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Effects of Rotation on the Colours and Line Indices of Stars
2. The Effect on *uvby* and Hβ Indices

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Abstract. The intrinsic *uvby* and Hβ indices of member stars of α-Persei, Pleiades and Scorpio-Centaurus association have been analysed in detail for rotation effects. These stars range in spectral type from B0 to F0 and the observed effects of rotation are found to be in agreement with photometric effects calculated by Collins & Sonneborn (1977) for rigidly rotating B0 to F0 stars.

Key words: stars, rotation—stars, colours—star clusters, individual.

1. Introduction

The need for determining the effects of rotation on the colours and line indices of stars, and the methodology adopted together with references to the earlier work in this field has been discussed in Paper 1 of this series in some detail (Rajamohan & Mathew 1988). Theoretical computations of rotation effects on the colours and spectral lines were carried out by a number of investigators (Collins & Sonneborn 1977; Slettebak, Kuzma & Collins 1980; Collins & Smith 1985 and references therein) while Guthrie (1963) Petrie (1965), Kraft & Wrubel (1965), Dickens, Kraft & Krzeminski (1968), Warren (1976) attempted to relate the hydrogen line equivalent widths and colour indices with $V \sin i$ with varying degrees of success. The works of Crawford & Barnes (1974) and Rajamohan (1978) indicated that the c_1 index is definitely affected but no systematic work in this field had been taken up until recently to resolve the varying results obtained by different authors. The present authors undertook such a study and showed that in α-Persei the rotation effects in various colour indices can be firmly established for B and A stars (Paper 1). The works of Gray (1988) and Gray & Garrison (1987, 1989) shows that rotation effects on colours are no more a subject of controversy. They refined the MK spectral classification system for A and F type field stars and considered the effect of rotation on the intermediate band indices c_1 and β.

In this paper we extend our analysis to Pleiades cluster and the Scorpio-Centaurus association and make a detailed comparison between observed effects and theoretical photometric effects due to rigid rotation predicted by Collins & Sonneborn (1977).

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2.1 *The Data*

References to the cluster data used in this study are given in Table 1. As discussed in Paper 1 before analysing these data for rotation effects, the factors that affect their colours other than rotation were first taken into account. They are differential reddening across the cluster, binary nature, peculiarity, evolutionary effects and systematic errors in photometry. Also the use of observed indices is likely to magnify the reddening due to rotation especially for clusters with large variable extinction. Hence we have dereddened the colour indices before analysing for rotation effects. The analysis of each cluster was carried out independently so that the evolutionary effects and any systematic error in photometry are kept to a minimum. Double-lined spectroscopic binaries and close visual doubles with a magnitude difference less than 2 were excluded. Emission-lined objects and known peculiar stars were in general excluded and only luminosity class IV and V stars were included for data analysis. The final group of stars left for analysis should therefore represent a sample of normal single stars and single-lined spectroscopic binaries at the same stage of evolution. Hence the reddening effect found should be due to rotation alone.

2.2 *The Analysis*

The methodology adopted is similar to that given in Paper 1. Assume that all stars in a cluster are formed at the same time with zero rotation. A colour-colour plot then would define, for example, the zero-age, zero-rotation, main sequence. If all the members are single, we expect this observed sequence to have a scatter of ± 0.01 magnitudes about the mean relationship purely due to observational uncertainties alone. If some of the objects happen to be binaries, this scatter would increase depending on the mass ratio distribution of the binary components. Further contribution to the scatter would come from the existence of circumstellar envelopes around some stars, differences in line blanketing effects at a given mass *etc.* Differential interstellar reddening across the cluster would further increase the scatter in their observed position. We have to add the effect of rotation to all these uncertainties to understand the observed cosmic scatter in the zero-age main sequence of a cluster.

Now a group of coeval main sequence single stars will move across the HR diagram as they age and the rate of this shift would depend only on their masses. This of course

Table 1. References to four colour, H_β, $V \sin i$ data for clusters.

Cluster	Data	Reference
α-Persei	$uvbyH_\beta$	Crawford & Barnes (1974)
	$V \sin i$	Kraft (1967)
Pleiades	$uvbyH_\beta$	Crawford & Perry (1976)
	$V \sin i$	Anderson, Stoeckly & Kraft (1966)
Sco-Cen	$uvbyH_\beta$	Glaspey (1971)
	$V \sin i$	Rajamohan (1976)
		Slettebak (1968)
		Uesugi & Fukuda (1982)

assumes that the rate of energy production and transport is independent of rotation which is a reasonable assumption for early type stars.

Hence our approach to this problem was to choose stars of a given mass and age, that are single and whose colours can be expected to be different from the mean just because they have different rotational velocities. There is an implicit assumption that two groups of stars of the same mass close to the main sequence but differing ages will be affected to the same extent by rotation. If many groups are indiscriminately combined, the mean colour for each group would be different due to the difference in age which in effect is likely to mask the effect of rotation by making the data noisy.

The problem is that of finding a statistically significant sample of single stars of a given mass on the main sequence at the same stage of evolution with observed colours that are not affected due to causes other than rotation. The problem gets further complicated by the fact that we can derive only the projected rotational velocity and i, the inclination of the line of sight to rotation axis, is unknown. However, theory predicts (Collins & Sonneborn 1977) that the effect of differences in true rotational velocity v is much larger than that due to differences in i.

Our approach, therefore, towards this problem is the following. A colour-colour plot of chosen main sequence, presumably single, stars of a cluster will define a sequence which depends only on the masses of the individual members. A single intrinsic line that defines the mean relationship, also defines their position for the mean rotational velocity of the cluster members. The advantage of this approach is that while we use all stars to get a statistically significant sample, the intrinsic differences in the angular momentum distribution at any given mass will not affect the results significantly. Also we have no reason to believe for example that in a cluster the B stars will all be fast rotators and late A stars will all be born as slow rotators. If there are differences between cluster to cluster, then it is taken care of automatically by analysing the clusters independently.

We have used the data for each cluster to define its own relationship between different colour indices. To calculate the colour excess for example in c_0 a plot of β versus c_0 was made. A second order polynomial was fitted to the data for each star, a calculated c_0 value was derived using the polynomial coefficients for its observed β, we define Δc_0, the colour excess in c_0 as the observed minus computed value of c_0 for its observed value of β.

3. Results

3.1 *The Effect of Rotation on the Colours of α-Persei Stars*

There is a possibility that the use of observed colour indices may serve to increase the magnitude of rotation effects found in Paper 1. Since any calibration of colour indices must be finally done using intrinsic indices, we have reanalysed the α-Persei cluster data in order to check whether we have overestimated the rotation effects in Paper 1. α-Persei cluster is highly suited to check rotation effects since it has the least frequency of binary and peculiar stars.

A procedure similar to that in Paper 1 was followed and stars in Tables 1 and 2 of Paper 1 were reanalysed using the dereddened indices rather than the observed indices.

Table 2. Effect of rotation for Pleiades B stars.

Hz	HD	Sp.	$V\sin i$	from β, c_0		from $(u-b)_0$, β		from β, $(b-y)_0$	
				Δc_0	$\Delta\beta$	$\Delta(u-b)_0$	$\Delta\beta$	$\Delta(b-y)_0$	$\Delta\beta$
255	23432	B8V	220	−0.041	0.021	−0.052	0.018	−0.004	0.021
436	23568	B9.5V	260	0.012	−0.006	−0.004	0.002	0.001	−0.006
722	23753	B8V	270	0.001	−0.008	0.006	−0.007	0.000	−0.008
910	23873	B9.5V	120	0.003	0.000	0.001	0.000	0.000	0.000
977	23923	B9V	310	0.037	−0.023	0.036	−0.014	0.004	−0.023
1129	24076	A2V	155	−0.016	0.011	0.023	−0.006	−0.002	0.011
508	23629	A0V	160	−0.019	0.014	−0.037	0.013	−0.002	0.014
510	23632	A1V	235	0.023	−0.009	0.025	−0.005	0.002	−0.009

3.1.1 *B Stars*

Δc_0, the colour excess in c_0 derived from the mean relationship between β and c_0, is plotted against $V\sin i$ in Fig. 1. The B stars of α-Persei cluster are represented by open circles. For the α-Persei members alone, a least square solution for the residuals give

$$\Delta c_0 = 0.442(\pm 0.033) \times 10^{-3} V\sin i - 0.032(\pm 0.007),$$

$$\Delta\beta = -0.150(\pm 0.013) \times 10^{-3} V\sin i + 0.028(\pm 0.003).$$

Similarly from the β, $(u-b)_0$ relation, we derive

$$\Delta(u-b)_0 = 0.528(\pm 0.045) \times 10^{-3} V\sin i - 0.097(\pm 0.009),$$

$$\Delta\beta = -0.125(\pm 0.011) \times 10^{-3} V\sin i + 0.023(\pm 0.002).$$

The residuals $\Delta(u-b)_0$ are plotted against $V\sin i$, in Fig. 2. From the β, $(b-y)_0$ relation, we derive

$$\Delta(b-y)_0 = 0.043(\pm 0.003) \times 10^{-3} V\sin i - 0.008(\pm 0.001),$$

$$\Delta\beta = -0.162(\pm 0.014) \times 10^{-3} V\sin i + 0.029(\pm 0.003).$$

The residuals, $\Delta(b-y)_0$ are plotted against $V\sin i$ in Fig. 3(a) as open circles.

