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AN ANALYSIS OF THE ATMOSPHERE OF T VULPECULAE

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Abstract. Ten spectrograms of T Vul at a dispersion of 8.47 Å mm^{-1} have been used for an analysis of the parameters of stellar atmosphere during its pulsation cycle. A differential curve of growth method relative to the Sun has been used to evaluate atmospheric parameters. The range in θ_{exc} is from 0.88 to 1.00. Mean abundances for twenty elements have been estimated relative to $[N_{\mathrm{Fe}}]$. A deficiency by a factor of 2.4 has been found in *s*-process elements with respect to those formed by the *e*-process.

1. Introduction

The cepheid variable T Vul having magnitude variation ranging from $5\overset{\mathrm{m}}{.}43$ to $6\overset{\mathrm{m}}{.}09$ and a period of 4.435 578 days (Kukarkin *et al.*, 1969) has been studied photometrically by Mitchell *et al.* (1964). The radial velocity measurements of T Vul by Lüst-Kulka (1954) show no significant difference between the phase of light maximum and phase of maximum velocity of approach. The light curve is of type A according to the classification by Eggen *et al.* (1957). However, atmospheric studies for this star have not been reported so far. In this paper we give a differential curve of growth analysis for the star.

2. Observational Material

The observational material for this study consists of ten, 8.47 Å mm^{-1} spectra of T Vul taken by Dr Abt at the coudé focus of the McDonald 82-inch reflector on baked IIa-0 emulsion and kindly loaned to us by Dr Schmidt.

Each plate taken at a different phase of the light cycle of T Vul covers a wavelength range 3900–4700 Å and is well exposed for spectrophotometry. Table I gives details of these plates.

Density tracings for these plates have been obtained using Zeiss microphotometer. The continuum level of these tracings was found by drawing lines through points that have been given as line-free or almost line-free continuum points in the Utrecht *Atlas of Solar Spectrum* (Minnaert *et al.*, 1940). It was very difficult to locate the continuum in the region shortward of 4000 Å, and therefore this region is not included in this analysis. The densities of the lines used by us for this study have been converted into intensities through necessary calibrations provided by the plates. The intensity curves have been planimetered to get the equivalent widths. We thus have log W/λ measures for the selected Fe I and Fe II lines at ten phases of the star. These are given in Tables II and III.

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TABLE I
Details of observations

Plate No.	Date	JD	Exposure time (m)	Phase
548	18.6.1954	2434911.864	90	0.42
572	1.7.1954	4924.871	105	0.36
587	3.7.1954	4926.871	90	0.81
591	4.7.1954	4927.893	70	0.04
624	7.7.1954	4930.821	75	0.70
642	12.7.1954	4935.910	60	0.85
1685	28.8.1955	5347.883	65	0.72
3310	7.10.1958	6483.618	60	0.78
3327	8.10.1958	6484.704	50	0.02
3344	9.10.1958	6485.615	65	0.23

TABLE II
Equivalent widths of Fe I ($-\log W/\lambda$)

Wavelength (Å)	RMT No.	$\log \eta_\odot$	Phase 0.02	0.04	0.23	0.36	0.42	0.70	0.72	0.78	0.81	0.85
4003.77	728	1.44	4.91	5.10	4.65	4.60	4.77	4.76	4.67	4.63	4.66	4.84
4044.61	359	2.11	4.61	4.80	4.52	4.44	4.51	4.56	4.73	4.51	4.60	4.80
4062.45	359	1.94	4.51	4.74	4.52	4.42	4.60	4.57	4.61	4.56	4.56	4.49
4063.60	43	4.10	4.09	4.41	4.30	4.20	4.37	4.23	4.35	4.23	4.25	4.20
4064.46	44	1.34	4.73	5.01	4.68	4.89	4.91	4.76	4.91	4.57	4.75	4.90
4071.74	43	4.04	4.23	4.45	4.28	4.23	4.35	4.12	4.36	4.22	4.26	4.16
4072.52	698	1.31	4.78	4.95	4.64	4.77	4.89	4.74	4.72	4.61	4.89	4.86
4079.85	359	1.87	4.71	5.01	4.59	4.69	4.64	4.47	4.62	4.53	4.65	4.61
4095.98	217	1.95	4.62	4.86	4.54	4.51	4.68	4.52	4.59	4.55	4.63	4.57
4104.94	694	1.14	4.92	4.97	4.68	4.81	4.89	4.80	4.80	4.82	4.69	4.86
4107.49	354	2.36	4.46	4.66	4.62	4.47	4.53	4.47	4.49	4.46	4.45	4.45
4112.35	695	1.39	4.84	4.85	4.63	4.85	5.04	4.61	5.01	5.03	4.79	4.71
4118.55	801	2.66	4.47	4.74	4.50	4.42	4.64	4.40	4.48	4.49	4.61	4.37
4122.52	356	1.71	4.67	5.05	4.65	4.52	4.65	4.71	4.66	4.59	4.62	4.59
4139.93	18	1.71	4.87	5.32	5.09	4.92	5.02	4.62	4.61	4.53	—	5.02
4140.41	695	1.38	5.01	5.36	5.11	4.82	5.02	5.04	4.80	4.78	4.09	5.00
4143.42	523	2.48	4.48	4.81	4.44	4.44	4.54	4.42	4.53	4.37	4.49	4.42
4143.87	43	3.68	4.24	4.56	4.30	4.26	4.42	4.23	4.43	4.22	4.35	4.27
4147.67	42	2.12	4.77	4.79	4.58	4.63	4.64	4.52	4.59	4.37	4.62	4.56
4149.38	694	2.16	4.53	4.69	4.62	4.49	4.71	4.57	4.55	4.39	4.53	4.45
4150.25	695	2.26	4.54	4.73	4.62	4.49	4.63	4.40	4.73	4.64	4.74	4.64
4156.81	354	2.35	4.50	4.75	4.65	4.42	4.58	4.51	4.54	4.41	4.56	4.46
4172.76	19	2.12	4.53	4.90	4.66	4.51	4.59	4.43	4.73	4.52	4.49	4.45
4174.94	19	1.97	4.76	4.91	4.54	4.82	4.60	4.50	4.57	4.48	4.73	4.47
4175.64	354	2.12	4.49	4.82	4.58	4.51	4.65	4.60	4.55	4.55	4.56	4.60
4187.04	152	2.17	4.54	4.83	4.68	4.54	4.65	4.49	4.53	4.63	4.45	4.66
4191.44	152	2.88	4.40	4.58	4.40	4.37	4.43	4.55	4.45	4.28	4.50	4.45
4199.97	3	1.54	4.94	5.28	—	4.76	4.88	4.85	4.67	5.02	5.00	4.77
4202.03	42	3.40	4.31	4.41	4.33	4.22	4.35	5.21	4.35	4.25	4.32	4.45
4218.22	172	0.94	5.21	—	4.98	5.32	5.32	—	5.15	5.28	4.05	—

