1942ApJ....96..254S

SPECTROGRAPHIC OBSERVATIONS OF PECULIAR STARS. IV.*

P. Swings and O. Struve

ABSTRACT

I. *New observational results.*—*AX Persei* in January and February, 1942, showed the lines of [*Fe* v] and [*Fe* vi] with considerable intensity. Other interesting changes in the spectrum have been recorded. *RW Hydrae* is interesting because of the absence of fluorescence excitation in *O* iii and because the *He* i singlets $(2p^1P^0 - nd^1D)$ are relatively strong. *Z Andromedae* has returned to a stage similar to that observed in August, 1940. *T Coronae Borealis* has bright *Fe* ii, but the absence of [*Ne* v] shows that the excitation is lower than in Z Andromedae. *Z Canis Majoris* has been observed near maximum light. Several Of and W stars have also been observed.

II. *Excitation mechanisms in shells.*—The importance of fluorescence excitation is discussed and is applied to the problem of selectivities among emission lines of peculiar stars. Of particular interest are the ratios of singlet to triplet intensities of *He* i. The great relative strength of the singlets in objects of low excitation, like RW Hydrae, is attributed (*a*) to the predominance of fluorescence over recombination and (*b*) to the presence of high radiation density in the nebulous shells of the singlet series $(1s^1S - np^1P^0)$ of *He* i. Similar considerations are applied to unusual intensities of emission lines in Of shells and in P Cygni or Be shells. The influence of departures of the exciting radiation from that of a black body is discussed for novae and for certain long-period variables. When fluorescence is produced by strong ultraviolet emission lines, as in the case of Bowen's mechanism for *O* iii, the gradient in the velocity of expansion of a shell produces important modifications. This may account for absence of the Bowen mechanism in Wolf-Rayet stars and in other rapidly expanding shells.

Our knowledge of the spectroscopic characteristics of stars surrounded by shells has made considerable progress in the last two years.[1] On the basis of the extensive observational material collected, it is appropriate at the present time to discuss the excitation mechanisms in shells; this is the main object of this paper. In section I additional observational data are given which have a direct bearing on the excitation mechanisms; the latter are discussed in section II.

I. NEW SPECTROSCOPIC DATA ON EXTENDED ATMOSPHERES

AX Persei.—In our last report on this star[2] we mentioned the very striking change which had taken place between January and August, 1941. In January, 1941, the [*Fe* vii] lines had disappeared, whereas they had recovered considerable intensity in August, 1941. Various changes were observed, indicating an increase in excitation since January, 1941. Several spectrograms of AX Per were obtained in January and February, 1942, with a dispersion of 40 A/mm at λ 3933 (Pl. XV). The following facts have been noted:

1. The [*O* ii] lines are fairly strong (int. 4 and 2); this is the first time that these lines have reached such an intensity since our observations were started in September, 1939. This suggests that the density has decreased appreciably since August, 1941, at least in the outer nebular regions where [*O* ii] originates. It is known that the transitions of nebular type of [*O* ii] have extremely low transition probabilities.
2. The intensity ratio of the auroral and nebular transitions of [*O* iii] has decreased since August, 1941, also indicating a decrease in density.
3. The comparisons with August, 1941, and January, 1941, are summarized in

---

* *Contributions from the McDonald Observatory, University of Texas,* No. 56.

[1] For reviews of the problems of gaseous shells see O. Struve, *Ap. J.*, **95**, 134, 1942, and P. Swings, *Ap. J.*, **95**, 112, 1942.

[2] *Ap. J.*, **95**, 152, 1942. Previous reports: *Ap. J.*, **91**, 607, 1940; **94**, 298, 1941. In our first paper (*Ap. J.*, **91**, 607, 1940), the line λ 3705.0 of Table 29 should be identified with *He* i, and the line λ 3820.4 is a blend of [*Fe* v] and *He* i.

Table 1. Compared with 1939, [*Fe* VII] 3587 has increased in intensity relative to *O* III 3444 (fluorescence line).

4. The Balmer series may be followed to H_{25}; H_{16}, H_{18}, and H_{20} are abnormally strong, but the blending elements are not identified with certainty. Using the formula of Teller and Inglis[3] on the termination of spectral series brought about by static Stark effect due to charged particles, we obtain for the regions of hydrogen emission an electron density

$$N < 10^{12} \text{ per cm}^3 .$$

5. The $4f^2F^0 - ng^2G$ series of *He* II is observed to at least $n = 21$.

6. The relative intensities of the singlets and triplets of *He* I are intermediate between those in nebulae and those in low-excitation objects like RW Hydrae (see sec. II).

7. *Si* I (λ 3905, int. 0) and *Ca* II (*K*, int. 1) are present, but they may belong to the late-type companion. [*S* II] (int. 2^+ and 1) and [*K* V] (int. 1) are also present. [*S* II] was not observed previously; a line of [*Fe* V] (int. 2) appears at λ 4072 between the two [*S* II] lines. *Fe* II 4179 (int. 1^+) is well separated from [*Fe* V] 4181 (int. 1^+).

TABLE 1

LINE INTENSITIES IN AX PERSEI IN JANUARY, 1942
COMPARED WITH INTENSITIES IN AUGUST, 1941
AND JANUARY, 1941

Elements	Jan. 1942 / Aug. 1941	Jan. 1942 / Jan. 1941
[*Ne* III]/*H*, *He* I......	Stronger	Same
N III/*H*............	Stronger	Probably weaker
Fe II...............	Same	Stronger
N III/*He* I...........	Stronger	Probably weaker
[*O* III]/*He* I..........	Stronger	Weaker
[*Fe* VII]/*He* I........	Same	Much stronger
$\frac{He\ \text{I}\ 4388^*}{He\ \text{I}\ 4026}$..........	About the same	Probably weaker

* $\lambda\,4388 = 2p^1P^0 - 5d^1D$; $\lambda\,4026 = 2p^3P^0 - 5d^3D$.

8. The late-type absorption features have about the same radial velocity as the bright lines.

9. The physical conditions in the nebular region have become such that [*Fe* V] and [*Fe* VI] appear with considerable intensity, making it the first striking example of this type (see Pl. XV). In the ultraviolet region a conspicuous line appears at λ 3664 which is the $^4F_{3\frac{1}{2}} - {}^2D_{2\frac{1}{2}}$ transition of [*Fe* VI]. Several other strong lines of [*Fe* VI] appear, especially in the visual region, although observations in the visual region are complicated by the presence of the late-type features belonging to the M-type companion. As for [*Fe* V], it is mainly characterized by λλ 3892 ($^5D_4 - {}^3F_4$), 3839 ($^5D_3 - {}^3F_3$), 3896 ($^5D_3 - {}^3P_2$), and 4071 ($^5D_2 - {}^3P_1$). It may be noted that these strongest lines correspond to the same transitions as the strongest lines of [*Fe* III], this being due to the fact that *Fe* III and *Fe* V have complementary electronic configurations $3d^6$ and $3d^4$ with regard to the half-closed shell $3d^5$. The lines λ 3892 and λ 3896 give a striking doublet to the red of H_8, whereas λ 3839 is near H_9; λ 4071 lies between the two [*S* II] lines and may have been mistaken for [*S* II] in previous descriptions of nova spectra.

Since the spectra of [*Fe* V] and [*Fe* VI] may play an important role in peculiar stars,

---

[3] *Ap. J.*, **90**, 439, 1939.

especially in certain nebular stages of novae, we have summarized our results in Tables 2 and 3.

From the intensity of [*Fe* VI] 3664, we may infer that the lines of [*Mn* V] and [*Cr* IV] that might be easiest to detect are those corresponding to the same transition $^4F_{3\frac{1}{2}} - {}^2D_{2\frac{1}{2}}$, i.e., [*Mn* V] 4203.5 and [*Cr* IV] 4971.8; these lines are absent from AX Per.

For the lines of λ < 4200 our measured wave lengths of [*Fe* V] and [*Fe* VI] are better than the values predicted from the analysis of the far ultraviolet spectrum by Bowen. Our measured wave lengths of the ultraviolet [*Fe* VII] lines are λ 3586.31 and λ 3759.4, but the latter is blended with *O* III.

TABLE 2

[*Fe* V] LINES IN AX PERSEI (JANUARY–FEBRUARY, 1942)

Notation*	λ Pred.	λ in AX Persei	Int. in AX Persei
$^5D-{}^3F$ 4-4........	3892	3891.4	3–4
3-3........	3839	3839.3	2
2-2........	3795	....	Blended with H_{10}
3-4........	3820	....	Blended with *He* I
2-3........	3783	3784.2	1–2
1-2........	3755	3754.8	2 blended†
4-3........	3911	....	Absent
3-2........	3851	....	Blended with [*Fe* VI]
4-2........	3765	....	Absent
3-1........	3744	....	Absent
$^5D-{}^3P$ 3-2........	3896	3895.4	3
2-1........	4071	4071.4	2
1-0........	4181	4180.6	1
2-2........	3838	3839.3	2 blended
1-1........	4027	....	Blended with *He* I
4-2........	3970	....	Blended with $H\epsilon$
3-1........	4136	....	Absent
2-0........	4230	....	Absent
1-2........	3798	....	Blended with H_{10}
0-1........	4003	4003.7	1–0 blended†
$^5D-{}^3G$ 4-5........	3430	3430.4	1–0
3-4........	3407	3405.8	1–0
2-3........	3400	?3403.1	0–1

* The $^5D - {}^3G$ transition is very weak. The situation with respect to $^5D - {}^3H$ is confused because of blends, but this multiplet is probably absent. There is no evidence of other transitions.

† The two lines measured in AX Per at λ 3754.8 and λ 4003.7 cannot be due entirely to [*Fe* V], since they are also present in CI Cygni, in which [*Fe* V] is very faint (see Pl. XVI). As is apparent from Plate XVI, *He* I, *Si* I, *Si* II, *Ca* II, and *Fe* II are stronger in CI Cyg (April, 1942) than in AX Per (February, 1942); although, from the intensity ratios [*Fe* VII]/[*Fe* VI]/[*Fe* V], CI Cyg reveals at the same time higher ionizations than AX Per. Hence CI Cyg combines very high and very low ionizations without intermediate stages to an extent still more pronounced than AX Per. A number of lines remain unidentified in CI Cyg and will be discussed later.