The $\Delta\beta$ values derived from β, c_0 and β, $(u-b)_0$ relationships are shown as open circles in Figs 4(a) and 5(a) respectively. For comparison, the predicted theoretical effects (see Section 3.4) are also shown for a representative value of $i = 45°$ and $60°$.

From c_0, $(b-y)_0$ plane for the B stars in the α-Persei cluster, we find that $\Delta(b-y)_0$ is not related to the rotational velocity of the stars in conformity with the expectations from theory (see Section 3.4).

3.1.2 *A Stars*

From β, c_0 for A stars in α-Persei we derive

$$\Delta c_0 = 0.305(\pm 0.040) \times 10^{-3} V\sin i - 0.040(\pm 0.006),$$

$$\Delta\beta = -0.156(\pm 0.029) \times 10^{-3} V\sin i + 0.021(\pm 0.005).$$

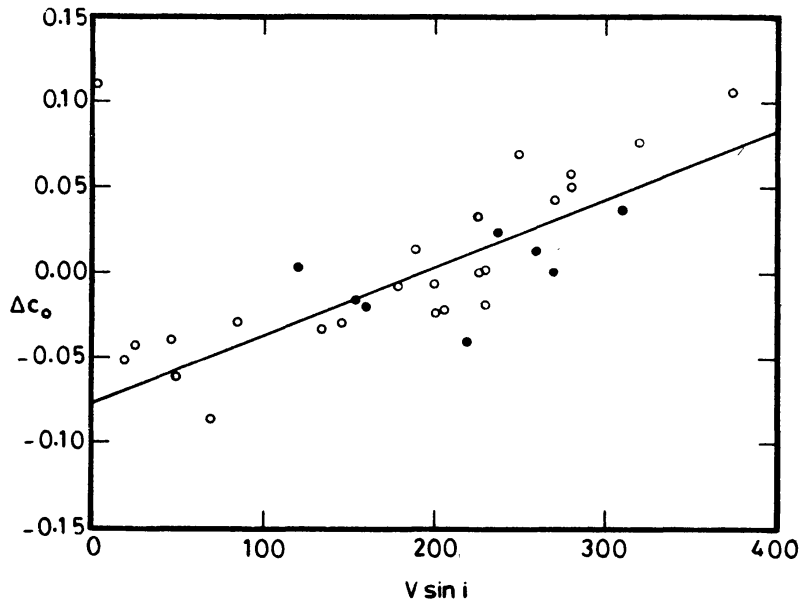

Figure 1. The deviations in c_0 from the observed mean relation between β and c_0 of Alpha Persei (open circles) and Pleiades B-stars (filled circles) are plotted against $V \sin i$.

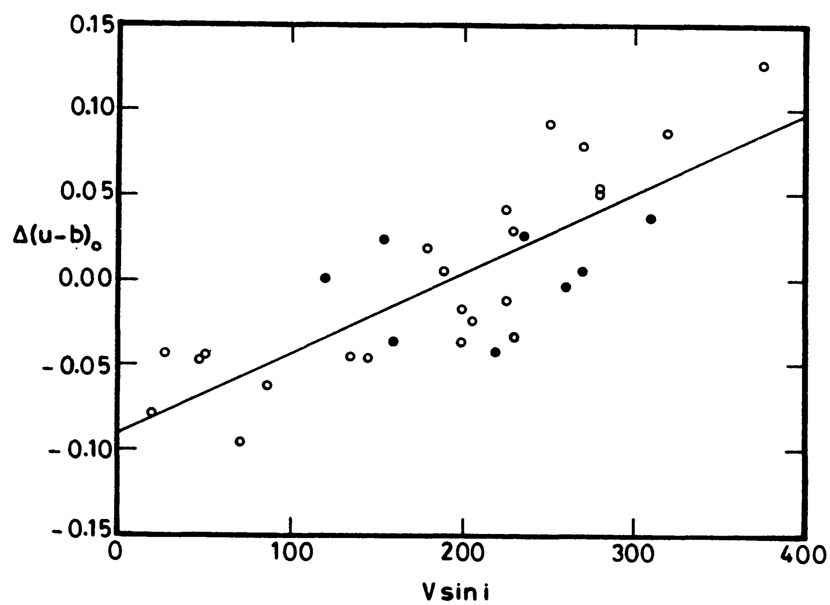

Figure 2. The deviations in $(u-b)_0$ for α-Persei (open circles) and Pleiades B-stars (filled circles) are plotted against $V \sin i$.

Δc_0 and $\Delta\beta$ are plotted against $V \sin i$ in Figs 6(a) and 7(a) respectively. The predicted theoretical effects (Section 3.4) are shown for comparison. From c_0, $(b-y)_0$ relation for A stars in α-Persei we derive

$$\Delta(b-y)_0 = 0.118(\pm 0.048) \times 10^{-3} V \sin i - 0.016(\pm 0.007),$$

$$\Delta c_0 = 0.198(\pm 0.041) \times 10^{-3} V \sin i - 0.026(\pm 0.006).$$

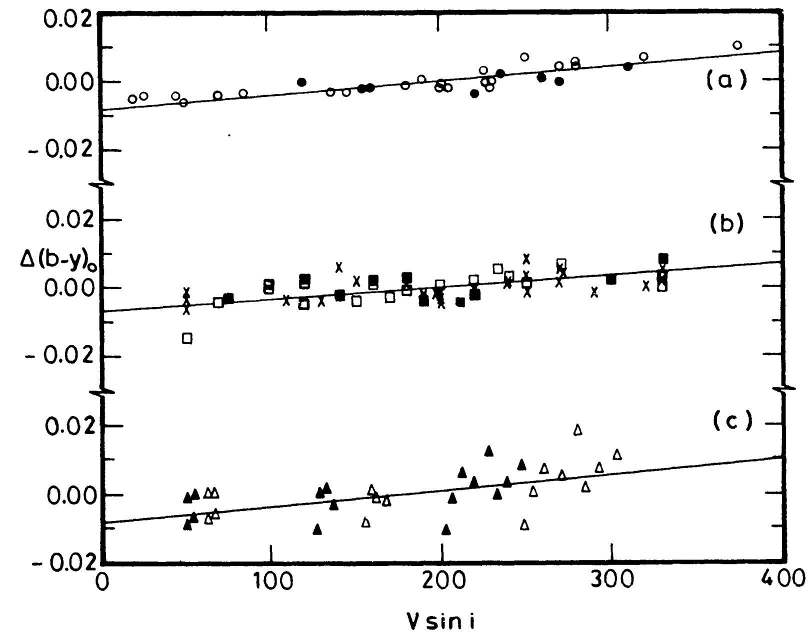

Figure 3. The deviations in $(b-y)_0$ derived from $\beta(b-y)_0$ for (a) Alpha Persei and Pleiades and (b) Scorpio-Centaurus association are plotted against $V\sin i$ for B-stars. The three subgroups in Sco-Cen are denoted by different symbols. (c) Theoretical effects predicted by Collins and Sonneborn's (1977) work for rigidly rotating B5 to B9 stars for $i=45°$ (filled triangles) and $i=60°$ (open triangles) are shown for comparison.

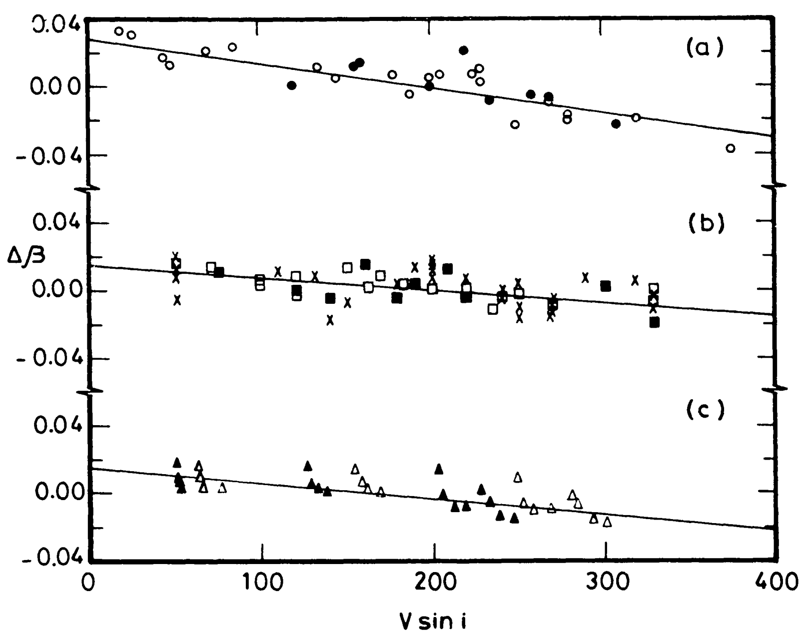

Figure 4. The deviations in β derived from observed β, c_0 for B-stars of (a) Alpha Persei and Pleiades, (b) Sco-Cen association, and (c) Theoretical model predictions for $i=45°$ and $60°$ are plotted against $V\sin i$. Theoretical values are shown for B5 to B9 stars. Symbols are as in Fig. 3.

