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THE EVOLUTION OF A PECULIAR STELLAR SPECTRUM Z ANDROMEDAE

(With a Note on the Spectrum of IC 4997)*

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ABSTRACT

The spectral lines of Z Andromedae have been measured on plates taken between May 12 and August 25, 1940, when the brightness had decreased to magnitude 9.7 after the outburst in 1939. The spectrum shows emission lines of a thin and dilute nebula and resembles the spectrum observed by H. H. Plaskett in 1923–1926. There is some evidence of a late-type companion, in addition to a hot nucleus, which resembles some of the slow novae, and a fairly pronounced P Cygni type spectrum of an expanding shell. The latter is a remnant of the shell which was formed in the outburst of 1939.

The nebular spectrum shows strong forbidden lines, but there are relatively few stages of ionization, which shows that the nebula consists of a fairly thin layer. The intensity of the auroral transition of [*O* III], λ 4363, is relatively strong—a phenomenon which is characteristic of other binaries of similar type, and of novae. Among the nebulae the stellar planetary IC 4997 shows the same feature. A list of lines of this object is given in Table 4.

I. INTRODUCTION

Z Andromedae is an exceptionally interesting object whose spectrum was first described in detail by H. H. Plaskett[1] on the basis of spectrograms taken during the period 1923–1926. At that time the spectrum showed no absorption lines but contained numerous bright lines, especially those of *H*, *He* I, *Mg* II, *Fe* II, *Ti* II, *He* II, *C* III, *N* III, *O* III, and the forbidden lines of [*O* III], [*Ne* III], [*Ne* V], [*Fe* III?] and [*S* II]. H. H. Plaskett divided the lines into two groups which he designated as the "stellar part" (lines of low excitation: *H*, *He* I, *Mg* II, *Fe* II, etc.) and the "nebular part" (lines of high excitation: *He* II, *N* III, [*O* III], [*Ne* III], etc.). The continuous spectrum was very strong in the red region, and on Plaskett's spectrograms Hogg[2] was able to see weak absorption band heads of *TiO;* these increased in intensity in the years following, when the star was fading in light. Mrs. Greenstein[3] determined the light-curve for the object until 1936; during the interval 1922–1936 the star slowly decreased in brightness with some irregular fluctuations. The light-curve has been extended by L. Campbell,[4] who recorded an increase in light from visual magnitude 10.7 in April, 1939, to 8.6 on August 21 and to 7.9 shortly afterward. Since the fall of 1939 the star has declined in brightness, reaching magnitude 9.7 on August 15, 1940.

It is tempting to consider Z Andromedae as a binary system consisting of a nova-like object, subject to moderate outbursts at somewhat irregular intervals of about fifteen years, and of a variable late-type companion whose period is probably not identical with the 650-day period suggested by Prager,[4] because the amplitude of the latter appears to be least when the nova-like object is faint.

This picture receives strong confirmation from a study of spectrograms taken at the McDonald Observatory during the past year. Spectrograms taken from September 14 to December 5, 1939, revealed a spectrum completely different from that described by

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* *Contributions from the McDonald Observatory, University of Texas,* No. 31.

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

[2] *Pub. A.S.P.,* **44,** 328, 1932; *Pub. A.A.S.,* **8,** 14, 1934.

[3] *Harvard Bull.,* No. 906, 1937.

[4] L. Campbell, *Pop. Astr.,* **47,** 335, 447, 571, 1939; K. Himpel, *Die Sterne,* **19,** 210, 1939, and **20,** 14, 1940.

Plaskett.[5] It was then of the P Cygni type with the "nebular part" of Plaskett's description completely missing. The spectrum showed many permitted lines of low excitation and was very similar to certain early stages of slow novae.

The transition from the high-excitation spectrum to one of P Cygni type must have occurred mainly between July 30 and September 14, 1939. On July 30, when the visual magnitude was about 8.9, the object was observed in Berlin-Babelsberg by P. Wellmann,[6] and the spectrum showed the lines of *He* II and *N* III; but there already seemed to appear weak absorption lines on the violet side of certain emissions, and traces of the *TiO* bands were still present at that time.[7]

The spectroscopic survey was resumed in the spring of 1940, when the star again became observable in the east; our first plate was taken on May 12. The entire aspect of the spectrum had changed. Again it resembled that described by Plaskett, although there were important differences. Strong nebular lines were again present; but, contrary to Plaskett's description, our spectrograms show many absorption lines. The development of the spectrum bears a strong resemblance to that of a slow nova.

This type of combination of a late-type star and an early-type companion—which, in this case, is nova-like—is by no means exceptional. Several other objects of the same type have recently been investigated, namely, T Coronae Borealis[8] (nova + M star), AX Persei and CI Cygni[9] (very high-excitation nebulosity + M star), RW Hydrae[10] (nebulosity of medium excitation + late K or early M), R Aquarii[11] (nebulosity + M7e + high-excitation companion), *α* Scorpii[12] (B4ne + M), *o* Ceti[13] (B8e + M), WY Geminorum[9] (B3e + M3e), W Cephei[9] (O? + Me), VV Cephei[14] (B9e + M2), etc.

The dynamical and physical processes involved in such binaries are not yet fully understood. It is probable that the emission lines are excited by the radiation of the early-type star outside its own reversing layer. There may be a departure from spherical symmetry in the excited layers, owing to the presence of the late-type companion. It is also probable that in some cases the radiation of the early-type component may excite the outer regions of the cool companion.

II. GENERAL DESCRIPTION OF THE SPECTRUM

The following description of the spectrum of Z Andromedae is based upon several spectrograms taken at the Cassegrain focus of the 82-inch reflector between May 12 and August 15, 1940, the best plate having been taken on August 15 with the quartz prisms and the 500-mm camera (dispersion 40 A/mm at λ 3933). The star was of about visual magnitude 9.7.

The visual region is quite strong, and a search for the *TiO* band heads found by Hogg (λλ 6159, 5448, 5167, and 4955) makes it appear probable that the red companion again begins to play an appreciable role in the visual region of the spectrum.

The results of the measurement of the spectrogram of August 15 are collected in Table 1, in which the late-type absorption features have not been included. The wave lengths have been corrected for the motion of the earth, but because of the complexity of the spectrum no attempt has been made to correct for the motion of the star.

