

THE RADIAL VELOCITIES OF FIVE STARS IN THE ζ PERSEI AGGREGATE

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Summary

New radial velocities are found for α Per, HD 22951, HD 24131, and HD 24640. Jordan's orbit for α Per is confirmed and HD 24640 is found to be a β -Cephei variable. The system reproduces the well-determined radial velocity of ζ Per.

Introduction.—Some years ago Ambartsumian (1952) demonstrated the existence of aggregates of O and B type stars. He showed that they were in general gravitationally unstable in the galactic field and a theory was developed in which the aggregates were identified as centres of star formation. More recently Blaauw and others have published detailed discussions of the proper motions of stars in these aggregates which can be interpreted in terms of linear expansion from a point. The scale of this expansion provides an estimate of the age of the aggregate and the stars in it. These ages have been made the basis of a large volume of theoretical work on Stellar Evolution. Thus Burbidge and Burbidge (1958) quote the following ages in support of their work.

Aggregate	Age	Analysed by
ζ Persei	1.3×10^6 years	Blaauw (1944, 1952 and 1953 with J. Delhaye)
Lacerta	4.2 „	Blaauw and Morgan (1953)
Cepheus II	4.5 „	Markarian (1953)
Cassiopeia-Taurus	~ 50 „	Blaauw (1956)

But Petrie in a recent paper (1958) has shown that the expansion of Cassiopeiae-Taurus is fictitious and has thrown much doubt on the aggregate's physical existence. Moreover Woolley and Eggen (1958) have shown that the expansion of the Lacerta aggregate is doubtful, although the aggregate probably exists physically.

The physical existence of a cluster of early type stars around ζ Persei is indisputable, and the evidence of expansion, derived from proper motions, is good (Delhaye and Blaauw 1953). However, the radial velocities are not in general well determined and the evidence of expansion from radial velocities is slim (Blaauw 1952). The object of this and subsequent papers is to improve the radial velocity data for the aggregate. It is hoped in a later paper to publish absolute magnitudes for the members, based on the MK type and also on the equivalent width of $H\gamma$. The effect of interstellar absorption can be calculated indirectly from the colour excesses published by Stebbins, Huffer and Whitford (1939). Improved radial

velocity measures combined with individual distance moduli may make it possible to arrive at a completely independent value of the expansion. Blaauw's latest value for the expansion (Delhaye and Blaauw 1953) is

$$+0''.00236 \text{ per year per degree} \\ \pm 0''.00025 \text{ p.e.}$$

which corresponds to an expansion-age of 1.5×10^6 years. Assuming spherical symmetry the aggregate has a diameter of 30 parsecs so that there should be a difference in radial velocity of 20 km/sec between front and back. Radial velocities can be measured to a far higher accuracy than this—the inherent difficulty is to measure individual distances sufficiently accurately.

Method of observation and reduction.—The spectrograph at the Cassegrain focus of the 36-in. Yapp reflector has an optical train highly transparent to the ultra-violet. It may be used in the 'one-prism' or 'three-prism' form; the former was used for these observations. The dispersion is then 122 Å/mm at H γ rising to 87 Å/mm at H ϵ (3750 Å), which is easily seen on a good plate. The collimator: camera ratio is 2.5:1 so that the slit-width of 30 μ which was habitually used projects to 12 μ on the plate. The spectra were broadened to 0.3 mm by trailing the star along the slit in hour angle, using a modified speed of telescope drive. The exposures were all made at zenith distances of less than fifty degrees, so no attempt was made to compensate for atmospheric dispersion, which was much smaller than the seeing disk (about 2").

A fifth-magnitude star requires an exposure of 7 minutes with Oa-O emulsion or 24 with baked IIa-O (U.K. Kodak). For B stars such spectra are measurable from 4471 Å He I to 3750 Å H ϵ ; H β can be seen with Oa-O emulsion but adds no weight to the radial velocity determinations. Each plate was measured in both directions against a comparison iron arc exposed for equal periods before and after each stellar exposure. The lines used with their adopted wavelengths are shown in Table I.