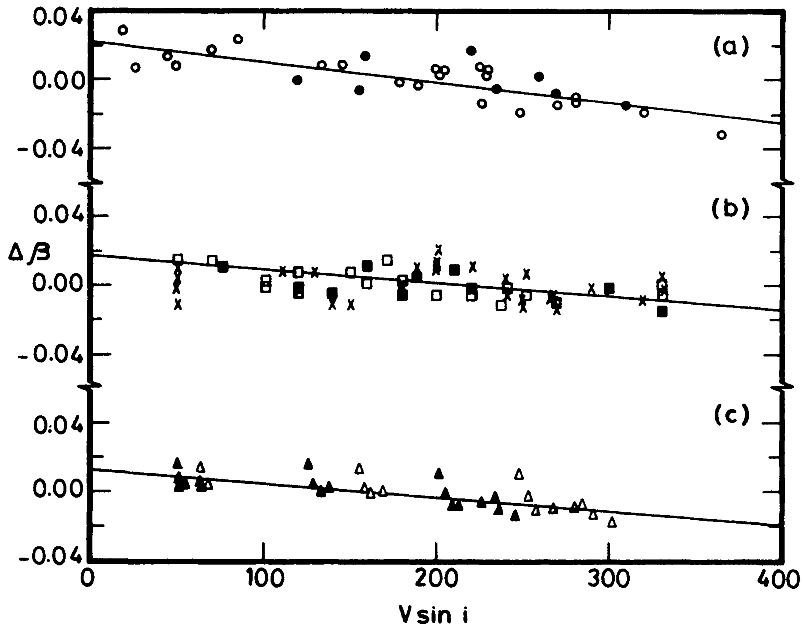

Figure 5. $\Delta\beta$ derived from β, $(u-b)_0$ relation is plotted against $V\sin i$. Other details are similar to Fig. 4.

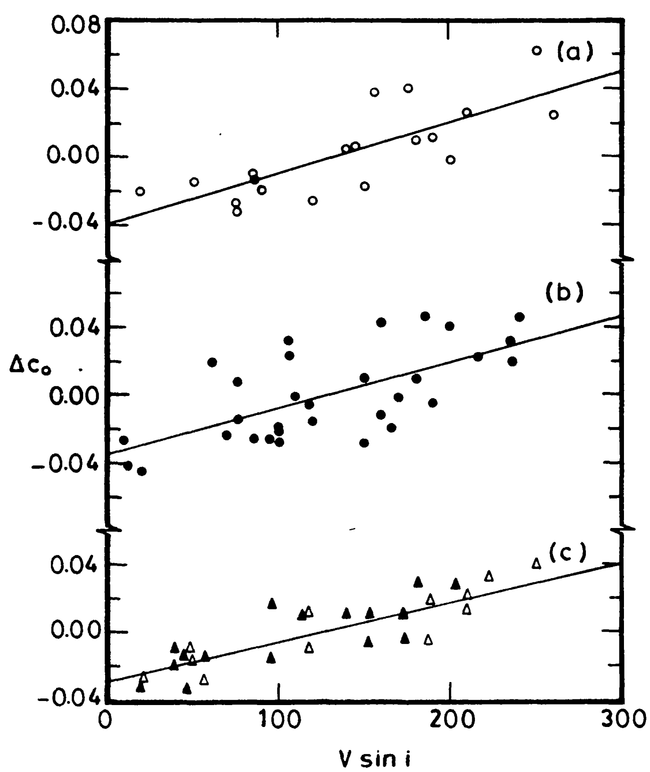

Figure 6. The deviations in c_0 derived from (observed) β, c_0 of A stars of (a) Alpha Persei, (b) Pleiades, (c) theoretical predictions for $i=45°$ and $60°$ are plotted against $V\sin i$.

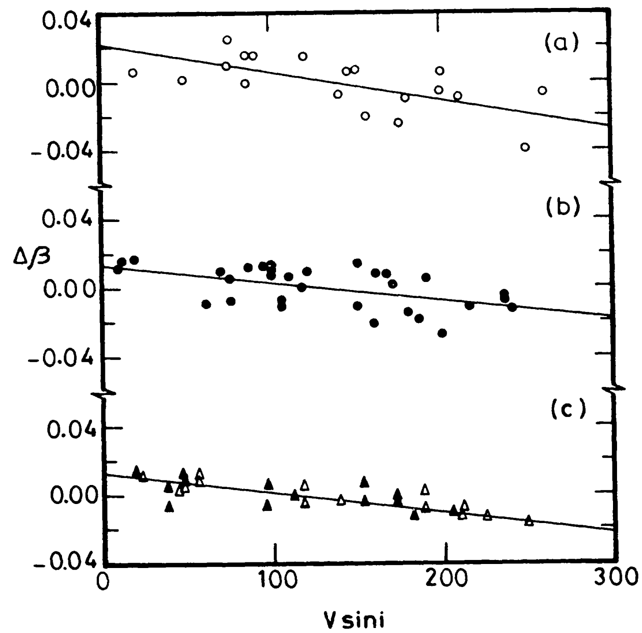

Figure 7. The deviations in β derived from (observed) β, c_0 of A-stars in (a) Alpha Persei, (b) Pleiades, and (c) theoretical predictions for $i=45°$ and $60°$ are plotted against $V\sin i$.

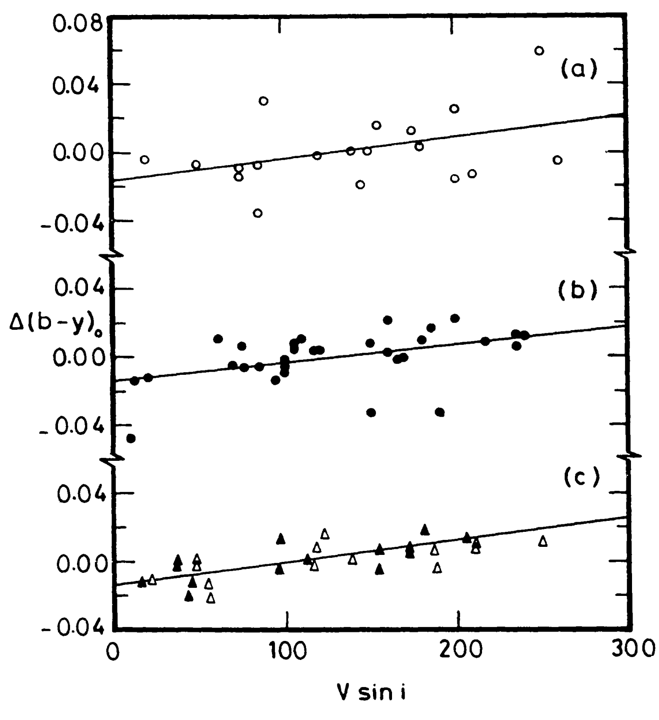

Figure 8. The deviations in $(b-y)_0$ derived from (observed) c_0, $(b-y)_0$ of A stars in (a) Alpha Persei, (b) Pleiades, and (c) theoretical predictions for $i=45°$ and $60°$ are plotted against $V\sin i$.

The colour excess $\Delta(b-y)_0$ derived from this is plotted against $V\sin i$ and is shown in Fig. 8 along with predicted theoretical effects (Section 3.4).

$\Delta(b-y)_0$ derived from β *versus* $(b-y)_0$ relation is found to be extremely small and is not related to the rotational velocity in good agreement with theoretical predictions.

These results are not much different from the conclusions arrived at in Paper 1. However, the derived magnitude of the rotation effect in $(u-b)$ for B stars is found to be larger with the use of observed indices compared to the derived results from dereddened indices. The results for c_1 index for both the B and A stars are similar whether we use dereddened or observed indices. This is as expected since the $(u-b)$ index is affected more by reddening than is c_1.

Gray & Garrison (1989) point out that the system calibration and dereddening procedures for A stars are themselves affected by rotation which would cast some doubt on the use of dereddened indices. This problem of the use of the observed indices as opposed to the use of the dereddened indices must be looked into in greater depth. While the dereddening procedure itself may be affected to some extent by rotation for A stars, the use of observed colour indices for cluster members strongly affected by variable extinction will lead to misleading results for B stars. Probably the variable reddening across the α-Persei cluster is not large enough to have affected our earlier results. However, such variable reddening may be serious for very young clusters embedded in nebulosities. We have therefore decided to use the dereddened indices in the present paper. We will address the question of the role of reddening by extinction and rotation finally when an attempt to calibrate these indices are made.

