Photometry of Hydrogen and Calcium Lines in Stellar Spectra.

By Cecilia H. Payne and Emma T. R. Williams.

1. The measurement and theory of line contour have recently been brought into prominence by several investigators. The recent papers of Milne (*M.N.R.A.S.*, **89**, 3, 1928; *ibid.*, 17, 1928) contain so complete a discussion of the subject and so important a contribution to the theory that it seems to be desirable to apply his methods at once to as large a body of data as possible. The writers have been for some time engaged in the measurement of the contours of spectral lines, and a summary of the relevant data is contained in the present paper.

2. *The Material.*—The investigations by the two authors were undertaken independently, and the methods used differed somewhat. Miss Payne's material and procedure have been fully described in previous papers (*H. Repr.* 48, 1928; *H.C.* 334, 1928). Miss Williams has used substantially Dunham's method (*H.B.* 853, 1927); her material has the advantage of being quite homogeneous, having been obtained with the same telescope and prism on plates of the same emulsion, and, moreover, she has measured at least two and usually three plates of each star.

It has seemed best to keep the material in two parts in discussing the results. Miss Payne's material, however, also includes the data published by Dunham (*H.B.* 858, 1928) and by Hogg (*H.B.* 859, 1928), which have already been discussed by Miss Payne and Hogg in *Harvard Circular* 334.

3. *Theoretical Predictions.*—The specific points in Milne's discussion on which data are presented are as follows:—

(*a*) When the maximum of a line in the spectral sequence is measured for various values of the intensity ratio r, it is predicted that the greater is r, the higher is T_{max}. Near the centre of a line (high in the atmosphere) the temperature at which a given line is "widest" should be lower than for the wing of the line (deep in the atmosphere).

(*b*) Another way of expressing (*a*) is to say that the observed contours of lines should differ in shape at different temperatures.

(*c*) The actual maximum of the H and K lines of ionized calcium is of great importance, and it is expected that it will occur at a temperature of about 5000°.

(*d*) The maximum for the Balmer lines is expected at a temperature of about 11,000°.

The data bearing on each of these predictions will now be briefly presented in tabular and diagrammatic form.

4. *Maxima of Lines at Different Levels.*—The only lines at all suitable for measurement with the available dispersion are those of hydrogen and ionized calcium. As tabulated below, the lines $H\gamma$, $H\delta$, H + $H\epsilon$, and K have been measured for values of r ranging from ·96 to ·40. The tabulated quantities are half-breadths of lines, expressed in angstroms.

Table I gives, in addition to the mean of the measures for a given class, the average deviation of the mean of the measures of each star from the mean for the class. Similarly, Table II gives the average deviation of the measures of each plate from the mean for each star.

TABLE I.

Mean Line Contour Data for Various Spectral Classes (Miss Williams's Data).
("Peculiar" stars excluded.)

Sp. Class.	No. of Stars.	No. of Plates.	Mean Value of $\|\lambda - \lambda_0\|$ for: r=·96.	r=·83.	r=·69.	r=·48.	Mean Value of r at λ_0.
			Hγ.				
B5	5	15	17·7±1·3	9·1± ·7	5·4± ·3	..	·44±·04
B8	9	27	19·9±2·0	11·2±1·5	6·9± ·9	2·5±1·0	·41±·05
B9	1	3	22·3 ..	13·9 ..	8·6 ..	4·1 ..	·34 ..
A0	22	62	29·4±3·6	16·8±1·6	11·2±1·2	5·4± ·4	·29±·02
A2	12	34	31·7±2·3	18·5±1·2	12·0±1·0	5·3± ·4	·30±·02
A3	3	9	34·0±4·1	20·0±1·6	12·3± ·9	5·1± ·3	·30±·03
A5	7	21	33·9±1·9	19·1± ·7	11·2±1·0	4·5± ·4	·33±·03
F0	8	24	23·5±3·9	13·1±2·8	7·3±1·8	3·1± ·7	·36±·04
F2	1	3	18·1 ..	8·3 ..	4·2 ..	..	·47 ..
			Hδ.				
B5	5	15	13·7±1·0	7·8± ·6	4·9± ·2	..	·40±·03
B8	9	27	16·9±1·6	9·7±1·2	6·4± ·8	2·8± ·7	·37±·06
B9	1	3	20·1 ..	11·5 ..	7·5 ..	3·8 ..	·32 ..
A0	22	62	24·5±2·8	14·5±1·4	9·7± ·8	5·1± ·3	·27±·02
A2	12	33	26·9±1·4	16·2±1·6	10·1±1·0	4·8± ·5	·28±·02
A3	3	9	28·4±2·2	16·7±1·3	10·2± ·7	4·8± ·1	·28±·02
A5	7	21	28·9± ·9	15·5± ·9	9·3± ·6	3·9± ·2	·30±·03
F0	8	24	19·0±3·5	10·8±1·7	6·6±1·5	2·6± ·6	·35±·04
F2	1	3	12·5 ..	7·3 ..	3·1 ..	..	·46 ..

TABLE II.

Mean Line Contour Data for Certain Stars (Miss Williams).

