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ON THE INTERPRETATION OF THE EMISSION LINES IN STARS OF EARLY SPECTRAL CLASS

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ABSTRACT

The emission-line spectra.—The presence of bright *Fe* II in the spectra of Be stars suggests that lines of other elements requiring similar conditions of excitation may also be present. A search in the spectra of several stars yielded definite evidence of the presence of *Mg* II and *Si* II; *Sc* II, *Cr* II, and *Ni* II are probably present; forbidden *Fe* II is uncertain. No lines belonging to *Ti* II could be identified, with certainty. The width of the bright line *Mg* II 4481 greatly exceeds those of the emission lines of *H*, and in one star the lines of *Fe* II are definitely wider than those of *H*. Attributing the origin of the bright lines to a rotating shell of gas, and neglecting support by radiation pressure, we find that the effective distance of *Mg* II from the center is about seven times the radius of the star, while that of *H* is ten times the radius of the star. A rough computation of the density of the shell gives 2.5×10^{-13} gr/cm³. The bright lines of *Mg* II and of *Si* II are always weak. *He* I and *Ti* II are rarely seen in emission.

Classification of bright-line spectra.—The published data on Be and Oe stars were collected and arranged according to the Harvard spectral class as derived from the absorption lines. The character of the emission lines shows a definite progression with spectral class. The degrees of effective excitation of the bright and dark lines are not very different in the Oe's but they differ by more than one spectral class in the Be's. There is relatively little dispersion within any given spectral subdivision. This would indicate, on the rotational hypothesis, that the product of the density of the shell and the dilution factor is approximately constant within a given subdivision, but that it varies as a function of spectral type.

A new Be star.—Data are given for the Be star 60 Cygni ($\alpha\ 20^{h}57^{m}.7\ \delta\ +45^{\circ}46'$), which has variable hydrogen lines.

Variations in the spectra of Be stars.—Variations in the hydrogen lines of 31 Pegasi ($\alpha\ 22^{h}16^{m}.6\ \delta\ +11^{\circ}42'$) are described. The Be star 31 *o* Aquarii ($\alpha\ 21^{h}58^{m}.1\ \delta\ -2^{\circ}38'$) is found to have broad and hazy absorption lines of *He* I and *Mg* II, and sharp and narrow lines of *Fe* II. The latter are probably variable. This star is similar to the Be star ϵ

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Capricorni; and the suggestion is advanced that the hazy lines are broadened by rotation, while the narrow lines originate through absorption in the same rotating gaseous shell which is believed to give rise to the bright hydrogen lines and to their narrow central absorptions.

The spectrum of 17 Leporis.—This spectrum seems to be related to spectra of the P Cygni type: 17 Leporis has bright $H\beta$ in the normal position, accompanied by a strong absorption line on its violet side. Preliminary measurements of one plate give: Mg II +14 km/sec., Fe II and Ti II −64 km/sec., H −93 km/sec.

The rotational hypothesis of the origin of bright lines.—A summary is given in support of the hypothesis that the bright lines originate in a rotating shell or ring of gas, and that the dispersion in line widths is mainly due to the effect of inclination.

Objections to the rotational hypothesis are discussed and found not to be of a sufficiently serious nature to outweigh the positive evidence. The rotational hypothesis is adopted as the one which fits the observed facts better than any other theory thus far proposed.

I. EMISSION-LINE SPECTRA

Various investigators[1] have pointed out that the presence of bright lines of Fe II in stellar spectra classified as B0, B1, B2, B3, or B5 constitutes an interesting astrophysical problem. The absorption lines of ionized iron observable in the ordinary photographic region of the spectrum reach maximum intensity in or near class F0; they are strong in many A stars (e.g., α Cygni), but are faint in B8 and B9 (e.g., β Orionis) and are last seen in certain stars classified at Harvard as B3 (e.g., ι Herculis).[2] On the other hand, the emission lines of ionized iron seem to be most frequent in class B3e, but they have also been observed in several stars of classes B2e, B1e, and even B0e.[3] It seems obvious that in these "normal Be stars," as they have been called by Paul W. Merrill,[4] the state of effective excitation corresponding to the bright lines is much lower than that corresponding to the absorption lines. A tentative explanation of this interesting phenomenon has recently been given in a paper by Struve and Schwede.[5]

We shall assume here that the bright lines originate in an outer gaseous shell or ring which is sufficiently far removed from the photosphere of the star to permit large deviations from thermodynamic equilibrium. Under such conditions the usual equations defining the state of ionization of the medium are not applicable, and

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[1] B. P. Gerasimovič, private communication; O. Struve and H. F. Schwede, *Physical Review*, 38, 1203, 1931; C. H. Payne, *Harvard Observatory Circular*, No. 364, 1931.

[2] O. Struve, *Astrophysical Journal*, 74, 225, 1931.

[3] P. W. Merrill, *ibid.*, 65, 290, 1927; Table II.

[4] *Ibid.*

[5] *Op. cit.*, p. 1204.

we must follow the treatment of A. S. Eddington[1] and S. Rosseland,[2] i.e., the ionization of a medium of temperature T and density ρ will be the same as that of a gas in thermodynamic equilibrium of the same temperature and of density $\rho\delta$, where δ is the dilution factor

$$\delta=\frac{4r^2}{R^2}\,,$$

r is the distance of the gas from the center of the star, and R is the radius of the star.

The rotational hypothesis of the origin of bright lines[3] attributes the broadening of the emission lines to the rotation of a gaseous shell or ring around the star. The actual measurements refer, of course, to the component of the velocity in the line of sight. It is therefore reasonable to assume that the greatest measured line-widths refer to cases in which the axis of rotation is perpendicular to the line of sight. A total width of about 6 A for $H\beta$ has been observed in several stars.[4] The corresponding velocity of rotation would be approximately 200 km/sec. Assuming that the particles of the shell move freely under the attraction of a star of class B0, having a mass ten times that of the sun, and a radius five times that of the sun, we find for the dilution factor (neglecting radiation pressure):

$$\delta=400\,.$$

In view of the uncertainty of the masses and diameters of the stars, this value merely indicates the order of magnitude concerned.[5]

In a former paper the suggestion was advanced[6] that the bright lines are caused by recombination of free electrons with positive ions. If this is correct, we should have a maximum concentration of Fe^{++} ions in the medium in order to observe strong emission lines of Fe II. The first two ionization potentials of iron are 7.8 and 16.5 volts. The

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[1] A. S. Eddington, *The Internal Constitution of the Stars* (German ed.), p. 478, 1928.

[2] S. Rosseland, *Astrophysik auf atomtheoretischer Grundlage*, p. 232, 1931.

[3] Struve, *Astrophysical Journal*, 73, 94, 1931.

[4] R. H. Curtiss, *Publications of the Observatory, University of Michigan*, 3, 9, 1923.

[5] This revises the earlier value of δ given in *Physical Review*, 38, 1204, 1931.

[6] Struve and Schwede, *Physical Review*, 38, 1195, 1931.

excitation potentials for the upper states of the lines of *Fe* II which are usually observed are about 5.5 volts above the ground level of the singly-ionized atom. The usual ionization equations indicate a maximum concentration of Fe^{++} in the late B's. It is therefore permissible to assume, in a rough computation, that the state of ionization of the nebulous shell is approximately the same as that of the reversing layer of the star. In other words, $\rho_0 \approx \rho\delta$, where ρ_0 is the density of the reversing layer. Assuming

$$\rho_0 \approx 10^{-10} \text{ gr/cm.}^3 \ (p = 10^{-4} \text{ atm.} \ ; \ T = 20{,}000^\circ) \ ,$$

we find

$$\rho \approx 2.5 \times 10^{-13} \text{ gr/cm.}^3 \ .$$

This density is not unreasonable, as it is similar to that of the solar chromosphere.[1] A more serious difficulty arises from the fact that in a nebula of this density the temperature may not be equal to that of the photosphere.[2] Whether or not the proximity of the nebula to a B star insures the equality of these temperatures cannot be definitely stated.