RW Hydrae.—This object has the remarkable characteristic of showing the complete *O* III spectrum in emission.[4] Plate XVII shows the $3s^3P^0 - 3p^3D$ and $3s^1P^0 - 3p^1S$ multiplets, without the usual enhancement of λ 3759.87 ($3s^3P^0_2 - 3p^3D_3$), which characterizes the line excitation by *He* II 303 in nebulae. The relative intensities of the *O* III lines are about the same as in the WC star BD+30°3639. But whereas BD+30^{0}3639 contains oxygen and carbon, RW Hydrae shows oxygen and nitrogen but no carbon. Thus it appears probable that the bright *O* III lines belong to a nebulosity and not to an exciting star of Wolf-Rayet type; the *O* III lines are also too sharp to belong to a normal Wolf-

---

[4] *Proc. Nat. Acad. Sci.*, **26**, 458, 1940.

Rayet star. There is no trace of [*Ne* v] lines. The Balmer series is observed to H_{31}. The *He* I singlet, λ 4388 ($2p^1P^0 - 5d^1D$), is stronger than the triplet λ 4026 ($2p^3P^0 - 5d^3D$), in striking contrast with the nebulae. The increase in excitation observed between 1940 and 1941[5] has continued, as is shown by the intensity decrease of *Ca* II relative to *He* I and by other criteria.

The excitation mechanisms will be discussed in section II. The radial velocities of the emission and absorption lines are identical and are the same as in 1940.

Z Andromedae.—Since August, 1941, the [*Ne* v] lines have increased considerably in intensity, so that the present appearance of the spectrum, six months after the minor outburst of 1941, is similar to the appearance in August, 1940,[6] approximately nine months after the major outburst of 1939 (Pl. XVIII).

TABLE 3

[*Fe* VI] LINES IN AX PERSEI (JANUARY–FEBRUARY, 1942)

Notation	λ Pred.	λ in AX Persei	Transition Probability*	Int. in AX Persei
$^4F-{}^2D$ 3½-2½	3664	3662.6	0.95	4
2½-1½	3558	3555.6	.68	1
2½-2½	3576	3577.9	.12	0–1
1½-1½	3495	3496.5	.37	1–0
$^4F-{}^2G$ 4½-4½	5177	5177	.56	3
3½-4½	4969	4970	.22	1
3½-3½	5147	....	.22	†
2½-3½	4974	4974	.20	1
3½-2½	5429	5430	.081	1
2½-2½	5237	....	.022	†
$^4F-{}^2H$ 4½-5½	3675	....	.0013	Probably absent
3½-5½	3569	....	.000046	Absent
4½-4½	3740	?	.0056	1 uncertain
3½-4½	3630	....	.0033	Absent
2½-4½	3543	....	.000082	Absent
$^4F-{}^2P$ 2½-½	3849	3851.8	.0042	0
1½-½	3775	....	.0067	Probably absent
2½-1½	3891	3891.4	.42	Blended with [*Fe* v]
1½-1½	3815	3813.9	.27	1–2
$^4F-{}^4P$ 3½-2½	5429	5430	.08	1 blended
2½-2½	5237	....	.022	†
3½-1½	5632	....	.15	†
2½-1½	5425	5424	.13	1 blended
1½-1½	5279	....	.048	Blended with [*Fe* VII]
2½-½	5486	....	.13	†
1½-½	5336	....	0.23	†

* From S. Pasternack, *Ap. J.*, **92,** 129, 1940.

† Observation difficult or impossible because of late-type features.

Very striking changes are observed in the intensity of *O* III 3444, excited by *He* II 303. This intensity appears to be very sensitive to changes in the density or velocity distribution in the ejected shell.

T Coronae Borealis.—The presence of bright *Fe* II lines in T CBr increases its simi-

---

[5] *Ap. J.*, **94,** 296, 1941.

[6] *Ap. J.*, **93,** 356, 1941. In Table 1 of this paper the lines λλ 3277.0 (1E), 3281.1 (1E), and 3323.6 (1E) should be attributed to *Fe* II.

larity to Z And, although the absence of [*Ne* v] in T CBr shows that the excitation still remains lower than in Z And.

A comparison between T CBr and Z And is especially interesting in the region $\lambda < 3400$ A.[7] Like Z And, T CBr shows *O* III 3340 (fluor.), *Fe* II 3323, *O* III 3312 (fluor.), *Fe* II 3277; but there is no trace of [*Ne* v].

Z Canis Majoris.—The spectrum of this variable star has been described near maximum brightness by Merrill[8] and near minimum brightness by us.[9] Spectrograms were obtained in January, 1942, with a dispersion of 40 A/mm at λ 3933, when the star was about of the same brightness as when observed by Merrill ($m_{\mathrm{vis}} \sim 9$). Our spectrograms (Pl. XIX) show strong Balmer lines (in pure absorption from H_{15} to H_9; the emission begins faintly at H_8 and increases regularly toward $H\alpha$); present are *Ca* II (*K:* int. 5E, 5A; *H* blended with $H\epsilon$); *Ti* II (λλ 3685, 3759, 3761, all in absorption only); *Fe* II (many permitted lines; no forbidden transitions are present, except a doubtful λ 4359). *He* I is absent. These features agree with Merrill's description. The differences between the radial velocities of the emission and absorption components are at present 192 km/sec for *Ca* II, and 390 km/sec for the mean of $H\epsilon$, $H\delta$, and $H\gamma$.

The violet-displaced absorption components of the Balmer and *Fe* II lines are fairly broad, and the displacements are very large. In this respect the star should be compared to the P Cygni object of higher excitation, CD−27°11944,[10] but this latter star shows *He* I, *N* II, and [*Fe* II] lines.

Merrill made the observation that the absorption components were not seen for all *Fe* II lines. This behavior of *Fe* II deserves careful scrutiny. We have listed in Table 4 the classified *Fe* II lines which are observed on our spectrograms.

The strong *Fe* II lines, λ 4233 and λ 4352, are present only as fairly sharp emissions, with no absorption components; but the lines λλ 4924, 5018, and 5169 have strong, violet-displaced absorption components. Actually, those *Fe* II lines which have the lower level a^{6}S possess strong absorption components, whereas those which have the lower levels b^{4}P, b^{4}F, or a^{4}G are present in emission only. Yet all the excitation potentials are very similar, and so are the intensities in the sun and in α Cygni. The *Nf*-values are also very similar; according to C. W. Allen,[11] λ 4924 and λ 4352 have the solar equivalent widths 0.131 and 0.124 A and the log *Nf*-values 3.14 and 3.13, respectively. The level a^{6}S has the same multiplicity as the ground level a^{6}D. The different behavior of the multiplets a^{6}S − z^{6}P^0, z^{6}F^0, compared with b^{4}P − z^{4}D^0, z^{4}F^0, b^{4}F − z^{4}D^0, z^{4}F^0, and a^{4}G − z^{4}F^0, is perhaps a phenomenon similar to the selectivities observed among the lines of *Si* III, *N* III, *N* IV, *C* III, *N* II, etc., in shells of higher excitation. This phenomenon is not unusual in astronomical sources. It is present in 17 Leporis, CD−27°11944,[12] BD+47°3487,[13] and HD 160529.[14] In some of these P Cygni type stars the velocities obtained from the different *Fe* II multiplets are quite different.[14]

---

[7] For comparison purposes the spectra of a number of nebulae were taken in the region λλ 3100–3400. In IC 2165 (high-excitation nebula) the lines observed are: [*Ne* v] 3346 (int. 5), *O* III 3340.5 fluor. (int. 4), *O* III 3312 fluor. (int. 3), *O* III 3299 fluor. (int. 1), *He* II 3203 (int. 3), *O* III 3132 fluor. (int. 4). In IC 418, only the *He* I lines λ 3356 (int. 1) and λ 3188 (int. 4) are observed. Similarly, only *He* I is observed in the Orion nebula. In this connection it is worth noticing that, whereas the [*Fe* III] lines λ 4658 (^{5}D$_4$−^{3}F$_4$) and λ 5270 (^{5}D$_3$−^{2}P$_1$) are definitely present on our spectrograms of the Orion nebula (in agreement with Wyse's observations [*Ap. J.*, **95**, 356, 1942]), there is no trace of the ^{5}D−^{3}D and ^{5}D−^{7}S forbidden multiplets of [*Fe* III]; these should appear in the region λλ 3200–3400.

[8] *Ap. J.*, **65**, 291, 1927.

[9] *Ap. J.*, **91**, 576, 1940.

[10] *Ap. J.*, **93**, 352, 1941.

[11] Mem. Commonwealth Solar Obs., Canberra, **5**, Part II, 91, 1934.

[12] *Ap. J.*, **93**, 352, 1941.

[13] *Ap. J.*, **91**, 577, 1940.

[14] *Ap. J.*, **91**, 592, 1940. In this connection it may be remarked that in the P Cyg type star, AG Peg, Merrill (*Ap. J.*, **95**, 386, 1942) measured a sharp bright line at λ 3938.3 A, whose identification with *Fe* II (λ 3938.29) he considered as improbable. There is little doubt that the line should actually be attributed to *Fe* II, since we measured a strong line at λ 3938.29 on our Coudé plates of α Cyg; in this

Of and W stars.—It is known that the Of shells often have variable spectra,[15] the best example being HD 108.[16] Until about November, 1940, the bright lines were decreasing in intensity, so that on November 12, 1940, $H\beta$ appeared purely in absorption, and the *N* III emission had also become very weak. Since then the intensities of the emission lines have been steadily increasing. In January, 1942, the bright component of $H\beta$ was fairly strong, and a faint emission component had appeared at $H\gamma$. The bright lines of *N* III (λ 4634 and λ 4641), *He* I (λ 5876), *He* II (λ 4686), and *C* III (λ 5696) had recovered an appreciable intensity. All have faint violet-displaced absorption components. The bright *C* III line, λ 5696, has approximately the same intensity as the *N* III and *He* II lines.

TABLE 4

Fe II LINES IN Z CANIS MAJORIS

MULTIPLET DESIGNATION	TRANSITIONS	LABORATORY WAVE LENGTH	LAB. INT.	INT. IN α CYGNI*	INT. IN Z CMA	
					Abs.	Em.
$b^4F-z^4F^0$....	2½-3½	4178.85	8	8	.....	0–1
$b^4P-z^4D^0$...	2½-3½	4233.17	11	12	.....	3
	1½-2½	4351.76	9	10	.....	2
	½- ½	4385.38	7	8	.....	1
$b^4F-z^4D^0$...	1½- ½	4508.28	8	7	.....	2
	2½-1½	4522.63	9	7	.....	2 blended
	3½-2½	4549.47	10	15 bl.	.....	2
	4½-3½	4583.83	11	9	.....	2
	3½-3½	4620.51	3	4	.....	1
$b^4F-z^4F^0$....	2½-2½	4515.34	7	7	.....	1
	3½-3½	4555.89	8	6	.....	1
	4½-4½	4629.34	7	9	.....	1–2
$a^6S-z^6P^0$....	2½-1½	4923.92	12	10	3	3
	2½-2½	5018.43	12	10	3	3
	2½-3½	5169.03	12	8	3	4
$a^4G-z^4F^0$....	2½-1½	5197.57	6	7	.....	1
	3½-2½	5234.62	7	7	.....	1
	4½-3½	5275.99	7	6	.....	1
	5½-4½	5316.61	8	8	0	2
$a^6S-z^6F^0$....	2½-3½	5284.09	3	4	0	1–0

* *Ap. J.*, **94,** 344, 1941.