Table 1 shows that the spectrum of Z Andromedae is very complex. We recognize at once the existence of the "nebula" whose spectrum was described by Plaskett. This

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[5] Struve and Elvey, *Pub. A.S.P.*, **51**, 297, 1939; Swings and Struve, *Ap. J.*, **91**, 601, 1940.

[6] *Beobachtungs-Zirkular d. A.G.*, **21**, 105, 1939.

[7] *Vierteljahrsschrift d. A.G.*, **75**, 53, 1940.

[8] *Pub. A.S.P.*, **52**, 199, 1940.

[9] *Ap. J.*, **91**, 546, 1940.

[10] *Proc. Nat. Acad.*, **7**, 458, 1940.

[11] *Ap. J.*, **91**, 616, 1940; P. W. Merrill, *Spectra of Long-Period Variable Stars*, p. 82, 1940.

[12] *Ap. J.*, **92**, 316, 1940.

[13] P. W. Merrill, *op. cit.*, p. 75, 1940.

[14] C. and S. Gaposchkin, *Variable Stars*, 1938.

TABLE 1

LIST OF LINES IN Z ANDROMEDAE

λ	INT.	IDENTIFICATION*		
		Elem.	λ	Int.
3121.5†	1E	*O* III	3121.71	5
3132.7†	6E	*O* III	3132.86	6
3202.9†	6E	*He* II	3203.16	....
3277.0†	1E	....	....	....
3281.1†	1E	....	....	....
3312.3†	4E	*O* III	3312.30	5
3323.6†	1E	....	....	....
3340.5†	5E	*O* III	3340.74	6
3345.8†	4E	[*Ne* V]	3345 8	....
3425.85	6E	[*Ne* V]	3425.8	....
3443.60	6E	*O* III	3444.10	5
3455.27	0E	*O* III	3455.12	5
3662.08	1A	H_{30}	3662.26	....
3663.03	1A	H_{29}	3663.40	....
3664.25 3664.92	1A 0E	H_{28}	3664.68	....
3665.70 3666.53	1A 0E	H_{27}	3666.10	....
3667.47 3668.26	1A 0E	H_{26}	3667.68	....
3669.12 3669.94	1A 1E	H_{25}	3669.47	....
3671.21 3672.00	1^{+}A 1E	H_{24}	3671.48	....
3673.24 3674.42	1^{+}A 1E	H_{23}	3673.76	....
3676.07 3676.94	2A 1E	H_{22}	3676.36	....
3679.10 3679.75	2A 1E	H_{21}	3679.35	....
3682.37 3683.27	2A 1E	H_{20}	3682.81	....
3686.19 3687.35	1^{+}A 1E	H_{19}	3686.83	....
3689.24 3690.37	1^{+}A 0E	....	....	....
3691.30 3692.21	1^{+}A 1^{+}E	H_{18}	3691.56	2
3696.88 3697.79	1^{+}A 1E	H_{17}	3697.15	3
3704.18 3705.62	1^{+}A 1^{+}Enn	H_{16} *He* I *Fe* I *Ti* II *Ca* II	3703.85 3705.00 3705.57 3706.23 3706.03	4 30 700 125 40
3711.56 3712.72	1^{+}A 2E	H_{15}	3711.98	5
3718.76 3719.91	0A 0E	*Fe* I	3719.93	1000*R*
3721.40 3722.53	1^{+}A 2E	H_{14}	3721.95	6
3733.43 3734.94	1A 2E	H_{13}	3734.37	8
3737.10	1E‡	*Fe* I *Ca* II	3737.13 3736.90	1000*r* 50
3741.39	0E	*Ti* II	3741.64	200
3748.34	1E	*Fe* II *O* II *Fe* I *Fe* I	3748.49 3749.47 3748.26 3749.49	8 125 500 1000*r*
3749.57 3750.86	1^{+}A 2E	H_{12}	3750.15	10
3755.00	2E	*N* III *O* III *Fe* II *He* I	3754.62 3754.67 3755.56 3756.09	6 7 4 1
3757.81	1E	*Ti* II *Fe* I *O* III	3757.69 3758.23 3757.21	100 700 5
3760.08	2En	*O* III *Ti* II *Fe* II	3759.87 3759.30 3759.46	9 400 6
3762.35	0E	*Fe* II *Ti* II *O* II	3762.89 3761.32 3762.51	5 300*r* 120
3770.52 3771.25	1A 2E	H_{11} *N* III	3770.63 3771.08	15 7
3795.27	1E	*Fe* I	3795.00	500
3797.30 3798.69	1A 3E	H_{10}	3797.90	20
3819.35 3819.93	1A 2E	*He* I *Fe* I	3819.61 3820.43	50 800
3824.47	0E	*Fe* II	3824.91	4
3834.48 3835.63	1A 3E	H_{9}	3835.40	40
3847.06	1E	....	....	....
3853.94	1E	*Si* II	3853.67	3
3855.92	3E	*Si* II	3856.09	8
3862.60	2E	*Si* II	3862.51	7
3868.75	7E	[*Ne* III]	3868.74	....
3880.69 3882.22	0A 0E	*O* II	3882.19	35
3887.84 3889.28	5A 5E§	*He* I H_{8}	3888.65 3889.05	1000 60
3899.58	1E	*Fe* I	3899.71	500
3902.91	1E	*Fe* I	3902.95	500
3905.62	1Es	*Si* I *Fe* II	3905.53 3906.04	20 5
3914.19	1En	*Ti* II	3913.46	70
3919.22	1En	*C* II *C* II *N* II *O* II	3918.98 3920.68 3919.00 3919.28	80 200 35 35
3923.24	1E	*Fe* I *He* II	3922.91 3923.51	600 ....
3926.55	1E	*He* I	3926.53	7
3930.47	1E	*Fe* I	3930.30	600
3934.95	1E	*Ca* II *He* I *Fe* II *N* III	3933.67 3935.91 3935.94 3934.41	600*R* 4 6 3
3938.39	1^{+}E	*Fe* II *N* III	3938.97 3938.52	4 4
3945.35	1E	*O* II	3945.04	20
3961.77	1^{+}E	*O* III *Al* I	3961.59 3961.53	8 3000

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* All the laboratory wave lengths and intensities have been taken from the M.I.T. wave-length table, except for *Fe* II (J. C. Dobbie, *Annals of the Solar Physics Observatory, Cambridge*, Vol. V, Part I) and the doubly or trebly ionized atoms (C. E. Moore, *Multiplet Table of Astrophysical Interest*). In the M.I.T. table the intensities in the arc or in the spark have been taken for the neutral or ionized elements. The lines of stellar intensity zero are uncertain.