The maximum concentration of Fe^{++} atoms in the spectral sequence depends, primarily, upon the value of the second ionization potential of iron, 16.5 volts. It is reasonable to expect that among the bright lines other elements having similar ionization potentials will be present. The following have been selected as being sufficiently abundant in the crust of the earth: *H* (13.5), *N* I (13.7), *O* I (13.6), *Mg* II (15.0), *Al* II (18.2), *Si* II (16.2), *Sc* II (12.8), *Ti* II (13.6), *Cr* II (16.6), *Fe* II (16.5), and *Ni* II (18.2).

N I has not been observed in Be stars. (The strongest laboratory lines are[3] 4109.98 [12], 4151.46 [12], and 4358.27 [10].) Two forbidden lines of *O* I (λλ 6300 and 6363) were observed by Merrill[4] in H.D. 50138 of spectral class B8ev. Bright *Al* II has not been seen in normal Be stars, but Merrill[5] thought that it was probably present

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[1] Rosseland, *Astrophysik*, p. 188, 1931.

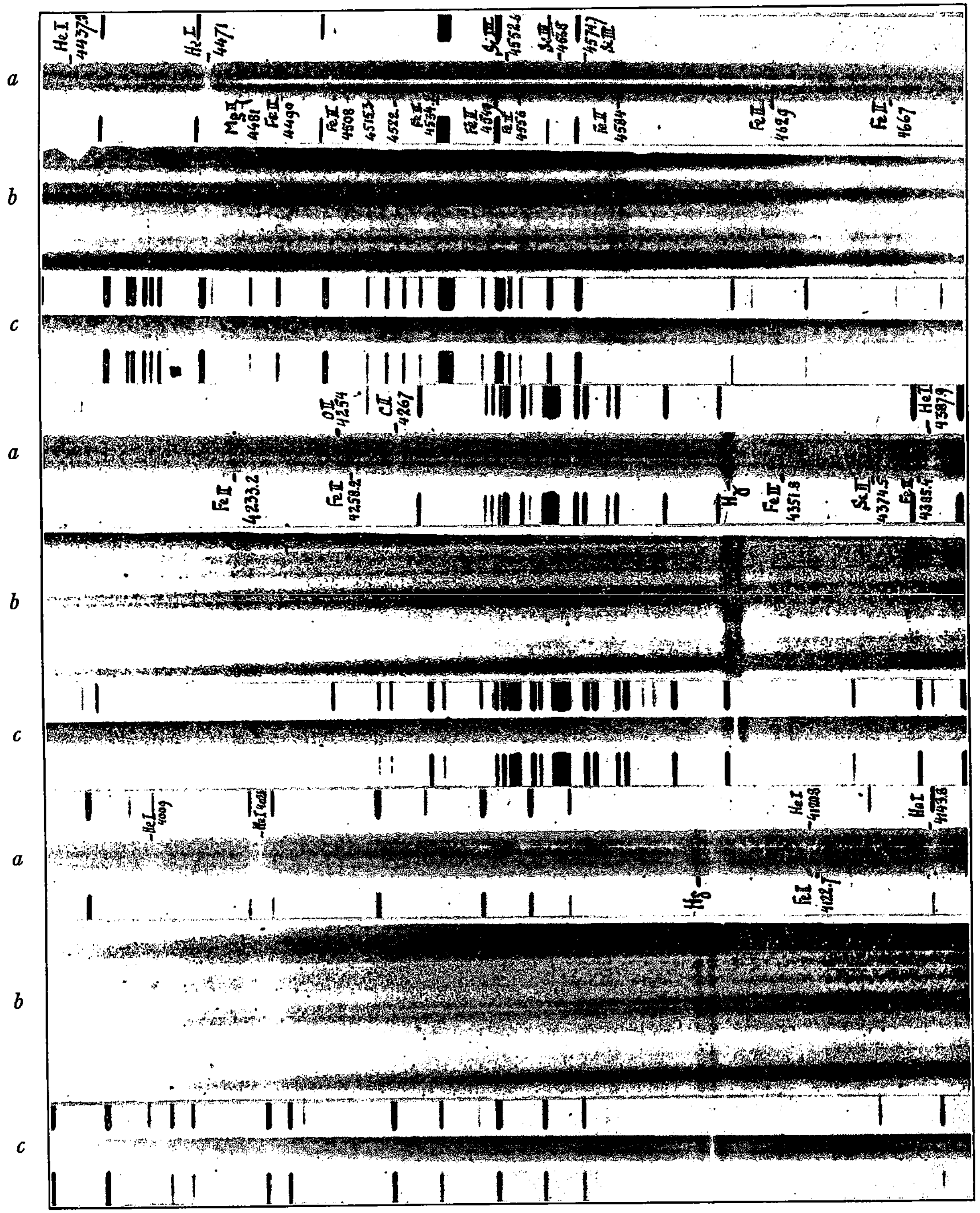
[2] Eddington, *op. cit.*, p. 477.

[3] O. S. Duffendack and R. A. Wolfe, *Physical Review*, 34, 409, 1929.

[4] *Astrophysical Journal*, 73, 348, 1931.

[5] *Ibid.*, 69, 330, 1929.

PLATE X



a) χ Ophiuchi; *b*) γ Cassiopeiae; *c*) φ Persei

in B.D. +11°4673, of the P Cygni type. Some new evidence concerning *Mg* II, *Si* II, *Sc* II, *Cr* II, and *Ni* II in normal Be's is given in Table I.

The observations used in this work were made with the single-prism Bruce spectrograph attached to the 40-inch refractor. Eastman Process emulsion was used for most of the spectrograms.

The presence of *Mg* II and *Si* II is certain; *Sc* II, *Cr* II, and *Ni* II are probable; while Merrill's forbidden lines of *Fe* II are uncertain; *Ti* II was not observed by us with certainty.

The comparatively low excitation of the emission lines in normal Be stars is thus amply confirmed. It resembles that of an average A star of high luminosity, with the following differences: (*a*) *Ti* II is absent; (*b*) *Mg* II and *Si* II are relatively faint. These peculiarities may perhaps be due to a scarcity of those particular elements in the nebulous shell. It should also be noted that one or two peculiar stars of class A are known, in which *Mg* II and *Si* II are nearly absent in absorption; 17 Leporis is a striking example.[1]

Table II contains a list of the absorption lines seen on our plates. From these we find that the spectral classes assigned in the *Henry Draper Catalogue* are approximately correct.

Table III is a summary of the line widths measured on our plates. The tabulated values represent the distances between the steepest points of the outer edges of the emission components. They are directly comparable with those of R. H. Curtiss.[2] In agreement with his results, the widths of the iron lines are strongly correlated with those of hydrogen.

However, in any given star the lines of different elements do not necessarily have the same widths. This is shown in Plate X, where *Mg* II is much wider than *H* or *Fe* II.

The general correlation between the widths of hydrogen and iron lines is so well established that there can be no reasonable doubt that the widening is due to Doppler effect. We are inclined to explain the differing line widths observed in individual stars as an effect of distance: Thus in χ Ophiuchi *Mg* II would be closer to the star than *H*. Since the widths are directly proportional to the rotational

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[1] Struve, *ibid.*, 72, 343, 1930.