With regard to the W stars, we wish to point out that, as far as we know, the brightest Wolf-Rayet star in the sky, γ Velorum,[17] has not been accurately classified, although a

---

latter star the line *Fe* II 3938.29 is stronger than *Fe* II 3938.97, in contradiction to the laboratory intensities according to Dobbie. In our first paper on AG Peg (*Ap. J.*, **91,** 546, 1940) the intensities of *He* I 4471 should be 7A and 7E, instead of 1A, 1E.

[15] *Ap. J.*, **95,** 122, 1942.

[16] *Pub. A.S.P.*, **53,** 35, 1941.

[17] $\alpha(1900)$ $8^h6^m27^s$; $\delta(1900)$ $-47°03'$; $m_{\text{vis}} = 2.22$; HD 68273; CD$-46°3847$.

1942ApJ....96..254S

good description was published by Miss Cannon forty years ago.[18] A spectrum of this star, as obtained at the McDonald Observatory, is given in Plate XX. It is apparent at once that the star is characterized by the five strong emission lines—*C* III + *C* IV 4650 (int. 10), *He* II 4686 (int. 5), *C* III 5696 (int. 8), *C* IV 5805 (int. 7), and *He* I 5876 (int. 5)—each of them possessing a violet-displaced absorption component. *C* IV 5805 is sharper than *C* III 5696. The other faint emissions in the spectrum belong to *He* I, *He* II, *C* II, *C* III, *C* IV, *O* III, and *O* IV. According to the criteria adopted by the I.A.U., γ Velorum is a typical WC7 star. As far as we know, the trigonometric parallax of γ Velorum is not known.

Several spectrograms have been obtained of the Of star ζ Puppis, which displays fairly strong bright lines of *He* II and *N* III, but no trace of *C* III.

II. EXCITATION MECHANISMS IN SHELLS

It is usually assumed that the three mechanisms of excitation of emission lines in nebulae are: (1) the recombination of ions and electrons, the ionization being produced by absorption of the ultraviolet radiation of the exciting star and of the nebula itself; (2) the excitation by impacts from electrons ejected by mechanism No. 1; and (3) the excitation of a few selected lines of *O* III and *N* III by the resonance line of *He* II.[19]

These three mechanisms of line excitation in nebulae have been discussed by various authors, especially by Bowen,[20] and they have accounted satisfactorily for the nebular spectra.

But the situation is different when we consider various stellar envelopes of much smaller extension, such as the Of, P Cygni, and Be shells, in which a number of observations cannot be explained by these three mechanisms. One of the most striking departures is the selectivity observed among the transitions of *He* I, *N* III, *N* IV, *C* III, *Si* III, *N* II, *Fe* II, etc., when they appear as bright lines. This selectivity has been considered in several recent papers.[21] We now suggest that fluorescence excitation by the underlying radiation may account for the observed selectivity, at least when combined with the general physical properties of the shells: the physical dilution of the exciting radiation, the stratification of the layers, the velocity and density distribution within the shell. When a variation occurs, the relaxation time has also to be considered. The fluorescence mechanism excited by the underlying radiation may in principle be treated by the theory of cyclical transitions of Rosseland.[22] Astronomical applications have been discussed by H. H. Plaskett,[23] C. H. Payne,[24] O. Struve,[25] and others, but have been more or less neglected in recent years. The spectroscopic material on peculiar stars, which we have gathered during the last three years at the McDonald Observatory permits a detailed observational discussion of the mechanism in a wide variety of shells.

The fluorescence mechanism may become active when the mean interval of time between two collisions becomes longer than the average lifetime of an atom in the excited states considered. In many shells we can determine the maximum value of the electron density by applying the formula of Inglis and Teller on the termination of spectral series; the maximum densities obtained in this way for nebulae, Of, P Cygni, or Be shells are

---

[18] *Harvard Ann.*, **28**, Part II, 244, 1901. See also Perrine, *Ap. J.*, **52**, 39, 1920; F. McClean, *Spectra of Southern Stars*, Pl. 6, London, 1898.

[19] Some other monochromatically excited fluorescences may exist in nebulae, e.g., the emission of *He* II 4686 (Bowen, *Ap. J.*, **81**, 1, 1935).

[20] *Ibid.*

[21] *Ap. J.*, **91**, 570, 1940; **95**, 122, 1942. Also sec. I of the present paper.

[22] *Ap. J.*, **63**, 218, 1926.

[23] *Pub. Dom. Ap. Obs., Victoria*, **4**, 119, 1928.

[24] *M.N.*, **92**, 368, 1931.

[25] *Ap. J.*, **81**, 66, 1935.

of the order of 10^{12}–10^{13} electrons per cm^3.[26] On the other hand, at an electron temperature of 25,000° the critical electron density for which the mean interval between two electron impacts on an atom becomes equal to 10^{-7} seconds, is about 10^{15} electrons per cm^3. Consequently, the densities in Of or P Cygni shells are favorable to fluorescence excitation.

It should be pointed out that the exciting radiation reaching an atom A at a specific location in the shell is usually different from the black-body radiation at the effective stellar temperature T_e, reduced by a geometrical dilution factor W independent of λ. Even if the photospheric radiation is that of a black body at a temperature T_e, the radiation reaching A will usually be depleted by discrete or continuous absorption features or will be enhanced by emission features. For example, strong Lyman absorption lines in an underlying star should strongly affect the intensities of the Balmer lines excited by fluorescence in an outer stationary shell.

A comparison with the classical laboratory experiments on atomic and molecular fluorescence is useful. The fluorescence of any atomic or molecular vapor excited in the laboratory by continuous "white light" is totally different from that excited monochromatically. Whenever the stellar exciting radiation possesses absorption or emission features, the resulting fluorescence should be considered as a superposition of monochromatically excited patterns, each of these having a specific intensity.[27] Similar considerations should be applied to atomic ionization and molecular dissociation.

The absorption coefficient for the fluorescence excited by the underlying radiation is much larger than the coefficient of photoelectric absorption. But, since the photoionization is produced by the continuous range of wave lengths beyond the ionization limit, the recombination mechanism will usually be more efficient than the fluorescence process, unless the ultraviolet ionizing region of the underlying radiation is depleted.

The relative efficiency of the recombination and fluorescence mechanisms may be stated as follows: As a first approximation, the probability of the capture of an electron by an ion A^+ (recombination mechanism) is proportional to $\rho_{A^+} \times \rho_e$, if ρ designates the density. If collisions of the second kind are absent, the probability of the fluorescence excitation of a specific line is proportional to $\rho_A I_*$, if I_* is the amount of exciting radiation in the appropriate wave lengths required for the excitation of the line. For example, in the case of the bright lines of *He* I, the relative efficiency of the recombination and fluorescence mechanisms is proportional to

$$\frac{\rho_{He^+} \cdot \rho_e}{\rho_{He}} \times \frac{1}{I_*} .$$

For a given density, ρ_{He^+}/ρ_{He} and ρ_e depend upon the amounts of radiation available beyond the ionization limit of *He* I and beyond the Lyman limit, respectively. I_* depends in a complicated manner on the spectral distribution of the exciting radiation, account being taken of the relative velocities of the excited atoms with respect to the regions emitting the exciting radiation.

In the discussions which follow, the ejection mechanism has been adopted for the W, Of, and P Cygni stars, as well as for the novae. Serious objections to this mechanism have recently been found, which tend to cast doubt upon the ejection hypothesis, as applied to Wolf-Rayet shells.[28] One essential difficulty is that no occultation effect is found in the profiles of the emission bands, whereas two spectroscopic observations seem to indicate that the radius R of the shell is not much larger than the radius r of the

---

[26] See sec. I; also *Ap. J.*, **95**, 124, 1942.

[27] The peculiar structure of the molecular bands in comets has been explained in this manner by taking into account the influence of the Fraunhofer lines of the exciting solar radiation (Swings, *Lick Obs. Bull.*, **19**, 131, 1941).

[28] Minkowski, *Ap. J.*, **95**, 243, 1942; O. C. Wilson, *Ap. J.*, **95**, 402, 1942; Swings, *Ap. J.*, **95**, 112, 1942.

photospheric surface. The first observation is that there is no appreciable strengthening of the *He* I absorption lines having lower metastable level: *He* I 3889 is often strong in absorption; but in such stars the other *He* I lines arising from nonmetastable levels are always present and the intensity ratio of λ 3889 and λ 5876 is not abnormal. The second observation is that the widths of the violet-displaced absorption lines always give a value of the order of 2 for the ratio R/r, if we attribute this width to the spread of the ejection-velocity component along the line of sight, within the cylinder of sight. But the interpretation of these two observations, as due to a small value of R/r is ambiguous. The exciting radiation responsible for the populations on the various *He* I levels is extremely different from black-body radiation, because of the numerous transformations occurring in the deeper layers. As a result the dilution effects must be quite different from the classical case in which only the geometrical dilution of the continuous radiation of the central star is considered. It is probable that in the shell of a W star the excitations are produced mostly by emission lines of the shell itself, which attain great radiation densities and are, therefore, subject to little or no dilution. The enhancement of λ 3889 is probably reduced, as compared with the case of pure geometrical dilution. As for the widths of the absorption lines, they may in part be due—even neglecting the possible broadening due to turbulence—to the dispersion in ejection velocity within the absorbing layer.

Moreover, the spectroscopic characteristics of W stars have such deep analogies to the phenomena in novae (in which the ejection is undoubtedly the essential mechanism), that it would be very difficult to abandon altogether the ejection hypothesis for the W stars. A high velocity of axial rotation is not excluded for a star of high temperature; but how could we explain a wide range in rotational widths among lines of different ionization potentials? Excessive turbulence does not appear very satisfactory. Hence it is advisable to continue to use the ejection mechanism as a working hypothesis and to try to explain the absence of the occultation effect in the emission profiles, either by adopting a value of R/r of the order of 4 for the *He* I emission shell or by assuming a re-absorption phenomenon which is not yet clearly understood.[29]

We shall now consider some of the atoms which show peculiar intensities not accounted for by the usual three mechanisms mentioned at the beginning of section II.

