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THE BINARY FREQUENCY OF IC 4665*

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ABSTRACT

New radial velocity observations of 13 stars in IC 4665 indicate that the spectroscopic binary frequency in this cluster is ~50 percent. It is suggested that the high frequency (95%) previously found by Abt, Bolton, and Levy is a spurious one. The methods of detecting variable velocities and comparing binary frequencies are discussed and applied to IC 4665 and other clusters. On this basis, we conclude that the correlation between mean rotational velocity and binary frequency in clusters is marginal.

Subject headings: clusters: open — stars: binaries — stars: rotation

I. INTRODUCTION

The hypothesis that the cause of the low mean rotational velocities measured in some open clusters is a high frequency of binaries in which tidal effects have been operating to slow the rotation has been developed by Abt and his co-workers in a series of papers (Abt and Hunter 1962; Abt *et al.* 1965; Abt *et al.* 1970; Abt *et al.* 1972; Abt and Levy 1972; Abt and Sanders 1973). For five clusters of similar age, their results indicate the binary frequency to be relatively low in clusters containing stars of high rotational velocity (α Per, Pleiades), while the converse is true for NGC 2516, NGC 6475, and IC 4665. The binary frequency and rotational velocity of M39, a slightly older cluster, are intermediate between those of the other clusters.

In the case of IC 4665, Abt *et al.* (1972) (hereafter referred to as ABL) found that 18 of the 19 stars surveyed were binaries. In order to substantiate this surprising result and to improve the orbits for the binaries, we decided to reobserve the brightest stars with slightly higher dispersion.

II. OBSERVATIONS

Spectra of the 13 brightest stars (excluding HD 161261, a shell star, and Kopff 23B which ABL found to have constant velocity) were obtained in the 1972, 1973, and 1974 seasons with the Cassegrain spectrograph of the 1.83 m telescope in Victoria. The dispersion of the spectra (taken with the "2161" arrangement) is 30 Å mm^{-1}, and the image slicer used produces a spectrum width of ~0.8 mm. Kodak IIa-O emulsion, hypersensitized by baking, was used throughout.

The stability and performance of the spectrograph particularly with regard to radial velocity measures is continually checked, mainly by the observation of standard velocity stars (Pearce 1955). No significant errors have been detected.

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Some earlier observations and measures of members of IC 4665 by R. M. Petrie as well as our measures are listed in Table 1. The heliocentric Julian date, the radial velocity, and the standard error of the mean are given for our observations. The number of lines measured on each spectrogram ranged from eight to 20 depending on the quality of the plate and the sharpness of the lines. No standard errors are quoted for Petrie's material, but the spectrograph employed is noted (IS–51 Å mm^{-1}, IM–30 Å mm^{-1}). Four observations of HD 161573 at a dispersion of 15 Å mm^{-1} by A. H. Batten are also included in the table.

Table 2 summarizes our observations with the 2161 spectrograph. To maintain homogeneity, all other observations were omitted. Most of the columns in Table 2 will be self-explanatory, but it is worthwhile emphasizing that the errors quoted are standard errors, as opposed to the use of probable errors by ABL. The "external" standard deviation, E, is estimated from the agreement of the average plate velocities; and the "internal" standard deviation, I, is estimated from the agreement of the velocities of the lines.

The errors given in Table 2 may be compared with those which Petrie (1962) gave as typical in the measurement of B stars at 30 Å mm^{-1}, 3.6 and 5.6 km s^{-1} for I and E, respectively (converted from probable errors). Our mean value of I, 3.1 km s^{-1}, is slightly better than average, partly because of modern measuring techniques and superior (wider, longer spectral range) spectra. The external errors are usually ~1.5 times the internal error because of the effects of guiding, flexure, etc. We will discuss this further in § V; but, for the moment, we adopt the commonly used (e.g., Abt *et al.* 1972) test for variability that if $E/I > 2$, velocity variation is indicated. On this basis, only 5 of the 13 stars in Table 2 would be judged to be variable whereas ABL found that all of them were variable. Furthermore, our data do not fit the periods and velocity amplitudes derived for these stars (except for HD 161480) by ABL. We will investigate the reason for this discrepancy before discussing the binary frequency in more detail.

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TABLE 1

RADIAL VELOCITIES

Helio. JD 2,400,000+	Radial Velocity (km s^{-1})	Internal Mean Error (km s^{-1})
HD 161165		
41,499.863.....	−15	3.8
41,503.819.....	−19	3.9
41,526.751.....	−6	5.8
41,527.746.....	−33	3.6
41,532.780.....	−18	4.1
41,533.754.....	−14	3.3
41,536.731.....	+1	4.3
41,564.684.....	−10	2.8
41,575.670.....	−12	6.0
HD 161184		
41,499.892.....	−24	1.9
41,503.872.....	−11	4.3
41,526.790.....	−11	2.1
41,527.789.....	−7	5.3
41,533.792.....	−5	2.1
41,536.768.....	−17	5.4
41,564.716.....	−16	2.3
41,575.706.....	−7	1.0
41,926.767.....	−12	3.7
42,244.733.....	−18	3.1
42,266.717.....	−16	3.3
42,272.738.....	−16	3.0
HD 161426		
33,859.790.....	−16	IS
33,866.762.....	−31	IS
33,901.694.....	−12	IS
41,476.863.....	−13	4.1
41,893.778.....	−10	3.3
41,897.754.....	−15	4.8
42,244.840.....	−26	3.9
42,256.868.....	−27	3.7
42,266.753.....	−12	1.8
42,272.793.....	−22	4.8
HD 161480		
41,472.913.....	−6	3.2
41,476.912.....	−50	1.5
41,498.870.....	−37	2.0
41,499.935.....	−10	1.4
41,503.948.....	+15	2.4
41,526.832.....	−27	2.0
41,527.829.....	−61	1.9
41,533.836.....	+40	1.7
41,536.809.....	−15	1.1
41,879.886.....	+11	1.3
41,884.769.....	−32	2.1
41,893.754.....	+1	2.2
41,897.731.....	−67	1.8
41,898.748.....	−40	1.4
41,926.721.....	−28	1.4
HD 161481		
33,829.749.....	+1	IS
33,859.742.....	−22	IS
33,866.810.....	−23	IS
33,890.701.....	−60	IS weak

