THE PASCHEN DISCONTINUITY IN B STARS

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Abstract. Measurements of the Paschen discontinuity in stars with $T_{\text{eff}} \geq 10^4 \text{K}$ leads to the conclusion that the D_P/D_B ratio increases with temperature faster than expected. The increase of D_P/D_B with $(\log g)^{-1}$ is also steep.

Résumé. Les mesures de la discontinuité de Paschen dans les étoiles de $T_{\text{eff}} \geq 10^4 \text{K}$ nous montrent que le rapport D_P/D_B augmente avec la température plus rapidement que prévu. L'augment de D_P/D_B avec $(\log g)^{-1}$ est aussi remarquable.

1. Introduction

The energy distribution in the continuum of main sequence stars is fairly well represented by the results of computations under L.T.E. hypothesis. As we move into the region of stars with lower surface gravity physical conditions become not so well established. With the aim of providing observational values which could be useful to any attempt of dealing with this problem and of discussing what has already been done, we determined Paschen discontinuities ($D_P = \lg I_{8200+} - \lg I_{8200-}$) for a group of stars with $T_{\text{eff}} > 10^4 \text{K}$.

2. Material

Among bright stars ($m_v \leq 6.0$) of spectral types ranging from O to A0 and luminosity classes V to Ia, 55 stars were selected, 27 of them showing emission lines. Spectrograms were taken in 39 Å/mm with the 193-cm reflector at Haute Provence. All data concerning the stars and plates are collected in columns 1 to 5 of Table I.

3. Corrections and Reductions of the Observational Material

The first intermediate results are the values of the continuum as obtained from the microphotometric tracings; to reduce them it appears that two corrections should be applied, namely, those that take into account,

- a) the atmospheric absorption,
- b) the variations in sensitivity with wavelength of the 1N emulsion.

On account of the results by Mianes for the site at Haute Provence (Mianes, 1963) and the fact that our observations were made close to the zenith, the differential correction for atmospheric absorption in the region we are interested in, turned out

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TABLE I

Star	HD	Sp	Pl. no	Date	$(B-V)_0$	θ	D_B	D_P	V rot.
10 Cas	144	B8e	V2068	11.7.65	-0.03	0.44		0.070	122
π Cas	2905	B1Iae	2075	12.7.65	_b		0.05	0.070	70
π And	3369	B5V ^a	2576		-0.17	0.30	0.27	0.015	33
σ Cas	4180	B5e ^a	2069	11.7.65	-0.07	0.41	0.25	0.060	230
ϕ And	6811	B8e ^a	2077	12.7.65	-0.08	0.40	0.36	0.050	71
	12953	A0Iae	2080	13.7.65	_b		0.02	0.100	
π Cet	17081	B5III ^a	2577			0.39	0.31	0.015;	15
20 Tau	23408	B5III ^a	2227	12.3.66	-0.09	0.39	0.29	0.090	30
53 Per	27396	B3V	2229	12.3.66	-0.04	0.43		0.030	20
π^A Ori	30836	B3III ^a	2214	11.3.66	-0.18	0.29	0.16	0.075	45
16 Ori	33254	Am						0.000	25
τ Ori	34503	B5V ^a	2215	11.3.66	-0.13	0.36	0.30	0.025	30
ε Ori	37128	B0Ia	2815	2.68	-0.21	0.26	0.05	0.000	90
			2817	2.68					
			2819	2.68					
ζ Tau	37202	B2e ^a	2248	14.3.66	-0.27	0.27	0.18	0.040	310
64 Ori	41040	B8III ^a	2230	12.3.66	-0.13	0.36	0.20	0.080	0
χ^2 Ori	41117	B2Iae ^a	2250	14.3.66	_b		0.06	0.000	30
73 Ori	43247	B9II	2217	11.3.66	-0.05	0.43		0.125	31
β Mon ^A	45725	B3e ^a	2251	14.3.66	-0.17	0.30	0.00	0.000	400
γ Gem	47105	A0IV	2822	2.68	-0.00	0.46	0.54	0.065	26
S Mon	47839	O7 ^a	E-305		-0.32;		0.03	0.020	86
			309						
β CMi	58715	B8e	2265	16.3.66	-0.13	0.36	0.41	0.040	260
η Leo	87737	A0Ib	2219	11.3.66	-0.09	0.40	0.42	0.120	29
			2226						
			2228						
α Sex	87887	A0III	2220	11.3.66	-0.05	0.43		0.120	8
α Leo	87901	B7V ^a	2825	2.68	-0.11	0.38	0.37	0.075	370
ϱ Leo	91316	B2Ia ^a	2222	11.3.66	-0.24	0.22	0.07	0.080	60
σ Leo	98664	B9V	2232	12.3.66	-0.07	0.41		0.055	67
γ UMa	103287	A0e ^a	2225	11.3.66	0.00	0.46	0.55	0.090	169