Helium I.—Collisional excitation is excluded for the *He* I lines because of their high excitation potentials. The two essential mechanisms are thus the capture of electrons by ions He^+ and the absorption of underlying radiation. The first mechanism is absent if the helium atoms are mostly un-ionized, either because the temperature of the underlying star is too low or because the radiations of wave lengths shorter than λ 504 (ionization limit of *He* I) have been strongly depleted by absorption in the deeper layers. As for the second mechanism, it depends essentially upon the spectral distribution of the underlying radiation, account being taken of the radial-velocity effects. It is reasonable to assume that the interval between the collisions of second kind in the shell is much longer than 10^{-8} seconds. If a large amount of continuous photospheric radiation has been converted into bright lines, coincidences of wave lengths, taking into account the velocities, may produce abnormally high intensities of certain bright *He* I lines in the shell. Conversely, the presence of intense absorption lines or continua at the wave lengths of the *He* I transitions connected to the ground level $1s^1S$ may reduce the intensities of certain bright *He* I lines in the shell.

Fluorescence excitation of the *He* I spectrum will have a tendency to enhance the singlet system relative to the triplet system, since the ground level of *He* I is $1s^1S$, since the lowest triplet level $2s^3S$ corresponds to a high-excitation potential (19.74 v.) and since there are no intercombinations between singlets and triplets. The exciting wave-length range is approximately λλ 500–580.

---

[29] This should not be construed as an attempt to diminish the seriousness of the difficulties encountered by O. C. Wilson in the case of the spectroscopic binary HD 193576.

Generally speaking, the relative intensities of the singlets and triplets of *He* I will give us some indication concerning the relative importance of excitation by electron captures or by absorption of underlying radiation. In objects of high excitation, like nebulae[30] (NGC 6572, 7027, and 7662), CI Cyg, RX Pup, etc., the *He* I singlets are much fainter than the triplets. For such a comparison the two series $2p^1P^0 - nd^1D$ and $2p^3P^0 - nd^3D$ are particularly suitable, especially the lines λ 4388 ($2p^1P^0 - 5d^1D$) and λ 4026 ($2p^3P^0 - 5d^3D$). When the *He* I spectrum is produced in a laboratory discharge, the singlets are also much weaker than the triplets, in agreement with the recombination hypothesis. In the high-excitation objects most of the *He* atoms are in the He^+ and He^{++} states, so that the recombination mechanism must be important. In applying these considerations, care must be taken not to overlook the stratification effects. It may be that neutral *He* atoms are abundant on the outskirts of a high-excitation object, where the underlying radiation has been so depleted in ultraviolet wave lengths that the ionization of *He* is considerably reduced. For these neutral *He* atoms the fluorescence excitation may again be preponderant. This is probably the case in the high-excitation shell of AX Per at certain stages of its nova-like evolution.

Conversely, objects of relatively low excitation, such as T CBr, RW Hya, +11°4673, P Cyg, the three nova-like binaries AX Per, RS Oph, and Z And at low-excitation stages, etc., will be rich in neutral helium; the fluorescence excitation of these *He* I atoms will enhance the singlets relative to the triplets.

The observations are summarized in Table 5. A comparison of λ 4388 and λ 4026 shows that the intensity ratio of these two lines is definitely larger than one in RW Hya, whereas it is smaller than one in all high-excitation objects and in the laboratory. In the same object a variation in excitation influences the intensities of the singlets and of the triplets to a different extent, as can be seen in the case of AX Per.

When cyclical transitions are active in the production of *He* I emission lines in a shell, they must also be important for the absorption lines arising in the shell. If the underlying radiation is depleted by absorption features or enhanced by emissions, the usual dilution effects on the absorption lines may be considerably modified.

The observations reported here are fundamentally different from those of absorption shells which led to the recognition of geometrical dilution in these shells.[31] If the exciting radiation is that of a black body, geometrical dilution tends to increase the populations of the triplet levels at the expense of the populations of the singlet levels. Increasing temperature has a tendency to reduce this effect and to make the populations approach those given by the Boltzmann relation. In the peculiar stars which we are considering the exciting temperatures are probably very high, but the dilutions are also great, as is attested to by the presence of many forbidden lines. Hence, the great intensity of the singlets in RW Hya and similar stars cannot be explained simply by an application of the theory of geometrical dilution.

To produce such an enhancement, we must have (*a*) a mechanism of line excitation which functions actively among the singlets and which does not require an equivalent enhancement of the mechanism of photoelectric ionization and (*b*) very low density, in order to prevent exchanges between singlets and triplets through collisions. Condition (*b*) is certainly fulfilled. Mechanism (*a*) may almost certainly be identified with the action of strong line emission in the *He* I series ($1^1S - n^1P^0$) produced in the lower levels of the nebulae. We can qualitatively think of this mechanism as increasing the excitations within the singlet system without increasing them in the triplet system. To obtain an idea of the order of magnitude of the effect, we consider a system of four levels: (1) the ground level of *He* I, (2) the combined excited levels of the singlets, (3) the combined triplets, and (4) the continuum. We treat the latter as a discrete level and apply to it

---

[30] Bowen and Wyse, *Lick Obs. Bull.*, **19**, 1, 1939.

[31] Struve and Wurm, *Ap. J.*, **88**, 84, 1938.

TABLE 5

BEHAVIOR OF *He* I EMISSION LINES IN VARIOUS BRIGHT-LINE OBJECTS*

DESIGNATION	λ	LAB. INT.†	OBJECTS OF HIGH EXCITATION								OBJECTS OF LOWER EXCITATION								
			NGC 6572	NGC 7027	NGC 7662	CI Cyg	RX Pup	N Her (in 1940)	AX Per		AX Per		RW Hya Jan 1942	T CBr	AG Peg	Z And	RS Oph	WC	P Cyg
									Sept. 1939	Aug. 1941	Jan. 1941	Jan. 1942							
$2s^1S-3p^1P^0$...	5015.67	100	4	5	.....	.....	1 bl.	.....	0	1	1	2	3	.....	.....	3	2	.....	10
$4p^1P^0$...	3964.73	50	.....	.....	.....	1	.....	bl.	1	.....	.....	3	2	1	3	2	.....	.....	11
$5p^1P^0$...	3613.64	30	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1	.....	.....	.....	6
$2p^1P^0-4d^1D$...	4921.93	50	3	6	4	1 bl.	1 bl.	1	1 bl.	1	2+	3	3	2	.....	2 bl.	2	.....	10
$5d^1D$...	4387.93	30	.....	2	1	1	0–1	.....	1	1	2+	3	4	1	5	2	1	3 bl.	6
$6d^1D$...	4143.76	15	.....	3	1	1	.....	.....	1	1	2+	2	2	.....	3	1	.....	1–2	2
$7d^1D$...	4009.27	10	.....	.....	1	1	.....	0	.....	.....	1	1	2	.....	2	1	.....	.....	2
$2p^1P^0-4s^1S$....	5047.74	15	2	5	.....	.....	.....	.....	.....	.....	.....	.....	1	.....	.....	.....	.....	.....	.....
$2s^3S-3p^3P^0$...	3888.65	1000	bl.	bl.	bl.	3 bl.	2 bl.	6 bl.	7 bl.	5 bl.	2 bl.	7 bl.	7 bl.	4	8 bl.	5 bl.	bl.	5 bl.	bl.
$2p^3P^0-3d^3D$...	5875.62	1000	25	50	30	5	5	4	9	7	7	8	5	5	.....	5	8	.....	30
$4d^3D$...	4471.48	100	.....	6	5	3	2	3	2	2	3	4	3	2	6	3	1	3	20
$5d^3D$...	4026.2	70	.....	4	4	2	0–1	2	2	1	2	3	2	.....	4	2	.....	3	20
$6d^3D$...	3819.6	50	.....	.....	.....	1 bl.	.....	2	1 bl.	.....	.....	2 bl.	1–2	.....	3	2	.....	1 bl.	9
$7d^3D$...	3705.0	30	.....	.....	.....	.....	.....	.....	1	.....	.....	1	bl.	.....	3	1+bl.	.....	bl.	bl.
$2p^3P^0-4s^3S$....	4713.2	40	.....	6 bl.	10 bl.	.....	1–0	.....	3 bl.	1	2	4	1	.....	3	1+	1	.....	10
$5s^3S$....	4120.8	25	.....	3	1	0 bl.	.....	.....	.....	.....	.....	1+	2	.....	2	1	0+	3 bl.	5
$6s^3S$....	3867.5	15	.....	.....	.....	.....	.....	.....	.....	.....	.....	bl.	bl.	.....	.....	.....	.....	.....	bl.
$7s^3S$....	3732.9	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	bl.	.....	.....	.....	.....	.....	.....	bl.

---

* When no intensity is indicated, the line is absent or the region has not been observed.

† From the *M.I.T. Wavelength Tables.*

the usual relations between the Einstein coefficients. Further, we neglect induced transitions, neglect all statistical weights, and assume that[32]

$$
\begin{aligned}
&A_{24}=A_{34}\,, && \rho_{ik}=\frac{1}{e^{\frac{h\nu_{ik}}{kT}}-1}\,,\\
&A_{42}=A_{43}\,, && \\
&A_{42}=A_{41}\,, && \\
&A_{21}=yA_{41}\,, && \rho_{14}=\rho_{12}\rho_{24}\,.\\
&\rho_{24}=\rho_{34}\,, &&
\end{aligned}
$$

We assume that level 3 is metastable and that there are no transitions between levels 2 and 3. If β is the dilution factor for transitions 1 → 4, 2 → 4, 3 → 4, and γ that for transitions 1 → 2, we have for the ratio of singlets to triplets

$$\frac{n_2}{n_3}=\frac{2\gamma y+\beta\rho_{24}}{y+\gamma y+\beta\rho_{24}}\,.$$

In our case y is large and $\gamma \gg \beta$, while $\rho_{24} < 1$. Hence, approximately,

$$\frac{n_2}{n_3}=\frac{2\gamma}{1+\gamma}\,.$$

The ratio n_2/n_3 approaches a constant when γ is large. This holds whenever y is finite, so that within the proposed scheme the singlets can never become stronger than the triplets. But, in practice, when y is very large and in consequence ionizations are infrequent, other mechanisms, such as collisions and forbidden transitions, will tend to depopulate the metastable level 3 and thereby increase n_2/n_3. It is, however, significant that in no case have the singlets been observed to be *much* stronger than the triplets.