Helio. JD 2,400,000+	Radial Velocity (km s^{-1})	Internal Mean Error (km s^{-1})
HD 161542		
32,753.740.....	−30	IS
32,756.733.....	−30	IS
32,761.733.....	−31	IS
32,762.719.....	−27	IS
32,763.724.....	−26	IS
32,777.765.....	−24	IS
33,036.971.....	−25	IS
33,047.903.....	−25	IS
33,057.878.....	−21	IS
33,380.001.....	−38	IS
HD 161572		
41,472.893.....	−25	3.8
41,476.937.....	−19	4.0
41,498.828.....	−24	3.9
41,499.796.....	−26	3.6
41,503.788.....	−19	1.6
41,526.849.....	−18	3.6
41,527.843.....	−16	3.0
41,533.848.....	−21	6.5
41,536.820.....	−26	2.5
41,564.750.....	−23	2.7
41,893.798.....	−20	3.0
41,897.782.....	−20	3.9
41,907.775.....	−24	1.6
41,910.786.....	−16	3.0
41,926.709.....	−17	1.2
HD 161573		
32,753.709.....	−23	IS
32,756.716.....	−10	IS
32,757.765.....	−24	IS
32,761.746.....	−20	IS
32,762.705.....	−12	IS
32,763.704.....	−11	IS
32,764.759.....	−14	IS
32,766.817.....	−20	IM
32,777.746.....	−31	IS
33,036.949.....	−7	IS
33,047.886.....	−10	IS
33,379.988.....	−4	IS
33,470.808.....	−11	IM
33,829.778.....	−17	IS
41,066.939.....	−8	15*
41,066.957.....	−9	15*
41,067.936.....	−3	15*
41,067.953.....	−1	15*
41,472.852.....	−20	2.1
41,476.816.....	−19	2.1
41,488.776.....	−10	1.9
41,498.798.....	−11	1.9
41,499.803.....	−11	1.7
41,503.780.....	−9	1.0
41,504.802.....	−12	1.3
41,526.727.....	−12	2.0
41,527.716.....	−10	2.0
41,533.713.....	−14	2.7
41,536.705.....	−10	1.9
41,537.833.....	−18	1.8
41,541.845.....	−8	1.9
41,879.875.....	−6	2.1
41,884.738.....	−8	2.1
41,893.728.....	−23	2.2

Helio. JD 24,000,00+	Radial Velocity (km s^{-1})	Internal Mean Error (km s^{-1})
HD 161573		
41,897.714.....	−12	2.2
41,898.719.....	−14	1.5
HD 161603†		
32,750.842.....	+1:	IS
32,753.731.....	−19	IS
41,472.865.....	−50	7
	+50	6
41,488.812.....	+69	9
	−110:	
41,498.816.....	−14	2.5
41,499.787.....	+50	6
	−86:	
41,503.798.....	−18	3.4
41,526.878.....	+35	11
	−151	18
41,527.727.....	−16	2.9
41,533.869.....	−19	3.8
41,536.710.....	+30	9
	−109	14
41,541.832.....	−6:	4.1
41,879.901.....	−8	1.7
41,884.752.....	−94:	
	+66:	
41,893.741.....	−19	1.8
41,897.721.....	−20	1.8
41,898.731.....	−14	2.2
41,907.754.....	−24	2.8
41,910.753.....	−26	3.4
HD 161621		
33,047.935.....	−16	IS
HD 161622		
32,753.785.....	−12	IS
32,756.830.....	+4	IS
32,763.736.....	−15	IS
HD 161660		
41,498.954.....	0	2.4
41,499.912.....	+2	2.5
41,503.924.....	−30	1.3
41,526.816.....	−39	1.7
41,527.816.....	−36	1.9
41,533.822.....	+1	2.1
41,536.797.....	−26	3.2
41,564.735.....	+3	1.9
41,879.918.....	−2	1.8
41,884.825.....	−21	1.6
41,893.820.....	−41	1.9
41,897.796.....	+5	1.8
41,898.767.....	+1	2.3
41,926.736.....	−34	1.3

