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THE FREQUENCY OF SPECTROSCOPIC BINARIES IN NGC 6475*

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ABSTRACT

This cluster is known to have unusually low projected rotational velocities among its B stars, in contrast to the Pleiades, a cluster of the same age, which has unusually high rotational velocities. In NGC 6475 eight of the nineteen brightest main-sequence stars are found to be short-period spectroscopic binaries; orbital elements are given for these. This frequency is high relative to that for field stars and especially high relative to that for the Pleiades, among whose B stars no short-period binaries were found. It is concluded that low rotational velocities are probably caused primarily by tidal interactions in binary systems and that open clusters differ significantly in their binary frequencies.

I. INTRODUCTION

It has been amply demonstrated (e.g., Abt and Jewsbury 1969) that young open clusters often differ from each other in their mean rotational velocities at a given spectral type. Two extreme examples are the Pleiades and NGC 6475, two clusters of approximately the same age. In the first cluster (Anderson, Stoeckly, and Kraft 1966) slow rotators are rare among its B stars, while in the latter they predominate. Rough calculations based on mass motions in gaseous nebulae indicate that, unless most of the angular momentum is lost during star formation, a typical star will be formed with rapid rotation, so that it is the slow rotators that require explanation. Some methods whereby angular momentum can be lost are (1) tidal interaction in closely spaced double-star systems, (2) magnetic braking due to differential rotation or interaction with interstellar magnetic fields, (3) ejection of mass, and (4) a redistribution of angular momentum within a star such that the external rotational velocity may not be indicative of the star's total angular momentum. Of these methods, the first is likely to be the most effective because close binaries are frequent in general whereas it is not obvious that normal main-sequence stars have, or have had, significant mass loss, internal or external magnetic fields, or differential rotation.

Specifically, we wish to know whether clusters differ in their frequencies of closely spaced binaries, perhaps in the sense that those with many binaries have relatively low rotational velocities. Part of the material is already available: Abt *et al.* (1965) found no closely spaced (periods <100 days) spectroscopic binaries among the fifteen generally rapidly rotating B stars in the Pleiades, although three such binaries were discovered among the more slowly rotating A0 V stars. In this paper we will discuss NGC 6475, in which most of the B stars are slow rotators, and will show that the binary frequency is relatively very high.

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II. OBSERVATIONAL MATERIAL AND DISCUSSION

Members of NGC 6475 (M7) were observed with the new Cassegrain spectrograph built by Boller & Chivens, Inc., for use on the Cerro Tololo 36-inch telescope. The spectrograph is a modified version of the Meinel spectrograph in operation on the Kitt Peak 36-inch telescope since 1960. The ultraviolet-transmitting optics for both spectrographs were made by Donald M. Loomis and have a resolution of 10–11 μ as photographed on Eastman Kodak IIa-O emulsions. Both spectrographs are fast in yielding spectra 0.3 mm wide and 62 Å mm^{-1} in dispersion on IIa-O emulsions of $B = 7.0$ mag stars in 4 min. These cluster stars were the first stars observed with this spectrograph.

Each of the nineteen brightest main-sequence stars in NGC 6475 were observed at 62 Å mm^{-1} almost nightly on eleven successive nights (J.D. 2439698–708) in 1967. Those stars that seemed variable in velocity were reobserved on one night (J.D. 2439994) with the Kitt Peak 84-inch Cassegrain spectrograph at 39 Å mm^{-1}, on three nights (J.D. 2440051–53) in 1968 with the Cerro Tololo 36-inch spectrograph at 62 Å mm^{-1}, and on five nights (J.D. 2440055–59) with the Cerro Tololo 60-inch Cassegrain spectrograph at 39 Å mm^{-1}. The spectra were measured with a Grant comparator; the lines employed were four Balmer lines, Ca II K, He I λ4471, and Mg II λ4481. The heliocentric Julian Dates, measured velocities corrected for instrumental errors, and probable errors per spectrum are listed in Table 1.

