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A SPECTROSCOPIC STUDY OF THE OPEN CLUSTER M39

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ABSTRACT

M39 is found to be intermediate among open clusters in its mean stellar rotational velocity and its frequency of binaries. A study of the 15 brightest members yielded orbital elements for four spectroscopic binaries; one other star has double lines. For six well-studied clusters there is a well-defined inverse correlation between mean rotational velocity and frequency of binaries with periods less than about 10 days; if longer-period binary motion is also effective in reducing rotational velocities, then the results imply preferential inclinations for some clusters.
Subject headings: binaries — open clusters — rotation, stellar

I. INTRODUCTION

There is a need for additional data on binary frequencies and rotational velocities of stars in open clusters to help us understand the large differences measured to date from cluster to cluster. This study of binaries and rotational velocities in M39 is intended to help fill that need.

M39 = NGC 7092 is a sparse open cluster in Cygnus. The cluster has measured proper motions and membership selection by Ebbighausen (1940) and van Schewick (1957). Photoelectric photometry of the members has been done by Johnson (1953) and Weaver (1953); the cluster distance is 275 ± 30 pc. Spectral classification by Morgan (Johnson 1953) and Weaver (1953) gives an earliest type of B9 or A0, respectively, and the likely presence of at least one Am star but probably no Ap stars. This cluster is somewhat older than the other clusters discussed below. Approximate rotational velocities of M39 stars estimated by Meadows (1961) indicate a mean value similar to that of field stars.

II. SPECTROSCOPIC BINARY FREQUENCY

For the 15 cluster stars brighter than $V = 9.5$ mag, we obtained spectra of 63 Å mm^{-1} reciprocal dispersion with the 36-inch (91-cm) Cassegrain spectrograph (JD−2441000 = 130 to 131, 254 to 561) and of 39 Å mm^{-1} with the 84-inch (213-cm) Cassegrain spectrograph (JD−2441000 = 139 to 251, 648). We measured with a Grant comparator eight hydrogen lines, λ3933 Ca II, and λ4481 Mg II. The velocity standards Vega and Procyon were observed 13 times with the result that we used velocity corrections of −3 and 0 km s^{-1}, respectively, for the two intervals of 36-inch observing and +4 to +9 km s^{-1}, respectively, for the 84-inch observing periods. The corrected radial velocities, ρ, and internal probable errors are listed in table 1, and a data summary is given in table 2. The format of these tables is similar to that in previous studies (e.g., Abt, Bolton, and Levy 1972).