[2] R. H. Curtiss, *op. cit.*, p. 1

TABLE I

BRIGHT LINES

Laboratory					χ Ophiuchi			γ Cassiopeiae			11 Camelopardalis		φ Persei	Remarks
λ	Element	Intensity	Notation	Total Excitation	λ	Int.	Width	λ	Int.	Width	Int.	Width	Int.	
3970.1	*H*	.....	$H\epsilon$	13.3	69.2	2	.....	70.0	5	.....	2	.....	1	
4067.1	*Ni* II	.....	$a^2G_5 - a^2F_4$	7.6+12.1	.....	.....	.....	66.9	3	.....	.....	.....	.....	1
4101.7	*H*	.....	$H\delta$	13.2	01.6	15	2.3	01.7	20	3.9	15	1.6	15	
4122.7	*Fe* II	.....	$b^4P'_3 - a^4F_3$	7.8+ 5.6	23.1	2	.....	23.0	2	.....	.....	.....	1	
4128.0	*Si* II	.....	$2^2D_2 - 3^2F$	8.1+12.7	.....	.....	.....	29.2	3	.....	.....	.....	.....	2
4130.0	*Si* II	.....	$2^2D_1 - 3^2F$	8.1+12.7	.....	.....	.....							
4173.5	*Fe* II	5	$b^4P'_3 - a^4D'_3$	7.8+ 5.5	73.4	3	.....	72.0	2	.....	2	.....	2	
4178.9	*Fe* II	8	$b^4P'_3 - a^4F_4$	7.8+ 5.5	78.6	3	.....	78.1	3	.....	2	.....	2	
?	?	.....	?	.....	.....	.....	.....	05.8	2	.....	.....	.....	.....	
4233.2	*Fe* II	10	$b^4P'_3 - a^4D'_4$	7.8+ 5.5	33.3	7	4.1	33.2	10	3.9	5	.....	5	
4244.0	[*Fe* II]	.....	$a^4F'_5 - a^4G_6$	7.8+ 3.1	.....	.....	.....	46.0	2	.....	.....	.....	.....	3
4244.9	[*Fe* II]	.....	$a^4F'_4 - a^4G_4$	7.8+ 3.2	.....	.....	.....							
4258.2	*Fe* II	.....	$b^4P'_2 - a^4F_2$	7.8+ 5.6	57.9	1	.....	58.0	2	.....	.....	.....	1	
4273.3	*Fe* II	1	$b^4P'_2 - a^4D_1$	7.8+ 5.6	73.0	1	.....	73.0	3	.....	.....	.....	1	
?	?	.....	?	.....	.....	.....	.....	81.2	2	.....	.....	.....	.....	
4287.4	[*Fe* II]	.....	$a^6D_5 - a^6S_3$	7.8+ 2.9	.....	.....	.....	89.0	1	.....	.....	.....	.....	4
4296.6	*Fe* II	3	$b^4P'_2 - a^4F_3$	7.8+ 5.6	96.3	2	.....	97.0	3	.....	1	.....	.....	
4303.2	*Fe* II	4	$b^4P'_2 - a^4D'_2$	7.8+ 5.6	02.9	1	.....	03.1	3	.....	.....	.....	.....	
4314.1	*Sc* II	10	$b^3F_4 - a^3D'_3$	6.7+ 3.5	.....	.....	.....	14.0	1	.....	.....	.....	.....	
?	?	.....	?	.....	.....	.....	.....	31.9	1	.....	.....	.....	.....	
4340.5	*H*	.....	$H\gamma$	13.0	39.5 41.0	50	2.6	40.5	50	.....	50	1.1	50	
4351.8	*Fe* II	10	$b^4P'_2 - a^4D'_3$	7.8+ 5.5	51.5	4	.....	51.6	6	.....	2	2.1	3	
4358.4	[*Fe* II]	.....	$a^4F'_2 - a^4G_3$	7.8+ 3.2	.....	.....	.....	59.7	1	.....	.....	.....	.....	5
4359.3	[*Fe* II]	.....	$a^6D_4 - a^6S_3$	7.8+ 3.2	.....	.....	.....							
4374.5	*Sc* II	10	$a^3F_4 - b^3F'_4$	6.7+ 3.4	75.2	2	.....	74.0	2	.....	.....	.....	.....	6
4385.4	*Fe* II	5	$b^4P'_1 - a^4D'_1$	7.8+ 5.6	85.7	2	.....	85.0	8	.....	1	.....	3	
4413.8	[*Fe* II]	.....	$a^6D_3 - a^6S_3$	7.8+ 2.9	.....	.....	.....	13.0	0	.....	.....	.....	.....	
4416.8	*Fe* II	8	$b^4P'_1 - a^4D'_2$	7.8+ 5.6	16.5	1	.....	17.0	1	.....	1	.....	.....	
4481.13	*Mg* II	.....	$3^2D_2 - 4^2F'_3$	7.6+11.6	81.2	3	5.7	81.0	3	6.6	.....	.....	.....	7
4481.33	*Mg* II	.....	$3^2D_3 - 4^2F'_3$	7.6+11.6										
4489.2	*Fe* II	10	$b^4F'_4 - a^4F_3$	7.8+ 5.6	90.5	3	.....	90.8	5	.....	2	.....	2	
4491.4	*Fe* II	8	$b^4F'_2 - a^4F_2$	7.8+ 5.6										
4508.3	*Fe* II	15	$b^4F'_2 - a^4D'_1$	7.8+ 5.6	08.1	4	.....	08.0	1	.....	3	.....	2	
4515.3	*Fe* II	15	$b^4F'_3 - a^4F_3$	7.8+ 5.6	14.8	5	.....	16.0	3	.....	3	.....	2	
4522.6	*Fe* II	10	$b^4F'_3 - a^4D'_2$	7.8+ 5.5	21.6	6	.....	22.4	5	.....	4	.....	5	
4534.2	*Fe* II	.....	$b^4F'_2 - a^4F_3$	7.8+ 5.6	35.3	4	.....	33.6	2	.....	3	.....	2	
4541.5	*Fe* II	.....	$b^4F'_2 - a^4D'_2$	7.8+ 5.6	42.0	2	.....	41.0	1	.....	1	.....	1	
4549.5	*Fe* II	20	$b^4F'_4 - a^4D'_3$	7.8+ 5.5	49.4	10	4.2	48.9	4	.....	6	.....	5	
4555.9	*Fe* II	15	$b^4F'_4 - a^4F_4$	7.8+ 5.5	55.6	7	4.0	56.7	4	.....	4	.....	3	
4558.7	*Cr* II	10	$b^4F'_{3,5} - a^4D'_4$	6.7+ 6.8	.....	.....	.....	59.0	3	.....	.....	.....	.....	
4576.3	*Fe* II	10	$b^4F'_3 - a^4D'_3$	7.8+ 5.5	76.0	2	.....	.....	.....	.....	1	.....	1	
4583.8	*Fe* II	30	$b^4F'_5 - a^4D'_4$	7.8+ 5.5	83.7	10	4.15	83.6	10	5.1	6	1.7	6	
?	?	.....	?	.....	93.3	2	.....	.....	.....	.....	.....	.....	.....	
4618.8	*Cr* II	10	$b^4F_3 - a^4D'_2$	6.7+ 6.7	.....	.....	.....	19.0	3	.....	.....	.....	.....	
4629.3	*Fe* II	20	$b^4F'_5 - a^4F_5$	7.8+ 5.5	28.3	2	.....	28.8	3	.....	1	.....	3	
?	?	.....	?	.....	.....	.....	.....	35.9	2	.....	.....	.....	.....	
?	?	.....	?	.....	45.6	4	.....	.....	.....	.....	.....	.....	.....	
4657.0	*Fe* II	.....	$a^6S_3 - a^4D'_3$	7.8+ 5.5	.....	.....	.....	56.6	3	.....	.....	.....	.....	
4666.7	*Fe* II	.....	$b^4F'_4 - a^4F_5$	7.8+ 5.5	65.2	2	.....	67.4	3	.....	1	.....	1	
4731.5	?*Fe* II	1	$a^6S - a^4D'_4$	7.8+ 5.5	.....	.....	.....	31.5	2	.....	.....	.....	.....	
4861.3	*H*	.....	$H\beta$	12.7	61.2	100	3.0	61.3	100	.....	100	.....	100	

