

ATOMIC LINES IN THE SPECTRUM OF R ANDROMEDAE*

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ABSTRACT

The spectrum of the long-period variable R Andromedae, spectral type Se, was photographed from λ 3340 to λ 5000 with dispersion 10 Å/mm. The observed portion of the light-cycle extended from 10 to 103 days after maximum. Because molecular bands do not interfere so seriously, this spectrum is better adapted than Me spectra to a general study of atomic lines. A few spectrograms were obtained of the region $\lambda\lambda$ 5000–6800, dispersion 20 Å/mm.

Dark lines.—The identifications and displacements of more than thirteen hundred dark lines have been studied. A survey of the behavior of numerous multiplets includes the elements *Li* I, *Na* I, *Mg* I, *Al* I, *K* I, *Ca* I, *Ca* II, *Sc* I, *Sc* II, *Ti* I, *Ti* II, *V* I, *Cr* I, *Mn* I, *Fe* I, *Co* I, *Ni* I, *Ga* I, *Sr* I, *Sr* II, *Y* I, *Y* II, *Zr* I, *Zr* II, *Cb* I, *Ru* I, *Rh* I, *Ag* I, *In* I, *Ba* II, *Eu* I, *Eu* II, *Yb* I. A detailed study of the residuals from the mean radial velocity yielded by individual lines shows that the displacements of lines of neutral atoms (and of at least one ionized atom, *Y* II) increase algebraically with excitation potential. Lines of ionized atoms have positive displacements with respect to the lines of neutral atoms. The mean velocity exhibits little variation with phase.

Bright lines.—The behavior of bright lines of *H*, *Mg* I, *Fe* I, and *Fe* II was studied in considerable detail. Other lines measured include those of *Si* I, *Mn* I, *In* I, *Ca* II, *Ti* II, *Mn* II, *Sr* II. Speaking broadly, the behavior in the light-cycle resembles that in Me variables, but with some interesting differences. The velocities exhibit smaller variations with phase. Table 12 lists 60 unidentified bright lines; several, particularly $\lambda\lambda$ 3735.35, 4372.50, and 4455.31, are strong.

General.—Atoms of *Y* and *Zr* appear to be more abundant in R Andromedae than in Me variables. It is suggested that the trifurcation of the low-temperature end of the stellar sequence may have some connection with the nuclear stability of certain chemical elements.

R Andromedae, 001838, is a well-known red variable star, of period 407 days, magnitude range 5.6–14.7, the variability having been detected at Bonn in 1858. In the *Henry Draper Catalogue* the spectrum is described as very peculiar and in the continuous portion between *H* β and *H* γ is said to resemble the spectrum of the southern star π^1 Gruis. Bright hydrogen lines are conspicuous. The star was observed many years ago with slit spectrographs at Ann Arbor¹ and at Mount Wilson.^{2,3} The spectrum is now considered a typical example of class Se.

The present investigation is based on a new series of spectrograms, dispersion 10.3 Å/mm (20.6 Å/mm in the visual region), similar to those recently used in my studies of several Me variables.^{4,5,6} Dates of observation are in Table 1, and their relationship to the light-curve is shown in Figure 1. The photometric data were again supplied through the courtesy of Leon Campbell, of the Harvard Observatory.

ABSORPTION LINES

Because a considerably larger region of wave length is free from serious interference by molecular bands, the spectrum of R Andromedae, class Se, is better adapted to a

* *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 730.

¹ P. W. Merrill, *Pub. Obs. U. Michigan*, 2, 45, 1916.

² P. W. Merrill, *Mt. W. Contr.*, No. 252; *Ap. J.*, 56, 457, 1922.

³ P. W. Merrill, *Mt. W. Contr.*, No. 325; *Ap. J.*, 65, 23, 1927.

⁴ U Ori, R Ser, R Aql, R Cas, *Mt. W. Contr.*, No. 713; *Ap. J.*, 102, 347, 1945.

⁵ R Hya, *Mt. W. Contr.*, No. 717; *Ap. J.*, 103, 6, 1946.

⁶ R Leo, *Mt. W. Contr.*, No. 720; *Ap. J.*, 103, 275, 1946.

general study of atomic lines than are the spectra of Me variables. The *ZrO* bands are much less extensive than the *TiO* bands of Me variables (see Figs. 2-5).

The continuous spectrum in the photographic region is well exposed on only four plates (at two epochs), Ce 3522, phase +9 days; Ce 3526, +10 days; Ce 3560, +44 days; and Ce 3564, +45 days. The rich dark-line spectrum with hundreds of measurable lines is very nearly the same at the two epochs. On the later plates, Ce 3611, phase

TABLE 1
JOURNAL OF OBSERVATIONS

Plate Ce	Date	JD 243	Mag.	Phase (Days)	Remarks
3078.....	1943 June 22	0898	7.0	+ 14	Sky spectrum superposed
3522.....	1944 Aug. 1	1304	6.9	+ 10	
3526.....	Aug. 2	1305	6.9	+ 11	
3560.....	Sept. 5	1339	7.3	+ 45	
3564.....	Sept. 6	1340	7.4	+ 46	Bright lines only
3565.....	Sept. 6	1340	7.4	+ 46	
3608.....	Oct. 6	1370	8.7	+ 76	Bright lines only
3611.....	Oct. 8	1372	8.8	+ 78	
3633.....	Nov. 2	1397	9.7	+103	Red region
4003.....	1945 Sept. 28	1727	7.2	+ 27	
4035.....	Oct. 24	1753	7.8	+ 53	
4040.....	Oct. 25	1754	7.8	+ 54	

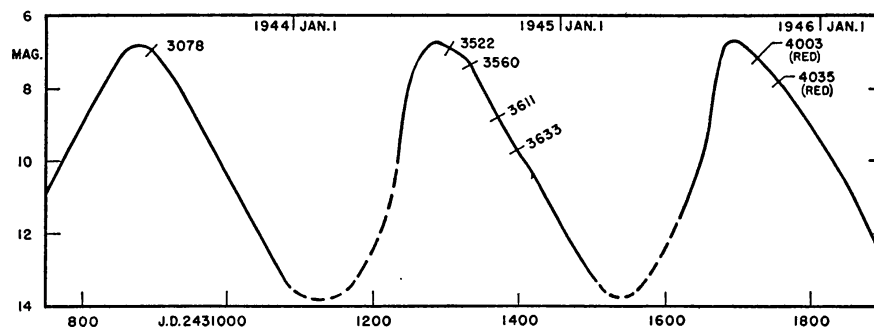


FIG. 1.—Light-curve of R Andromedae, showing dates of spectrograms (see Table 1)

+77 days, and Ce 3633, +102 days, the weak continuous spectrum allowed the measurement of 20-30 lines, enough to yield a fairly reliable radial velocity. All three red plates (Table 1) are measurable. The number of atomic lines, in absorption, measured on one or more plates is as shown in the accompanying tabulation.

λ	Dark Atomic Lines Measured
3340-4000.....	563
4000-4500.....	558
4500-5064.....	150
5800-6800.....	62
Total.....	1333

In the following condensed description of the behavior of the absorption lines of numerous chemical elements, the excitation potentials, E.P. (volts), are of the lower levels of the various multiplets. The multiplet references, Arabic numbers in parentheses, are to the Revised Multiplet Table.⁷

LINES OF *Li* I

E.P.

- 0.0 The ultimate line λ 6708, multiplet (1), is present in low intensity. The measurements (of relatively low weight) indicate that it is shifted shortward about 0.2 Å. The observed shift is similar to that of the cores of the D lines of *Na* I.

LINES OF *Na* I

- 0.0 The D lines, multiplet (1), are strong and unsymmetrical, being shaded longward. In each line a narrow core, not well resolved from a broader component, is shifted shortward about 0.2 Å with respect to the dark lines of most other elements.

LINES OF *Mg* I

- 0.0 Near maximum light the $^1S - ^3P$ line λ 4571, (1), is of moderate intensity and in its normal position. As the cycle advances, the dark line is weakened and crowded longward by an emission fringe of increasing intensity. After phase +60 days the emission line dominates.
- 2.7 The lines of (3) are bright on all plates; on well-exposed plates taken near maximum, weak absorption lines were measured on the longward sides.

