Bull. Astr. Soc. India (1986) 14, 73–78

On some visible and infrared atomic hydrogen lines in three photospheric models

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Received 1985 August 2; accepted 1986 March 15

Abstract. The behaviour of the line profiles in the wings of the first four lines of the Balmer, Paschen and Brackett series in the solar spectrum at the disc centre has been investigated with a view to comparing the computed profiles (Holweger & Müller 1974; Vernazza, Avrett & Loeser 1976, 1981) with observations. The comparison shows that, in general, the Holweger & Müller model can explain the lines of Balmer series better than the lines of Paschen and of Brackett series. The reverse is the case with the Vernazza, Avrett & Loeser models.

Key words : hydrogen lines—photospheric models—Stark-broadening

1. Introduction

Strong atomic lines form in a large region of the solar atmosphere. As is known, the Doppler core originates in the higher layers *i.e.* in the chromosphere, while the wings originate in the deeper layers, where LTE conditions can be assumed to hold. Since hydrogen line wings are broadened by the Stark effect, they are sensitive to a variation of the electron pressure with depth. Since the various hydrogen series embrace a larger part of the solar atmosphere as compared to moderate intensity atomic and molecular lines, they are better probes to test the existing model atmospheres.

Chapman (1977) concluded that weak Fraunhofer lines are not useful for discrimination amongst various facular models and that the K-line wing of Ca II may offer a better discriminator. Tripathi & Pande (1981) computed the wings of Brackett gamma line (λ 2.1655 μm) of hydrogen in two photospheric and four facular models and showed that the wings of this line can distinguish amongst different facular models and that high resolution spectrum of this line can improve the existing models. With a view to seeing whether the wings of other hydrogen lines are also sensitive, we have computed the Stark profiles in the wings of the first four lines of the Balmer, Paschen and Brackett series in photospheric and facular models.

We consider the photospheric models of Holweger & Müller (1974 ≡ HM 74) and of Vernazza, Avrett & Loeser (1976, 1981 ≡ VAL 76, 81). To our surprise we found that these well accepted photospheric models do not at the same time explain the wings of the Balmer series lines, the Paschen, or of the Brackett lines. The HM 74 model does not have a temperature inversion region. It explains the visible and the infrared regions (λ 0.5 to 300 μm), both in the continuum and in the line profiles. Recently Blackwell, Shallis & Simmons (1982) have used this model to determine elemental abundances.

The VAL 76 and 81 are non-LTE models of the quiet photosphere and of the temperature minimum regions at 4150 K and 4170 K respectively. VAL 76 fits the continuum limb-darkening data more satisfactorily than do other photospheric models, but the disc-centre intensities in the optical and in the infrared regions fall below the observed values. Following this, Ayres (1978) and Blackwell, Shallis & Simmons (1980) respectively suggested that the temperatures in VAL 76 model should be raised by a factor of 1.105 and by about 100 K at each depth. In the case of VAL 81, the temperature minimum determination is based on continuum observations in the 0.135-0.168 μm range but their minimum temperature values are lower than those implied by the Ca II and Mg II lines. In view of this, we choose these three photospheric models to calculate the line profiles in the wings of the Balmer, Paschen, and Brackett lines. The computed results have been compared with the available observational results for these lines.

2. Computational procedure

Following Mitropol'skaya (1967), we have calculated the selective absorption coefficient $S_\nu(\Delta\lambda)$ per atom for Stark broadened lines from the relation

$$S_\nu(\Delta\lambda) = \alpha_H(\Delta\lambda)\, N_e\, [1 + R(N_e, T)\, (\Delta\lambda)^{1/2}], \qquad \ldots(1)$$

where $\alpha_H(\Delta\lambda)$ is the asymptotic Holtsmark distribution function calculated for each wavelength, as given in Jefferies (1968); $R(N_e, T)$ is the ratio of electron and ion contribution to the absorption coefficient at a distance of one wavelength unit from the line centre; and N_e the electron concentration. The $R(N_e, T)$ values at each depth in the models were calculated using Griem (1960). The residual intensities at disc centre for $\Delta\lambda$ = 5, 10, 20, 25, 30, 40 and 50 Å were calculated for each line in the chosen models.

Calculations for HM 74 and VAL 76 assume LTE. In the case of VAL 81, however, the calculations have been done for non-LTE populations, using the departure coefficients of hydrogen given in Vernazza, Avrett & Loeser (1981).

These residual intensities *r*, are plotted against the distance from the line centre, $\Delta\lambda$, in figure 1; the averaged observed profiles are given for comparison.

