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Stellar rotation on the zero age main sequence

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Summary. Analysis of rotational velocities of unevolved members in clusters indicates that for a given mass the dispersion in the true rotational velocities is small for normal, single main-sequence stars. The envelope of highest rotation of rich clusters and associations is utilized to derive the rotational velocities on the zero age main sequence.

It is suggested (1) that the zero age main-sequence rotation curve defines the star's stability against fission and (2) that the frequency of spectroscopic binaries in a cluster is determined by the total angular momentum available to the gas cloud before fragmentation.

1 Introduction

In studies of stellar rotation, it is customary to group stars by absolute magnitude or spectral type and derive a mean value for the actual rotational velocities for each group from the relation $\langle V\rangle = 4/\pi\langle V\sin i\rangle$ based on the assumption that the inclination 'i' of the line of sight to the rotation axis is distributed at random. Such studies have been made for a large number of galactic clusters and associations and a comparison of the distribution of their rotational velocities with that of the field-star distribution reveals the following (Abt 1970). The distribution of the rotational velocities in various clusters is not the same; the differences are caused by (1) different frequency of occurrence of spectroscopic binaries, (2) evolutionary expansion which would lead to lower rotational velocities as the star evolves away from the zero age main sequence; this is however important only for stars of early spectral classes, (3) magnetic braking; the A_p and A_m stars, which are found in clusters as well as in the field, have intrinsically low rotational velocities and therefore must be excluded before one can make a comparison between various clusters and the field stars.

Thus any study of stellar rotation in galactic clusters involves considerable work at high dispersion to determine and eliminate the frequency of spectroscopic binaries and the peculiar A and metallic-line stars. It was suggested by Abt (1970) that the goal for future research on stellar rotation in galactic clusters is to see whether, after allowing for the obvious effects described above, the clusters have a common dependence of mean rotational velocity on spectral type.

However, Slettebak (1966) found that a smooth relationship exists between spectral type and the highest observed rotational velocities and only stars earlier than B8 are fairly close to

Table 1. Rotational velocities and spectral types of normal, single main-sequence stars in clusters and associations.

HD or BD	Spectral type	$V \sin i$ (km/s)	Cluster
21152	B9	225	α Per
21398	B9	135	
21931	B9	205	
23441	B9	225	Pleiades
23923	B9	310	
141774	B9	185	Sco–Cen
142315	B9	275	
143567	B9	235	
143600	B9	310	
145483	B9	200	
145519	B9	300	
145554	B9	180	
146029	B9	250	
146706	B9	270	
147703	B9	280	
148579	B9	200	
148594	B9	300	
162678	B9	20	NGC 6475
162804	B9	20	
162888	B9	225	
Cox 37	B9	300	NGC 2516
Cox 10	B9	80	
Cox 8	B9	265	
139486	B9.5	235	Sco–Cen
141404	B9.5	200	
145631	B9.5	180	
146416	B9.5	315	
147009	B9.5	190	
148860	B9.5	300	
20961	B9.5	25	α Per
23568	B9.5	250	Pleiades
23873	B9.5	90	
162631	B9.5	185	NGC 6475
162781	B9.5	205	
205116	B9.5	90	M39
+47° 3458	A0	130	
204917	A0	110	
20842	A0	85	α Per
20931	A1	85	
21479	A1	180	
23632	A1	225	Pleiades
320859	A1	220	NGC 6475
20391	A2	260	α Per
23409	A2	170	Pleiades
23872	A2	240	
23948	A2	120	
24076	A2	155	
320863	A2	215	NGC 6475
−34° 12195	A2	175	
−34° 12210	A2	215	
Koebl 79	A2	230	
+47° 3433	A2	260	M39
+47° 3438	A2	150	
+47° 3456	A2	250	
20986	A3	210	α Per
21046	A3	70	
23361	A3	235	Pleiades
23886	A3	165	
−34° 12196	A3	165	NGC 6475
23628	A4	215	Pleiades
21005	A5	250	α Per
+48° 944	A5	120	
21553	A6	150	
21600	A6	200	
21619	A6	90	
73819	A7	150	Praesepe
73576	A7	200	
74028	A7	160	
74050	A7	150	
21480	A7	50	α Per
23156	A7	70	Pleiades
23479	A7	150	
23607	A7	6	
23924	A7	100	
23934	A7	85	Hyades
27946	A7	210	
30780	A7	150	
32301	A7	130	
+47° 3445	A7	150	M39
20969	A8	10	α Per
29499	A8	70	Hyades
23246	A8	200	Pleiades
23791	A8	85	
23567	A9	95	
23585	A9	100	
23733	A9	180	
31236	A9	110	Hyades
73430	A9	80	Praesepe
73450	A9	140	
73161	F0	160	
73175	F0	180	
73345	F0	100	
73746	F0	110	
73798	F0	175	
19767	F0	140	α Per
+49° 918	F0	175	
28294	F0	135	Hyades
28556	F0	140	
29375	F0	155	
30034	F0	75	
108007	F0	165	Coma