REMARKS.—The intensities of *Fe* II have been taken from Russell and Merrill; those of *Cr* II and *Sc* II, from Kayser. In the notations we have added 1/2 to the inner quantum number *j*, in cases of even multiplicities. The wave-lengths of χ Ophiuchi have been corrected for the radial velocity as determined from the absorption lines. The bright lines observed by us in φ Persei agree with the results of W. J. S. Lockyer (*Monthly Notices of the Royal Astronomical Society*, 85, 580, 1925). Forbidden iron lines are designated [*Fe* II]. 1. The presence of *Ni* II is probable in view of the similarity of the potentials of ionization and excitation with those of *Mg* II. 2. In B.D.+11°4673 and in Z Andromedae, these lines are very weak. 3. Uncertain. May be *Ni* II (4244.8) or *Sc* II (4246.8). 4. May be a blend of several lines. 5. Uncertain. May be *Ni* II 4362 ($a^2G_5 - a^4F_4$). 6. Uncertain identification. 7. Given by Curtiss as an absorption line in γ Cassiopeiae. The excitation potentials refer to the upper states.

TABLE II

ABSORPTION LINES

Laboratory					χ Ophiuchi		γ Cassiopeiae		11 Camelopardalis
λ	El.	Int.	Notation	Total Energy of the Lower Term	λ	Int.	λ	Int.	Int.
3964.7	*He* I	4	$2^1S_0 - 4^1P_1$	20.5	……	…	65.0	1	
3995.0	*N* II	10	$1^1P_1' - 1^1P_1$	14.5+18.5	……	…	95.5	4	
4009.3	*He* I	1	$2^1P_1 - 7^1D_2$	21.1	09.1	3	09.2	8	2
4026.2	*He* I	5	$2^3P_{2,1} - 5^3D_{3,2,1}$	20.8	26.2	10	26.8	10	6
4042.0	*N* II	3	?	14.5+?	……	…	42.6	2	
{4060.6	*O* II	1	?	13.5+?	……	…	}60.0	2	
{4061.0	*O* II	1		13.5+?	……	…			
{4069.9	*O* II	9	$3^4D_2 - 3^4F_2$	13.5+24.4}	……	…	71.1	3	
{4072.2	*O* II	8	$3^4D_1 - 3^4F_2$	13.5+24.4}					
4088.9	*Si* IV	10	$2^2S_1 - 3^2P_2$	8.1+16.3+31.6+23.5	……	…	88.8	3	
4116.0	*Si* IV	8	$2^2S_1 - 3^2P_1$	8.1+16.3+31.6+23.5	……	…	16.0	1	
4120.8	*He* I	3	$2^3P_{2,1} - 5^3S_1$	20.8	20.6	4	20.5	6	3
4132.8	*O* II	6	$3^4P_1 - 3^4P_2'$	13.5+24.8	……	…	33.0	4	
4143.8	*He* I	2	$2^1P_1 - 6^1D_2$	21.1	43.7	5	44.1	6	3
4153.3	*O* II	6	$3^4P_2 - 3^4P_3'$	13.5+25.7	53.7	2			
4169.0	*He* I	1	$2^1P_1 - 6^1S_0$	21.1	69.3	1	……	…	1
4254.0	*O* II	8	$a^2G_{5,4} - a^2H_{6,5}$	13.5+31.3	54.2	2			
{4267.0	*C* II	…	$3^2D_3 - 4^2F_{4,3}$	11.3+17.9}	66.8	3	……	…	1
{4267.3	*C* II	…	$3^2D_2 - 4^2F_{4,3}$	11.3+17.9}					
4366.9	*O* II	7	$3^4P_3 - 3^4P_2'$	13.5+23	67.0	1			
4387.9	*He* I	3	$2^1P_1 - 5^1D_2$	21.1	87.8	5	88.0	4	3
4437.5	*He* I	1	$2^1P_1 - 5^1S_0$	21.1	36.8	2	37.6	1	
4447.0	*N* II	10	$2^1D_2' - 1^1D_2$	14.5+20.3}	……	…	48.0	1	
4448.2	*O* II	6	$a^2F_4 - b^2F_4'$	13.5+27.4}					
4471.5	*He* I	6	$2^3P_{2,1} - 4^3D_{3,2,1}$	20.8	71.3	10	71.1	3	6
4481.2	*Mg* II	…	$3^2D_{2,3} - 4^2F_3'$	7.6+11.6	……	…	……	…	2
4552.6	*Si* III	10	$2^3S_1 - 3^3P_2$	10.3+16.3+19.5	52.2	4	uncertain		2
4567.9	*Si* III	9	$2^3S_1 - 3^3P_1$	10.3+16.3+19.5	67.9	3	……	…	1
4574.7	*Si* III	7	$2^3S_1 - 3^3P_0$	10.3+16.3+19.5	75.1	1	……	…	1
4630.5	*N* II	10	$1^3P_2' - 2^3P_2$	14.5+18.5	……	…	30.0	1	
{4638.9	*O* II	6	$3^4P_1 - 3^4D_2$	13.5+21.7}	……	…	40.2	3	
{4641.8	*O* II	9	$3^4P_2 - 3^4D_3$	13.5+21.7}					
4643.1	*N* II	5	$1^3P_2' - 2^3P_1$	14.5+18.5	……	…	44.0	1	
4650.8	*O* II	6	$3^4P_1 - 3^4D_1$	13.5+21.7	……	…	50.7	4	
4673.7	*O* II	3	$3^4P_2 - 3^4D_1$	13.5+21.7	……	…	74.3	2	
4685.8	*He* II	…	$3^2D_3 - 4^2F_4$	24.5+48.1	……	…	86.0	2	
{4713.14	*He* I	3	$2^3P_{2,1} - 4^3S_1$	20.8}	……	…	13.0	2	
{4713.37	*He* I	3	$2^3P_0 - 4^3S_1$	20.8}					

velocities and since the latter are inversely proportional to the square roots of the distances:

$$V^2=\frac{k^2M}{r},$$

we infer that for χ Ophiuchi

$$\frac{r(Mg\ \text{II})}{r(H)}=\left(\sqrt{\frac{2.7}{5.7}}\right)^{2}=\cancel{0.69}\ 0.2.$$

This interpretation is supported by the fact that in χ Ophiuchi and in γ Cassiopeiae the central depression of *Mg* II 4481 is much more conspicuous than in the lines of *H* or of *Fe* II. This is probably due to the fact that the ratio: Size of star/size of nebula, is greater for *Mg* II than for *H* and that, consequently, absorption in front of the star and obstruction of the nebula back of it are relatively more conspicuous in *Mg* II than in *H*.

TABLE III

SUMMARY OF LINE WIDTHS

Star	Hβ	Hγ	Hδ	Fe II	Mg II
11 Camelopardalis	………	1.1 A	1.6 A	1.9 A	………
7 χ Ophiuchi	3 A	2.6	2.3	4.1	5.7 A
γ Cassiopeiae	………	………	3.9	4.5	6.6

The effect described above seems to be a counterpart of the well-known observation that the images of planetary nebulae photographed in the lines of different elements are not always the same.

The widths of the bright lines of *Si* II could not be measured because of blending, but apparently they resemble the iron lines.

Interesting differences have been observed in the shapes of the lines of φ Persei. The hydrogen lines consist of two bright components with a deep central absorption. Between the emission components and the deep absorption line there seems to be a narrow region (or step) where the intensity is similar to that immediately outside the emission. The lines of *Fe* II, while also double, show no trace of central absorption: the residual intensity in the center is nearly the same as that of the continuous spectrum. Apparently *Fe* II does not appreciably absorb the light of the photosphere.