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TABLE 1—*Continued*

Helio. JD 2,400,000+	Radial Velocity (km s^{-1})	Internal Mean Error (km s^{-1})
HD 161677		
32,750.831.....	−1	IS
32,753.720.....	−36	IS
41,472.878.....	−15	2.8
41,476.955.....	−14	3.8
41,488.795.....	−5	4.8
41,498.842.....	−11	3.3
41,499.968.....	−19	4.2
41,526.734.....	−8	5.1
41,527.875.....	−16	6.5
41,533.722.....	−13	2.9
41,536.848.....	−8	7.8
41,564.764.....	−10	4.3
41,572.737.....	−19	4.6
41,893.806.....	−17	3.4
41,897.807.....	−9	3.8
41,907.738.....	−26	2.4
41,910.768.....	−22	2.2
41,926.666.....	−12	3.7
HD 161698		
41,472.938.....	−12	2.0
41,488.855.....	−12	5.7
41,498.926.....	−7	2.8
41,499.815.....	−16	2.4
41,503.850.....	−8	3.3
41,526.774.....	−16	3.9
41,527.769.....	−14	2.6
41,533.766.....	−17	2.7
41,536.752.....	−15	2.1
41,926.694.....	−12	1.7
HD 161733		
32,753.803.....	−26	IS
41,498.900.....	−14	0.9
41,499.836.....	−12	1.4
41,503.898.....	−10	2.2
41,504.862.....	−7	1.9
41,526.804.....	−10	1.5
41,527.803.....	−11	2.2
41,533.808.....	−14	1.8
41,536.784.....	−7	2.4
41,537.819.....	−20	3.3
41,893.835.....	−13	1.8
41,897.818.....	−14	1.8
41,926.678.....	−16	1.6
HD 161734		
41,897.844.....	−17	3.3
42,244.758.....	−22	2.6
42,256.837.....	−21	5.6
42,266.733.....	−13	3.0
42,272.755.....	−20	6.0
HD 162028		
32,753.754.....	−33	IS
41,472.964.....	−1	9.3
41,498.854.....	−7	2.5
41,499.953.....	−16	4.4
41,504.824.....	−7	2.9
41,526.865.....	−4	3.0
41,527.857.....	−13	3.0
41,533.885.....	−2	2.5
41,536.834.....	−3	6.2
41,537.845.....	−9	5.3
41,541.861.....	−1	6.2
41,879.863.....	−20	1.7
41,884.790.....	−16	2.4
41,893.847.....	−9	2.2
41,897.871.....	−10	3.5
41,926.749.....	−6	1.3

* Measures by A. H. Batten of 15 Å mm^{-1} spectrograms.

† Where double lines were measured, the velocity of the component thought to be the stronger is given first, although there is some doubt about this. The lines were really only obviously double on JD 2,441,399.

III. COMPARISON WITH ABT, BOLTON, AND LEVY

Comparison of the results in Table 2 with those given in Table 1 of ABL shows that the main difference is that their external errors are much larger than ours, even though the spectrograph dispersions are not very different (30 Å mm^{-1}, 40 Å mm^{-1}). The reason for this, of course, is that ABL observed a much larger velocity range for each star than we did. For example, in two extreme cases, ABL observed velocity ranges of 64 and 83 km s^{-1} for HD 161572 and HD 161698 as contrasted to $\sim$10 km s^{-1} that we observed. For three of the stars, the large amplitudes observed rest on only one or two deviant points, and the resulting orbital eccentricities are extraordinarily large. To investigate whether night-to-night systematic errors could have affected ABL's velocities, differences were taken between all the velocities (excluding those of HD 161480 and HD 161660) observed on a given

TABLE 2

Summary of Radial Velocities

Kopff Number	HD	Number of Spectra	Average Velocity and Mean Error (km s^{-1})	External s.d. (km s^{-1})	Internal s.d. (km s^{-1})	Ratio	Velocity Range (km s^{-1})	$V \sin i$ (km s^{-1})
22...........	161165	9	-14.1 ± 3.2	9.5	4.2	2.3	34	240
23A.........	161184	12	-13.3 ± 1.6	5.5	3.1	1.8	19	240
43...........	161426	7	-17.9 ± 2.7	7.1	3.8	1.9	17	185
49...........	161480	15	-20.4 ± 7.6	29.6	1.8	16.4	107	25
58...........	161572	15	-21.0 ± 0.9	3.5	3.2	1.1	9	200
62...........	161573	18	-12.6 ± 1.1	4.6	1.9	2.4	17	50
64...........	161603	16	-18.0 ± 1.7	6.9	2.3	3.0	...	...
72...........	161660	14	-15.6 ± 4.9	18.2	2.0	9.1	46	35
73...........	161677	16	-14.0 ± 1.5	5.7	4.1	1.4	21	210
76A.........	161698	10	-12.9 ± 1.0	3.3	2.9	1.1	10	80
82...........	161733	12	-12.5 ± 1.0	3.6	1.9	1.9	13	40
81...........	161734	5	-18.7 ± 1.7	3.8	4.1	1.1	10	225
105..........	162028	15	-8.3 ± 1.5	5.8	3.8	1.5	19	...