computed equatorial break-up velocities. Slettebak (1976) also found that the distribution of $V \sin i$ of Be stars is consistent with the view that they all rotate with the same equatorial velocity V and their axes are distributed at random. These results suggest the possibility that a study of stars other than Be may also lead to the same results provided the sample chosen consists purely of normal single stars at the same stage of evolution. The results of such an investigation and inferences made from them are reported here.

2 The results

If a given group of stars rotates with the same equatorial velocity V, the frequency distribution of $V \sin i$ is expected to show a pronounced maximum at V provided the axes of rotation are distributed at random (Struve 1945; Chandrasekhar & Münch 1950). The basic difficulty in analysis of observed rotational velocities is that we really do not know how the axes of rotation are actually distributed. There is no *a priori* reason to believe that the axes of rotation of cluster members are randomly distributed and most likely they are not.

Further, star formation in clusters extends over a period of time as evidenced by the various subgroups that can be distinguished in them. During each epoch of formation of a subgroup, the distribution of rotational axes is likely to be different from those of the other subgroups. The assumption of random orientation of rotational axes in clusters is not likely to be valid and the observed distribution is likely to show one or more pronounced maxima depending upon the number of subgroups in a cluster. The randomness assumption is probably true only in the case of field stars. However, before one can take up an analysis of the field stars, extensive studies must be taken up to derive the frequency of spectroscopic binaries and peculiar stars, such as that carried out for clusters by Abt and his co-workers. Also the ages of field stars remain unknown.

We can at most hope, therefore, that by grouping the rotational velocities of various clusters, the final distribution of 'i' is randomized. In Table 1, all main-sequence normal stars in the range B9–F0 chosen from clusters and presumed to be single are listed. The Orion association is not included since extensive radial-velocity studies aimed at identifying the spectroscopic binaries have not been made so far. IC 4665 was excluded since the frequency of spectroscopic binaries is extremely high in this cluster (Abt, Bolton & Levy 1972). Crampton, Hill & Fisher (1976) have questioned the high binary frequency in this cluster, but its inclusion will not drastically change our conclusions. Sources for rotational velocities and spectral types are listed in Table 2. One of the main references considered in choosing the stars listed in Table 1 is the catalogue of stellar rotational velocities by Bernacca & Perinotto (1970).

Fig. 1 shows the frequency distribution of rotational velocities in different spectral

Table 2. Sources of rotational velocity and spectral-type data.

