1957ApJ...126..291B

RADIAL-VELOCITY VARIATIONS IN FOUR SHORT-PERIOD VARIABLE STARS

WALTER K. BONSACK
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received April 29, 1957

ABSTRACT

Complete radial-velocity-curves have been obtained with the Cassegrain spectrograph of the Mount Wilson 60-inch telescope. Conspicuous variations in the velocity amplitude are not found The velocity-curves of two of the stars cannot be represented as mirror images of the published light-curves Integrated velocity-curves show a variation from star to star in the fraction of the period spent near maximum radius. Spectrum variations are discussed by comparisons with MK standards

I. INTRODUCTION

The four stars SW Andromedae, DX Delphini, DY Herculis, and DH Pegasi are examples of the variable stars of period less than 0.5 day. Their BD numbers, positions, and periods are given in Table 1. Relatively few radial-velocity data are available for

TABLE 1

STARS OBSERVED

Name	BD	α(1955)	δ(1955)	Period (Day)
SW And	+28° 54	$00^h21^m.4$	+29° 09′	0 442
DX Del	. ....	20 45 3	+12 18	473
DY Her	+12 3028	16 29 2	+12 06	149
DH Peg	+ 6 4990	22 13 2	+06 36	0 255

the short-period variables, in spite of the current great interest in these stars, largely because most of the known examples are too faint for effective spectroscopic observations. The short-focus camera of the new Cassegrain spectrograph of the Mount Wilson 60-inch telescope (Wilson 1956) is well suited to an investigation of these stars because of both its high speed and the transparency of its optics to ultraviolet radiation, which makes many more lines available for velocity measurements, especially in the stars of earlier types. The foregoing four variable stars have been observed with this instrument.

II. OBSERVATIONS

The spectrograms for this program were obtained between June, 1955, and September, 1956. The camera used has a focal length of 4 inches and a focal ratio of $f/1$. This camera, in conjunction with a grating having 15000 lines per inch used in the second order (blazed at λ 3500), gives a dispersion of 80 A/mm. The projected width of the slit on the plate was 16 μ (95 km/sec), and its projected length was varied from 0.10 to 0.25 mm, depending on the brightness of the star. The spectrograph was adjusted to give usable density in the region $\lambda\lambda$ 3500–4500. Under these circumstances the spectrum of a tenth-magnitude star could be recorded with an exposure of 30 minutes on a baked IIa-O plate. Exposure times were no longer than one-sixth the period.

The features to be measured in the spectrograms were selected from a list given by Smith (1955). This list was compiled from papers of McDonald (1948*a*, *b*), Petrie (1948*a*, *b*), and Wright (1951). These features are mostly blends of atomic lines which have been found to be satisfactorily invariant (in effective laboratory wave length) over the cycles of variable stars in a specific range of spectral types. The features were checked for systematic residuals and large deviations on velocity-standard stars (see below); as a result, a few were discarded, and others were assigned slightly different effective laboratory wave lengths. The final list included fifty-one features, of which twelve were hydrogen lines, twenty-two were unblended metallic lines, and the remainder were blends of metallic lines. In each spectrogram those features were measured which were found by the above authors to be invariant for the spectral type of the star and which were clearly visible on the plate. From nine to twenty-four features were measured on each plate.

In reducing the measurements, each feature was given a weight dependent upon (1) the wave length, since the mean residual velocity for the features was found to increase systematically in absolute value as the wave length decreased, and (2) the accuracy with which the feature could be measured—a function of both strength and sharpness.

Several causes might produce systematic differences between velocities recorded at different times for the same star: (1) the camera was necessarily removed from the spectrograph whenever the 16-inch camera was used; (2) the entire spectrograph was removed from the telescope several times; and (3) the camera underwent considerable mechanical and optical modifications during the course of these observations. However, no such differences in excess of the internal probable error of the plates (2–5 km/sec) were detected.