The velocity corrections for the three spectrographs used were determined in the following way. A dozen BA field stars with velocities quoted (Moore 1932) as having probable errors smaller than 1.0 km sec^{-1} were observed with the 60-inch spectrograph and yielded a spectrograph correction that was not significantly different from zero within an estimated accuracy of 2 km sec^{-1}. With the same spectrograph the mean cluster velocity is -14 km sec^{-1} as determined from ten constant-velocity stars. This velocity is in fair agreement with the value of -8 km sec^{-1} by Buscombe and Kennedy (1968) and -11 km sec^{-1} by Feinstein (1961). The mean cluster velocities from the same ten stars as observed with the 36-inch and 84-inch telescopes suggest instrumental corrections of $+7.2$ and $+10.1$ km sec^{-1}, respectively; these corrections have been included in the velocities listed in Table 1.

For eight of the cluster stars it was possible to obtain orbital elements, although in some cases the scatter was too large for the least-squares fitting of the orbital elements as programmed by John S. Varga for the Kitt Peak CDC-6400 computer to be successful. Probable errors are listed in Table 2 when the least-squares solutions converged. The velocity curves are shown in Figure 1.

Several stars require special comment. HD 162724 is a known eclipsing binary (Koelbloed 1959) with fragmentary unpublished photometry by K.-C. Leung; it is a double-lined binary in which only the K-line or λ4481 can be resolved, and the velocities quoted were generally obtained from a single spectral line. The provisional period given here seems to satisfy both the photometric and the spectroscopic data, but its uniqueness has not yet been established. The estimated rotational velocities of $V \sin i = 60$ and 50 km sec^{-1} for the primary and secondary, respectively, are very close to the computed value of 52 km sec^{-1} for synchronous rotational and orbital motions. HD 162656 and HDE 320861 seem to have gamma velocities that vary slowly with time, probably due to third companions. The gamma velocities were greater by 7.0 and 6.1 km sec^{-1}, respectively, in 1968 than in 1967; the 1967 values are listed in Tables 2 and 3.

The results for the cluster stars are listed in order of decreasing visual brightness in Table 3, where successive columns give the identification number by Koelbloed (1959), the Henry Draper number, the spectral type and rotational velocity by Abt and Jewsbury (1969), the mean radial velocity, the scatter in the measured velocities expressed as a probable error per spectrum, the number of spectra measured, and comments about the velocity variation, where SB1 and SB2 refer to single- and double-lined spectroscopic binaries, respectively.