Sp. Class.	Star.	*H* lines.	No. of Plates.	Mean Value of $\|\lambda - \lambda_0\|$ for: r=·96.	r=·83.	r=·69.	r=·48.	Mean Value of r at λ_0.
				Hδ.				
A0	ο Her	Narrow	3	17·6± ·6	10·7± ·3	6·8± ·2	3·8±·2	·31±·03
	β UMa	Average	3	24·1±1·5	14·6±1·4	10·6± ·6	5·3±·3	·26±·01
	α Lac	Broad	3	29·2± ·9	18·0±1·0	11·6±1·3	5·9±·8	·24±·03
A5	α Cep	Narrow	3	26·4±2·9	13·8±1·0	8·1± ·0	3·6±·2	·34±·02
	ι UMa	Average	3	28·8± ·8	15·2±1·4	9·2± ·5	3·8±·2	·31±·00
	δ Cas	Broad	3	30·2±1·7	17·8± ·7	10·8± ·6	4·8±·5	·26±·03

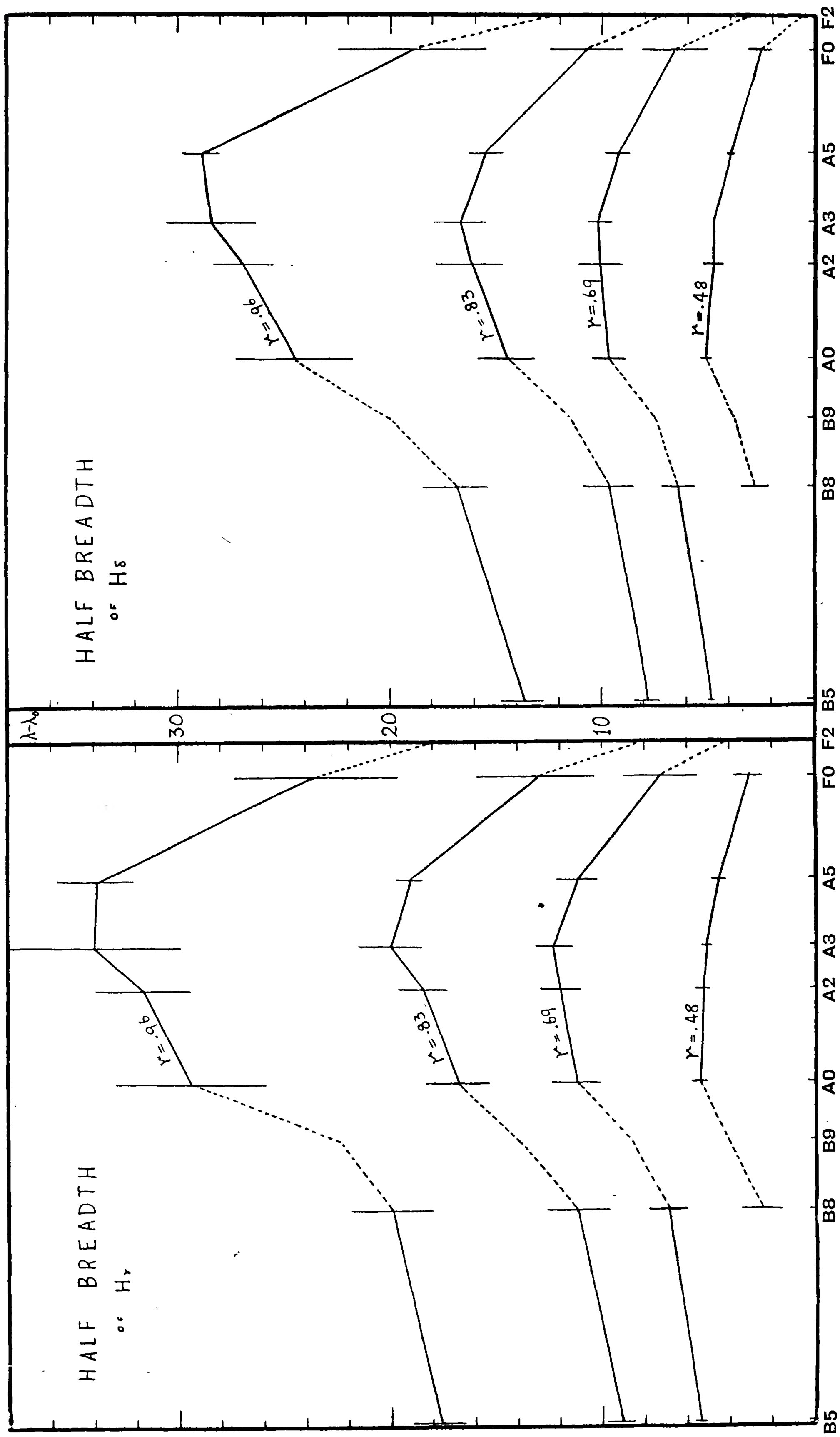


FIG. 1.—Relation of Half-breadths of Hydrogen Lines to Spectral Class (Miss Williams). Ordinates are half-breadths; abscissæ are spectral classes, spaced according to approximate temperatures.