TABLE I

Adopted wave-lengths

Element	Laboratory wavelength	Adopted wavelength
He I	4471.48	same
H γ	4340.47	same
H δ	4101.74	same
He I	4026.19	same
H ϵ	3970.08	same
He I	3964.73	same
H8	3889.05	same
H9	3835.39	3835.64
He I	3819.61	same
H10	3797.90	3797.80
H11	3770.63	same
H12	3750.15	same

The wavelengths were arrived at empirically from the plates of ζ Persei (a standard-velocity supergiant). With the accuracy obtainable it was found possible to use the laboratory wavelength for all but two of the lines, viz. H9 and H10.

These were adjusted to agree with the mean of the remaining lines. The lines He 4471 and 4026 require careful attention. In the Victoria system they have different wavelengths for supergiants and for main-sequence stars because of differing strengths of the forbidden absorptions (Petrie 1953b). However it is difficult to extrapolate these results to the low dispersion used here. Instead it is proposed to use the system as it stands and calibrate it against further standard-velocity stars of different luminosities and spectral types. This work is at present in hand at the Royal Greenwich Observatory.

No attention was paid to interstellar lines. The K line of Ca II is barely visible on a typical plate of these five stars and is only measurable on a few. The intensity of the H line is considerably less than the K line, so its possible effect on He or He 3964 was disregarded.

The mean of the velocities of the lines was taken as the velocity of the star, rejecting lines which appeared doubtful during measurement and deviated widely. Each measure was corrected for the solar motion in the usual way. The internal probable error of a good plate was of the order of ± 5 km/sec. There was some evidence of short exposures producing incorrect results because of uneven illumination of the slit, so all exposures of two minutes or less were rejected. At a declination of $+30^\circ$ a star requires $1\frac{1}{2}$ minutes to trail down the slit.

Stars with constant velocities.—The first three columns of Table II contain the Henry Draper number, name and visual magnitudes of the stars. Columns four and five are the spectral types on the Henry Draper and Morgan-Keenan systems (Johnson and Morgan 1953, Slettebak and Howard 1955). The sixth column is the radial velocity in km/sec which is the weighted mean of the individual spectra. The weights are calculated from the internal probable errors of the plates, by the usual method of least squares. Column seven is the probable error of the weighted mean and column eight contains the number of spectra measured. The velocities from Wilson's general catalogue (1953) are given in column nine together with their qualities.

TABLE II

Stars with constant velocities

HD	Star	m_v	Sp. HD	Sp. MK	RV	p.e.	n	Wilson	p.e. of unit wt.
22951	40 Per	5.04	B2	B0.5 V	+20	± 1	33	+19c	± 7
24131	GC 4649	5.73	B3	B1 V	+10	± 1	17	+17.8a	± 5
24398	ζ Per	2.91	B1	B1 Ib	+19	± 1	11	+20.6a	± 4

A typical plate has an internal probable error of ± 5 km/sec, and this was taken as the unit of weight. However, intercomparison of the individual plate measures gives an external value of the probable error of unit weight, and this quantity is shown in the last column. For a star with constant velocity it should be $\sim \pm 5$ km/sec but where the velocity is variable it is greater. Thus the constant velocities of HD 24131 and ζ Persei are confirmed. There is evidence of real variation in HD 22951 but the amplitude is too small for it to be investigated with this accuracy.

Stars with variable velocity.—Table III gives essentially the same quantities for the variable stars as Table II for the constant stars. However, the radial

TABLE III

Stars with variable velocities

HD	Star	m_v	Sp. HD	Sp. MK	RV	p.e.	n	Wilson
23180	o Per	3.94	B1	B1 III	+ 14	± 3	42	+ 18.5a
24640	GC 4734	5.48	B3	B2 V	+ 7	± 2	33	+ 17c