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TABLE 1

Individual Radial Velocities

Helio. JD 2441000+	ρ (km s^{-1})	p.e. (km s^{-1})
1. E33		
130.755	-8.5	±2.0
131.736	-16.4	1.9
139.877	-13.3	1.2
140.840	-10.7	0.9
170.930	-11.2	1.3
171.983	-15.1	0.9
177.770	-10.7	1.6
251.696	-10.0	2.2
254.608	-3.8	0.5
496.804	-8.2	1.6
497.839	-6.2	0.9
560.699	-6.0	1.6
561.716	-14.8	2.8
648.560	+1.6	1.9
2. E26		
130.750	-4.2	1.1
131.740	-18.2	1.9
139.880	+1.6	1.2
140.843	-0.9	1.8
170.938	-10.8	1.6
172.868	-11.4	1.1
177.773	-17.4	3.1
177.790	-19.5	1.2
251.634	-13.9	1.1
254.612	-2.7	0.4
496.808	-2.8	1.8
497.844	-8.1	2.3
560.703	-10.7	2.5
561.724	-12.0	2.6
648.563	-3.9	2.3
3. E40a		
130.745	-9.8	1.9
131.743	-18.2	1.0
139.883	-4.1	0.7
140.845	-2.1	0.7
170.949	-8.4	1.2
170.953	-7.3	0.7
177.781	-11.9	1.4
251.643	-4.3	1.1
254.617	-0.8	2.8
496.813	-4.2	1.7
497.848	-4.4	1.8
560.708	-9.0	2.8
561.730	-9.6	1.9
648.567	-3.8	1.3
4. E1		
130.755	-0.8	1.2
131.747	-13.9	±2.4
139.886	-2.3	±0.7
140.848	-9.4	2.7
170.963	-9.6	1.0
172.893	-4.9	1.3
177.787	-13.2	2.3
251.649	-7.0	1.9
254.623	-7.1	1.2
496.818	-4.6	1.8
497.854	-9.6	2.3
560.714	-6.7	2.6
561.734	-6.1	2.3
648.571	+3.3	2.4
5. E23		
130.761	+24.6	0.8
131.751	-1.3	1.2
139.890	-10.6	1.1
140.853	-2.8	1.6
170.976	-16.1	1.3
172.914	-11.4	1.3
177.817	-6.7	0.9
251.655	-5.1	1.7
254.630	-11.5	1.6
496.826	-2.9	2.8
497.861	-6.6	2.8
560.721	-4.1	2.7
561.740	-3.0	2.9
648.609	-17.5	2.3
648.670	-17.9	2.0
6. E5		
130.769	-4.7	1.5
131.756	+13.0	2.4
139.897	-24.7	0.7
140.863	-20.0	1.9
170.989	+13.8	1.3
177.823	-23.2	1.6
251.661	-8.3	2.2
254.645	-15.5	1.7
496.842	-12.1	1.5
497.873	+5.3	1.9
560.740	-0.1	2.6
561.750	-10.2	2.6
648.615	-30.6	1.5
7. E17		
130.782	-2.8	2.2
131.766	+1.1	5.4
139.902	+2.2	1.2
140.868	+1.6	0.7
251.668	+5.3	1.7
254.663	+1.8	±1.2
496.854	-10.7	±3.0
497.882	-14.4	3.5
560.754	-14.4	3.4
561.758	-12.9	3.7
648.622	-14.6	1.9
8. E38		
130.796	-15.4	2.5
131.775	-17.3	1.3
139.908	+11.1	0.9
140.875	+8.4	1.1
177.837	-9.5	1.6
251.679	-17.5	1.0
254.678	-6.4	2.3
496.865	-20.8	1.8
497.893	-12.3	1.7
560.764	-25.5	1.3
561.770	-16.0	1.1
648.635	-19.4	0.7
9. E31		
130.808	-2.7	1.4
131.784	-9.7	0.8
139.916	+0.8	0.4
140.881	-7.2	0.4
177.846	-6.8	1.1
251.689	-5.0	1.3
254.693	+4.3	3.4
496.881	-10.2	2.9
497.907	-6.1	1.6
560.777	-11.1	1.5
561.784	-11.4	1.5
648.653	-11.1	2.6
10. E22		
130.864	-16.3	1.9
131.809	-7.3	2.1
139.939	-11.9	1.8
140.906	-13.6	1.2
251.711	-25.8	2.1
254.730	-31.8	1.8
496.923	-3.9	4.1
560.818	-24.6	3.7
561.883	-20.0	3.2
648.683	-5.3	1.7
11. E19		
130.844	-12.0	2.0
131.796	-9.3	1.2
139.925	-5.5	0.8
140.891	-2.8	1.2
177.866	-5.7	2.5
251.701	-3.9	±2.1
254.711	+1.8	±0.4
496.901	-8.6	3.3
497.925	-3.6	2.8
560.798	-20.8	4.1
12. E35		
130.884	-9.4	0.9
131.828	-8.7	2.3
139.949	-7.9	1.7
140.915	-6.7	1.1
251.724	-11.9	2.2
254.755	-14.1	0.1
560.842	-12.0	2.4
561.859	+19.1	2.7
648.580	-6.3	2.3
13. E3		
130.911	-15.6	2.9
131.846	-15.3	3.6
139.961	-6.9	2.3
140.927	-6.2	0.9
251.734	-3.7	1.4
253.808	-13.6	2.6
254.777	-1.7	1.2
560.870	-15.3	5.5
561.908	-6.8	3.8
616.796	-0.6	5.6
648.585	-11.8	2.3
14. E45		
130.936	-18.3	2.5
131.862	+1.7	2.2
140.940	-21.2	2.3
251.745	-3.0	1.7
252.785	-5.6	2.2
254.799	-9.3	0.1
496.953	-24.9	5.6
497.946	-13.4	4.4
561.805	-24.0	3.9
616.767	-17.4	4.7
648.592	-4.1	2.5
15. E4		
130.961	-10.9	3.4
131.881	-12.7	1.8
140.953	-7.5	2.0
251.756	-10.6	2.4
252.765	+0.5	3.1
561.831	-16.8	2.9
616.734	-13.1	3.5
648.598	-9.6	1.9
16. E20		
131.901	-8.5	±0.9