Characteristic atoms observed in the Of shells.—The spectra of Of shells are characterized not only by *H*, *He* I, and *He* II but also by bright lines of *N* III, *N* IV, *N* V, *C* III, and *Si* IV. In the late Of stars, like 9 Sagittae, HD 108, etc., *N* III (λ 4634 and λ 4641) and *C* III (λ 5696)[33] display selectivities which cannot be explained by Bowen's mechanism.[34] In earlier Of stars, like BD+35°3930N, we observe bright lines of *N* III, *N* IV, *N* V, and *Si* IV, and the selectivity among the *N* III transitions is less pronounced than that in later Of stars. In all cases the observed spectrum is that of the underlying star, which has strong *N* III lines of its own, *plus* the spectrum of the shell.[35]

In O7f stars, like 9 Sagittae, the $3p^2P^0 - 3d^2D$ transitions of *N* III (λ 4634 and λ 4641) are present in emission (shell), whereas the $3s^2S - 3p^2P^0$ transitions (λ 4097 and λ 4103) are observed in absorption (star). In the earlier O5f objects, like BD+35°3930N, the absorption lines λ 4097 and λ 4103 of the star have disappeared, and there may even be faint emissions in their places; this means that the shell provides appreciable emission in the $3s^2S - 3p^2P^0$ transitions. The essential difference between O7f and O5f shells is that the ionization is much more pronounced in the latter. Accordingly, we may expect the *N* III recombination mechanism to be more efficient in O5f than in O7f stars. On the basis of the results obtained for the *He* I spectrum it is thus tempting to consider the possibility that the *N* III lines in O7f shells are due to fluorescence excited by the underlying radiation.

But we immediately encounter a serious difficulty due to the state of ionization in an O7f shell. A calculation was made recently,[36] assuming a temperature of 40,000° for the

---

[32] See O. Struve, *Proc. Amer. Phil. Soc.*, **81**, 216, 1939.

[33] The relative intensities of the *N* III and *C* III lines vary from star to star (*Ap. J.*, **95**, 128, 1942).

[34] *Ap. J.*, **91**, 563, 1940.

[35] The continuous absorption by the shell reduces the spectrum of the underlying star.

[36] *Ap. J.*, **95**, 124, 1942.

underlying star and an electron density of the order of 10^{13} per cm^3. In such conditions *He* is almost completely in the doubly ionized state He^{++}, N^{+} is practically nonexistent, N^{+++} is more abundant than N^{++} (by a factor of more than 100), and N^{++++} is somewhat less abundant than N^{+++}. Similarly, C^{+++} is much more abundant than C^{++}, and this in turn is more abundant than C^{+}.

Now, if we wish to attribute the emission of strong *N* III lines in O7f shells to a fluorescence effect, we have to assume that an important proportion of the nitrogen atoms are in the N^{++} state, instead of N^{+++} and N^{++++}, as obtained in the preceding calculation; otherwise the recombination spectrum would be observed. The ionization of N^{++} may actually be much lower than was stated in the preceding paragraph, since it requires wave lengths shorter than λ 261, which is not far to the red of the He^{+} ionization limit λ 228. Moreover, since the absorption lines of *N* III are very strong in the underlying star, we may expect that the continuous stellar spectrum is appreciably reduced beyond the ionization limit of N^{++} at λ 261. In other words, the underlying radiation must be depleted between λ 261 and λ 228 and still more beyond λ 228, thus reducing the ionization of N^{++}. Similar considerations may be applied also to C^{++} (ionization limit λ 259) and still more to O^{++} (ionization limit λ 226, very close to that of He^{+}).

The absorption of the stellar radiations at λ 374.44 and λ 374.20 by the N^{++} atoms of the shell will bring these to the level $3d\,^2D$ in one absorption process. According to the general theory of cyclical transitions in a field of diluted radiation,[37] there will be a number of downward transitions of longer wave lengths at the expense of λ 374. Especially λ 4634 and λ 4640 will be emitted and will lead to the $3p\,^2P^0$ level. From here a large number of possible upward and downward transitions arise that will reduce the intensity of $3s\,^2S - 3p\,^2P^0$ (λ 4097 and λ 4103) relative to λ 4634 and λ 4640. On the other hand, the odd level $3p\,^2P^0$ cannot be reached directly by one permitted transition from the ground level $2p\,^2P^0$. The total emission at λ 4097 and λ 4103 may thus be too weak to fill up the absorption lines of the underlying star. Moreover, the lower level $3s\,^2S$ may itself be populated by absorbing stellar radiations of wave lengths λ 451.87 and λ 452.23.

Since the absorption lines of *N* III are strong in the spectrum of the underlying star, we may ask whether enough stellar radiation of wave length λ 374 will reach and excite the N^{++} atoms of the shell, since the lines λ 374.44 and λ 374.20 should be expected to be strong in absorption in the stellar spectrum. But the effect of these absorption lines must be quite minor because of the radial velocities of the ejected atoms of the shell, relative to the stellar reversing layer. Actually, since no fluorescence of Bowen's type is excited in the O^{++} atoms by the resonance line of *He* II, we may assume that the differences of radial velocity existing between the different layers of the envelope are sufficient to shift the lines, which would otherwise coincide in wave lengths.

We have a similar case for *C* III and *N* IV. In O7f stars and in P Cyg[38] the line λ 5696 ($3p\,^1P^0 - 3d\,^1D$) of *C* III is observed in emission, whereas the line λ 4647.4 ($3s\,^3S - 3p\,^3P^0$), which is much stronger in the laboratory, is a pure absorption line. The ground level of *C* III is a singlet ($2s\,^1S$), and no intercombination has been found in the laboratory between singlets and triplets (except a doubtful faint one). The line λ 5696 may thus be excited by absorption of stellar radiation from the ground level of the C^{++} atoms. The excitation of *C* III 4647 would have to go through the triplet levels.

A similar observation may be made for *N* IV, whose ground level is a singlet ($2s\,^1S_0$); the line λ 4057 ($3p\,^1P^0 - 3d\,^1D$) appears in emission in O5f shells, whereas λλ 3479, 3483, and 3485 ($3s\,^3S - 3p\,^3P^0$), which are stronger in the laboratory and in ordinary reversing layers, appear only in stellar absorption. No intercombination is known for *N* IV between singlets and triplets.

---

[37] The dilution factor is of the order of 0.1 in the Of shell.

[38] *Ap. J.*, **91**, 574, 1940.

Strictly speaking, the populations in the lowest triplet, $2p^3P^0$, of *C* III and *N* IV (6.5 v. for *C* III; 8.3 v. for *N* IV) are quite comparable to the populations in the ground singlet level. Some factor must therefore exist which reduces the excitation to higher triplets, compared with the singlets. There may be more stellar radiation available to ionize the C^{++} or N^{+++} atoms from the $2p^3P^0$ level, so that the transitions from $2p^3P^0$ to the ionization continuum may not be neglected.

The case of *O* III is also interesting. The lowest singlet $2p^1D$ is only 2.5 v. higher than the ground term, $2p^3P$. The radiations required to ionize O^{++} from $2p^1D$ are depleted by an amount comparable to $2p^3P$. Moreover, there are strong intercombinations between the singlets and triplets. Hence the fluorescence spectrum excited by the underlying star should be similar to the complete recombination spectrum. For example, it is difficult to ascertain whether the complete spectrum of *O* III observed in RW Hya is produced by fluorescence or by recombination. From the fact that *He* I is to a considerable extent excited by fluorescence in RW Hya (strong singlets), we might at first sight expect that the *O* III spectrum is also produced by fluorescence. But this is not necessarily the case. The excitation of the observable *O* III lines by absorption from the three lowest levels, $2p^3P$, $2p^1D$, and $2p^1S$, requires wave lengths between λ 300 and λ 345 A.[39] It does not seem plausible to attribute the absence of bright lines of *O* III in 9 Sagittae to a depletion of the stellar spectrum in the region λλ 300–345. The nearest ionization limit to the red is that of O^+ at λ 353, but the *O* II absorption lines are very weak in 9 Sagittae. Hence the absence of bright *O* III lines in 9 Sagittae results probably from the conditions of this particular cycle. As a consequence, it would seem more logical to attribute the *O* III spectrum of RW Hya to a recombination process.

CHARACTERISTIC ATOMS OBSERVED IN THE P CYGNI OR Be SHELLS

The densities in most P Cyg or Be shells are lower than the critical densities at which the fluorescence mechanism ceases to operate. For example, the electron density in the shell of Pleione is of the order of 3×10^{11} per cm³;[40] in P Cyg (at least in the regions of hydrogen absorption) it is found to be lower than 10^{13} per cm³, according to the formula of Inglis and Teller. Hence we may expect the fluorescence excitation to be present, alone or together with the recombination mechanism.

The case of *He* I was considered previously. The most striking selectivities observed in P Cyg occur in *Si* III and *Si* II. In *Si* III the transitions $4p^1P^0 - 5s^1S$, $4p^1P^0 - 4d^1D$, $4p^3P^0 - 4d^3D$, whose lower levels are $4p^1P^0$ and $4p^3P^0$, appear in emission; whereas the transitions $4s^1S - 4p^1P^0$, $4s^3S - 4p^3P^0$, $3d^3D - 4p^3P^0$, whose higher levels are $4p^1P^0$ and $4p^3P^0$, are present in absorption only. Such behavior is so similar to that of *N* III in Of shells that it is plausible to consider it also as a result of cycles. The *Si* III spectrum presents also a striking similarity to *He* I. If we refer to Plate XVIII of the paper on P Cyg by Struve and Roach,[41] we notice that, whereas the triplet line $4p^3P^0 - 4d^3D$, λ 3806, is strong in absorption in τ Sco and 55 Cyg, the singlet line $4p^1P^0 - 4d^1D$, λ 3590, is extremely weak. The opposite is true for the emission in P Cyg, in which the singlet line λ 3590 is much stronger than the triplet line λ 3806. This is quite similar to the enhancement of the singlet lines relative to the triplets in the case of *He* I. Fairly strong absorption lines of *Si* IV are observed in the spectrum of P Cyg; their radial velocities are very different from those of the absorption lines of *Si* III (−90 and −40 km/sec, respectively), suggesting stratification. From the observations the conclusion is drawn that the boundary of the Si^{++} and Si^{+++} regions is fairly sharp and that the fluorescence mechanism is very efficient for Si^{++} compared with recombination.

---

[39] See the Grotrian diagram of the *O* III spectrum in Edlén's thesis, pp. 122 and 123, Upsala, 1934.

[40] *Ap. J.*, **93**, 446, 1941.

[41] *Ap. J.*, **90**, 727, 1939 (plate facing p. 751).