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night and an approximate mean velocity of the cluster, -14 km s^{-1}. Not only do systematic errors of $\sim +14$ km s^{-1} on the nights of JD 2,439,304, 2,439,308, and 2,439,309, and $\sim +30$ km s^{-1} on JD 2,439,337, 2,439,339, 2,439,342, and 2,439,344, appear to be present, but large random errors as well. Dr. Abt (private communication) has recently reanalyzed the observations from these two observing runs and agrees that some of the velocities may be in error, most likely as a result of some problems encountered when the 2.1 m Cassegrain spectrograph was first installed. Unfortunately, no properly exposed spectra of standard stars are available to test its performance during these two runs. We therefore reject these velocities from further discussion. The large amplitudes disappear for most of the stars as a result of this rejection, and the remaining velocities agree very well with those measured by other observers.*

IV. COMPARISON WITH OTHER PUBLISHED VELOCITIES

All velocity determinations of stars thought to be members of IC 4665 are collected in Table 3. New averages, errors, and E/I ratios were computed for the remaining ABL velocities (now, unfortunately, only five or six per star). The velocities denoted by "L" are the unpublished measures of R. J. Trumpler which Abt and Snowden (1964) (hereafter referred to as AS) and ABL included in their analyses. These velocities and the Victoria ("V") observations are based on lower dispersion spectra (50–70 Å mm^{-1}) than the ABL or our ("DAO") velocities. The V velocities are either from Petrie and Pearce (1962) or Table 1. The AS and Albitsky (1947) (hereafter referred to as S) velocities are also based on lower dispersion (70–128 Å mm^{-1}) spectra.

After omission of the binaries (§ VI), the results indicate that there are no significant differences between the velocity systems of the various sources of data. The mean differences, and the errors of the mean, are the following: DAO − ABL = $+0.4 \pm 1.3$ (6 stars) km s^{-1}, DAO − L = 2.0 ± 3.4 (5) km s^{-1}, DAO − V = $+1.8 \pm 7.4$ (3) km s^{-1}, DAO − AS = -5.2 ± 4.8 (6) km s^{-1}, DAO − S = $+4.8 \pm 6.8$ (2) km s^{-1}. The errors indicate that the DAO and ABL velocities are much superior to the others, and so the mean cluster velocity is computed in two ways: (*a*) from only the ABL and DAO velocities, and (*b*) from a weighted mean of all the velocities. By averaging the DAO and ABL velocities, a mean cluster velocity of -15.5 ± 1.2 km s^{-1} with a standard deviation of 2.9 km s^{-1} is derived from the six stars remaining after exclusion of all possible binaries. The mean velocity for each star shown in the last column of Table 3 is a weighted mean derived by assigning weights of 4 per plate for DAO and ABL velocities, 2 per plate for L and V, and 1 per plate for AS and S. Anticipating the results of § VI, we adopted the orbital

* A referee has admitted to feeling "a profound sense of discouragement about the whole field of identifying binaries . . ." as a result of the discovery that several of the stars in IC 4665 were classed as binaries as a result of a malfunctioning spectrograph. We do not believe that the situation is quite so bad and that all published velocities or orbits must be corroborated by observations at another observatory, but rather that this was an (unfortunate) isolated incident. Indeed, the velocities from the 2.1 m spectrograph after JD 2,439,344 are in very good agreement with our velocities. However, the importance of obtaining spectrograms of standard velocity stars to continually check the performance of a spectrograph cannot be overemphasized.

TABLE 3
COMPARISON OF RADIAL VELOCITIES

Kopff Number	HD	DAO			ABL			L		V		AS		S		Mean
		RV	*n*	*E/I*	*RV*	*n*	*E/I*	*RV*	*n*	*RV*	*n*	*RV*	*n*	*RV*	*n*	
22	161165	−14	9	2.3	−13	6	3.3	...	...	...	...	−8	5	...	...	−13.6
23A	161184	−13	12	1.8	−18	5	1.4	...	...	...	...	−21	2	...	...	−15.0
43	161426	−18	7	1.9	−27	5	2.0	−16	4	−19	3	+5	4	...	...	−19.1
49	161480	−20	15	16	−26*	6	8.9	−36	5	+3	3	...	...	...	...	−15.9†
58	161572	−21	15	1.1	−20*	5	1.2	−14	6	−9	3	−10	11	−19	6	−18.2
62	161573	−13	18	2.4	−11	6	1.8	−16	4	−16	14	−12	9	−7	5	−12.8
64	161603	−18	16	2.2	−14	5	0.7	−18	5	−9	2	−20	10	−8	7	−16.5
72	161660	−16	14	9.1	−13	6	4.3	−14	4	...	...	...	...	...	...	−14.0†
73	161677	−14	16	1.4	−13	6	2.8	−14	5	−18	2	−22	9	−26	5	−15.1
76A	161698	−13	10	1.1	−14	6	1.4	−16	4	...	...	−6	14	...	...	−12.3
82	161733	−12	12	1.9	−15	6	1.5	−19	6	−26	1	−6	7	...	...	−13.9
81	161734	−19	5	1.1	−15	4	1.9	−6	6	...	...	+4	4	...	...	−12.7
105	162028	−8	15	1.5	−14	6	...	...	...	−33	1	−7	8	−6	8	−9.8
23B	...	...	...	...	−10	3	...	...	...	...	...	−14	2	...	...	...
32	161261	...	...	...	−13	6	2.2	−7	4	...	...	−4	9	...	...	...
39	161370	...	...	...	−13	1	...	−15	4	...	...	+6	3	...	...	...
50	161481	...	...	...	DSB‡	...	...	−12	4	−23	4	+10	4	...	...	...
67S	161621	...	...	...	−18	1	...	−17	5	−16	1	−23	5	...	...	...
102	161940	...	...	...	−20	2	...	...	...	...	...	+5	3	...	...	...

