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On the behaviour of some visible and infrared atomic hydrogen lines in facular models

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Abstract. The behaviour of line profiles in the wings of the Balmer, Paschen, and Brackett lines (alpha to delta) has been theoretically investigated in five facular models at disc centre. These profiles have been compared amongst the chosen facular models, and also compared with the photospheric observations. We find that these profiles can distinguish amongst different facular models. It is suggested that low-noise high resolution spectra of these lines can help in improving the existing facular models. Efforts should also be made to study faculae right from the ultraviolet to far-infrared.

Key words: facular models—line profiles—the sun

1. Introduction

The study of the strong atomic line profiles of the most abundant element hydrogen is not only useful in distinguishing amongst different models of the quiet solar photosphere but also in distinguishing amongst facular models. Earlier, Mitropol'skaya (1963, 1967) had computed the Balmer H-alpha and H-beta lines, the Paschen beta and the Brackett gamma lines in the then available photospheric and facular models and compared these profiles with observations. She found a good agreement between the computed and the observed profiles. Following Mitropol'skaya (1967), Tripathi & Pande (1981) computed the wings of Brackett gamma lines in two photospheric and four facular models. They showed that the profile of Brackett gamma line can distinguish amongst different facular models, and suggested that Brackett series lines should be more sensitive to temperature changes as compared to other hydrogen series lines. One can therefore use these line wings as probes to test the existing photospheric models and the facular models The line profile computations in the wings of Balmer alpha to delta, Paschen alpha to delta, and Brackett alpha to delta were carried out in three photospheric models and the results obtained were discussed in an earlier paper (Bondal & Gaur 1986). Here, we present similar computations of hydrogen line profiles in some selected models. As very little line profile observational data for faculae exist in the literature, we have compared the results with photospheric observational data. Some details of the selected facular models are given in the next section.

2. Facular models

Facular models are usually constructed on the basis of centre-to-limb observations of facular contrast with respect to nearby undisturbed photosphere in continuum or on the basis of observed contrast in absorption lines It has been seen that facular continuum contrast has very little dependence on the size of facula whereas line contrast shows changes as the size of faculae changes. This situation led to two kinds of facular models. The first kind is called 'average facula' models, and the other 'spatially limited' models. The models chosen by us are of Schmahl (1967), Stellmacher & Wiehr (1973), Stenflo (1975), Chapman (1979), and of Caccin & Severino (1979). The first two are average facula and the remaining spatially limited models.

Schmahl's (1967) model is based on continuum intensity measurements in the wavelength region λλ 3659 Å–6540 Å and refers to a mixture of granules and intergranules. He calculated the intensity differences in faculae and in the undisturbed photosphere and showed that even for weak faculae the contrast is greater than unity at the centre of the disc and therefore there is no temperature deficit in the deeper layers of faculae. Schmahl (1967) has used only medium strong lines in his facular models and has shown that only models of faculae with rather small temperature differences beginning at $\tau_{0\cdot 5\mu m} = 1$ are in agreement with the measured equivalent widths of these lines. Models with temperature differences beginning at smaller optical depths ($\tau_{0\cdot 5\mu m} \approx 0.01$ or so) are not in agreement with the measurements of the lines. Since only medium strong lines have been used the chromospheric layers may not be well represented.

Profile changes in going from photosphere to faculae were investigated by Stellmacher & Wiehr (1971) using five magnetically insensitive and unblended lines of atomic iron and titanium in visible region. They also observed continuum contrast at the disc centre. Stellmacher & Wiehr (1973) constructed three facular models and calculated for each of them the continuum contrast and profiles of the above mentioned lines. One of their models represents well the moderate intensity line profiles and wavelength dependence of the continuum contrast relative to Holweger's (1967) photospheric model. However, the centre-to-limb variation of the contrast could not be reproduced well by their model. They are of the view that this discrepancy has to be explained by geometry. The reduction in gas pressure in facula as compared to the photosphere is a consequence of an assumed constant magnetic field of 400 gauss. Strong lines have not been used by Stellmacher & Wiehr (1973) while constructing their facular model. Their model does not have a temperature inversion indicative of chromospheric layers above. The calculated profiles of the lines of atomic iron show departures from observations near the core. This again leads to a model not a good representative of chromospheric layers.