Table II (continued)

Wavelength (Å)	RMT No.	log $\eta_\odot$	Phase 0.02	0.04	0.23	0.36	0.42	0.70	0.72	0.78	0.81	0.85
4233.61	152	3.32	4.40	4.50	4.41	4.40	4.48	4.31	4.47	4.27	4.30	4.38
4250.79	42	3.60	4.31	4.42	4.35	—	4.38	—	4.42	4.20	—	4.35
4260.48	152	3.84	4.18	4.29	4.32	4.31	4.44	4.21	4.44	4.31	4.31	4.21
4265.26	993	1.47	5.12	—	4.57	4.80	5.03	4.93	4.91	4.95	—	—
4267.83	482	2.24	4.71	4.99	4.42	4.60	4.73	4.53	4.63	4.35	4.53	4.65
4271.76	42	4.04	4.24	4.34	4.32	4.59	4.34	4.22	4.37	4.15	4.34	4.25
4276.68	976	1.14	5.15	5.29	4.99	4.95	4.97	5.09	4.97	4.09	4.90	—
4282.41	71	2.54	4.43	4.54	4.55	4.44	4.54	4.38	4.55	4.38	4.49	4.42
4304.55	414	2.03	4.55	4.88	4.52	4.77	4.63	4.45	4.53	4.36	4.72	4.66
4346.56	598	1.31	4.87	5.09	4.83	4.72	4.83	4.71	5.08	4.80	4.74	4.68
4347.84	828	1.26	4.74	5.01	4.85	4.79	5.08	4.83	4.34	4.63	4.86	4.68
4365.91	415	0.97	5.44	5.19	4.98	5.34	5.39	5.30	5.10	5.07	5.02	—
4383.55	41	4.21	4.19	4.29	4.33	4.23	4.29	4.15	4.31	4.15	4.18	4.23
4387.90	476	1.40	5.02	5.15	4.86	4.60	—	4.75	4.63	4.68	4.89	4.77
4389.24	2	1.30	5.26	5.50	5.00	5.01	5.20	4.92	4.91	4.95	—	4.97
4430.62	68	2.10	4.60	4.78	4.51	4.47	4.58	4.58	4.56	4.44	4.54	4.79
4432.57	797	0.95	5.39	5.13	4.87	4.92	5.07	5.02	5.20	4.98	4.85	—
4433.22	830	1.80	4.77	5.14	4.75	4.78	4.78	4.71	4.63	4.63	4.64	4.74
4442.34	68	2.81	4.37	4.69	4.40	4.39	4.62	4.45	4.51	4.14	4.41	4.38
4447.72	68	2.81	4.36	4.79	4.54	4.57	4.53	4.44	4.56	4.35	4.89	4.52
4466.55	350	2.25	4.75	4.82	4.54	4.42	4.34	4.54	4.61	4.47	4.73	4.49
4485.68	830	1.22	4.85	5.12	4.82	4.65	4.86	5.05	4.77	4.70	4.76	5.08
4587.13	795	0.91	5.13	5.16	5.00	5.06	4.09	4.88	4.95	4.95	4.90	5.13
4602.01	39	1.13	5.06	5.23	5.04	4.76	4.94	5.03	4.85	4.96	4.86	4.90
4611.28	826	1.91	4.67	5.11	4.62	4.81	4.63	4.45	4.74	4.50	4.68	4.70
4619.29	821	1.28	4.93	5.12	4.97	4.88	4.82	5.00	4.68	4.93	4.98	4.82
4625.05	554	1.38	4.92	5.16	4.66	4.71	—	4.68	4.70	4.77	4.89	4.78
4637.51	554	1.40	4.83	5.12	4.68	4.66	4.90	4.60	4.89	4.62	5.01	4.64
4638.02	822	1.47	4.81	5.02	4.70	4.66	4.97	4.79	4.82	4.75	4.68	4.68
4647.44	409	1.40	4.83	5.10	5.64	4.77	4.84	4.70	4.70	4.65	4.93	4.82

Lines of other elements have been measured only at four phases well distributed over the cycle. The log W/λ values for these lines are given in Table IV.