* According to Abt (private communication), there are two typographical errors in Table 2 of ABL; for HD 161480 read 40110.742 for 40188.742, and for HD 161572 read 39304.968 for 39226.968.

† Orbital gamma velocities from Table 4.

‡ Double-lined spectroscopic binary.

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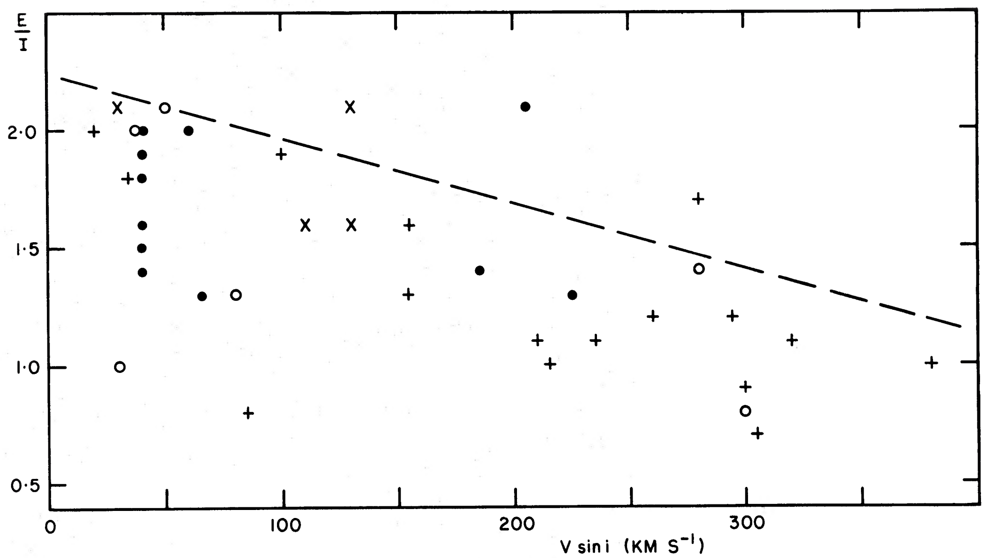

FIG. 1.—The ratio of the external to internal errors plotted versus rotational velocity for "constant velocity" stars. For large $V \sin i$, the internal (measuring) errors become large, and the ratio approaches 1.0. The line represents an approximate upper bound to the ratio for constant velocity stars. For a given $V \sin i$, stars with ratios above the line are assumed to be variable in velocity. The symbols represent stars in different clusters: NGC 6475 (●), NGC 2516 (○), Pleiades (+), M39 (×).

gamma velocities for HD 161480 and HD 161660. The mean cluster velocity from the 13 well-observed stars in Table 3 is then -14.5 ± 0.7 km s^{-1} with a dispersion of 2.5 km s^{-1}. The cluster velocity is therefore ~ -15 km s^{-1}, and the dispersion is ~ 3 km s^{-1}.

The available observations for the six additional stars for which ABL had observations are also collected in Table 3. Since fewer observations exist for these stars, it is difficult to include them in the discussion of the binary frequency which follows.

V. ESTIMATION OF BINARY FREQUENCIES

Spectroscopic binaries are, of course, detected through the appearance of double lines or velocity variations which lead to large values of E or E/I. The ratio E/I might be thought to be a better discriminant of whether or not a star is variable than E alone, but E/I is affected by the line width, too. This is illustrated in Figure 1 where the E/I ratios for supposedly constant velocity stars in several clusters are plotted as a function of $V \sin i$. The reason for the variation in the E/I ratio is that for spectra in which the lines are broad due to rotational broadening or to the spectral type, the internal errors (chiefly measuring errors) can become dominant, and so $E/I \approx 1.0$, while for sharp-lined spectra $E/I \approx 2.0$. Application of a uniform value of $E/I = 2.0$, say, for the detection of variability would hence lead to an approximately correct value for low rotational velocity but an underestimate for high rotational velocity. For these reasons, the value of E alone may be an equally good indication of variable velocity provided the dispersions are similar for all the observations discussed.

The use of E/I ratios for the detection of binaries should be limited either to large values where there is no question, or to groups of stars having similar spectra. Alternatively, some sliding scale of E/I should be used to allow for the effects of line width. In the following discussion of binary frequency, we use E/I limits which are a function of $V \sin i$ to detect variable velocities. The upper boundary (*dotted line*) of the points plotted in Figure 1 is taken to be the maximum value that E/I can attain for a constant velocity star of a given rotational velocity. It could be argued that application of this "E/I test" involves a circular argument, since Figure 1 is based on "constant velocity" (no periodicity detected) stars in the very clusters for which we are determining the binary frequency, but our justification is that at least the method allows a criterion to be applied which is independent of rotational velocity. It should also be noted that both the magnitude of the external errors and the E/I ratio can become spuriously large if the spectrograph is not stable.

The detection of binaries is very difficult, but the comparison of binary frequencies among different groups of stars is even more difficult. Abt and Levy (1972) summarized some of the problems encountered, and concluded that the most reliable comparison could be made by using the minimal value given by that fraction of stars for which orbital elements are available or double lines have been detected. Two difficulties with this approach not mentioned by Abt and Levy are the following: (i) it is much harder to resolve double lines if the lines are intrinsically broad, and (ii) a comparison such as this still must be made on the basis of identical surveys. For example, the observations of stars in α Per by Petrie and Heard (1970) were carried out over several years, and the number of observations per star is not large; consequently, it is virtually impossible to derive orbital elements for the stars which are variable. This criticism does not

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apply to the observations of the Pleiades by Abt *et al.* (1965), but obviously the detection of double-lined and low amplitude binaries and the derivation of orbital elements are more difficult due to the larger errors associated with the measurement of broad lines. One way to avoid this problem is to compare the binary frequencies of groups of stars having similar rotational velocities in each cluster as Batten (1973) has done; but, unfortunately, the sampling errors render the statistics poor.