Star E22 has double lines on one plate (JD 2441648) but with too small a separation for measurement. Four other stars with large velocity variations yielded orbital elements; these elements are listed in table 3 and the radial velocity curves are illustrated in figure 1. For two of these stars (E19, E38) the computerized least-squares program did not produce improved elements (mostly because of a poor distribution in phase of the measures), so their probable errors are large. Two additional stars (E23, E17) are probably binaries; the latter one seems to have a long period. One star (E35) has a very constant velocity except for one discordant measure; this and the remaining seven

TABLE 2

SUMMARY OF DATA ON M39

Order of Brightness	Ebbighausen No.	HD or BD	Spectral Type (Morgan)	$V \sin i$ (km s^{-1})	$\langle\rho\rangle$ (km s^{-1})	⟨int. p.e.⟩ (km s^{-1})	ext. p.e. (km s^{-1})	n	Conclusions
1..........	E33	205210	B9.5 IV	130	− 9.5	±1.5	±3.3	14	Constant velocity
2..........	26	205116	B9.5 V	90	− 9.0	1.7	4.5	15	Constant velocity:
3..........	40a	205331	B9 IV	30	− 7.0	1.5	3.1	14	Constant velocity
4..........	1	204917	A0 V	110	− 6.6	1.9	3.1	14	Constant velocity
5..........	23	205117	A0 IVs	80	− 5.4	1.8	6.9	15	Probably variable
6..........	5	205073	A0 Vs	0	− 3.2	1.8	9.5	13	SB1, $P = 5^d.4730$
7..........	17	205085	A1 V	145	− 5.3	2.5	5.4	11	Variable, $P > 100^d$
8..........	38	205198	A1 V	30	+ 0.5	1.4	7.6	12	SB1:, $P = 11^d.03$
9..........	31	+47°3458	A0 V	130	− 6.4	1.6	2.6	12	Constant velocity
10..........	22	+47°3452	A1m	40	−16.0	2.4	6.3	10	SB2
11..........	19	+47°3454	A2 Vs	85	−11.4	2.1	4.8	10	SB1:, $P = 110^d.0$
12..........	35	+47°3462	A2	100	− 6.4	1.7	6.6	9	Constant velocity:
13..........	3	+47°3433	A2 V	260	− 8.9	2.9	3.8	11	Constant velocity
14..........	45	+47°3472	A7 V	110	−11.8	2.9	6.2	11	SB1, $P = 13^d.1330$
15..........	E4	+47°3438	A2 V	150	−10.1	±2.6	±3.4	8	Constant velocity