3. The Curve of Growth Analysis

T Vul shows a spectral variation ranging from F7 Ib to G3 Ib, therefore, the differential curve of growth technique relative to sun for which equivalent widths are accurately known, has been applied to derive the atmospheric parameters. In an ideal situation, however, it would have been more appropriate to use the precise equivalent widths of a supergiant for this purpose. Since precisely measured equivalent widths for a supergiant in the spectral region of our analysis were not available, we have taken recourse to the equivalent widths of the Sun. Using observed log W/λ values as ordinates and relative solar line

TABLE III

Equivalent width of Fe II lines ($-\log W/\lambda$)

Wavelength	RMT		Phase									
(Å)	No.	$\log \eta_\odot$	0.02	0.04	0.23	0.36	0.42	0.70	0.72	0.78	0.81	0.85
4002.07	29	0.80	4.41	5.00	4.65	4.56	4.51	4.51	4.40	4.41	4.41	4.87
4128.74	27	1.12	4.62	4.85	4.56	4.74	4.71	4.55	4.56	4.52	4.51	4.26
4178.86	28	1.62	4.21	4.24	4.41	4.47	4.62	4.51	4.48	4.05	4.55	4.59
4233.17	27	1.94	4.28	4.40	4.51	4.31	4.32	4.09	4.32	4.17	4.55	4.34
4273.32	27	2.18	4.37	—	—	—	4.59	—	4.55	4.35	4.36	—
4296.57	28	1.71	4.46	4.47	4.53	—	4.49	4.46	4.43	4.31	4.56	4.25
4369.28	28	1.04	4.32	4.72	4.72	—	4.55	4.60	4.54	4.36	4.56	4.89
4413.60	32	0.80	4.85	5.44	4.47	—	4.74	4.64	4.87	4.29	4.79	4.98
4416.82	27	1.48	4.31	4.54	4.37	4.58	4.54	4.37	4.47	4.33	4.33	4.39
4472.92	37	0.95	4.56	4.65	4.65	4.49	4.52	4.79	4.75	4.49	4.31	4.51
4489.18	37	1.20	4.32	4.71	4.35	4.62	4.75	4.38	4.38	4.26	—	—
4491.44	37	1.37	4.26	4.46	4.31	4.44	4.47	4.73	4.42	4.40	4.44	4.46
4508.28	38	1.45	4.45	4.43	4.51	4.30	4.64	4.33	4.36	4.25	4.52	4.31
4515.34	37	1.48	4.26	4.38	4.23	4.36	4.52	4.39	4.37	4.14	4.36	4.52
4520.23	37	1.37	4.29	4.58	4.36	4.43	4.45	4.38	4.65	4.19	4.32	4.40
4576.33	38	1.11	4.57	4.50	4.45	4.68	4.47	4.66	4.75	4.47	4.56	4.43
4582.84	37	0.98	4.60	4.62	4.88	4.60	4.60	4.66	4.72	4.60	4.70	4.60
4583.83	38	2.05	4.69	—	4.35	—	4.39	4.26	4.46	4.21	—	—
4620.51	38	0.95	4.62	4.92	4.58	4.38	4.64	4.59	4.75	4.52	4.57	4.48
4635.33	186	0.88	4.66	—	4.82	—	5.06	5.10	5.04	4.90	—	4.71

TABLE IV

Equivalent widths

Wavelength	RMT		Phase			
(Å)	No.	$\log \eta_\odot$	0.02	0.36	0.72	0.85
Mg I						
4167.27	15	3.15	4.39	4.51	4.47	4.53
4571.10	1	1.76	4.75	4.40	4.61	4.66
Si II						
4128.05	3	2.25	4.43	4.36	4.55	4.38
Ca I						
4226.73	2	4.69	4.24	4.13	4.29	4.26
4283.00	5	2.51	4.55	4.71	4.57	4.58
4302.53	5	2.84	4.33	4.37	4.29	4.38
4318.65	5	2.32	4.56	4.57	4.35	4.50
4355.10	37	1.92	4.60	4.75	4.96	4.93
4425.44	4	2.60	4.75	4.54	4.80	4.57
4435.69	4	2.44	4.47	4.41	4.66	4.36
4455.89	4	0.18	4.74	4.42	4.46	4.43
4578.56	23	1.50	4.91	4.57	4.88	4.75

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Table IV (continued)

