Bull. Astr. Soc. India (1987) **15**, 13–17

On the solar limb darkening in the wings of some atomic hydrogen lines

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Received 1986 November 15; accepted 1987 January 10

Abstract. The centre-to-limb behaviour of the first four lines of the Balmer, Paschen, and Brackett series of atomic hydrogen at selected distances from the line centre, i.e. at $\Delta\lambda$ = 5, 10, 20 and 30 Å has been theoretically investigated in three photospheric models. The results have been compared with observations of David (1961) for the Balmer lines, the corresponding observations for Paschen and Brackett lines not being available in published sources. After a detailed comparison of the computed results with the observations, it is concluded that limb-darkening data in the wings of hydrogen series lines can distinguish amongst the various photospheric models.

Key words : photospheric models—hydrogen lines—limb darkening

1. Introduction

In an earlier paper (Bondal & Gaur 1986) we reported our computed results on the behaviour of the line profiles in the Balmer, Paschen, and Brackett lines (alpha to delta) in the solar disc centre and compared them with the available observations for some of the lines. The photospheric models chosen for these calculations were of Holweger & Muller (1974 = HM 74) and of Vernazza, Avrett & Loeser (1976, 1981 = VAL 76, VAL 81). The comparison showed that at disc centre VAL 76 model yields the best fit with observations, followed by HM 74, and by VAL 81. However, no single model can explain all the hydrogen series lines equally well.

Limb darkening observations of Hα, Hβ, and Hγ lines near the line centre up to ± 1 Å have been made by White (1962) who compared his results with the observations of de Jager (1952) and David (1961). The continuum limb-darkening parameters of Pierce & Waddell (1961) have been used by White (1962) in the conversion of residual intensities relative to the continuum at disc centre. White (1962) found good agreement between his observations and those of David (1961).

The centre-to-limb (CL) behaviour of these Balmer lines in the far wings up to ±30 Å where Stark broadening plays a very dominant role in the line formation have been reported by David (1961) alone. Here, in this paper, we present computed CL behaviour of the first four lines of Balmer, Paschen, and Brackett series of atomic hydrogen at four selected distances from the line centre, i.e. at $\Delta\lambda$ = 5, 10, 20, and 30 Å. The photospheric models are HM 74, VAL 76, and VAL 81. The problem has been taken up to see whether limb darkening data in the hydrogen line wings can distinguish amongst various photospheric models and can also help in improving the existing models.

2. Computational procedure

Following the method outlined in Bondal & Gaur (1986), the residual intensities for the chosen Balmer, Paschen, and Brackett series lines at selected $\Delta\lambda$s from the line centre were computed for HM 74, VAL 76, and VAL 81. The selected CL positions were sec θ = 1, 1.77, 2.0, 2.5, 3.0, and 4.0. The residual intensities were then converted into intensities in units of continuum intensity at sec θ = 1, so as to obtain the limb darkening behaviour of a given line at a given $\Delta\lambda$ value. For converting David's (1961) residual intensities of Balmer series lines into intensities in units of continuum at sec θ = 1, the continuum limb darkening parameters of Pierce & Waddell (1961) were used. Intensities in units of continuum intensity at sec θ = 1 for the four Balmer series lines at $\Delta\lambda$ = 5, 10, 20 and 30 Å are given as a function of cos θ (=μ) in figure 1. For the Paschen and Brackett series lines computed limb darkening data are given in table 1. The results obtained by us