TABLE 3

ORBITAL ELEMENTS OF THE SPECTROSCOPIC BINARIES

Parameter	E5	E19	E38	E45
P (days)	5.4730 $\pm$0.0010	110.000 $\pm$0.004	11.03 $\pm$0.0005	13.1330 $\pm$0.0004
T_0 (JD 2441000+)	127.89 $\pm$0.86	131.4 $\pm$15.9	129.7 $\pm$1.1	131.1 $\pm$0.8
γ (km s^{-1})	-3.2 $\pm$2.9	-11.4 $\pm$5.7	+0.5 $\pm$8.4	-11.8 $\pm$1.2
K (km s^{-1})	18.5 $\pm$3.7	10.3 $\pm$11.4	19.7 $\pm$9.9	11.9 $\pm$1.8
e	0.29 $\pm$0.20	0.35 $\pm$0.69	0.29 $\pm$0.35	0.35 $\pm$0.13
ω	73° $\pm$42°	270° $\pm$73°	91° $\pm$36°	286° $\pm$28°
$a_1 \sin i$ (10^6 km)	1.33	14.6	2.86	2.01
$f(\mathfrak{M})$ ($\mathfrak{M}_\odot$)	0.0032	0.010	0.0077	0.00047
0.6745 rms (O − C) (km s^{-1})	5.0	1.6	4.4	2.6

stars are tentatively considered to be constant-velocity stars. We conclude that probably at least six stars (40 percent) are binaries, and orbital elements are given for four stars (27 percent).

The mean velocity of the cluster from all 15 stars is -7.8 ± 2.6 (p.e. per star) km s^{-1}. However, much of this scatter is due to uncertainties in the determination of orbital elements for the binaries. For the eight stars with likely constant velocities, the mean

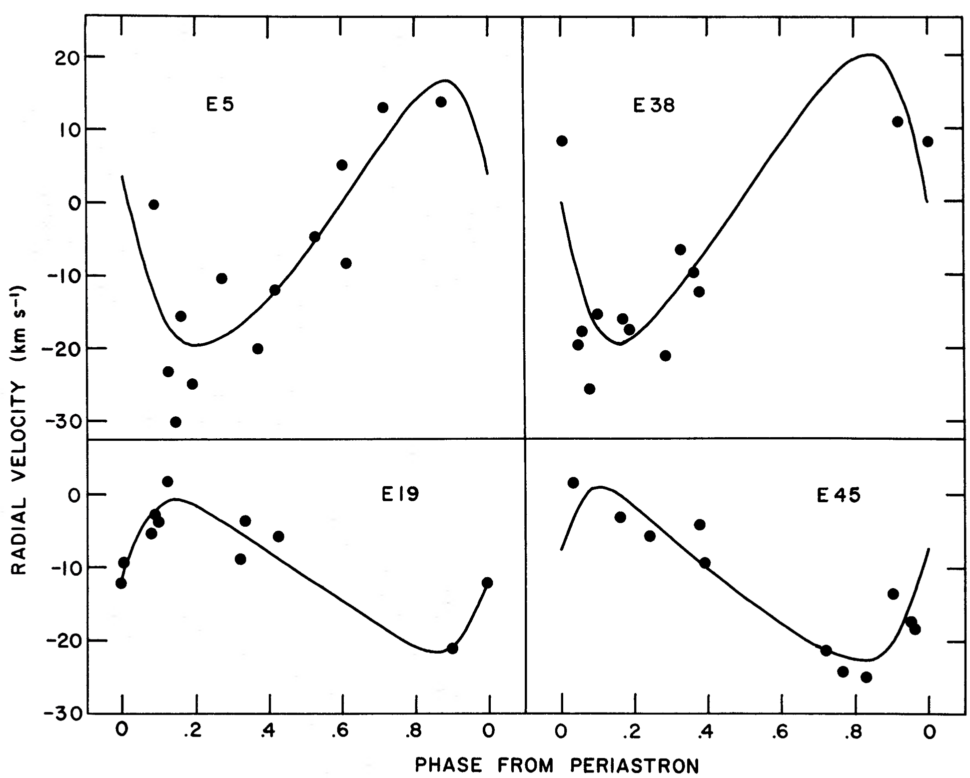

FIG. 1.—Computed radial-velocity curves and measured radial velocities (*dots*) for four spectroscopic binaries.

cluster velocity is -8.0 ± 1.0 (p.e. per star) km s^{-1}. Since the mean external probable error is ± 0.6 km s^{-1} per star, it is likely that most or all of the scatter shown in the mean velocities is due to measuring error, rather than to individual stellar motions. The quality of the data does not warrant using weighted data in forming the means.

