

RADIAL-VELOCITY-CURVES OF T MONOCEROTIS AND SV VULPECULAE

ROScoe F. SANFORD

Mount Wilson and Palomar Observatories
Carnegie Institution of Washington

Received November 11, 1955

ABSTRACT

Radial-velocity-curves of T Mon and SV Vul from the Fe I lines are the mirror images of the light-curves except for a slight lag in the velocity-curves. There seems to be a faithful repetition of these variations from epoch to epoch. Velocities from the Fe II, Ti II, Sr II, and H lines tend to greater positive values than the Fe I velocities near maximum light. It is suggested that this may occur because the lifetime of a given surge of gas is slightly longer than the period associated with the light- and the Fe I velocity variations. Interstellar velocities of +16.9 and -14 km/sec derived from the sharp absorption H and K lines of T Mon and SV Vul, respectively, are consistent with the velocities from the D lines assumed as blends of stellar and interstellar lines and with the galactic position of the two variables. Emission lines of H and K, greatly displaced shortward, were found on spectrograms of T Mon in the phase interval 22.3-26.9 days and at phase 43.3 days on one spectrogram of SV Vul. Mean radii of 119 $\odot$ (T Mon) and 142 $\odot$ (SV Vul) have been derived.

T Monocerotis and SV Vulpeculae are cepheids of special interest on account of their relatively long periods. Spectrograms of these have been obtained in the photographic region (10 A/mm) with the coude spectrograph of the 100-inch telescope in the interval 1946-1952 inclusive. Eggen (1951) obtained their light- and color-index-curves from photoelectric observations in the interval from July, 1948, to November, 1951. His observations are therefore fairly suitable for a comparison between light- and velocity variations, although it is recognized that it would have been still better if photometric and velocity measures had been made at the same time. The elements that Eggen used represent his photometric observations of T Mon satisfactorily, but the epoch for the maximum of SV Vul apparently needs to be decreased by 4.5 days. Consequently, the elements used here are as follows:

$$\text{Maximum} = \text{JD } 2428193.08 + 27^{\text{d}}018E \text{ G.M.T. (T Mon) ,}$$

$$\text{Maximum} = \text{JD } 2429020.87 + 45^{\text{d}}145E \text{ G.M.T. (SV Vul) .}$$

Radial velocities have been derived from five classes of lines, i.e., Fe I, Fe II, Ti II, Sr II, and H lines. Numerous arc lines were used for the first class, and Table 1 shows the lines used for the other four classes. Table 2 gives the spectrograms of T Mon in order of phase and lists the velocities from the Fe I lines and the residuals from these Fe I lines given by the Fe II, Ti II, Sr II, and H lines. Table 3 of SV Vul is similar to Table 2.

VELOCITY-CURVES FROM Fe I LINES

Figures 1 and 2 have in order, from top to bottom, *A*, Eggen's Pg_p light-curves; *B*, the Fe I velocity-curve and the curves *C*, *D*, *E*, and *F* of the residuals of the H, Sr II, Ti II, and Fe II velocities. Table 4 gives the phases of the maxima and minima of light and velocity read from these curves. It is evident that the velocity variations are the mirror images of the light-variations of these two variables except that the velocity-curves lag somewhat after the light-curves—T Mon by 1.20 days and SV Vul by 3.25

days. The lag of the velocity extremes after magnitude extremes and the tendency of this lag to be larger, the longer the period is, has been previously brought out (Joy 1937).

Although the Fe I velocities of both variables belong to many different epochs, they fall into smooth curves when assembled and thus indicate a faithful repetition of the velocity change from epoch to epoch. The Fe I systemic velocities of T Mon and SV Vul are +32.5 and -0.5 km/sec, respectively, compared with +32 (Sanford 1927) and -2.5 km/sec (Joy 1937) from spectrograms of much lower dispersion. There is no evidence of secondary inflections in the light- or velocity variations of either variable.

VELOCITIES FROM Fe II, Ti II, Sr II, AND H LINES

The curves (C and D, Figs. 1 and 2) of the H and Sr II residual velocities reveal only minor departures from the Fe I velocities from light-maximum to the following

TABLE 1
LINES SOMETIMES DISPLACED LONGWARD

Hydrogen	Sr II, etc.	Ti II	Fe II
δ	λ 4077 714 Sr II	λ 4395 031	λ 4508 283
γ	4215 524 Sr II	4443 802	4515 337
β	4246 829 Sc II	4468 493	4520 225
	4554 033 Ba II	4501 270	4522 634
		4533 966	
		4549 622	
		4563 761	
		4571 971	