TABLE IV

Measures of individual spectra of stars with variable velocity

o Per					HD 24640						
Plate	Date	RV	p.e.	Ph.	Plate	Date	RV	p.e.	Ph.		
Y1p				d	Y1p				d		
30a	1958 Oct.	13.069	- 43	± 5	0.675	48c	1958 Nov.	1.014	- 8	± 4	0.092
b		13.075	- 6	8	0.681	71a		19.069	- 12	7	0.106
45d		31.838	+ 84	6	1.767	c		19.141	- 1	6	0.047
e		31.845	+ 88	7	1.774	72b		19.900	- 6	4	0.015
72a	1958 Nov.	19.880	+ 33	10	3.132	75a	1958 Dec.	1.065	+ 32	4	0.118
d		19.966	+ 4	16	3.218	76a		1.159	+ 18	6	0.080
73b		19.853	+ 55	7	3.105	b		1.178	+ 24	9	0.099
78d	1958 Dec.	1.883	+ 108	5	1.817	d		1.215	+ 25	11	0.004
e		1.889	+ 72	7	1.823	79a		2.087	+ 26	3	0.086
f		1.898	+ 97	7	1.833	b		2.113	+ 32	6	0.112
79c		2.135	+ 81	7	2.068	81a		2.851	- 16	4	0.060
d		2.142	+ 122	5	2.075	b		2.899	+ 27	4	0.108
e		2.149	+ 118	7	2.083	d		2.955	+ 3	8	0.033
81c		2.925	+ 52	6	2.854	88a		14.883	- 3	5	0.108
e		2.980	+ 49	5	2.913	c		14.908	+ 21	4	0.002
83f		4.130	- 70	6	4.063	d		14.923	- 1	4	0.017
97c		31.936	- 1	5	0.936	94a		22.013	+ 1	5	0.127
g	1959 Jan.	1.008	+ 12	4	1.008	96b		31.858	+ 11	4	0.095
98b		1.012	+ 4	4	1.012	97a		31.894	- 1	5	0.000
111e		10.075	+ 14	9	1.237	b		31.917	- 1	4	0.023
114b		10.960	+ 127	6	2.122	d		31.952	- 19	4	0.058
140b		27.899	+ 29	5	1.384	f		31.991	+ 10	7	0.097
156b	1959 Feb.	3.847	- 70	5	3.913	98a	1959 Jan.	1.039	+ 10	6	0.013
c		3.851	- 46	5	3.917	d		1.071	+ 1	5	0.045
164b		15.769	+ 66	8	2.577	f		1.113	+ 11	4	0.087
c		15.778	+ 88	8	2.585	100a		1.942	+ 15	5	0.126
165a		15.797	+ 93	7	2.605	c		1.994	- 12	5	0.046
173c		25.834	- 31	6	3.804	103a		3.947	- 30	6	0.024
175b		26.797	- 70	9	0.344	111a		9.898	+ 14	6	0.049
c		26.802	- 79	6	0.347	b		9.984	- 2	5	0.003
d		26.809	- 85	4	0.353	c		10.040	+ 31	4	0.059
181b		27.826	+ 31	7	1.385	122a		12.944	+ 5	7	0.066
188a	1959 Mar.	10.834	+ 4	8	3.447	b		12.974	+ 29	± 4	0.096
b		10.837	- 10	5	3.550						
c		10.844	- 3	5	3.557						
d		10.851	- 5	3	3.564						
e		10.856	- 28	8	3.569						
198b		13.857	+ 117	4	2.150						
211b		25.856	- 21	4	0.892						
c		25.863	- 14	5	0.899						
d		25.870	+ 7	4	0.906						
e		25.877	- 44	± 14	0.913						

velocity and its probable error are not the weighted means but the values adopted for the reasons given in the subsequent discussion. Table IV gives the individual measures with their dates. It also gives the phase of each observation with respect to the period finally adopted for each star, viz $4^d.41916$ for α Per and $0^d.13169$ for HD 24640.

(i) α Persei HD 23180. This star is a spectroscopic binary whose orbit was calculated by Jordan (1910) and confirmed by Muller, Walraven and Woltjer (1956). The orbit has $e=0.0$ and $P=4^d.41916$. Jordan also observed the spectrum of the secondary but this cannot be seen on the Yapp plates, and its presence has not been confirmed by investigation subsequent to Jordan's discovery. Using the above period and eccentricity the observations were fitted to the best sine-curve by the method of least squares (Fig. 1). The solution gave the following results.