LINES OF *Al* I

- 0.0 Lines λ 3944 and λ 3961 of (1), although very strong, are not so outstanding as in R Leonis. On Ce 3526 the dark lines appear unsymmetrical, having a wing longward with a more abrupt boundary and possibly some emission on the shortward edge. On several of the later plates there is a trace of weak displaced emission like that exhibited so prominently by H and K of *Ca* II.

LINES OF *Si* I

- 1.9 The bright line λ 4103, (2), is notched by a dark line, but it is not certain that the absorption is due to atoms of *Si* I.

LINES OF *K* I

- 0.0 Lines λ 4044 and λ 4047 of (3), although weaker than in R Leonis, are easily identified. Their mean residual in radial velocity is small; as in several Me variables,⁴ λ 4044 has a slight negative displacement with respect to λ 4047.

LINES OF *Ca* I

- 0.0 (1) moderate intensity; (2) λ 4226 extremely strong.
- 1.9 (3)–(6), (9) moderate intensity.
- 2.5 (23) and (25) probably present in low intensity.

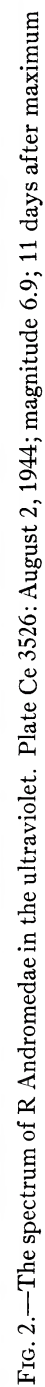
LINES OF *Ca* II

- 0.0 The H and K lines, (1), are not extremely intense on these post-maximum plates. The profiles, especially that of the H line, are greatly distorted by the curious displaced emission within the shortward wings. This phenomenon, similar to that observed in several Me variables, will be described in the section on emission lines.

LINES OF *Sc* I

- 0.0 (1) doubtful; (2), (3) moderate intensity; (5), (6), (7), (8) strong.
- 1.4 (14) weak.
- 2.0 (20) weak.

⁷ C. E. Moore, "A Multiplet Table of Astrophysical Interest," rev. ed., *Contributions from the Princeton Observatory*, No. 20, 1945.



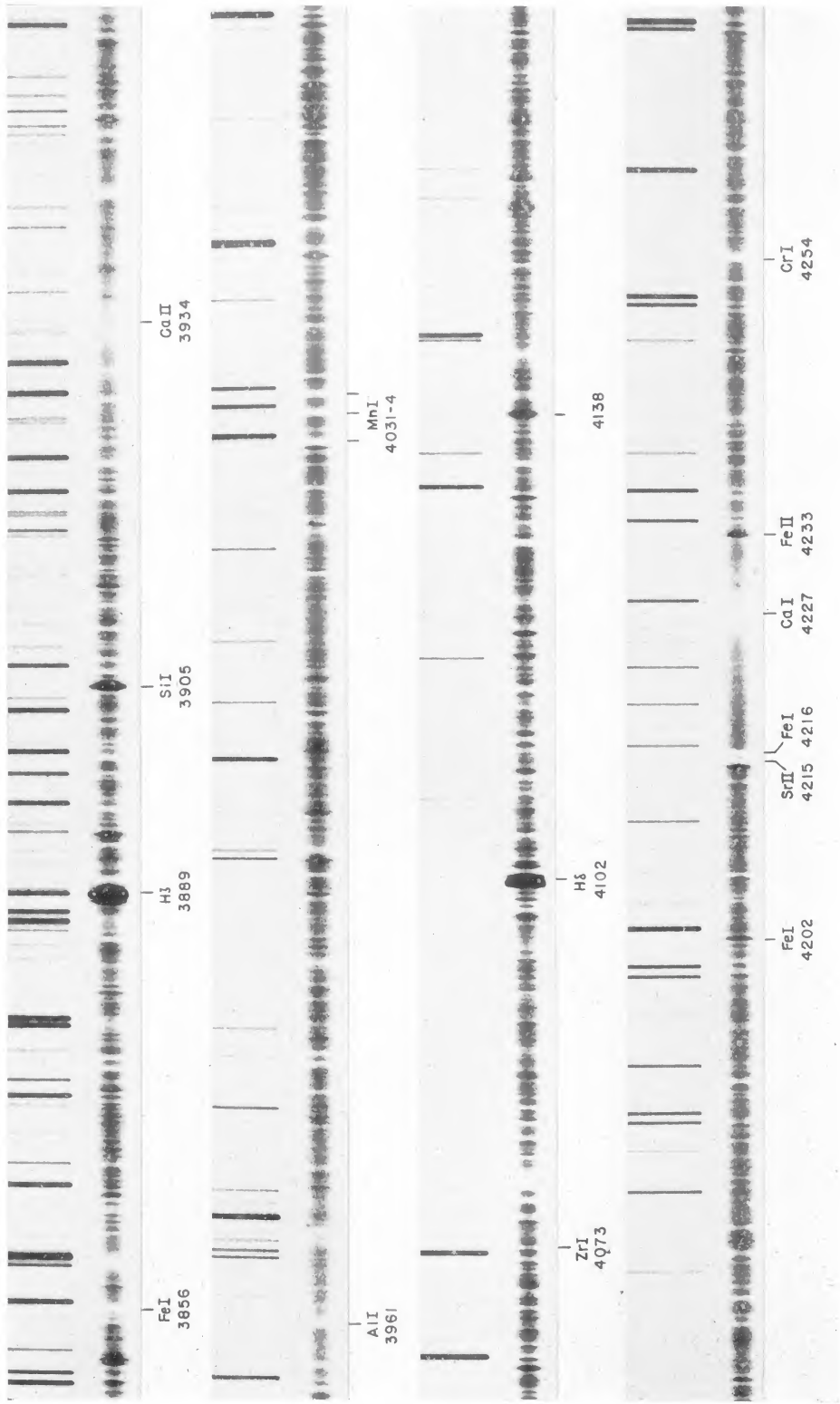


FIG. 3.—The spectrum of R Andromedae $\lambda\lambda$ 3850–4270. Plate Ce 3526: August 2, 1944; magnitude 6.9; 11 days after maximum