III. ROTATIONAL VELOCITIES AND DISCUSSION

The projected rotational velocities for the stars numbered in table 2 were determined from visual comparisons on a Boller & Chivens spectra comparator of 0.9-mm-wide spectra of 39 Å mm^{-1} reciprocal dispersion with similar spectra of field stars; the latter have measured rotational velocities by Slettebak (1954, 1955). The resulting values in table 2 agree well in most cases with values by Meadows (1961).

A comparison of the rotational velocities of individual stars in M39 with the averages of large numbers of field stars (measured by Slettebak) of the same Morgan types showed the former to be rotating insignificantly slower, i.e., $(\langle V \sin i \rangle)(\langle V \sin i \rangle_{FS})^{-1} = 0.94 \pm 0.10$ (p.e. in the mean). This confirms Meadows's conclusion that M39 stars do not differ significantly from field stars in their mean rotational velocity.

The binary frequency and mean stellar rotational velocity of this cluster can be compared with results for five other clusters (Abt and Levy 1972) studied with mostly similar material. Figure 2 (*left*) shows the relation between (1) the frequency of binaries (with periods less than 100 days) plus Ap stars, and (2) the mean rotational velocity relative to that of field stars of the same types. The former parameter refers only to binaries with known double lines or orbital elements. Also, the former parameter was used because two mechanisms that are likely to modify the rotational velocities of individual stars are the tendency toward synchronous motion in closely spaced binaries and the magnetic braking in Ap stars. Figure 2 (*left*) shows an approximate inverse correlation in the sense that clusters (α Persei, Pleiades) with rapidly rotating stars have far fewer binaries plus Ap stars than clusters (M39) with normal rotational velocities or, especially, with clusters (NGC 6475, NGC 2516, IC 4665) having low rotational velocities.

There is a large amount of scatter in figure 2 (*left*), and this scatter suggests that the parameters plotted are insufficient data for a tight correlation. The greatest discrepancy is between NGC 6475 and IC 4665. We can think of several reasons for the scatter.

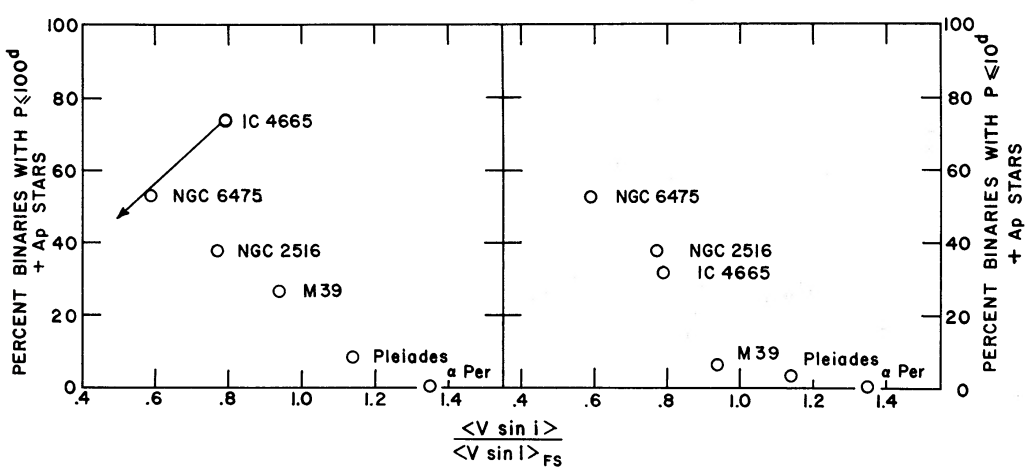

FIG. 2.—The percentage of spectroscopic binaries (*ordinates*) with periods less than 100 days (*left*) or less than 10 days (*right*) plus the Ap stars for open clusters with various mean rotational velocities (*abscissae*) relative to those of field stars of the same spectral types.