† These lines were measured on a plate taken January 5, 1941.

‡ Probably absorption of P Cygni type.

§ Violet wing weaker.

TABLE 1—*Continued*

λ	Int.	Identification*		
		Elem.	λ	Int.
3964.84	2E	*He* I	3964.73	50
3967.33	2E	[*Ne* III]	3967.51	....
3970.34	4E	*H*ε	3970.07	80
3973.83	1E	*O* II	3973.27	125
4009.24	1E	*He* I	4009.27	10
4013.95	2A	....	....	....
4014.85	1E			
4016.62	1^+A	....	....	....
4017.56	0E			
4025.56	2A	*He* I	4026.19	70
4026.43	2E			
4070.30	2En	*C* III	4068.94	10
		C III	4070.30	8
		O II	4069.90	125
		O II	4072.16	300
		[*S* II]	4068.50	....
4073.89	2A	*O* II	4075.87	800
4075.82	2E			
4097.35	4Es	*N* III	4097.31	10
4101.97	6E‖	*H*δ	4101.73	100
4103.54	2E‖	*N* III	4103.37	9
4121.31	1E‖	*He* I	4120.81	25
4123.65	0E‖	*Fe* II	4122.64	4
4144.25	1En	*He* I	4143.76	15
4162.35	1E	*C* III	4162.80	4
4173.12	2En	*Fe* II	4173.45	8
4175.78	2A	*Fe* II	4178.87	8
4178.17	2En			
4225.15	0A	?*Ca* I	4226.73	500*R*
4226.21	0E	?*Al* II	4226.81	35
4230.95	1A	*Fe* II	4233.17	11
4233.13	3E			
4244.83	0En	[*Fe* II]	4243.97	....
4264.55	1A	*C* II	4267.02	350
4267.17	1E	*C* II	4267.27	500
4277.23	0E	[*Fe* II]	4276.87	....
4288.70	0E	[*Fe* II]	4287.40	....
4340.67	8E	*H*γ	4340.46	200
4351.83	3E	*Fe* II	4351.77	9
4363.46	6E	[*O* III]	4363.20	....
4366.92	0E	*O* II	4366.91	100
4369.24	1^+E	?*O* II	4369.28	50
4379.66	0E	*N* III	4379.09	10
4384.16	1E	*Fe* I	4383.55	1000
		Fe II	4385.38	7
4387.63	2E	*He* I	4387.93	30
4395.19	1E	*Ti* II	4395.03	150
		O II	4395.95	80
4399.92	1E	*Ti* II	4399.77	100
4404.65	1E	*Fe* I	4404.75	1000
4413.86	0E	[*Fe* II]	4413.78	....
4416.78	2En	*Fe* II	4416.82	7
		[*Fe* II]	4416.28	....
		Ti II	4417.72	80
		O II	4416.97	150
4437.67	0E	*He* I	4437.55	10
4444.97	0E	?*Ti* II	4443.80	125
4447.41	0E	*N* II	4447.03	300
		O II	4448.20	70
4451.23	0E	*Fe* II	4451.54	4
4457.57	1E	?[*Fe* II]	4457.97	....
4470.08	1A	*He* I	4471.48	100
4472.08	3E			
4480.96	2E	*Mg* II	4481.33	100
4488.98	1E	*Fe* II	4489.19	4
4491.32	1E	*Fe* II	4491.41	5
4501.07	1E	*Ti* II	4501.27	100
4506.84	1A	*Fe* II	4508.28	8
4508.26	1^+E			
4514.10	1A	*Fe* II	4515.34	7
4515.29	2E	*N* III	4514.89	7
4521.06	1E‖	*Fe* II	4520.22	7
4522.89	1^+E‖	*Fe* II	4522.64	9
4528.75	1E	*Fe* I	4528.62	600
		?*Al* III	4529.18	6
4534.64	1E	*N* III	4534.57	3
		Ti II	4533.97	150
4540.92	1^+E	*He* II	4541.61	5
		Fe II	4541.52	4
4549.04	1E‡	*Fe* II	4549.47	10
		Ti II	4549.63	200
4556.30	1E	*Fe* II	4555.89	8
4576.51	0E	*Fe* II	4576.33	4
4583.11	2E	*Fe* II	4583.83	11
4629.86	3E	*Fe* II	4629.34	7
		N II	4630.55	300
4631.69	1A?	*N* III	4634.16	8
4634.70	3En	*Fe* II	4635.33	5
4637.66	3A	*N* III	4640.64	10
4640.30	4En			
4645.74	3A	*C* III	4647.40	10
4648.10	3En‖			
4651.05	2En‖	*C* III	4650.16	9
		C III	4651.35	8
4653.87	1A?	*C* IV	4658.64	5
4657.92	1^+E	[*Fe* III]	4658.18	....
4685.46	10E	*He* II	4685.75	300
4713.82	1^+E	*He* I	4713.14	40
4861.59	10E	*H*β	4861.33	500
4920.08	2A	*He* I	4921.93	50
4922.59	2^+En	*Fe* II	4923.92	12
4958.86	3E	[*O* III]	4958.91	....
5007.23	5Es	[*O* III]	5006.84	....
5012.21	2A	*He* I	5015.67	100
5015.74	3E‖			
5018.93	2E‖	*Fe* II	5018.43	12
5169	1E	*Fe* II	5169.03	12
5235	1E	*Fe* II	5234.62	7
5317	2E	*Fe* II	5316.61	8
5412	2E	*He* II	5411.55	50
5876	5Es	*He* I	5875.62	1000
6563	20E	*H*α	6562.82	2000

‖ Separation difficult, but the line seems definitely double.

spectrum consists of two groups of lines: the first includes forbidden and permitted lines usually associated with planetary nebulae; the other includes permitted lines, principally in the region λλ 4632–4658, of *N* III, *C* III, and *C* IV, bordered by absorption on the violet side. This second group—which exhibits some of the characteristics of lines in Wolf-Rayet stars, except that in Z Andromedae they are fairly sharp—we shall attribute somewhat arbitrarily to the hot nucleus. We do not wish to imply that this nucleus is a normal Wolf-Rayet star, and it is possible that what we have designated as the nuclear lines are really lines produced in the innermost layer of the nebular shell.