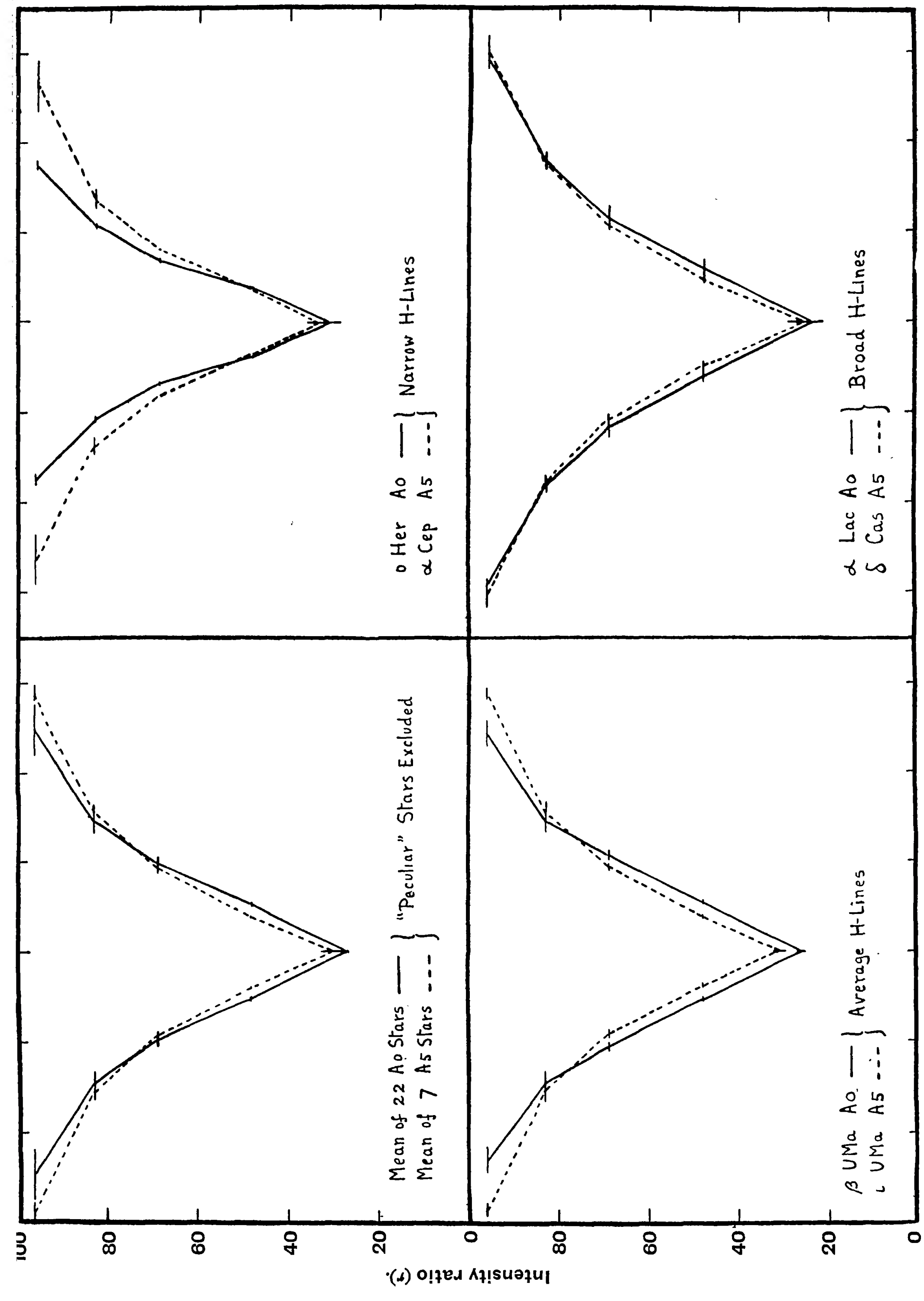


FIG. 2.—Comparison of Mean Contours and Individual Contours of $H\delta$ for Classes A0 and A5 (Miss Williams). Abscissæ are angstroms; ordinates are values of r.

TABLE III.

Mean Values of $|\lambda - \lambda_0|$ *for Various Spectral Classes (Miss Payne's Data).*

Spectral Class.	Line.	No. Stars.	$r = \cdot 96$.	$r = \cdot 83$.	$r = \cdot 69$.	$r = \cdot 58$.	$r = \cdot 48$.
O	$H\gamma$	3	7·8	3·7	2·2	1·3	..
B2		1	14·0	6·0	..	..	..
B5		4	18·4	8·0	4·2	3·0	2·6
A2*		3	33·2	19·2	12·8	9·8	7·2
A5		3	33·7	14·4	8·4	5·3	4·2
F0		1	21·5	12·0	7·5	4·8	3·2
F2		1	17·2	8·6	3·7	2·4	1·6
F5		2	12·9	6·8	3·8	2·4	..
K5		1	2·0	..	..	..	..
O	$H\delta$	3	4·4	2·3	1·1	..	..
B2		1	10·2	2·7	0·6	..	..
B5		4	15·9	7·2	3·8	3·0	2·0
A2*		3	36·6	22·4	14·7	10·6	7·8
A5		4	34·4	15·3	8·8	5·8	3·8
F0		2	19·5	10·3	5·7	3·5	2·8
F2		1	18·5	10·2	5·4	3·0	1·1
F5		2	12·9	6·5	3·6	2·1	0·6
K5		1	3·0	..	..	..	..

* Three stars with abnormally strong hydrogen lines.

TABLE IV.

Mean Values of $|\lambda - \lambda_0|$ *for Class A (Dunham's Data).*

Spectral Class.	Line.	No. Stars.	$r = \cdot 96$.	$r = \cdot 83$.	$r = \cdot 69$.	$r = \cdot 58$.	$r = \cdot 48$.
A0	$H\gamma$	11	27·0	15·1	9·1	6·5	4·6
A2		2	28·2	14·4	9·2	6·2	4·4
A5		1	30·6	14·4	8·2	5·0	2·6
A0	$H\delta$	11	25·5	12·9	9·4	6·9	5·1
A2		2	26·8	13·6	9·2	5·8	3·4
A5		1	33·0	14·0	7·8	5·9	3·6
A0	H + $H\epsilon$	11	22·4	13·3	9·4	7·0	5·6
A2		2	24·4	14·1	9·2	6·2	4·2
A5		1	32·0	15·1	8·2	5·4	3·2

It would seem from the diagrams 1, 3, and 4 that the maximum of the lines of hydrogen differs for different levels; but the difference is in the sense that the value of T_{max} is lower, not higher as predicted, for large values of r than for small ones. For $r = \cdot 96$ the maximum apparently occurs at A3–A5; for r = ·48 it is at A0.* This effect is shown independently by the data of Miss Williams and Miss Payne.

Table V.