TABLE 2
VELOCITIES AND RESIDUAL VELOCITIES OF T MONOCEROTIS

COUDÉ PLATE No.	JD 2430000+	PHASE (DAYS)	Fe I VEL. (km/sec)	RESIDUALS FROM Fe I VELOCITIES			
				Fe II (km/sec)	Ti II (km/sec)	Sr II (km/sec)	H δ γ β (km/sec)
4186..	1895 681	1.107	+ 4 5		+0 8	- 5.6	+ 3.0
4211 .	1925 671	4 079	+10.9	-0.2	+0.1	- 6.2	+ 3 0
4543 .	2196 792	5 020	+14 0	-1 0	-2.1	- 5.5	- 3 4
4590 .	2224 748	5 958	+14 9	+2 2	+0 3	- 4 0	- 0 3
4218 .	1927 650	6 058	+15 5	+0 3	+0 5	- 5.8	- 2 8
4230 .	1929 653	8 061	+22 2	-0 1	+0 6	- 3 2	- 1 9
4598 .	2228 694	9 904	+26 1	-0 1	+0 7	- 4 0	- 2 2
4617 .	2256 663	10 855	+30 3	-1 5	-0 9	- 2.6	- 4 3
4626 .	2258 677	12 869	+37 4	-0 8	+1 2	- 3 7	- 4 2
4644 .	2286 632	13 806	+41 1	-1 9	-0 4	- 9 2	- 4.3
5112 .	2612 741	15 699	+44 4	-0 2	+1 7	- 1 8	- 8.5
4111 .	1831 832	18 312	+52 4	-6 8	+1 4	+ 0 1	-10.4
4088 .	1806 864	20 362	+58 4	-4 6	+2 1	+ 0 1	- 4.1
4124 .	1835 798	22 278	+52 8	-4 7	+3 8	+ 6 2	+ 1.3
6206..	3376 693	23 147	+54 7	-2 5	+2 1	+11 9	- 4 9
6209 .	3377 658	24 112	+53 6	-2 5	+1 9	+10 1	- 0.3
6210 .	3377 717	24 171	..	..	..	..	..
4162 .	1865 757	25 219	+42 6	+5 6	+9 8	+24 4	+23.1
4468...	2108 937	25 237	+42 8	+1 6	+8 1	+17 8	+16 7
5418..	2866 800	26 596	+10 2	+1.1	-1.7	- 4.2	+54.2
6948..	3731 675	26 895	+ 7 0	-0.1	-2.4	- 5.4	+16.6

light-minimum but definite increases between light-minimum and the succeeding maximum, with the greatest increase tending to fall nearly midway. However, the greatest residual of the H velocities of T Mon seems to be a little later. H α velocities are treated separately later. The Ti II residual curves of both T Mon and SV Vul also show the greatest positive residuals in the interval between minimum and maximum light. The Fe II velocity residuals of T Mon have a rather insignificant maximum at about the same phase, but there is also an interval of low values between phases 16 and 24 days.

TABLE 3
VELOCITIES AND RESIDUAL VELOCITIES OF SV VULPECULAE

COUDÉ PLATE No.	JD 2430000+	PHASE (DAYS)	Fe I VEL. (km/sec)	RESIDUALS FROM Fe I VELOCITIES			
				Fe II (km/sec)	Ti II (km/sec)	Sr II (km/sec)	H $\delta\gamma\beta$ (km/sec)
4870..	2455.800	3.910	-28.4	+2 3	- 0 3	- 1 7	+ 3 4
4875..	2456.769	4.879	-26 3	-1 4	- 1 1	- 4 0	+ 3 6
4881..	2457.776	5.886	-24 7	+0 9	- 1 1	- 3 1	+ 8 4
4741...	2370.922	9.322	-19 3	+0 1	- 0 3	- 3 9	- 2 9
4744	2371.736	10.136	-18 8	-0 7	+ 1 1	- 5 2	- 3 3
4917..	2466.672	14.782	-10 0	+0 2	+ 1 6	- 6 5	- 0.6
4968..	2515.619	18.584	- 3 5	-0 9	+ 0 1	(- 0 8)	(+ 8 8)
5452..	2879.604	21.409	+ 1 3	-0 5	+ 1 7	- 4 9	- 1 5
4716..	2343.934	27.479	+13 2	-1 7	+ 2 0	- 0 3	- 4 7
4752..	2392.876	31.276	+19 4	+2 8	+ 1.0	+ 0 7	- 3 2
4670..	2308.951	37.641	+22 5	-5 7	+ 2 7	+11 2	+ 7 4
4962..	2493.639	41.748	+19.5	-0 7	+10 5	+15 3	+10 9
5324..	2809.701	41.796	+18 3	-1 3	+ 6 0	+15 9	+14 1
8045..	4163.913	42.658	+ 1 5	+3 9	+23 2	+28 1	+31.7
4804..	2404.914	43.314	- 3 3	+2 3	+ 7 0	+19 9	+36 4
5331	2812.700	44.795	-15.4	-1 2	- 0 5	+12 4	+16 8

TABLE 4
PHASES OF MAXIMA AND MINIMA OF LIGHT
AND VELOCITY (DAYS)

Star	Light- Maxima	Velocity Minima	Light- Minima	Velocity Maxima
T Mon	+0 5	+1 5	+19 6	+21 0
SV Vul	0 0	+3 0	+34 0	+37 5

Fe II velocities of SV Vul do not differ significantly from its Fe I velocities. It seems open to question whether there is any real difference between Fe I and Fe II velocities in either star.