One reason might be the existence of preferred orientations of rotational and orbital axes in open clusters. Arguments for such a preferred orientation have been given by Ferrer and Jaschek (1973). On the contrary side, Abt, Chaffee, and Suffolk (1972) have shown that field Ap stars have random orientations of rotational axes and Kraft (1965) has shown that orbital axes of visual orbits in open clusters are probably inclined at random, but admittedly we do not know whether axes of closely spaced binaries or rotational axes of stars in open clusters are oriented at random. However, one thing is likely to be true: axes of closely spaced binaries and rotational axes in the same systems are probably parallel because of the strong tidal forces involved. Therefore, if a cluster has a systematically small $\langle \sin i_{\rm rot} \rangle$ in its values of $V \sin i$, then it should also have systematically small mass function, $f(\mathfrak{M}) = (\mathfrak{M}_2{}^3 \sin i_{\rm orb})(\mathfrak{M}_i + \mathfrak{M}_2)^{-2}$.

Observationally, the mean logarithm of the mass function of the eight binaries in NGC 6475 is smaller by 0.62 than that of the 13 binaries in IC 4665. The arrow[1] in figure 2 (*left*) on the symbol for the latter cluster shows where that symbol is moved if the rotational and orbital inclinations are both changed so that the mean mass functions of the two clusters are made to agree. We see that the parameters in figure 2 (*left*) for the two clusters are more nearly the same with this modification. We dare not make the same modification for the remaining clusters because they have too few binaries (maximum of three) with periods less than 100 days for a statistical discussion of mass functions.

However, there is a more natural explanation for the discrepancy between the results for NGC 6475 and IC 4665. This involves consideration of only the binaries with periods less than 10 days (plus the Ap stars) on grounds that duplicity with periods between 10 and 100 days may not be very effective in reducing rotational velocities by tidal interactions. In fact, Abt, Bolton, and Levy (1972) have shown that complete synchronization of rotational and orbital motions does not generally occur for periods above six days. In M39, the only binary (E5) with a period less than 10 days may be rotating synchronously, but the binaries with longer periods are not, including those (E38, E45) with periods of 11 and 13 days. When this lower period limit of, say, 10 days is used in figure 2 (*right*), NGC 6475 and IC 4665 fall on a consistent relation with the clusters of rapidly rotating stars. The data for M39 may seem inconsistent, but they are based on too small a frequency of binaries, namely, only one binary. Perhaps one can obtain information on binaries with periods between 10 and 100 days to see whether their rotational velocities are low relative to those of single stars, but we hesitate to use existing data on field stars for this purpose because orbital periods have generally been derived only for sharp-lined stars.

Obviously data on richer clusters are needed to help distinguish between a preferred inclination effect and an orbital-period break above which orbital motion is no longer effective in reducing rotational velocities.

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[1] This arrow could be drawn because of a well-defined linear relation between mean velocity dispersion per star in a cluster and the frequency of binaries found: for M39, NGC 2516, NGC 6475, and IC 4665 the mean external probable errors per spectrum are 5.2, 7.9, 8.8, and 15.6 km s^{-1}, and the frequencies of binaries with periods less than 100 days are 27, 38, 42, and 74 percent, respectively. The values for the Pleiades (7.6 km s^{-1} and 9 percent) do not agree, probably because they are based on spectra having lower dispersions by a factor of 2; the values for the α Persei clusters (6.2 km s^{-1} and zero percent) do not agree, probably because orbital elements were not determined by Petrie and Heard (1970) for any of the variable-velocity stars. Thus for similar material, the rotational velocities, the velocity dispersions, and the binary frequencies all have a linear dependence on mean inclination.

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