Wavelength (Å)	RMT No.	$\log \eta_\odot$	Phase 0.02	0.36	0.72	0.85
Sc II						
4246.83	7	2.86	4.14	4.38	4.12	4.13
4294.77	15	1.23	4.47	4.28	4.42	4.58
4325.01	15	2.44	4.32	4.28	4.38	4.37
4354.61	14	1.37	4.39	4.64	4.57	5.12
4374.46	14	2.16	4.13	4.47	4.14	4.25
4415.56	14	1.76	4.21	4.38	4.66	4.36
4431.37	14	0.61	4.87	4.47	4.69	5.04
Ti I						
4286.01	44	2.44	4.85	4.81	4.54	4.87
4290.93	44	1.25	4.70	4.50	4.57	4.81
4457.43	113	1.50	4.47	4.82	4.55	4.73
Ti II						
4163.63	105	2.97	4.37	4.40	4.30	4.27
4287.89	20	1.92	4.49	4.43	4.31	4.13
4300.75	21	2.86	4.24	4.17	4.12	4.30
4301.95	41	2.74	4.22	4.34	4.28	4.37
4312.86	41	2.71	4.35	4.22	4.38	4.26
4330.26	94	0.87	4.34	4.28	4.42	4.55
4350.83	94	1.18	4.55	4.54	4.19	4.56
4394.06	51	1.48	4.61	4.52	4.59	4.59
4395.03	19	2.51	4.10	4.16	4.14	4.23
4395.85	61	1.25	4.43	4.39	4.63	4.33
4399.77	51	2.20	4.18	4.38	4.32	4.60
4411.94	60	1.00	4.66	4.43	4.67	4.63
4417.72	40	1.87	4.36	4.26	4.17	4.28
4418.34	51	1.34	4.49	4.48	4.47	4.58
4421.95	93	1.00	4.65	4.47	4.63	4.84
4443.80	19	2.52	4.17	4.35	4.29	4.00
4468.49	31	2.44	4.35	4.24	4.39	4.16
4501.27	31	2.40	4.18	4.09	4.21	4.17
4545.14	30	0.98	4.54	4.35	4.50	4.45
4563.76	50	2.40	4.34	4.30	4.40	4.11
4568.31	60	0.49	4.95	4.64	4.72	4.79
4636.35	38	0.49	4.83	4.50	4.87	4.80
V I						
4111.78	27	2.32	4.87	4.46	4.60	4.55
4379.24	22	2.20	4.71	4.60	4.93	4.94
4389.97	22	1.60	4.89	4.71	4.65	4.89
V II						
4023.39	32	1.35	4.80	4.53	4.61	4.83
4036.78	9	0.71	4.64	4.56	4.70	4.69
4065.07	215	1.12	4.77	4.66	4.61	4.88
4178.39	25	0.55	4.69	4.64	4.45	4.70
4183.44	37	1.56	4.43	4.56	4.57	—

Table IV (continued)

Wavelength	RMT		Phase			
(Å)	No.	$\log \eta_\odot$	0.02	0.36	0.72	0.85
4232.06	225	1.25	4.95	4.91	4.76	5.12
4564.61	56	0.28	4.78	4.56	4.76	4.91
Cr I						
4254.36	1	3.57	4.27	4.41	4.21	4.31
4371.28	304	2.20	4.85	4.48	—	4.74
4545.96	10	1.44	4.98	4.63	—	5.00
4591.39	21	1.16	4.58	4.61	4.88	4.78
4616.14	21	1.48	5.02	4.51	4.62	4.53
Cr II						
4051.95	19	1.76	4.70	4.42	4.37	4.45
4207.35	26	1.12	4.52	4.35	—	4.55
4252.62	31	0.67	4.66	4.47	4.74	4.63
4278.15	161	1.00	4.57	4.69	4.79	4.68
4539.63	39	2.40	4.73	4.34	4.68	4.79
4555.02	44	0.76	4.41	4.40	4.52	4.64
4558.66	44	1.29	4.64	4.33	4.35	4.35
4592.09	44	0.87	4.66	4.23	4.42	4.58
4616.69	44	0.76	4.49	4.62	4.52	4.62
4618.80	44	1.42	4.38	4.41	4.62	4.46
Mn I						
4034.49	2	3.06	4.28	4.21	4.42	4.40
4055.54	5	2.44	4.54	4.39	4.48	4.56
4059.39	29	1.25	4.86	4.52	4.55	4.97
4082.94	5	2.04	4.32	4.41	4.37	4.36
4502.22	22	1.06	5.61	4.31	5.14	6.05
Mn II						
4510.21	17	0.31	—	4.97	4.96	5.61
Co I						
4020.91	16	1.63	4.50	4.58	4.52	4.80
4110.53	29	1.94	4.73	4.57	4.56	4.28
4121.32	28	2.55	4.45	4.48	4.31	4.74
Ni I						
4331.60	52	1.12	4.72	4.47	4.86	4.87
4410.52	88	1.03	4.92	4.83	5.28	—
4551.24	236	0.41	5.21	4.73	4.85	5.06
Ni II						
4015.51	12	0.48	4.54	4.46	4.67	4.52
4192.07	10	0.55	4.96	5.28	5.02	5.32
4244.80	9	0.24	4.85	5.15	4.58	5.17
4362.10	9	0.61	5.00	4.83	4.91	5.11
Sr II						
4077.74	1	3.67	3.97	3.84	4.12	4.12
4215.52	1	3.18	4.04	4.04	4.28	4.28
Y II						
4374.92	13	1.63	4.50	4.50	4.56	4.40
4398.02	5	1.00	4.51	4.64	4.65	4.48

Table IV (continued)

Wavelength (Å)	RMT No.	$\log \eta_\odot$	Phase			
			0.02	0.36	0.72	0.85
Zr II						
4050.32	43	0.48	4.75	4.66	4.61	4.91
4150.97	42	0.92	4.69	4.67	4.70	4.79
4179.81	99	0.31	4.98	5.14	5.02	5.05
4208.99	41	1.00	—	4.47	4.58	—
4211.86	15	1.20	4.58	4.50	4.63	4.57
4317.32	40	0.26	4.95	4.59	4.79	4.79
4333.28	132	0.22	4.99	5.03	4.93	5.01
4379.76	88	0.55	5.39	5.00	4.94	5.64
4403.33	79	0.90	4.74	4.64	4.77	4.89
Ba II						
4166.00	4	0.14	5.04	4.84	4.93	5.09
La II						
4123.23	41	0.98	4.37	4.47	4.45	—
4238.38	41	0.85	4.72	4.78	—	4.47
4263.59	84	0.80	4.92	4.86	5.01	5.20
4286.97	75	1.63	5.23	4.92	—	4.90
4322.51	25	0.21	4.98	—	5.01	5.19
4333.76	24	0.70	4.96	4.92	5.12	4.97
Ce II						
4073.48	4	0.41	4.72	4.59	—	4.56
4120.83	112	0.27	5.01	4.71	4.91	4.69
4186.60	1	2.04	4.67	4.31	4.57	4.59
4248.68	1	1.63	5.02	5.07	5.00	4.95
4382.14	2	0.08	4.87	4.84	4.75	5.19
4562.36	1	0.31	—	—	4.63	5.00
Pr II						
4026.82	26	0.29	4.80	4.80	4.77	4.79
4222.98	4	0.17	4.99	5.08	4.88	4.65
Nd II						
4061.12	10	1.20	4.99	4.65	4.71	4.79
4109.47	10	0.78	4.47	—	4.54	—
4303.57	10	1.18	4.75	4.66	4.61	4.65
4358.17	10	0.80	4.86	—	5.08	5.41
4462.98	50	0.26	5.50	4.91	5.14	4.84
Sm II						
4424.34	45	0.06	5.23	4.61	5.01	5.21
4434.32	36	0.32	4.97	4.32	4.78	4.93
4458.53	7	0.10	5.14	4.78	—	5.03
Gd II						
4215.02	32	0.61	4.98	4.85	4.70	4.76
4251.74	15	0.22	4.87	4.85	4.78	5.14

