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THE SPECTRUM OF P CYGNI

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ABSTRACT

Measurements are given of 158 absorption lines, of which 24 are unidentified, and of 63 emission lines, of which 15 are unidentified.

The *H* lines are found to be relatively sharp and strong, their contours suggesting the absence of Stark broadening and the presence of turbulence broadening. The pressure in the *H* atmosphere must be very low.

The intensities of the absorption lines suggest a spectral class similar to B1, but the lines of *C* II and *Mg* II are much too faint and those of *S* III are too strong. The absorption spectrum has certain points of resemblance to 17 Leporis and to the B5 component of β Lyrae.

The intensity gradient of the *He* I lines is steep, suggesting active turbulence. The high-level transitions in *N* II and *O* II are weakened relative to the low-level transitions. This may be a result of departures from thermal excitation, although a similar but smaller effect is observed in ordinary B stars as a result of the Boltzmann law.

Recombination is probably responsible for the lines of *H* and *He* I, and possibly for *N* II. For atoms of high ionization potential such as *Si* IV, *N* III, etc., recombination is negligible.

The weakness of *Mg* II in P Cygni and in other Be stars is attributed to the depletion of the star's continuous spectrum at the Lyman limit of *H*. Similarly, the weakness of *C* II is caused by depletion at the ultra-violet limit of *He* I.

The prevalence of low-level transitions in *O* II, and especially in *N* II, is regarded as an argument against recombination in these ions, and in favor of fluorescence.

The absorption lines are characteristic of a higher level of excitation than the emission lines. Thus, *Si* IV (45.0 volts), *C* III (47.7 volts), and *N* III (47.4 volts) occur only in absorption. The limit is probably at *He* II (54.2 volts). The absorption spectrum is roughly B0–B1, while the emission spectrum is more nearly B2–B3.

The elements of high ionization potential are found to originate at greater depths in the shell than the elements of low ionization potential. This suggests that the density of the shell decreases outward slower than $1/R^2$, or that the dilution constant increases more rapidly than R^2.

A strong line at λ 4396 agrees in position with an *O* II line. The possibility is discussed that this line is excited by Bowen's mechanism of abnormal fluorescence. In this case a line of *He* I at λ 515.60 agrees closely with *O* II 515.50. No other cases of abnormal fluorescence have been found.

The radial velocities indicate that $|V|$ increases with the intensity of the line and decreases as we pass from elements of low ionization potential to those of high ionization potential. This suggests an accelerated outward motion of the shell.

I. INTRODUCTION

There have been a number of investigations of the spectrum of P Cygni. After the discovery of bright lines by E. C. Pickering,[1] J. E. Keeler,[2] Miss Maury,[3] and Vogel and Wilsing[4] published de-

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[1] *Nature*, **34**, 439, 1886.

[2] *Astronomy and Astrophysics*, **12**, 361, 1893.

[3] *Harvard Ann.*, **28**, 101, 1897; **76**, 31, 1916.

[4] *Pub. Potsdam Ap. Obs.*, **12**, 13, 1899.

scriptions and identifications of its stronger lines. A Belopolsky[5] identified nitrogen and obtained the displacements of a few lines. E. B. Frost[6] and P. W. Merrill[7] made accurate measurements of the radial velocities of the stronger lines. R. H. Curtiss[8] also obtained accurate radial velocities of numerous lines. C. S. Yü,[9] B. P. Gerasimovič[10] and J. Dufay[11] investigated its continuous spectrum and derived a very low color temperature for P Cygni. C. S. Beals[12] recently applied the method of Zanstra to the emission lines of H and of He I and derived a temperature of about 20,000° K for the exciting star. C. T. Elvey[13] published a set of accurate measurements of the total absorptions and emissions of the more prominent lines, together with their radial velocities. Still more recently W. J. Williams[14] gave a brief summary of his measurements of radial velocities.

In spite of this abundance of information collected in the course of nearly half a century, the problem of P Cygni is far from its solution, and a new contribution toward its elucidation is particularly desirable at this time. Within the last few years considerable advances have been made in the interpretation of the spectra of novae and Wolf-Rayet stars on one side, and of ordinary Be stars on the other. A new point of view, not available to earlier investigators, can therefore be taken. The present work is an attempt to test the theory of an expanding nebular shell in the case of P Cygni.

The fact that P Cygni is itself an old nova (discovered in 1600) renders it especially interesting. Furthermore, its absorption lines are not only numerous, but fairly sharp, and should therefore yield reliable radial velocities. Similarly, its emission lines, though not nearly as narrow as its absorption lines, are narrower than the emission lines of most recent novae, and are therefore suitable for measurement and identification. Finally, the character of its spectrum

[5] *Ap. J.*, **10**, 319, 1899.

[6] *Ibid.*, **35**, 286, 1912.

[7] *Lick Obs. Bull.*, **6**, 156, 1911; **8**, 24, 1913.

[8] *Pop. Astr.*, **22**, 133, 1914.

[9] *Pub. A.S.P.*, **39**, 118, 1927.

[10] *Harvard Bull.*, Nos. 852, 857, 867, 1927–28.

[11] *C.R.*, **194**, 1454, 1932; *J. des obs.*, **15**, 45, 1932.

[12] *Pub. Dom. Ap. Obs. Victoria*, **6**, 95, 1934.

[13] *Ap. J.*, **68**, 416, 1928.

[14] *Pub. A.A.S.* (44th meeting), p. 377, 1930. For a complete bibliography containing forty-three references see Merrill and Burwell, *Ap. J.*, **78**, 87, 1933, star No. 338.

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suggests a stage of excitation which is not usually found in the spectra of nebulae, novae, or ordinary Be stars.

The immediate incentive in beginning this study was furnished by the similarity of P Cygni, in many respects, to two other stars recently investigated at the Yerkes Observatory. It had been noticed many years ago by Frost[6] that certain spectroscopic features of P Cygni resembled those of β Lyrae, and I have recently found convincing confirmation of this.[15] No less interesting is its similarity to 17 Leporis,[16] a star containing only one emission line of the P Cygni type ($H\beta$), but possessing a set of absorption lines the behavior of which in many respects duplicates that of P Cygni.

II. OBSERVATIONAL MATERIAL

Two excellent spectrograms taken on September 12.25, 1931 (by Struve and Morgan), and on October 30.10, 1934 (by Henyey), with the single-prism Bruce spectrograph attached to the 40-inch refractor were measured for the purpose of identifying the spectral lines. Both spectrograms are on the high-contrast Eastman Process emulsion, and they record the photographic spectrum from about λ 3925 to λ 4800. Only two strong lines were measured outside this range. The results of the measurements are in Table I. The estimated intensities are on an arbitrary scale, which is not identical with that used for τ Scorpii[17] in column 6.

Table II contains all elements for which a search was made, with their ionization potentials and with the numbers of lines actually observed. The total number of absorption lines measured in P Cygni is 110, of which 10 are unidentified. The number of emission lines is 43, of which 9 are unidentified and of which all but 3 have corresponding absorption lines on their violet sides.

Special attention should be called to the unidentified lines, some of which are quite strong. They are not listed among the permitted or forbidden lines of atoms and ions which may normally be expected in P Cygni.

Plate II shows enlargements of spectrograms of P Cygni (October 30, 1934) and of τ Scorpii (July 7, 1931).

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[15] *Observatory*, **57**, 265, 1934.

[16] *Ap. J.*, **76**, 85, 1932.

[17] Struve and Dunham, *ibid.*, **77**, 321, 1933.

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PLATE II

a) Spectrum of P Cygni; *b*) Spectrum of *τ* Scorpii

TABLE I

SPECTRAL LINES IN P CYGNI

λ	ABSORPTION		EMISSION		INTENSITY		REMARKS
	Int.	Vel.	Int.	Vel.	τ Sco	Lab.	
	H I.P. 13.5						
3970.08......	20	−146	30	− 4	8?	....	
4101.75......	25	184	40	30	30	....	
4340.48......	20	195	40	6	40	....	
4861.34......	20	−200	30	− 2	....	....	
	He I I.P. 24.5						
3926.53......	2	−122	1	− 15	....	1	
3964.73......	10	167	20	− 33	8	4	
4009.27......	8	120	2	− 6	4	1	
4026.19......	15	153	20	− 4	30	5	
4120.85......	6	114	5	− 3	8	3	
4143.77......	9	115	2	− 8	10	2	
4168.97......	1	83	0	....	6	1	
4387.93......	10	123	6	− 12	20	3	
4437.55......	2	104	1	+ 16	5	1	
4471.48......	15	158	20	− 8	20	6	
4713.20......	7	136	10	− 7	8	3	
4921.93......	10	−154	10	+ 6	....	4	
	He II I.P. 54.2						
4685.81......	0–1	−118	0	......	8	....	Uncertain
	C II I.P. 24.3						
4267.20......	1	−138	2	− 38	9	10+8	
	C III I.P. 47.7						
4187.05......	1	....	0	....	5	10	
4647.40......	1	....	0	....	9	10	
4650.16......	1	....	0	....	5	9	Bl. *O* II
4651.35......	1	....	0	....	5	8	Bl. *O* II