TABLE 1

RADIAL VELOCITIES

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
	HD 162374	
39698.564	- 14.3	±2.6
698.568	- 14.7	1.1
699.590	- 21.7	3.8
700.597	- 18.8	1.5
701.502	- 3.2	3.0
702.622	+ 8.4	3.6
703.646	- 4.4	3.9
705.515	- 9.3	3.2
707.515	- 9.0	1.8
708.496	- 8.9	3.7
994.812	- 14.9	0.9
40051.552	- 10.6	2.2
052.465	+ 5.4	3.7
053.478	- 8.8	3.0
055.576	- 15.9	3.7
056.485	- 9.9	3.2
057.490	- 11.4	1.8
057.562	- 26.3	3.8
058.471	- 9.6	0.7
059.727	- 9.8	1.6
	HD 162817	
39698.859	- 6.8	5.7
699.747	- 13.7	2.0
700.761	- 15.3	1.8
701.691	- 11.4	1.8
702.628	- 18.7	3.4
703.656	- 18.2	3.9
705.532	- 7.6	3.5
707.520	- 1.3	2.0
708.502	- 11.2	2.0
994.895	- 7.5	1.3
40055.621	- 13.3	2.0
056.579	- 17.6	1.5
	HD 162586	
39698.585	- 13.4	1.2
699.598	- 24.5	2.7
700.608	- 24.2	1.6
701.561	- 12.8	4.3
702.632	- 18.9	3.5
703.659	- 21.6	2.9
705.522	- 14.7	2.0
707.524	- 13.3	1.4
708.505	- 10.0	3.1
994.826	- 8.7	0.8
40055.584	- 17.2	0.9
056.497	- 14.6	1.8
	HD 162678	
39698.597	- 4.8	1.6
699.607	- 16.8	2.6
700.620	- 9.8	4.1
701.565	- 10.0	2.3
702.637	- 7.0	2.3
703.666	- 5.1	3.0
703.692	- 9.6	2.0
705.525	- 5.4	1.8
707.531	- 10.0	1.5
708.514	- 13.5	1.1
994.835	- 11.6	0.6
40055.666	- 19.1	0.8
056.513	- 7.9	2.8
	HD 162725	
39698.603	- 12.7	±2.1
699.613	- 19.0	2.2
699.616	- 22.4	3.0
700.629	- 20.3	1.3
701.575	- 11.1	1.7
702.640	- 8.8	1.3
703.670	- 10.9	4.2
703.695	- 15.5	1.2
705.535	- 7.1	0.9
707.535	+ 1.8	1.4
708.518	- 12.7	1.4
994.846	- 8.7	1.5
40051.565	- 15.9	1.5
052.474	- 10.6	2.6
053.489	- 10.4	3.7
055.593	- 19.5	1.7
055.626	- 9.8	2.8
056.522	- 9.5	0.4
057.501	- 6.5	1.2
059.735	- 9.2	1.4
	HD 162515	
39698.823	- 12.1	4.7
699.724	- 50.6	1.7
700.743	- 68.0	4.2
701.676	- 22.5	2.7
702.644	+ 8.3	1.7
703.673	+ 48.6	4.6
705.538	- 10.0	1.8
707.538	- 65.5	2.0
708.522	- 17.1	2.5
994.901	- 65.3	3.6
40051.602	+ 47.4	2.9
052.481	- 10.1	4.1
055.605	- 32.9	2.5
056.505	+ 16.1	2.5
057.569	+ 51.5	3.3
058.511	+ 31.2	1.6
059.791	- 18.4	1.9
	HD 162780	
39698.621	- 20.7	2.7
699.621	+ 4.2	4.4
700.640	- 12.6	0.5
701.578	- 6.5	2.6
702.652	- 18.5	2.6
705.547	- 9.8	1.9
707.547	- 15.8	0.8
708.530	- 17.4	3.7
994.860	- 22.4	2.0
40051.542	- 14.1	3.2
052.487	- 13.6	5.0
055.635	- 31.9	5.2
056.583	- 8.2	3.4
057.506	- 7.8	2.7
058.481	- 11.6	0.8
059.739	- 6.6	1.3
	HD 162888	
39698.852	- 20.8	5.5
699.750	- 18.7	4.7
700.765	- 22.6	2.0
702.648	- 6.3	5.6
39703.679	- 14.7	±3.2
705.542	+ 1.5	4.4
707.543	- 18.9	3.3
708.526	- 12.2	2.1
994.908	- 20.4	4.4
40055.614	- 12.4	0.8
056.568	- 15.1	2.5
	HD 162576	
39698.626	- 9.3	2.5
699.628	- 10.3	1.7
700.645	- 14.9	2.4
701.587	- 5.5	2.3
702.661	- 12.8	3.5
705.556	- 9.8	3.4
707.556	- 20.3	2.3
708.538	- 27.1	2.3
994.871	- 12.0	0.7
40055.657	- 15.8	0.7
	HD 162804	
39698.843	- 8.0	2.9
699.742	- 10.5	0.9
700.756	- 18.2	1.2
701.686	- 6.1	1.5
702.685	- 17.8	3.5
705.566	- 15.8	2.6
707.568	- 18.3	2.9
708.548	- 20.1	1.8
994.919	- 13.4	1.0
40055.685	- 13.9	1.8
056.537	- 21.6	2.0
	HD 162679	
39698.631	- 9.5	1.1
699.632	- 15.2	2.0
700.655	- 0.9	2.4
701.592	- 9.2	1.2
702.669	- 10.9	1.5
705.560	- 19.6	2.2
707.561	- 10.7	1.3
708.543	- 16.9	1.5
994.883	- 13.8	0.8
40055.672	- 12.0	1.3
056.517	- 17.0	1.3
	HD 162588	
39698.833	- 4.8	4.6
699.733	- 30.1	0.9
700.747	- 22.2	3.8
701.680	- 15.1	3.2
702.691	- 5.8	2.1
705.572	- 12.2	3.5
707.575	- 20.9	1.6
708.554	- 3.1	1.9
994.934	- 29.9	4.2
40051.609	- 11.5	5.3
052.496	- 19.3	3.6
055.694	- 15.9	2.7
056.558	- 25.6	4.6
057.574	- 11.3	3.4
059.795	+ 0.7	4.5