strengths as abscissae. Solar line strengths have been obtained from the solar equivalent widths given in the Utrecht *Photometric Catalogue of Fraunhofer Lines* and solar curve of growth given by Cowley and Cowley (1964) has been used to obtain $\log \eta_\odot$. By use of the analogy

$$[X] = \log X^* - \log X^\odot ,$$

Equation (2) of Rodgers and Bell (1963) can be written as

$$\log \eta'_* = \log \eta_* - \left[\frac{N}{\kappa V}\right] = \log \eta_\odot + \chi(\theta^\odot_{\mathrm{exc}} - \theta^*_{\mathrm{exc}}) ,$$

where $\log \eta_*$ for each line is expressed in terms of solar $\log \eta$, a Boltzmann correction excitation inequality between the Sun and the star and a constant for each ion which involves abundances, opacities and velocity parameter both for the Sun and the star. Primary curves of growth for each phase have been formed using a trial value of θ^*_{exc}. Plots of $\log W/\lambda$ against $\log \eta'_*$ were then compared with a Milne-Eddington curve of growth computed by Wrubel (1949) and found that $B^0/B^1 = \frac{1}{3}$ curves give the best fit through the points. We then obtained a value of $\log \eta_*$ (obs) by making the individual observed $\log W/\lambda$ values to fall on the theoretical curve, and reading the corresponding abscissae. For each line we now have

$$\Delta\eta = \log \eta_* (\mathrm{obs}) - \log \eta_\odot = \mathrm{Constant} + \chi\, \Delta\theta ,$$

where $\Delta\theta = \theta^\odot_{\mathrm{exc}} - \theta^*_{\mathrm{exc}}$. Next plotting $\Delta\eta$ against χ we carried out a least-square solution to determine $\Delta\theta$ and used this value of $\Delta\theta$ in the next trial. This process is repeated iteratively until the assumed and calculated values agree with each other. The Fe I lines used for constructing curve of growth have values of excitation potentials of lower level ranging from 0.05 eV to 4 eV. The mean error in the evaluation of θ^*_{exc} is ± 0.04.

In Figures 1–3, $\log W/\lambda$ are plotted against $\log \eta_*$ in which solid lines represent theoretical curve of growth. In Figure 4(c) the variation of θ^*_{exc} with phase has been shown. In the same figure we have plotted m_v (Figure 4a) and $\mathrm{d}r/\mathrm{d}t$ (Figure 4b) with phase for comparison purposes. The value of $[V]$ has been calculated from vertical shift of the curve of growth obtained by us to match with the theoretical curve of growth given by Wrubel (1949), while horizontal shift yields $[N_{\mathrm{Fe\,I}}/\kappa V]$.

4. The Determination of Electron Pressure Ratio of Ionized and Neutral Iron, Opacity and Gas Pressure

Schmidt (1971) has found that for cepheids θ_{exc} and θ_{ion} are related by the relation $\theta_{\mathrm{exc}} - \theta_{\mathrm{ion}} = +0.03$. Using this relation we have estimated the value of θ_{ion} for T Vul. From the shift of Fe II lines with respect to the curve of growth for Fe I lines as shown in Figures 1–3, we have estimated the value of $[N_{\mathrm{Fe\,II}}/N_{\mathrm{Fe\,I}}]$ by