TABLE I—*Continued*

λ	Absorption		Emission		Intensity		Remarks
	Int.	Vel.	Int.	Vel.	τ Sco	Lab.	
N II I.P. 29.5							
3955.85......	4	−113	1	+ 3	1	6	
3995.00......	9	110	9	− 13	10	10	
4035.09......	1	91	1	+ 20	3	4	
4041.32......	1	79	0	....	1	5	
4043.54......	1	....	0	....	3	3	
4082.28......	1	71	0	....	1	2	
4227.83......	1	95	0	....	2	3	
4236.98......	0–1	....	0	....	4	6	
4241.80......	1	142	0	....	4	8	
4426.05?.....	1	82	0	....	0	0	
4441.99......	1	38	0	....	1	3	
4447.04......	2	122	2	− 14	3	10	
4530.37......	0–1	....	0	....	1	5	
4601.49......	4	98	4	+ 4	2	8	
4607.17......	5	92	3	+ 18	2	7	
4613.88......	3	86	2	+ 31	2	6	
4621.40......	5	106	4	+ 12	2	7	
4630.55......	7	100	9	+ 15	5	10	
4643.11......	8	− 87	7	+ 8	(1)	8	Bl. *N* III
N III I.P. 47.4							
4097.31......	2	− 75	1	+ 34	6	10	Bl. *O* II
4379.09......	1	....	0	....	3	10	
4510.92......	2	54	0	....	3	6	
4514.89......	1	50	0	....	3	7	
4634.16......	1	− 46	0	....	3	8	
4640.64......	9	....	3	....	3	10	Bl. *N* II
O II I.P. 34.9							
3973.27......	4	− 67	0	....	3	10	
4069.90......	2	83	0	....	7	6+4	
4072.11......	2	39	0	....	6	8	
4075.87......	3	63	0	....	8	10	
4078.86......	1	51	0	....	3	4	
4085.12......	1	72	0	....	3	3	
4119.22......	2	....	0	....	7	8	Bl. *He* I
4132.82......	1	....	0	....	5	6	
4153.31......	1	− 60	0	....	5	7	
4185.45......	0–1	....	0	....	4	8	
4189.79......	1	....	0	....	6	10	

TABLE I—*Continued*

λ	ABSORPTION		EMISSION		INTENSITY		REMARKS
	Int.	Vel.	Int.	Vel.	τ Sco	Lab.	
	O II I.P. 34.9—*Continued*						
4303.82......	0–1	....	0	....	7	5	
4317.60......	2	−105	0	....	6	8	
4319.65......	3	90	0	....	7	8	
4345.57......	1	107	1	+ 20	10	7	
4349.44......	5	86	0	....	12	8	
4351.28......	1	49	0	....	8	6	
4366.91......	3	76	0–1	+ 46	8	7	
4369.28?.....	2	(4)	1	(+109)	1	4	
4378.40......	1	74	0	....	3	3	
4395.95......	5	(144)	4	− 35	3	7	
4414.89......	2	71	1	+ 11	10	10	
4416.97......	2	103	0	....	10	8	
4443.05......	1	....	0	....	2	5	
4452.38......	1	90	0	....	2	6	
4506.50?.....	1	142	0	....	1	2	
4590.98......	2	64	0	....	5	9	
4596.19......	1	60	0	....	5	8	
4638.86......	2	63	0	....	3	6	
4649.15......	5	82	0	....	6	10	Bl. *C* III
4661.65......	3	69	0	....	4	9	
4676.25......	2	104	0	....	3	8	
4705.36......	1	....	0	....	3	8	
4710.04?.....	1	− 74	0	....	1	5	
	Mg II I.P. 15.0						
4481.23......	2	−118	1	− 3	8	100	
	Si III I.P. 33.3						
4552.61......	8	− 95	1	− 7	7	9	
4567.83......	7	103	0	....	7	7	
4574.75......	5	− 92	0	....	6	4	
	Si IV I.P. 45.0						
4088.86......	4	− 60	0	....	10	10	
4116.10......	4	− 46	0	....	10	8	
4212.38......	1	....	0	....	4	3	
4654.14......	1	....	0	....	4	4	

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TABLE I—*Continued*

λ	Absorption		Emission		Intensity		Remarks
	Int.	Vel.	Int.	Vel.	τ Sco.	Lab.	
	S II I.P. 23.3						
4162.64......	1	− 32	0	....	3	10	Bl. *C* III
	S III I.P. 34.9						
3928.59......	1	− 98	0	....	....	9	Bl. *O* II
3983.76......	1	42	0	....	1	7	
4253.51......	4	85	0	....	12	10	
4285.00......	2	118	0	....	3	8	
4361.57......	1	92	0	....	3	7	
4364.77......	1	−108	0	....	2	5	
	Ca II I.P. 11.8						
3933.68......	1	−133	0	....	....	200	Stellar
3933.68......	9	+ 14	0	....	....	200	Interstellar
3968.49......	3	− 86	0	....	....	150	Doubtful stellar
	Fe II I.P. 16.5						
4233.17?.....	1	− 65	0	....	0	10	

III. COMPARISON OF P CYGNI WITH NORMAL B STARS

The spectrum of P Cygni is listed in the *Henry Draper Catalogue* as B1p. Its absorption lines may therefore be compared with those of three normal stars, τ Scorpii (B0), β Canis Majoris (B1), and γ Pegasi (B2). P Cygni exhibits a number of interesting features:

1. The *H* lines are extremely sharp; in fact, they are much sharper than in any normal B-type giant. Curtiss and Gerasimovič have reported diffuse absorption borders on the red sides of the emission lines. In the case of $H\gamma$ this must be due to the group of strong *O* II lines λλ 4345–4350; at $H\epsilon$ a similar effect is caused by *O* II 3973; at

Hδ a faint indication of absorption may be caused by *O* II 4105, although I have not measured this line. The appearance of the *H* lines suggests complete absence of Stark broadening.

2. The *He* I lines are exceptionally strong, surpassing in this respect ordinary B1 stars.

3. *He* II 4686 is almost completely absent. This is in agreement with the assignment of P Cygni to class B1.

TABLE I*a*

UNIDENTIFIED LINES

λ(Star)	Int.	λ(P Cyg) Abs.	Int.	λ(P Cyg) Em.	Int.
		3957.20	2		0
		4003.42	3	4004.62	2
		4020.44	2	4022.12	3
4039.24	1	4037.13	2	4038.74	1
				4164.07	3
4352.47	1			4352.07	2
		4372.66	1		
		4382	1	4383.07	3
4419.62	3	4417.42	7	4419.24	5
4431.03	2	4429.04	4	4430.91	3
		4501.14	1		
				4512.30*	0–1
		4616.45	1		

* Uncertain.

4. *Si* IV is fairly strong, which would place P Cygni between O9 and B2.

5. *O* II and *N* II are both strong, but exhibit peculiar intensities which are discussed separately in section v.

6. The great strength of the *S* III lines is unusual.

7. Equally unusual is the weakness of *C* II, which is very strong in all three normal stars, and of *Mg* II, which is fairly strong in τ Scorpii and in β Canis Majoris, and very strong in γ Pegasi.

It is fairly obvious that the absorption spectrum of P Cygni does not correspond to that of a normal B star. On the other hand, there is a definite resemblance to the absorption spectrum of the B5 component of β Lyrae.[18] The latter corresponds to a lower stage of excitation, and the absorption lines of *O* II, *N* II, *S* III, *N* III, etc., are

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[18] H. Pillans, *ibid.*, **80**, 51, 1934; Struve, *Observatory*, **57**, 265, 1934

TABLE II

LIST OF ELEMENTS

ELEMENT	I.P.	NO. OF LINES		REMARKS
		Abs.	Em.	
H	13.5	4	4	Very strong
He I	24.5	12	11	Very strong; all lines present except λλ 3935 (1), 4023 (1), and forbidden transitions
He II	54.2	1?	0	λ 4686 is extremely faint or absent
C II	24.3	1	1	λ 4267 is surprisingly weak
C III	47.7	4	0	Strongest lines are very weak
N II	29.5	19	10	Strong
N III	47.4	6	2	All strong lines are present
O II	34.9	34	4	Many lines in absorption
O III	54.9	0	0	λ 3961.59 is absent
Ne II	40.8	0	0	Absent
Mg II	15.0	1	1	λ 4481 is surprisingly weak
Al III	28.3	0	0	Absent
Si II	16.3	0	0	Absent
Si III	33.3	3	1	Strong in absorption; extremely weak or absent in emission
Si IV	45.0	4	0	Fairly strong in absorption
P II	19.8	0	0	A weak line suspected at λ 4091 is probably not *P* II; λ 4475 is absent
P III	30.3	0	0	λλ 4080, 4222, 4247 are absent
S II	23.3	1	0	λ 4162 is extremely weak in absorption
S III	34.9	6	0	Surprisingly strong
Cl II	23.1	0	0	Probably absent; a weak line was suspected at λ 4572 but this may not be real, or may be due to *Ca* III
K II	31.7	0	0	Absent
Ca II	11.8	3	0	Stellar K and H (the latter doubtful); interstellar K
Ca III	51.0	0	0	Absent
Sc II	12.8	0	0	Absent
Ti II	13.6	0	0	Absent
V II	14.7	0	0	Strongest two lines in this range are 4005.71 (60) and 4023.39 (50). These were suspected to be identical with the stellar lines 4003.42 (abs.); 4004.62 (em.); 4020.44 (abs.); 4022.12 (em.). However, the normal velocities of −100 km/sec. for absorption lines and 0 km/sec. for emission lines leave a discrepancy of 1 A. Weaker laboratory lines of *V* II, λλ 3952 (4); 4036 (4); 4183 (35); and 4202 (35) are missing in P Cygni
Cr II	16.6	0	0	λ 4559 is absent
Mn II	15.7	0	0	Absent
Fe II	16.5	1	0	λ 4233 is probably present
Ni II	18.2	0	0	Absent
Sr II	11.0	0	0	Absent
Zr II	14.0	0	0	Absent
Unidentified	......	10	9	

missing. However, the character of the *H* lines, the exceptional strength of the *He* I lines, and the weakness of *Mg* II and *C* II are similar features.