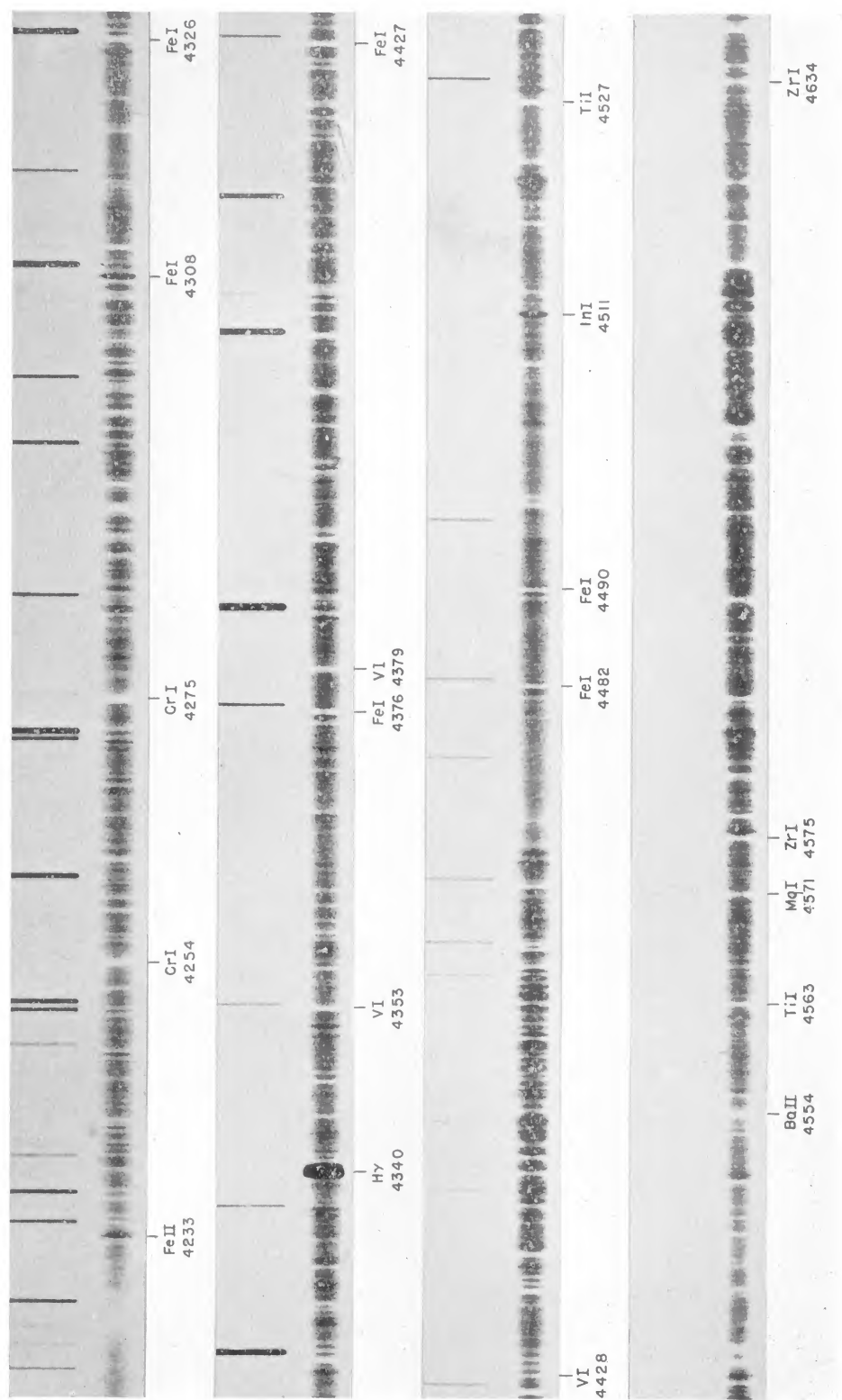


FIG. 4.—The spectrum of R Andromedae $\lambda\lambda$ 4220–4640. Plate Ce 3522: August 1, 1944; magnitude 6.9; 10 days after maximum

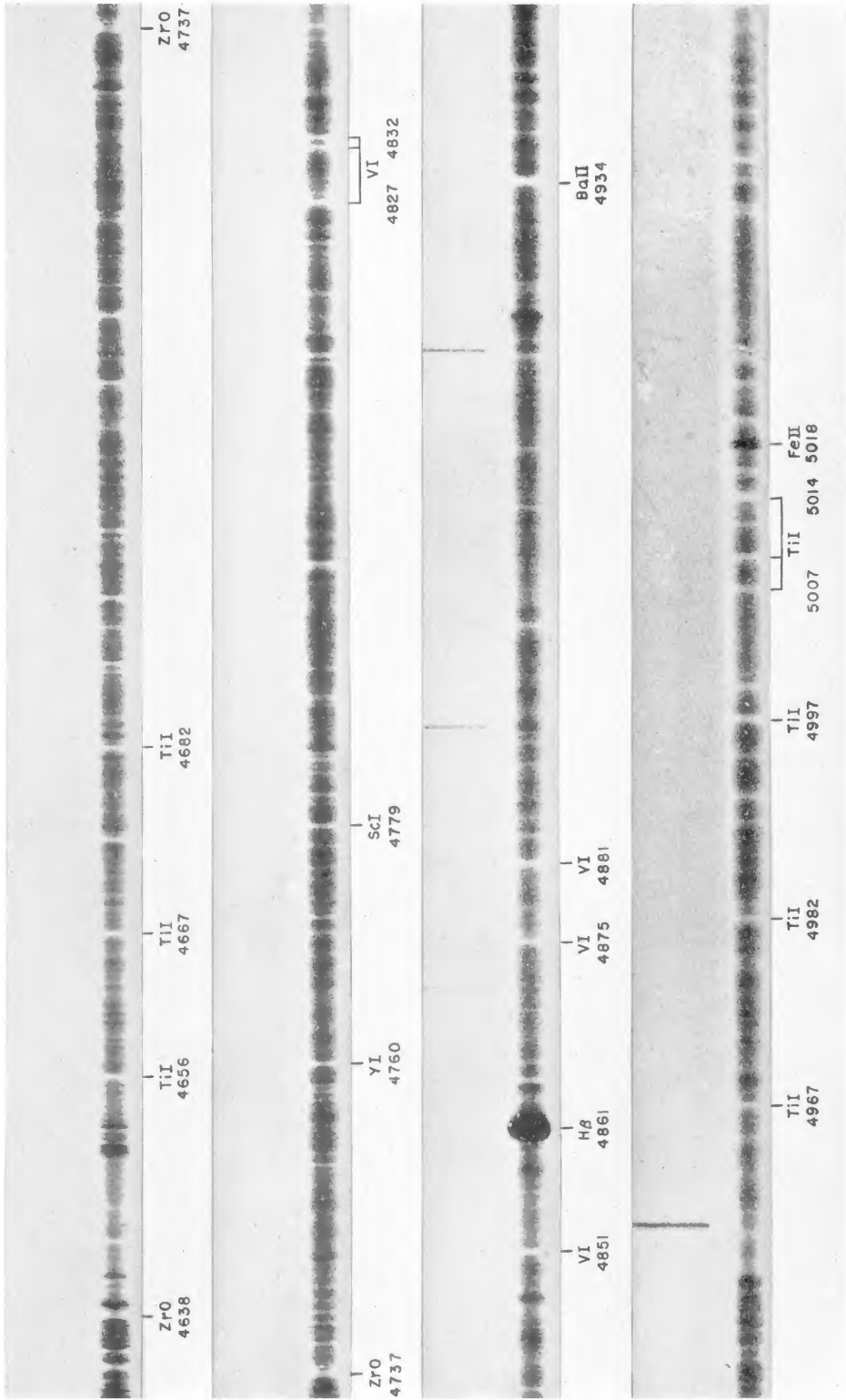


FIG. 5.—The spectrum of R Andromedae $\lambda\lambda$ 4630–5050. Plate Ce 3522: August 1, 1944; magnitude 6.9; 10 days after maximum

LINES OF *Sc* II

E.P.

- 0.0 (1) doubtful; (2), (3) strong.
 0.3 (7), (11) strong; (8) weak; (10) probably present in low intensity.
 0.6 (14), (15) probably present in low intensity.

LINES OF *Ti* I

- 0.0 (1) moderate intensity; (2) apparently present in low intensity; (6)–(21) strong, except (8), (16), which are weak and blended; (22) possibly present, observations inadequate.
 0.8 (38), (41)–(44) strong; (39) doubtful.
 1.0 (75), (80), (83) strong.
 1.9 (160) moderate intensity; (157), (159), (161), (162), (163) probably present in low intensity.
 2.1 (185) weak; (187), (188) little evidence.
 2.2 (233) probably present in low intensity.

LINES OF *Ti* II

- 0.6 Near maximum light *Ti* II is represented by the three strongest lines of (13) and (14), $\lambda\lambda$ 3759, 3761, 3685. These dark lines are weak; the pair near λ 3760 have bright edges shortward, which strengthen somewhat as the light fades and which persist as weak emission lines throughout the observed interval.

LINES OF *V* I

- 0.0 (3)–(11) strong.
 0.3 (19), (21), (22), (24), (25)?, (27), (28), (29) moderately strong; (20), (23), (26)? weak.
 1.0 (34) moderate intensity.
 1.1 (39), (40) not found; (41), (42) weak.

LINES OF *Cr* I

- 0.0 (1) very strong; (2), (3), (10) moderate intensity; (4) $\lambda\lambda$ 3579, 3593, 3605 extremely strong; (9), (11) apparently absent.
 1.0 (21), (22), (23) moderate intensity; (24) weak.
 2.5 A few strong lines of (38), (46), and (47) are probably present in low intensity.

LINES OF *Mn* I

- 0.0 The three lines of (2) near λ 4030 are very strong, with marked emission developing on the shortward edges during the post-maximum phase, as in Me variables.
 2.1 (5) surprisingly strong; (6), (8) weak or absent.
 2.3 (18) may be present in low intensity but blends interfere.

LINES OF *Fe* I

- 0.0 (2)–(5) strong; (6) present but not measured because of underexposure at the shortward end of the photographed spectrum.
 0.9 (18)–(23) fairly strong; (24), (25) probably present but observations inadequate.
 1.5 (41), (42), (43), (45) moderate intensity; (44), (46), (48) weak or absent.
 2.2 (68) probably present in low intensity; (73), (78) possible; (71), (72), (74), (76) little evidence.
 2.4 (152) apparently present in low intensity.
 2.8 (354), (355) the strongest lines are probably present in low intensity.

LINES OF *Co* I

- 0.0 (1)–(6) fairly strong.
 0.4 (16), (18), (19), (21), (22) fairly strong; (17), (20) weak or absent.
 0.9 (28)–(35) except (32) moderate or low intensity; (32) weak or absent.
 1.9 (58), (62) weak or absent.