In addition to the "nebula" and the "nucleus" there is a spectrum of the P Cygni type. It consists of *H*, *He* I, and *Fe* II; and we are inclined to attribute to it also the bright lines of low excitation: *Mg* II, *Si* I, *Si* II, *Ti* II, *Fe* I, and extremely weak [*Fe* II]. This spectrum is the remnant of the P Cygni type spectrum which predominated in the fall of 1939, when the star was near maximum light. It has undergone large changes since December, 1939, having developed strong lines of *He* I and having lost most of its violet-absorption features. But it has not yet returned to the character of spectrum designated by Plaskett as "Z Andromedae-Star."

The strong continuous spectrum of Z Andromeda in the photographic region must come from the hot nucleus. It is too blue to be associated with the M star.

III. THE SPECTRUM OF THE NUCLEUS

Carbon is represented by very weak *C* II (λ 4267), strong *C* III (λλ 4648–4651), and *C* IV (λ 4658); all these bright lines are flanked by absorption components on the violet side. The carbon lines have the usual intensities of Wolf-Rayet stars and of pure recombination spectra; in an O star of the 9 Sagittae type, λ 5696 *C* III would be an emission line instead of λλ 4648–4651, according to previous investigations by the authors.[9]

TABLE 2

VELOCITIES OF EJECTION

Element	V_{ej} in km/sec
Balmer lines of P Cygni type	83
λ 3889 *He* I	111
Other lines of *He* I	81
C III	174
N III	182
C II	186

Nitrogen is characterized by the strong bright lines of *N* III at λ 4634 and λ 4641, with P Cygni absorption components. It is difficult to decide whether broader lines are superposed on the strong, sharp nebular *N* III lines measured at λλ 4097–4103.

Several weak *O* III lines which cannot be excited in the nebulosity by Bowen's fluorescence mechanism probably belong to the nucleus. The question arises whether the lines of *H* and *He* I also belong to the nucleus. Strong evidence against such an assumption is found in the measured differences between the radial velocities of the emission and absorption components of the lines. These are collected in Table 2.

The spectrum of the nucleus contains both nitrogen and carbon. Like the nucleus of NGC 6543,[15] it is an object intermediate between the usual carbon and nitrogen sequences. It would, indeed, be difficult to apply to it the usual classification criteria for Wolf-Rayet stars.[16] For example, we are not allowed to use the intensities of the *He* I lines which belong mainly to the P Cygni layer or those of the *He* II lines which belong to the nebula. This difficulty presents itself in all cases where a Wolf-Rayet star having relatively narrow lines is surrounded by an emission nebulosity. The absence of *N* V and the intensity ratio of the *C* IV and *C* III lines suggest that the nucleus may have a temperature of the order of 70,000°.

This would be in agreement with the lines observed in the nebula, where [*Ne* III] is stronger than [*Ne* V]. It should be remembered that the lines of the nucleus of Z Andromedae are much sharper than those of Wolf-Rayet stars. But the nucleus of HD 167362, which is an object resembling Campbell's hydrogen-envelope star, has also fairly narrow lines of Wolf-Rayet type. It is possible that the nucleus of Z Andromedae is of the same character.

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[15] *Ap. J.*, **92**, 289, 1940.

[16] *Trans. I.A.U.*, **6**, 248, 1938.

IV. THE NEBULAR SPECTRUM

The following observed lines belong to a dilute nebulosity: (*a*) the transitions of nebular type of [*O* III] (int. 3–5), [*Ne* III] (int. 7–3), and [*Ne* V] (int. 6–4); (*b*) the transition of auroral type of [*O* III] (int. 6); and (*c*) the lines of *He* II (at least in part) and the fluorescence lines of *O* III and *N* III excited by the resonance line of *He* II. The emission lines of *H* and *He* I may also belong in part to the nebulosity. The excitation of this nebular spectrum may be attributed to the hot nucleus described in section III. The mean radial velocities of the pure emission lines are: forbidden lines, +5.8 km/sec; *N* III 4097–4103, +7.6 km/sec; Balmer lines (*H*ε–*H*β), +16.0 km/sec.

Since the nucleus continuously ejects nitrogen and since λλ 4097–4103 are fairly strong in the nebula, we should have expected to observe [*N* II] or [*N* I] in the nebulosity. In reality, neither their nebular nor their auroral transitions are observed.[17] This is certainly an effect of ionization, as [*O* II] and [*O* I] are also absent despite the high intensity of [*O* III]. This is quite different from what we normally observe in planetary nebulae and in the nebulosities of slow post-novae. For example, in Nova Herculis, 1934, we observe at the present time [*O* I], [*O* II], [*N* II], [*S* II], [*Fe* VII], and other elements,[18] in addition to strong [*O* III], [*Ne* III], and [*Ne* V]. Essentially similar elements are also present in the extremely slow nova RT Serpentis, 1909. The absence of other stages of ionization in the nebulosity of Z Andromedae suggests that this nebulosity consists of a rather thin layer.

TABLE 3

COMPARISON OF INTENSITIES OF EMISSION LINES IN PLASKETT'S "NEBULAR PART"

λ	Elem.	Intensity		Notes	λ	Elem.	Intensity		Notes
		Plaskett	Swings-Struve				Plaskett	Swings-Struve	
3425.8	[*Ne* V]	4	6		4634.2	*N* III	3	3	
3444.1	*O* III	4	2		4640.6	*N* III	6	4	
3759.9	*O* III	3	2	1	4647.4	*C* III	2	3	
3868.7	[*Ne* III]	2	6	2	4650.2	*C* III	4	2	
3967.5	[*Ne* III]	2	2		4685.7	*He* II	9	10	
4068.9	*C* III	<1	2		4958.9	[*O* III]	2	3	
4097.3	*N* III	2	4		5006.8	[*O* III]	5	5	
4199.9	*He* II	<1	0		5411.6	*He* II	2	2	
4363.2	[*O* III]	6	6		5801.4	*C* IV	2	0	
4541.6	*He* II	3	1						

1. Blend.
2. Plaskett estimates intensity 6 on ultraviolet spectra.

The intensities of the nebular and nuclear lines, which we observed in the summer of 1940, closely resemble those observed by Plaskett[1] in 1923–1926. Table 3 contains those lines which Plaskett attributed to the "nebular part" and which are not seriously blended with lines of the P Cygni spectrum. There are only minor differences in the intensities. We conclude that the nucleus and the nebula have not been appreciably altered by the outburst.