TABLE 1 (concluded)

RADIAL VELOCITIES

HD 162631

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
39698.650	- 20.4	±3.7
699.638	- 7.0	±4.9
700.660	- 12.2	1.4
701.597	- 8.0	2.4
702.679	- 14.3	2.5
705.578	- 21.7	3.0
707.582	- 9.0	3.5
708.559	- 25.4	1.9
994.947	- 14.3	3.8
40055.702	- 6.4	1.8
056.552	- 12.1	2.7

HD 162781

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
39699.645	- 11.2	2.4
700.667	- 13.2	2.6
701.604	- 23.0	1.7
702.707	- 33.8	3.0
705.589	- 17.8	4.1
707.590	- 27.0	3.7
708.570	- 20.5	1.5
40051.572	- 2.9	2.4
052.580	- 17.7	3.3
055.713	- 13.1	2.3
056.528	- 16.4	2.8
057.515	- 13.0	1.9
058.490	- 11.6	1.1
059.748	- 8.3	0.5

HD 162630

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
39698.669	- 10.9	2.0
699.651	+ 7.5	2.2
700.674	- 9.8	2.5
701.611	- 13.7	3.7
702.716	- 13.1	2.7
705.646	- 10.7	2.9
707.596	- 9.8	4.5
708.577	- 1.4	3.9
994.978	- 12.0	2.5
40051.579	- 10.3	3.8
052.588	- 19.3	3.1
055.731	- 19.0	0.7
056.631	- 13.0	2.0
057.522	- 14.0	1.1
058.498	- 18.9	0.6
059.755	- 15.8	1.9

HD 162680

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
39698.675	- 13.2	3.6
699.667	- 30.2	3.4
700.683	- 14.4	3.6
701.618	- 2.4	2.6
702.729	- 22.4	4.8
705.653	- 29.3	3.6
707.604	- 15.1	1.4
708.586	- 17.8	2.7
40055.745	- 7.4	1.3

HD 162656

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
39698.693	+ 16.4	±2.2
699.677	- 19.2	±2.8
700.698	- 41.5	2.4
701.627	- 43.3	0.9
702.740	+ 3.3	2.3
707.615	- 13.8	7.7
708.599	+ 6.6	2.7
40051.591	+ 14.7	4.7
052.597	+ 13.4	1.1
055.762	- 45.3	1.4
056.622	- 6.3	1.1
057.533	+ 9.0	1.8
058.506	+ 9.2	1.1
059.765	- 13.8	1.8

HD 320861

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
39698.711	- 3.4	3.4
699.695	- 16.5	1.5
700.712	- 19.1	3.4
701.638	- 31.4	6.2
702.753	- 6.3	2.6
707.627	- 20.7	2.1
708.611	- 17.8	4.4
40051.620	- 6.2	1.0
052.608	- 18.7	2.2
055.791	- 7.9	1.7
056.592	- 7.6	0.8
057.546	- 15.9	0.7
058.528	- 18.3	1.5
059.778	+ 0.1	1.1