Cluster	Reference
Scorpio–Centaurus	Slettebak (1968) Rajamohan (1976)
α Persei	Kraft (1967); Morgan, Hiltner & Garrison (1971)
Pleiades	Anderson, Stoeckly & Kraft (1965)
Hyades	Kraft (1965)
Coma	Kraft (1965)
Praesepe	Dickens, Kraft & Krzeminski (1968)
NGC 6475	Abt & Jewsbury (1969); Abt (1975)
NGC 2516	Abt *et al.* (1969); Abt & Morgan (1969)
M39	Abt & Sanders (1973); Abt & Levato (1976)

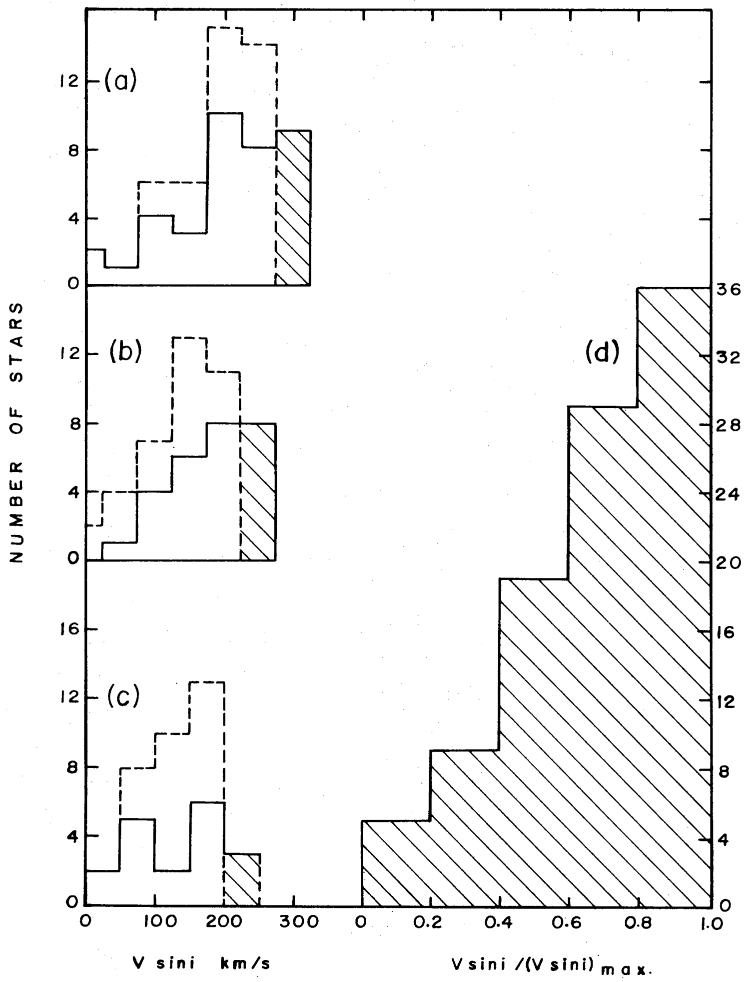

Figure 1. Histograms showing the frequency distribution of observed rotational velocities of single main-sequence stars listed in Table 1 for B9–A2, A1–A8 and A7–F0 stars; full line refers to B9 stars in (a), to A1–A6 stars in (b) and to A7–A8 stars in (c). Fig. 1(d) represents the distribution when the observed rotational velocities are expressed in terms of the maximum observed rotational velocity at each spectral class.

intervals of stars listed in Table 1. In Fig. 1(a), the solid line refers to B9–A0 stars and the dotted line to the derived distribution when A1–A2 stars are also included. The contribution to the shaded portion of Fig. 1(a) is entirely due to the B9 stars. Similar frequency distributions for A1–A8 and A7–F0 stars are shown in Fig. 1(b) and (c) respectively. The spectral intervals have been chosen such that there are about equal numbers of stars in each group. It should be noted that in each interval the contribution to the shaded portion of the histograms is always by objects of the early spectral classes.