It is of great interest to compare Z Andromedae with the binaries of similar excitation. T Coronae Borealis, which, like Z Andromedae, consists of an M-type star and of a nova-like companion, has shown an irregular increase in brightness since 1936. The forbidden

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[17] [*O* I], [*O* II], and [*N* II] were also absent on Plaskett's spectrograms.

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

lines now present in its spectrum belong to [*O* III], [*O* II], and [*Ne* III].[8] Hachenberg and Wellmann[19] have shown that the nebulosity of T Coronae was optically too thin to permit the application of the theory of Zanstra, which requires complete absorption of all the nuclear radiation beyond the Lyman limit. In RW Hydrae [*O* II] is extremely weak, whereas [*O* III] and [*Ne* III] have similar intensities.[10]

The striking intensity of the transition of auroral type, λ 4363, compared with the transitions of nebular type, N_1 and N_2, is well known in the novae at the beginning of their nebular stages. It is also a characteristic feature of all similar binaries, such as T Coronae, AX Persei, CI Cygni, RW Hydrae, etc. On the other hand, in only one planetary nebula observable in our latitude, IC 4997, is the auroral transition λ 4363 very strong compared with N_1 and N_2. In almost all other nebulae, N_1 and N_2 are much stronger than λ 4363.[20] Actually, IC 4997 is often considered as an object intermediate between nebulae and stars. The following section contains a description of its spectrum.

V. THE SPECTRUM OF IC 4997

Except for the high intensity of λ 4363, the spectrum of IC 4997 has the usual appearance of a planetary nebula, according to W. H. Wright[21] and R. H. Stoy.[22] It is certainly not a nebula of very high excitation,[23] because [*Ne* V] is absent. On the other hand, there is no reason to suspect an abnormally low abundance of oxygen, nitrogen, etc. Hence, the cooling effect[24] of the elements other than *H* upon the electrons, resulting from the photoionization of hydrogen, must be of the usual type. According to the work of Menzel and his collaborators,[25] the presence of a strong λ 4363 implies that the electron density of IC 4997 is much higher than in the other nebulae thus far investigated—say between 10^5 and 10^6 electrons per cubic centimeter, instead of 10^4. The following questions arise in connection with this stellar planetary: (*a*) Of what type is the exciting nucleus (which has not been observed previously)? (*b*) How do the elements other than [*O* III] behave? (*c*) Is there any way to observe "stratification-effects" in stellar planetaries of higher electron density and in which slitless spectra cannot reveal appreciable differences among the monochromatic images?

We secured in June and August, 1940, four spectrograms of IC 4997 with the 82-inch McDonald reflector. Three were taken with the quartz prisms and the F/2 Schmidt camera (exposures, 1^h20^m, 1^h57^m, 8^h44^m). The fourth was obtained with the glass prisms and the same camera (exposure, 8^h40^m). On the two long-exposure spectrograms the continuous spectrum is relatively strong and the Balmer continuum is very strong, extending at least to λ 3300. Superimposed on the strong Balmer continuum are eight lines of *He* I which we could measure only with difficulty;[26] these have not been included in Table 4, which contains all the other lines. The radial velocities given by the different lines are entirely consistent, and Table 4 gives the wave lengths corrected for the motion of the object.

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[19] *Zs. f. Ap.*, **17**, 246, 1939.

[20] The majority of the brighter Magellanic nebulae are similar to IC 4997 (C. and S. Gaposchkin, *op. cit.*, p. 316, 1938).

[21] *Lick Obs. Pub.*, **13**, 193, 1918.

[22] *Lick Obs. Bull.*, **17**, 179, 1935.

[23] Even if the excitation were high, this would not have a great influence upon the electron temperature. Menzel and his collaborators have shown that the electron temperatures, which range from 6,000° to 10,000°, seem to be independent of the temperature of the central star.

[24] Because of the loss of energy by the electrons in the collisional excitation of the metastable levels of *O* III, *Ne* III, etc. (Menzel).

[25] Series of papers in *Ap. J.*, 1938–1940.

[26] Wave lengths: λλ 3634 (2), 3614 (2), 3599 (1), 3587 (1), 3554 (1), 3537 (1), 3530 (1), 3517 (1).

a) THE SPECTRUM OF THE NUCLEUS

The main characteristic of the nucleus is the group from λ 4637 to λ 4690. There is probably also a trace of *N* III 4634. Some *He* I lines seem to have weak P Cygni absorption components, which would indicate that *He* I plays some role in the nuclear spectrum. There is also a trace of *N* IV 4058 and of *C* III 4070, which belong to the nucleus.

It is immediately seen that the group of *N* III, *C* III, and *C* IV lines near λ 4650 is similar to that observed in the nucleus of Z Andromedae. *C* III and *C* IV are of the regular Wolf-Rayet type; *N* III is more nearly of the 9 Sagittae type. The nucleus must be a Wolf-Rayet star containing both *N* III and *C* III and *C* IV. NGC 6543 is another planetary whose Wolf-Rayet nucleus also contains both nitrogen and carbon with similar intensities, but it is of earlier type than in IC 4997. We should classify the nucleus of IC 4997 as W7 or W8. The bright lines are abnormally narrow, but they are appreciably broader than the lines of the nebula.