There are some differences between our estimated intensities for χ Ophiuchi and those obtained in the laboratory. Thus, according to Russell[1] and to Merrill,[2] *Fe* II 4508 ($b^4F_2'-a^4D_1'$) is stronger than *Fe* II 4523 ($b^4F_3'-a^4D_2'$), while the opposite is true in the star. Since these lines are close together, it is not possible to attribute this to the photographic emulsion or to the superposition of the continuous spectrum. The question of blends has not been investigated. The intensities of the absorption lines are normal.

II. CLASSIFICATION OF BRIGHT-LINE SPECTRA

If the bright lines in Be stars originate in a distinct shell not connected with the reversing layer of a star, it will be desirable to devise a classification for the emission spectra which is independent of that of the absorption lines. There is no theoretical reason for a one-to-one correspondence of the two spectra. The spectrum of the reversing layer is defined by its temperature (T) and density (ρ_0); that of the gaseous shell depends upon this same temperature (T), upon the density of the shell (ρ) and upon the dilution factor (δ). There is no a priori reason to suppose that the product $\rho\delta$ stands in any definite relation to ρ_0. In an isothermal nebula $\rho \propto r^{-2}$ at great distances from the center,[3] and $\rho\delta \rightarrow$Const. This may explain why the bright-line spectrum of any given star usually corresponds to a very definite stage of excitation and does not contain a superposition of many different stages. But the absolute value of $\rho\delta$ may not be the same in all stars of the same spectral subdivision, nor is it necessary for the ratio $\rho\delta/\rho_0$ to be constant all along the spectral sequence.

Whatever the theory of bright lines may be, they are in some way excited by the radiation of the photosphere. It is therefore appropriate to arrange the bright-line spectra in order of spectral class as given by the absorption lines. This has been done in Table IV. No attempt was made to include all "normal" Be stars. Only those were included for which detailed observations were available in the literature.

Within any one subdivision there is a marked similarity in the emission spectra. There are only two very discordant stars: the companion of *o* Ceti, and β Lyrae. The first may be safely disregarded, for its spectral type was determined by Joy from the distribution of energy in the continuous spectrum. The second case is

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[1] *Astrophysical Journal*, 64, 194, 1926; *Contributions from the Mount Wilson Observatory*, No. 318, 1926.

[2] *Astrophysical Journal*, 69, 353, 1929.

[3] Eddington, *op. cit.*, p. 489.

TABLE IV

BRIGHT LINES IN STARS OF CLASSES Oe AND Be

Star	Emission Lines	Remarks
	Spectrum O6e	
22 λ Cep	*He* II, *N* III	*He* II 4686 is broad and double; its width is 11 A; the absorption lines are broad; *N* III 4638 is also broad and double
	Spectrum O7e	
29 CMa	*He* II, *N* III	On our plates *He* II 4686 is bright and narrow (4 A), the absorption lines are narrow
	Spectrum O8e	
B.D.+6°1309	*H*, *He* II, *He* I	*H* emission broad (25 A) with strong central absorption. Absorption lines: *He* I, *Si* IV, *N* II, *Mg* II
	Spectrum B0e	
γ Cas	*H*, *Fe* II, *Mg* II, *Si* II [*Fe* II]?, *Ni* II, *Sc* II, *Cr* II? (*He* I)	Absorption lines: *He* I, *He* II, *O* II, *N* II, *Si* IV, *Si* III?; of the helium lines D3 is bright but faint
φ Per	*H*, *Fe* II, *Ti* II?, *Ca* II?	*H* lines have strong central absorptions; all bright lines are double; *Mg* II is absent
	Spectrum B1e	
H.D. 163181	*H*, *He* I	Absorption lines *H*, *He* I, *N* II, *Mg* II, *O* II, *Si* III, *Si* IV
52 π Aqr	*H*, *Fe* II	Bright *Fe* II fainter than in φ Persei
	Spectrum B2e	
H.D. 45677	*H*, *Fe* II [*Fe* II]	Bright *H* very strong, double, variable; *Fe* II narrow, single. Strongest forbidden [*Fe* II]: 4244, 4287, 4414; *Mg* II only in absorption
κ CMa	*H*, *Fe* II	Bright *H* double, variable
−22°1874	*H*, *Fe* II	
μ Cen	*H*, *Fe* II	Bright lines variable
B.D.−6°1391	*H*, *Fe* II	*Fe* II faint
H.D. 20336	*H*, *Fe* II	*Fe* II faint

TABLE IV—*Continued*

Star	Emission Lines	Remarks
	Spectrum B3e	
31 Peg	*H*	*Fe* II absent, although bright *H* fairly strong
11 Cam	*H*, *Fe* II	
χ Oph	*H*, *Fe* II, *Mg* II, *Sc* II?	
β Mon	*H*, *Fe* II	
ω CMa	*H*	
25 Ori	*H*, *Fe* II	
ζ Tau	*H*, *Fe* II	
r Pup	*H*, *Fe* II	
δ Cen	*H*, *Fe* II	
ι Ara	*H*, *Fe* II	*H* double
υ Cyg	*H*, *Fe* II	*H* double
	Spectrum B5e	
ψ Per	*H*, *Fe* II	*H* and *Fe* II lines double
27 CMa	*H*	Variable bright, unsymmetrical *H* lines
κ Dra	*H*, *Fe* II	Variable
β Pis	*H*	Double
β Lyr	*He* I, *H*, *Ca* II, *Mg* II	Interpretation uncertain. May not belong to B5 component
κ^1 Aps	*H*, *Fe* II	*H* double, variable
	Spectrum B8e	
H.D. 50138	*H*, forbidden *O* I	Variable *H*; [*O* I]: λλ 6300, 6363. Absorption lines: *He* I, *Fe* II, *Ca* II, *Na* I, *Mg* II?
Companion of *o* Cet	*H*, *He* I, *Ca* II, *Fe* II, *Ti* II?	Bright *H* broad (9 A) with absorption centers. No absorption lines visible except those accompanying the *H* lines

somewhat more puzzling; but here, too, there is considerable uncertainty as to the origin of the bright lines. Otherwise, there is a definite progression in the state of excitation of the emission lines which runs in the same direction as that of the absorption lines. In the B's there is a lag corresponding to more than an entire spectral class. The most striking feature, however, is an apparent discontinuity between Boe and O9e. The presence of bright *He* II 4686 in B.D.+6°1309, 29 Canis Majoris, and λ Cephei, shows that for the O's the lag is much smaller. The relative infrequency of emission lines of *He* I is conspicuous. There are indications that D3 appears more frequently in emission than any of the *He* I lines in the violet or blue regions. It is possible that some of the discordances in the relative intensities may have their explanation in a tendency of bright lines to favor certain electronic transitions.

Bright *He* II 4686 in λ Cephei is double and very broad, while in 29 Canis Majoris it is narrow. The absorption lines are also broad in λ Cephei and narrow in 29 Canis Majoris. This agrees with our correlation between widths of emission and absorption lines.

The appearance of bright lines of *Fe* II and of other elements depends in a large measure upon the intensities of the bright hydrogen lines. Thus, failure to observe *Fe* II in a B3 star does not necessarily indicate that *Fe* II is missing, but may simply mean that all bright lines are weak. If we allow for a considerable dispersion in the total intensities of all lines, there is a suprising similarity in the bright lines of any given spectral subdivision. We have tried to ascertain whether the ratios of the intensities of the lines of *H* to those of *Fe* II are really constant within any given spectral subdivision. A very good plate of 31 Pegasi, on Process emulsion, fails to show any trace of *Fe* II, although its absorption lines are similar to those of χ Ophiuchi. But the bright hydrogen lines are appreciably stronger in χ Ophiuchi, and the test is consequently not conclusive. A comparison of 31 Pegasi with 11 Camelopardalis is more instructive. In these two stars the total intensities of the Balmer lines are not very different; but the iron lines are fairly strong in 11 Camelopardalis, while they are absent in 31 Pegasi. The absorption lines are very similar in these two stars.