Table 1 (continued)

Star	HD	Sp	Pl. no	Date	$(B-V)_0$	θ	D_B	D_P	$V_{\text{rot.}}$
γ Crv	106625	B8V ^a	2824	2.68	-0.11	0.38	0.34	0.085	20
δ Crv	108767	B9V ^a	2827	2.68					
α Dra	109387	B7e ^a	2254	14.3.66	-0.05	0.43	0.47	0.025:	186
α Dra	123299	B9V ^a	2007	18.6.65	-0.15	0.33	0.25:	0.060	226
θ CrB	138749	B5e	2242	13.3.66	-0.05	0.43	0.52	0.050	10
	138764	B6IV	2224	11.3.66	-0.14	0.34	0.24	0.025	400
48 Lib	142983	B3e	2234	12.3.66	-0.10	0.38		0.070	13
ν Her	144206	B9p	2262	15.3.66	-0.11	0.38		0.050	400
η Oph	155125	A2V	2246	13.3.66	-0.12	0.36		0.035	0
66 Oph	164284	B2e ^a	2236	12.3.66			0.48	0.020:	5
67 Oph	164353	B5Ib	2004	17.6.65	-0.05	0.43	0.10	0.050	300
μ Sgr	166397	B8Iae	2235	12.3.66	_b		0.17	0.065	15
β Cyg	183914	B8Iae	2056	10.7.65				0.065	65
25 Cyg	189687	B3e	2005	17.6.65	-0.11	0.38		0.055	
28 Cyg	191610	B3e	2017	19.6.65	-0.20	0.27		0.050	240
P Cyg	193237	B1p	2018	19.6.65	-0.14	0.34		0.035	315
ν Cap	193432	B9V ^a	1996	14.6.65	_b		0.00	0.070	59
1 Del	195325	A0e	2572		-0.06	0.42	0.38	0.045	5
55 Cyg	198478	B3Iae	2024	20.6.65	-0.01	0.46		0.100	
	199478	B8Iae	2014	18.6.65	_b		0.10	0.100	25
ν Cyg	202904	B2e ^a	2013	18.6.65	_b			0.120	65
ϵ Cap	205637	B3e ^a	1997	14.6.65	-0.13	0.36	0.10	0.050	255
λ Cep	210839	O6	2027	20.6.65	-0.18	0.29	0.14	0.050	280
31 Peg	212076	B3e ^a	2040	22.6.65	_b		0.03	0.075	160
π Aqr	212571	B0e ^a	2057	10.7.65	-0.12	0.36	0.16	0.020	129
10 Lac	214680	O9V	2059	10.7.65	_b		0.10	0.020	153
β Pisc	217891	B5e	2061	10.7.65	-0.27		0.05	0.065	29
			2067	11.7.65	-0.13	0.36	0.28	0.060	140

In column (3) luminosity class has been omitted for Be stars belonging to classes V, IV and III. Rotational velocities in column (10) are from Boyarchuk and Kopylov (1964).

^a Chalonge's classification.

^b Too reddened.

to be less than 0.006 mag. In spite of this an independent test for atmospheric absorption was carried out with plates of S Mon, taken at different hour angles, which were kindly obtained and generously put at my disposal by Mme. Andrillat. We verified that it was possible to select regions which were not differentially affected by this factor, at least within the range of observational errors. These regions were large enough so as to allow the determination of the slope of the continuum at both sides of the Paschen discontinuity. The adopted intervals were, in wavelength

$$7450 \leq \lambda \leq 7500; \quad 7700 \leq \lambda \leq 8100; \quad 8300 \leq \lambda \leq 8700.$$

This result was further confirmed in a simultaneous check for variations in sensitivity with wavelength of the emulsion, with the stars γ Crv and ε Ori and 16 Mon included in Oke's photometry (Oke, 1964; Oke and Conti, 1966).

The relevant problem was the loss of sensitivity of the IN emulsion for wavelengths larger than λ 7950. The emulsion behaviour was checked on plates of 16 Mon with different density levels. We found that it was necessary to build three different correction curves, depending on the mean value of the transmission factor for the continuum,

- i) $T_{c_{\lambda 8600}} \leq 0.250$,
- ii) $0.250 < T_{c_{\lambda 8600}} < 0.350$,
- iii) $T_{c_{\lambda 8600}} \geq 0.350$.

We further tested these results by determining the Paschen discontinuity in α Leo and ε Ori – studied by Oke (1964) – and γ UMa and γ Gem, studied by Mlle. Bloch and Mao-Lin (1956).