In order to check any possible systematic error in the radial velocities yielded by this spectrograph, a number of standard-velocity stars were observed early in the program. These were chosen from the list of the International Astronomical Union (1950) and from the velocities of quality "a" listed in the *General Catalogue of Radial Velocities* (Wilson 1953). Sixteen such plates were obtained. Eight of these deviated from the standard velocity by more than three times their probable errors, and three of this group deviated by more than ten times their probable errors. The deviations of these plates showed no systematic trend. Similarly, the group with small deviations was distributed approximately normally about a mean deviation of zero. The cause of the unusual number of large deviations may be the wide slit, which was not uniformly illuminated in the short exposures on the velocity standards. The results of the velocity measurements of the variable stars, based on longer exposures, gave more consistent results. In eighty-two spectrograms measured, only five showed deviations from the mean velocity-curves which were greater than would be expected from the internal probable errors. Since this was true despite the frequent disturbance of the spectrograph, it would seem that the results are free from significant systematic errors. The five with the greatest deviations from the mean curves are plates Xf 145 (DY Her), Xf 303 (DX Del), Xf 310 (DH Peg), Xf 311 (SW And), and Xf 1386 (DY Her). These have been included in Table 2 and plotted in their appropriate places in Figures 1–4.

III. RESULTS

Table 2 gives the velocity, internal probable error, heliocentric epoch, exposure time, and number of lines measured for each plate. The epochs were all reduced to phases (ϕ) and the velocities plotted as a single cycle for each star in Figures 1–4. The reduction to phases was made, using the most recently published light-elements, which are given, together with their sources, in Table 3. The epoch given for SW And includes an 0.5-day correction for non-periodic variation which is probably not accurate,

TABLE 2

RADIAL VELOCITIES

Date	Helioc JD 2435000	Exp Time (min)	No Lines	Vel (km/sec)
	SW And			
7-31-55	320 910	36	9	−58 3
	0 950	40	13	−47 8
	0 983	39	13	−51 4
8- 5-55	325 982	40	24	−11 9
8-26-55	347 009	36	10	−87 1
8-27-55	347 968	37	14	−40 0
	7 999	36	19	−29 3
	8 023	16	15	−33 3
8-28-55	348 791	42	15	−50 0
	8 830	37	10	−40 8
	8 864	40	19	−39 0
	8 894	30	13	−19 7
	8 921	25	23	−24 5
	8 946	28	22	−20 6
	8 975	35	19	− 7 2
	9 005	38	18	− 8 8
6-23-56	648 920	51	16	+15 0
	8 959	52	15	− 3 7
8-16-56	702 773	62	15	−22 9
	2 816	61	19	+ 2 4
	2 863	60	19	− 8 1
	2 901	60	17	+ 3 8
	2 954	60	16	+ 6 2
	2 995	50	18	−20 7
8-17-56	703 783	60	16	+ 3 8
	3 828	60	14	− 7 0
	3 873	61	18	−12 6
	3 911	41	17	−49 8
	3 938	35	19	−50 7
	3 968	40	16	−44 8
	3 999	40	19	−35 7
	DX Del			
7- 2-55	291 988	20	7	−81 3
7- 5-55	294 978	64	17	−50 5
7-30-55	319 704	62	17	−20 6
	9 748	51	14	−17 7
	9 789	45	20	−41 5
	9 830	42	16	−61 8
	9 880	45	23	−72 4
	9 930	45	20	−56 1
8-26-55	346 673	60	15	−40 1
	6 716	43	14	−34 7
	6 752	38	11	−73 4
	6 897	54	18	−66 1

TABLE 2—*Continued*

Date	Helioc JD 2435000	Exp Time (min)	No Lines	Vel (km/sec)
	DX Del—*Continued*			
8-27-55	347 661	44	18	−27 6
	7 697	38	17	−64 6
6-24-56	649 787	41	21	−59 5
	9 896	46	22	−51 1
	9 933	45	16	−29 7
	9 967	45	15	−28 9
6-25-56	650 781	46	20	−46 6
	0 814	45	19	−55 6
	0 850	45	24	−32 8
	0 884	45	23	−39 3
	0 924	55	28	−28 2
	0 966	55	21	−20 8
	DY Her			
7- 1-55	290 715	40	9	−60 1
7- 5-55	294 681	30	18	−47 2
	4 707	30	13	−59 6
	4 797	30	16	−49 1
8-28-55	348 651	32	12	−48 9
	8 683	38	14	−65 3
	8 714	31	14	−35 9
	8 742	37	14	−35 9
3-27-56 .	560 943	35	11	−58 8
	0 972	35	19	−35 3
	561 000	35	14	−25 3
	DH Peg			
7-29-55	318 835	30	17	−48 7
	8 861	30	10	−68 8
	8 897	30	15	−73 5
	8 932	30	15	−54 0
	8 956	30	18	−53 2
	8 989	30	11	−48 0
8-26-55	346 949	32	13	−66 6
	6 988	30	17	−85 8
8-27-55	347 738	35	11	−67 7
	7 769	31	13	−68 7
	7 794	31	14	−57 1
	7 820	28	16	−59 7
	7 846	29	18	−44 3
	7 874	31	19	−47 3
	7 903	37	20	−47 5
	7 936	30	18	−47 6