Although it is probable that there exist small differences in the relative intensities of lines of different elements, it is safe to say that the effective temperature of the star is the most important factor in defining the character of the emission spectrum. We should, therefore, conclude that $\rho\delta$ remains approximately constant within each subdivision, and it is therefore permissible to retain, for the emission lines, the usual Harvard classification, provided we remember that there is a difference in the effective excitations of bright and dark lines and that this difference is probably itself a function of spectral class, being small for the O's and comparatively large for the B's.

A somewhat similar classification was suggested some years ago by Miss Payne.[1]

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[1] *Harvard Observatory Bulletin*, No. 855, 1928.

III. A NEW Be STAR

60 Cygni ($\alpha\ 20^h57^m.7\ \delta\ +45°46'$, mag. 5.2, Sp. B3)

The line $H\beta$ is variable in this star. A description of the Yerkes plates is given in the accompanying tabular matter.

Date	Time	Description of $H\beta$
1919 May 12.......	21^h20^m G.M.T.	Absorption very weak; faint, widely spaced emission components probably present
Sept. 1.......	14 27 G.M.T.	Same
1920 June 7.......	20 07 G.M.T.	Same
1930 July 29.......	4 52 U.T.	Normal strong absorption line
1931 Oct. 22.......	1 56 U.T.	Absorption rather weak

Dr. Merrill writes concerning this star:[1] "$H\beta$ is nondescript on several plates, but on one taken by Mr. Joy on 1917 October 3, it appears to have two faint, widely-separated bright components."

IV. VARIATIONS IN THE SPECTRA OF Be STARS

31 Pegasi ($\alpha\ 22^h16^m.6\ \delta\ +11°42'$, mag. 4.9, Sp. B3p)

This is a well-known Be star, the spectrum of which has been described by Merrill.[2] It appears from the Yerkes observations, in the accompanying table, that the bright lines show large variations in total intensity.

DATE	TIME	DESCRIPTION	
		Bright $H\beta$	Bright $H\gamma$
1908 Oct. 16....	16^h35^m G.M.T.	Single, very strong	Single, or narrow double, fairly strong
1910 Sept. 30....	14 33 G.M.T.	Same	Same
Oct. 14....	15 02 G.M.T.	Same	Same
1918 Aug. 26....	18 06 G.M.T.	Weak, very narrow double	Weak
Sept. 16....	17 50 G.M.T.	Weak single, or very narrow double	Weak
1928 Aug. 29....	8 10 U.T.	Very strong, single	Strong, very narrow double or single
Sept. 20....	6 07 U.T.	Same	Same
1931 June 15....	8 52 U.T.	Same	Same
June 17....	9 01 U.T.	Probably slightly weaker than in 1928	Probably slightly weaker than in 1928

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[1] Private communication.

[2] *Lick Observatory Bulletin*, 7, 173, 1913.

31 *o* Aquarii ($\alpha\ 21^h58^m.1\ \delta\ -2°38'$, mag. 4.7, Sp. B5p)

This is also a well-known Be star,[1] having narrow bright hydrogen components superposed over wide absorption lines. Our plates show that *o* Aquarii belongs to that small group of Be stars which have sharp and probably variable absorption lines of *Fe* II. The lines of *He* I and of *Mg* II are very broad and hazy and show no variation. A description of the Yerkes plates is given in the accompanying table.

Date	Time	Description
1908 Oct. 9.......	12^h25^m G.M.T.	*Fe* II sharp and fairly strong absorption lines; *He* I and *Mg* II very broad and faint
1910 July 8.......	20 43 G.M.T.	Same
Aug. 27.......	15 39 G.M.T.	Same? (poor plate)
Sept. 19.......	14 00 G.M.T.	Same
1928 Aug. 29.......	5 06 U.T.	*Fe* II absent or very faint
Sept. 17.......	3 03 U.T.	*Fe* II faintly visible
1930 June 27.......	8 13 U.T.	*Fe* II extremely faint
1931 Oct. 10.......	0 29 U.T.	Same

There were no appreciable changes in the emission lines of hydrogen. The simultaneous existence in the same spectrum of wide and diffuse lines of *He* I and *Mg* II and of narrow lines of *Fe* II is very unusual; there are two or three other stars, however, which show the same phenomenon; it is present in ϵ Capricorni, described below, and perhaps also in H.D. 45910,[2] except that the latter has hydrogen lines of the P Cygni type, while in *o* Aquarii they are normal, double, bright lines.

The fact that there are several stars of this kind makes it seem improbable that we are dealing with a superposition of two separate stellar spectra not resolved on the slit of the instrument.[3] The broad lines of *He* I and *Mg* II are of exactly the type which we have ascribed to rapid axial rotation.[4] We are therefore forced either to abandon

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[1] *Ibid.*

[2] Merrill, *Publications of the Astronomical Society of the Pacific*, 35, 303, 1923; J. S. Plaskett, *ibid.*, p. 145; J. S. Plaskett, *Publications of the Dominion Astrophysical Observatory* (Victoria), 4, 1, 1927. Other stars exhibiting similar features were found by Merrill, *Astrophysical Journal*, 72, 98, 1930.

[3] See also J. S. Plaskett's discussion of υ Sagittarii, *Publications of the Dominion Astrophysical Observatory* (Victoria), 4, 1, 1927.

[4] Elvey, *Astrophysical Journal*, 71, 221, 1930; Struve, *ibid.*, 72, 1, 1930.

the rotational hypothesis of the broadening of stellar absorption lines or to seek a new explanation for the origin of the narrow lines. The evidence in favor of the rotational explanation of dish-shaped lines is so strong that we accept the latter alternative.[1]

While we have hardly enough observational material to develop a complete theory, it is possible to affirm that our present ideas concerning the origin of some of the stellar absorption lines must be modified. In the past we have supposed that all absorption takes place within the narrow domain of the reversing layer.[2] We now believe that the strong violet absorption lines in Novae and in stars of the P Cygni type originate in an expanding nebula which surrounds the star. Similarly, we are willing to attribute the narrow and deep central absorptions in some Be stars to gases which are far removed from the photosphere. Is it not possible that the narrow metallic lines in *o* Aquarii, *ε* Capricorni, etc., are also produced in a rotating nebulous shell surrounding the star, and that they are therefore similar in nature to the central absorptions of the hydrogen lines described on page 169 for *φ* Persei and also observed in *o* Aquarii? Since such absorption lines would be formed by those parts of the nebulous shell which are directly in front of the star, it is clear that a rotating shell (or ring) will give rise to relatively narrow absorption lines and to broad emission lines; the star itself, on the other hand, would produce "dish-shaped" absorption lines of *He* I and of *Mg* II.

39 *ε* Capricorni (α $21^{h}31^{m}.5$ δ $-19^{\circ}55'$, mag. 4.7, Sp. B5p)

Variable lines of *Fe* II and of *H* in this star have been known since 1897.[3] Our plates show a spectrum distinctly resembling that of *o* Aquarii: the hydrogen lines have variable emission components, the *α* Cygni lines are at times strong and narrow, while the lines of *He* I and of *Mg* II are very diffuse and broad. Our first plate, taken September 17, 1915, $16^{h}2^{m}$ G.M.T., shows a faint emission component on the violet side of a strong and very narrow central absorption in the normal position of $H\beta$. The absorption lines of *Fe* II and *Cr* II are fairly strong and narrow, while those of *Ti* II are faint and narrow. On the succeeding plates, taken on July 15, 1930, $6^{h}47^{m}$ U.T., and on various dates between May 14, 1931, and October 10, 1931, the hydrogen lines have very little (if any) emission, showing only the narrow central absorption superposed upon a broad normal absorption line. *He* I and *Mg* II are conspicuously dish-shaped, while *Fe* II can be barely seen as faint narrow lines.