1942ApJ....96..254S

Si II has a very typical behavior in P Cyg stars.[42] The lines arising from the level $4d^2D$ (which can be reached directly from the ground level) are present in the spectrum:

$$4p^2P^0 - 4d^2D:\ \lambda\,5041\ (1E),\ \lambda\,5056\ (1E);$$
$$4s^2S - 4p^2P^0:\ \lambda\,6347\ (3E, 0A),\ \lambda\,6371\ (2E, 0A),$$

while the—usually stronger—doublet λ 4128, λ 4131 ($3d^2D - 4f^2F^0$) is absent. Such behavior cannot be explained on the basis of the recombination mechanism and must undoubtedly be due to a fluorescence process. In order to excite the $3d^2D - 4f^2F^0$ lines by absorption of radiation from the ground state $3p^2P^0$, the level $5d^2D$ (nearest to $4f^2F^0$, connected to $3p^2P^0$ and $4f^2F^0$) must be reached. The excitation potential of $5d^2D$ is 13.87 v., which is only slightly more than the ionization potential of hydrogen (13.54 v.). The absence of *Si* II 4128, 4131 in P Cyg shells would thus indicate that the underlying radiation is appreciably depleted on the short-wave-length side of the Lyman limit. The photospheric temperature obtained for P Cyg by applying Zanstra's theory to the *H* lines is quite satisfactory.[43] This suggests that the hydrogen emission lines are mainly due to the recombination mechanism and that the stellar radiation is appreciably depleted beyond λ 912.

Other selectivities affecting the *N* II, *C* II, and *Fe* II lines have been pointed out in P Cyg stars and may be interpreted qualitatively by considerations similar to those concerning *N* III, *Si* III, *Si* II, etc. In the shells of lowest excitation (late Be and Ae stars) the Balmer lines themselves are excited by fluorescence. The efficiency of this mechanism depends on the velocity and density distributions of the hydrogen atoms of the shell and on the profile of the absorption lines of the exciting radiation; any variation in these factors will give rise to changes in intensity and profile of the Balmer emission lines.

ADDITIONAL EFFECTS OF THE DEPARTURES OF THE EXCITING RADIATION FROM BLACK-BODY DISTRIBUTION

We have discussed elsewhere the following effects: (*a*) shells with very weak lines of hydrogen,[44] (*b*) nebulae excited by nuclei possessing absorption or emission lines,[45] (*c*) structure of the molecular emission bands in comets,[46, 47] (*d*) interstellar gas,[47] and (*e*) peculiar intensities of absorption lines in A stars.[48]

In addition to the effects listed above, we may now add the following:

f) *Novae.*—The discussions of Of and P Cyg shells are directly applicable to the nova shells. The excitation and ionization of a specific atom, at a specific location in a shell, will be conditioned by the radiation as it has been transformed before it reaches the atom. This may modify the effects of pure geometrical dilution which have been discussed previously.[32] The mechanism of bright-line emission is also identical.

We may consider in this connection the absorption lines of molecules (*CN* and C_2) in certain novae, especially Nova Herculis 1934. At first sight the physical conditions do not seem to be adequate on the outskirts of a nova for the presence of abundant molecules; the photospheric temperature is too high to obtain an appreciable molecular abundance if the conditions were the same as in an ordinary reversing layer. But, whereas molecules may be formed, it is possible that, because of the stratification, they cannot be dissociated; the reason is that the radiation reaching the "molecular layers" may have

---

[42] Beals, *M.N.*, **95**, 581, 1935; Merrill, *Ap. J.*, **95**, 386, 1942 (AG Peg).

[43] Beals, *M.N.*, **92**, 677, 1932.

[44] Struve, *Pub. A.S.P.*, **54**, 11, 1942.

[45] Swings, *Ap. J.*, **95**, 112, 1942.

[46] Swings, *Lick Obs. Bull.*, **19**, 131, 1941.

[47] Swings, *Lick Obs. Contr.*, No. 3; *Ap. J.*, **95**, 270, 1942.

[48] Struve and Swings, *Observatory* (in press).

been previously depleted in the spectral regions required to photodissociate the molecules. As a consequence the molecules may be more abundant than in thermodynamic equilibrium at the photospheric temperature. The simultaneous presence of *CN* molecules and *O* atoms in Nova Herculis has been considered as strange, since bands of oxides are absent in the carbon stars. But the difficulty disappears when we consider that we do not have thermodynamic equilibrium and that the possibilities of photodissociation of the various molecules formed (*CN*, *CO*, etc.) are very different.

g) The anomalous selectivities observed among certain emission lines in long-period variables.—The problem is essentially that of *Fe* I, which shows bright λλ 4202, 4308, 3565, and 3521, all arising from the sublevel $z^3G_4^0$, whereas the lines corresponding to $z^3G_3^0$ and $z^3G_5^0$ are found in absorption only. Other similar incomplete multiplets are also observed. Peculiar selectivities have already been discussed for *N* III, *Si* III, etc., in stellar envelopes of early type; and, although the situation may not be similar in *Me* variables it seems logical to compare the two cases closely.

Thackeray and Merrill[49] have tried to explain the favored excitation to $z^3G_4^0$ by a selective fluorescence mechanism similar to Bowen's process in nebulae (close coincidence of a primary emission line with a resonance line of another element). Although promising results have been obtained, it is possible that the fluorescence mechanism which we have suggested may also operate.

In long-period variables the radiation reaching the various reversing layers (deep as well as high) is very different from the black-body type, and the difference must increase when the temperature decreases. As was emphasized by Thackeray, the temperature and pressure in late-type giants are so low that "collision excitation can only maintain atoms in the lowest energy levels, and the atmosphere approximates a state of monochromatic, or more strictly polychromatic, radiative equilibrium." Hence a strong distortion of the exciting radiation from the black-body curve may give rise to complex cycles and may possibly enhance certain populations on specific levels.[50] Since the selectivity is very sharp—$z^3G_4^0$ (4.416 v.) of *Fe* I is excited but not $z^3G_3^0$ (4.454 v.) and $z^3G_5^0$—it cannot be attributed to an ionization or a dissociation continuum. If we wish to attribute the selectivity to cycles, we must consider the effect of absorption or emission of atomic lines and of absorption or emission of molecular bands. The emission of atomic lines has been discussed by Thackeray and Merrill. The atomic lines of absorption do not explain the incomplete *Fe* I multiplets. But molecular bands may provide possibilities. From the ground level a^5D of *Fe* I the excitation to z^3G^0 is provided by lines of wave lengths between λ 2795 and λ 2828. This is the region of the (1, 0) band of *OH* ($^2\Sigma \leftarrow {}^2\Pi$), whose lower level is the ground electronic and vibrational state of the *OH* molecule.[51] This absorption band of *OH* should be very strong in stellar atmospheres, despite the rather small value of the oscillator strength. Actually, the *OH* molecules are much more abundant than *TiO* (by a factor of 10^3–10^4), and the *OH* bands should therefore cut the entire stellar radiation into narrow strips of bright continuum separated by deep minima.[52]

The abundance of *OH* molecules increases rapidly when the temperature decreases, and the selective effect of the absorption bands on the atomic excitation should thus be greatest at minimum temperature.

---

[49] *Pub. A.S.P.*, **48,** 331, 1936; **49,** 120, 1937; Thackeray, *Ap. J.*, **86,** 499, 1937.

[50] Gerasimovič, *M.N.*, **89,** 272, 1929.

[51] Other molecular absorption bands belonging to abundant stellar molecules are present in this region, i.e., the (2,7) and (3,8) bands of *SiO* ($^1\Pi \leftarrow {}^1\Sigma$), the (1,6) bands of *NO* (γ system $^2\Sigma \leftarrow {}^2\Pi$ and β system $^2\Pi \leftarrow {}^2\Pi$), and others (*CO*, *SO*, etc.). But their lowest vibrational levels are excited and the corresponding populations are reduced by a factor of from 20 to 250.

[52] The (1,0) band of *OH* is degraded to the red and begins at λ 2811. Hence, it affects only the region $\lambda > 2811$ A: it can explain the absence of excitation from a^5D to $z^3G_5^0$, which requires λ 2825.689. Other molecular or atomic absorption lines should be considered in other cases.

The present suggestion does not apply to the strong hydrogen emissions (in layers, which are deeper than those of *TiO*, Ca^+, etc.), the forbidden lines of *Fe* II, or the resonance line of *Mg* I.

Another interesting suggestion was made by Wyse,[53] in order to explain the simultaneous presence of the *Ca* II transition $4s^2S - 4p^2P^0$ (H and K) in absorption, together with $3d^2D - 4p^2P^0$ (infrared triplet) in emission. The $3d^2D$ level may be depopulated by photoelectric absorption of the bright Lyman α line from the $3d^2D$ level. The ionization energies of *Ca* II are 82,098 cm^{-1} from $3d^2D_{1\frac{1}{2}}$ and 82,037 cm^{-1} from $3d^2D_{1/2}$; and these are only slightly smaller than the energy of Lyman α (82,257 cm^{-1}). Considering the strong departures of the exciting radiation from the black-body distribution, the mechanism suggested by Wyse may have wide applications.

MECHANISMS OF EXCITATION OF *He* II, *O* III, AND *N* III IN BRIGHT-LINE OBJECTS

The absorption coefficient of an atom for radiation coinciding with one of its transitions leading to the ground level is very much larger than the photoelectric absorption coefficient for radiation having a wave length shorter than the ionization limit. For this reason Bowen's fluorescence mechanism—excitation of *O* III by the resonance line *He* II 304 and subsequent excitation of *N* III by the resonance line *O* III 374—plays a very important role in nebulae and other similar objects. Yet this type of excitation is not observed in ordinary Wolf-Rayet envelopes, which do not reveal an appreciable enhancement of the incomplete multiplets excited by *He* II. Actually, *O* III is always very weak or absent in the WN stars; it is strong in WC stars but does not show any selectivity, so that there is no reason to make a difference between the excitation of *O* III and that of *O* II or *O* IV. The absence of Bowen's fluorescence is due to the velocities of the radially ejected atoms. The O^{++} atoms located at a specific place in the Wolf-Rayet shell are able to absorb the resonance radiation of only a small fraction of ejected He^+ atoms, since these must have a definite radial velocity with respect to the O^{++} atoms considered. In various objects, bright *He* II lines are observed, whereas the fluorescence multiplets of *O* III and *N* III are not enhanced. In the WC nucleus of BD+30°3639, *He* II 4686 is present, λ 3444 and λ 3760 of *O* III are not enhanced; the same is true for the similar object HD 167362. No Bowen fluorescence is observed in RW Hya or in the deep layers of Wolf-Rayet type of Z And. In the nebula NGC 6543, *N* III is not excited by Bowen's mechanism. In other objects, like T CBr, AX Per,[54] CI Cyg, RX Pup, the incomplete multiplets of *O* III and *N* III are prominent: in all these cases the ejection velocity is extremely small, and the situation is very similar to the planetaries.