HD 320859

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40056.645	- 10.4	0.9

CD-34°12211

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40056.662	- 13.7	1.4

HD 320863

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40056.685	- 16.7	1.8

Koelbloed No. 79

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40056.703	- 5.2	2.4

CD-34°12210

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40056.720	- 4.2	4.2

CD-34°12195

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40056.741	0.0	2.2

CD-34°12196

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40057.659	- 14.1	1.6

Koelbloed No. 78

Helio.JD 2400000+	Rad. Vel. (km/sec)	p.e. (km/sec)
40057.694	- 19.9	3.5

HD 162724

Helio.JD 2400000+	Rad. Vel. (km/sec) Primary	Rad. Vel. (km/sec) Secondary
39701.557	- 10	-115
705.518	+ 1	....
994.818	-127	+131
40051.556	+ 88	-211
052.470	- 19	....
053.484	-171	+ 56
055.582	-130	+105
056.492	- 13	....
057.495	+ 47	-118
059.731	+ 71	-139

TABLE 2

BINARY ORBITAL ELEMENTS

Element	HD 162724	HD 162515	HD 162780	HD 162679	HD 162588	HD 162630	HD 162656	HD 320861
P (days)	2.7754	6.6783±0.0013	6.6226±0.0004	3.051	6.1411±0.0003	9.499	5.4505±0.0003	6.052
T (periastron) (J.D. 2439000+)	698.22±0.25	...	698.675±0.171	...	693.561±0.138	690.215	696.08±0.23	696.593
T (max. ρ) (J.D. 2439000+)	...	697.104±0.047	...	697.761	...	...	...	...
γ (km sec^{-1})	−32±9	−8.7±1.4	−16.0±1.1	−8.8	−12.0±1.1	−9.3var	−12.6±1.2	−12.4var
K_1 (km sec^{-1})	121±14	57.6±2.1	13.2±2.2	8.5	15.6±1.9	10.3	32.1±2.0	13.3
K_2 (km sec^{-1})	153±23	...	...	...	...	...	...	...
e	0.18±0.12	0.02±0.04	0.54±0.09	0.00	0.55±0.08	0.64	0.23±0.05	0.37
ω	221°±34°	245°±104°	261°±19°	...	130°±14°	11°	215°±17°	274°
$a_1 \sin i$ (10^6 km)	4.54	5.29	1.01	0.36	1.10	1.03	2.34	1.03
$\mathfrak{M}_1 \sin^3 i$ ($\mathfrak{M}_\odot$)	3.15	...	...	...	...	...	...	...
$\mathfrak{M}_2 \sin^3 i$ ($\mathfrak{M}_\odot$)	2.49	...	...	...	...	...	...	...
$f(\mathfrak{M})$ ($\mathfrak{M}_\odot$)	0.49	0.132	0.00094	0.00020	0.0014	0.00049	0.0173	0.0012
$\langle O-C \rangle$ (km sec^{-1})	19.3	6.5	4.3	2.1	4.0	2.9	4.7	4.0