In the spectral range B9–A2, there are very few stars in the $V \sin i$ range 0–175 km/s. Stars with $V \sin i$ higher than 275 km/s are all of spectral class B9. The distribution does show a pronounced maximum in the range 175–275 km/s. Similarly the tendency for the distribution to peak at higher values of $V \sin i$ is also evident at other spectral intervals. The mean and the root mean-square deviation of the true distribution calculated from equation (20) of Chandrasekhar & Münch (1950) are listed below

B9:	276 ± 42 km/s
A0–A2:	233 ± 25 km/s
A3–A6:	216 ± 34 km/s
A7–F0:	160 ± 43 km/s.

Six objects in the spectral class B9 belonging to NGC 6475 and NGC 2516 are excluded in calculating the above means since these two clusters are known to be very rich in A_p stars (Abt & Jewsbury 1969; Abt *et al.* 1969). A separation between the sharp and broad-lined stars in the HR diagram of NGC 6475 is known to exist (Abt & Jewsbury 1969).

The tendency for the maximum rotational velocity to shift towards lower values with advancing spectral type is another cause which introduces a spread in the observed distribution when we group stars into wide spectral intervals. The resultant distribution, when the observed rotational velocity is expressed in terms of the maximum rotational velocity at each spectral class, is shown in Fig. 1(d). The observed rotational velocity was plotted as a function of spectral type and a smooth upper envelope was drawn to derive the maximum observed rotational velocity at each spectral class. The tendency for the resultant distribution to peak at the highest observed rotational velocity is clearly evident.

In this analysis, the effect of rotation on spectral types has not been taken into account. Collins (1974) has suggested a systematic later classification for late B stars as a result of rotation. This effect has probably introduced the observed spread of the maximum in Fig. 1(d).

These results strongly suggest the possibility that the rotational velocities of normal main-sequence single stars are a function of spectral type or equivalently of the stellar mass.

In Fig. 2(a) and (b) we have plotted $\Delta\beta$ and ΔC_0 against $V \sin i$ for the upper Scorpius and α Persei members for which *uvby* and Hβ photometry by Glaspey (1971) and Crawford & Barnes (1974) are available. $\Delta\beta$ and ΔC_0 are the deviations from the mean relationship between β and C_0. The mean β index as a function of C_0 was derived for the two clusters