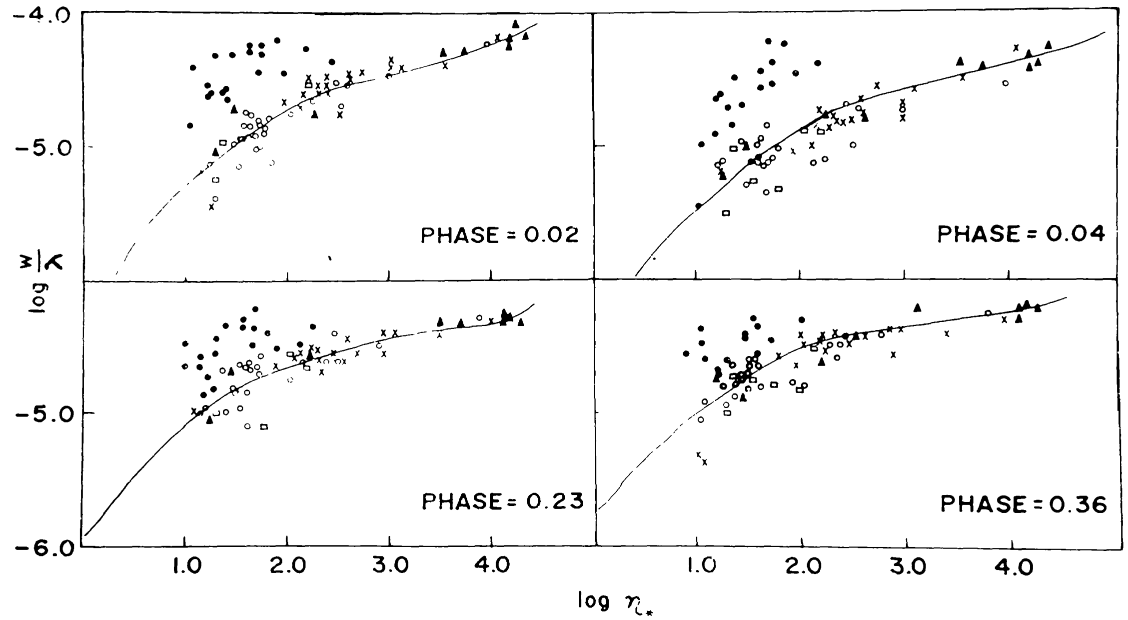

Fig. 1. Differential curves of growth of T Vul relative to the Sun. Different symbols have the code; □ – Fe i(0–1 eV); △ – Fe i(1–2eV); × – Fe i(2–3 eV); ○ – Fe i(3–4 eV) and ● – Fe ii.

taking the mean difference in abscissae of Fe ii points from Fe i curve of growth. Using these values of [$N_{\text{Fe II}}/N_{\text{Fe I}}$], θ^*_{ion} and partition function, electron pressure for each phase (Figure 4d) has been determined using Saha ionization equation. Solar values of $N_{\text{Fe II}}/N_{\text{Fe I}}$ and $\theta^{\odot}_{\text{ion}}$ have been taken from Rodgers (1969).

Searle, *et al.* (1963), have calculated the opacity for supergiants as a function of θ_{ion} and electron pressure taking into account the contribution due to electron scattering, Rayleigh scattering by neutral hydrogen, photoionization of neutral

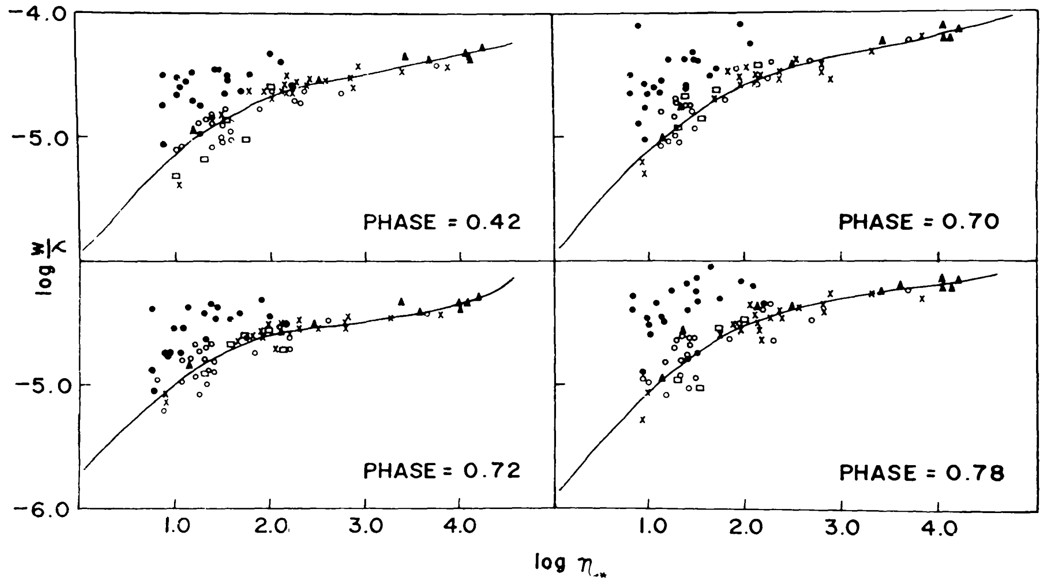

Fig. 2. Notation as on Figure 1.

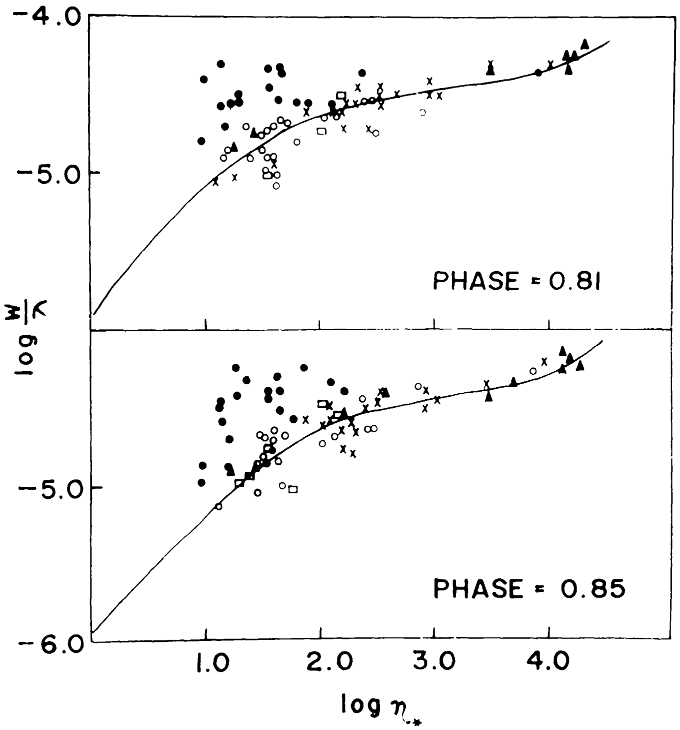

Fig. 3. Notation as on Figure 1.

hydrogen and photo-detachment of the negative hydrogen ion. Using these tables we have evaluated total absorption coefficient per gram of stellar material at λ4400 Å, corresponding to θ_{ion} and P_e for the star determined above. Gas pressure for each phase of the star has been obtained from Aller's (1963) compilation of gas pressure as a function of θ_{ion} and electron pressure for solar-like abundances. Using perfect gas law we have derived the density for each phase.