The ease with which binaries can be detected among groups of stars is a function of the spectral type, too. Not only is it harder to detect binaries at, say AO, than at B2 due to the line widths as previously discussed; but also the velocity amplitude, or the velocity separation of double lines, decreases with decreasing mass down the main sequence, so that only groups of stars of similar spectral type should be compared. Thus one should see, for a given spectrograph, a decrease in the observed velocity dispersion down the main sequence. This is, in fact, observed (Petrie 1960). Because of these uncertainties, we decided to make an analysis only down to ~A0 in each cluster.

Now that the methods of detecting binaries and of comparing binary frequencies have been discussed, we will critically examine the available data on the six clusters previously analyzed by Abt and his coworkers.

VI. BINARY FREQUENCY

a) IC 4665

The probable and possible binaries in this cluster are the following:

HD 161165.—The *E*/*I* ratios and external errors of both our data and the ABL data indicate probable variable velocity. However, when a combination of these data was analyzed with the period-finding program developed by Morbey (1973), no unique period emerged. Orbital elements derived for the best period are given in Table 4. The nonzero eccentricity is obviously not significant. The velocity curve is shown in Figure 2.

HD 161426.—The total velocity range among the *mean* values is 34 km s^{-1} and one well-defined velocity (ABL, $RV = -27 \pm 2$ km s^{-1}) lies more than 6 standard deviations from the cluster mean. We consider this to be a spectroscopic binary.

HD 161480.—This star is the only large amplitude binary yet found in the cluster. The orbital elements (Table 4) are based on DAO and ABL data only, but the elements are not changed significantly if the older, less accurate data are included. The velocity curve is shown in Figure 2.

HD 161573.—Although Petrie (1953) suggested that this star might be a good velocity standard, the modern observations indicate that the velocity is probably variable. The orbital elements for the best period are given in Table 4 and the velocity curve is shown in Figure 2.

HD 161603.—Asymmetric lines, which could be interpreted as line doubling on six of our spectra, and discrepancies between the H and He I velocities indicate that this is a double-lined binary. No period has been determined.

HD 161660.—Orbital elements for this star are given in Table 4, and the velocity curve is shown in Figure 2.

HD 162028.—ABL observed a doubling of the Ca II K line. Although we specifically looked for this on our spectra, it was not observed. We class this star as a "possible" binary.

To this list, two of the six stars which are not so well observed should probably be added:

HD 161481.—ABL note that the metallic lines were discovered to be double on a 16 Å mm^{-1} spectrogram, but, at lower dispersion, the binary nature is not obvious.

HD 161621.—The L and AS velocities indicate variable velocity.

Of the 13 well-observed stars, six, or possibly seven (54 percent), are binaries; of the 19 stars, the numbers are eight (42 percent) or nine. If the survey had been made at a lower dispersion, or if the stars had higher rotational velocities, four of the binaries, HD 161426, HD 161573, HD 161603, HD 161481, and possibly a fifth, HD 161165, would not have been detected, and the known binary frequency would then be only 21 percent.

As expected from the inclusion of erroneous data, the orbital elements derived by ABL are very different (except those for HD 161480) from those listed

TABLE 4

ORBITAL ELEMENTS OF BINARIES

ELEMENT	HD 161165	HD 161480	HD 161573	HD 161660
V_0 (km s^{-1})	−10. ± 2.3	−15.9 ± 2.0	−13.4 ± 0.9	−14.0 ± 1.0
K (km s^{-1})	14. ± 3.4	46.5 ± 2.9	6.7 ± 1.7	20 ± 1.3
e	0.2 ± 0.3	0.06 ± 0.6	0.08 ± 0.2	0.22 ± 0.06
ω (radians)	0.6 ± 1.6	2.9 ± 0.8	2.7 ± 1.8	3.3 ± 0.4
T (JD 2,440,000)	108.2 ± 1.5	1528.3 ± 1.4	1058.2 ± 5.5	1904.9 ± 0.5
P (days)	5.882 ± 0.002	10.526 ± 0.001	18.92 ± 0.01	10.793 ± 0.002
σ (km s^{-1})	7.7	7.5	3.7	4.2
N	15	21	28	20