Some of the strongest unidentified emission lines in P Cygni have been observed by Merrill[19] in BD+11°4673. These are λλ 4383, 4419, and 4431.

The gradient effect[20] in P Cygni is very pronounced, thus resembling such peculiar stars as 17 Leporis and the B5 component of β Lyrae. This is strikingly illustrated by the intensities of the *He* I lines in τ Scorpii, γ Pegasi,[21] and P Cygni. The estimates for τ Scorpii and γ Pegasi were made on Mount Wilson coudé spectrograms, and their scale is approximately twice as extended as that used for P Cygni. The intensities plotted in Figure 1 have been reduced to the same scale. It is clear, both from Figure 1 and from Plate II, that the strong *He* I lines predominate in P Cygni, while the weaker lines are much more conspicuous in τ Scorpii and γ Pegasi.

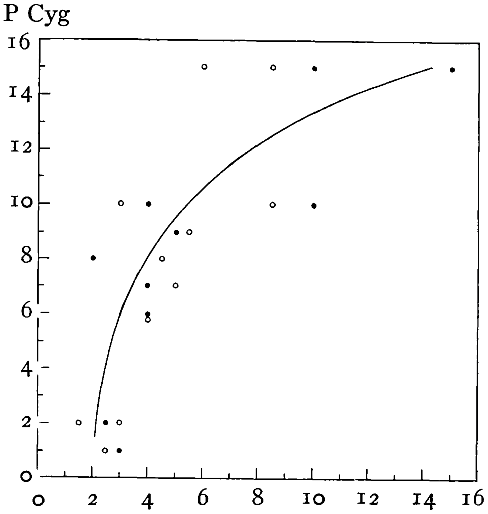

FIG. 1.—*He* I in P Cygni (ordinate), τ Scorpii (abscissa, ●) and γ Pegasi (abscissa, o).

While the gradient has not yet been measured, I estimate it to be approximately similar to that of β Lyrae (B5) and of 17 Leporis. Consequently, the total absorption is proportional to the number of atoms, for weak and moderately strong lines, while for very strong lines the total absorption is almost independent of the number of atoms.

In a recent paper on the gradient effect[20] it was pointed out that turbulence could explain the observed phenomena. It is probable that the same explanation holds for the case of P Cygni. The absorption lines, as well as the emission lines, are believed to originate

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[19] *Ap. J.*, **69**, 330, 1929.

[20] Struve and Elvey, *ibid.*, **79**, 409, 1934.

[21] *Ibid.*, **74**, 225, 1931.

in an expanding nebula. The emission lines are appreciably broadened. For *He* I 4472 I find $\Delta\lambda = 2.8$ A. The contour of the bright line is fairly flat at the top, but the edges are not perfectly sharp, as would be the case if there were no dispersion in the velocities of expansion (or turbulence). In fact, Beals[12] has shown that the amount of dispersion can be determined from the contours.

The shape of the stronger absorption lines in P Cygni confirms this view. They are appreciably widened and resemble contours produced by turbulence broadening.[22]

IV. THE INTENSITIES OF THE ABSORPTION LINES

The absorption lines of *O* II and *N* II are sufficiently numerous for a detailed discussion. Table III gives the more important lines of these elements, arranged according to multiplet. The corresponding atomic transitions are shown in Figures 2 and 3, which are taken partly from Becker and Grotrian[23] and partly from Bacher and Goudsmit.[24] The multiplets of both spectra may be roughly subdivided into two groups: in *O* II the group of lower excitation starts from configurations $2s^2 2p^2 3s$ (limit $^3P_{012}$) and $2s^2 2p^2 3s$ (limit $^1D_2$) and ends in configurations $2s^2 2p^2 3p$ (limit $^3P_{012}$) and $2s^2 2p^2 3p$ (limit $^1D_2$). The lower states of these transitions connect directly with the low metastable states $2s^2 2p^2 2p[^2P$ and $^2D]$, and, in a few cases, with

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[22] In this connection reference may be made to Menzel's recent criticism of our hypothesis of turbulence (*Pub. A.S.P.*, **46**, 216, 1934). The formulae used were originally derived for the case of thermal Doppler effect. Their extension naturally presupposes that the turbulence varies along the radius. This is entirely reasonable, not only in expanding nebular shells, like those of P Cygni, β Lyrae, and 17 Leporis, but also in giant atmospheres like those of ϵ Aurigae and ζ Aurigae, which have a thickness of the order of one astronomical unit. The effect of convection currents (or of turbulent velocities which are essentially constant along the radius) has been investigated in connection with our work on stellar rotation and found to be inappreciable, at least in those spectroscopic binaries in which a direct test of axial rotation is possible. The broadened lines in stars having large intensity gradients are not, however, produced by rotation. The contours of lines in 17 Leporis, ϵ Aurigae, etc., cannot be reconciled with rotational or convectional broadening. They are in good agreement with the theory of turbulence, in the limited sense specified above.

[23] *Ergebnisse der exakten Wissenschaften*, **7**, 8, 1928.

[24] *Atomic Energy States*, New York, 1932. For *O* II see Russell, *Phys. Rev.*, **31**, 27, 1928. The multiplet designations in Table III are from C. E. Moore, *A Multiplet Table of Astrophysical Interest*, Princeton, 1933.

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the ground level of the *O* II ion, $2s^2 2p^2 2p^4S$. The upper levels of these transitions do not directly connect with the low 2p-levels. In the second group the transitions, corresponding generally to higher-excitation energies, start from those levels which were upper levels in the preceding group and end in transitions $2s^2 2p^2 3d$ (limits $^3P_{012}$ and

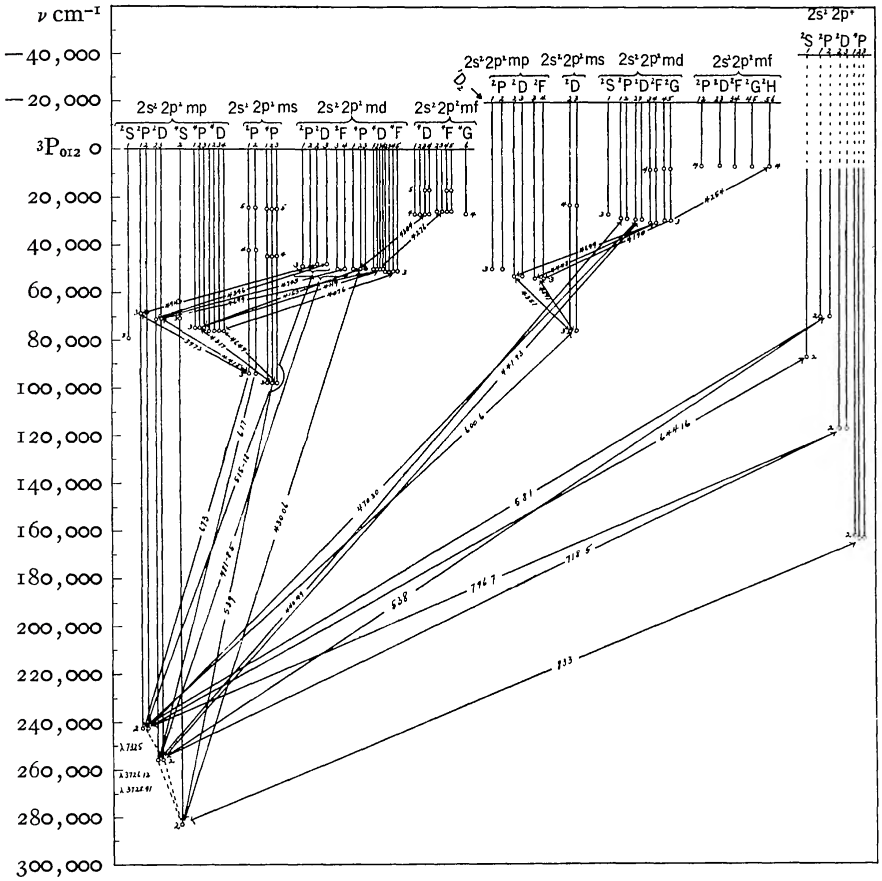

Fig. 2.—Grotrian diagram for *O* II

$^1D_2$). Finally there are a few lines, also included in the second group, which start from configurations $2s^2 2p^2 3d$ and end in configurations $2s^2 2p^2 4f$. The average excitation potentials of the two groups are 23 volts for the lower and 26 volts for the upper state, in the first group; and 26 volts for the lower and 29 volts for the upper state, in the second group.

A similar division has also been made in the case of *N* II. Here the excitation potentials of the first group are approximately 18 and 21 volts, while those of the second group are 21 and 23 volts.