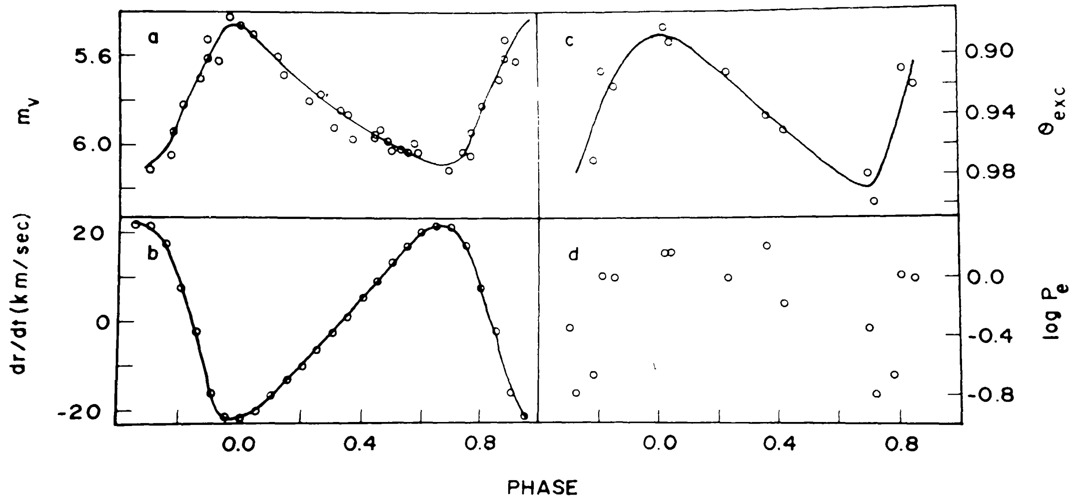

Fig. 4. The variation of a few physical parameters of T Vul over a pulsation cycle.

5. Abundance Determination

The horizontal shift of the curve of growth with respect to the theoretical curve given by Wrubel (1949) gives $[N_{\mathrm{Fe\,I}}/\kappa V]$. This can be written as

$$[N_{\mathrm{Fe\,I}}] = \left[\frac{N_{\mathrm{Fe\,I}}}{\kappa V}\right] + [\kappa] + [V] .$$

Using derived values of $[N_{\mathrm{Fe\,II}}/N_{\mathrm{Fe\,I}}]$ and $[N_{\mathrm{Fe\,I}}]$ we can calculate the value of $[N_{\mathrm{Fe}}]$ with the aid of the equation

$$[N_{\mathrm{Fe}}] = [N_{\mathrm{Fe\,I}}] + \log \frac{1 + (N_{\mathrm{Fe\,II}}/N_{\mathrm{Fe\,I}})}{1 + (N_{\mathrm{Fe\,II}_\odot}/N_{\mathrm{Fe\,I}_\odot})} .$$

We have estimated $[N_{\mathrm{Fe}}]$ for the ten plates and these are listed in Table V; the mean value is -0.37 ± 0.14. Rodgers and Bell (1963) obtained a similar value of -0.38 ± 0.15 for κ Pav, while Bappu and Raghavan (1969) found somewhat a higher value of -0.21 ± 0.15 for the cepheid RT Aur. These results show that iron is deficient in these cepheids as compared to the Sun.

Abundances for other elements have been determined at four phases well distributed over the cycle. The estimated $\log W/\lambda$ values were entered into the corresponding curve of growth to give $\log \eta_*$ for any ion. The horizontal shift Δ, which is

$$\Delta = \log \eta_* - \log \eta_\odot - \chi(\theta^\odot_{\mathrm{exc}} - \theta^*_{\mathrm{exc}})$$

gives $[N_{\mathrm{ion}}/N_{\mathrm{Fe\,I}}]$.

The values of $[N_{\mathrm{ion}}/N_{\mathrm{Fe\,I}}]$ for each ion have been determined at the said four phases, then, using Saha's equation and appropriate partition functions (Corliss, 1962; Allen, 1973), we obtained the relative abundance of the element with respect to the Sun using the equation

$$\left[\frac{N_{\mathrm{el}}}{N_{\mathrm{Fe}}}\right] = \left[\frac{N_{\mathrm{el\,I}}}{N_{\mathrm{Fe\,I}}}\right] + \log \frac{1 + (N_{\mathrm{el\,II}}/N_{\mathrm{el\,I}})}{1 + (N_{\mathrm{Fe\,II}}/N_{\mathrm{Fe\,I}})} - \log \frac{1 + (N_{\mathrm{el\,II}_\odot}/N_{\mathrm{el\,I}_\odot})}{1 + (N_{\mathrm{Fe\,II}_\odot}/N_{\mathrm{Fe\,I}_\odot})}$$