A model of facular atmosphere which has tried to explicitly incorporate photometric, geometric, and magnetic aspects of the region had been proposed by Stenflo (1975). Both plages and the network break up into small subarcsecond structures during excellent seeing conditions. Magnetograph data were used together with continuum, line profile and EUV observations to derive a model of these subarcsecond elementary structures. A field strength of about 2000 gauss in these structures and a temperature enhancement with respect to photospheric layers are the two main features of Stenflo's (1975) model. The model of the quiet solar atmosphere adopted by Stenflo is based on HSRA given by Gingerich, Noyes & Kalkofen (1971).

A number of semiempirical models of solar faculae have been constructed by Chapman (1970, 1977). Chapman (1977) showed that facular models with moderately high temperatures and strong magnetic fields can produce line profiles in reasonable agreement with the observations. Ca II K line was used as a diagnostic tool. Chapman's (1979) facular model is a refinement and extension of his 1977 model. The photospheric model used by him is an extension of HSRA made by matching the convection zone model of Spruit (1974). The facular model 7B14/HSRASP of Chapman (1979) used in our calculations is essentially the same as the facular model 7B13/HSRA of Chapman (1977) but extended to greater depths.

Caccin & Severino (1979) proposed a facular model based on the intensity contrast in continuum at λ 5000 Å. Following Spruit (1976), they used a two component axially symmetric model whose thermodynamic structure was derived from that of a magnetostatic flux tube of diameter 84 km with a Wilson depression of 100 km. The photospheric model used by them is also of Spruit (1976).

3. Computational procedure

The procedure adopted for the calculations of the profile in line wings has been described earlier (Bondal & Gaur 1986). The residual intensities r in all chosen facular models were calculated at $\Delta\lambda = 2, 3, 5, 10, 15, 20, 25, 30, 40$, and 50 Å at disc centre and also at $\sec\theta = 1.77, 2.0, 2.5, 3.0$, and at 4.0. Here, we present the results for $\sec\theta = 1$ only; centre-to-limb variations of the line profiles will be given separately. The residual intensities r against $\Delta\lambda$ for Balmer, Paschen, and Brackett series lines are shown in figure 1, which also shows averaged observational photospheric results as very little observational data on facular lines exist in the literature.

4. Discussion of the results

It is obvious from figure 1 that for a given line the residual intensity and extension of the wings varies widely from model to model. In Chapman's (1979) model almost all series lines show very strong and deep wings as compared to other facular models and to photospheric observations.

The higher temperatures and smaller gas pressures in line-forming layers of Chapman's (1979) model as compared to other facula models lead to higher electron densities and probably decreased continuous opacity (H^- ion). As Stark