3.2 *The Effect of Rotation on the Colours of Pleiades Stars*

3.2.1 *B Stars*

Amongst B stars in Pleiades the majority belong to the category of variable radial velocity and emission-lined objects. There are 23 stars of type B in table 4 of Crawford & Perry (1976). If we drop the giants, double-lined binaries, and close visual pairs with $\Delta m < 2.0$ magnitudes, we are left with only 8 stars which can be considered as normal main sequence objects whose colours are free from effects other than that due to rotation. These objects are listed in Table 2. Notwithstanding the fact that this sample is too small to warrant a separate analysis, we derived the residuals in β, c_0, $(u-b)_0$ and $(b-y)_0$ and have listed them in Table 2. The identification numbers for the stars are from Hertzsprung (1947).

From a second-order polynomial fit to β, c_0 values, the residuals Δc_0 and $\Delta\beta$ were derived. The residuals in c_0 for Plèiades B stars are superposed (in Fig. 1) over those derived for the members of the α-Persei cluster. Similarly $\Delta\beta$ for B stars in Pleiades are superposed (in Fig. 4(a)) over those derived for the members of the α-Persei cluster. From the combined data points, we derive

$$\Delta c_0 = 0.402\,(\pm 0.032) \times 10^{-3}\, V \sin i - 0.077\,(\pm 0.007),$$

$$\Delta\beta = -0.145\,(\pm 0.013) \times 10^{-3}\, V \sin i + 0.028\,(\pm 0.003).$$

Similarly from the combined data for Pleiades and α-Persei B stars (Fig. 2) we derive from the β, $(u-b)_0$ relation

$$\Delta(u-b)_0 = 0.468\,(\pm 0.045) \times 10^{-3}\, V \sin i - 0.090\,(\pm 0.009),$$

$$\Delta\beta = -0.114\,(\pm 0.012) \times 10^{-3}\, V \sin i + 0.022\,(\pm 0.002).$$

The $\Delta(b-y)_0$ derived for β, $(b-y)_0$ are superposed over the data for α-Persei in Fig. 3(a). The combined data points yield

$$\Delta(b-y)_0 = 0.039(\pm 0.003) \times 10^{-3} V \sin i - 0.008(\pm 0.001).$$

For comparison in Figs 3, 4 and 5 the predicted values from Collins & Sonneborn (1977) are also shown (see Section 3.4).

3.2.2 *A Stars*

The frequency of double-lined binaries, peculiar stars, emission-lined objects and visual binaries of small separation and small magnitude difference are very small amongst the 32 A type stars listed by Crawford & Perry (1976) in the Pleiades cluster. Following similar procedures we derive from β, c_0 and c_0, $(b-y)_0$ relations

$$\Delta c_0 = 0.273(\pm 0.039) \times 10^{-3} V \sin i - 0.035(\pm 0.006),$$

$$\Delta\beta = -0.108(\pm 0.014) \times 10^{-3} V \sin i + 0.014(\pm 0.003),$$

$$\Delta(b-y)_0 = 0.110(\pm 0.029) \times 10^{-3} V \sin i - 0.014(\pm 0.004),$$

$$\Delta c_0 = 0.345(\pm 0.051) \times 10^{-3} V \sin i - 0.044(\pm 0.007).$$

These results for A stars are displayed in Figs 6(b), 7(b) and 8(b). For comparison we also show in each of these figures the expected theoretical relationship (see Section 3.4) from Collins & Sonneborn (1977). The residuals in c_0, β and $(b-y)_0$ for the Pleiades A stars are listed in Table 3.

3.3 *The Effect of Rotation on Colours of Scorpio-Centaurus Association Stars*

The existence of different subgroups in this association and the fact that the upper Scorpius subgroup is younger than the other two subgroups was pointed out by Blaauw (1959, 1964). If the sample does not confirm to a homogeneous coeval group this would introduce a spread in the observed colour–magnitude diagrams. This is illustrated in Figs 9 and 10. A second-order common polynomial fit was determined for the β versus c_0 relation for the stars in the upper Centaurus and upper Scorpius regions and the colour excess Δc_0 was determined. Fig. 9 is a plot of Δc_0 versus $V \sin i$. Only the two subgroups—upper Centaurus and upper Scorpius—are plotted. Upper Centaurus stars are represented by open squares and upper Scorpius stars by crosses. Similarly in Fig. 10 $\Delta(u-b)_0$ is plotted against $V \sin i$. It is clear from Figs 9 and 10 that the upper Scorpius stars which are younger, lie below the upper Centaurus stars. This would appear as a scatter in the diagram if all the points are plotted with the same symbol. In order to take into account such evolutionary effects even on the main sequence, the data analysis was carried out independently for the lower Centaurus, upper Centaurus and upper Scorpius subgroups. Removing the binaries, peculiar and emission-lined stars, whose colours may be affected due to reasons other than rotation, we are left with 10 stars out of the 13 possible stars of luminosity class IV and V in the lower Centaurus subgroup and 27 stars out of the possible 42 in the upper Centaurus subgroup listed in table 3 of Glaspey (1971). We have analysed them

Table 3. Effects of rotation for Pleiades A stars.

Hz	HD	Sp.	$V \sin i$	from β, c_0		from c_0, $(b-y)_0$		from β, $(b-y)_0$	
				Δc_0	$\Delta\beta$	Δc_0	$\Delta(b-y)_0$	$\Delta(b-y)_0$	$\Delta\beta$
27	23157	A9V	100	−0.021	0.010	−0.023	−0.007	0.003	0.001
28	23156	A7V	70	−0.024	0.010	−0.036	−0.005	0.002	−0.003
43	23194	A5V	20	−0.044	0.017	−0.034	−0.012	0.006	0.004
92	23246	A8V	200	0.040	−0.027	0.031	0.022	−0.004	−0.005
146	23325	Am?	75	0.008	−0.007	−0.006	0.006	−0.002	−0.005
187	23361	A3V	235	0.019	−0.007	0.009	0.005	−0.003	−0.004
206	23375	A9V	75	−0.014	0.005	−0.007	−0.006	0.000	0.002
248	23410	A0V	190	−0.005	0.005	−0.029	−0.033	−0.027	−0.011
251	23409	A2V	170	−0.001	0.002	0.008	−0.002	0.001	0.003
313	23479	A7	150	0.010	−0.011	0.021	0.007	−0.001	0.002
341	23489	A2V	110	−0.001	0.006	0.048	0.010	0.018	0.018
371	23512	A0V	150	−0.029	0.014	−0.027	−0.033	−0.015	−0.001
447	23567	A9	95	−0.026	0.013	−0.036	−0.014	−0.001	−0.004
457	23585	A9V	100	−0.027	0.013	−0.023	−0.010	0.004	0.003
501	23607	A7V	12	−0.040	0.017	−0.053	−0.014	0.002	−0.004
508	23629	A0V	160	−0.012	0.008	0.020	0.002	0.011	0.012
510	23632	A1V	235	0.032	−0.005	0.059	0.013	0.009	0.010
513	23628	A4V	215	0.023	−0.011	0.003	0.009	−0.004	−0.007
520	23631	A2V	10	−0.026	0.011	−0.071	−0.048	−0.036	−0.019
534	23643	A3V	185	0.046	−0.019	0.026	0.016	−0.005	−0.008
693	23733	A9V	180	0.010	−0.015	0.043	0.010	0.001	0.008
742	23763	A1V	105	0.031	−0.011	0.054	0.028	0.016	0.011
792	23791	A8V	85	−0.025	0.012	−0.034	−0.007	0.003	−0.001
885	23863	A7V	160	0.043	−0.022	0.018	0.021	−0.004	−0.009
891	23872	A2V	240	0.045	−0.011	0.059	0.013	0.003	0.005
924	23886	A3V	165	−0.020	0.008	−0.014	−0.003	0.005	0.003
975	23924	A7V	100	−0.019	0.007	−0.028	−0.002	0.003	−0.002
996	23948	A2V	120	−0.016	0.009	0.027	0.004	0.016	0.016
Tr47	23155		106	0.023	−0.007	0.019	0.005	−0.002	−0.002
S84	23430		118	−0.005	0.001	−0.014	0.003	0.002	−0.002
S108	23610			0.006	−0.005	−0.009	0.009	0.001	−0.004
S115	23664		61	0.017	−0.010	−0.002	0.011	−0.002	−0.006

separately and the colour excesses were calculated in c_0, $(u-b)_0$, β and $(b-y)_0$. $\Delta\beta$ was calculated from both β, c_0 and β, $(u-b)_0$ relations.