Mean Values of $|\lambda - \lambda_0|$ *for Various Spectral Classes (Miss Payne's Data).*

Spectral Class.	Line.	No. Stars.	r=·96.	r=·83.	r=·69.	r=·58.	r=·48.
O	H + *Hε*	4	4·2	1·6	0·7	0·3	..
B2		1	16·2	12·7	3·2	1·2	..
B5		5	21·0	10·8	6·3	3·8	2·8
A2*		3	35·8	20·7	14·5	13·2	8·5
A5		4	33·4	17·6	9·8	7·7	5·7
A7		1	18·6	10·3	6·3	4·6	4·0
A8		1	20·5	11·3	7·2	5·4	4·0
F5		2	11·2	8·6	6·7	5·6	4·7
F8		2	13·2	8·6	6·9	5·8	4·8
G0		2	13·4	9·6	7·4	6·4	5·3
G5		3	11·7	9·6	8·1	6·6	5·1
K0		6	25·4	13·3	9·1	7·1	5·9
K2		3	27·3	15·3	9·6	7·0	5·3
K2 (Hogg)		2	25·8	12·5	9·2	7·4	5·8
M0 ,,		6	19·0	10·2	6·3	4·8	3·6
M1 ,,		1	20·5	9·5	4·5	3·3	2·5
M2 ,,		1	17·8	7·5	5·0	3·8	2·8
M3 ,,		2	16·1	7·9	5·2	3·6	2·5
M5 ,,		2	11·9	6·6	4·1	3·2	2·4

* Three stars with abnormally strong hydrogen lines.

Table VI.

Mean Values of $|\lambda - \lambda_0|$ *for Various Spectral Classes (Miss Payne's Data).*

Spectral Class.	Line.	No. Stars.	r=·96.	r=·83.	r=·69.	r=·58.	r=·48.	r=·40.
A0	K	1	2·5	0·8	0·5	..	..	..
A2		4	5·9	2·4	0·5	..	..	..
A3		1	6·7	4·0	2·5	1·8	1·5	1·3
A5		1	8·5	5·5	3·8	3·0	2·5	2·0
A7		1	9·3	5·6	4·4	3·8	3·2	2·8
A8		1	11·5	7·0	5·3	4·2	3·1	1·7

* It should be noted that an explanation for this contradiction of the theory would be forthcoming if it could be shown that the line representing continuous background on the microphotometer tracings of stars of classes A3 and A5 has been drawn systematically too high by at least 0·06 magnitudes (*cf.* fig. 8). This seems improbable, particularly so inasmuch as the effect is shown by both sets of data.

TABLE VI.—*continued.*

Spectral Class.	Line.	No. Stars.	r=·96.	r=·83.	r=·69.	r=·58.	r=·48.	r=·40.
F0	K	4	13·2	7·5	5·5	4·3	3·8	3·3
F2		2	16·0	10·0	7·5	6·5	6·0	5·0
F8		3	22·2	12·8	8·6	6·5	4·8	3·9
G0		1	18·0	11·0	8·0	6·0	5·0	4·0
K0		5	23·4	16·8	12·4	10·9	8·2	7·2
K2		3	30·6	20·6	15·0	11·0	8·6	7·0
K2 (Hogg)		2	28·0	16·1	11·8	9·4	7·1	5·7
K5 ,,		1	19·4	14·2	9·7	6·4	4·2	3·0
M0 ,,		6	22·2	15·8	10·9	8·2	6·2	4·8
M1 ,,		1	27·2	18·0	10·0	6·8	4·8	3·2
M2 ,,		1	22·3	15·6	10·6	7·9	6·1	5·0
M3 ,,		2	22·2	10·8	7·0	5·0	4·0	3·2
M5 ,,		2	23·2	15·8	10·2	7·9	5·1	3·8