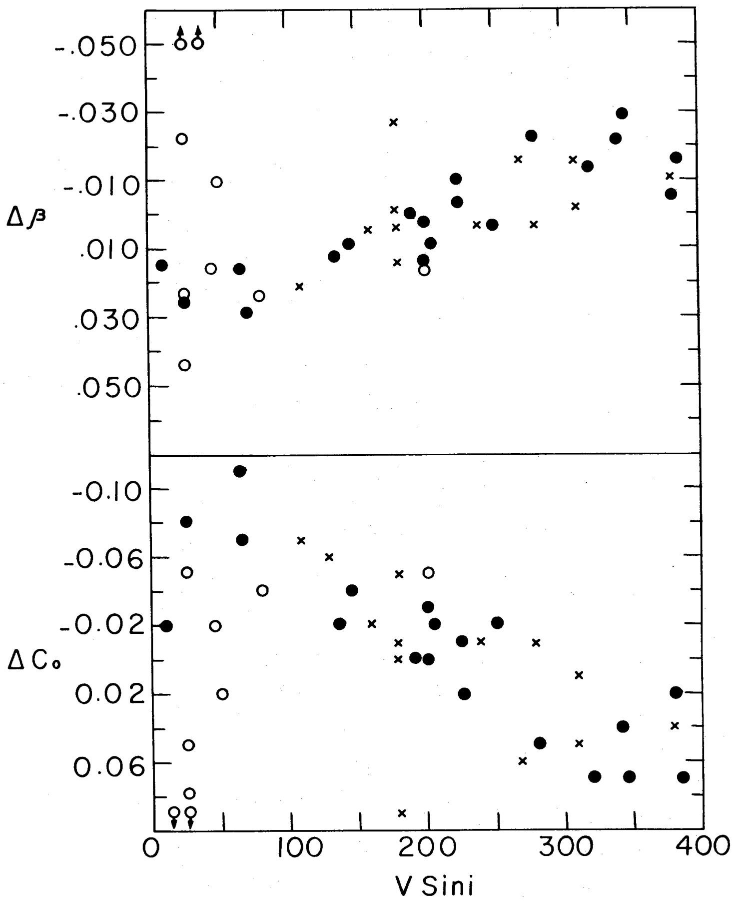

Figure 2. The deviations $\Delta\beta$ and ΔC_0 from the mean relation are plotted against $V \sin i$ for Upper Scorpius (crosses) and α Per (filled circles) members. Peculiar and metallic-line stars are indicated by open circles.

separately. A total range of 0.06 mag in β is obvious as i goes from 0 to 90°. Similarly the range in C_0 is about 0.15 mag. These results are consistent with predicted effects of rotation on narrow band and Hβ indices (see Collins 1970 and references therein). The positions of the peculiar stars in these two clusters are also indicated in Fig. 2(a) and (b). A large range in $\Delta\beta$ and ΔC_0 relative to normal stars for $V \sin i$ in the range 0–100 km/s is evident.

3 The zero-age rotation curve

We have shown that for main-sequence single stars of a given mass the dispersion in true rotational velocities is small and the observed rotational velocity depends only on i, the angle between the line of sight and the axis of rotation. Based on this result we can argue that if the observed $V \sin i$ of stars in a cluster are plotted against their spectral type the envelope of highest rotation closely represents the true distribution of rotational velocities of single main-sequence stars. Spectroscopic binaries, evolved stars and peculiar objects which are all characterized by low rotational velocities would lie well below this curve and the frequency of their occurrence will not affect the derived distribution. The method is especially applicable to rich clusters and associations.

This envelope of highest rotation can now be utilized to derive the rotation on the zero age main sequence (ZAMS) from the known ages of clusters and published evolutionary tracks provided there is no loss of angular momentum during the main-sequence lifetime of these stars. Angular-momentum losses due to stellar winds are important only for stars later than F4 and can be neglected during the main-sequence lifetime of early-type stars (Kraft 1970). We shall assume that the angular momentum is conserved in shells. This assumption seems justified since there is no conclusive evidence to prove whether angular momentum is conserved in shells as the star evolves away from the main sequence or whether it rotates as a rigid body (Kraft 1970). Based on this assumption and the derived distribution of true rotational velocities given by the envelope of highest rotation, we can derive

$$\frac{V_{\mathrm{ZAMS}}}{V_{\mathrm{P}}} = \frac{R_{\mathrm{P}}}{R_{\mathrm{ZAMS}}}$$

where R is the radius of the star, V the equatorial rotational velocity and the subscript P refers to the present value.

The ZAMS rotation curve was derived from the first five clusters listed in Table 2. For each cluster a smoothed-out envelope of highest rotation was determined as a function of spectral type and is given in Table 3. The adopted masses of stars for the appropriate spectral type are given in column 2 of Table 3. These are mean values found from the mass–luminosity law given by Harris, Strand & Worley (1963) and from those given by Allen (1963). The absolute visual magnitudes for the appropriate spectral types were taken from Blaauw (1963) and bolometric corrections from Morton & Adams (1968). Evolutionary tracks for masses in the range 1–15$M_\odot$ of Iben (1965, 1966, 1967) were utilized to calculate the ratios of the present radii to the radii on the ZAMS appropriate to the age of the cluster. (Sco-Cen 1×10^7, αPer 2.5×10^7, Pleiades 6.5×10^7, Hyades and Coma 50×10^7yr). The calculated rotational velocities on the ZAMS for various clusters are displayed in Fig. 3. The probable errors of rotational velocities on the ZAMS derived here would range from about ±20 per cent at B0 to about ±10 per cent at F4. These estimates reflect only the probable errors of $V \sin i$ estimates. Neglect of gravity darkening in early B stars actually leads to lower estimates of rotational velocities at these spectral classes. Also shown in Fig. 4 are the envelopes of highest rotation of the five clusters studied here. The mean adopted value of stellar rotation as a function of spectral type is given in the last column of Table 3.