In Figure 4 I have plotted the estimated absorption intensities in the spectrum of P Cygni against those of τ Scorpii, β Canis Majoris, and γ Pegasi. The first group of lines is represented by filled circles, while the second group is represented by open circles. A few unclassified lines of *N* II have arbitrarily been added to the second group. The two *O* II lines, λ 4469 and λ 4396, have been omitted for reasons which are explained in section vii. Several other lines which are complicated by blends have been omitted. These are shown in parentheses in Table III.

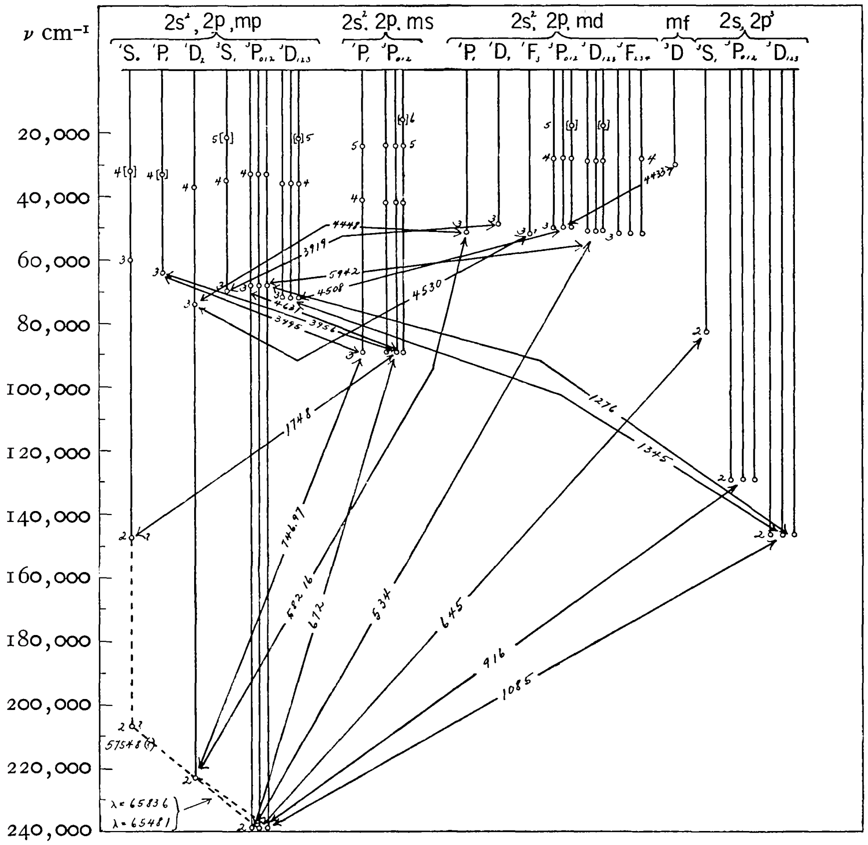

FIG. 3.—Grotrian diagram for *N* II

In all four sections of Figure 4 the filled circles are systematically above the open circles, indicating that for both *O* II and *N* II the upper transitions are weakened relative to normal B stars. This may also be confirmed by an inspection of Plate II.

The suggestion might be made that this is a normal effect of excitation. Indeed, I have found some time ago[25] that the *O* II lines do not all come to a maximum at the same place in the spectral sequence, but that those of higher excitation are, in accordance with theory, slightly stronger in the earlier spectral subdivisions.

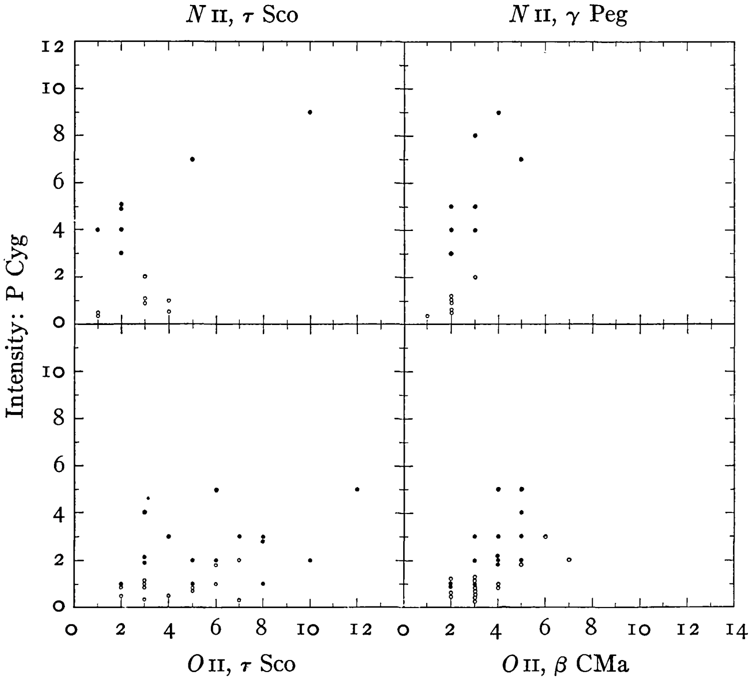

FIG. 4.—Intensities of high-level transitions (o) and of low-level transitions (●)

In order to test this effect, I have compared [26] in Table IV several of the most conspicuous lines of both groups in P Cygni, 10 Lacertae (O9), and ι Herculis (B3). Of the two comparison stars, the first corresponds to a higher general level of excitation than P Cygni and the second to a lower level. The relative strengthening of the high-level lines, in passing from class B3 to class O9, is obvious.

[25] *Ap. J.*, **78**, 73, 1933.

[26] The intensities of lines in stars other than τ Sco are taken from *ibid.*, **74**, 225, 1931; those of τ Sco are from *ibid.*, **77**, 321, 1933.

TABLE III

WAVE-LENGTH	MULTIPLET	INTENSITY				REMARKS
		P Cyg Abs.	Lab.	τ Sco	β CMa	
	Low Transitions of *O* II					
3973	$z^2P-e^2P^o$	4	10	3	5	
4415	$z^2P-e^2D^o$	2	10	10	5	
17		(2)	8	10	4	
52		1	6	2	2	
4317	$y^4P-e^4P^o$	2	8	6	4	
20		3	8	7	5	
45		(1)	7	10	3	
49		5	8	12	4	
67		3	7	8	4	
4649	$y^4P-e^4D^o$	5	10	6	5	Bl. *C* III in τ Sco
38		2	6	3	4	
61		3	9	4	3	
76		2	8	3	3	
4351	$y^2D-f^2D^o$	1	6	8	3	
47		(0)	5	8	2	
4591	$y^2D-e^2F^o$	2	9	5	4	
96		1	8	5	2	
	High Transitions of *O* II					
4396	$e^2D^o-x^2D$	(5)	7	3	3	
69		(2)	4	1	1	
4705	$e^2D^o-z^2F$	1	8	3	3	
4699	$e^2D^o-z^4D$	0	7	....	2	
4153	$e^4P^o-x^4P$	1	7	5	4	
32		1	6	5	3	
4119	$e^4P^o-z^4D$	(2)	8	7	4	
4076	$e^4D^o-z^4F$	3	10	8	6	
72		2	8	6	5	
69		2	6	7	7	
78		1	4	3	3	
85		1	3	3	3	

TABLE III—*Continued*

WAVE-LENGTH	MULTIPLET	INTENSITY				REMARKS
		P Cyg Abs.	Lab.	τ Sco	β CMa	
	High Transitions of *O* II—*Continued*					
4304	$\mathrm{x^4P-f^4D^o}$	0–1	5	7	3	
4276	$\mathrm{z^4D-e^4F^o}$	0	4	2	3	
4448	$\mathrm{e^2F^o-y^2F}$	0	6	3	2	Bl. *N* II
43		1	5	2	2	
4190	$\mathrm{e^2F^o-z^2G}$	1	10	6	4	
85		0–1	8	4	3	
4254	$\mathrm{z^2G-e^2H^o}$	(4)	8	12	5	Bl. *S* III
	Low Transitions of *N* II					
3995	$\mathrm{3s^1P^o-3p^1P}$	9–9	10	10	4	
3956	$\mathrm{3s^3P^o-3p^1P}$	4–1	6	1	2	
4631	$\mathrm{3s^3P^o-3p^3P}$	7–9	10	5	5	
43		8–7	8	(1)	3	
21		5–4	7	2	2	
13		3–2	6	2	2	
07		5–3	7	2	3	
01		4–4	8	2	3	
	High Transitions of *N* II					
4530	$\mathrm{3p^1D-3d^1F^o}$	0–1	5	1	2	
4508	$\mathrm{3p^3D-3d^3P^o}$	0	3	1	1	
4448	$\mathrm{3p^1D-3d^1P^o}$	2–2	10	3	3	
	Unclassified *N* II					
4237		0–1	6	4	2	
41		1	8	4	2	
4043		1	3	3	2	
35		1	4	3	2	
4433		0	6	1	1	

Considering the strength of some *O* II lines in P Cygni, it is somewhat difficult to assign to it a class later than B1. On the other hand, the relative intensities of the high-level and the low-level lines would place it nearer to B2, or even to B3. Such a late spectral class is not possible because of the strength of the *S* III lines and the presence of *N* III, *Si* IV, etc.

In the case of *N* II the effect is even more striking. No possible excitation can account for the enormous strengthening of low-level lines of *N* II in P Cygni. Table V illustrates this. There is little difference between β Canis Majoris (B1) and 67 Ophiuchi (B5), and the enormous enhancement of the low-level lines in P Cygni must be due to causes other than thermal excitation.

