 1969, *Bull. A.A.S.*, **1**, 187.  
Parkinson, W. H., and Reeves, E. M. 1970, *Ap. J., Suppl.*, **21**, 1.  
Parsons, S. B. 1969, *Ap. J. Suppl.*, **18**, 127.  
Peach, G. 1970, *Mem. R.A.S.*, **75**, 1.

- Salomonovich, A. E., and Losovskii, B. Ya. 1962, *Astr. Zh.*, **39**, 1074.  
Staelin, D. H., Barrett, A. H., and Kusse, B. R. 1964, *A.J.*, **69**, 69.  
Tarafdar, S. P., and Vardya, M. S. 1972*a*, *Ap. J.*, **171**, 185 (Paper I).  
———. 1972*b*, *ibid.*, **178**, 503 (Paper II).  
Tolbert, C. W., and Straiton, A. W. 1961, *Ap. J.*, **134**, 91.  
Vardya, M. S., 1964, *Ap. J. Suppl.*, **8**, 277.  
———. 1966, *M.N.R.A.S.*, **134**, 347.