One has to be careful in the choice of the stars for determining rotation effects on colours. We illustrate this for the members of upper Scorpius subgroup. The notes given in various papers listed in Table 1 and the work of Garrison (1967) and Rajamohan & Pati (1980) were used for the selection of stars. Out of the 61 stars listed by Glaspey (1971) in the upper Scorpius region 4 have no β value. 8 stars deviate considerably in the β, c_0 plot. Among these 8, HD 142983 is classified as B5III Pe and HD 147196 as B8V nnP (Bright Star Catalogue: Hoffleit & Jaschek 1982) and therefore are emission-lined objects. HD 142301 and HD 147890 are spectroscopically peculiar. HD 148594 is classified as B8Vnn with a $V \sin i$ value of 300 km s^{-1}. It was probably an emission-lined object at the time of Glaspey's observation. HD146332 is not a main-sequence star (B5II). That leaves HD 146029 and HD 147889 without any specific explanation. Their $V \sin i$ values are 250 and

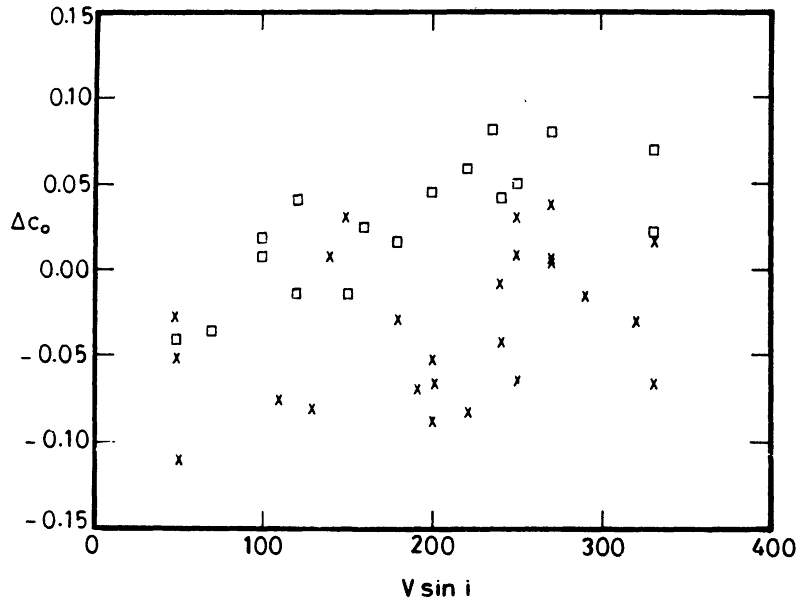

Figure 9. The deviations in c_0 derived from the observed β, c_0 of the two large subgroups of Scorpio-Centaurus association members are plotted against $V \sin i$. Note the different distribution of upper Centaurus (open squares) and upper Scorpius (crosses) members due to evolutionary effects.

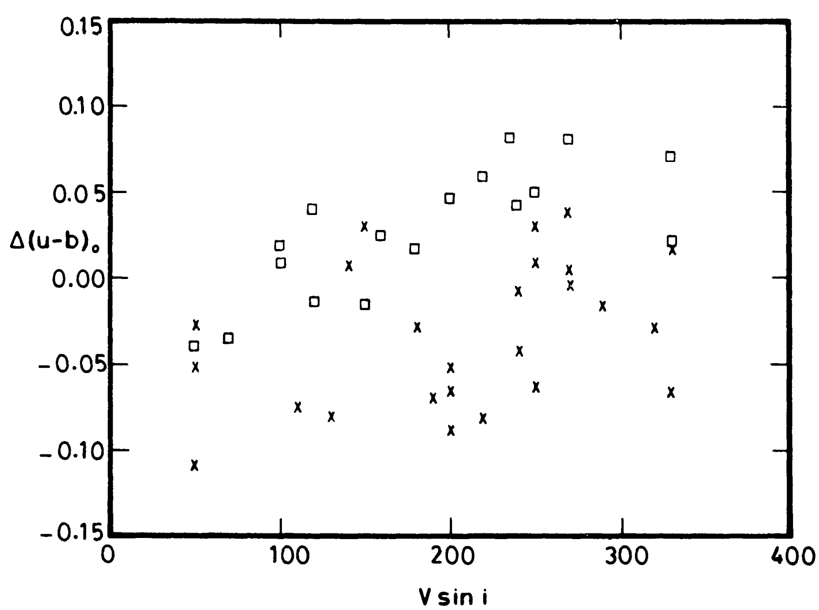

Figure 10. The deviations in $(u-b)_0$ derived from the observed β, $(u-b)_0$ of the two large subgroups of Scorpio-Centaurus association members are plotted against $V \sin i$. Notice the different distributions of upper Centaurus (open squares) and upper Scorpius (crosses) members due to evolutionary effects.

100 km s^{-1}. Among the rest of the 49 stars 3 are giants. This leaves a sample of only 46 stars, of which 28 are apparently normal single main-sequence stars, 7 peculiar, 3 probably peculiar, 3 emission-lined objects, 3 double-lined spectroscopic binaries and 2 very close binaries with Δm less than 2 magnitudes.

We used this sample of 28 apparently normal stars to derive the relationship between β and c_0. Seven of the objects deviate considerably while we found that six out of the 10 peculiar stars seem to fit the Δc_0 versus $V \sin i$ relationship defined by normal single stars. Probably the line blanketing effects for these six stars are not large enough to have affected their colours. These 27 were used to derive the relationship between β and c_0.

The deviation Δc_0 for these 27 stars together with Δc_0 for 27 upper Centaurus and 10 lower Centaurus members are given in Table 4 and are plotted in Fig. 11. Fig. 11 may be compared with Fig. 9 to see the effect produced by small evolutionary differences between the subgroups even on the main sequence. Rotation effects cannot be noticed for such groups unless this evolutionary effect is taken into account. It must be emphasized once again that in the methodology adopted, only differences in age of stars within a cluster will produce a scatter. Differences in age of main sequence stars from cluster to cluster is taken care of by analysing them independently. On an average, we still find that the upper Scorpius subgroup objects lie slightly below the upper Centaurus subgroup. One possible cause could be the highly variable reddening across the upper Scorpius subgroup. A least square fit excluding HD 145792 and 142669 gives

$$\Delta c_0 = 0.280(\pm 0.033) \times 10^{-3} V \sin i - 0.059(\pm 0.007).$$

Similarly $\Delta\beta$ for these 27 stars together with $\Delta\beta$ for 27 upper Centaurus and 10 lower Centaurus members derived from β, c_0 relation are plotted in Fig. 4(b). A least square fit gives

$$\Delta\beta = -0.070(\pm 0.009) \times 10^{-3} V \sin i + 0.015(\pm 0.002).$$

The same 27 stars of upper Scorpius are used to derive the relationship between β and $(u-b)_0$. The deviations $\Delta(u-b)_0$ for these 27 stars together with $\Delta(u-b)_0$ for 10 lower Centaurus and 27 upper Centaurus members are plotted in Fig. 12. In the $\Delta(u-b)_0$ versus $V \sin i$ diagram HD 129116, 144294, 142114, 144334, 145792, and 146285 are found to deviate considerably. Excluding them, we derive

$$\Delta(u-b)_0 = 0.327(\pm 0.044) \times 10^{-3} V \sin i - 0.064(\pm 0.009).$$

$\Delta\beta$ for the 27 stars in upper Scorpius together with $\Delta\beta$ for 10 lower Centaurus and 27 upper Centaurus stars derived from β, $(u-b)_0$ relation are plotted in Fig. 5(b). A least square fit excluding the 6 stars listed above gives

$$\Delta\beta = -0.078(\pm 0.010) \times 10^{-3} V \sin i + 0.018(\pm 0.002).$$

The colour excess in $(b-y)_0$ is calculated from β, $(b-y)_0$ relation for the 27 stars in the upper Scorpius and is plotted in Fig. 3(b) together with $\Delta(b-y)_0$ for 10 lower Centaurus and 27 upper Centaurus stars. From this (excluding 145792 and 142669) we derive

$$\Delta(b-y)_0 = 0.030(\pm 0.004) \times 10^{-3} V \sin i - 0.006(\pm 0.008).$$

The various colour excesses due to rotation derived for the Scorpio-Centaurus association members are given in Table 4.

Table 4. Effect of rotation for Sco-Cen association B stars.