LINES OF *Ni* I

E.P.

- 0.0 (1)–(4), (6) fairly strong.
 0.1 (15), (16) fairly strong; (17), (18) present, observations inadequate.
 0.4 (28), (30)–(33), (35), (36) fairly strong.

LINES OF *Ga* I

- 0.0 (1) seems to be represented by λ 4172, but the observation needs confirmation; λ 4030, if present, is blended with the strong line of *Mn* I.

LINES OF *Sr* I

- 0.0 (2) λ 4607 strong.

LINES OF *Sr* II

- 0.0 (1) λ 4077, λ 4215 strong. See description of emission edges in the section on emission lines.

LINES OF *Y* I

- 0.0 (1)–(8) fairly strong; blends interfere with some identifications.

LINES OF *Y* II

- 0.0 (1), (2) fairly strong.
 0.1 (5)–(9) fairly strong.
 0.4 (12) weak or absent; (13) fairly strong; (14), (15), (16) moderate or low intensity.
 1.0 (22) may be represented by traces of the two leading lines, but the identification is doubtful because of blends.

LINES OF *Zr* I

- 0.0 (1), (2), (3), (5)–(16) fairly strong; (4) doubtful; (7), (11), (14) badly blended.
 0.5 (29), (31), (32) moderate intensity; (28) not observed; (30), (33) doubtful because of blends.
 0.6 (43), (45), (46) moderate intensity; (44) weak.
 0.6 (48)–(52) moderate intensity.
 1.0 (58) moderate intensity.
 1.4 (61) weak.
 1.5 (63), (64) no evidence.
 1.8 (66) no evidence.

LINES OF *Zr* II

- 0.0 (1) fairly strong.
 0.4 (2) moderate intensity, observations incomplete; (3) possible, observations incomplete; (7) little evidence; (8) doubtful; (9) strongest lines may be present in low intensity.

LINES OF *Cb* I

- 0.0 (1), (3) moderate intensity; (2), (4) doubtful.

LINES OF *Ru* I

- 0.0 (1), (2), (4) moderate intensity; (3) doubtful.

LINES OF *Rh* I

- 0.0 (1), (2), (3) strongest lines may be present in low intensity.

LINES OF *Ag* I

- 0.0 (1) λ 3382 moderate intensity. This may be the first observation of silver in the stars. Both lines of (1) are faintly present in the solar spectrum.

LINES OF *In* I

- 0.0 (1) λ 4101 may be present as a notch in bright *H* δ . The other line of (1), λ 4511, is a strong emission line.

LINES OF *Ba* II

E.P.

- 0.0 (1) strong; the strength of λ 4554 and λ 4934 is characteristic of S-type spectra.
 2.7 (3) probably absent; (4) probably present in low intensity.

LINES OF *Eu* I

- 0.0 (1) little evidence for or against.

LINES OF *Eu* II

- 0.0 (1) moderate intensity; (2) perhaps present in low intensity.
 0.2 (4) no evidence for or against; (5) perhaps present in low intensity.

LINES OF *Yb* I

- 0.0 (2) moderate intensity.

TABLE 2
 RADIAL VELOCITIES DERIVED FROM DARK LINES
 ON ONE-PRISM SPECTROGRAMS

Year	Phase (Days)	Rad. Vel. (Km/Sec)	No. Plates
1919.....	-12	- 8.2	2
1921.....	-16	(-14)	1
1928.....	+ 6	- 4	1

TABLE 3
 RADIAL VELOCITIES FROM ABSORPTION LINES

Plate Ce	Date	Phase (Days)	Rad. Vel. (Km/Sec)
3522.....	1944 Aug. 1	+ 9)	-10.7
3526.....	Aug. 2	+ 10)	
3560.....	Sept. 5	+ 44)	-12.1
3564.....	Sept. 6	+ 45)	
3611.....	Oct. 8	+ 77	-11.0
3633.....	Nov. 2	+102	-13.5
4003.....	1945 Sept. 28	+ 27	- 9.5
4035.....	Oct. 24	+ 53)	-11.4
4040.....	Oct. 25	+ 54)	
Mean.....	.....	+ 57	-11.3

Radial velocities from dark lines.—The radial velocities previously derived^{8, 9} from one-prism spectrograms, dispersion 35 Å/mm, are listed in Table 2.

The values obtained from the present series of grating spectrograms are in Table 3. The observed interval extends only from 9 to 102 days after maximum. During this time there appears to be a slight decrease (algebraic) in velocity, but the change is small, scarcely exceeding errors of observation. With the possible exception of the observation in 1928, there is no evidence of differences between various maxima.

The measured relative displacements of numerous multiplets of various elements are recorded in Table 4, in which the tabulated residuals are the means from measurements

⁸ P. W. Merrill, *Mt. W. Contr.*, No. 264; *Ap. J.*, **58**, 215, 1923.

⁹ P. W. Merrill, *Mt. W. Contr.*, No. 649; *Ap. J.*, **94**, 171, 1941.

TABLE 4
DISPLACEMENTS OF MULTIPLETS (ABSORPTION LINES)

Element	E.P. (Volts)	Mult.	Resid. (Km/Sec)	Wt.	Element	E.P. Volts	Mult.	Resid. (Km/Sec)	Wt.
<i>Mg</i> I.....	0.0	1	(Var.)	2	<i>V</i> I.....	0.0	3	-2.4	16
	2.7	3	(+1.9)	1.5			4	-0.8	11
							5	+0.5	13
<i>Al</i> I.....	0.0	1	(+2.6)	1			6	+0.4	9
<i>K</i> I.....	0.0	3	-1.0	4			7	-2.1	14
<i>Ca</i> I.....	0.0	2	(-2.1)	1			8	-0.3	5
	1.9	4	-0.2	8			9	-2.2	9
		5	0.0	6		0.3	10	-1.6	3
		9	+0.3	2			11	-2.2	1
	2.5	23	+0.7	1			21	+0.3	14
		25	+5.5	1			22	+0.5	22
<i>Sc</i> I.....	0.0	5	-0.6	6			23	+4.3	1
		6	-1.8	4			24	+1.3	8
		7	-0.4	4			25	+0.4	2
		8	-0.7	4			27	+0.6	10
	1.4	14	-0.1	2		1.1	28	+0.9	16
	2.0	20	-1.9	1			29	+0.8	6
<i>Sc</i> II.....	0.0	2	+2.8	4	<i>Cr</i> I.....	0.0	1	(-2.2)	4
		3	+2.4	4			2	-2.2	4
	0.3	7	+2.0	2			3	-0.8	1
		8	+4.2	1			4	0.0	0.5
		10	+2.3	0.5		1.0	10	+1.2	6
		11	0.0	2			21	+1.2	11
	0.6	14	+0.8	0.5			22	+0.4	11
		15	+5.6	0.5			23	+1.0	10
<i>Ti</i> I.....	0.0	5	-1.2	5		2.5	24	0.0	2
		6	-3.0	10			38	+2.9	2
		7	-3.8	3			46	+0.5	1
		8	-0.7	4	<i>Mn</i> I.....	0.0	2	(-3.5)	5
		9	-1.0	3		2.1	5	+2.6	4
		10	+0.3	2	<i>Fe</i> I.....	0.0	2	-1.2	19
		11	+1.2	3			3	-1.7	9
		12	-5.8	10			4	-0.5	15
		13	-1.8	6		0.0	5	-1.2	7
		14	-3.7	5		0.9	18	+3.5	2
		15	-1.2	8			19	+0.9	5
		17	-3.0	12			20	+0.4	12
		18	-1.8	10			21	-0.5	16
		19	-0.7	11			22	+1.3	3
		20	-1.4	4			23	-0.6	13
		21	-2.5	1			24	+1.0	3
	0.8	38	+2.9	8			25	+3.7	1
		41	-0.2	2		1.5	41	+1.2	6
		42	+0.7	16			42	+1.0	10
		43	+2.0	9			43	+1.8	9
		44	-0.5	11			45	+0.5	6
	1.0	75	+0.3	5		2.2	68	+2.7	3
		80	-0.6	8			73	(+0.1)	1.5
		83	-0.7	1			78	(+5.8)	0.5
	1.9	157	-5.0	0.5		2.4	152	+3.6	6
		159	+2.3	1		2.8	354	(-3.4)	2
		160	-0.9	5			355	+1.4	1
		161	+2.2	1	<i>Co</i> I.....	0.0	1	+2.0	4
	2.1	185	+1.0	2			2	-0.8	6
	2.2	233	-0.6	2			3	-1.2	6
<i>Ti</i> II.....	0.6	13	+2.2	2			4	+0.8	4
		14	+1.5	1			5	0.0	1.5