The widths of the lines in Table 1 have been micrometrically measured and mean values taken for each element on each plate. It is, of course, recognized that the strength of the exposure could have an effect upon such means. However, the widths as plotted in Figure 3 define fairly well the smooth curves drawn through them. The second column of Table 5 gives the mean widths of the lines at phases $0.5P$, and the third column their maximum mean widths from the curves of Figure 3. The fourth column has half the difference between the third and the second column expressed as a velocity. The last column contains the maximum positive residuals read from curves *C*, *D*, *E*, and *F* of

Figures 1 and 2. If the values in the fourth and the last columns agreed, there would be good evidence that the widening of these lines is all longward. Though this is not precisely fulfilled, the widening seems largely, if not entirely, longward, thus giving rise to the large positive velocity residuals which have been found at critical phases for the lines of Table 1.

Figures 4 and 5 reproduce the spectral region $\lambda\lambda$ 4300–4600 and the $H\beta$ regions of four coude spectrograms of T Mon and of SV Vul. They exhibit numerous contrasts of relative intensities of line pairs between maximum and minimum of light (Table 6). Contrasts are particularly striking between the second and third spectrograms, wherein comparison can be made between lines near minimum and those just before maximum of light. Also $H\gamma$ and $H\beta$ are shown to have a large range in strength and $H\beta$ to vary from a symmetrical to a markedly asymmetrical shape, in which its longward portion is much the stronger.

Plates Ce 4468 and Ce 4804 of Figures 4 and 5 have Ti II lines which seem nearly resolved into two components. However, the spectrogram Ce 8045 of SV Vul was ob-

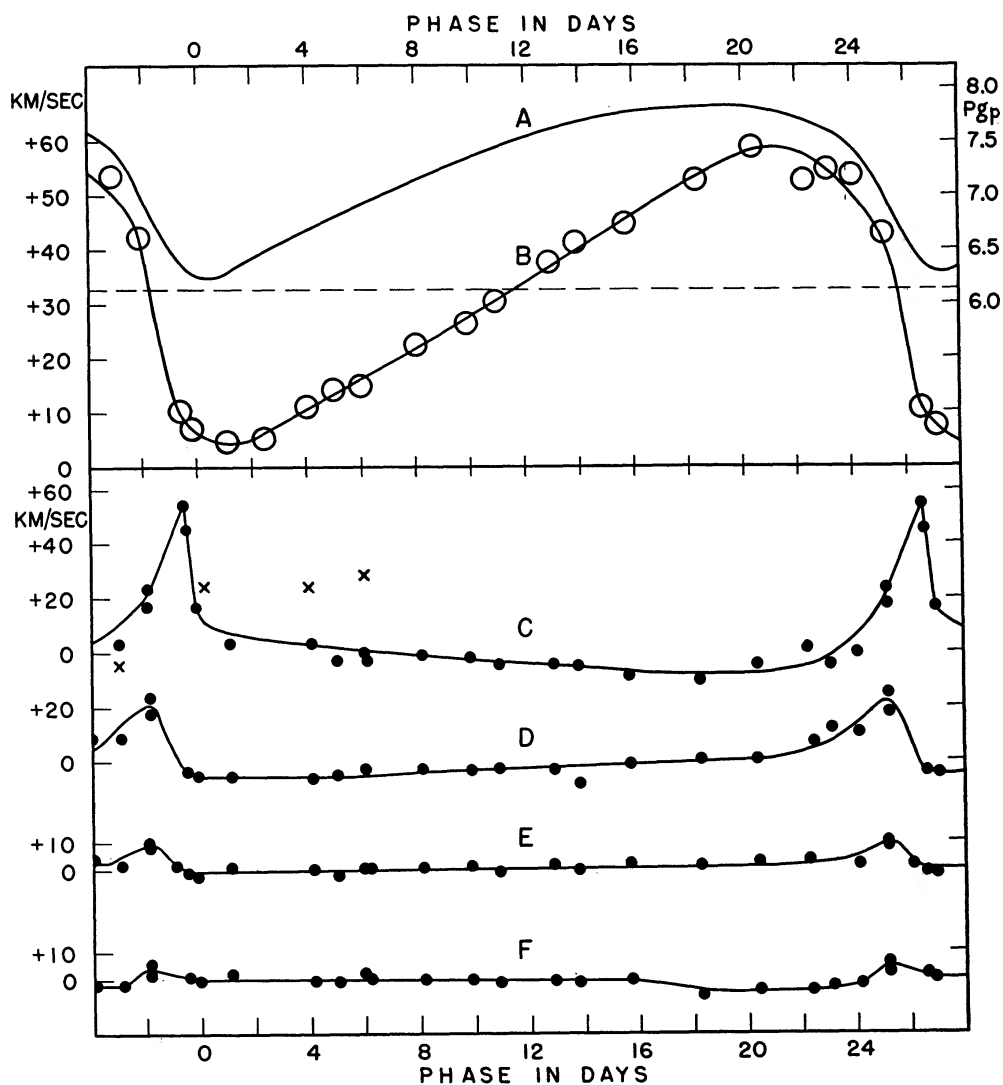


FIG. 1.—T Mon: A, Eggen's P_g light-curve; B, the Fe I velocity-curve; and C, D, E, and F the curves of the residuals of the H, Sr II, Ti II, and Fe II velocities, respectively.

tained with a dispersion of 4.5 Å/mm within 0.656 day of the phase of Ce 4804 and failed to show any better resolution of these lines. The mean width in kilometers per second was closely the same on Ce 8045 and Ce 4804.