HD	Sp.	$V\sin i$	from β, c_0		from $(u-b)_0, \beta$		from $\beta, (b-y)_0$	
			Δc_0	$\Delta\beta$	$\Delta(u-b)_0$	$\Delta\beta$	$\Delta(b-y)_0$	$\Delta\beta$
				Lower-Cen				
105937	B3V	210	−0.026	0.010	−0.022	0.008	−0.005	0.014
106490	B2IV	120	0.022	−0.001	0.028	−0.002	0.002	0.001
106983	B2.5V	140	−0.014	−0.005	−0.009	−0.004	−0.002	−0.005
108483	B2V	220	−0.023	−0.005	−0.028	−0.003	−0.002	−0.006
109026	B5V	180	0.026	−0.005	0.046	−0.007	0.003	−0.005
109668	B2IV–V	190	−0.046	0.004	−0.056	0.004	−0.004	0.001
110956	B3V	75	−0.038	0.009	−0.057	0.011	−0.003	0.008
112078	B4V	330	0.084	−0.021	0.079	−0.018	0.008	−0.020
113703	B5V	160	0.002	0.013	−0.008	0.011	0.001	0.013
116087	B3V	300	0.014	0.000	0.027	−0.002	0.002	0.000
				Upper-Cen				
120307	B2IV	100	−0.008	0.004	−0.010	0.003	−0.001	0.000
121743	B2IV	120	−0.027	0.007	−0.040	0.007	−0.005	0.012
121790	B2V	200	0.006	−0.001	0.022	−0.005	0.000	−0.002
123291	B9	—	0.088	−0.022	0.115	−0.022	0.008	−0.021
125238	B2.5IV	235	0.044	−0.013	0.053	−0.012	0.005	−0.015
125823	B3P	100	−0.003	0.000	−0.009	0.001	0.000	−0.002
126110	B9	—	0.031	−0.004	0.032	−0.003	0.002	−0.002
126135	B9V	—	0.024	−0.009	0.038	−0.009	0.002	−0.005
128819	B7	—	0.017	−0.006	0.028	−0.007	0.001	−0.002
129116	B2.5V	170	−0.039	0.008	−0.089	0.016	−0.003	0.006
132094	B8	—	−0.002	0.006	−0.008	0.006	−0.001	0.006
132955	B3V	50	−0.065	0.014	−0.081	0.014	−0.015	0.039
133937	B7V	330	0.021	−0.010	0.025	−0.008	0.003	−0.009
136298	B2IV	240	0.033	−0.006	0.028	−0.004	0.003	−0.010
136482	B8	—	0.070	−0.021	0.079	−0.017	0.008	−0.020
136504	B2IV–V	120	0.003	−0.002	0.013	−0.004	0.001	−0.004
136664	B3V	220	0.003	−0.004	0.022	−0.006	0.002	−0.006
137432	B3V	160	−0.017	0.001	−0.016	0.001	0.000	0.000
138564	B9V	—	−0.109	0.043	−0.124	0.035	−0.010	0.034
138690	B2V	250	0.017	−0.004	0.029	−0.006	0.002	−0.008
138769	B3IVP	150	−0.050	0.011	−0.052	0.008	−0.004	0.010
138940	B8	—	0.032	−0.005	0.033	−0.004	0.003	−0.006
139233	B7V	—	−0.020	0.009	−0.034	0.010	−0.002	0.010
140008	B6V	70	−0.065	0.013	−0.080	0.014	−0.005	0.013
143118	B2V	270	0.051	−0.011	0.065	−0.012	0.005	−0.015
143699	B6V	180	−0.021	0.002	−0.024	0.002	0.000	−0.002
144294	B2.5	330	−0.011	0.001	−0.013	0.001	0.000	0.000
				Upper-Sco				
139160	B7IV	200	−0.040	0.011	−0.037	0.008	−0.003	0.009
141637	B2V	270	0.017	−0.007	0.046	−0.010	0.001	−0.006
142096	B2.5Vn	200	−0.043	0.012	−0.056	0.011	−0.004	0.011
142114	B2.5Vn	330	0.013	−0.005	−0.030	0.005	0.001	−0.005
142165	B6IVn	250	0.038	−0.011	0.038	−0.008	0.003	−0.010
142315	B8V	250	0.069	−0.017	0.059	−0.012	0.007	−0.018
142378	B3V	240	0.020	−0.007	0.025	−0.006	0.002	−0.007
142669	B2IV–V	140	0.059	−0.019	0.049	−0.011	0.006	−0.020
142883	B3V	110	−0.042	0.011	−0.045	0.009	−0.004	0.010
142884	B9P Si	220	−0.017	0.004	−0.051	0.010	−0.001	0.004

Table 4. Continued.

HD	Sp.	$V \sin i$	from β, c_0		from $(u-b)_0$, β		from β, $(b-y)_0$	
			Δc_0	$\Delta\beta$	$\Delta(u-b)_0$	$\Delta\beta$	$\Delta(b-y)_0$	$\Delta\beta$
142990	B5IV	150	0.024	−0.008	0.065	−0.014	0.002	−0.008
143567	B9V	290	−0.017	0.006	0.016	−0.002	−0.002	0.006
143600	B9V	320	−0.001	0.003	0.005	0.001	0.000	0.002
144334	B8P	50	−0.020	0.005	0.003	−0.001	−0.001	0.004
144470	B1V	130	−0.034	0.008	−0.034	0.005	−0.004	0.009
144844	B9IVP?	190	−0.044	0.012	−0.040	0.009	−0.004	0.012
145554	B9V	180	0.001	0.002	0.003	0.001	0.000	0.002
145631	B9.5Vn	200	−0.029	0.009	−0.018	0.006	−0.003	0.010
145792	B5V	50	0.022	−0.007	0.059	−0.012	—	—
146001	B7IV	240	0.008	−0.002	−0.014	0.003	0.001	−0.003
146285	B8IV	200	−0.039	0.011	−0.090	0.020	−0.002	0.007
146416	B9V	330	0.058	−0.013	0.047	−0.009	0.005	−0.012
146706	B9V	270	0.061	−0.014	0.069	−0.014	0.005	−0.013
147010	B9P	50	−0.061	0.017	−0.022	0.005	−0.006	0.016
148579	B9V	250	−0.008	0.004	−0.032	0.008	−0.001	0.004
148605	B2V	270	0.050	−0.016	0.043	−0.010	0.004	−0.015
149438	B0V	50	−0.044	0.011	−0.058	0.009	−0.004	0.009

3.4 *Theoretical Predictions*

3.4.1 *The B-Stars*

Collins & Sonneborn (1977) have calculated theoretical values of $(b-y)$, c_1, m, and β for rigidly rotating model stars. Plots are made with β and the different predicted colour indices at each value of i, the inclination between the line of sight and the rotation axis for various values of fractional angular velocity ω. Fig. 13 is a plot shown as an example between β and c_1 for $i=60°$ and $\omega=0.2$, 0.5, 0.8 and 0.9 for B0 to B9 stars. The points corresponding to different ω values are marked with different symbols and joined by dotted lines for each spectral class. The shift Δc along the x-axis for each value of ω for a given spectral type was determined from Fig. 12. Similarly the shift $\Delta\beta$ along the y-axis was determined for each value of ω. This was repeated for each value of i and the deviation in c_1 and β from the relation for $\omega=0.2$ is given in Table 5. We chose to derive the reddening due to rotation relative to $\omega=0.2$ for the following reason. Observationally one derives only the projected rotational velocity and the value of i is unknown. We do not know whether a really nonrotating, single, normal, main-sequence star exists (Rajamohan 1978). Also for comparison of observations with theory, it is sufficient if we derive the slope of the reddening effect due to rotation.

In $(u-b)$ also a similar analysis was done for various values of i and different values of ω and for different spectral types of the stars. These deviations are given in Table 6.

As an example we have plotted in Figs 14 and 15 the deviations in Δc_1 and $\Delta(u-b)$ in Tables 5 and 6 against $V \sin i$ for a representative value of $i=60°$ and $\omega=0.2$ to 0.9 for B0 to B9 stars. It is evident that the slope of the predicted effect is a function of the spectral type: low for B0 stars and high for B9 stars.

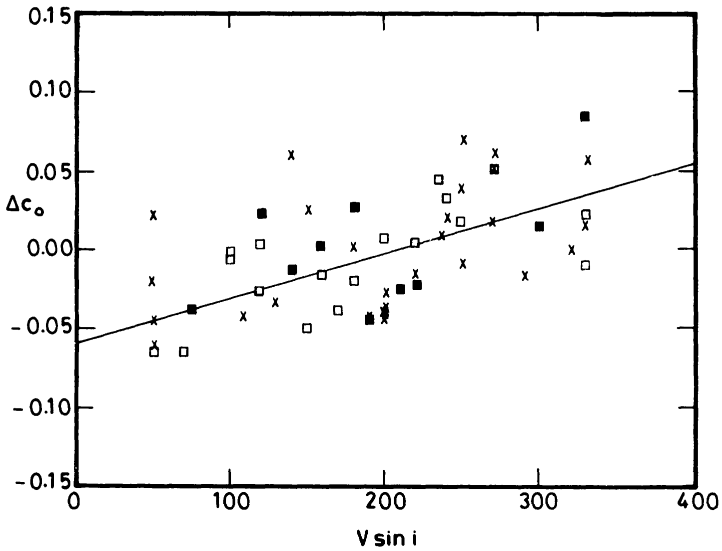

Figure 11. The deviations in c_0 derived from β, c_0 are plotted against $V\sin i$ for Scorpio-Centaurus members. Each subgroup was analysed independently and then superposed in this figure. Lower Centaurus (filled squares), upper Centaurus (open squares) and upper Scorpius (crosses).