TABLE IV

O II

Wave-Length	Intensity		
	P Cyg(B1p)	10 Lac (O9)	ι Herc (B3)
	Low Transitions		
4415	2	0	2
4317	2	0	3
4320	3	1	0
	High Transitions		
4076	3	4	1
4072	2	2	1
4069	2	4	2
4705	1	1	0
4699	0	1	0

V. COMPARISON OF EMISSION LINES WITH ABSORPTION LINES

It is generally recognized that the most effective mechanism in the production of bright lines in stellar spectra is photo-electric ionization with subsequent recombination. This mechanism has been analyzed by Zanstra,[27] Menzel,[28] Bowen,[29] Miss Payne,[30] Beals,[31] Woolley,[32] and others. Beals has applied Zanstra's theory to the emission lines of *H* and of *He* I in P Cygni and has found a temperature of 19,300° K in the former case and 26,000° K in the latter case.

TABLE V

N II

Wave-Length	Intensity		
	P Cyg	β CMa (B1)	67 Oph (B5p)
	Low Transitions		
3995	9	4	3
4631	7	3	4
4613	3	2	1
4621	5	1	2
	High Transitions (and Unclassified)		
4530	0–1	1	0
4448	2	2	2
4035	1	2	1
4242	1	3	2

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[27] *Ibid.*, **65**, 50, 1927; *Zs. f. Ap.*, **2**, 1, 1931.

[28] *Op. cit.*, **38**, 295, 1926.

[29] *Ap. J.*, **67**, 14, 1928; **81**, 1, 1935.

[30] *M.N.*, **92**, 368, 1932. Miss Payne's criticism of my rotational hypothesis of bright lines is of no consequence to this paper. There is no disagreement in so far as recombination and fluorescence is concerned. In fact, I have mentioned these mechanisms in several papers and have accumulated observational evidence in favor of recombination as the principal source of bright *H* lines in Be stars. There are five major questions to be answered in connection with stellar emission lines: (1) Where do these lines originate? (2) How do the atoms get there? (3) By what mechanism are they excited to radiation? (4) Why are some bright lines broad and flat-topped while others are narrow? (5) Why do many bright lines vary in intensity and contour? There is no discordance with regard to question 1. I have attempted to answer questions 2 and 4 by the rotational hypothesis for ordinary Be stars, and by the expanding shell hypothesis for stars of the P Cygni type. Question 3 is satisfactorily answered by the work of Rosseland, Miss Payne, and others. Question 5 has not yet been adequately answered, although McLaughlin and Gerasimovič have made interesting attempts in this direction.

[31] *Pub. Dom. Ap. Obs. Victoria*, **4**, 271, 1930.

[32] *M.N.*, **94**, 631, 1934.

Since the emission lines of *He* I are very strong, it is obvious that there must be a large amount of energy in the star's spectrum toward the violet from λ 504. This agrees with the temperature derived by Beals. The energy-curve corresponding to 20,000° K and a few of the series limits are shown in Figure 5.

N II is only partly in emission, indicating that at λ 418 the energy-curve is somewhat depleted. *Si* III and *O* II appear almost exclusively in absorption, which might indicate an insufficient amount of radiation at λ 370 and λ 353. Elements of higher ionization potential, such as *S* III, *N* III, *Si* IV, and *C* III, are seen only in absorption, while *O* III is completely absent.

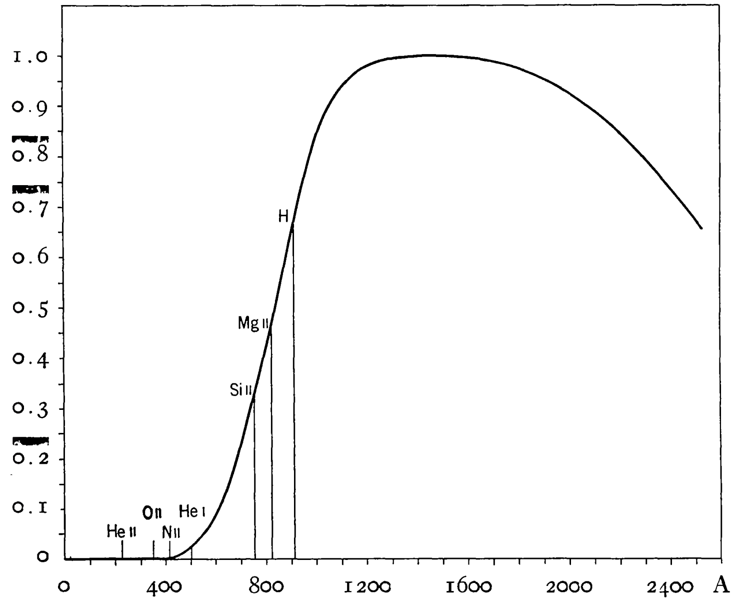

FIG. 5.—Black-body curve for $T = 20,000°$ K

The emission lines agree fairly well with the recombination hypothesis, but there are a few anomalies. The absence of *Si* II and the weakness of *Mg* II are interesting. The first, though its ionization potential of 16.3 volts is slightly above that of *H*, would not normally be expected in a B2 spectrum, since in ordinary stars the relatively low ionization potentials of *Si* III and *Si* IV will lift a large number of atoms into higher stages of ionization, thus preventing a recombination spectrum of *Si* II. However, we have just pointed out that there is probably no recombination spectrum of *Si* III, so that the majority of the *Si* atoms must be in the ground level of the *Si* III ion. Even more surprising is the weakness of *Mg* II. In normal B2 stars, λ 4481 is a fairly strong line, and it usually persists into the O's. Now, the ionization potential of *Mg* III is 80 volts, so that the majority of *Mg* atoms must be in the ground level of *Mg* III, and should thus favor recombination processes forming the line λ 4481 in emission.

The most obvious explanation of the weakness of *Mg* II, a phenomenon that seems to be prevalent in Be stars, is that the star's continuous spectrum in the neighborhood of λ 824 is still sufficiently depleted of radiation by the strong photo-electric ionization at the limit of the Lyman series of *H*, at λ 911. This would not be surprising, since the mechanism of Zanstra, which is justified by its results, demands that a large fraction of the entire energy on the violet side of λ 911 is utilized in producing the emission lines of *H*.

A similar but even more striking anomaly exists in the case of *C* II, which should normally be strong in class B2. Here the ionization potential, 24.3 volts, is almost identical with that of *He* I, 24.5 volts, and the limits, at λ 508 and λ 504, are so close to one another that the recombination spectrum of *C* II will doubtless be suppressed by continuous absorption at the ultra-violet *He* I limit.

Much less satisfactory is the behavior of *N* II. Here the ionization potential of 29.5 volts corresponds to λ 418. The amount of radiation available for ionization at this wave-length is about one-seventh of that available at the *He* I limit and about one two-hundredth of that available at the *H*-limit. At the limit of *O* II, λ 353, where no appreciable recombination occurs, the energy is one-eightieth of that at λ 504, *He* I. We are therefore uncertain whether recombination does or does not occur in *N* II.

However, the observations show clearly that the emission is limited to low-level lines, strong high-level lines being devoid of emission. This is distinctly unfavorable to the hypothesis of recombination: in the laboratory, recombination has invariably increased the intensities of high-level lines, and Mohler and Beckner[33] have even succeeded in observing new high-level lines which are not seen

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[33] *J. of Research, Bureau of Standards*, **2**, 489, 1929. See also Ruark and Urey, *Atoms, Molecules and Quanta*, p. 470, 1930.

in ordinary laboratory sources. The anomaly of the *N* II emission lines is probably related to that of the absorption lines discussed in the preceding section.

The absorption lines of P Cygni are characteristic of a much higher degree of excitation than are the emission lines. The limit is probably in the vicinity of 50 volts: *Si* IV, ionization potential 45.0 volts, and *N* III, ionization potential 47.4 volts, are present; *C* III, ionization potential 47.7 volts, is very weak.

It is quite clear that while the absorption lines of P Cygni correspond to a class intermediate between B0 and B1, the emission lines are more nearly at B2 or B3. It might be thought that the appearance of emission is merely a function of the intensity of the absorption lines, but that is not true. Thus, some faint lines of *He* I and of *N* II are accompanied by emission, while some of the stronger lines of *O* II are devoid of it.

The radial velocities discussed in section viii leave no doubt that the absorption lines originate in the expanding shell, and in this respect there is no great difference between absorption lines which are accompanied by emission lines and those which are not.

There is at present no adequate theory of the origin of absorption lines in expanding nebular shells. It is obvious, however, that in a general way we are dealing with the same process of absorption and re-emission (or scattering) which gives rise to the absorption lines in a reversing layer.

Ignoring for the moment all anomalies arising through departures from thermodynamic equilibrium, such as were mentioned in the preceding paragraphs, we should expect that for a thin shell of radius R around a star of radius r, the ratio of absorption intensity to emission intensity would be roughly proportional to the ratio of the volume of gas projected upon the star's disk to that of the entire shell visible to the observer. This gives

$$\frac{A}{E}=\frac{1-\sqrt{1-\frac{r^2}{R^2}}}{1+\sqrt{1-\frac{r^2}{R^2}}}f(N, \sigma) .$$

Accordingly, if for two equal absorption lines the emission lines are not the same, we conclude that they must originate in layers of differ-

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ent R. The function of (N, σ), depending upon the number of atoms and the absorption coefficient, takes care of the gradient effect, etc. The formula, of course, fails if $R=r$, for then we should use the customary treatment of a scattering reversing layer. The factor f (N, σ) also shows that it is not permissible to compare unequal absorption lines.