TABLE 4

LIST OF LINES IN IC 4997

λ	Int.	Identification			Note
		Elem.	λ	Int.	
3676.7......	1	H_{22}	3676.36	....	
3679.5......	1	H_{21}	3679.35	....	
3683.0......	1	H_{20}	3682.81	....	
3687.0......	2	H_{19}	3686.83	....	
3691.69.....	3	H_{18}	3691.56	2	
3696.98.....	3	H_{17}	3697.15	3	
3703.87.....	3	H_{16}	3703.85	4	W
3711.91.....	4	H_{15}	3711.97	5	W
3721.92.....	4	H_{14}	3721.94	6	W
3726.1......	7	[*O* II]	3726.12	.....	W1
3728.7......	5	[*O* II]	3728.91	.....	
3734.25.....	4	H_{13}	3734.37	8	W
3744.37.....	1	....	....	....	
3750.03.....	5	H_{12}	3750.15	10	W
3770.87.....	5	H_{11}	3770.63	15	W
3797.93.....	6	H_{10}	3797.90	20	W
3819.59.....	3	*He* I	3819.61	50	W
3835.53.....	6	H_9	3835.39	40	W
3868.82.....	15	[*Ne* III]	3868.74	....	W
		He I	3867.5	15	
3888.48*....	7	*He* I	3888.65	1000	W1
3888.99*....	8	H_8	3889.05	60	
3964.71.....	3	*He* I	3964.73	50	W1
3967.40.....	10	[*Ne* III]	3967.51	.....	
3970.14.....	8	$H\epsilon$	3970.07	80	
4009.11.....	2	*He* I	4009.27	10	
4026.30.....	4	*He* I	4026.19	70	W
4058.2......	on	*N* IV	4057.8	2	
4068.70.....	3	[*S* II]	4068.62	....	W
4071.0......	1	*C* III	4070.43	8	
4076.37.....	2	[*S* II]	4076.22	....	W
4098.0†.....	0	*N* III	4097.31	10	
4101.70.....	10	$H\delta$	4101.75	100	W
4120.67.....	2	*He* I	4120.81	25	
4143.56.....	2	*He* I	4143.77	15	
4340.63.....	12	$H\gamma$	4340.46	200	W
4363.25.....	15	[*O* III]	4363.2	....	W
4387.79.....	3	*He* I	4387.93	30	
4471.41.....	6	*He* I	4471.48	100	W
4637.06.....	2A	*N* III	4640.64	10	
4640.64.....	2En				
4645.22.....	2A	*C* III	4647.40	10	
4649.11.....	2^+En	*C* III	4650.16	9	
		C III	4651.35	8	
4653.33.....	1^+A	*C* IV	4658.64	5	
4658.86.....	2En				
4685.5......	1^+n	*He* II	4685.81	300	
4702.2......	2n	....	....	....	1
4712.8......	3	*He* I	4713.14	40	
		[*A* IV]	4711.4	....	
4740.6......	1–2	[*A* IV]	4740.3	....	
4861.5......	18	$H\beta$	4861.34	500	W
4921.8......	2^+s	*He* I	4921.93	50	
4958.8......	20	[*O* III]	4958.91	....	W
5006.4......	25	[*O* III]	5006.84	....	W
5016........	4	*He* I	5015.67	100	
5048........	1	*He* I	5047.74	15	
5755........	3	[*N* II]	5755.0	....	S
5876........	8	*He* I	5875.62	1000	S
6300........	6	[*O* I]	6300.2	....	S
6310........	4	[*S* III]	6310.2	....	S
6364........	3	[*O* I]	6363.9	....	S
6548........	5	[*N* II]	6548.4	....	S
6563........	25	$H\alpha$	6562.82	2000	S
6584........	7	[*N* II]	6583.9	....	S
6678........	3	*He* I	6678.15	100	S

* Separation difficult.

† Doubtful line.

W. Observed by W. H. Wright.

W. 1. Observed by Wright as a blend.

S. Observed by R. H. Stoy.

1. Also present in BD+30°3639.

The simultaneous presence of nitrogen and carbon in several planetary nuclei of Wolf-Rayet type is of great importance for the classification of the Wolf-Rayet stars. Other nuclei are typical members of the usual sequences; for example, the nuclei of Campbell's envelope star[27] and of HD 167362[28] are pure carbon stars containing no nitrogen, despite the high abundance of nitrogen in the surrounding nebulosities.

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[27] *Proc. Nat. Acad.*, **26**, 548, 1940.

[28] *Ibid.*, p. 454.

b) THE SPECTRUM OF THE NEBULA

The nebula is responsible for the continuous spectra[29] at the *H* limits, for the Balmer series up to H_{22}, for a rich spectrum of *He* I, and for a large number of forbidden lines. The latter are collected in Table 5.

There is no trace of the auroral transition of [*O* I] at λ 5577, although the transition probabilities are practically the same for [*O* I] and [*O* III].[30] This suggests stratification. We should expect the collisional cross-sections to be of the same order of magnitude for the corresponding metastable levels ^{1}S of *O* I (4.2 v.) and *O* III (5.3 v.). The different behavior of [*O* I] and [*O* III] may be due to the fact that the O^{++} ions are excited near the nucleus, whereas neutral oxygen occurs mostly at the outskirts of the nebula where the density is considerably reduced. [*S* III] also shows a strong line of the auroral type. It would be interesting to search for the auroral transitions of [*O* II] at λλ 7319.0–7330.3 and for the nebular transitions of [*S* II] at λλ 6717.3–6731.5. This region is not covered by our spectrograms. [*Ne* III] is very strong: λ 3869 is certainly as strong as *H*γ. On our spectrograms we do not find the auroral transition of [*Ne* III] at λ 3342.8; it must be much weaker than the transitions of nebular type. [*Ne* III] is probably excited in the denser regions near the nucleus, together with [*O* III], [*A* IV], and, to a lesser extent, [*S* III]. The absence or weakness of the auroral transition of [*Ne* III] may be due either to the higher excitation potential required (6.9 v.) or to specific atomic properties affecting the collisional cross-section. The ionization potentials of Ne^{+} and A^{++} being 40.9 v. and 40.7 v., respectively, we should expect the presence of [*A* IV] because we know that [*Ne* III] is very strong. The auroral transition of [*Ne* III] is also absent in Z Andromedae.

TABLE 5

FORBIDDEN LINES IN IC 4997

Nebular Type		Auroral Type		Transauroral Type	
Element	Intensity	Element	Intensity	Element	Intensity
O I	6–3	*O* III	15	*S* II	3–2
O II	7–5	*N* II	3	....	....
O III	25–20	*S* III	4	....	....
N II	5–7	....	....	....	....
Ne III	15–9	....	....	....	....
A IV	3–2	....	....	....	....

The ratio of intensity of the auroral to the nebular transition is much smaller for [*N* II] than for [*O* III]. This can also be understood if we assume that the collisional cross-sections for [*O* III] and [*N* II] are the same, because N^{+} must extend much farther from the nucleus than O^{++}, but not as far as neutral oxygen.

VI. THE SPECTRUM OF THE P CYGNI TYPE OF Z ANDROMEDAE

In the Balmer lines the ratio of intensity of the emission components and the absorption components decreases steadily toward the higher members. From *H*ε to *H*α the

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[29] A part of the continuous spectrum is probably due to the nucleus.