Absorption $H\alpha$ appears on four spectrograms of T Mon and on two of SV Vul. On Ce 4186 of the first variable and Ce 5331 of the second, the $H\alpha$ lines have mild gradients on the shortward and steep gradients on the longward sides, producing lines with well-marked longward cores and whole widths that are not easy to bisect, similar to the $H\beta$ line of Ce 5331 of Figure 5. The $H\alpha$ lines on the other spectrograms are nearly symmetrical. Velocities from these lines were derived from bisections of the whole widths and are given in the fifth column of Table 7. Their re-

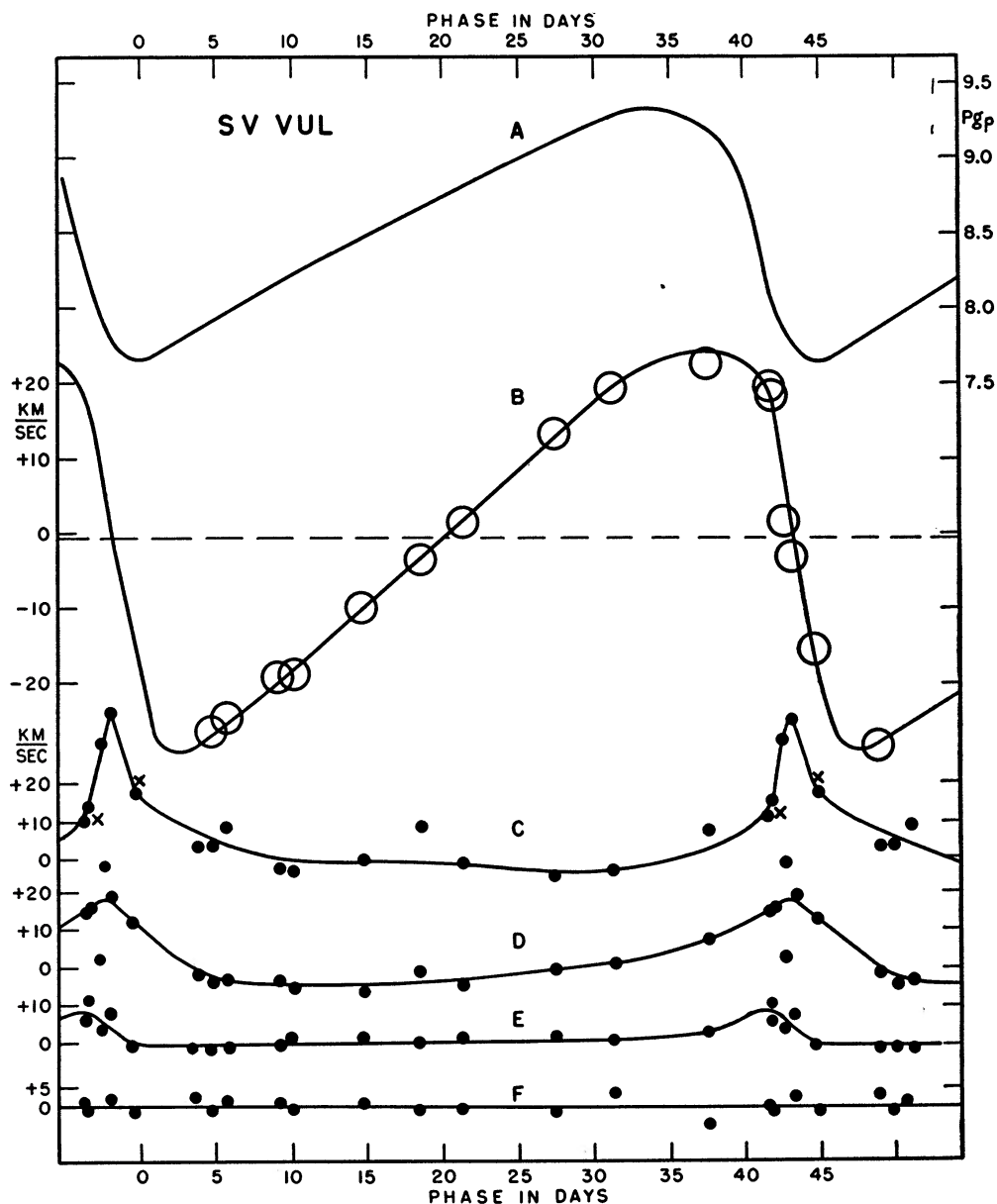


FIG. 2.—SV Vul: A, Eggen's PgP light-curve; B, the Fe I velocity-curve; and C, D, E, and F the curves of the residuals of the H, Sr II, Ti II, and Fe II velocities, respectively.

siduals from the corresponding Fe I velocities are in the eighth column. The smallest of these residuals belong to Ce 6210 (T Mon) and Ce 5324 (SV Vul), both preceding light-maximum by about $0.1P$. The others are large positive residuals, the mean of which is $+24.4$ km/sec, compared with $+5.6$ km/sec, the corresponding mean residual of the $H\delta\gamma\beta$ velocities. The $H\alpha$ residual velocities of the eighth column of Table 7 are plotted as crosses with the C -curves of Figures 1 and 2.