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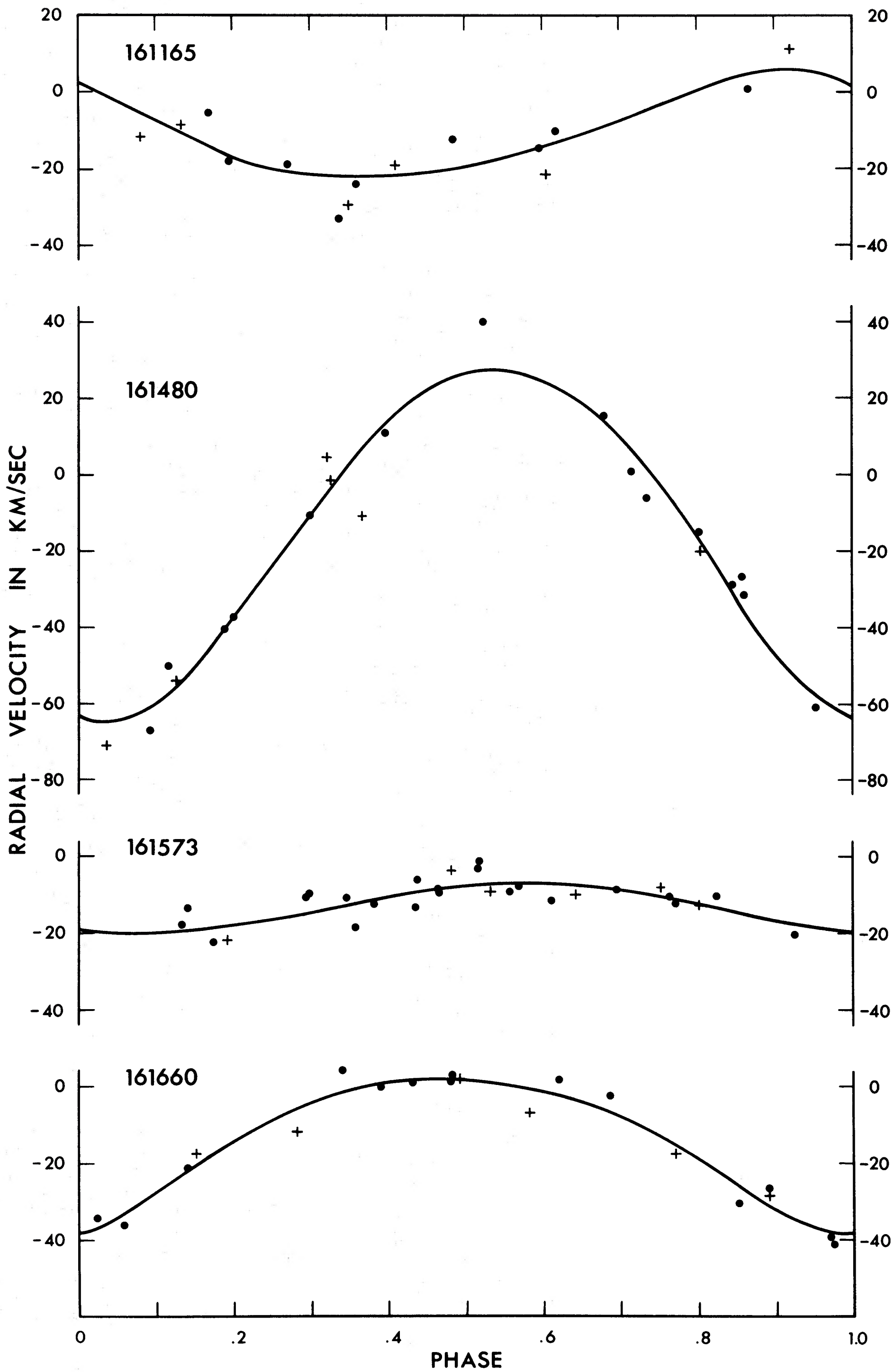

FIG. 2.—Computed velocity curves and measured radial velocities for four binaries. The velocities measured by ABL are shown as (+), our velocities by (●).

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in Table 4. These latter elements are based on the "good" ABL data as well as the DAO data.

b) NGC 2516

According to Abt and Levy (1972), 56 percent of the 16 stars (B2–B9.5) for which they have observations are probably variable in velocity. Application of the E/I ratio test to their data yields 44 percent variable. Although no orbital elements could be derived from their data due to the limited (10 day) period of observation, Abt and Levy claimed that six of the stars probably had $P < 10^{d}$. The "variability" of some of the stars (e.g., Cox 11) depends on only one or two discrepant observations each, however, and we suggest that these "possible" binaries should be reobserved.

c) NGC 6475

Abt *et al.* (1970) estimated that 47 percent of the 19 stars surveyed (B6–A1) had variable velocity. Application of the E/I ratio test leads to an estimate of 37 percent. In this cluster, also, there is a preponderance (4/8) of binaries with $e > 0.5$ which is not typical of the frequencies found in field stars of similar spectral type, and a further investigation of these binaries is indicated.

d) M 39

Abt and Sanders (1973) conclude that 50 percent of the 10 B9.5–A1 stars are variable in velocity. The E/I ratio test predicts 70 percent of the stars to be variable in velocity, but perhaps the external errors are slightly larger for these observations.

e) *Pleiades*

From observations with a dispersion of 63 or 128 Å mm^{-1}, Abt *et al.* (1965) detected binary motion for 26 percent of the 23 B6–A1 stars in the Pleiades. From the more accurate material (15–51 Å mm^{-1}) recently published by Pearce and Hill (1975), we find that 48 percent (11) of these stars are at least "possibly variable." In the latter analysis (as in IC 4665), some of the stars were classed as variable because the velocities from different observatories at different epochs did not agree, and so some of these stars may have very long period variations. The E/I ratio test applied to the data of Abt *et al.* indicates 22 percent of the stars to be variable; Pearce and Hill's data yield 32 percent variable.