[30] The transition probabilities are shown in the accompanying table.

	Nebular	$(^3P - {}^1D)$	Auroral $(^1D - {}^1S)$
[*O* III]	0.016	0.0055	2.7
[*O* I]	0.013	0.0040	2.8

lines appear purely in emission. The Balmer continuum is still weakly present in absorption,[31] but it has decreased much since last fall, together with the absorption components of the lines of *H*, *Ti* II, *Fe* II, etc.

The radial velocities of the *H* and *He* I lines are collected in Table 6; all the Balmer lines with definite P Cygni characteristics have been included (from H_{15} to H_9), and they give very consistent results.

The lines of *Ti* II, *Fe* I, and [*Fe* II] are all very weak, and some identifications may be doubtful, but their presence may be regarded as very probable. The extreme weakness of [*Fe* II] and the absence of forbidden lines of any other element indicates that the P Cygni layer is rather dense or that its distance from the exciting nucleus is small.

In many respects this part of the spectrum is very similar to the present spectrum of BD+11°4673,[9] which also shows *Fe* I, *Ca* I, *Si* I, and *Si* II; but higher stages of excitation are present in BD+11°4673. Of course, the comparison with a P Cygni type star which is single may be quite artificial, as the presence of the late-type companion may substantially distort the P Cygni layer. The dilution effect is apparent in the absorption component of *He* I 3889. This line, which arises from the metastable $2s^3S$ level, shows a fairly strong absorption component. The line λ 3965, which arises from the metastable $2s^1S$ level, is complicated by the strong neighboring line of [*Ne* III] 3967, but we believe that it has also a violet absorption line. In the series $(2p^3P^0 - nd^3D)$ of *He* I, λ 4026 shows an absorption line of intensity 2, while λ 4472 shows one of intensity 1. The fact that these triplet lines are present at all in absorption proves that the dilution is not excessive. The dilution factor can hardly be less than 0.01, and we doubt that it is more than 0.1. The P Cygni type shell should, therefore, have a radius $r \sim 5R$.

TABLE 6

RADIAL VELOCITIES OF THE LINES OF P CYGNI TYPE

(In Km/Sec)

Lines Used	v_{Emission}	$v_{\text{Absorption}}$	Differences
Balmer lines.	+46.2	−37.2	83.4
λ 3889 *He* I.	+50.1	−60.9	111
Other *He* I lines.	+27	−53.8	80.8

The selectivity observed in the *Si* II spectrum is striking. The presence of the group λλ 3853.7–3856.0–3862.6 $(3s\,3p^2\,{}^2D - 3s^2\,4p\,{}^2P^0)$ is certain, although the group λλ 4128–4130 $(3s^2\,3d\,{}^2D - 3s^2\,4f\,{}^2F^0)$ is absent; this had been noticed by H. H. Plaskett. It is also observed in P Cygni itself and in BD + 11°4673.[9] It may be due to the fact that the lower level $3s\,3p^2\,{}^2D$, although not really metastable, is connected with the ground level $3s^2\,3p\,{}^2P^0$ by a weak transition (weak lines at λ 1817 and λ 1808). It should be noticed that the electron configuration of the ${}^2D$ level is $3s\,3p^2$, whereas all the other terms giving strong lines are due to the addition of one excited electron to the closed subshell $3s^2$.

VII. CONCLUSIONS

During the outburst of Z Andromedae in 1939 the only spectrum which could be observed was that of the P Cygni type expanding shell. The M spectrum, the spectrum of the nebula, and that of the nucleus were not visible. At the time of our observations the visual magnitude of Z Andromedae was 8.2.

In the summer of 1940, when the visual magnitude was 9.7, the P Cygni shell was still present, but the violet-absorption components were weaker and the emission spectrum

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[31] On Plaskett's spectrograms the Balmer continuum was in emission. On a spectrogram which we have taken on January 5, 1941, the Balmer continuum is clearly in emission and the P Cygni features are no longer visible.

had changed from that corresponding to an A star to one corresponding to a B star. Its evolution resembled that of a slow nova and evidently approached the kind of spectrum which Plaskett observed in 1923–1926. The forbidden lines of [*Fe* II], which were strong on Plaskett's plates, were still very weak on our 1940 plates.

The velocity of expansion of this shell has been approximately 100 km/sec. Since about 450 days have elapsed since the beginning of the outburst, the shell must have expanded over a distance of about 10^9 km. But the observable spectrum of the shell may not come from the same layer if material is being fed into the expanding mass over an appreciable period of time. Hence, the value of 10^9 km represents the upper limit of our estimate for the present distance between the P Cygni type shell and the surface of the nucleus.

When the star's brightness had declined to magnitude 9.7, the M star, the nebula, and the nucleus were again present in the spectrum. To all appearances they had not changed since before the outburst. It is possible that they never did change appreciably during the outburst and that their absence in the fall of 1939 was caused solely by the brightness of the P Cygni shell which required relatively short exposures. A search for the strong nebular emission line *He* II 4686 on our best plates of last fall shows that it was not visible at that time, also that it would not have been complicated by blending with strong lines of the P Cygni spectrum. The very strong nebular line should have shown quite readily with the shorter exposure required for Z Andromedae last fall, provided it was not superposed over a strong continuous spectrum. Whether it would still have been visible on top of the continuous spectrum is difficult to decide, but we have the impression that the line was really weaker last fall.

It is of interest to compute the relaxation time, τ, considered by Grotrian.[32] If we suppose that the ultraviolet exciting radiation of the nucleus was completely extinguished by the dense P Cygni shell in 1939 and that the nebular radiation had ceased completely, then τ would measure the length of time a pure hydrogen nebula would require to return to within 1.67 mag. of the final (normal) brightness. We follow Grotrian, but assume for the radius of the nucleus

$$R^* = 0.3 R_\odot \; ,$$

$$T^* = 70{,}000^\circ \; .$$

We also assume, following Menzel, that the

$$\text{Number of electrons per cm}^3 = 10^6 \; .$$

Using Cillié's data for hydrogen, we find for the volume of the nebula

$$V = 10^{48}\text{cm}^3$$

and

$$\tau \sim 2 \times 10^6 \text{ sec} \sim 3 \text{ or } 4 \text{ weeks} \; .$$

This is quite consistent with the observations, if we assume that the P Cygni shell in August, 1940, was completely transparent to the ionizing radiation.