Since we have shown that equal absorption lines may have widely different emission lines, we conclude that, in general, the former originate in other shells than do the latter. This agrees with the result that the level of excitation is much higher for absorption than for emission.

This effect is seriously complicated by departures from thermodynamic equilibrium. These must be made responsible for the enormous difference in the emission and absorption ratios of *He* I lines belonging to different series. Thus, Schwede[34] has found, in agreement with Elvey:[13]

He 4388:	total absorption . .	0.62 A	*He* 4388:	total emission	0.16 A
4472:	total absorption . .	0.69	4472:	total emission	1.56

It is difficult to explain this result, unless the processes of absorption and emission are far from being balanced.

Eddington[35] has shown that the state of ionization in a nebula is equal to that of a reversing layer having a density of $\rho\delta$, where ρ is the density of the nebula and δ the dilution factor $4R^2/r^2$. Since, for the absorption lines of highest excitation, A/E is smaller than for lines of low excitation, we conclude that R(high exc.)$<R$(low exc.), and that, consequently, the factor $\rho\delta$ decreases as we approach the star. Since $\delta \sim R^2$, we find that ρ must increase inward more slowly than $1/R^2$. According to Eddington,[36] in an isothermal nebula $\rho \sim 1/R^2$. An alternative explanation would be that δ increases outwardly more rapidly than R^2.

VI. NORMAL EXCITATION OF SPECTRAL LINES IN P CYGNI

If the absorption lines of P Cygni originate in an expanding shell, it may not be permissible to apply to them the ordinary theory of stellar absorption lines. Especially does it seem dangerous to apply the Boltzmann law for the derivation of the numbers of atoms in

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[34] *Ap. J.*, 77, 348, 1933.

[35] *Internal Constitution of the Stars* (German ed.), p. 478, 1928.

[36] *Ibid.*, page 489.

various quantum states. The problem of radiative equilibrium in a nebula has been treated by Rosseland[37] and applied by him to the case of three levels of increasing energy, 1, 2, 3. If a_{ki} and a_{ik} are the transition probabilities, the condition of equilibrium is

$$\sum_k a_{ki}x_k = 0 ; \quad a_{ii} = -\sum_k a_{ik} .$$

The solution of these equations gives the numbers of atoms in the various states,

$$x_k = \lambda_m a^{km} ,$$

where λ_m is a constant and a^{km} is the subdeterminant of the determinant a_{km}. For three states we have

$$\begin{aligned} a^{11} &= a_{21}(a_{31}+a_{32})+a_{23}a_{31} , \\ a^{21} &= a_{12}(a_{31}+a_{32})+a_{13}a_{32} , \\ a^{31} &= a_{13}(a_{21}+a_{23})+a_{12}a_{23} . \end{aligned}$$

Rosseland applies these formulae to the case where the second level is metastable, i.e., $a_{21}=a_{12}=0$, and finds that in this case the number of atoms in the metastable level is similar to that given by Boltzmann's law.

To represent more closely the conditions prevailing in the lower levels of the two groups of transitions of O II and of N II, we shall assume that $a_{31}=a_{13}=0$. In that case

$$a^{11} = a_{21}a_{32} , \quad a^{21} = a_{12}a_{32} , \quad a^{31} = a_{12}a_{23} ,$$

and, accordingly,

$$\frac{x_2}{x_1} = \frac{a^{21}}{a^{11}} = \frac{a_{12}}{a_{21}} ,$$

$$\frac{x_3}{x_1} = \frac{a^{31}}{a^{11}} = \frac{a_{12}a_{23}}{a_{21}a_{32}} .$$

Now, according to Einstein, for emission $a_{ki} = \alpha_{ik}(1+\bar{\rho}[\nu_{ik}])$ and for absorption $a_{ik} = \alpha_{ik}^{-}(\nu_{ik})\, \omega_k/\omega_i$.

$\bar{\rho}(\nu_{ik})$ is the energy density of the radiation divided by $8\pi h\nu^3/c^3$. Accordingly,

$$\bar{\rho}(\nu_{ik}) = \frac{1}{\delta}\, \rho(\nu_{ik}) ,$$

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[37] *Astrophysik auf atomtheoretischer Grundlage*, p. 224, 1931.

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where $\rho(\nu_{ik})$ is the energy density given by Planck's law. Substituting this, we find

$$\frac{x_2}{x_1}=\frac{\omega_2}{\omega_1}\,\frac{\rho(\nu_{12})}{1+\frac{1}{\delta}\rho(\nu_{12})}\cdot\frac{1}{\delta}\,,$$

$$\frac{x_3}{x_1}=\frac{\omega_3}{\omega_1}\,\frac{\rho(\nu_{12})\rho(\nu_{23})}{(1+\frac{1}{\delta}\rho[\nu_{12}])(1+\frac{1}{\delta}\rho[\nu_{23}])}\cdot\frac{1}{\delta^2}\,.$$

For small values of $\rho(\nu)$ the number of atoms in the second state is proportional to $1/\delta$ and the number in the third state is proportional to $1/\delta^2$. It is obvious that if δ is large enough, there must be a markedly smaller number of atoms in state 3 than would be given by Boltzmann's law. Furthermore, it would appear that for suitable values of δ, x_3 is smaller if $a_{13}=a_{23}=0$ than if $a_{13}=a_{23}\neq 0$.

In a nebula with large δ we should therefore expect that aside from recombination lines and resonance lines (which, for most atoms, are not in the observable range), only those lines would be strong which have lower levels connecting directly with the ground level or with one of the low metastable levels.[38] This condition is fulfilled for *N* II and probably also for *O* II. It may hold in the case of *Si* III, whose lower levels are reached directly from the metastable ^{3}P-state, but it is violated in the case of *Si* IV, whose lines λ 4089 and λ 4116 originate in the 2s^{2}S-state, which does not directly connect with the ground level, 1s^{2}S, but can only be reached from it by two or more jumps. It is therefore probable that, at least for *Si* IV, δ is not very large. A numerical evaluation of the quantities involved is not, at present, possible. We can only conclude that slight departures from thermal excitation are present, but that for *Si* IV conditions resemble those prevalent in ordinary stars.

VII. ABNORMAL FLUORESCENCE

The spectrum of P Cygni contains a peculiarly strong line, present both in absorption and in emission, at λ 4396. This line has been

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[38] We ignore transition probabilities from the ground level to the upper states of the high-level lines. Although this is not rigorously correct, it seems probable that these transitions will have little effect in lifting atoms into a state from which emission of the high-level lines is possible. In the first place, the continuous spectrum in the required wave-lengths (λ 430±) is relatively weak; in the second place, their coefficients a are probably small.

tentatively identified as *O* II 4395.95, and all available measurements prove that the agreement in wave-length is excellent. However, the violet absorption line is distinctly too strong for its laboratory intensity and the emission line, if really due to *O* II, is by far the strongest line of this atom.

Two possibilities suggest themselves: either (1) the agreement in wave-length is a mere coincidence, the line being really unidentified, or (2) the *O* II atom has an abnormal tendency to enhance this particular transition.

It is difficult either to support or to disprove the first possibility. There are four other unidentified lines in the region λλ 4300–4500, and λ 4396 may belong to this group. On the other hand, a chance coincidence of an unidentified line with *O* II 4395.95 is improbable.

The second possibility merits a careful scrutiny. Bowen[29] has recently found a powerful secondary mechanism of excitation which depends upon the close agreement in wave-length of a strong ultraviolet emission line (itself produced by the primary mechanism of recombination) with an absorption line of another atom. The question in our case is: Is there such an anomalous mechanism at work in *O* II which would lift an abnormal number of atoms into either the upper or the lower level of the line λ 4396?

The line *O* II 4396 is a member of the multiplet $2s^2 2p^2 3d\,^2D - 2s^2 2p^2 3p\,^2D$. The upper terms are $\nu = 48{,}618.4$ and $\nu = 48{,}566.4$. The lower terms are $\nu = 71{,}498.9$ and $\nu = 71{,}308.2$. The first upper level leads to the lines λ 4369.28 (4) and λ 4406.02 (1), while the second gives λ 4395.95 (7) and λ 4359.38 (1). The two upper levels do not connect with the ground level, which is a ^4S, but they connect with the very low metastable level $2s^2 2p^2 2p\,^2P$, viz., $\nu = 242{,}555.5$ and $\nu = 242{,}560.0$. These lead to the two following close pairs: λ 515.62 and λ 515.49. Bowen[39] has actually measured λ 515.62 (2) and λ 515.47 (2). The first of these feeds λ 4367 and the second feeds λ 4396.

Bowen has pointed out that only *H* and *He* could reasonably be expected to produce abnormal fluorescence. *H* and *He* II have no lines near λ 515. But there is a conspicuous *He* I line, $1\,^1S - 5\,^1P$ (see Grotrian diagram, Fig. 6), which gives, from the term values, λ 515.07 and which has been measured by Lyman[40] at λ 515.65 and

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[39] *Phys. Rev.*, **29**, 243, 1927.