In certain novae the importance of Bowen's fluorescence mechanism has varied. For example, the observations of the nebular stage (1936) of Nova Herculis by Adams and Joy[55] reveal lines of *O* III and *N* III that cannot be attributed to fluorescence; but other observations by Dufay and Bloch[56] show an enhanced *O* III 3760.[57] In 1940 the spectrum of Nova Herculis showed that *N* III was not excited by Bowen's mechanism alone, since λ 4379 was present;[58] yet Bowen fluorescence was probably present, as was revealed by the *O* III spectrum.

In an expanding gaseous atmosphere, a photon *He* II 304 emitted by a specific He^+ atom may be absorbed only by a fraction of the other He^+ and O^{++} atoms. Thus, contrary to what happens in a nebula, the λ 304 photons may escape from the atmosphere

---

[53] *Pub. A.S.P.*, **53**, 184, 1941.

[54] In AX Per the intensity of *O* III 3444 (fluor.) is highly variable (see Sec. I).

[55] *Ap. J.*, **84**, 14, 1936.

[56] *C.R.*, **201**, 1463, 1935; *Zs. f. Ap.*, **13**, 36, 1936.

[57] The influence of the blending [*Fe* VII] line is not clear.

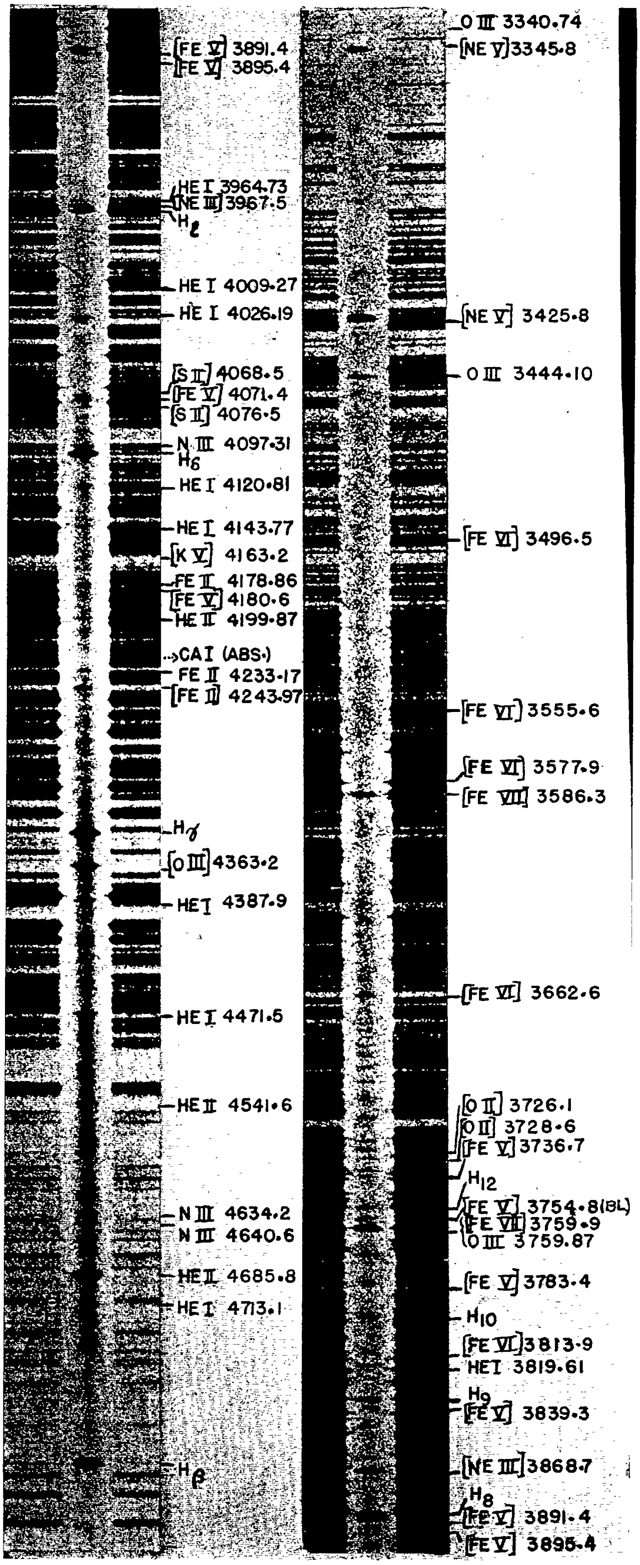
[58] *Ap. J.*, **92**, 295, 1940.

without being slowed down by successive absorptions and re-emissions by the abundant He^+ atoms. Whereas in an ordinary planetary nebula the mean free path of a quantum before photoelectric absorption occurs is very large compared to the mean free path of a λ 304 photon before resonance absorption and emission take place, this may not be true in an expanding atmosphere. In other words, the probability that a λ 304 photon emitted by an He^+ atom may be absorbed photoelectrically by the abundant H or He I atoms (also C^+, N^+, O^+) may become important, compared with the probability of a fluorescent absorption by O^{++}. A similar reduction will be present in the excitation of N^{++} by O III 374.

In the case of spherical symmetry and of large constant expansion velocity v_{ej} within the layers containing He^{++}, O^{++}, and N^{++}, Bowen's fluorescence mechanism should be practically absent. When a velocity gradient is present, fluorescence will be excited in the O^{++} atoms by a definite fraction of He II 304 quanta, depending essentially on the velocity gradient dv_{ej}/dr and on the stratification conditions within the layers containing He^{++} and O^{++}. If, as is very likely, the He^{++} ions giving rise to the He II recombination spectrum lie mostly in deeper layers than the O^{++} ions, a decelerated motion is required to give rise to strong fluorescence. In the case of Nova Geminorum 1912 the observed decrease with time of the mean ejection velocity suggests a decelerated motion. But the situation is very uncertain in the Wolf-Rayet stars.