Table 3. Envelope of highest rotation and ZAMS rotational velocities.

Spectral type	Mass $M_\odot$	$V \sin i$ (km/s) envelope					$V \sin i$ (ZAMS) (km/s)
		Sco–Cen	α Per	Pleiades	Coma	Hyades	
B0							(630)
B1	11.6	405					590
B2	9.3	400					545
B3	7.7	395					510
B4	6.3	390	400				470
B5	5.5	385	388				440
B6	4.8	375	378				415
B7	4.3	365	365				390
B8	3.8	350	350	300			370
B9	3.3	335	334	290			345
A0	3.0	318	315	285			320
A1	2.7		295	275			305
A2	2.5		275	265			290
A3	2.3		260	255	179		275
A4	2.2		245	245	177	174	260
A5	2.1		234	235	176	172	250
A6	1.9		220	225	174	170	235
A7	1.8		210	215	172	166	220
A8	1.7		197	200	170	163	205
A9	1.6		185	190	166	158	190
F0	1.5		175	175	161	153	180
F1	1.5		162	160	154	145	165
F2	1.4		150	145		139	150
F3	1.3		140	130		127	140
F4	1.3		130	115		112	130
F5	1.2		120			90	(115)
F6	1.2					60	(105)
F7	1.1					42	(95)
F8	1.1				35	30	(85)
F9	1.1				20	20	(75)
G0	1.0				12	12	(70)
G1	1.0					6	(60)

4 Discussion

An inspection of Figs 3 and 4 reveals:

(a) At the points of overlap between two clusters the agreement is excellent and the transition from cluster to cluster is smooth – a result which seems to justify the validity of our assumption that the dispersion in true rotational velocities of stars of a given mass in a cluster is indeed very small. Further, a single normal star arrives on the main sequence with close tolerances on the angular momentum it can have. This depends only on its mass and not on which gas cloud it fragmented from (at least in the solar neighbourhood); an important result that must be borne in mind in studies of star formation and subsequent evolution.

(b) The sharp break at spectral type F4 at about $1.4 M_\odot$ is caused by the onset of convection in the uppermost layers which sets in around this spectral type. Convection is a powerful mechanism in driving stellar winds, further retarding the rotation of these stars. The actual values of rotation as soon as the stars arrive on the ZAMS for stars later than F4 is probably given by the dotted line in Fig. 4, and extrapolation of the values derived for late A and early F stars. Convection seems to halve the rotational velocities of these objects within their main-sequence lifetime.

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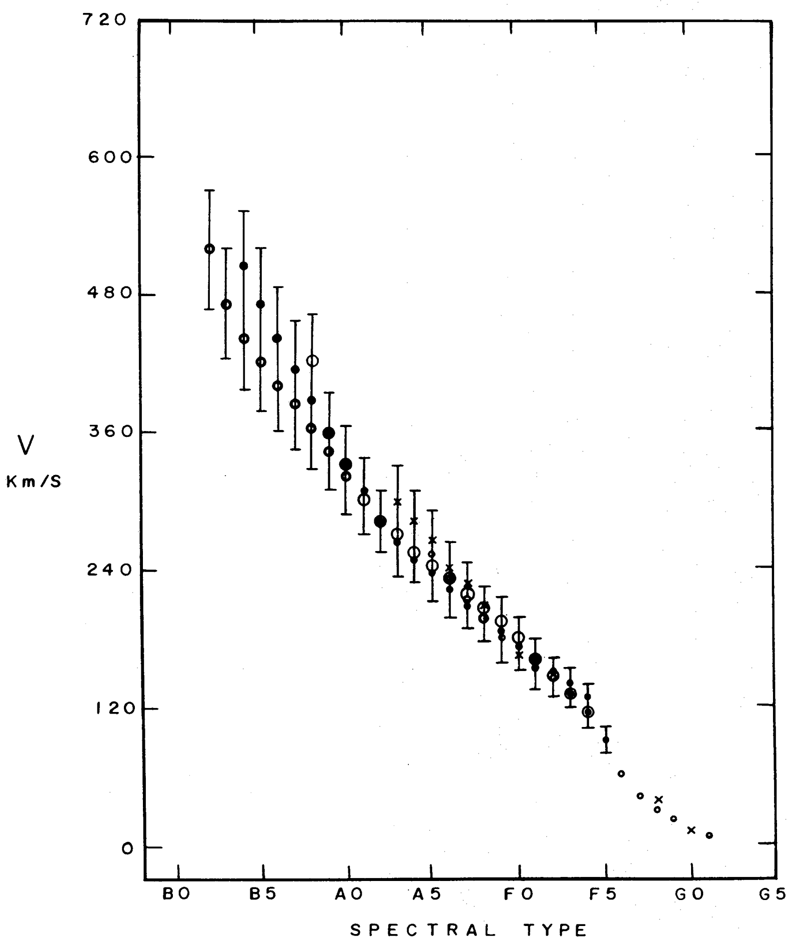