especially over the interval of more than twenty years since its derivation. In Figures 1–4 the radius of the circle used to represent each measurement is approximately equal to the average of the probable errors determined for the measurements of that star. The circles are filled differently for each night of observation. Crosses on these figures represent velocity values observed by Dr. Joy, which he has not published individually but has kindly permitted the writer to include here for comparison. These observations were made in 1920, 1923, and 1924 (SW And); 1938 (DH Peg); and 1946 (DY Her).

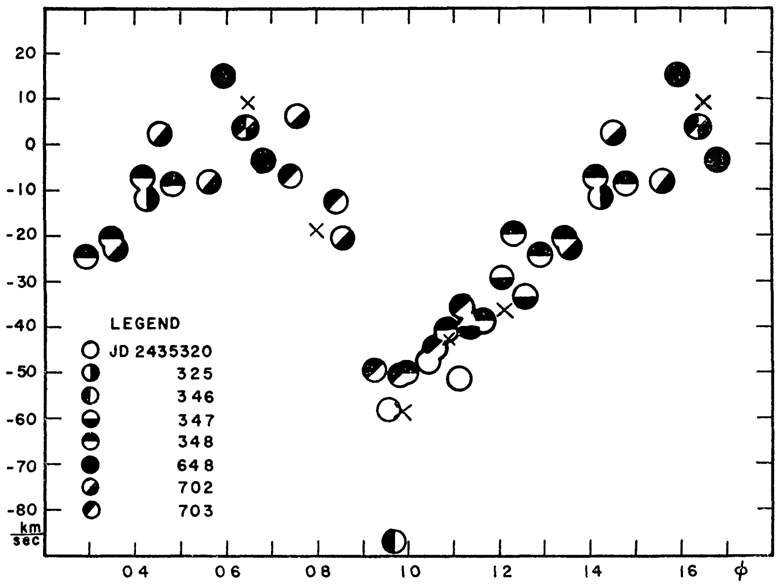

FIG 1 —SW And: radial-velocity observations; crosses are Joy's values

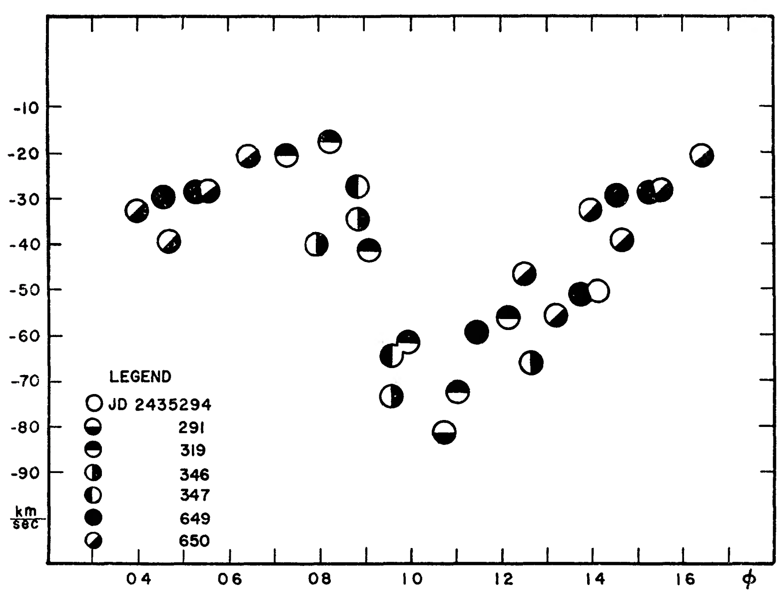

FIG 2.—DX Del: radial-velocity observations

Inspection of these figures shows that, except for the few discordant values discussed above, the velocities define a mean curve as well as the internal accuracy of the measurement permits, except possibly for DH Peg. Here there seems to be a difference in phase between the velocities observed on different dates. The difference is not large with respect to the errors of measurement and the lengths of the exposures but is apparently systematic and probably real. An increase of the period to 0.25546 day improves the agreement between the different dates and yields a mean velocity-curve