TABLE 4—*Continued*

Element	E.P. (Volts)	Mult.	Resid. (Km/Sec)	Wt.	Element	E.P. (Volts)	Mult.	Resid. (Km/Sec)	Wt.				
<i>Co I—Cont.</i>	0.4	6	−1.8	4	<i>Y II—Cont.</i>	0.4	13	+5.2	2				
		16	+0.2	5			14	+4.3	1				
		18	+0.6	4			15	−1.5	0.5				
		19	+1.6	5			16	+3.0	0.5				
		20	−0.8	0.5			<i>Zr I.....</i>	0.0	5	−2.0	6		
	21	+0.3	5	6	−1.3	8							
	22	−0.1	4	8	−1.7	4							
	23	+1.6	1	9	−0.6	1							
	0.9	28	+1.6	2	10	−1.2			8				
		29	+3.1	1	12	−1.8			4				
		30	+3.0	2	13	−0.1			1				
		31	+2.5	1	15	−1.1			3				
		33	+3.6	0.5	16	+1.9			1				
	1.9	34	+2.1	1	0.5	29			−4.0	2			
		62	+2.4	1		31	+3.3	6					
<i>Ni I.....</i>	0.0	1	−2.6	2		0.6	32	+1.5	4				
		2	+2.6	5			43	+0.1	12				
		3	−2.7	2.5			44	+0.4	6				
		4	+0.3	5	45		+0.3	17					
		6	−1.7	2	46		−0.5	5					
	0.0	9	+1.6	0.5	0.6	48	−4.0	1					
		15	+0.2	7		49	−0.9	1					
		16	−0.6	5		50	+3.4	2					
		17	−2.2	1		51	+1.9	2					
		18	−2.4	1		52	+1.7	2					
	0.4	30	+1.6	1	1.0	58	−0.8	2					
		31	+1.8	4		61	+1.9	2					
		32	+1.4	1		<i>Zr II.....</i>	0.0	1	+3.1	6			
		33	+3.0	5				2	+4.3	2			
		35	+3.6	2				3	+5.5	1			
36		+3.9	1	8				(+3.6)	1				
<i>Ga I.....</i>		0.0	1	(+1.2)				2	9	(+0.6)	1.5		
	<i>Sr I.....</i>		0.0	1	(−1.6)			2	<i>Cb I.....</i>	0.0	1	+0.4	13
				3	+0.2			6					
<i>Sr II.....</i>	0.0	1	(−4.6)	4	<i>Ru I.....</i>	0.0	1	+0.9	1				
<i>Y I.....</i>	0.0	4	−1.6	5		2	+2.1	7					
		5	−2.9	6	<i>Rh I.....</i>	0.0	2	+1.8	1				
		6	−0.2	2			<i>Ag I.....</i>	0.0	1	+1.3	1		
		7	−1.1	2					<i>Ba II.....</i>	0.0	1	(−2.8)	4
		8	+1.7	1		2.7	4	+0.5			2		
<i>Y II.....</i>	0.0	1	−1.6	1	<i>Eu II.....</i>	0.0	1	−0.8	5				
		2	0.0	2			0.2	5	+2.6	0.5			
	0.1	5	+1.5	4	<i>Yb I.....</i>	0.0		2	−1.8	2			
		6	−0.2	2									
		7	+0.4	4									
		8	−0.2	3									
		9	+0.3	9									

of four plates with numerous lines, Ce 3522, 3526, 3560, 3564. The residuals in parentheses correspond to multiplets omitted in forming the velocities adopted for each plate. The weights in the last column depend largely on the number of lines measured. A well-defined line of suitable intensity for accurate settings measured on two plates was given

unit weight. Thus a multiplet with three good lines measured on all four plates would have weight 6.

The detailed results in Table 4 are summarized in Tables 5 and 6. Table 5 shows that residuals of lines of neutral atoms (and of at least one ionized atom, $Y II$) increase

TABLE 5
DISPLACEMENTS OF ABSORPTION LINES AT VARIOUS EXCITATION POTENTIALS

Element	E.P. (Volts)	Resid. (Km/Sec)	Wt.	Element	E.P. (Volts)	Resid. (Km/Sec)	Wt.
<i>Sc I</i>	0.0	-0.9	18	<i>Fe I</i>	1.5	+1.2	31
	1.4	-0.1	2		2.2	+2.7	3
	2.0	-1.9	1		2.4	+3.6	6
					2.8	+1.4	1
<i>Sc II</i>	0.0	+2.6	8	<i>Co I</i>	0.0	-0.3	25.5
	0.3	+1.7	5.5		0.4	+0.6	24.5
	0.6	+3.2	1		0.9	+2.5	7.5
<i>Ti I</i>	0.0	-2.2	97		1.9	+2.4	1
	0.8	+1.0	46	<i>Ni I</i>	0.0	-0.2	17
	1.0	-0.3	14		0.4	+2.6	14
	1.9	-0.3	7.5	<i>Y II</i>	0.0	-0.5	3
	2.1	+1.0	2		0.1	+0.4	22
	2.2	-0.6	2		0.4	+3.9	4
<i>Ti II</i>	0.6	+2.0	3	<i>Zr I</i>	0.0	-1.4	36
<i>V I</i>	0.0	-1.2	81		0.5	+1.5	12
	0.3	+0.7	79		0.6*	+0.1	40
	1.1	-0.6	4		0.6†	+1.1	8
<i>Cr I</i>	0.0	-0.2	11.5		1.0	-0.8	2
	1.0	+1.0	34		1.4	+1.9	2
	2.5	+2.1	3	<i>Zr II</i>	0.0	+3.7	9
<i>Fe I</i>	0.0	-1.0	50		0.4	(+1.8)	2.5
	0.9	+0.2	55				

* Lower term, a^5F .

† Lower term, a^1D .

TABLE 6
DISPLACEMENTS OF LINES OF VARIOUS ELEMENTS

Element	Resid. (Km/Sec)	Wt.	Element	Resid. (Km/Sec)	Wt.
<i>Al I</i>	(+2.6)	1	<i>Sr I</i>	(-1.6)	2
<i>K I</i>	-1.0	4	<i>Sr II</i>	(-4.6)	2
<i>Ca I</i>	+0.3	18	<i>Y I</i>	-1.7	16
<i>Sc I</i>	-0.9	21	<i>Y II</i>	+0.8	29
<i>Sc II</i>	+2.4	14.5	<i>Zr I</i>	-0.2	100
<i>Ti I</i>	-1.0	168.5	<i>Zr II</i>	+3.7	9
<i>Ti II</i>	+2.0	3	<i>Cb I</i>	+0.3	19
<i>V I</i>	-0.3	164	<i>Ru I</i>	+1.9	8
<i>Cr I</i>	+0.8	48.5	<i>Rh I</i>	+1.8	1
<i>Mn I</i> *.....	+2.6	4	<i>Ag I</i>	+1.3	1
<i>Fe I</i>	+0.2	146	<i>Ba II</i> †.....	+0.5	2
<i>Co I</i>	+0.4	58.5	<i>Eu II</i>	-0.6	5.5
<i>Ni I</i>	+0.7	45	<i>Yb I</i>	-1.8	2
<i>Ga I</i>	(+1.2)	1			

* E.P. 2.1 volts.

† E.P. 2.7 volts.

algebraically with excitation potential. A similar effect was previously found in the spectra of several Me variables.¹⁰ The relative displacements in R Andromedae are equal to, or less than, those in the Me variables.

The results for various elements (Table 6) yield no evidence of differences in behavior between heavy metals and light ones. The lines of ionized atoms, however, have positive displacements with respect to those of neutral atoms. The most reliable displacements, shown in the accompanying tabulation, have a mean value, II *minus* I, of +3.2 km/sec.