In conclusion, all of our measurements of the continuum are given relative to 16 Ori. No special correction for atmospheric absorption is included, but we were very careful about sensitivity corrections of the IN plates, as these turned out to be dependent of the density. In Figure 1 we present a comparison between our measurements and the ones by the authors mentioned above.

The Paschen discontinuity, as compared to the Balmer discontinuity, is much more masked by the overlapping of the wings of the absorption members of the series and therefore, a criterion had to be adopted in order to give a numerical value. The

Fig. 1.

procedure chosen was to represent the continuum in the interval $7450 \leq \lambda \leq 7850$ (interval *a*) by a straight line; on the other side of the Paschen jump we selected the region where the 'Paschen depression' appears to end (interval *b*) and use it for a second determination of the continuum, drawing another straight line. The value of our Paschen discontinuity corresponds to the difference at $I_{\lambda 8200}$ defined by the two straight lines.

D_p depends upon the determination of levels and gradients in the continuum; we must control, somehow, the behaviour of these two elements. As far as we know, no gradients are available for this region, except for the ones which could be deduced from Oke's photometric work. From his measurements, gradients in region *a* and *b* — ∇a and ∇b — seem to differ slightly and always in the same sense, as ours do. The stars we have in common reproduce the figures and the whole set of values fit with the few points obtained from his data. We checked for any kind of correlation between D_p and V and we found that the only correlation present is the one expected from the running of V with $(B - V)_0$ for main sequence stars.

4. Masking of the Data

Before presenting our results we must consider the factors that tend to mask the real value of the discontinuity. Even though they are of different nature we will discuss them together,

- a) presence of emissions in the Paschen series,
- b) extent of the absorption wings,
- c) presence of companions to the stars — binary systems.

Some of the Be stars included in our list have the Paschen series in emission and among these a few show emission in the region towards the violet of the Paschen jump. The presence of emission in the lines does not influence our measurements as in most cases the absorption wings do not disappear completely and the same appears to be true for the continuum; a comparison with normal stars renders improbable that this emission could extend further than $\lambda 7700$ (at least in the cases we handled).

As to the effect of the absorption wings we verified that an elementary line profile for P_{12} , computed by considering only radiation damping, overlaps with the neighbouring lines when $I = 0.90 I_{\text{continuum}}$, so it appears necessary to introduce a correction to raise the continuum at the long wavelength side of the discontinuity. This correction may amount, taking into account the influence of the Stark effect, up to 30% of the original value for luminosity class V stars. We do not know whether this consideration applies to Be stars. Even though these objects deserve a thorough discussion we will not include it here as the different suitable corrections do not modify the general tendency of the figures in Tables II and III. We feel that in no case the correction should be larger than 10%.

In regard to the presence of binary components, we found three stars included in Batten's catalogue (1967) and two in his list of rejected objects; their value for the discontinuity falls very close to the mean value for their group. Moreover, considering

TABLE II
Uncorrected values of D_P

Spectral range	Luminosity class		Be	No obj		III	No obj		Supergiants	No obj	
	V										
A0-B5	0.047 ± 0.007 0.030		0.061 ± 0.006	9	10	0.094 ± 0.009	4	0.099 ± 0.011		6	
B5-B0			0.036 ± 0.005	1	10	0.075	1	0.053 ± 0.008		6	
> B0			0.053 ± 0.017 (3 obj.)								

the objects that may be double systems, we verified that there is no systematic difference with the rest.

5. Results

We grouped stars by spectral type and luminosity class to show – in the following tabulation – the mean value and the corresponding mean errors of the Paschen discontinuity, without including correction 4b.

We may note that the scatter of individual values relative to the mean is of the same amount as the scatter of the Balmer discontinuity values – as derived from the work by Chalonge and Divan (1952). Individual values are given in Table I, column 9; the corresponding error of one determination is ± 0.005 .

From Table II it appears that D_P decreases, within one luminosity class, with increasing temperature as it is expected from the behaviour of the continuum absorption coefficient of hydrogen. What does not appear so simple to understand are the variations related to luminosity class. If we introduce correction 4b, we obtain, the data given in Table IIa.

TABLE IIa
Corrected values of D_P

Spectral range	Luminosity class			
	V	Be	III	SG
A0–B5	0.061	0.067	0.094	0.099
B5–B0	0.039	0.040	0.075	0.053
> B0		0.053		

We cannot be sure whether or not there is a real difference between main sequence and Be stars – we cannot establish, if it does exist, the effect of the envelope – but, anyway, the general tendency we observed before remains true.