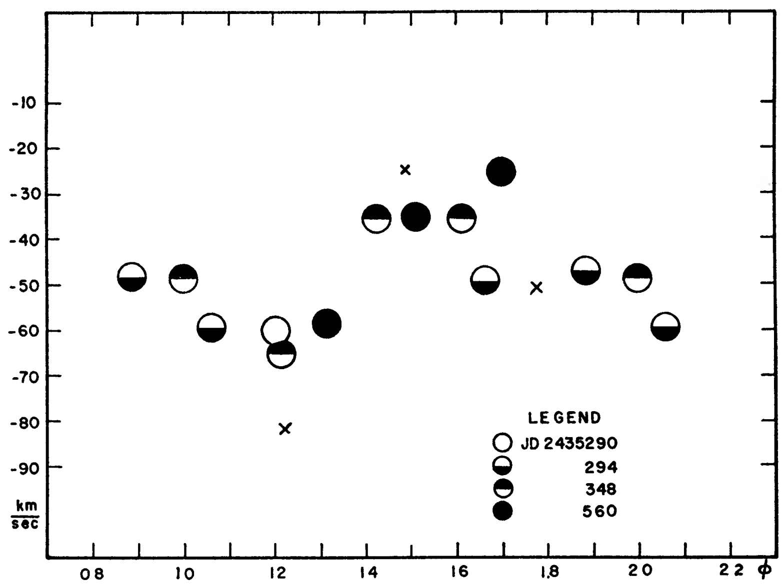

FIG. 3.—DY Her: radial-velocity observations; crosses are Joy's values

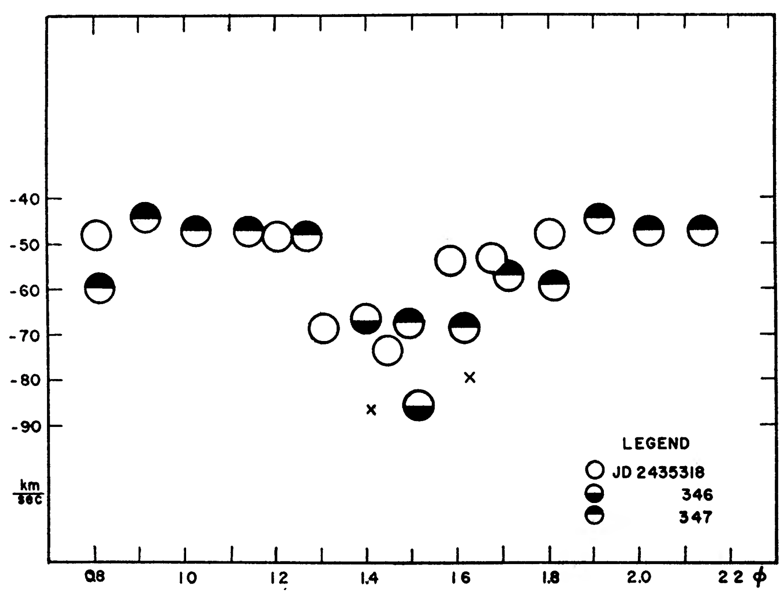

FIG. 4.—DH Peg: radial-velocity observations; crosses are Joy's values

as well defined as the measuring accuracy permits. It is possible that the period may be increasing systematically or changing in a non-monotonic fashion. The period given by Ashbrook (1948), which was used to compute the phases in Figure 4, is longer than the earlier one it replaces, and the period suggested above is longer than Ashbrook's. This problem can best be settled by accurate photometry.

Each of Figures 1–4 contains at least one of the five points of large deviation from the mean curve mentioned above. Two of these occur in Figure 3 (DY Her). These have nearly the same phase, and their average agrees well with the mean curve. In view of the probable cause of these deviations, it seems justified to ignore them in drawing the mean curves. Mean velocity-curves thus drawn are given in Figures 5 and 6.