Element	II-I	Element	II-I
Sc.....	+3.3 km/sec	Y.....	+2.5 km/sec
Ti.....	+3.0	Zr.....	+3.9

EMISSION LINES

Lines of hydrogen.—The bright lines of the Balmer series are outstanding on all plates, although at the faintest observed phase, +102 days, the intensities are somewhat decreased (see Figs. 2-7). Near maximum light the slightly widened *H* lines are badly

TABLE 7
RADIAL VELOCITIES FROM EMISSION LINES
(KM/SEC)

ELEMENT AND LINE OR MULTIPLET	PHASE (DAYS)				
	+10	+45	+76	+102	+58 (Mean)
<i>H</i> (several).....	-26.0	-28.6	-28.3	-27.0	-27.5
<i>Fe</i> I (many).....	33.8	31.7	29.8	28.5	30.7
<i>Mg</i> I λ 4571.....	.....	33.2	30.1	27.7	30.3
<i>Mg</i> I (3).....	30.6	29.6	28.5	29.8	29.6
<i>Si</i> I (2), (3).....	29.8	30.9	30.7	32.5	31.4
<i>Mn</i> I (2).....	47.3	48.2	48.3	47.7	48.0
<i>In</i> I λ 4511.....	28.5	29.1	28.8	28.0	28.6
<i>Ti</i> II (13).....	30.8	29.3	29.2	29.5	29.7
<i>Fe</i> II (many).....	26.0	27.6	26.8	27.2	26.9
<i>Sr</i> II λ 4215.....	-42.0	-42.0	-40.0	-39.3	-40.8
Absorption-Line Velocities					
Neutral metals...	-10.7	-12.1	-11.0	-13.5	-11.3

mutilated by absorption lines of other elements; as the cycle advances, they tend to become narrower and to assume their normal (laboratory) relative intensities. At the later phases they are evidently subject to the absorption of the reversing layer to a far less degree than they are when near maximum. In this respect their behavior strongly resembles that in Me variables. A detailed study of the apparent structure of the bright lines before maximum when the mutilations are the greatest would be especially interesting. It might be possible to demonstrate that the hydrogen emission occurs at first not only below the reversing layer but even below the level of the normal photosphere.

Radial velocities, which depend chiefly on measurements of lines from *H* β to *H* 18, are listed in Table 7. The differences do not exceed errors of measurement. The mean velocity, -27.5 km/sec, agrees within errors with the value -29 km/sec, previously adopted,⁹ which depends on one-prism spectrograms obtained during the years 1915-1939.

¹⁰ o Ceti, W. S. Adams, *Mt. W. Contr.*, No. 638; *Ap. J.*, 93, 11, 1941; U Ori, see n. 4; R Hya, see n. 5; R Leo, see n. 6.

Lines of Fe I.—The emission-line spectrum of *Fe I* is somewhat more fully developed in R Andromedae than in Me variables. The pattern of behavior with advancing phase in the light-cycle is similar to that in R Leonis, although not identical in all details. Some of the observed differences are probably due to the absence of *TiO* bands in R Andromedae.

The number of measurable bright lines increased from about 15 at phase +10 days to about 60 at +120 days (see Figs. 6 and 7). The three strongest lines are $\lambda\lambda$ 3852, 4202, and 4308. The lines λ 4202 and λ 4308 with the common upper level $z^3G_4^o$ have abnormally high intensities compared with other lines of multiplet (42) which appear faintly at the later phases. As in R Leonis,¹¹ the only observed lines of (24) are λ 3521 and λ 3565, which also have upper level $z^3G_4^o$. A comparison of the intensities of lines of multiplet (2) in R Andromedae and in R Leonis has previously been published.¹² The measured displacements of lines in 16 multiplets are included in Table 8. The mean displacements become slightly larger algebraically as the phase advances. This behavior, which differs from that of the hydrogen lines (Table 7), closely resembles that of *Fe I* λ 4202 in R Leonis.⁶

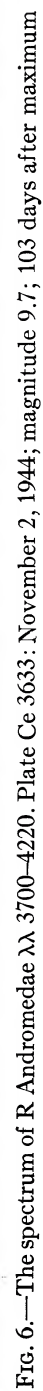
The negative residuals of (21) seem to be characteristic of this multiplet. The positive residuals in (41) at phases +10 and +45 depend on measurements of low weight, but they may be characteristic of the multiplet at these phases; at later phases the residuals, although smaller, are still positive. The positive residuals of (72) for phases +45, +76, and +102 days are the means of reasonably accordant values from three slightly diffuse lines and are probably characteristic of the multiplet. The behavior of λ 3852.57 is remarkably similar to its behavior in R Hydrae.⁵ The shortward component yields the same displacements as those of other lines of multiplet (73). The close companion line longward, which gains in relative intensity as the phase advances, has a measured wave length of 3852.8. Since it occupies approximately the position corresponding to the displacement of the dark-line spectrum, it may possibly be a component of the iron line itself. On the whole, the measurements in the spectrum of R Andromedae tend to confirm the identification of this outstanding line with λ 3852.57, *Fe I* (73). Careful intercomparison of the behavior in the spectra of R Hydrae, R Leonis, R Andromedae, and χ Cygni of bright *Fe I* lines of various multiplets may assist in the detailed interpretation of their intensities and displacements.

Lines of Mg I.—The bright $^1S - ^3P$ line λ 4571 multiplet (1) behaves much as it does in the spectra of Me variables, appearing a few weeks after maximum and becoming outstanding toward minimum. The apparent radial velocity increases algebraically by a few kilometers per second, as in R Hydrae and R Leonis. The bright lines of (3) are present in moderate intensity on all plates and increase only slightly with advancing phase. The radial velocity exhibits almost no change.

Lines of Si I.—Both of the lines λ 4102 (2) and λ 3905 (3) appear as close doubles, with a separation of about 0.32 Å at phases +10 and +45 days, and about 0.23 Å at phases +76 and +102 days. The shortward component yields the same velocities as other bright lines (Table 7). In λ 3905, the shortward component is much the stronger on all plates; in λ 4103, it is the stronger at phase +10 days, weaker at phases +45, +76, and +102 days, although the differences in intensity are not great. Both components appear somewhat narrower at phases +76 and +102 days than at +10 and +45 days, in conformity with the general tendency of bright lines to become narrower as the phase advances. The behavior of the components of these *Si I* lines resembles qualitatively that of λ 3852 *Fe I*. In all three lines the separation corresponds approximately to the general displacement between bright and dark lines; and in all three the longward components gain in relative intensity as the phase advances. These longward components,

¹¹ P. W. Merrill, *Mt. W. Contr.*, No. 720; *Ap. J.*, **103**, 275, Table 6, 1946.

¹² P. W. Merrill, *Pub. A.S.P.*, **58**, 304, 1946.