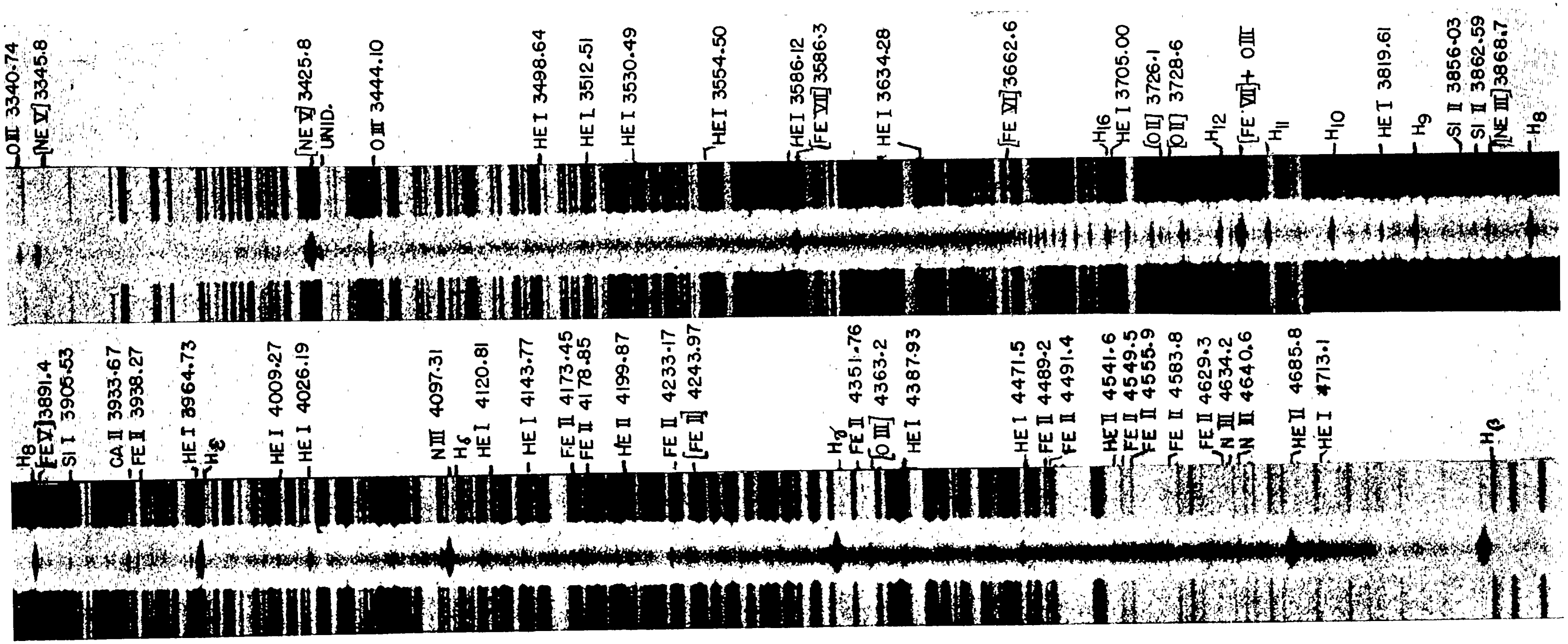
McDonald Observatory
May 1, 1942

PLATE XV



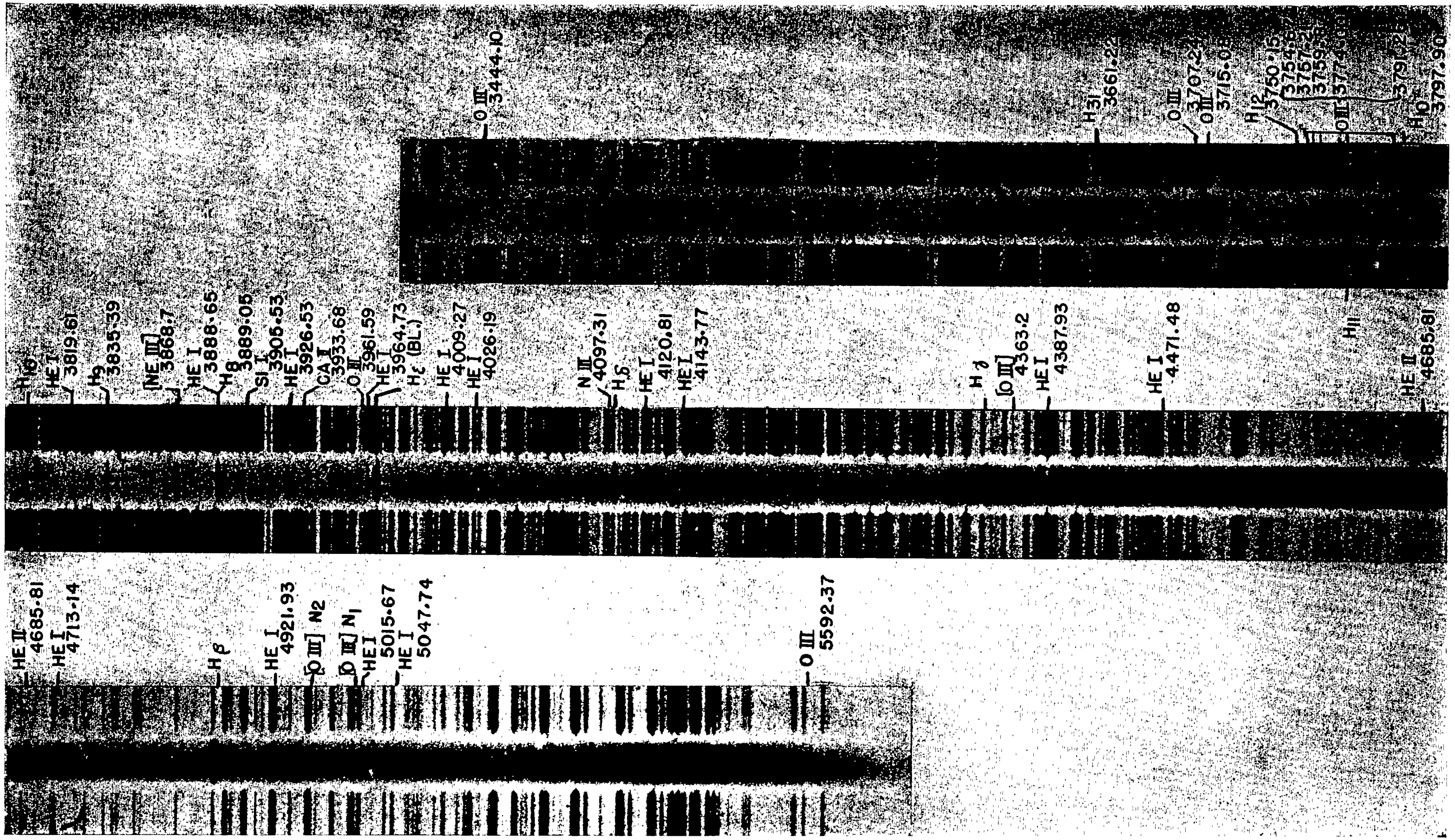
Spectrum of AX Persei (Feb. 2, 1942)

PLATE XVI



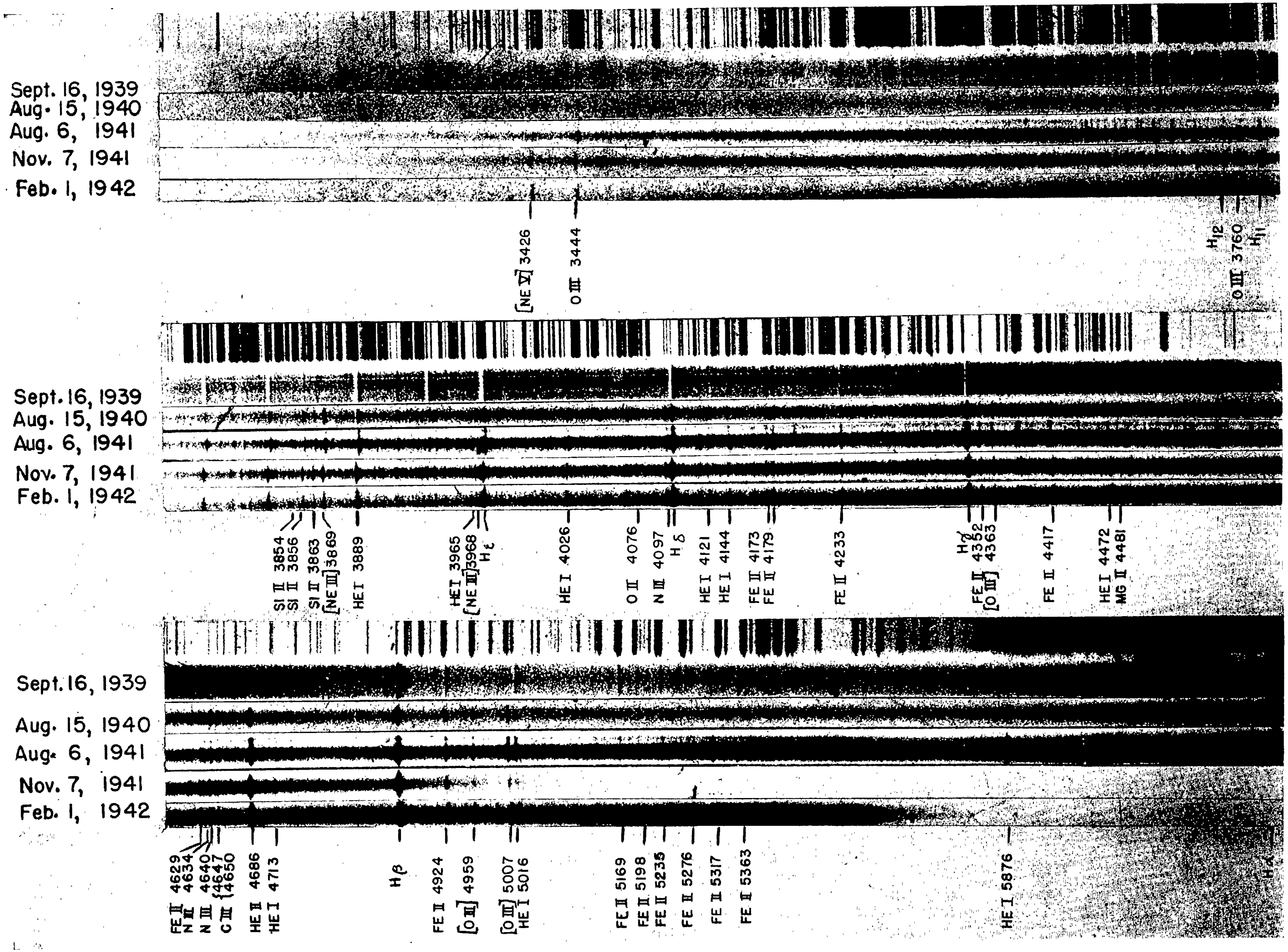
Spectrum of CI Cygni (April 26, 1942)

PLATE XVII



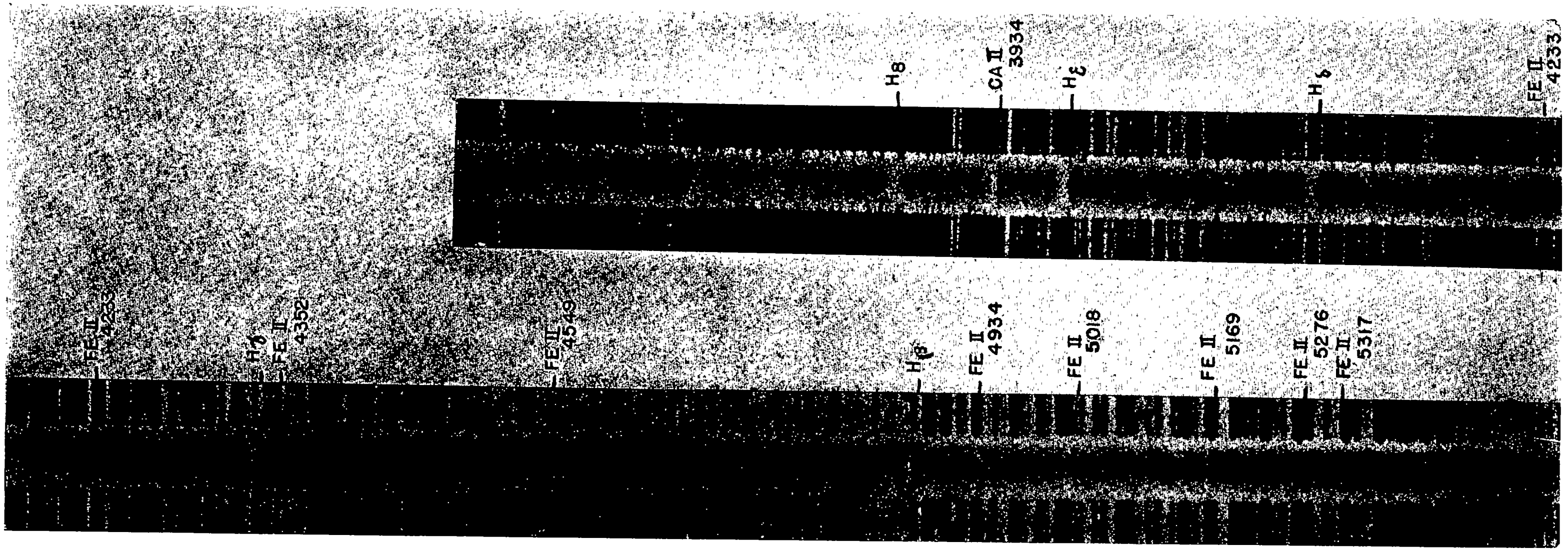
Spectrum of RW Hydrae (Feb. 1, 1942)

PLATE XVIII



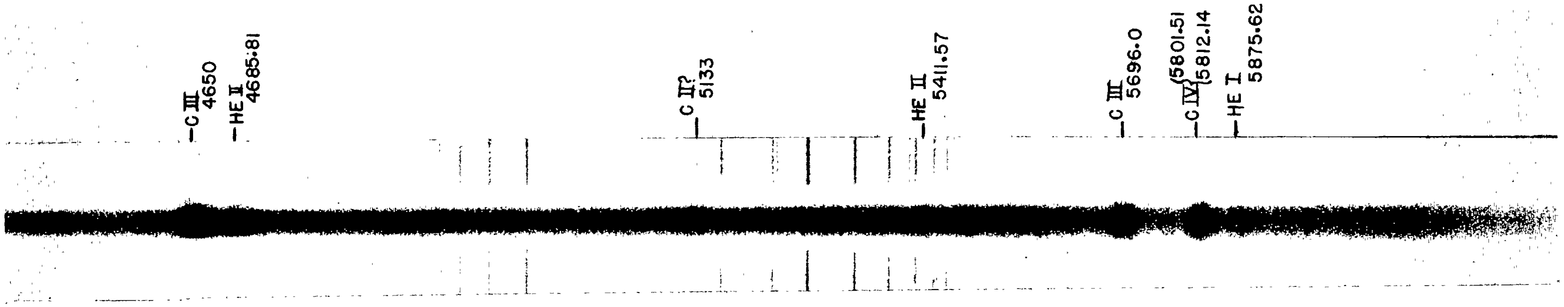
Spectra of Z Andromedae

PLATE XIX



Spectrum of Z Canis Majoris (Feb. 1, 1942)

PLATE XX



Spectrum of γ Velorum