These velocity shifts of the H, Sr II, Ti II, and Fe II lines with respect to the Fe I lines, which are especially pronounced shortly before light-maximum, suggest that the lines

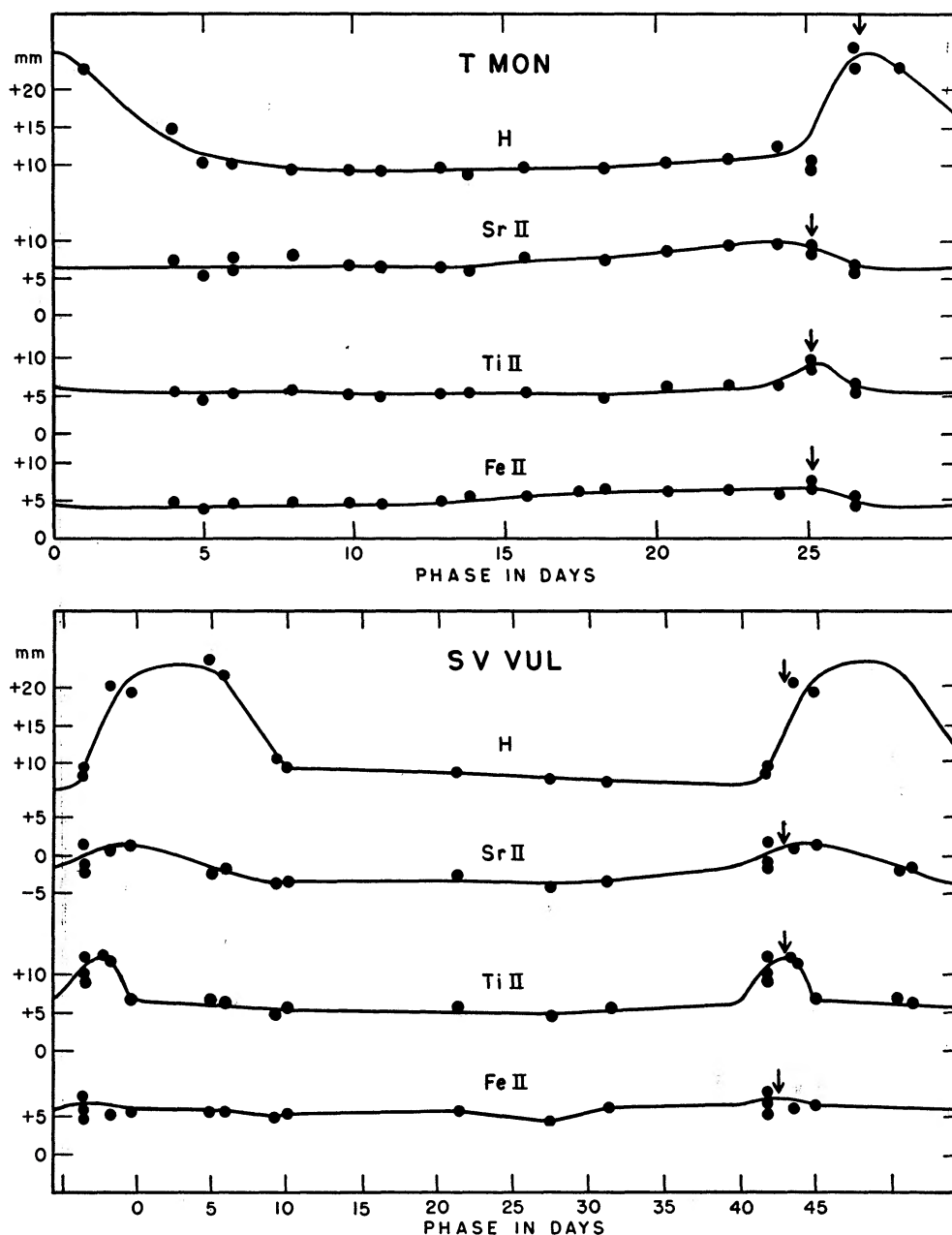


FIG. 3.—The measured widths of the H, Sr II, Ti II, and Fe II lines plotted and represented by freehand curves; *upper four*, T Mon; *lower four*, SV Vul.