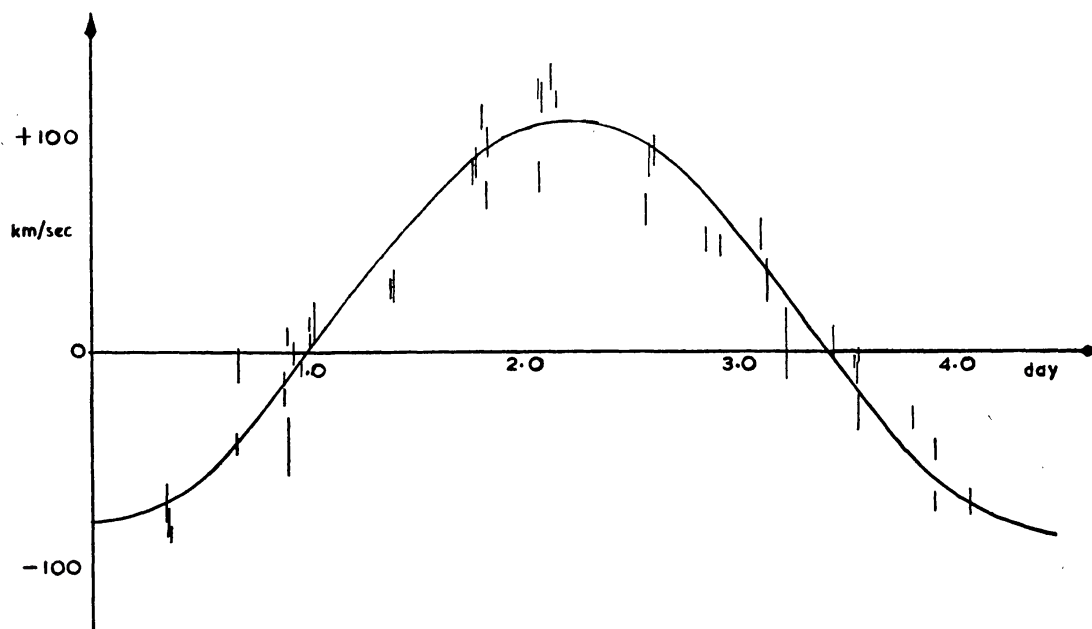


FIG. 1.— α Persei: comparisons of least squares solution with observation. (Length of vertical line twice p.e. of observation.)

$$\begin{array}{lll} v = +14 & +93 \sin \theta & \theta = 81^\circ.4634 \text{ (} t^d - \text{Jan. } 1.114 \pm 0.027 \text{)} \\ \pm 3 \text{ p.e.} & \pm 4 \text{ p.e.} & \text{(p.e. of unit weight } \pm 15 \text{).} \end{array}$$

Jordan found

$$\begin{array}{ll} v = +18.5 & +111.9 \sin \theta \\ \pm 0.7 & \pm 1.0 \end{array}$$

from 70 plates, p.e. of a plate ± 7.0 at 40 A/mm at $H\gamma$. Muller, Walraven and Woltjer derived

$$\begin{array}{ll} v = +14.0 & +112.0 \sin \theta \\ \pm 3.0 & \pm 1.0 \end{array}$$

from 27 plates, p.e. of a plate ± 10 at 25 A/mm at $H\gamma$, and by harmonizing their phase with Jordan derived the improved period

$$4^d.419175 \pm 0.000013 \text{ p.e.}$$

Similarly this discussion gives

$$4^d.4191666 \pm 0.000006 \text{ p.e.}$$

in excellent agreement. More disturbing is the high probable error of unit weight, viz. ± 15 km/sec. This cannot be lowered significantly by introducing eccentricity into the spectroscopic orbit. It is impossible to tell whether this is due to a superimposed variation of, perhaps, the β Cephei type with period $\sim 0^d.25$, because of the distribution of the plates. The star has been suspected of light variation by Walker (1952) and has the same spectral type as stars known to be β Cephei variables. The high probable errors found by other investigators, who only took one plate a night in general, might also be symptomatic of this effect.