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[1] Our reasons for believing that broad absorption lines of all elements are caused by rotation, have been explained in various papers. The evidence is so convincing that it does not seem reasonable to doubt it on the basis of the observations of the few peculiar Be stars with sharp *Fe* II lines.

[2] Excepting the lines of interstellar origin.

[3] *Harvard Annals*, 28, 183, 1897; *Lick Observatory Bulletin*, 7, 72, 1913.

V. NOTE ON THE SPECTRUM OF 17 LEPORIS

This spectrum has been described previously.[1] The lines of *Ti* II, *Sc* II, *Fe* II, *Fe* I, etc., are variable in intensity and structure. At times they show a tendency to be narrow doubles. *Mg* II 4481 is somewhat broader and more diffuse than the other lines, and does not vary in intensity; together with the lines of *Si* II, 4128 and 4131, it is unusually weak for a star which otherwise displays the characteristics of a supergiant.

The hydrogen lines consist of normal broad absorption lines over which there are unsymmetrically superposed strong and narrow absorption cores. On several plates $H\beta$ shows a faint emission line on the red side of its core.

If the presence of a normally placed emission line with strong violet absorption is to be regarded as typical for stars of the P Cygni type, 17 Leporis would belong to that class. Measurement of the radial velocity on one plate (November 28, 1930, $6^{h}12^{m}$ U.T.) gave the following approximate results:

Mg II (4481)	+14 km/sec.
Fe II and *Ti* II	−64 km/sec.
$H\gamma$, $H\beta$ (absorption)	−93 km/sec.
$H\beta$ (emission)	+61 km/sec.

While 17 Leporis shows little in common with P Cygni, except the structure of the hydrogen lines, it resembles in certain respects the peculiar spectrum of H.D. 45910.[2] In the latter, the bright lines of

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[1] Struve, *Astrophysical Journal*, 72, 343, 1930.

[2] J. S. Plaskett, *Publications of the Dominion Astrophysical Observatory* (Victoria), 4, 18, 1927.

H are more pronounced than in 17 Leporis. Furthermore, in H.D. 45910 "emission at the enhanced iron lines 4233, 4352, 4549, 4584, 4922, 5015, incipient or moderately strong, is often present, which, on four occasions has developed into a complete enhanced absorption spectrum: an almost exact replica of *α* Cygni."[1]

Here, as in the case of *o* Aquarii and of *ε* Capricorni, the question might be asked whether the variable *α* Cygni lines should not be attributed to gaseous shells around the stars, rather than to the reversing layers.

VI. THE ROTATIONAL HYPOTHESIS OF THE ORIGIN OF BRIGHT LINES

The observational evidence that has led to our acceptance of the rotational hypothesis for the origin of bright lines in Be stars, is summarized as follows:

1. The total widths of the bright lines in nearly every case exceed those expected on theoretical grounds for a quiescent gas. Laboratory lines produced under low pressure and having total energies comparable to those of the stellar lines are invariably much narrower.

2. The objection might be raised that the stellar lines may not originate under low pressure; but this is eliminated by the fact that laboratory lines broadened by pressure show wide wings similar to the wings of stellar absorption lines which are broadened by Stark effect. No such wings are observed in the emission lines of Be stars: their contours have steep outer gradients and are frequently flat, or even depressed, at the top.

3. The theoretical emission coefficient for a quiescent gas is proportional to $1/(\lambda-\lambda_0)^2$ (in the wings), and the contour should be given by Const. $N/(\lambda-\lambda_0)^2$, where N is the total number of emitting atoms. We should therefore expect a definite correlation between line width and total intensity, but none is observed. The great widths of faint emission lines strongly suggest that we are dealing with Doppler effect.

4. The total widths of the bright lines range from about 1 to 10 A. There is no definite correlation with spectral type or temperature, nor with absolute magnitude or pressure.

5. There is, however, a very definite correlation between the widths of bright lines and of absorption lines which are not affected by emission: narrow emission lines of *H* always occur in stars with fairly sharp absorption lines of *He* I, *Mg*, II *Si* III, etc. (e.g., *β* Piscium, 11 Camelopardalis, *χ* Ophiuchi, 31 Pegasi, etc.); broad emission lines are invariably observed in stars having exceedingly diffuse and shallow absorption lines suggestive of rapid axial rotation (e.g., *φ* Persei, *π* Aquarii, *β* Monocerotis, *ψ* Persei). If the dish-shaped absorption lines are due to rotation, this establishes a connection between radial component of rotational velocity and width of emission line.

6. It might be urged that the shallow contours of the absorption lines of *He*, etc., in many Be stars are due to incipient emission. This is not probable, however, because all stars that have narrow hydrogen emission lines show normal lines of helium without any trace of incipient emission.

7. The widths of the emission lines of *H* and of *Fe* II are proportional to the wave-lengths—in agreement with the Doppler effect.

8. The widths of the emission lines of *Fe* II, *Si* II, etc., are strongly correlated with those of *H*, although in any given star they are not necessarily the same. In *γ* Cassiopeiae the contours determined by Higgs show that the widths of *Fe* II lines are nearly identical with those of *H*. Numerous measures by R. H. Curtiss also establish the fact for this and for other stars. No physical theory as yet proposed explains this correlation. It is, however, in agreement with the mechanical hypothesis of rotation.

9. The intensities of the Balmer emission lines agree with the hypothesis that they are produced by recombination. This suggests that they originate in a nebulous shell, sufficiently far away from the photosphere to permit large deviations from thermodynamic equilibrium.

10. The doubling of many emission lines is easily explained by the mechanism of rotation. This is also true of flat-topped contours of single emission lines.

11. The discovery of forbidden lines of *Fe* II and of *O* I by Merrill might add some weight to the hypothesis of a nebulous shell, but it is not certain whether the peculiar stars of Merrill are similar to the normal Be stars.

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[1] *Ibid.*

12. Emission lines predominate in classes B and O (if we exclude the peculiar spectra of late-type variables). This agrees with the fact that rapid axial rotation is most frequently observed in these classes.

13. The pronounced difference in the excitation conditions for bright and dark lines of the same stars (see section 1) has a logical explanation in the mechanism of recombination. It would remain wholly unexplained if the origin of the emission lines were placed in the reversing layer.

14. There might be some doubt that a star of spectral class B3 or B5 possesses enough radiant energy beyond the limit of the Lyman series to render a nebula visible. It is generally believed that stars of $T=30,000^\circ$ can excite an ordinary gaseous nebula to visibility. Computation[1] shows that the ratio of energy involved in a star of $T=30,000^\circ$ to that of one having $T=15,000^\circ$, is approximately 400 to 1. It is clear, therefore, that the cooler star might not render a diffuse nebula visible. In a Be star, however, the nebula is practically a point-source, and it is highly probable that it would show in the spectrum. To illustrate this, imagine two large diffuse nebulae like that of Orion. Let one be excited to visibility by a star of $T=30,000^\circ$ while the other surrounds a star of $T=15,000^\circ$. According to our computation, the total luminosities of the two nebulae would be in the ratio of 400 to 1. But if one nebula is large while the other is 400 times more compact, we should observe the same line intensities in the spectrograph. Apparently there is no theoretical reason to doubt the possibility of hydrogen emission in a nebulous shell, produced by the mechanism of photo-electric ionization and recombination.

VII. OBJECTIONS TO THE ROTATIONAL HYPOTHESIS

In a recent paper Misses C. H. Payne and G. Maulbetsch[2] have raised several objections to the rotational hypothesis of bright lines. We shall discuss these here in the order in which they are given in their paper.