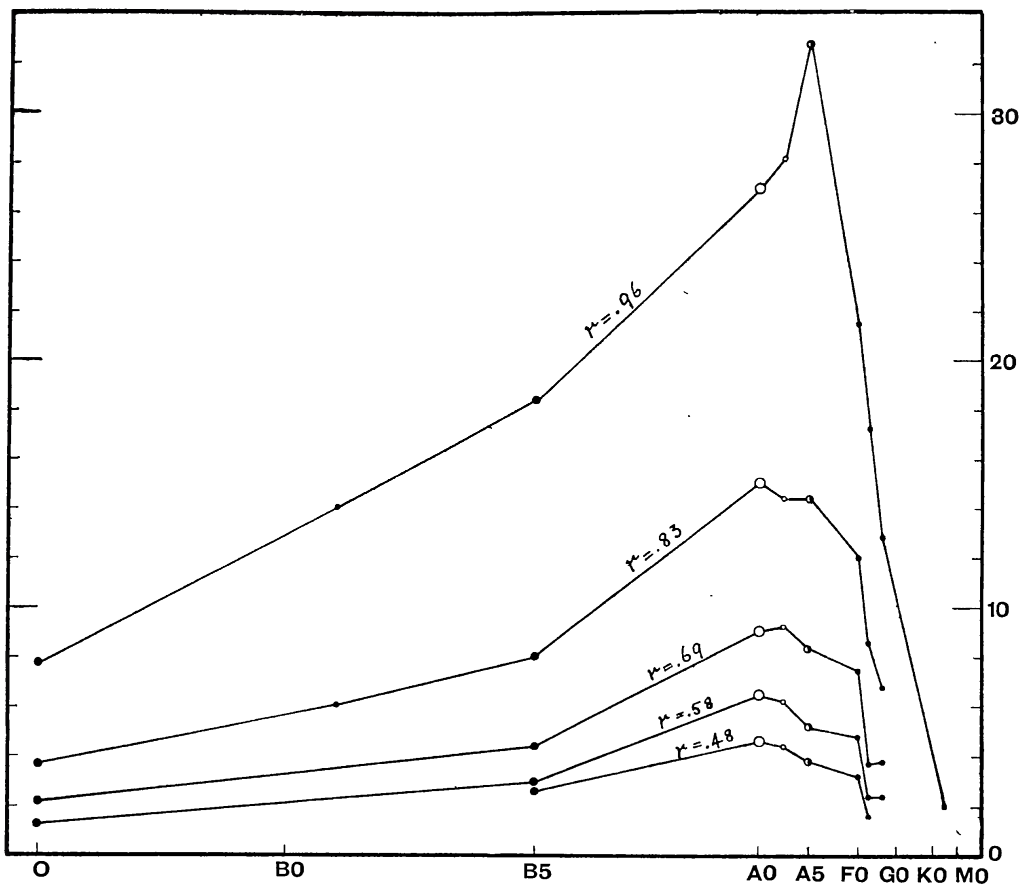


FIG. 3.—Relation of Half-breadth (ordinates) to Spectral Class (abscissæ) for $H\gamma$ from Miss Payne's data. Small, medium, and large dots represent the weights of points, according to the numbers of stars contributing to the means. Values plotted with open circles are data by Dunham.

For the lines of calcium the case is not so clear, though there is apparently a very slight effect in the same sense