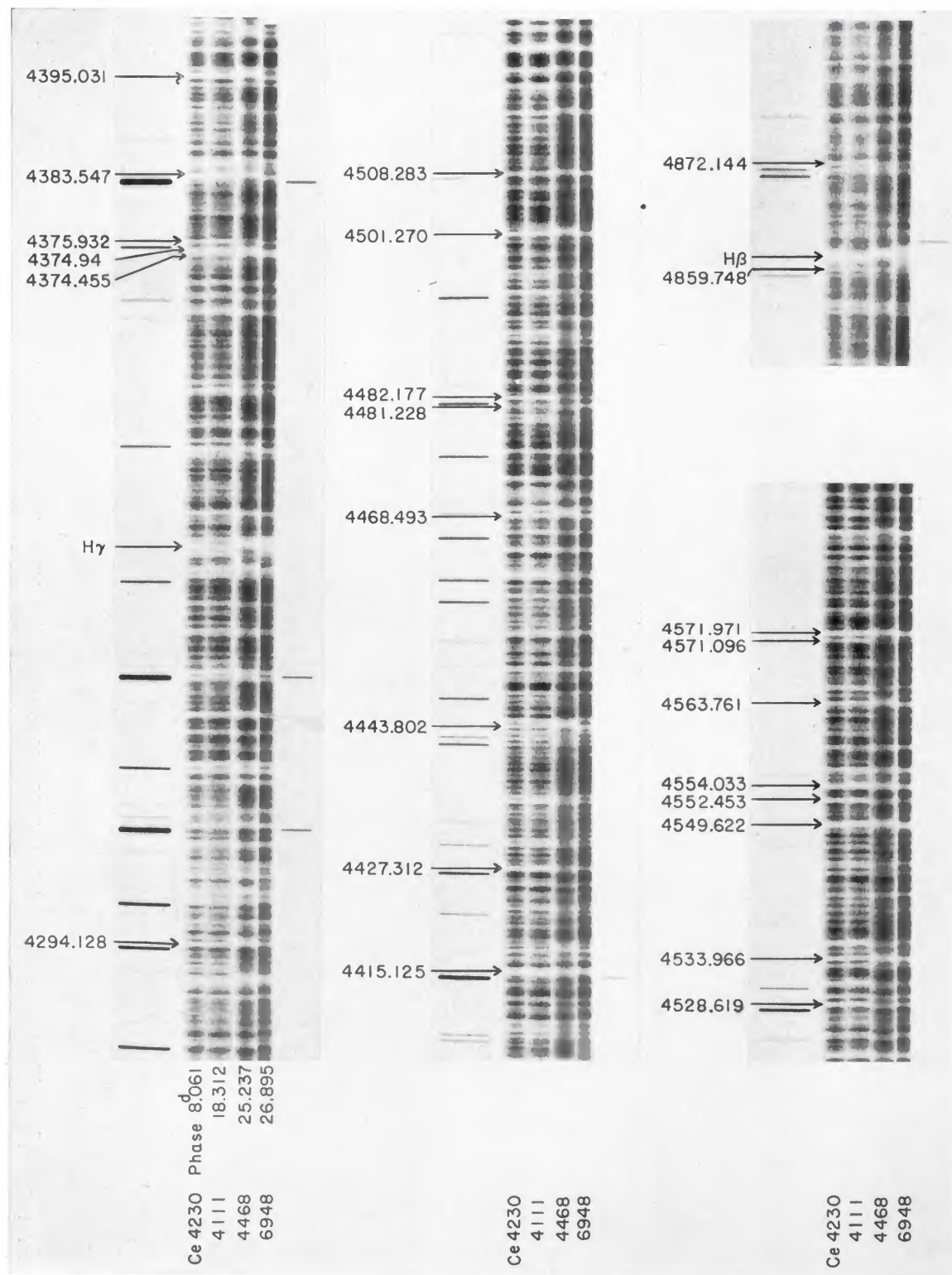


FIG. 4.—Portions of four spectrograms of T Mon which illustrate changes of line widths and relative intensity of the components of certain pairs of line with phase.