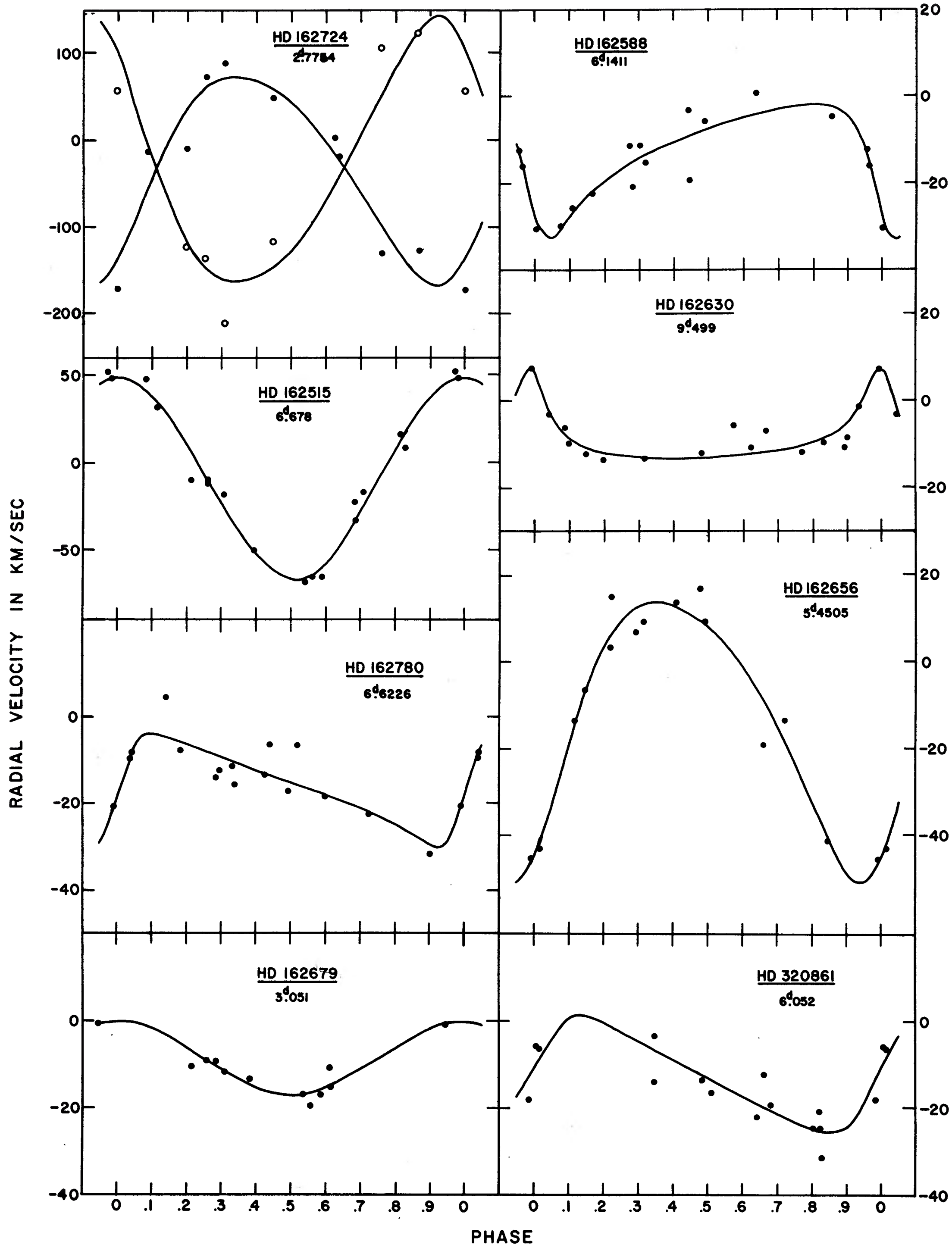

FIG. 1.—Computed radial-velocity curves and measured values for the eight binaries in NGC 6475. The phases are computed from periastron except for HD 162515 and 162679, for which they are computed from maximum velocity.

It was found before that most of the B6–A0 stars in this cluster are narrow-lined but that the A1–A3 stars are broad-lined. From Table 3 we see that seven of the seventeen B6–A0 stars are closely spaced spectroscopic binaries with orbital elements derived; this frequency of 41 percent is unusually high compared with the frequency of zero for the fifteen B6–B9.5 Pleiades stars or 20 percent for B6–B9 main-sequence field stars as determined by Jaschek and Jaschek (1957). We conclude from these three frequencies that tidal interaction seems to be effective in modifying rotational velocities, and that samples of early-type stars having a high frequency of closely spaced binaries have a low mean rotational velocity while samples having a low binary frequency have a high mean rotational velocity.

This result usually cannot be applied to individual stars because we do not know whether the small value of $V \sin i$ for a given star is due to a small rotational velocity or to a small inclination between the axis of rotation and the line of sight.