f) *α Per*

Of the 32 B3–A0 cluster members observed by Petrie and Heard (1970), 10 were considered to be possibly variable. In addition to these 10 stars, we suggest that two more stars, HD 21455 and HD 22192, which were excluded as members primarily on the basis of velocities differing from the cluster mean, are actually members which have variable velocity. The frequency of "possible binaries" is then increased to 35 percent. Unfortunately, the internal errors were not published by Petrie and Heard, and so the E/I test cannot even be tried. In α Per (as in the Pleiades) Abt (e.g., Abt and Levy 1972) has claimed an extremely low (even 0%) binary frequency. The main reasons for the difference between his estimate and ours are (1) Abt considered all 77 stars, we restricted the discussion to the 32 B3–A0; and (2) we included as binaries all stars which appear to have variable velocity, Abt restricted the number to those stars with known periods. As mentioned earlier, the number of observations per star and the frequency of observation of the stars in this cluster were not optimum for the discovery of binaries.

VII. CORRELATION OF BINARY FREQUENCY AND ROTATIONAL VELOCITY

The data on the frequency of spectroscopic binaries in the six clusters just discussed is collected together in Table 5. The ratio of the mean rotational velocity of the cluster members to that of the field stars in

TABLE 5

COMPARISON OF BINARY FREQUENCIES

Cluster (1)	n (2)	$\langle V \sin i\rangle / \langle V \sin i\rangle_{FS}$ (3)	Frequency (%): Possibly Variable (4)	Frequency (%): E/I Test (5)	Frequency (%): $P < 10^{d}$ (6)	Number of Stars with $K > 30$ km s^{-1} (7)	Number of Stars with Double Lines (8)
α Per..........	32	1.35	35	...	...	0:	0
Pleiades........	23	1.14	26*–48†	22*–35†	9	1	2
M39...........	10	0.94	50	70	10	0	1
IC 4665........	19	0.79	21‡–50	38:	5	1	2
NGC 2516.....	16	0.77	56	44	38	1	0
NGC 6475.....	19	0.59	47	37	42	2	1

* Abt *et al.* 1965.

† Pearce and Hill 1975.

‡ Estimated percentage which would have been detected if the observations had been made at a lower dispersion.

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TABLE 6

STARS REQUIRING FURTHER OBSERVATION*

α Per	Pleiades	NGC 2516	NGC 6475	IC 4665	M39
18537........	23324	Cox A	162780	161165	205117
19893........	23387	Cox 15	162679	161426	+47°3452
20135........	23512	Cox 19	162588	161481	
20487........	23629	Cox 13	162630	161603	
20863........	23753	Cox 29	320861	161621	
21091........	23763	Cox 91		161628	
21181........	23850	Cox 20			
21278........		Cox 83			
21362........		Cox 11			
21455........		Cox d			
21641........					
22192........					

* HD numbers, except for one BD number in M39 and Cox numbers in NGC 2516.

column (2) is taken from similar analyses by Abt and Levy (1972) and Abt and Sanders (1973). There is a slight tendency for the frequencies of stars which are possibly variable, or detected as variable by the E/I test, to increase with decreasing ratios of the rotational velocity. However, the values of the binary frequency in the Pleiades and IC 4665 are similar despite the large difference in mean rotational velocity, so that any "trend" is marginal.

As mentioned previously, Abt and Levy (1972) concluded that the percentage of binaries with known periods should be compared among the clusters. Abt and Sanders (1973) suggested that comparisons should be further restricted to those binaries with $P < 10^d$. Pearce and Hill's observations of the Pleiades indicate that although the binary frequency may be ~50 percent as in most other clusters (and field stars), some of these may be long period binaries. Only two of the 23 Pleiades members have $P < 10^d$, but then, strictly speaking, only one of the 19 stars in IC 4665 has $P < 10^d$ (there are 2 with $P \approx 10^d.6$). Thus, as the numbers in Table 5 indicate, the correlation between short period binaries and rotational velocity is poor, too. Actually, the frequency of short periods in NGC 2516 and NGC 6475 appears to be abnormally high, but, as suggested earlier, the orbital elements (large e) of some of the stars are suspect. To encourage further observations to clarify this situation, the stars for which the available data are inadequate to determine and establish the period are listed in Table 6.

The last two columns of Table 5 show that the numbers of stars in each cluster which exhibit large amplitude velocity variations, or double lines in their spectra, are approximately constant. The absence of *any* such stars in α Per is surprising, although a more thorough survey might uncover them.

We conclude that, from the data presently available, any correlation between rotational velocity and binary frequencies in clusters appears to be a weak one, and that further observations are required to establish it. The Trumpler catalog of radial velocities of stars in clusters would provide a wealth of relatively homogeneous data on which a survey of binary frequencies could be based; we urge that it be published as soon as possible.

There is obviously some disagreement between our conclusions and those of Abt and his co-workers. The basic reasons for this difference are the following: (i) new observations of IC 4665 and the Pleiades, (ii) somewhat different methods of assessing binary frequency, and (iii) restriction of our analysis to the same range of spectral type in each cluster. The observations of stars in IC 4665 (low $\langle V \sin i \rangle$) and the Pleiades (high $\langle V \sin i \rangle$) indicate that the frequencies of stars which are variable in velocity are not very different. The resolution of the question of whether there is a basic difference between the distribution of periods of binaries in the two clusters awaits further observations. These conclusions also appear to be applicable to the other clusters which we have discussed in this paper.

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