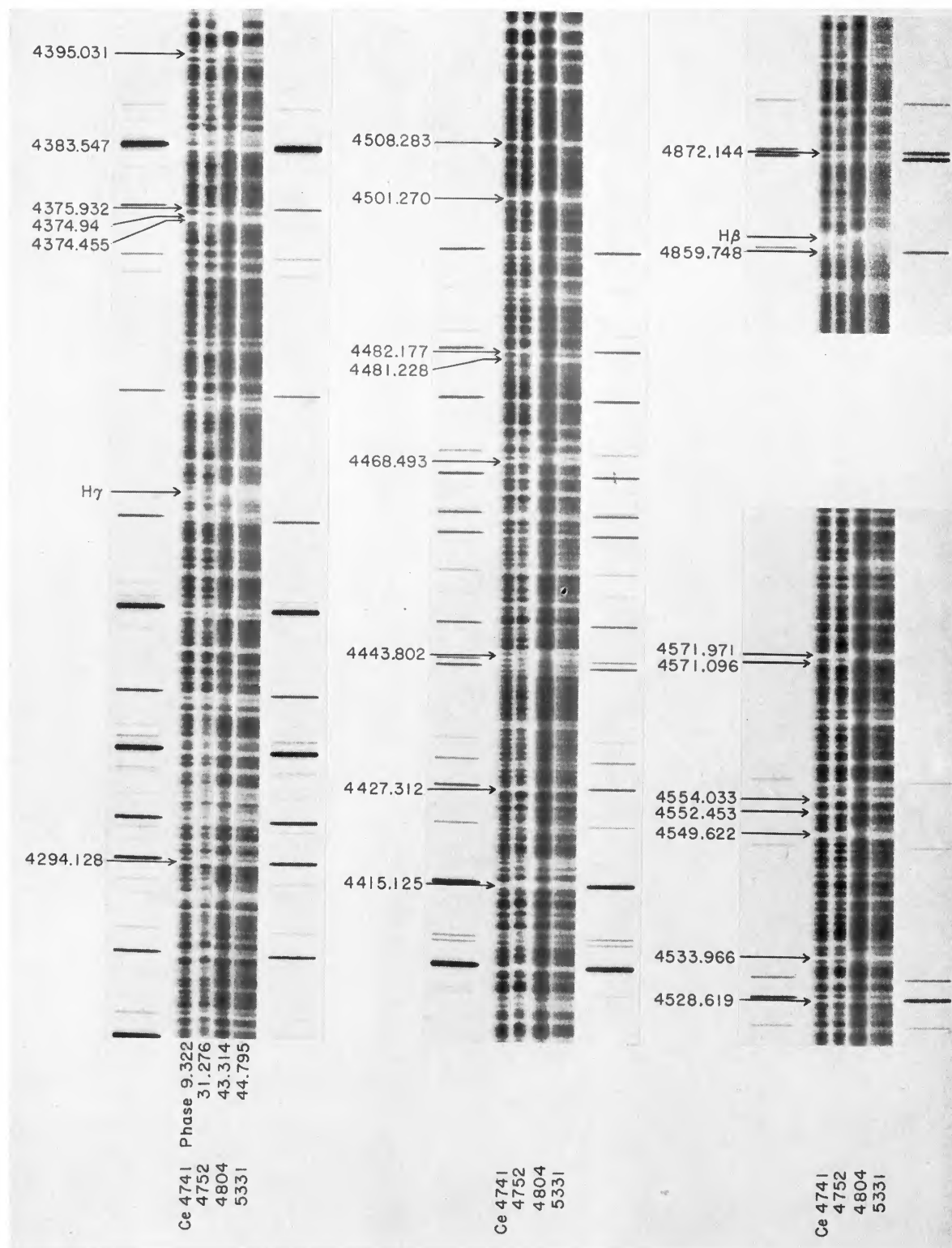


FIG. 5.—Portions of four spectrograms of SV Vul which illustrate changes of line width and relative intensity of the components of certain pairs of lines with phase.

involved may be the blends of lines of a new outward surge of gas and the lines of a previous surge which has reached its maximum velocity of recession. In other words, certain sets of lines may persist somewhat longer than the period of light-variation or the period of the Fe I line velocity variation.

INTERSTELLAR VELOCITIES

The H and K lines of Ca II vary considerably throughout a cycle of T Mon. There are always very broad absorptions of these lines covering many angstroms. But when the exposures are strong enough to show detail in the bottoms of these broad lines, there are also narrow absorption cores, which seem to undergo little, if any, velocity change, such as the change of the Fe I lines. The mean of the velocities from these cores (fourth col. of Table 7) is $+16.9$ km/sec. This is assumed to be the interstellar velocity of T Mon. Velocities have also been derived from such cores of two spectrograms of SV Vul (also in the fourth column of the same table), and their mean is -14 km/sec. Both are reasonable values of interstellar velocity for the galactic positions of these two stars.

TABLE 5

LINE WIDTHS AND VELOCITY SHIFTS

ELEMENT	WIDTH AT PHASE 0.5P (mm)	MAX WIDTH (mm)	Δ WIDTH/2 (km/sec)	MAX. VEL. RESIDUAL (km/sec)
T Mon				
H. . .	0 090	0.245	54	54
Sr II	063	.100	14	22
Ti II	053	.093	19	9
Fe II	043	.068	8	4
SV Vul				
H. .	.087	.230	50	31
Sr II	.060	.120	22	18
Ti II	050	.122	26	9
Fe II	0 045	0 075	9	0

TABLE 6

LINE PAIRS WITH VARYING RELATIVE INTENSITY

Strengthened near Maximum	Strengthened near Minimum	Strengthened near Maximum	Strengthened near Minimum
λ 4374 455 Sr II (14) versus	λ 4375 932 Fe I (2)	λ 4501 270 Ti II (31) versus	λ 4482 171 Fe I (2)
4374 94 Y II (13) versus	4375 932 Fe I (2)	4508 283 Fe II (38) versus	4482 171 Fe I (2)
4395 031 Ti II (19) versus	4375 932 Fe I (2)	4533 966 Ti II (50) versus	4528 619 Fe I (68)
4443 802 Ti II (19) versus	4427 312 Fe I (2)	4549 622 Ti II (82) versus	4552 453 Ti I (42)
4468 493 Ti II (31) versus	4482 171 Fe I (2)	4554 033 Ba II (1) versus	4552 453 Ti I (42)
4481 228 Mg II (4) versus	4482 171 Fe I (2)	4571 971 Ti II (82) versus	4571 096 Mg I (1)

The available D-line velocities are in the sixth column of Table 7. They differ from the Fe I velocities of the seventh column in the direction to be expected if stellar D lines with the displacement of the Fe I lines are blended with interstellar lines having the velocity displacement of the H and K interstellar lines.