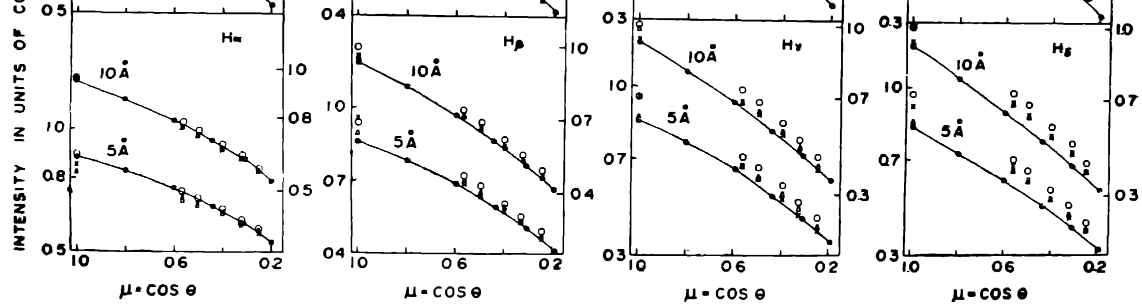

Figure 1. Observed and computed limb darkening values at four wing points $\Delta\lambda$ = 5, 10, 20 and 30 Å for Hα, Hβ, Hγ, and Hδ lines in three photospheric models. Each box contains two curves of a given line at two $\Delta\lambda$ values where the right-hand side ordinate corresponds to the upper curve.

Table 1. Computed line intensities for Paschen and Brackett series in units of intensity at sec θ = 1 at Δλs 5, 10, 20 and 30 Å as a function of sec θ

Line	Δλ (Å)	HM 74 sec θ 1.0	1.77	2.0	2.5	3.08	4.0	VAL 76 sec θ 1.0	1.77	2.0	2.5	3.08	4.0	VAL 81 sec θ 1.0	1.77	2.0	2.5	3.08	4.0
Paα	5	.639	.719	.731	.738	.726	.689	.714	.702	.703	.699	.686	.657	.736	.857	.851	.812	.779	.717
	10	.726	.679	.671	.659	.654	.662	.800	.759	.753	.741	.728	.714	.585	.561	.582	.634	.687	.740
	20	.818	.789	.775	.747	.723	.699	.896	.829	.816	.795	.778	.758	.722	.704	.697	.678	.660	.657
	30	.846	.796	.789	.775	.758	.732	.928	.867	.854	.828	.804	.779	.893	.737	.722	.709	.703	.693
Paβ	5	.835	.746	.732	.711	.696	.681	.864	.794	.778	.755	.735	.712	.756	.695	.690	.694	.707	.707
	10	.875	.801	.787	.759	.733	.704	.929	.842	.823	.790	.762	.731	.889	.775	.765	.751	.739	.707
	20	1.000	.840	.813	.774	.744	.713	.976	.867	.844	.806	.774	.739	.955	.846	.819	.776	.742	.707
	30	1.000	.863	.832	.784	.749	.715	.993	.874	.850	.811	.777	.741	.947	.846	.819	.776	.742	.707
Paγ	5	.884	.802	.783	.752	.726	.700	.927	.825	.806	.773	.746	.715	.848	798	.789	.774	.744	.708
	10	.965	.822	.802	.768	.739	.708	.971	.848	.826	.788	.756	.722	.981	.844	.819	.777	.745	.708
	20	1.000	.845	.817	.775	.743	.710	.991	.859	.834	.793	.759	.724	.977	.845	.819	.777	.745	.705
	30	.996	.849	.821	.777	.744	.711	.998	.861	.836	.794	.760	.724	.996	.845	.819	.777	.745	.708
Paδ	5	.899	.807	.788	.754	.725	.696	.940	.829	.808	.771	.740	.707	.899	.814	.803	.772	.737	.699
	10	.989	.825	.801	.764	.733	.701	.978	.846	.821	.780	.747	.711	.986	.841	.814	.772	.737	.699
	20	.999	.840	.812	.769	.736	.702	.995	.852	.826	.784	.749	.711	.991	.840	.814	.772	.738	.699
	30	.996	.842	.814	.770	.736	.702	.999	.854	.827	.784	.749	.712	1.000	.841	.814	.772	.737	.699
Brα	5	.769	.918	.938	.925	.915	.905	1.000	.877	.840	.792	.779	.799	.907	.772	.747	.718	.712	.723
	10	.823	.806	.807	.812	.826	.861	.786	.915	.941	.932	.925	.918	.775	.840	.856	.875	.870	.841
	20	.969	.924	.906	.876	.860	.857	.897	.875	.868	.865	.875	.896	1.000	.953	.915	.861	.835	.830
	30	.897	.936	.934	.921	.903	.884	.911	.904	.904	.901	.897	.896	1.000	.956	.955	.944	.909	.863
Brβ	5	.848	.782	.758	.716	.689	.674	.784	.722	.706	.689	.694	.728	1.000	.829	.779	.707	.672	.672
	10	.727	.743	.756	.779	.791	.784	.823	.790	.786	.784	.784	.780	.712	.886	.884	.855	.836	.821
	20	.842	.781	.775	.765	.760	.757	.886	.845	.837	.825	.815	.804	.786	.732	.738	.763	.795	.821
	30	.878	.827	.814	.793	.779	.767	.929	.869	.859	.843	.830	.816	.826	.804	.797	.788	.789	.821
Brγ	5	.650	.715	.732	.754	.756	.735	.754	.727	.728	.731	.727	.711	.716	.875	.864	.828	.797	.766
	10	.763	.713	.706	.695	.689	.690	.832	.789	.782	.771	.761	.747	.662	.611	.624	.666	.713	.762
	20	.834	.805	.793	.768	.746	.724	.914	.769	.835	.815	.798	.780	.774	.749	.744	.729	.715	.709
	30	.862	.809	.801	.786	.768	.745	.936	.875	.863	.838	.816	.793	.931	.780	.766	.752	.744	.735
Brδ	5	.671	.639	.644	.664	.688	.712	.765	.731	.723	.711	.706	.705	.518	.678	.714	.769	.782	.745
	10	.815	.736	.722	.703	.691	.679	.846	.799	.790	.773	.759	.744	.716	.635	.618	.602	.609	.643
	20	.834	.798	.792	.776	.758	.732	.916	.865	.851	.825	.802	.777	.862	.726	.717	.708	.701	.687
	30	.965	.815	.801	.781	.765	.744	.967	.882	.868	.843	.821	.793	.977	.824	.791	.746	.721	.705