(ii) HD 24640. The weighted mean of all the plates is $+8 \pm 2$ p.e. km/sec. However the probable error of unit weight is ± 12 compared to ± 5 for constant velocity stars. A few trials show that there is no simple sine-curve which fits the observations—the motion is periodic in about $0^d.13$ but there appear to be large variations in amplitude. Fortunately 9 spectra (75a to 81d) fall in a compact group around December 2.0 and 10 spectra (96b to 100c) are closely

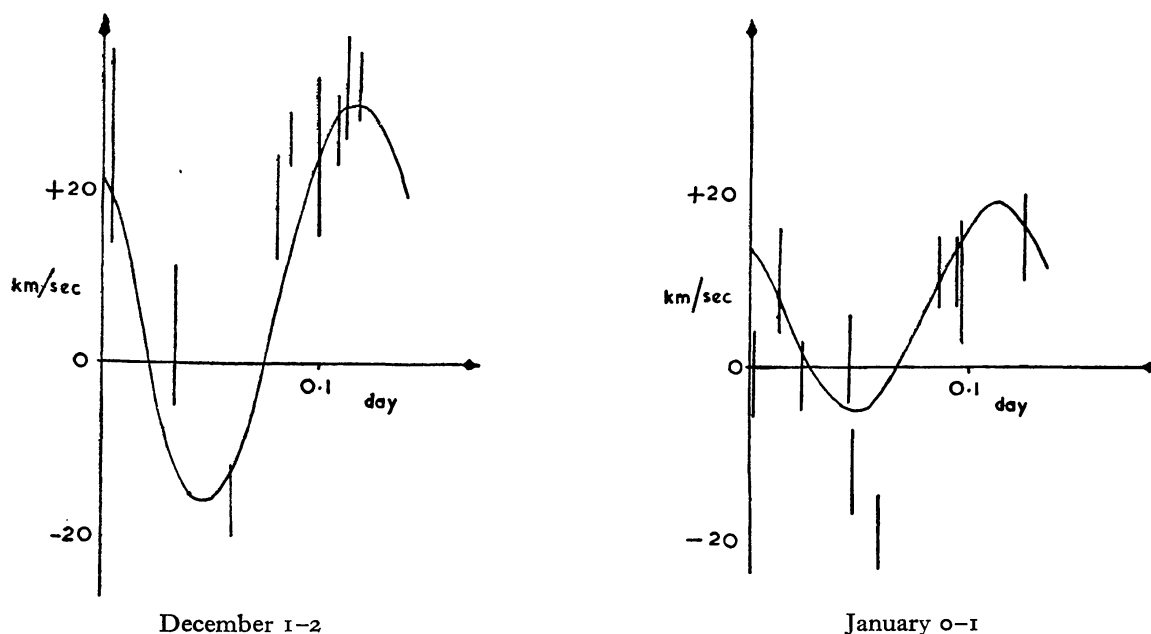


FIG. 2.—Velocity curves of HD 24640 reduced to a single cycle, $0^d.13169$. (Length of vertical line twice p.e. of observation.)

grouped around January 1.0. Each of these groups was reduced to a single cycle using the period $0^d.13169$. A sine curve was then fitted to each group with constant mean velocity throughout but different amplitudes. The solutions were

$$v = 6.7 + 23.0 \sin \theta \quad \theta = 2734^\circ (t - \text{Dec. } 1.028)$$

$$v = 6.7 + 11.7 \sin \theta \quad \theta = 2734^\circ (t - \text{Jan. } 0.844)$$

The agreement of these curves with the observations is shown in Fig. 2. However when all the observations are reduced to a single cycle with period $0^d.13169$ the sinusoidal variation is largely obscured. Several other periods were tried without success. Using $0^d.13169$ a sine curve (Fig. 3) was forced through the observations by least squares with the following result

$$v = 6.3 + 8.3 \sin \theta \quad \theta = 2734^\circ (t - \text{Nov. } 0.065)$$

This reduces the probable error of unit weight from ± 12 to ± 10 . Because the periods are arbitrary no probable errors can be assigned to the parameters in these solutions. However, the different assumptions (including that of constant velocity) agree very closely on the mean velocity. *A priori* the value adopted is more likely than the weighted mean itself and so we can transfer the p.e. of the weighted mean to it. Thus we adopt.