as that observed for hydrogen. Results for the H line are to be considered of greater weight than for the K line, because in the spectral classes at which the maximum occurs the background for the K line is very difficult to trace. It should be noted, however, that the results of Miss Payne and Hogg, for which the backgrounds were drawn independently, are closely

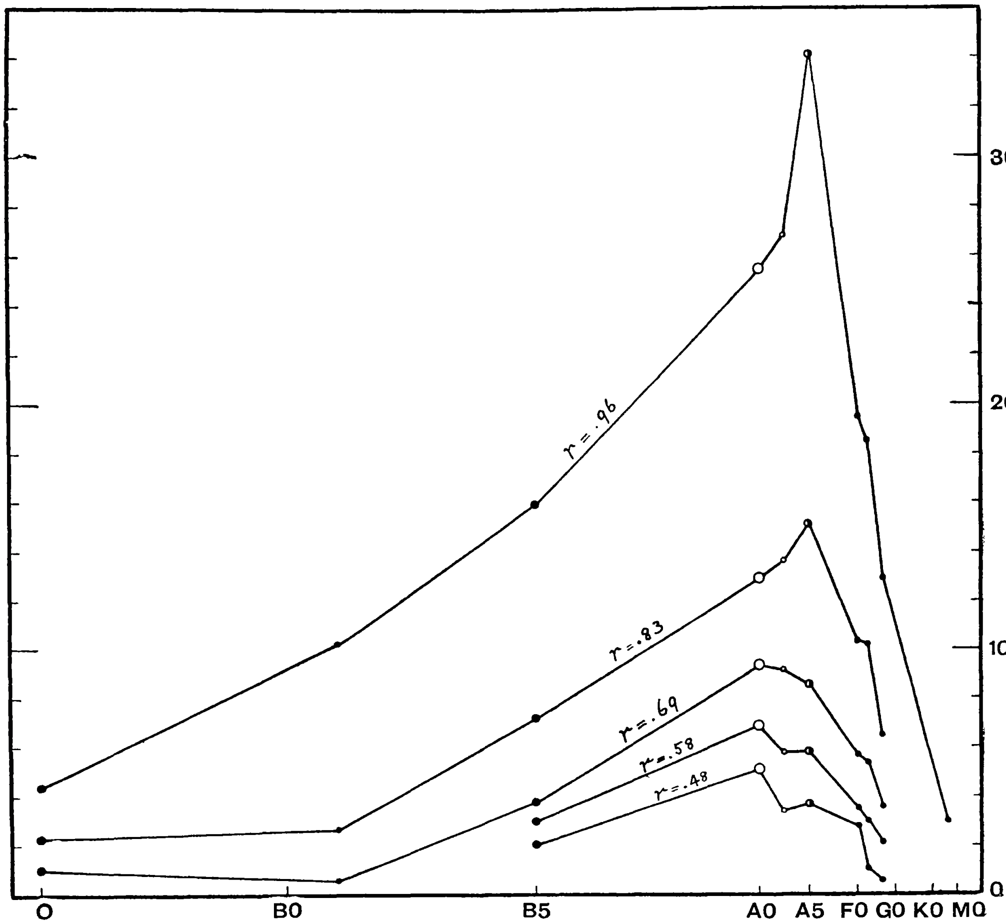
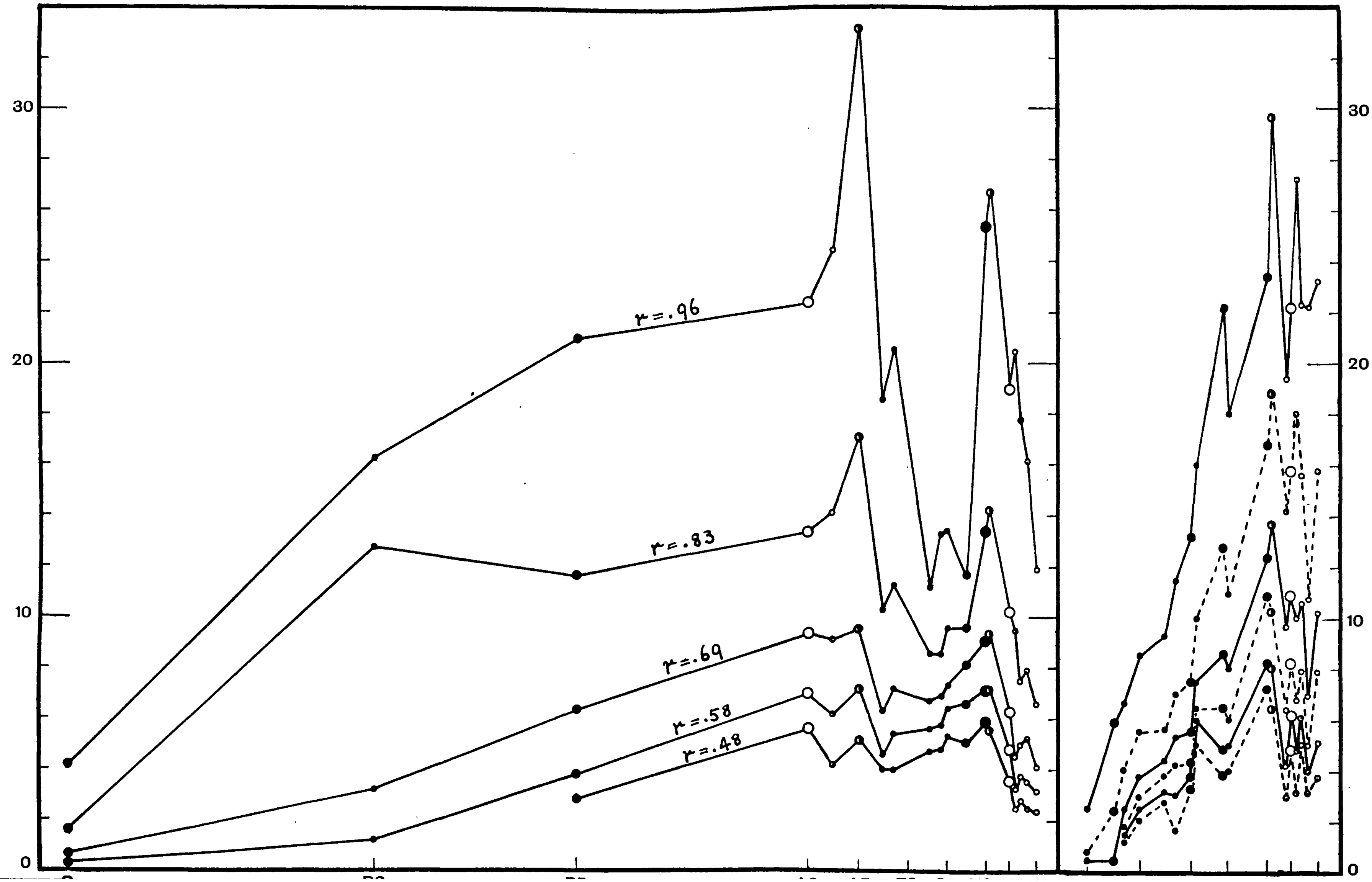