TABLE 3

SPECTROGRAPHIC RESULTS IN NGC 6475

Koelbloed No.	HD	Spectral type	$V \sin i$ (km sec^{-1})	$\langle \rho \rangle$ (km sec^{-1})	p.e. per spectrum (km sec^{-1})	n	Comments
26........	162374	B6 V	≤40	−10.4	± 5.3	20	Probable var. vel.
86........	724	B9 V+B9 V	60+50	−32.	±57.0	10	SB2, P=2ᵈ7754
110........	817	B9.5 V	65	−11.9	± 3.4	12	
56........	586	B8 V	≤40	−16.2	± 3.4	12	
....	678	B9 V	≤40	−10.0	± 2.8	12	
88........	725	Ap (Si)	≤40	−11.9	± 3.6	20	
42........	515	B9.5V	95	− 8.7	±26.0	17	SB1, P=6ᵈ678
104........	780	B9 V	295	−16.0	± 5.3	16	SB1, P=6ᵈ6226
121........	888	B9 V	225	−14.6	± 4.6	11	
55........	576	Ap (Si)	≤40	−13.8	± 4.0	10	
108........	804	B9 V	≤40	−14.9	± 3.2	11	
77........	679	B9 V	≤40	− 8.8	± 3.3	11	SB1, P=3ᵈ051
59........	588	A0p	≤40	−12.0	± 6.1	16	SB1, P=6ᵈ1411
71........	631	B9.5 V	185	−13.7	± 4.1	11	
103........	781	B9.5 V	205	−16.4	± 5.1	14	
63........	630	B9 V	≤40	− 9.3v	± 4.4	16	SB1, P=9ᵈ499
82........	680	A1 V	60	−16.9	± 5.9	9	
72........	162656	B9.5 V	≤40	−12.6	±14.5	14	SB1, P=5ᵈ4505
92........	320861	A1 V	150	−12.4v	± 5.5	14	SB1, P=6ᵈ052

It might initially be thought that more binaries were discovered in NGC 6475 than in the Pleiades because the narrower lines exhibited by the stars of NGC 6475 allow the detection of more binaries of small amplitude. In fact, the mean internal probable error was 4.6 km sec^{-1} for the Pleiades B stars and only 2.4 km sec^{-1} for the NGC 6475 stars. However, consider the evidence that (1) three of the binaries in NGC 6475 have much larger variations in velocity (14.5, 26.0, and 57.0 km sec^{-1} mean probable errors per spectrum) than any encountered among the Pleiades B stars, and (2) in the Pleiades we discovered three long-period binaries with amplitudes, K, of only 8.0, 14.5, and 26.0 km sec^{-1}; these amplitudes are as small as the smallest amplitudes measured in NGC 6475. We conclude that if there had been as many short-period binaries among the Pleiades B stars as among the NGC 6475 stars, the similar measuring techniques (primarily spectra of 62–63 Å mm^{-1}) used for the two clusters would have revealed them.

We therefore attribute differences in mean rotational velocities for various clusters primarily to differences in their binary frequencies. This still leaves unexplained why some clusters should have been formed with more binaries than others. A secondary factor in producing low rotational velocities may be the magnetic-braking mechanism that probably occurs in Ap stars: it seems likely that the narrow lines in Ap spectra are due neither to tidal effects in binary systems nor to a selective aspect effect. This suggests that a cluster like NGC 2516 that is very rich in Ap stars (Abt and Morgan 1969) does not necessarily have many binaries.

Two final comments concern the mean velocities of the cluster stars. First, we note that the mean velocities decrease with increasing projected rotational velocity, as was found from published material for other clusters by Hughes (1969). This could be due to (1) systematic inaccuracies in measuring broad-lined spectra or (2) asymmetrical rotational broadening of lines or (3) some mechanism causes the gamma velocities to be affected in the same way that the Barr effect causes the longitudes of periastron to be incorrect in closely spaced early-type binaries. Nevertheless, the velocity dispersion for the stars listed in Table 3 is rather small: except for Koelbloed No. 86, for which the velocities are poorly determined, and the two binaries with variable gamma velocities, the velocity dispersion is only 2.6 km sec^{-1}. This is still far above the $\frac{1}{2}$ km sec^{-1} expected from the virial theorem (Schwarzschild and Bernstein 1955); the present velocities are probably not accurate enough to determine the intrinsic velocity dispersion of the cluster stars.

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