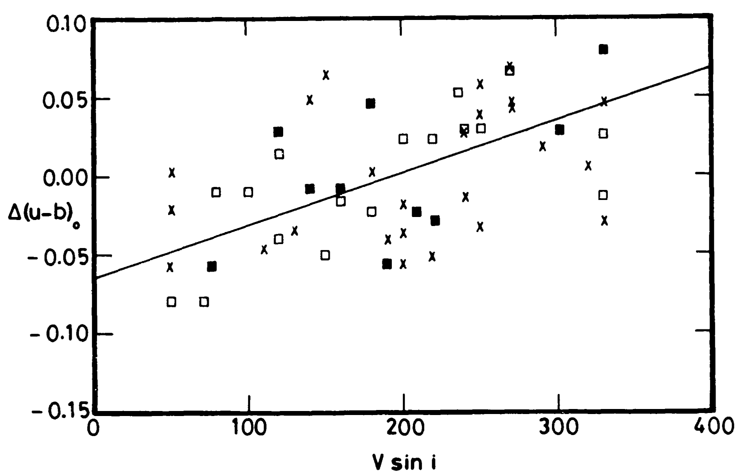

Figure 12. The deviations in $(u-b)_0$ are plotted against $V\sin i$ for Scorpio-Centaurus members. Symbols have the same meaning as in Fig. 10.

In order to compare these predictions from theoretical models of Collins and Sonneborn (1977) we have analysed the theoretical u, v, b, y and H_β indices in a similar way as we did for the cluster data. For this we have arranged the B stars into two groups B0 to B3 and B5 to B9. For each group at a given value of i and different values of ω, a second order polynomial fit was determined for the β versus c_1, β versus $(u-b)$ and β versus $(b-y)$ relation and the deviations $\Delta\beta$, Δc, $\Delta(u-b)$ and $\Delta(b-y)$ were determined. This was done for $i = 30, 45, 60$ and $90°$. The slopes of the relation between $V\sin i$ and the colour excess derived for different values of i for B5 to B9 stars are given

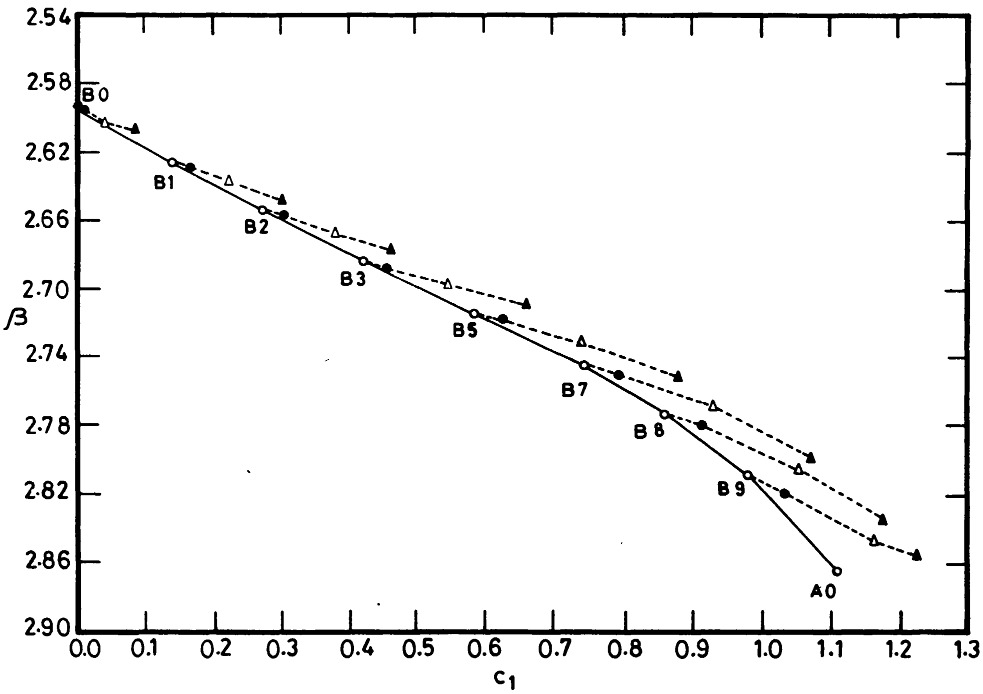

Figure 13. β versus c_1 plot from Collins & Sonneborn (1977) for $i=60°$ and $\omega=0.2$ (open circles), $\omega=0.5$ (filled circles), $\omega=0.8$ (open triangles) and $\omega=0.9$ (filled triangles).

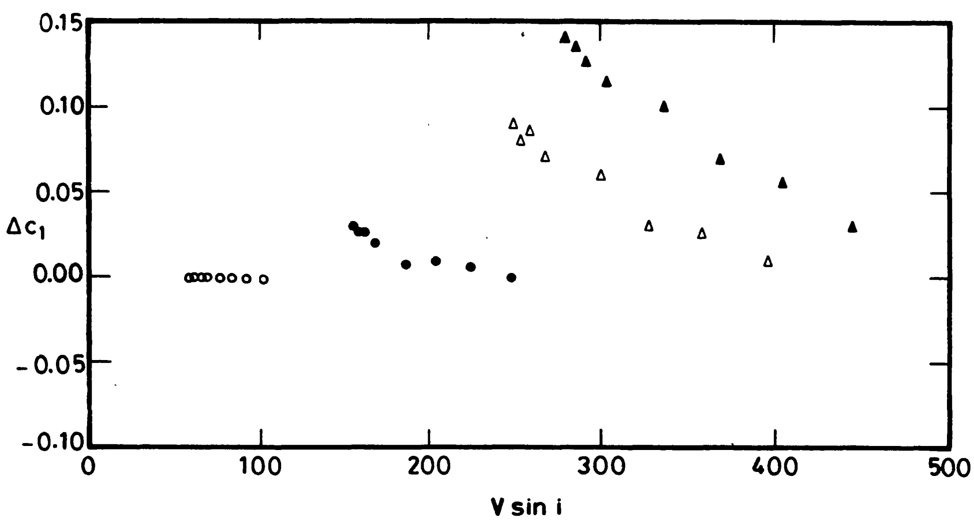

Figure 14. The deviations in c_1 derived from Fig. 12 are plotted against $V\sin i$ for $\omega=0.2$ (open circles), $\omega=0.5$ (filled circles), $\omega=0.8$ (open circles) and $\omega=0.9$ (filled triangles). The deviation at any given ω increases from B0 to B9.

in Table 7 and for B0 to B3 stars are given in Table 8. These were derived in the following manner. Four values of ω were assigned to each spectral type. There are four spectral subclasses between B0 to B3 and B5 to B9 for which predicted values of β and various colour indices are available. Hence for each group at a given value of i we have sixteen values of various colour indices. These sixteen values were analysed the same way as we did the cluster stars. This was repeated for the next value of i.

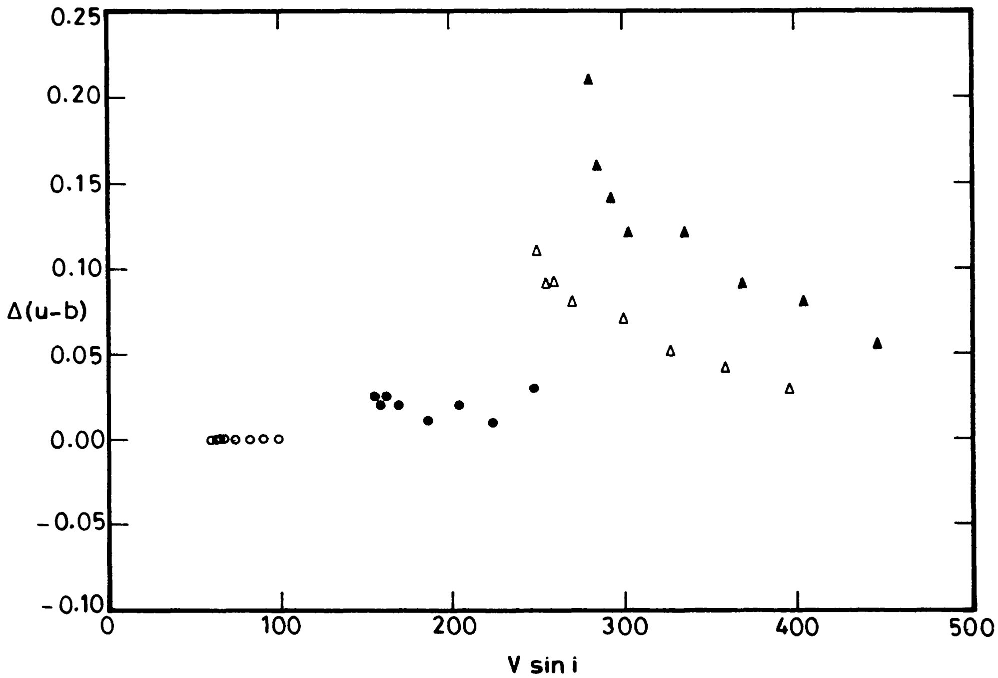

Figure 15. Deviations in $(u-b)$ derived from theoretical predictions for β, $(u-b)$ are plotted against $V \sin i$. Symbols have the same meaning as in Fig. 13. Note that the slope of the rotation effect is a function of spectral type in Figs 14 and 15.