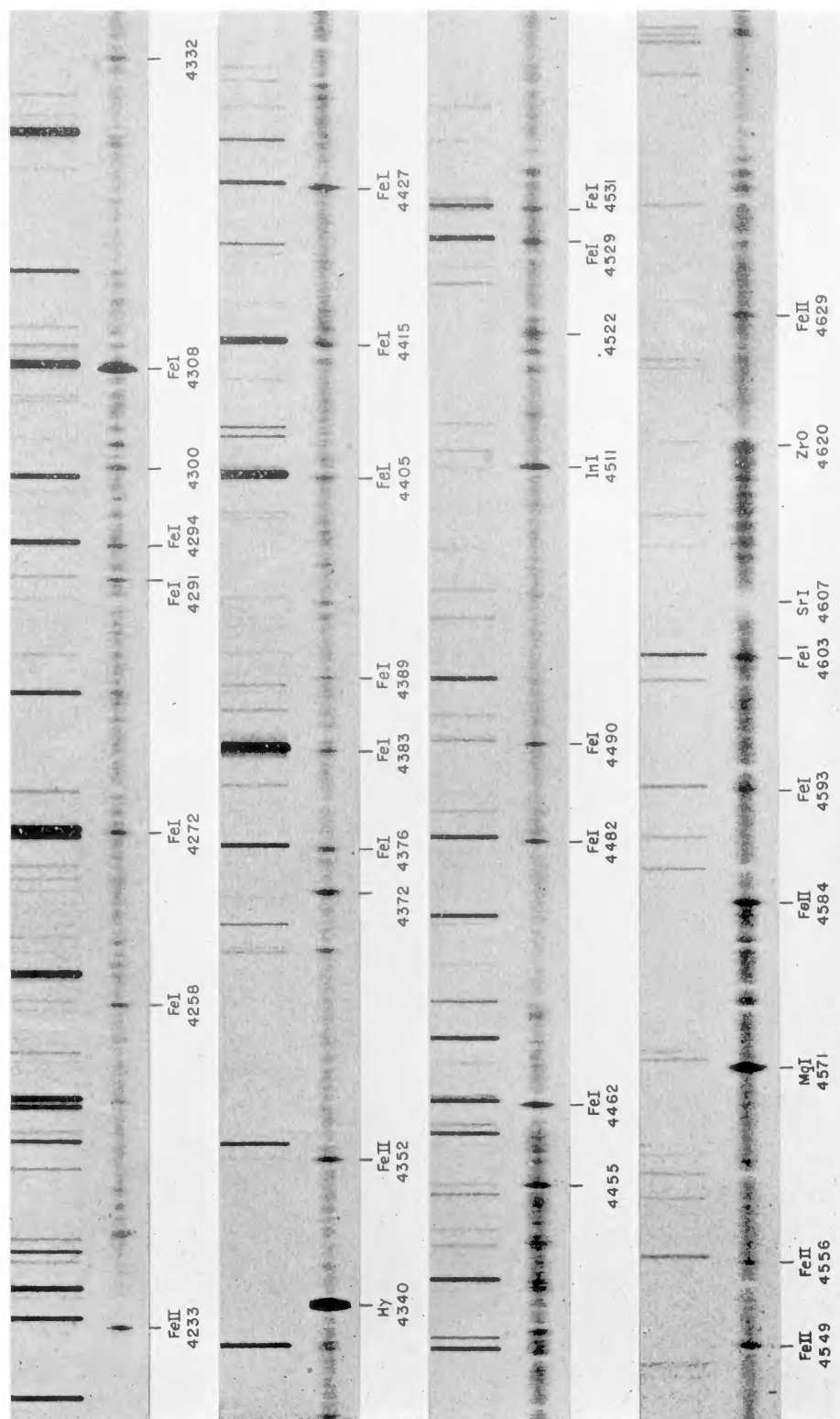


Fig. 7.—The spectrum of R Andromedae $\lambda\lambda$ 4230–4650. Plate Ce 3633: November 2, 1944; magnitude 9.7; 103 days after maximum

therefore, probably have the same atomic origins as the shortward components. Their positions suggest a relationship to the body of gas which produces the dark lines. Possibly the high-excitation potentials (about 2 volts for the lower levels) are responsible for the fact that the components appear in emission rather than in absorption. This slight clue to the enigmatic relationship between bright and dark lines in the spectra of long-period variables should be followed up in future investigations.

Lines of Mn I.—Emission in the well-known triplet of (2) near λ 4030 grows stronger as the cycle advances. At phase +10 days it consists only of a weak edge to the strong dark line λ 4030; later all three lines are bright, λ 4030 becoming outstanding. It is

TABLE 8
RADIAL VELOCITIES FROM EMISSION LINES OF Fe I
(KM/SEC)

MULTIPLY	UPPER LEVEL		PHASE (DAYS)				
	Desig.	E.P. (Volts)	+10	+45	+76	+102	+58 (Mean)
2.....	z ⁷ F°	2.8	-35.4 3*	-32.9 5*	-31.7 5*	-29.1 6*	-32.3
3.....	z ⁷ P°	2.9	.....	31.2 1	32.8 2	28.0 4	30.7
20.....	y ⁵ D°	4.1	35.6 1	32.8 2	27.4 6	27.3 7	30.8
21.....	y ⁵ F°	4.2	40.1 1	40.2 2	33.7 4	31.6 6	36.4
22.....	z ³ P°	4.2	30.9 1	28.7 2	24.5 2	29.1 2	28.3
23.....	z ⁵ G°	4.3	36.5 1	37.1 2	29.8 3	29.6 3	33.2
24.....	z ³ G°	4.4	.....	31.3 2	30.2 2	31.6 2	31.0
39.....	y ⁵ F°	4.2	.....	.....	26.0 3	25.5 3	25.8
41.....	z ⁵ G°	4.3	(21.2) 1	25.3 3	26.0 6	26.7 6	26.0
42.....	z ³ G°	4.4	35.4 2	32.9 3	33.8 3	28.4 5	32.6
43.....	y ³ F°	4.6	39.2 2	35.2 2	34.3 5	28.8 6	34.4
45.....	y ³ D°	4.7	29.9 1	27.3 1	32.3 1	29.4 1	29.7
68.....	x ⁵ D°	4.9	26.9 1	31.7 3	28.5 2	26.4 2	28.4
72.....	x ⁵ P°	5.3	29.0 3	23.0 3	20.6 3	18.5 3	22.8
73.....	w ⁵ D°	5.4	28.0 1	28.8 3	27.0 3	-28.4 2	28.0
74.....	w ⁵ F°	5.4	-30.4 3	-28.4 2	-27.1 1	.....	-28.6
Mean { All.....	.....	.....	-33.1 20	-31.0 36	-29.2 51	-28.0 58	-29.9 16†
Mean { All except (72).....	.....	.....	-33.8 17	-31.7 33	-29.8 48	-28.5 55	-30.4 15

* Number of lines.

† Number of multiplets.

remarkable that the measured velocity does not change with phase; throughout the interval of observation it remains about 18 km/sec less than the velocity yielded by most other bright lines (Table 7).

The line λ 4511 (In I).—This bright line is moderately strong, 10 days after maximum, and becomes outstanding as the phase advances. The radial velocity is constant (Table 7).

Lines of Fe II.—About 25 bright lines of Fe II have been measured on one or more plates. Their intensities are greater during the interval from phase +45 to +102 days than at +10 days. Lines of multiplet (1) with wave lengths between λ 3200 and λ 3300 are remarkably strong, although little continuous spectrum is recorded in their region (Fig. 2). The line λ 3227.73 of (6) was measured on three plates; λ 3196.07 of (7) on one. Nearly all these lines have been observed by Swings and Struve¹³ in bright-line stars of other types, and two or three of the strongest appeared on my spectrograms of R Leonis.⁶

¹³ *Ap. J.*, 97, 194, 1943.

The relative intensities of various lines of (1) estimated in BF Cygni and R Andromedae (Table 9) exhibit interesting departures from the laboratory values. The marked weakness of λ 3255 in R Andromedae suggests that this line may be partially suppressed by a dark line, but there is no direct evidence of this effect. Several lines in R Andromedae seem to change in relative intensity during the observed interval. In BF Cygni, λ 3281 and λ 3295 are relatively weak.

The line λ 3938.29 of (3), although rather weak 10 days after maximum, grew stronger during the observed interval. The companion line, λ 3914.48, was not observed. The strong dark line λ 3914.33 *Ti* I (15) may be responsible for its absence; the difference of wave length 0.15 Å is only a few hundredths less than the observed difference between displacements of bright and dark lines.

TABLE 9
INTENSITIES OF EMISSION LINES OF *Fe* II MULTIPLET (1)

I.Å.	J	INTENSITIES			
		Lab.	BF Cygni*	R Andromedae	
				Ce 3526	Ce 3633
3277.35.....	$3\frac{1}{2}-4\frac{1}{2}$	9	6	6	6
3302.86.....	$2\frac{1}{2}-3\frac{1}{2}$	4	1	1.5	1
3312.71.....	$1\frac{1}{2}-2\frac{1}{2}$	(1)	.....	.....	.....
3314.00.....	$\frac{1}{2}-1\frac{1}{2}$	1	.....	0.5†	tr
3255.88.....	$3\frac{1}{2}-3\frac{1}{2}$	8	4	tr	0.5
3281.29.....	$2\frac{1}{2}-2\frac{1}{2}$	7	1-2	6†	4
3295.81.....	$1\frac{1}{2}-1\frac{1}{2}$	6	1	3†	1.5
3303.47.....	$\frac{1}{2}-\frac{1}{2}$	4	1-0	2†	0.8
3234.92.....	$3\frac{1}{2}-2\frac{1}{2}$	0	.....	.....	.....
3264.76.....	$2\frac{1}{2}-1\frac{1}{2}$	P	.....	tr	tr
3285.42.....	$1\frac{1}{2}-\frac{1}{2}$	(3)	1-0	.....	.....

* Swings and Struve, *Ap. J.*, **97**, 194, 1943.

† Slightly widened; the other lines are very narrow.