3. Results and conclusions

In the case of the Balmer lines, the calculated profiles are compared with the observations of David (1961) and of Kuli-Zade (1965) For Paschen α, the observations

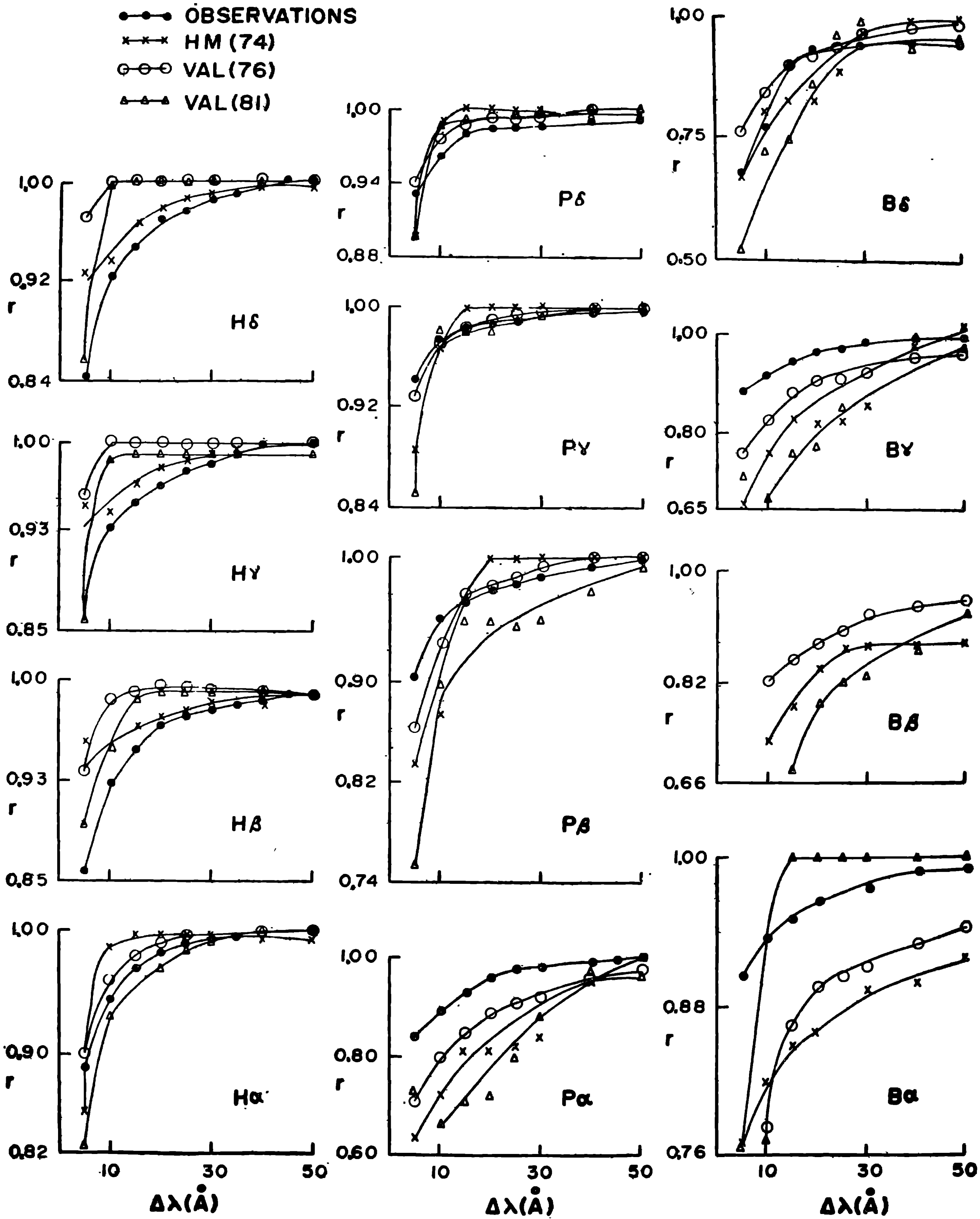

Figure 1. Computed profiles on Hα, Hβ, Hγ, Hδ, Pα, Pβ, Pγ, Pδ, Bα, Bβ, Bγ, and Bδ in three photospheric models are shown as a function of Δλ, alongwith observed profiles.

of Zander (1972) are taken; and for Paschen β, γ and δ those of de Jager (1952) and of Delbouille *et al.* (1981). For Paschen β, Hall's (1970) observations were also included. For Brackett lines, observational data come from de Jager (1952), de Jager, Migeotte & Neven (1956), Mitropol'skaya (1965), Hall (1970), Zander (1972), and Delbouille *et al.* (1981). For Brackett β it was difficult to locate the true continuum from the observations of Zander (1972). In view of this, we have not included the observed profile of Brackett β in figure 1.

We have averaged the observed profile and then determined the area between this averaged profile and the computed profiles in the range $\Delta\lambda = 15$ Å to $\Delta\lambda = 50$ Å. If this area turns out to be the minimum for any line in a particular model, then this line is taken to be best explained in the wings by that particular model. The estimated areas for all chosen hydrogen lines are given in table 1. From table 1 and figure 1, we arrive at the following conclusions :

The H-alpha line wing is best explained by VAL 81 followed by VAL 76. The HM 74 seems to deviate considerably from the observations. The computed profiles of Hβ, Hγ and Hδ lines in HM 74 are close to observations, while VAL 76 and VAL 81 seem to depart considerably.