[40] *Ap. J.*, **60**, 11, 1924.

by Hopfield[41] at λ 515.596. The agreement of this value with the two *O* II lines is rather striking, being 0.02 A in the first case and 0.11 A in the second.[42] The second, larger, residual applies to the case of *O* II 4395.

The visible *He* I lines, especially of the series $2^1S - m^1P$, are very strong in emission. The width of λ 4472 is approximately 2.8 A, and the contour is fairly flat at the top. Since the broadening is due to Doppler effect of expansion,[43] we have

$$\Delta\lambda \sim \lambda \ ,$$

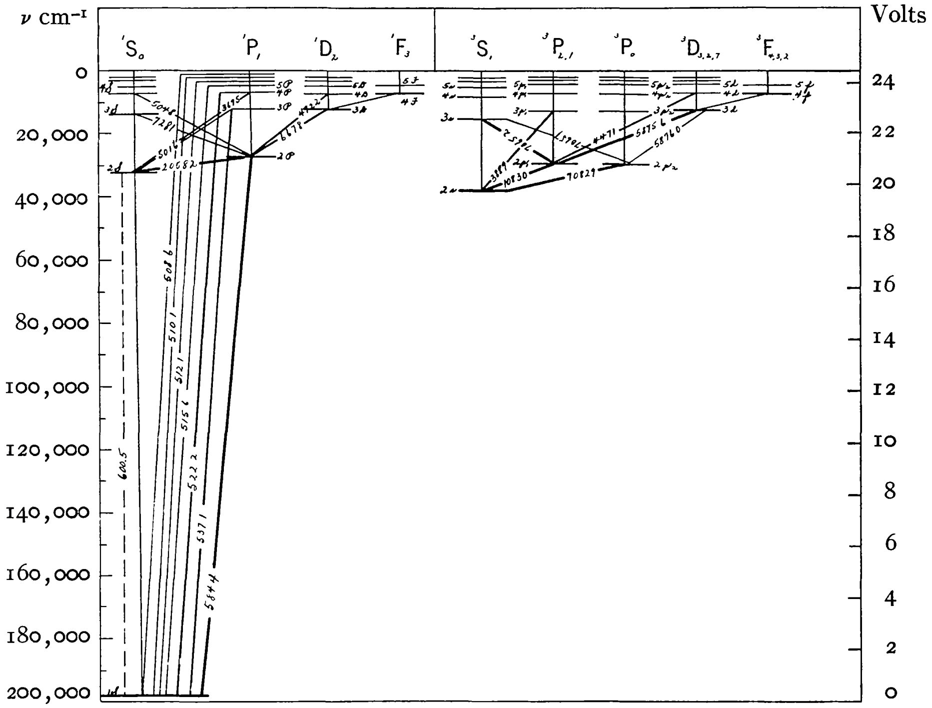

FIG. 6.—Grotrian diagram for *He* I

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[41] *Ibid.*, **72**, 136, 1930.

[42] Since writing the foregoing, Professor Bowen has called my attention to the measurements of the *O* II lines by B. Edlén (*Nova Acta Regiae Societatis Scientiarum Upsaliensis* [4th ser.], **9**, No. 6, 1933): λ 515.640 and λ 515.498. These values are estimated to be accurate to 0.01 A or 0.02 A. The residuals are therefore reduced to 0.098 A in the case of λ 4396 and 0.044 A in the case of λ 4369. There is still a decided preference for λ 4369. Professor Bowen also mentions that K. T. Compton and J. C. Boyce (*J. of Franklin Inst.*, **205**, 497, 1928) found for the *He* I line a value which is 0.004 A higher than Hopfield's more recent result.

[43] Beals has found that in the visible region the line widths are proportional to their wave-lengths (*op. cit.*, p. 297).

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and the width of *He* I 515.60 should be 0.32 A. Allowing a similar width for *O* II 515.5, we find that both *O* II lines should profit from the excessive radiation available for absorption from the bright *He* I line. It is obvious, however, that unless our computation is in error, λ 4369 should profit a great deal more than λ 4395. Normally λ 4369, of laboratory intensity 4, would not be expected to show in P Cygni. There is a faint, but definite, absorption line at approximately the correct wave-length, and there is also an emission line, but its position is rather markedly displaced toward the red. (A slight displacement of the absorption line in the same direction is not serious, because it blends with a weak bright line at *O* II 4367.) I am therefore in doubt whether λ 4369 is really the *O* II line. Should it not be *O* II, I should be inclined to abandon also the hypothesis of abnormal fluorescence in λ 4396 (laboratory intensity 7) and should prefer to regard this line as unidentified.

Unfortunately, no other multiplets which are easily observable arise from the *O* II level $\nu=48{,}566.4$. The multiplet λλ 4941, 4943, 4956 cannot be photographed with the Eastman Process emulsion.

I have made a search for other coincidences in ultra-violet wave-lengths (see Fig. 7). The nearest are:

H	937.81	*He* I	601.4	*He* I	537.1
S II	937.69	*O* II	600.6	*O* II	537.8
S II	937.41			*O* II	538.3

The first coincidence may be sufficiently close to produce observable effects, but unfortunately the ordinary lines of *S* II are all faint. Not one of the unidentified emission lines agrees with classified lines of *S* II listed by S. B. Ingram.[44] The second coincidence is not close enough; furthermore, the *He* line corresponds to a forbidden transition and is probably weak in P Cygni. The third case is too remote.

VIII. THE RADIAL VELOCITIES

It has been known for a long time that radial velocities obtained from different lines of P Cygni are not consistent among themselves. Thus, the absolute values of the negative velocities from the *H* lines become larger as we pass from the violet to the red, and for this reason the hypothesis has been advanced that $V=f(\lambda)$. For *He* I

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[44] *Phys. Rev.*, **32**, 172, 1928.

this functional relationship was found to hold when only a few of the stronger lines were measured.

I have made no attempt to obtain accurate velocities from the stronger lines, but have measured velocities for as many lines as possible. The results are given in Table I and are summarized in Table VI, in which there are given for each element the mean velocities corresponding to lines of approximately equal absorption intensity. The elements are arranged in order of their ionization potentials.

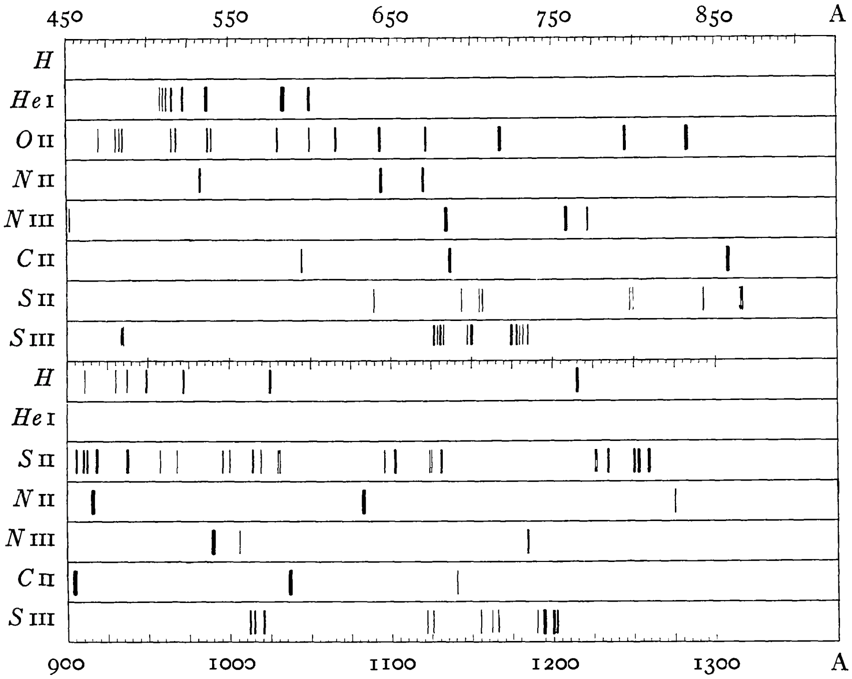

FIG. 7.—Ultra-violet spectra

In spite of the large scatter, there is a fair degree of correlation between intensity and velocity; for any given element the strong lines show a larger velocity of approach than the faint ones. There can be no doubt that this is the true correlation, and that the physically absurd correlation with wave-length was merely a result of the general tendency in H and He I for the stronger lines to have the longer wave-lengths. Exactly the same phenomenon has been observed in the B5 component of β Lyrae.

The most interesting result, however, is the obvious correlation between velocity and ionization potential: for two lines of a given intensity, the one of lower ionization potential has the larger velocity of approach. This effect is not caused by the presence of emission lines; thus for *C* II and *Mg* II, which are very little affected by emission, $|V|$ is much larger than for *N* II, which has strong emission. Furthermore, the transition from emission to absorption is gradual, not sudden.