1. The widths of the broad hydrogen absorption lines which form the background of the bright lines were measured by the authors on the original spectrograms and plotted against wave-length. The result is a straight line indicating that width is proportional to λ. The slope of the line, however, corresponds to the absurd velocity of 2000 km/sec., and the intercept on the y-axis of the extrapolated straight line is negative, instead of positive as required by Doppler-broadening. The helium lines, on the contrary, give a small slope which corresponds to fairly reasonable rotational velocities.

The test is based upon two assumptions: (*a*) that within any one spectral series the original absorption lines not broadened by rotation have the same contours; and (*b*) that, in the process of measuring line widths, settings are made upon points having equal percentage of absorption, irrespective of the structure of the line. Both assumptions are subject to doubt. The first one, especially, is known to be incorrect, for normal hydrogen lines are broadened by Stark effect and the latter depends upon serial number. Therefore, even if assumption (*b*) were correct, the data of Miss Payne and Miss Maulbetsch would merely show that the dark hydrogen lines are much more affected by causes other than rotation—a result in harmony with earlier investigations.

2. Payne and Maulbetsch also assert that the widths of the helium lines disagree with the rotational hypothesis. But within the errors of measurement their helium line widths agree well with the theoretical slopes drawn by them for velocities of 250 and 500 km/sec. The fact that slightly different results are obtained for different series proves that even for helium the assumption of equal original contours is incorrect—again in agreement with expectation. Aside from this, there is no real disagreement: on the contrary, it seems to us that their measurements agree well with the rotational hypothesis.

3. Measurements of line widths are not sufficiently sensitive for establishing rotational velocities of less than 500 km/sec. Thus, it would be difficult to choose between the theoretical lines for 250 and 500 km/sec.

4. Our objection raised in (1) to the use of the hydrogen lines

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[1] Struve and Schwede, *op. cit.*, p. 1195.

[2] C. H. Payne and G. Maulbetsch, *Harvard Observatory Circular*, No. 364, 1931. There is a misunderstanding on page 2 (last paragraph) of this circular. The rotational velocities in Struve's paper (*Astrophysical Journal*, 73, 94, 1931) were estimated from the appearance of the absorption lines, and not from the bright lines, as stated by Payne and Maulbetsch. The fact that these velocities are correlated with the widths of the emission lines led to the rotational hypothesis.

refers also to the result of Payne and Maulbetsch for the Pleiades. The helium lines give no evidence of unusual or equal velocities. The existence of bright lines in many members of the Pleiades would in itself suggest (on the basis of the rotational hypothesis) that these stars rotate rapidly. But unless all of them have emission lines of exactly the same width, there is no evidence that the rotational components in the line of sight are equal.

5. The tendency of Be stars to be more luminous than normal B's is in agreement with the rotational hypothesis: if the nebulous shell results from equatorial ejection of matter, it is clear that for constant equatorial velocity a star of small surface gravity would eject more than one of large gravity.

6. The tendency of emission lines to be more frequent in early B stars than in late may be connected with the general tendency of early-type stars to have the more dish-shaped lines (or faster rotations).

7. The remark that "narrow lined B stars are absolutely brighter than hazy lined bright line B stars, as illustrated in *h* and χ Persei, NGC 6231 and the cluster in Carina" does not find a ready explanation in the rotational hypothesis, but may perhaps not be contrary to it.

8. There are, as Payne and Maulbetsch remark, many B stars with high rotational velocities which do not show emission lines; V Puppis is an example. A possible explanation of this effect we owe to Dr. C. T. Elvey. The formation of a ring by rotational instability must depend not only upon the linear equatorial velocity but also upon surface gravity: a giant might be expected to shed matter at lower velocities than a dwarf. The same argument has been already used in (5). It is also possible that the companion in a *very close* system would break up any nebulous shell.

9. The occurrence of *Fe* II in the spectra of stars of early class B has been explained in section I as a consequence of the mechanism of recombination.

10. The rotational hypothesis does not provide a simple explanation for the frequent variations in the relative intensities of the emission components. It is possible that the period of the variation in intensity is equal to the orbital period in a binary system, the presence of the secondary causing a lack of symmetry in the distribution of the nebula around the primary. It should be remembered in this connection that several Be stars are known to be binaries with fairly long periods, e.g., β Lyrae and φ Persei. Another hypothesis involving a mechanism of rotation and pulsation has recently been advanced by D. B. McLaughlin.[1]

We believe, in spite of these possible explanations, that the frequent variation of the bright lines constitutes the most vulnerable point of the rotational hypothesis.

11. The preceding paragraph refers also to those Be stars which have completely lost (Pleione, μ Centauri) or regained their emission lines for long periods of time. We doubt that it would be easier to meet these difficulties with a "physical" explanation of the emission lines.

VIII. CONCLUSIONS

In forming an opinion concerning the origin of bright lines in Be stars, it is best to consider separately two questions: (*a*) "Do we know that dish-shaped absorption lines are caused by rotation?" and (*b*) "Is it proved that the widening of emission lines is due to the rotation of a nebulous ring or shell?"

A complete answer to our first question has been given in other papers. It is certain that rapid axial rotation does exist in many stars and that it has an appreciable effect upon the line contours of such stars as Algol, V Puppis, W Ursae Majoris. For the stars in general, our evidence is of a more statistical nature; and while it seems probable that rotation is the most important cause of the broadening of lines which are not subject to Stark effect, it is not possible to prove that this is true for every individual star.

Our answer to the second question is closely connected with that given to the first one. In fact, the rotational hypothesis of the bright lines rests upon the correlation of emission and absorption line widths and upon the assumption that dish-shaped absorption lines are caused by rapid rotation. It must be admitted that this correlation is based upon a comparatively small amount of material, and future work on this subject should be directed toward testing it with

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[1] D. B. McLaughlin, *Publications of the American Astronomical Society* (Delaware meeting), 7, 31, 1931.

the aid of more extensive material. But granted the correlation, and granted that our assumption is correct, there is no escape from the conclusion that the broadening of the emission lines is due to rotation.

This does not yet prove that their origin is not in the reversing layer.[1] But the facts accumulated in section VI make it seem probable that these lines originate in a nebulous shell or ring. Perhaps the best evidence is obtained from the widths of the emission lines. It is not at present possible to compare directly the rotational velocities derived from the absorption lines with those resulting from the widths of the emission lines. But in two stars we found conclusive proof that the width of the bright *Mg* II line was almost twice that of the hydrogen lines. This could not be the case if both elements were in the same layer. Unless we abandon rotation altogether, we must assume that the bright lines originate in nebulous shells or rings and that the effective distances of the various elements from the photosphere are not exactly the same.

We are under great obligation to Professor H. N. Russell for valuable suggestions and criticisms.

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[1] A very simple method suggests itself for testing whether a bright line originates in the reversing layer or above it. Consider a member of a multiplet which happens to fall upon the wing of a strong absorption line: for example, upon one of the hydrogen lines. If the bright line originates in the reversing layer, its intensity will be cut down by the opacity which is caused by the wing of the hydrogen line. On the other hand, if the bright line originates above the reversing layer, its intensity should be normal. In order to make this test, the intensities should be measured on some absolute scale and freed from the effect of overlapping with the continuous background (see Struve and Schwede, *op. cit.*, p. 1198; Struve, *Zeitschrift für Astrophysik* [in press]). The same effect, in its application to absorption lines, has been observed for stellar and interstellar *Ca* II lines, and has been found useful in distinguishing between these two types of lines (Unsöld, Struve, and Elvey, *Zeitschrift für Astrophysik*, 1, 324, 1930). Among the stars observed by us, we have not been able to find a suitable bright line, free of blends, that could be used for this test.