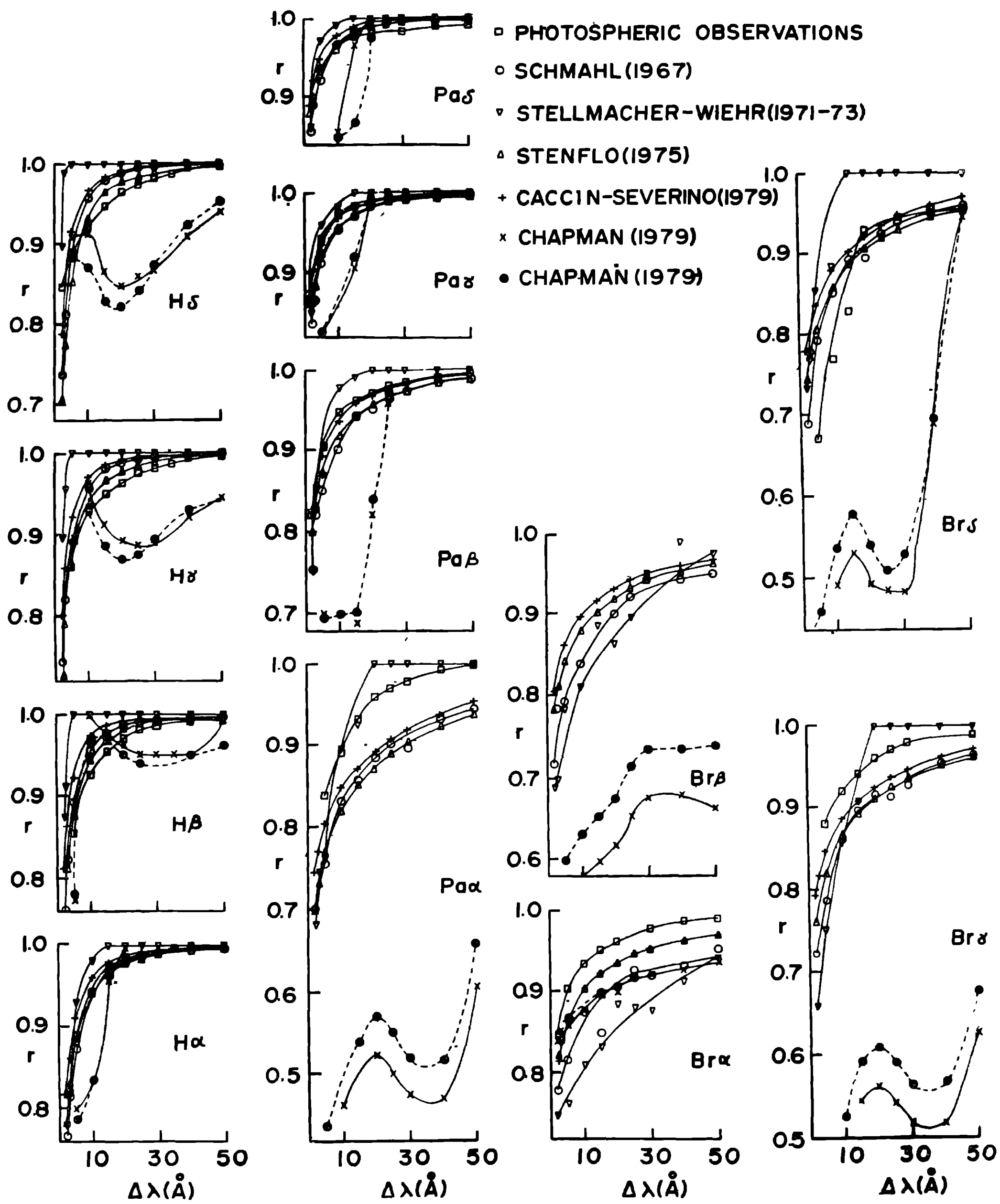

Figure 1. Computed profiles of Hα, Hβ, Hγ, Hδ, Paα, Paβ, Paγ, Paδ, Brα, Brβ, Brγ, Brδ in five facular models are shown as a function of Δλ along with observed photospheric profiles. Filled circles and crosses represent two versions of Chapman's facular model (see text).

broadened wings of these hydrogen lines strongly depend on electron density, the resulting hydrogen line wings in Chapman model may comparably be deeper and more extended than obtained by us. These profiles depart very significantly from the observed photospheric line wings. Chapman (1979) himself states. 'The facular model presented here is intended as a tool to help in understanding small scale magnetic fields. It may be a guide in search for a proper physical treatment of flux tubes but it is not meant to be a substitute for a proper physical model. It is not intended that the present model be used above a height of 200 km.' In the light of the above, we used that part of the model which is lower than this height and again calculated the residual intensities for these lines in the truncated model. However, these residual intensities do not differ much from the previous results for the complete model. Therefore, our calculations also confirm the view that Chapman's (1979) facular model does not represent a proper physical model.

For intercomparing the line wings for a given line from $\Delta\lambda = 2$ Å to 50 Å among the chosen facular models we have estimated the area embraced by the line in this wavelength span. However, in view of the fact the Chapman's model gives extremely deep and extended wings we have not estimated the areas of the profiles for this model.