TABLE VI

RADIAL VELOCITIES IN P CYGNI

Element	Average Intensity (Absorption)	Average Velocity	No. of Lines
		km/sec.	
H (13.5)	22	−181	4
Mg II (15.0)	2	118	1
C II (24.3)	1	138	1
He I (24.5)	1	83	1
He I	2	113	2
He I	7	123	3
He I	10	140	4
He I	15	156	2
N II (29.5)	1	85	7
N II	3	105	4
N II	5	99	2
N II	8	99	3
Si III (33.3)	5	92	1
Si III	7.5	99	2
S III (34.9)	1	85	4
S III	3	102	2
O II (34.9)	1	78	10
O II	2	79	8
O II	3	75	4
O II	4.5	78	3
Si IV (45.0)	4	53	2
N III (47.4)	1	48	2
N III	2	− 64	2

We have consistently been led to the result that lines of high excitation originate deeper inside the shell. Consider a single element, e.g., *He* I. The strong lines originate in smaller optical depths within the nebula than the fainter lines. The velocities of the strong lines are greater than those of the faint lines, suggesting an accelerated motion of the nebula outward. Now consider two lines of the same intensity but of different elements. The one of lower potential, as

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found in section vi, originates at a greater distance from the star than the one of higher potential. Consequently, the former should show a larger velocity of approach than the latter. This is in agreement with observation.

There is good evidence in favor of this acceleration, from the emission lines. These are by no means all of equal width, but a closer study of their behavior must be postponed until actual contours are available. In passing, however, attention may be called to the sharpness of the unidentified emission line λ 4164.

IX. THE ULTRA-VIOLET AND GREEN REGIONS

For completeness I have measured several spectrograms on coarse-grained, isochromatic plates taken by Mr. J. A. Hynek with the prism-spectrograph attached to the 69-inch Perkins reflector. The measures are uncertain, especially in the green region, where the dispersion is small and where the comparison lines are not favorably located. The list contains the designations or the laboratory wave-lengths of all identified lines and the measured wave-lengths (corrected to the sun) of the unidentified lines. Attention is called to the peculiar intensity of *Si* III 3806.56, which is a high-level line. The forbidden *O* II lines λλ 3726, 3729 are not present, thus confirming the conclusion that δ is relatively small. The *O* II multiplet 4941, 43, 56 (referred to in section vii) is not definitely seen on the coarse-grained plates, although the first member may be identical with λ 4938.01 (unidentified). The list contains 48 absorption lines (of which 14 are unidentified) and 20 emission lines (of which 6 are unidentified).

ABSORPTION LINES

H_{25} (1) −136; H_{23} (1) −122; H_{22} (2) −143; H_{21} (2) −143; H_{20} (2) −138; H_{19} (2) −105; H_{18} (3) −134; H_{17} (4) −152; H_{16} (7) −164; H_{15} (4) −122; H_{14} (4) −146; H_{13} (4) −105; H_{12} (5) −133; H_{11} (4) −142; H_{10} (7) −138; H_9 (8) −143; $H_\zeta=H_8$ (20 bl. *He* I) *He* I: 3587.30 (2) −198; 3613.64 (3) −183; 3634.30 (6) −113; 3705.10 (bl. *H*); 3819.63 (8) −132; 3867.50 (3) −111; 3871.80 (3) −91; 5015.68 (7) −180; 5047.74 (1) −176; *O* II 3727.33 (2) −95; *S* III: 3632.03 (1) −216?; 3709.37 (2) −72; 3717.77 (1) −130; 3778.91 (1) −96; 3860.64 (1) −47; *Si* III? 3791.41 (1) −152; *Si* IV? 3773.13 (1) −68.

Unidentified: 3599.56 (3); 3602.51; 3648.34 (1); 3723.89 (1); 3782.19 (2); 4938.01 (*O* II 4941.12?); 5052 (1); 5071 (1); 5082 (2); 5097 (1); 5125 (2); 5131 (1); 5139 (2); 5154 (3).

EMISSION LINES

H_{18} (1) −17; H_{17} (2) +1; H_{16} (3) +21; H_{15} (2) +26; H_{14} (2) −14; H_{13} (3) −26; H_{12} (3) −17; H_{11} (3) −14; H_{10} (4) −14; H_9 (6) +0; *He* I 3819.63 (6) −10; 3888.90 (bl. *H*); 5015.68 (10) −6; *Si* III 3806.56 (4) −32.

Unidentified: 3600.88 (3); 3603.49 (2); 3757.57 (1); 5055 (3); 5127 (2); 5156 (3).

X. CONCLUSIONS

As a result of the preceding discussion the following tentative picture of P Cygni suggests itself:

The nucleus is a star of effective temperature 20,000° K, situated at a distance of approximately 1000 parsecs from the sun. Owing to its great distance, the interstellar line K is exceptionally strong. Selective interstellar absorption reduces the color temperature to approximately 6000° K. There is no line spectrum belonging to a stationary reversing layer similar to that found in 17 Leporis. The absorption lines and the emission lines originate in an expanding nebular shell. The velocity of this shell is accelerated outward, being approximately 200 km/sec. in the region of formation of the *H* lines and approximately 50 km/sec. in the region where *Si* IV and *N* III are formed.

For a given element the stronger absorption lines originate at lesser depths than the weaker lines. For two equal lines of different elements the one of higher ionization potential originates at the greater depth.[45]

The mechanism of line excitation deviates from thermal excitation, and peculiar cases of fluorescence may be present. It is probable, however, that the dilution constant in P Cygni is much smaller than that found for novae or planetary nebulae.

YERKES OBSERVATORY
November 1934

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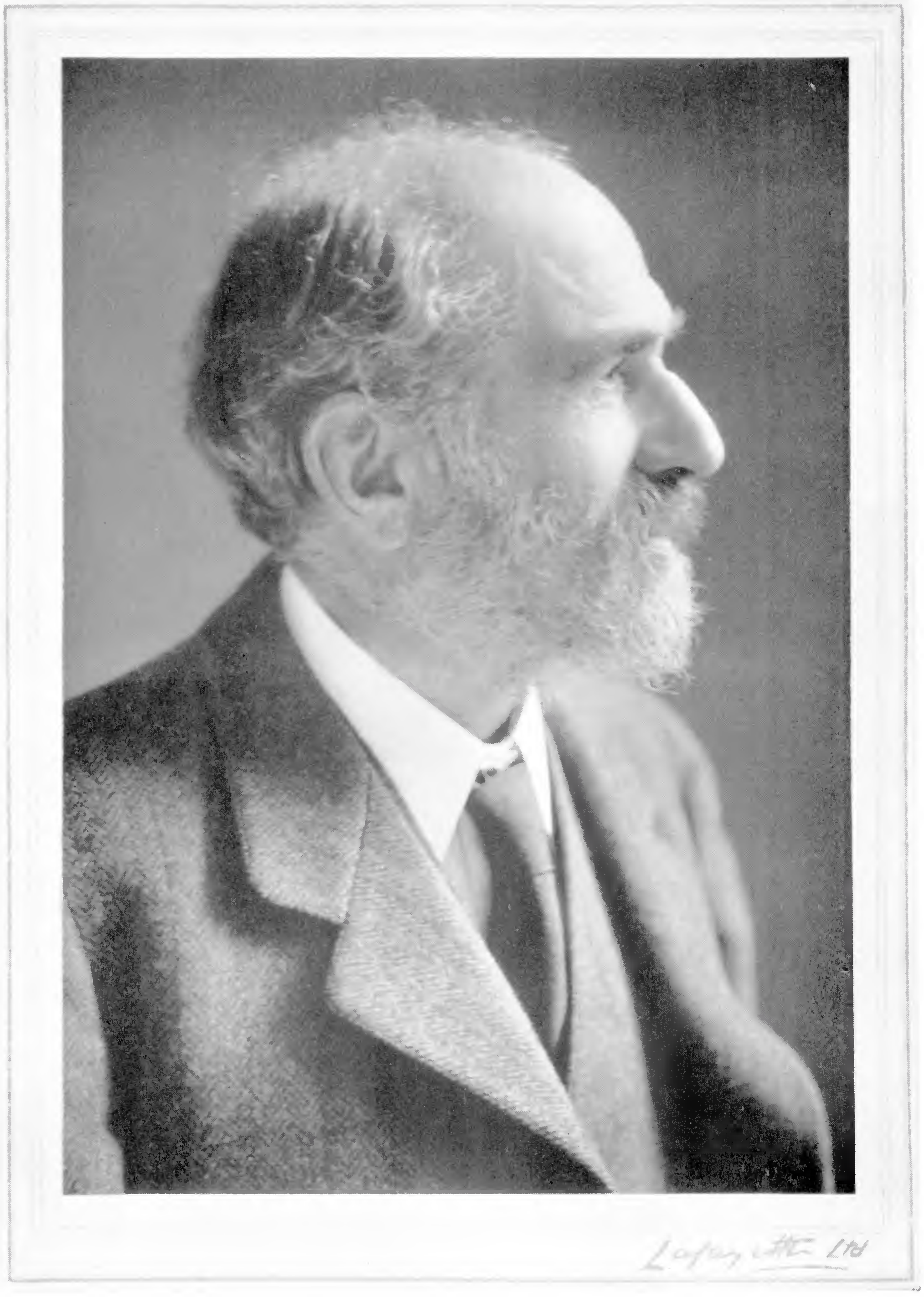
[45] Since this paper was written, I have received the November, 1934, issue of the *Observatory*, containing an article by C. S. Beals on P Cygni (p. 319). It is gratifying to find that his conclusions in regard to stratification in the shell agree with mine. In this connection attention may be called to the star 17 Leporis in which the ratio emission/absorption is very small and for which I concluded that the ratio: radius of shell/radius of star, must be relatively close to 1; this is, of course, the same result as that given by *O* II and by other atoms of high ionization potential, in P Cygni (*Ap. J.*, **76**, 103, 1932). Beals now favors a temperature of 30,000° K.



SIR ARTHUR SCHUSTER