TABLE V

Curve of growth parameters for T Vul

Plate	Phase	$\log a$	θ^*_{exc}.	V km s^{-1}	$\log N_{\mathrm{FeII}}/N_{\mathrm{FeI}}$	$\log P_e$	$\log P_g$	$\log \rho$	$[N_{\mathrm{Fe}}]$
3327	0.02	−2.20	0.88	3.00	2.58	0.16	2.91	−8.69	−0.26
591	0.04	−2.20	0.89	2.38	2.48	0.17	3.06	−8.53	−0.49
3344	0.23	−2.60	0.91	2.80	2.48	−0.01	2.72	−8.86	−0.18
572	0.36	−3.00	0.94	3.29	1.99	0.21	3.76	−7.81	−0.22
548	0.42	−3.00	0.95	2.67	2.99	−0.18	3.18	−8.38	−0.47
624	0.70	−2.60	0.98	3.36	2.19	−0.35	3.24	−8.31	−0.63
1685	0.72	−3.00	1.00	2.38	2.47	−0.80	2.64	−8.90	−0.42
3310	0.78	−3.00	0.97	3.78	2.61	−0.67	2.53	−9.02	−0.49
587	0.81	−2.60	0.91	3.21	2.46	0.01	3.03	−8.55	−0.20
642	0.85	−2.60	0.92	3.00	2.39	−0.01	3.12	−8.46	−0.36

TABLE VI
Mean abundances relative to [N_{Fe}]

Element	Process	N	No. of lines	Mean deviation
Mg	α, s	−0.02	8	0.25
Si	α, s	−1.03	4	0.40
Ca	α, s	+0.17	36	0.13
Sc	s	−0.04	28	0.13
Ti	α, s, e, r	+0.08	100	0.18
V	e(m)	−0.46	39	0.17
Cr	(e)	−0.11	57	0.33
Mn	(e)	−0.13	23	0.35
Fe	(e)	0	305	—
Co	(e)	+0.33	12	0.27
Ni	(e)	−0.50	27	0.19
Sr	s(m)	−0.05	8	0.42
Y	s(m)	−0.50	8	0.04
Zr	s	−0.41	34	0.19
Ba	s, r	−0.46	4	0.08
La	s(m)	−0.63	20	0.07
Ce	s(m)	−0.53	21	0.16
Pr	s(m)	−0.15	8	0.15
Nd	s(m), s	−0.58	17	0.17
Sm	r, s	−0.43	10	0.08
Gd	r, s	−0.21	8	0.17
Mean abundance	α, s	+0.02	48	
	s	−0.41	131	
	e	−0.03	424	

Mean abundances of the twenty elements relative to iron are given in Table VI along with the various processes of their formation. The mean abundances weighted on the basis of number of lines measured, determined separately for α, s; e- and s-process elements, are also given in Table VI. s-process elements are found to be deficient with respect to e-process elements by a factor of 2.4, it seems that the cepheids show a general s-process elements deficiency compared to e-process elements, because κ Pav (Rodgers and Bell, 1963) and RT Aur (Bappu and Raghavan, 1969) also show the s-process elements deficiency with respect to e-process elements by a factor of 7 and 3.5 respectively. Helfer *et al.* (1959) have also found s-process elements deficiency in their study of the star III-13 in the metal deficient cluster M92 and pointed out that a deficiency of s-process elements could occur if the material from which the star formed was the interstellar product of mass loss from stars so massive that their evolutionary time scale was shorter than the times required for the production of s-process elements. In the light of the above it appears that the A type cepheids T Vul, κ Pav and RT Aur and the product of a somewhat similar process.

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References

Aller, L. H.: 1963, *Astrophysics*, Vol. I, Ronald Press, New York, p. 130.

Allen, C. W.: 1973, *Astrophysical Quantities*, 3rd ed. Athlone Press, London, p. 35.

Bappu, M. K. V. and Raghavan, N.: 1969, *Monthly Notices Roy. Astron. Soc.* **142**, 295.

Corliss, C. H.: 1962, *J. Res. Nat. Bur. Stand.* **66A**, 169.

Cowley, C. R. and Cowley, A. P.: 1964, *Astrophys. J.* **140**, 713.

Eggen, O. J., Gascoigne, S. C., and Burr, E. J.: 1957, *Monthly Notices Roy. Astron. Soc.* **117**, 406.

Helfer, H. L., Wallerstein, G., and Greenstein, J. L.: 1959, *Astrophys. J.* **129**, 700.

Kukarkin, B. V., Kholopov, P. N., Efremov, Yu. N., Kukarkin, N. P., Kurochkin, N. E., Medvedeva, G. I., Perova, N. B., Fedorovich, V. P., and Frolov, M. S.: 1969, *General Catalogue of Variable Stars*, 3rd ed. Moscow.

Lüst-Kulka, R.: 1954, *Z. Astrophys.* **33**, 211.

Minnaert, M., Mulders, G. F. W., and Houtgast, J.: 1940, *Photometric Atlas of the Solar Spectrum*, Sterrewacht, Sonnenborgh, Utrecht.

Mitchell, R. I., Iriarte, B., Steinmetz., D., and Johnson, H. L.: 1964, *Bull. Obs. Tonantzintla Tacubaya* **24**, 153.

Rodgers, A. W. and Bell, R. A.: 1963, *Monthly Notices Roy. Astron. Soc.* **125**, 487.

Rodgers, A. W.: 1969, *Monthly Notices Roy. Astron. Soc.* **145**, 151.

Schmidt, E. G.: 1971, *Astrophys. J.* **170**, 109.

Searle, L., Sargent, W. L. W., and Jugaku, J.: 1963, *Astrophys. J.* **137**, 268.

Wrubel, M. H.: 1949, *Astrophys. J.* **109**, 66.