TABLE 3

Name	γ (km/sec)	Epoch (JD 2400000+)	Period (Day)	Source
SW And	−21 8	18132 261*	0 44227818	Zessewitsch (1937)
DX Del	−43 9	25807 49*	472616	Ahnert *et al* (1947)
DY Her	−45 8	33439 488*	14863081	Ashbrook (1954)
DH Peg	−55 5	27695 342†	0 2551267	Ashbrook (1948)

* Maximum light
† Median light

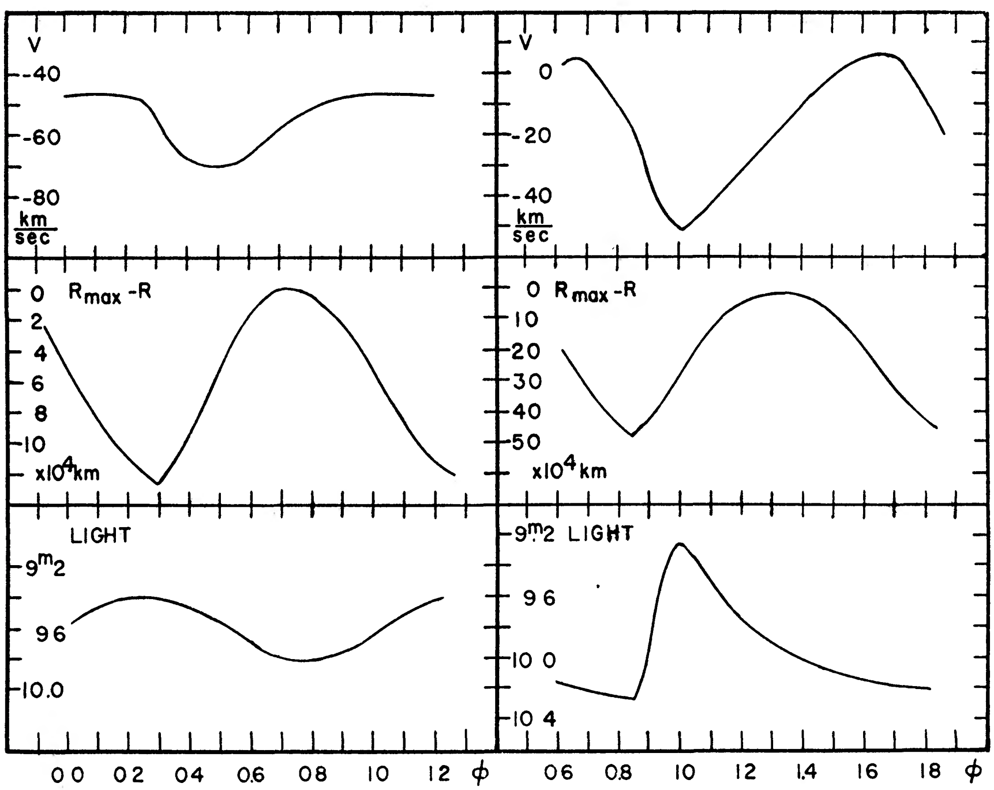

FIG. 5.—Velocity, radius, and light-variations (DH Peg, *left;* SW And, *right*)

For each star the mean velocity-curve was integrated mechanically to give the average velocity and radial displacement of the surface. The average velocity, γ, for each star is given in Table 3. An integration of the curve of $V - \gamma$, corrected for the projection of the velocities of a limb-darkened stellar hemisphere on the line of sight, yielded the radial displacement in kilometers as a function of phase. The correction $V(\text{pulsation})/[V(\text{obs}) - \gamma]$ was taken as 24/17, as adopted by Schwarzschild, Schwarzschild, and Adams (1948). The results of the integrations are presented in Figures 5 and 6; here curves of light, radius, and velocity variations are displayed on common abscissae. The light-curves are taken from the most recent data that the writer was able to find. The references are as follows: SW And, Detre (1934); DX Del, Ahnert, Hoffmeister, Rohles, and van de Voorde (1949); DY Her, Smith (1955); and DH Peg, Jensch (1935).