$$\text{Mean velocity} = +7 \pm 2 \text{ p.e. km/sec.}$$

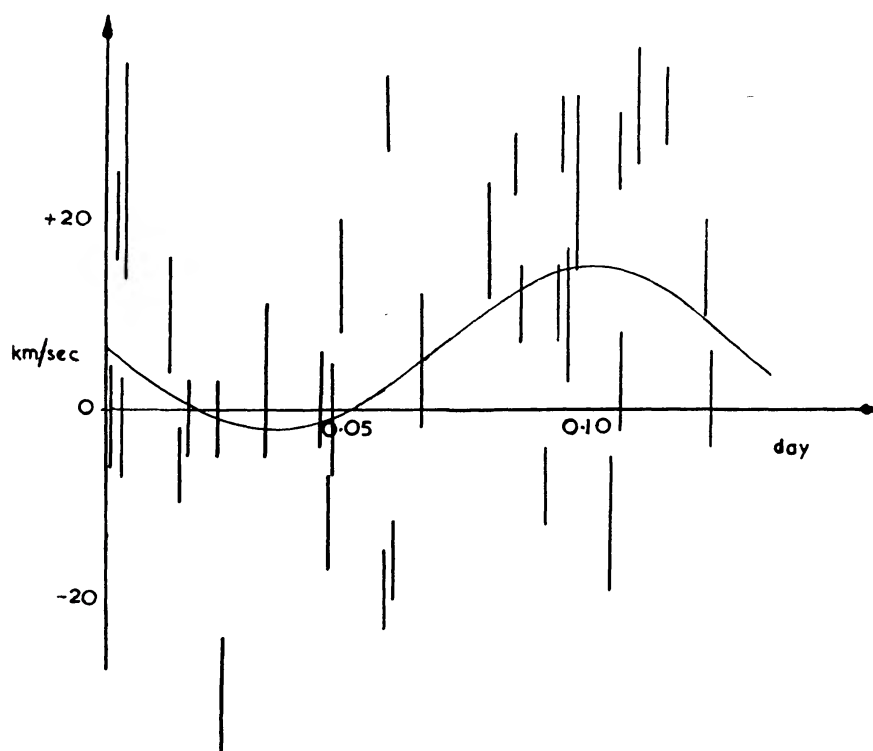


FIG. 3.—HD 24640. All observations reduced to a single cycle, $0^d.13169$, and least squares solution. (Length of vertical line twice p.e. of observation.)

The unsatisfactory nature of these results is clearly caused in part by variations in amplitude. However variations in the mean velocity and period cannot be ruled out. This radial velocity behaviour is typical of that of a β Cephei variable. Moreover its light is slightly variable—it was discarded as a standard by Huffer (1931) when observing the eclipsing variable AG Persei but has never been further investigated. There are two current period-luminosity relationships for β Cephei stars (Blaauw and Savedoff 1953, Petrie 1954). For a period of $0^d.13169$ the former predicts an absolute magnitude of -2.1 and the latter -2.0 . However Petrie's relation refers to the Victoria absolute magnitude system (Petrie 1953 a) which is 0.4 magnitudes faint on that generally adopted. The MK spectral type of this star, B2V, implies an absolute magnitude of -2.6 (Morgan and Keenan 1951). In his discussion of the ζ Persei aggregate, Blaauw (1944) estimated it at -2.3 . It is clear that HD 24640 fits the period-luminosity relationship very well in spite of the fact that its period is shorter than any previously known β -Cephei variable and it is luminosity class V where the others are mostly II-IV. In fact, the luminosity classification of V might be expected from the run of period with

position in the M_v , $U-B$ diagram for the known β -Cephei variables listed by Struve (1955). Struve's results indicate that a star with $P \sim 2-3$ hours would lie on the unevolved main sequence.

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