Figure 3. Calculated ZAMS rotational velocities as a function of spectral type derived from maximum observed rotational velocities of the first five clusters in Table 1. The error bars shown correspond to ±10 per cent of the derived rotational velocities. The errors are expected to be much larger for early spectral types. See text for details.

(c) Angular-momentum losses due to stellar winds for the early-type stars during their main-sequence lifetime is definitely small since the transition from Pleiades to α Per to Sco–Cen clusters is smooth with ages ranging from 1 to 7 x 10^7 yr. The ultraviolet observations of early-type main-sequence stars lead to very small mass-loss rates (Morton 1969) lending further support to this result.

(d) Comparison shows that the largest observational rotational velocities by Slettebak (1966) closely follow our ZAMS rotation curve while his computed curve for equatorial break-up velocities begins to deviate considerably beyond B8. It seems, therefore, likely that stars earlier than B8 arrive on the ZAMS almost with critical speeds and that evolution during the main-sequence lifetime restores the balance quickly. We must expect the frequency of Be stars in clusters with early-type stars to be a function of age. The high frequency of Be stars in the extremely young cluster *h* and χ Per as well as the high frequency of emission-line objects at B2 relative to B8 tend to confirm these results. However, the frequency of stars in clusters would also critically depend on the total angular momentum available to the gas cloud before fragmentation.

5 Conclusions

The results indicate that the dispersion is small in true rotational velocities of normal, single main-sequence stars of a given mass. The envelope of highest rotation, especially of rich