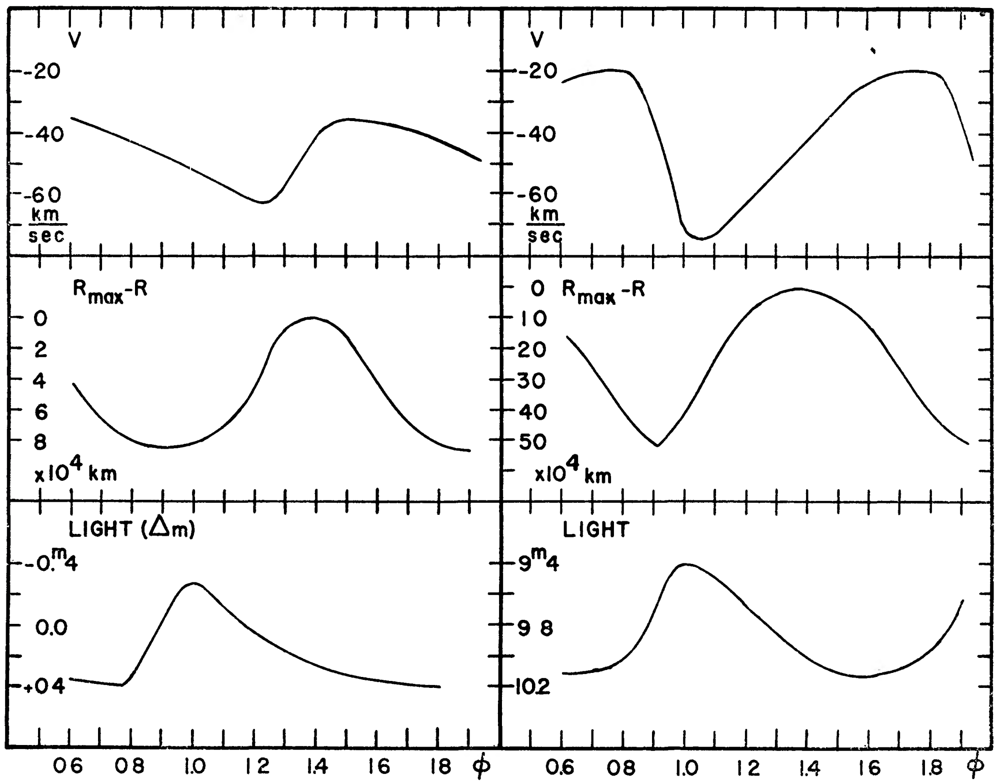

FIG. 6.—Velocity, radius, and light-variations (DY Her, *left;* DX Del, *right*)

IV. DISCUSSION

a) Constancy of the Velocity-Curves

The short-period variable stars are often characterized by a variation in the velocity amplitude and the phase of maximum, which may sometimes be described as the result of the compounding of two or more periodic variations. Fitch (1955) has shown that there is an apparent relation between the beat period of these variations and the primary period, with the beat period encompassing fewer cycles of the primary variations in stars with shorter primary periods. What is more to the point in relation to the present observations is the range of the velocity variation which may be expected for a given period. A survey of the literature seems to show that the period and the change of the velocity amplitude from one cycle to the next are not simply related. Among the RR Lyrae variables of period near 0.5 day, Struve and Blaauw

(1948) found a small variation—about 5 km/sec—in the 60-km/sec amplitude ($2K$) of RR Lyr ($P = 0^{d}.567$); Joy (1938) found no variation in the 70-km/sec amplitude of W CVn ($P = 0^{d}.552$); but Struve and Van Hoof (1949) found that the velocity amplitude of XZ Cyg ($P = 0^{d}.466$) varies in the range 53–64 km/sec. Among the more rapid variables, constant amplitudes of 40 and 64 km/sec, respectively, were found for SX Phe ($P = 0^{d}.055$) by Wilson and Walker (1956) and for CY Aqr ($P = 0^{d}.061$) by Struve (1948); on the other hand, Paddock and Struve (1954) found a variation of 7–14 km/sec in the amplitude of δ Sct ($P = 0^{d}.194$); Wilson and Walker (1956) found 12–24 km/sec for CC And ($P = 0^{d}.125$); and Gratton and Lavagnino (1953) found 6–40 km/sec for AI Vel ($P = 0^{d}.112$).

Inspection of Figures 1–4 reveals no conspicuous segregation of points which would indicate an amplitude variation in any of the stars. The differences in DH Peg indicate a phase variation, as mentioned above. A variation in the velocity amplitude of more than 10 km/sec seems unlikely for DX Del and SW And, which were each observed on two well-separated pairs of consecutive nights; and no positive evidence of such a variation exists for any of the stars.