EMISSION LINES OF H AND K

Emission components of H and K are present within the broad H and K absorption lines on all strongly exposed spectrograms of T Mon in the phase interval 22.278–26.895 days but not at other phases. There is only one spectrogram of SV Vul (Ce 4804

TABLE 7
VELOCITIES FROM H AND K LINES, H α
LINES, AND D LINES (KM/SEC)

SPECTROGRAMS COUDÉ No.	PHASE (DAYS)	H AND K LINES		H α	D LINES	Fe I LINES	H α -Fe I
		Emis	Abs.				
T Mon							
4186.. . .	1.107	. . .	+16	+28	+ 9 5	+ 4 5	+23 5
4211.. .	4.079	. . .	. . .	+35		+10 9	+24 1
4543... ..	5 020	. . .	+21			+14 0	. . .
4218... ..	6 058	. . .	. . .	+44		+15 5	+28 5
4124.. .	22 278	-30	+18			+52 8	. . .
6209.. .	24 112	-35	+ 8			+53 6	. . .
6210... ..	24 171	. . .	. . .	+49	+48 4	+53 6	- 4 6
4162.. .	25 219	-20	+18			+42 6	. . .
4468.. .	25 237	-20	+11			+42 8	. . .
5418.. .	26.596	-40	+22			+10 2	. . .
6948.. .	26 895	-45	+21			+ 7 0	. . .
Mean	. . .	-30	+16 9				. . .
SV Vul							
5324.. .	41.796	. . .	. . .	+30	+ 1 3	+18 3	+11 7
4804.. .	43 314	-66	-14			- 3 3	. . .
5331... ..	44.795	. . .	-14	+ 6	-13 6	-15 4	+21 6
Mean..	..		-14				

at phase 43.314 days) sufficiently exposed to show such emissions. All these emission lines are diffuse on the shortward and sharp on the longward sides where they are in contact with the presumed interstellar lines. They are weak and difficult to measure accurately except on Ce 5418. The third column of Table 7 contains the measured velocity displacements. The mean of their displacements from the corresponding Fe I lines is -66 km/sec (T Mon). The displacement of the emission H and K of Ce 4804 of SV Vul is -63 km/sec. These values are considered as showing only the order of magnitude of the shift of bright H and K. No emission was found longward of the interstellar lines.

MEAN RADII OF T MON AND SV VUL

The radial-velocity variations found here and the light- and color-index-curves found by Eggen suffice to compute the mean radii of these two variables as Stebbins, Kron, and Smith (1952) did that of η Aql. This assumes that, at two phases 1 and 2 with the same color index in a given cepheid, the difference in radius and therefore area accounts for the difference in apparent magnitude at the two phases. Their formula is $R = (\Delta r_1 - n\Delta r_2)/(n - 1)$, in which $n = \log^{-1}(0.2\Delta m)$, wherein Δm is the difference in the apparent magnitudes at phases 2 and 1; Δr_1 and Δr_2 are the differences from R at phases 1 and 2 and involve correcting the observed radial velocities for the integration effect over the stellar hemisphere and for limb darkening. Table 8 gives the calculation of the

TABLE 8
CALCULATION OF MEAN RADIUS R

<i>T Mon:</i>				
Phase 1 . . .	3 ^d 0	4 ^d 7	6 ^d 5	8 ^d 8
Phase 2 . . .	25 3	24 8	24 0	21.6
Δ mag..	0 40	0 46	0 48	0 52
Δr_1 10 ⁵ km .	0	+ 48	+ 87	+119
Δr_2 10 ⁵ km.	-164	-157	-145	- 65
R 10 ⁷ km	8 1	8 7	9.4	6.8
<i>SV Vul:</i>				
Phase 1* .	- 2 ^d 2	2 ^d 3	7 ^d 1	11 ^d 4
Phase 2 .	32 1	30 7	29 4	27 6
Δ mag..	0 26	0 66	0 60	0 50
Δr_1 10 ⁵ km	+ 16	+ 95	+176	+205
Δr_2 10 ⁵ km	-190	-154	-117	- 61
R 10 ⁷ km .	9 5	8.6	10 2	10.9

* Phases based on the epoch JD 2429020.87.

mean radii of T Mon and SV Vul, in which the corrections for hemispheric integration and limb darkening follow the procedure of Schwarzschild, Schwarzschild, and Adams (1948), as was done by Stebbins, Kron, and Smith for η Aql. This gives a mean R of $8.2 \pm 0.7 \times 10^7$ km or $119\odot$ for T Mon and $9.8 \pm .07 \times 10^7$ km or $142\odot$ for SV Vul.

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