The velocities measured at various phases, tabulated by multiplets, are in Table 10. The velocities do not vary with phase during the observed interval; moreover, they agree with the velocity derived from the hydrogen lines. In these respects the *Fe* II lines differ in behavior from those in the *Me* spectra of R Hydrae⁵ and R Leonis.⁶

Lines of Ti II.—Bright lines of a number of multiplets of *Ti* II were present on all the well-exposed spectrograms. The lines λ 3759 and λ 3761 of (13) are accurately measurable; their displacements remained constant throughout the observed interval (Table 7). Line λ 3685 of (14) was missing, probably because it is near the head of a narrow absorption band (of unknown origin). A few of the stronger lines of (11), (12), (19), (20), (34), and (41) were measured on two or more plates; the mean displacements for the four epochs were, respectively, -29.9 , -27.8 , -26.0 , -26.3 km/sec.

Lines of Mn II.—Lines λ 3438 and λ 3460 of *Mn* II are probably present in emission in low intensity.

Displaced Lines of Ca II.—After maximum the broad displaced emission lines of *Ca* II behave much as in R Hydrae and R Leonis. The negative displacements (Table 11) are somewhat greater, however, especially at the latest observed phase +102 days.

Lines of Sr II.—Ten days after maximum light, λ 4215, (1), is a strong dark line with emission on the shortward edge; as the cycle advances, the emission grows stronger until

at the later phases it appears well marked on plates on which the near-by continuous spectrum is very weak. Despite the increase in intensity, the measured displacements change less than 3 km/sec (Table 7). The average velocity, however, is about 10 km/sec less (algebraically) than that of most other emission lines. In the companion line λ 4077 the emission is much weaker and apparently more greatly displaced shortward. Weak bright lines near the shortward edge of the dark line λ 4077 measured at phases +78 and

TABLE 10
RADIAL VELOCITIES FROM EMISSION LINES OF Fe II
(KM/SEC)

MULTIPLY	UPPER LEVEL		PHASE (DAYS)				
	Desig.	E.P.	+10	+45	+76	+102	+58 (Mean)
1.....	z^6D^o	4.8	-28.4 4*	-28.2 5*	-27.4 5*	-28.8 7*	-28.2
3.....	z^6D^o	4.8	25.3 1	25.4 1	25.1 1	24.7 1	(25.1
6.....	z^4D^o	5.5	26 1	33 1	.....	29 1	(29)
7.....	z^4F^o	5.5	26 1	.....	.....	.....	(26)
27.....	z^4D^o	5.5	25.6 2	26.4 2	26.4 3	26.5 3	26.2
37.....	z^4F^o	5.5	.....	25 1	20 1	25.3 3	(24)
38.....	z^4D^o	5.5	23 2	27 3	29.1 3	-26.1 3	26.7
42.....	z^6P^o	5.3	-23.6 2	-27.0 2	-26.4 1	.....	-25.7
Weighted mean...	.....	.....	-26.0	-27.6	-26.8	-27.2	-26.9

* Number of lines.

TABLE 11
DISPLACEMENTS OF BROAD Ca II EMISSION LINES
WITH RESPECT TO DARK LINES

PHASE (DAYS)	H		K	
	Km/Sec	Int.	Km/Sec	Int.
+ 10.....	.....	.....	.....	.....
+ 44.....	-102	2	.....	tr
+ 76.....	- 94	3	-107	1
+102.....	- 79	5	- 97	2

+103 days, if properly identified with Sr II, yielded the values -62 and -59 km/sec, respectively. These negative displacements are larger than those for λ 4215. The behavior of the Sr II lines resembles qualitatively that of the analogous pair H and K of Ca II. This fact suggests that the anomalous reversal of intensities may have some relationship to atomic structure.

Unidentified lines.—Many bright lines, a few of them outstanding, remain unidentified; 60 are collected in Table 12. Their behavior during the post-maximum phase is indicated by the abbreviations "Inc." for increasing intensity, "Dec." for decreasing. In a complicated spectrum of this kind it is sometimes difficult to determine whether certain features are actually emission lines or only narrow spaces left in the continuous spectrum by closely packed absorption lines. Measured wave lengths believed to cor-

respond to spaces have been omitted from Table 12; others concerning which there is doubt are marked with an asterisk.

Although a few of the lines have been observed previously in the spectra of other long-period variables, many of them are new. It is hoped that additional information concerning these unidentified lines may be obtained from a study of the spectrum of χ Cygni.

TABLE 12
UNIDENTIFIED EMISSION LINES

I.A.	Change with Phase	Max. Obs.Int.	I.A.	Change with Phase	Max. Obs. Int.
3421.19*	Dec.	1	3952.82*	?	1
3535.54	Inc.	2	95.28	?	2
45.14*	Dec.	2	97.93	Inc.	4
56.58*	Dec.	1	4020.89*	Inc.	1
69.33*	Dec.	1	86.4	?	2
3677.56*	Dec.	1	95.48	Inc.	3
3735.35	Inc.!	6	98.9	Dec.	3
36.75	Inc.	1	4110.38	Dec.	2
42.30	Dec.	3	18.8	Inc.	2
58.0	Inc.	2	19.46	Dec.	2
60.6	?	2	21.30	?	2
63.32	?	3	38.43	?	6
64.2	?	1	49.34*	Dec.	1
75.51	Dec.	1	54.48	?	2
83.50	?	2	56.8	?	2
86.00	Dec.	2	66.61	Inc.!	4
87.57	Dec.	2	4172.00	Inc.	2
94.62*	Dec.	2	4240.33	?	2
3807.12	Inc.	1	40.70	Inc.	1
09.57*	Dec.	1	4300.15	Inc.	3
13.99*	?	1	31.72	Inc.	2
19.51	?	1	37.53*	?	1
22.86*	Dec.	1	71.30*	Dec.	1
27.80	Dec.	2	72.50	Inc.!	5
45.45	Inc.	1	4400.50	Inc.	1
58.26	Inc.	1	47.23	Inc.	1
65.42*	Dec.	1	55.31	Inc.!	6
81.30*	Dec.	1	4518.76	Inc.	1
93.91	?	4	21.60	?	5
3936.09	?	1	80.89	?	1

* Possibly a narrow space of continuous spectrum between dark lines.

REMARKS

Small differences in the structure and displacement of dark lines are apparently quite common in the spectra of giant red stars (e.g., α Orionis, γ Herculis, long-period variables). These differences, showing well-marked relationships to excitation potential and to ionization, indicate that the reversing layers of these stars differ observably from homogeneous strata in thermodynamic equilibrium. Data on displacements may eventually, when the interpretation becomes clearer, be an effective means of increasing our knowledge of the atmospheric structure.

A cursory comparison of the dark-line spectrum of R Andromedae with that of R Leonis has yielded the following conclusions:

I. In the reversing layer of R Andromedae the concentration of atoms in their ground levels is less than in R Leonis.

II. In R Andromedae the ionization is greater (except for $Ca?$) than in R Leonis. I and II agree in indicating a higher temperature (and a lower density?) in R Andromedae.

III. The elements Y and Zr (atomic numbers 39 and 40) are relatively more abundant in R Andromedae. Otherwise it is difficult to explain the fact that neutral, ionized, and oxide lines (Y I, Y II, YO , Zr I, Zr II, ZrO) are all stronger in R Andromedae. (A comprehensive investigation will be required to rule out the possibility that this conclusion may be invalidated by lower general opacity in R Andromedae.) If, as now appears probable, the three types of red stars—M, S, and N—differ in the relative abundance of various atoms, then the trifurcation of the low-temperature end of the spectral sequence of giant stars may have some connection with the nuclear stability of chemical elements of the second, fourth, and fifth periods.

In the current series of *Contributions* devoted to the spectra of long-period variables, the emphasis is on identifications and displacements of atomic lines. For future consideration are studies of molecular lines, extensive measurements of line intensities, and detailed comparisons of several variables.

Note added in proof.—A study of the rich bright-line spectrum of χ Cygni, made after the present *Contribution* was written, shows the presence of numerous lines of cobalt and nickel. Comparison with the data for R Andromedae indicates that the following lines in Table 12 are probably due to these elements:

Co I		Ni I
3569.33	3997.93	3736.75
3845.45	4020.89	3775.51
3893.91	4086.4	3783.50
3936.09	4118.8	3807.12
3952.82	4121.30	3858.26
3995.28		4331.72