The remarkable similarity of the nebular spectrum before and after the outburst suggests that its distance from the nucleus is great compared with the radius of the P Cygni type shell. The best estimate we can get for the latter depends upon the dilution factor:

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[32] *Zs. f. Ap.*, 13, 228, 1937.

$r = 5R^*$. The radius of the nucleus is not known. But all available evidence points to a radius R^* for a nova-like object which is considerably smaller than the radius of the sun.[33] If we adopt $R^* = 0.3 R_\odot$, the radius of the P Cygni type shell would be about $1.5 R_\odot$ or, roughly, 10^6 km. This is much smaller than the upper limit derived from the velocity of expansion. We are inclined to believe that the phenomenon cannot be treated as a single, thin layer which expands with a velocity of 100 km/sec. This is not surprising, since in all normal P Cygni type stars we are already accustomed to think of a continuous process of ejection. Once we accept the order of magnitude suggested for R^*, the small radius of the P Cygni shell follows from the dilution effect and from the weakness of the forbidden lines.

The radius of the nebula remains unknown. But the order of its size may be inferred from the estimate of the volume which we have made previously:

$$V = 10^{48} \text{cm}^3 .$$

If the entire sphere were occupied, we should find for the radius

$$r_{\text{nebula}} = 10^{16} \text{cm} = 10^{11} \text{km} .$$

This is of the same order of magnitude as the radius of the forbidden [*Fe* II] nebula which surrounds the B-type companion of α Scorpii.[34] This nebula, located at a distance of 100 parsecs, has a radius of 3″.

The entire picture of the system agrees well with that which results from Kuiper's dynamical theory[35] of binaries, such as β Lyrae, WY Gem, etc. The late-type component of Z Andromedae must be a supergiant, and its outer atmosphere may have a radius which is considerably larger than that determined with the interferometer for α Orionis and α Scorpii. It is entirely possible that the nebular material of Z Andromedae is concentrated within the limiting surface computed by Kuiper.

We are indebted to Professor Leon Campbell of the Harvard Observatory for information concerning the light-curve of Z Andromedae, and to Dr. D. M. Popper for some of the spectrograms taken last winter.

McDonald Observatory
and
Yerkes Observatory
September 1940

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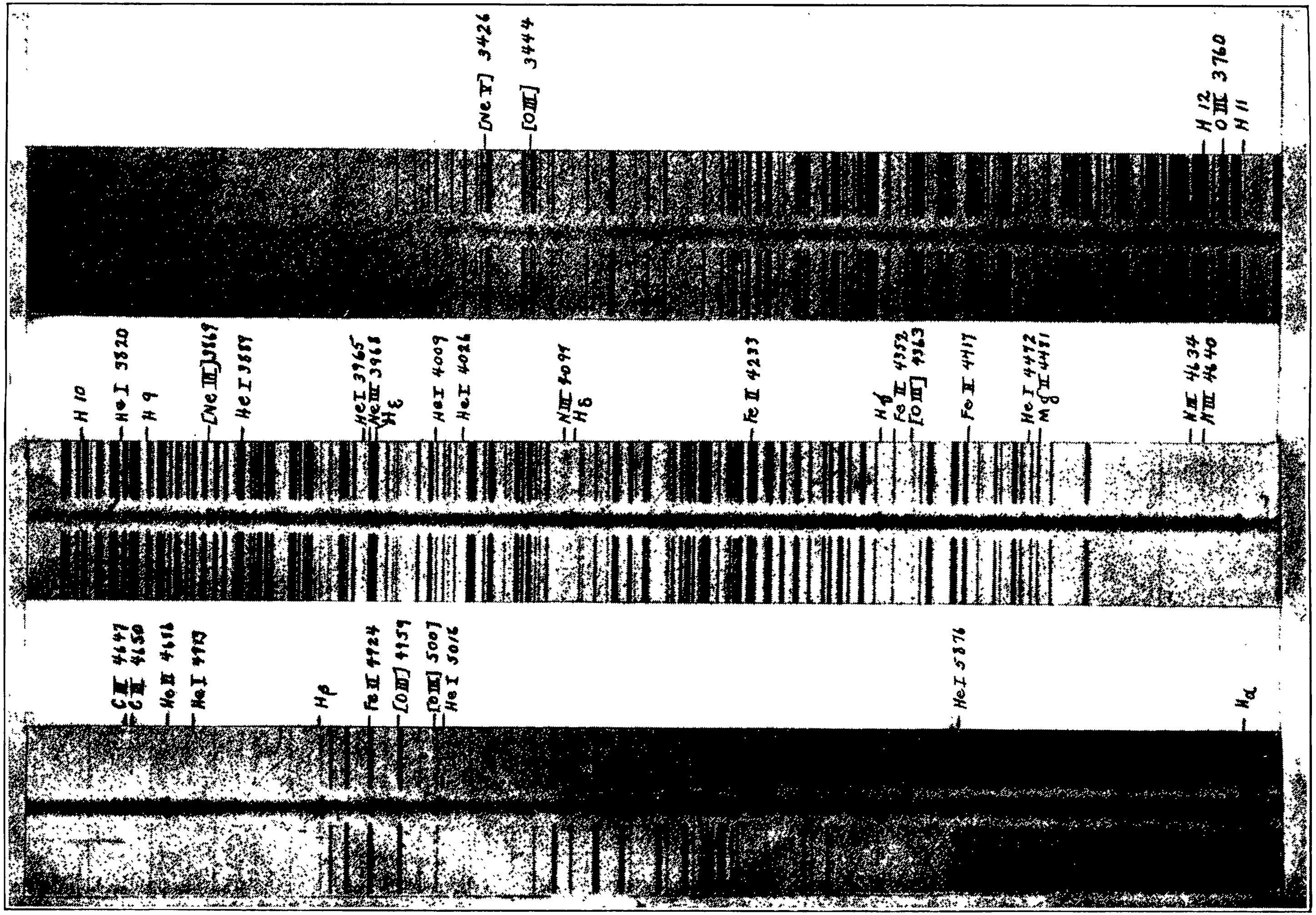
[33] We are indebted for this suggestion to Dr. G. P. Kuiper.

[34] *Ap. J.*, **92**, 316, 1940.

[35] *Ap. J.*, **93**, 133, 1941.

PLATE XVI



The Spectrum of Z Andromedae, August 15, 1940