All the Paschen line wings are best explained by VAL 76. The only exception is the Paschen β line which can be better reproduced by HM 74. In the other cases VAL 81 and HM 74 depart considerably from observations. The situation with Brackett α, γ and δ lines is as follows :

Brackett α line is best explained by HM 74 followed by VAL 81 and VAL 76. Brackett γ and δ lines are best explained by VAL 76 followed by VAL 81 and HM 74. As we have not compared the computed Brackett β profiles with the observations as explained earlier, it is difficult to comment upon the behaviour of this line in the models.

Summing up, we conclude that VAL 76 seems to be the best model followed by HM 74 and VAL 81. However, no single model can explain all the hydrogen series lines equally well.

Table 1. $|O - C|$ values

	Line	Wavelength	HM 74	VAL 76	VAL 81
Balmer	α	6562.80	0.184	0.135	2.5×10^{-3}
	β	4861.32	0.219	0.471	0. 65
	γ	4340.46	0.213	0.440	0.440
	δ	4101.73	0.157	0.423	0.423
Paschen	α	18751.0	2.560	1.325	3.252
	β	12818.1	0.014	0.258	0.677
	γ	10938.1	0.121	0.028	0.074
	δ	10049.4	0.185	0.075	0.138
Brackett	α	40512.0	0.380	1.832	0.819
	β	26252.0	—	—	—
	γ	21655.0	2.608	0.752	1.704
	δ	19445.6	0.506	0.118	0.450

Figures represent profile area difference in Angstrom.

It is to be noted that a wavelength span from H δ(λ 0.4101 μm) to Brackett α(λ 4.0512 μm) has been covered over which the continuous opacity changes significantly. The line formation is basically a result of the ratio of selective to continuous opacity. However, the depth of formation of these lines at each point would be decided by additive opacity, that is, by the continuous plus the selective. Moreover, the depths of formation of lines are model-dependent parameters. In order to see which layers of these models contribute significantly to the formation of wings of Balmer, Paschen, and Brackett series lines, we have chosen the lines Balmer α and δ, Paschen α to δ, Brackett α and δ, and proceeded as follows. For each line wing at $\Delta\lambda = 15$ Å and at $\Delta\lambda = 25$ Å those values of τ(λ 0.5 μm) are calculated for which an optical depth of unity is attained in the line wings for the HM 74 and VAL 76 models. For Hβ and Hγ lines the above mentioned depth $\tau = 1$ will fall between Hα and Hδ as opacity monotonically decreases from Hα to Hδ. The same is true for Brackett β and γ lines. Such depths have not been calculated for VAL 81 because it seems to depart too much from the observed profiles. The results of our calculations are shown in table 2.

Table 2. Depth of formation τ(λ 0.5 μm) of hydrogen line wings

Line	τ in HM 74 at		τ in VAL 76 at	
	$\Delta\lambda = 15$ Å	$\Delta\lambda = 25$ Å	$\Delta\lambda = 15$ Å	$\Delta\lambda = 25$ Å
Hα	0.770	0.790	0.800	0.823
Hδ	1.120	1.250	1.250	1.275
Paα	0.840	1.010	1.010	1.080
Paβ	0.835	0.925	1.007	1.060
Paγ	0.790	0.875	0.900	0.913
Paδ	0.765	0 790	0.812	0.850
Brα	0.160	0.245	0.248	0.256
Brδ	0.927	1.110	1.000	1.010

It is seen that an optical depth of unity for all line wings at both $\Delta\lambda$ values reaches earlier in HM 74 than in VAL 76. The T — τ and Pg — τ runs show that HM 74 is hotter than VAL 76 but has smaller gas pressures at a given depth $\tau_{0.5}$. It seem that such a physical situation is more conducive to the formation of H^- ions in HM 74 model which in turn helps to reach unit optical depth earlier here than in VAL 76. As HM 74 explains Balmer series lines better than does VAL 76, it appears that the latter model should have higher temperature in the line formation region of these visible lines. A suggestion to this effect has already been made by Ayres (1978) and Blackwell, Shallis & Simmons (1980).

In the light of the above we suggest that stronger lines of other elements should be taken to work out a new photospheric model which would ascertain the behaviour of the atmosphere in the continuum as well as in the weak and the strong lines. This photospheric model would then be in a better position to explain the behaviour of the ultraviolet region, such as of the Lyman, and also of the far-infrared like the Pfund.

Acknowledgements

The authors thank Dr M. C. Pande for suggesting the problem and for useful discussions throughout the course of this work. The authors also thank the computer centre, department of mathematics and statistics of the G. B. Pant University of Agriculture and Technology at Pantnagar, for the use of their TDC 316 computer. Special thanks are due to the programmer, Mr. S. C. Tewary.

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