The estimated areas are given in table 1. These areas are in fact fractions of the equivalent widths of the lines. From table 1 it is clear that the Stellmacher & Wiehr (1973) model predicts the shallowest profiles for all series lines except for the Brackett alpha and beta, where the profiles are deeper as compared to other facular model profiles. As we have already emphasized, this model does not have a temperature minimum and hence is devoid of chromospheric layers. This may be a reason for very shallow profiles for most of the lines.

In three facular models with temperature inversion, *i.e.* Schmahl (1967), Stenflo (1975), and Caccin & Severino (1979), the line wings show different profile shapes with respect to one another for a given line but the departures from photospheric observations are small (*cf.* figure 1). Some lines appear weaker with respect to photospheric lines in facular model, namely, all Balmer lines and Paschen delta line. On the other hand, Paschen alpha to gamma, Brackett alpha and gamma lines appear stronger in these facular models as compared to photospheric observations. In Brackett delta line, some part of the profile appears shallower in facular models while the line wing with $\Delta\lambda \geqslant 20$ Å appears deeper as compared to photospheric observations. It seems that atomic hydrogen lines with wavelengths up to $\lambda = 1\ \mu$m show a positive facula-to-photosphere contrast while lines with

Table 1. Estimated area of profiles in the range $\Delta\lambda = 2$Å to 50Å

Series	Line	Wavelength (Å)	Photospheric	Schmahl	Stellmacher-Wiehr	Stenflo	Caccin-Severino
Balmer	α	6562.80	1.282	1.537	0.628	1.573	0.976
	β	4861.32	1.695	1.148	0.136	1.537	0.881
	γ	4340.46	1.695	1.262	0.097	1.707	0.865
	δ	4101.73	1.880	1.257	0.094	1.851	0.917
Paschen	α	18751.0	2.329	5.601	1.904	5.631	4.960
	β	12818.1	1.253	2.483	0.688	2.380	1.854
	γ	10938.1	0.638	1.053	0.343	1.157	0.895
	δ	10049.4	1.043	1.007	0.331	0.923	0.600
Brackett	α	40512.0	1.620	4.513	6.328	3.121	3.143
	β	26252.0	—	4.704	5.570	3.731	3.404
	γ	21655.0	1.824	4.910	2.151	4.237	3.547
	δ	19445.6	5.116	4.212	1.190	4.527	3.680

wavelength $\lambda > 1$ μm show negative contrast in these models. In case of Brackett beta, available photospheric observations could not be used because of uncertainty in locating the true continuum (*cf.* Bondal & Gaur 1986). It is clear from figure 1 and table 1 that maximum departure in line wings among the chosen facular models and from photospheric observations appear in the case of the Brackett alpha line. An interesting point to note here is that in case of Brackett alpha line, even Chapman's model (1979), which predicts very strong lines, shows the least deviations from other facular models and also from photospheric observations.

Secondly, spatially limited models of Stenflo (1975) and Caccin & Severino (1979) show closely similar profiles. In distinguishing different facular models, Brackett series lines of hydrogen seem to have an advantage over other strong lines of Balmer and Paschen series as they originate from levels with principal quantum number $n = 4$ and are therefore more sensitive to temperature variations than those lines originating from $n = 2$ or 3 levels.

It is clear from the above results that Stark-broadened line wings of Balmer, Paschen, and Brackett series lines can distinguish amongst different facular models. Brackett series lines will therefore be most sensitive lines for choosing the better facula model. However, observations in the wings of these series lines for faculae at various centre-to-limb positions are a must for differentiating amongst various existing facular models. Almost all facular models so far constructed are based on the continuum observations restricted to visible region and tested only for visible continua, for weak absorption lines, or for moderately intense lines. It is suggested that low noise, high resolution continuum observations from ultraviolet to millimetre wavelength region for faculae be made along with the observations of the profiles of strong lines. The model constructed with such a long data base will help in improving the existing facular models and in arriving at a realistic facular model.

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