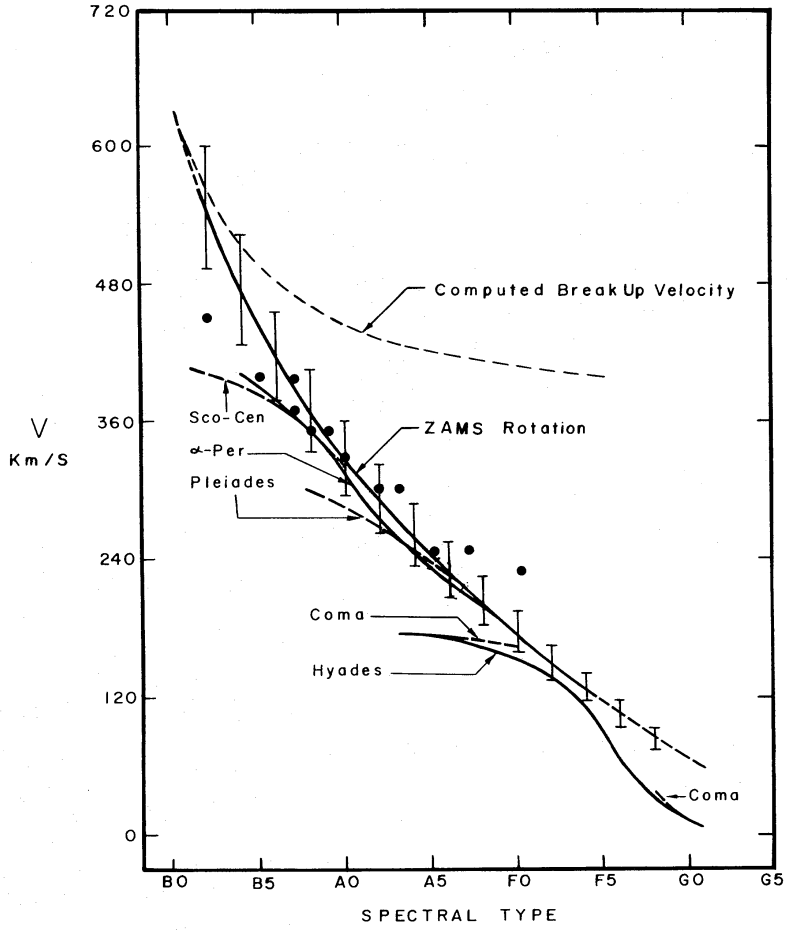

Figure 4. The envelope of highest rotation as a function of spectral type of five representative clusters along with the adopted ZAMS rotation curve. The computed break-up velocity and the highest observed rotational velocities for field stars (filled circles) by Slettebak (1966) are also shown.

clusters and associations, closely approximates the true distribution of rotational velocities in them. Once their ages are taken into account, there seems to be no difference in their distribution of rotational velocities. Normal single stars seem to arrive on the main sequence with a small range in angular momentum. This leads to the very interesting possibility of deriving the inclination of the axis of rotation to the line of sight and of testing predicted effects of rotation on colours and luminosities of stars.

It is proposed that a majority of the sharp-line objects on the main sequence in clusters are either spectroscopic binaries or peculiar objects. The differing frequency of spectroscopic binaries and peculiar objects from cluster to cluster definitely needs an explanation. It is probably to be found in the total angular momentum available in the gas cloud before fragmentation. If the ZAMS rotation curve, which is the curve of highest observed rotational velocities of single stars, defines its stability to fission, one should expect the frequency of spectroscopic binaries in clusters to be a function of the angular momentum per unit mass available in the gas clouds before fragmentation occurred. Incapability of fission (Ostriker 1970) seems the most likely explanation available at present for the smooth relationship between spectral type and the highest observed rotational velocities. That the highest observed rotation also tends towards critical break-up velocities for early B stars is responsible for the Be phenomenon.

The same arguments can be extended to the peculiar stars which are intrinsic slow rotators, where magnetic fields play an important role in inhibiting rotation and therefore the formation of binary systems. The analogues of these objects at the high-temperature end must be especially looked for amongst the slowly-rotating B stars. It is tempting to attribute the variables just above the main sequence to evolved Bp, Ap and Am objects with higher heavy-element abundances. Spectra obtained in the ultraviolet region should definitely indicate if such peculiarities exist, since analysis in the visual region does not indicate any anomalous abundances for the β CMa and δ Scuti type variables.

Finally, the bimodal distributions found by earlier investigators (Deutsch 1970; Day & Warner 1975) are due to the fact that all objects irrespective of age have been pooled to derive such distributions. The bimodal distributions found for clusters by Abt (1970) are partly due to the inclusion of giants which are characterized by low rotation compared to their main-sequence counterparts. Also many undiscovered binaries and peculiar stars of the hot Am type and the Hg–Mn stars which require very high dispersions in the range 2–4 Å/mm (Dworetsky 1975) are probably responsible for the high frequency of slowly-rotating stars. Observations in the ultraviolet region of all cluster members in the $V \sin i$ range 0–100 km/s are essential for discovery of these peculiar objects.

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