In order to compare our observational results with the ones theoretically predicted we need to assign effective temperatures and these were obtained through the colours. The $(B-V)$ adopted are from the *Lunar and Planetary Lab. Publ.* No. 63 corrected for interstellar reddening in the following way: we plotted $(B-V)_0$ against spectral types from Arp (1958). In the same plot we represented our stars with the observed $(B-V)$ and then we shifted the set of points to the left, as much as possible, thus providing a value for $E(B-V)$. The best representation of our stars, in relation to Arp's curve, was obtained with $E(B-V)=0.11$ mag/kpc, a value which is admissible taking into account that our stars are all nearby objects. These $(B-V)$ were taken as $(B-V)_0$ and from them, using the temperature-colour scale also given by Arp (1958), effective temperatures were deduced. The distances involved are spectroscopic parallaxes and the adopted spectral types are in Chalonge's system (1952), when available; otherwise, we accepted the most probable in the literature (Jaschek *et al.* 1964). All related data are collected in columns 6 and 7 of Table I.

Figure 2 shows D_P against $\theta=5040/T$ for the model atmospheres computed by

Fig. 2. The three main sequence stars with large D_P value deserve a comment; HD 138764 is a class IV object, α Leo is the only main sequence star – in our group – with high rotational velocity and α Dra is a peculiar object in the sense that the Chalonge's system locates it, beyond any doubt, in class V but according to the M.K.K. system belong, beyond any doubt, to the giants and therefore, its position would not be surprising.

Saito (1956) and Mihalas (1964) – in both sets the Rosseland mean opacity coefficient was used. Our values are shown there (some extremely reddened super giants and π Aqr* were left aside); luminosity class V and Be stars are corrected to take care of the absorption wings effect. The dotted line represents the mean deviation due to a rotational velocity at the limit of stability, through different $\sin(i)$, as deduced from the work of Hardorp and Strittmatter (1968). In Figure 2 it appears that main sequence and Be stars agree with predictions by L.T.E. models. Under this assumption, to lower surface gravity – in the range $0.20 \leq \theta \leq 0.42$ – lower D_P values should be expected, as it appears to be the case in τ Ori and 53 Per, both stars displaying characteristics of class III objects. γ Cor is not a suitable object to discuss because it is the only case in which V_a is large and therefore we cannot rely upon the value. We also observe that some Be stars fall on the dotted line. The rotational velocity of these objects justifies, exactly, their location; that means that they hold the necessary but not sufficient condition $v_0 \sin(35^\circ) \leq v_{\text{rot}} \leq v_0 \sin(55^\circ)$, with $v_0 = 390$ km/sec.

Giants and supergiants do not fit in this scheme under L.T.E. conditions. Nor the present calculations following non-L.T.E. approximations approach the actual values. To show this numerically we present, in Table III, the ratio $\phi = D_P/D_B$ – which is not affected either by rotational velocity or reddening – for stars for which D_B was available. The D_P used for the main sequence stars are corrected values.

This table can be compared with Table IV which represents the ϕ values computed from Mihalas' work (1967). Values in both tables match approximately in the upper left region. The rest is far from agreement. This discrepancy becomes larger as the dimensions of the atmospheres increase. The present state of non-L.T.E. compu-

* See Münch and Lirin (1961).

TABLE III
 D_P/D_B ratio (corrected)

Spectral range	Luminosity class							
	V	No obj	Be	No obj	III	No obj	SG	No obj
A0-B5	0.13 ± 0.02	7	0.17 ± 0.02	7	0.32 ± 0.04	3	0.40 ± 0.06	3
B5-B0			0.32 ± 0.06	7	0.47	1	0.89 ± 0.26	6
> B0			1.49 ± 0.57 (3 obj.)					

TABLE IV
 D_P/D_B from Mihalas (1967)

θ	$\log g$					
	4.5	4.0	3.5	3.0	2.0	1.0
0.500		0.15		0.16	0.16	0.04
0.320	0.16	0.17	0.17			
0.210	0.18	0.18	0.17			

tations (Strom and Kalkofen, 1967; Mihalas, 1967) does not appear to give the solution; we do not know whether the presently obtained coincidence of the population numbers, n_1 , n_2 , etc. obtained under L.T.E. and non-L.T.E. conditions is a consequence of the ad-hoc hypothesis introduced in non-L.T.E. computations. Whatever the solution may be, our ϕ values will provide an interesting test for any new theoretical approach.

Before concluding we may quote that, even though a discussion involving single values of the discontinuity is not adequate – considering the weight of each determination – it will be worth while to revise whether or not a small percentage of giants (in the M.K.K. system) appear with a D_P value smaller than that corresponding to class V objects – 31 Peg, 53 Per, τ Ori. We wonder if there is any relation with this feature and the fact that two supergiants from our group – ϵ Ori and χ^2 Ori – present no discontinuity.

It is opportune to comment that if we adopt, exclusively, the M.K.K. system of spectral classification, our results do not change.

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