Fig. 4.—Relation of Half-breadth (ordinate) to Spectral Class for $H\delta$ (Miss Payne's data).

accordant for Class K2. The difference between the two results is of the order of the actual difference that is found for stars of similar spectral class.

5. *Shapes of the Observed Contours.*—Another way of expressing the result embodied in the preceding tables is to say that the higher the temperature the narrower are the extreme wings in comparison with the rest of the line. Individual contours show this effect well, as do the means contained in the first tables. The contours of the various lines examined are reproduced in figs. 2 and 7. Fig. 8 shows the actual microphotometer tracings made by Miss Williams for a star of Class A0 and for one of Class A5. Fig. 2 and Table II compare individual stars


30
20
10
0
r = .96
r = .83
r = .69
r = .58
r = .48
30
20
10
0

of Ao and A5. Thus, among the non-peculiar Ao stars examined, *o* Her has the narrowest H lines; it is compared with *α* Cep, the corresponding star for Class A5. The broader wings and shallower centres of the lines in the A5 stars are apparent in all the comparisons. This would be even more striking if two stars with the same central intensity

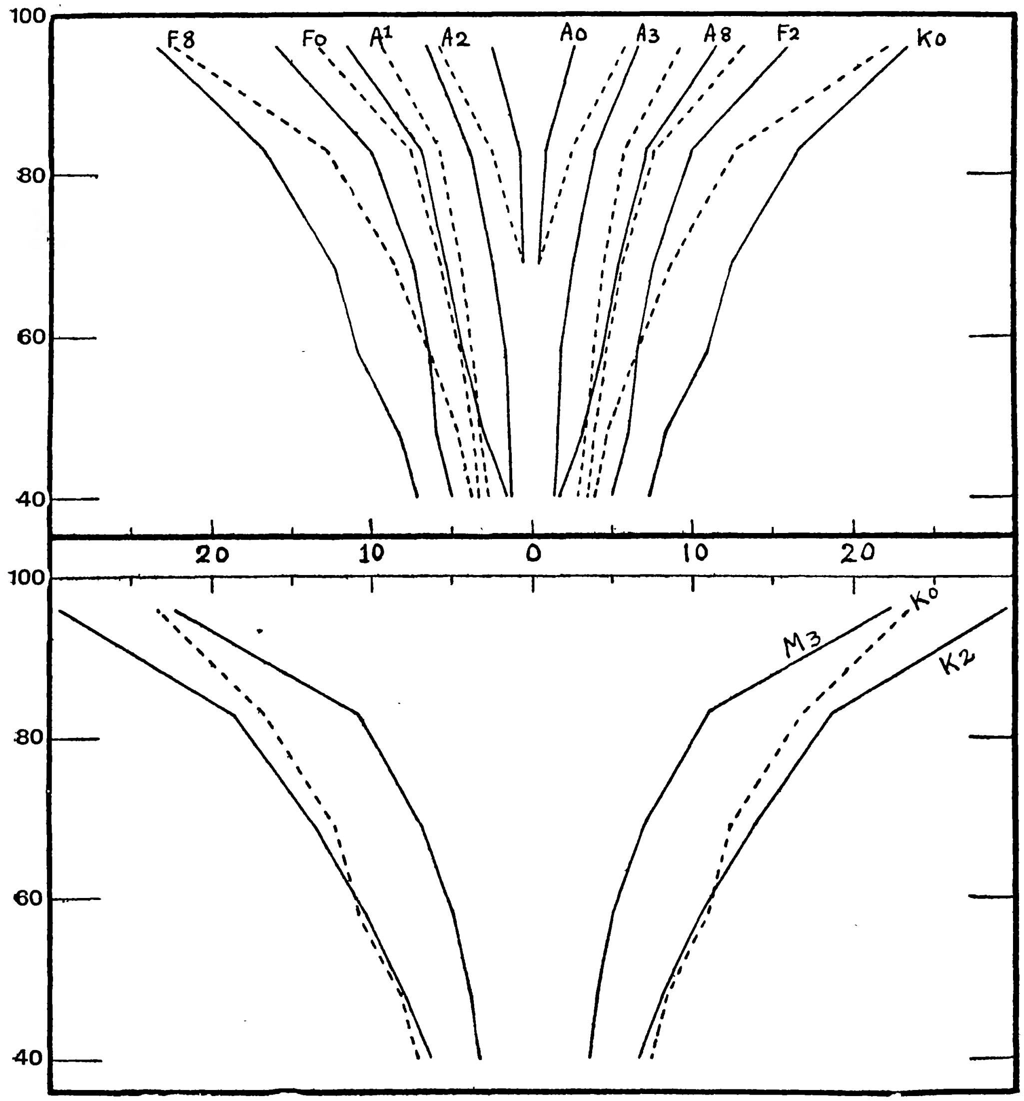


Fig. 7.—Comparison of Contours of the K line for various Spectral Classes. Ordinates are values of *r*; abscissæ are angstroms.

were compared, *i.e.* *o* Her compared with *ι* UMa and *β* UMa with *δ* Cas. Fig. 7 contains similar results from Miss Payne's data for various spectral classes. The increasing wing with low temperature may be traced throughout the series.

6. *The Maximum for Ionized Calcium.*—Both the calcium lines definitely have maxima within Class K, probably at Class K2 for the wings. This is in accordance with estimates of line intensity and with measures discussed on the basis of the Unsöld fit (*H.R.* 48, 1928),

which showed an evident maximum at the same spectral class. The suggested maximum at or above 5000° is therefore not substantiated. Probably the temperature for Class K0 is not greater than 4200°; temperatures based on radiation measurements cease to be of much weight in classes for which band absorption is on the verge of coming into prominence, and it is likely that the temperatures for the K and M stars are even lower than is supposed at present. There is, indeed, an indication that the temperature scale is too high almost all along the spectral sequence.

7. *The Maximum for Hydrogen.*—The wings of the hydrogen lines have a maximum at Class A3–A5, and the more central regions of the

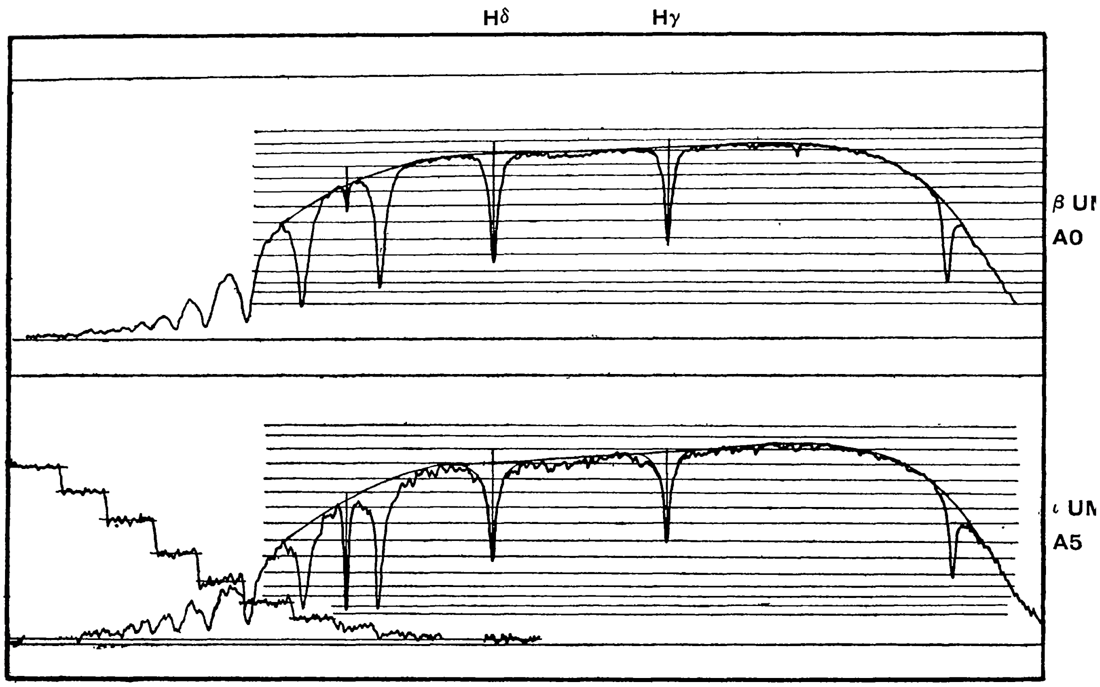


FIG. 8.—The parallel lines are ruled at intervals of 0·2 magnitudes: the "steps" at the left show the method of calibration.

lines at Class A0. The latter class may be at a temperature of 11,000°, but is probably not higher, and Class A5 is certainly much lower. The classification of the A stars is at present so unphysical that it is not possible to be sure of the temperature of a given star when its spectral class has been assigned in the Draper System, but there is no doubt that the mean of a number of stars of Class A5 is at a lower temperature than the mean for Class A0.