cannot be compared with observations as observational data in the far wings of these series lines are not available.

3. Results and discussions

From figure 1, we find that the computed intensities for the Hα lines at the selected $\Delta\lambda$s agree best with VAL 76 followed by HM 74 and then by VAL 81. For the Hβ and Hγ lines HM 74 model agrees best with the observations, followed by VAL 81, and by VAL 76. For Hδ line, the best fit is attained by VAL 81, followed by HM 74. Here, VAL 76 shows maximum deviation.

The deviations that occur at different centre-to-limb values at a given wing point could be due to model effect, such as atmospheric inhomogeneities. These inhomogeneities differently affect the core of the lines and the wings, even in the same model (Basri *et al.* 1979). An account of the three photospheric models has been outlined earlier (Bondal & Gaur 1986), where we had calculated the depths of formation of the Hα and the Hδ lines in HM 74 and in VAL 76. These depths were found to increase from Hα to Hδ as the opacity decreases. We had found that VAL 76 explains the Hα line wing better than does HM 74, which is confirmed by the present investigation.

The computed intensities of Hβ, Hγ and Hδ lines in HM 74 and VAL 81 are closer to observational values, while those of VAL 76 show considerable departure. The deviation is the largest in Hδ, which is in agreement with our earlier result (Bondal & Gaur 1986). As we move from centre to limb the deviation of the computed intensities from the observed values decreases, showing that the higher layers in the models represent the observations better than the deeper ones. For the Paschen and Brackett series lines, observations in the wings of these lines are needed for comparison. Mitropol'skaya (1965) has reported her observations for the Brackett γ line (λ 2.1655 μm) at different CL points, but as she has not tabulated her results and the profiles are plotted on an unsuitable scale, we have not used her observed profiles for comparison with our calculated ones. We therefore tabulate our results for these series lines (table 1).

From our results, we conclude that limb darkening data in the wings of the hydrogen series lines can distinguish amongst the various photospheric models and so these lines can be used as a diagnostic tool to improve the existing photospheric models.

Acknowledgements

We thank the computer centre, department of mathematics and statistics of the G. B. Pant University of Agriculture and Technology, Pantnagar, for the use of their TDC 316 computer facility. Special thanks are due to the programmer, Mr S. C. Tewary.

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