The velocities observed by Dr. Joy very nicely confirm the constancy of the variation in SW And but suggest that the amplitudes of DH Peg and DY Her may have been larger in the past. It was necessary to apply a uniform shift to the computed phases of Joy's velocities for SW And and DH Peg, to make them fall on the observed curves, apparently because of inadequate light-elements.

b) Radius and Light-Variations

The velocity-curves of SW And and DX Del resemble closely the curve of RR Lyr and those of the cepheids, e.g., η Aql (Schwarzschild *et al.* 1948). The dispersion used in the present study would not show a discontinuity, such as that observed by Sanford (1949) in RR Lyr, if it existed in these stars. DH Peg has a similar velocity-curve, which, although it is not so well determined in shape, seems to indicate that the star spends more time near its maximum (algebraic) velocity. DY Her, on the other hand, has a velocity-curve which is describable as a rapid rise to maximum velocity, followed by a relatively slow decline to minimum—just the reverse of the behavior of the other stars.

To show more clearly the nature of the differences in radius variation represented by the various velocity-curve shapes, the radius variation-curves of Figures 5 and 6 are presented. The radius-curves differ in what may be termed the pulse duration—DY Her, for example, spends a smaller fraction of its period near maximum radius than do the other stars. A shortening of the phase interval from minimum to maximum velocity corresponds to a decrease in the duration, which would seem to be a superficial phenomenon depending strongly on the surface gravity and may not be directly related to the period.

The shapes of the light-curves given in Figures 5 and 6 indicate that the so-called "mirror-image" relationship between the light- and velocity-curves is not a general property of the short-period variables. Since the time elapsed between the derivation of the light-elements and the velocity measurements is in all cases greater than one-third the time interval considered in deriving the elements and since the foregoing results indicate some inadequacies in the elements, it is probably not justified to draw inferences from the relative phases of the light- and velocity- or radius-curves. But no shift in phase can make the velocity-curves of DH Peg and DY Her look like mirror images of their light-curves. Thus it appears that the light-curves alone do not provide significant groupings among these stars. SW And, DX Del, and DY Her have similar light-curves, but the velocity- and radius-curves of DH Peg resemble those of the first two stars more closely than do those of DY Her.

c) Spectrum Variation

The spectrograms taken in this program are not well suited to accurate spectral classification; they are, in general, too narrow. However, the spectral variation is often quite conspicuous. The most striking variation is the strength of the K line of Ca II. It appears to change in strength in phase with the radius, apparently corresponding to changes in the electron pressure as the star expands and collapses. The plates were compared with spectrograms of standards of the MK system taken by W. G. Tifft with the same equipment as that used for the velocity studies. In general, the standard line-strength criteria and the general appearance of the spectra indicated a luminosity classification close to III. The lines were not conspicuously different in strength from the standards, although the weak metallic lines often did not correspond to the same spectral class as the hydrogen or ionized calcium lines.

1. *SW And*.—At maximum radius this star is quite similar to an F8 III standard; at minimum the H and Ca II lines resemble A7 III, while the remaining lines are closer to F0 III. Münch and Terrazas (1946) state that SW And resembles closely an F6 giant on one of two plates obtained and is of mixed type near A7 on the other.
2. *DX Del*.—This star is quite similar in spectral variation to SW And.
3. *DY Her*.—The variation in this star is from about F4 III at maximum radius to A7 III at minimum, with no conspicuous lack of agreement among the lines.
4. *DH Peg*.—This star is conspicuously earlier than the other three; the variation is not so great and is confined mostly to the K line. This line varies in strength corresponding to about A7 at maximum radius and A2 at minimum, while the hydrogen lines vary only slightly in the vicinity of A5.

The mean velocities of these stars have been referred to the local standard of rest, taking the solar motion to be 20 km/sec toward $\alpha = 18^h$, $\delta = +30°$. The results are -18 km/sec for SW And; -29 km/sec for DX Del; -28 km/sec for DY Her; and -47 km/sec for DH Peg. These values are not large enough to establish these stars as members of population II; neither is there any conspicuous weakness of lines relative to the standards, as would be expected in population II stars. The differences in spectral types indicated by the different lines probably result from stratification effects in the non-equilibrium atmospheres.

This paper is a result of a program undertaken in co-operation with William G. Tifft to obtain both light- and velocity measurements of a number of cluster-type variable stars. The stars discussed here, with the exception of DY Her, are those for which complete spectroscopic data, but not complete light-data, were obtained. The writer wishes to thank Dr. O. C. Wilson for much helpful advice, Dr. A. H. Joy for making available his velocity measurements, and Mr. Tifft for many useful discussions and for obtaining some of the spectrograms.

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