8. *Data for Supergiant Stars.*—The powerful methods opened up by the idea of considering an isolated level instead of an integrated line should permit the comparison of the atmospheres of stars of different luminosities. The next table contains a concise comparison of the contours of lines for normal and supergiant stars. The data for the latter are not yet complete enough for the determination of maximum at different levels, but by analogy with sections (4) and (5) above

the same effect could be detected from the change in the shapes of individual contours. There is another reason for not examining the data for supergiants for shift of maximum. The analysis of any set of data in that manner presupposes that the atmospheres of the stars concerned are homologous. It is evident that the atmospheres of supergiants are not homologous with those of giants, and, further, unpublished material indicates clearly that individual supergiants differ greatly in atmospheric structure. To a lesser extent the same is undoubtedly true of the normal giants, and this deprives the observed maxima of some of their significance. Probably, however, the atmospheres of the giant stars are homologous enough for the present investigation to be justified.

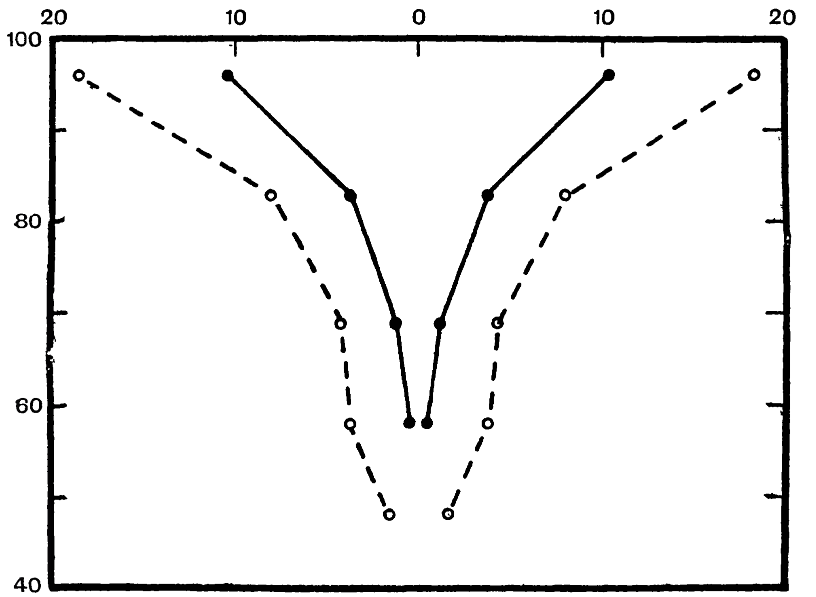


Fig. 9.—Comparison of Contours for Class B5 (below) and Class *c*B5. Ordinates are values of *r*; abscissæ are angstroms.

Table VII.

Comparison of Contours for Normal and Supergiant Stars (Miss Payne's Data).

Spectral Class.	Line.	No. of Stars.	r=·96.	r=·83.	r=·69.	r=·58.	r=·48.	r=·40.
cB5	$H\gamma$	6	10·3	3·8	1·1	0·6	..	..
B5		4	18·4	8·0	4·2	3·8	1·6	..
cB5	$H\delta$	6	8·7	4·3	1·8	0·3	..	..
B5		4	15·9	7·2	3·8	3·0	2·0	..
cB5	H + $H\epsilon$	6	11·0	4·8	2·2	0·8	..	..
B5		5	21·0	10·8	6·3	3·8	2·8	..
cB5	K	1	5·8	2·6	..	..	..	..
B5		1	0·4	..	..	..	..	..

9. *Conclusion.*—It does not at present seem to be profitable to go further in the comparison of theory and observation. The data contained in the present paper do not appear to be in accordance with the arrangement of a stellar atmosphere suggested by Milne, and therefore we have not proceeded to evaluate absolute abundances according to the method that he outlines.

The results of the investigation are definite in disagreeing with the predictions referred to in sections 3*c* and 3*d*; however, the predicted shift of maximum referred to in sections 3*a* and 3*b* is contradicted definitely by the hydrogen lines only. Since the hydrogen lines are anomalous in other respects, perhaps they may be in this one too.

The results lay especial stress on the value of considering the changes of a line at various levels instead of regarding it as arising, for the purposes of the investigation, at one part of the star's atmosphere.

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The Physical Conditions in New Stars. By the late S. R. Pike, M.A.

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Although the true cause underlying the sudden flare up of new stars remains completely obscure, the idea seems to be gaining ground that the effects are due to some sort of explosion taking place in a single star. It has been shown * that the simplest explanation of the mixed bright and dark line spectrum is provided by the hypothesis of one or more expanding shells of gas. These expanding shells are presumably the chromosphere and reversing layer of the star, and the question therefore naturally arises whether the photosphere of the star also moves outwards to an appreciable extent. The following simple argument shows that this must actually occur.

When a star increases in brightness there are just two ways in which it can do so: it can either raise its surface temperature or it can increase its radius. In general, if m_0, m are the initial and final magnitudes,

$$m_0 - m = 5 \log_{10} \frac{\mathrm{RT}^2}{\mathrm{R}_0\mathrm{T}_0{}^2} \quad . \quad . \quad . \quad (1)$$

where R_0, T_0, and R, T are the initial and final radii and temperatures respectively.

In this equation m_0 and m are the *bolometric* magnitudes (*i.e.* the magnitudes reckoned for radiation of all wave-lengths), and to obtain

* Evershed, *Monthly Notices*, **79**, 483, 1919; Adams, *Jour. R.A.S. Can.*, **13**, 75, 1919.