Typical examples for $i=45°$ and $i=60°$ (32 values each set) are plotted in Figs 3c, 4c and 5c.

3.4.2 *A Stars*

For A type stars, we followed a similar procedure and analysed the theoretical data the same way as we did for cluster data. We chose the theoretical indices for A3 to F0 type stars since the α-Persei and Pleiades cluster A type groups that we analysed contain mainly A3 to F0 type stars. For each value of i and different values of ω a second order polynomial fit was determined for β, c_1; c_1, $(b-y)$; and β, $(b-y)$ and the deviations $\Delta\beta$, Δc and $\Delta(b-y)$ were determined. This was done for $i=30$, 45, 60 and 90°. The slopes of the relation between $V \sin i$ and the colour excess derived for different values of i are given in Table 9.

4. Discussion

4.1 *The B Stars*

Before analysing the available observational data for determining rotation effects, we first had to choose a homogeneous group of stars, at a common stage of evolution, with colours unaffected due to reasons other than rotation. However, the sample of such a group available is small in each cluster and further division by spectral type is

Table 5. Theoretical effects of rotation.

Sp.	ω	$i=30$		$i=60$		$i=90$	
		$\Delta\beta$	Δc_1	$\Delta\beta$	Δc_1	$\Delta\beta$	Δc_1
BO	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.010	0.070	0.000	0.000	0.010	0.070
	0.8	0.010	0.070	0.002	0.010	0.010	0.070
	0.9	0.010	0.070	0.008	0.030	0.012	0.090
B1	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.003	0.015	0.002	0.005	0.001	0.005
	0.8	0.008	0.035	0.006	0.025	0.006	0.035
	0.9	0.009	0.050	0.012	0.055	0.014	0.080
B2	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.003	0.015	0.007	0.010	0.002	0.015
	0.8	0.005	0.025	0.017	0.030	0.007	0.040
	0.9	0.010	0.050	0.014	0.070	0.016	0.080
B3	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.003	0.015	0.005	0.007	0.002	0.015
	0.8	0.005	0.025	0.010	0.060	0.013	0.060
	0.9	0.010	0.050	0.020	0.100	0.020	0.100
B5	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.003	0.025	0.004	0.020	0.004	0.020
	0.8	0.012	0.060	0.014	0.070	0.016	0.080
	0.9	0.018	0.090	0.030	0.115	0.030	0.120
B7	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.003	0.015	0.006	0.025	0.005	0.030
	0.8	0.020	0.060	0.026	0.085	0.023	0.080
	0.9	0.040	0.110	0.040	0.125	0.047	0.130
B8	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.005	0.020	0.008	0.025	0.006	0.025
	0.8	0.027	0.070	0.031	0.080	0.038	0.090
	0.9	—	0.130	—	0.135	—	0.150
B9	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.010	0.030	0.012	0.030	—	0.030
	0.8	—	0.085	—	0.090	—	0.100
	0.9	—	0.130	—	0.140	—	0.160

not possible at this stage. Therefore a comparison with theoretical predictions at each spectral type is impossible except for B2 and B3 stars in upper Centaurus: Further, only projected rotational velocities can be derived from observations and i remains unknown. Therefore, the α-Persei and Pleiades B and A stars were analysed separately. The Scorpio-Centaurus association members are all of type B. However, we found that the predicted slope of the rotation effect for various colour indices is strongly dependent on the spectral type. The slope increases as we go from B0 to B9. Therefore, we decided to subdivide the B-stars into two subgroups; namely B0 to B3 and B5 to B9. The choice of this subdivision was based on the spectral type distribution in these three clusters.

In α-Persei and Pleiades, out of the total 31 apparently normal main sequence stars 19 are in the spectral type range B5 to B9, 2 stars in the range B0 to B3 and 10 in the range A0 to A2. In Scorpio-Centaurus association, out of the 64 apparently normal

Table 6. Theoretical effects of rotation

Sp.	ω	$i=30$		$i=60$		$i=90$	
		$\Delta\beta$	$\Delta(u-b)$	$\Delta\beta$	$\Delta(u-b)$	$\Delta\beta$	$\Delta(u-b)$
B0	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.001	0.004	0.003	0.030	0.001	0.010
	0.8	0.003	0.020	0.004	0.030	0.002	0.020
	0.9	0.006	0.040	0.008	0.055	0.009	0.070
B1	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.001	0.010	0.002	0.010	0.001	0.010
	0.8	0.005	0.035	0.006	0.040	0.006	0.040
	0.9	0.008	0.050	0.012	0.080	0.013	0.090
B2	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.001	0.010	0.003	0.020	0.002	0.010
	0.8	0.004	0.030	0.008	0.050	0.007	0.050
	0.9	0.008	0.060	0.012	0.090	0.015	0.100
B3	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.002	0.010	0.002	0.010	0.002	0.020
	0.8	0.006	0.045	0.009	0.070	0.010	0.080
	0.9	0.012	0.080	0.017	0.120	0.020	0.120
B5	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.002	0.015	0.003	0.020	0.002	0.020
	0.8	0.009	0.060	0.010	0.080	0.014	0.090
	0.9	0.016	0.100	0.020	0.120	0.020	0.140
B7	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.002	0.020	0.005	0.025	0.006	0.025
	0.8	0.015	0.070	0.018	0.090	0.025	0.110
	0.9	0.030	0.120	0.033	0.140	0.024	0.160
B8	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.004	0.020	0.005	0.020	0.006	0.030
	0.8	0.020	0.080	0.022	0.090	0.024	0.100
	0.9	—	0.140	—	0.160	—	0.180
B9	0.2	0.000	0.000	0.000	0.000	0.000	0.000
	0.5	0.005	0.020	0.006	0.025	0.010	0.030
	0.8	—	0.090	—	0.110	—	0.120
	0.9	—	0.180	—	0.210	—	0.250

Table 7. Theoretical reddening due to rotation for 100 km s^{-1} of $V \sin i$ for B5 to B9 stars.

i	from β, c_1		from β, $(u-b)$		from β, $(b-y)$		from c_1, $(b-y)$	
	c_1	β	β	$(u-b)$	β	$(b-y)$	c_1	$(b-y)$
30	0.058	−0.014	−0.012	0.066	−0.010	0.006	0.006	0.000
	±0.007	±0.002	±0.002	±0.009	±0.003	±0.002	±0.005	±0.002
45	0.046	−0.011	−0.010	0.054	−0.009	0.005	0.000	0.000
	±0.005	±0.001	±0.002	±0.007	±0.002	±0.001	±0.004	±0.001
60	0.041	−0.010	−0.009	0.049	−0.008	0.005	0.001	0.000
	±0.004	±0.001	±0.001	±0.006	±0.002	±0.001	±0.003	±0.001
90	0.038	−0.009	−0.008	0.047	−0.007	0.005	0.000	0.000
	±0.004	±0.001	±0.001	±0.005	±0.002	±0.001	±0.003	±0.001
mean	0.046	−0.011	−0.010	0.054	−0.009	0.005	0.002	0.000

Table 8. Theoretical reddening due to rotation for 100 $\mathrm{km\,s^{-1}}$ of $V\sin i$ for B0 to B3 stars.

i	from β, c_1		from β, $(u-b)$		from β, $(b-y)$		from c_1, $(b-y)$	
	c_1	β	β	$(u-b)$	β	$(b-y)$	c_1	$(b-y)$
30	0.021	−0.004	−0.004	0.027	−0.004	0.004	−0.001	0.001
	±0.002	±0.000	±0.000	±0.003	±0.000	±0.000	±0.001	±0.000
45	0.016	−0.003	−0.003	0.022	−0.004	0.003	−0.004	0.001
	±0.002	±0.000	±0.000	±0.003	±0.000	±0.000	±0.001	±0.000
60	0.016	−0.003	−0.003	0.021	−0.004	0.003	−0.003	0.001
	±0.002	±0.000	±0.000	±0.002	±0.000	±0.000	±0.001	±0.000
90	0.015	−0.003	−0.003	0.021	−0.003	0.003	−0.002	0.001
	±0.002	±0.000	±0.000	±0.002	±0.000	±0.000	±0.000	±0.000
mean	0.017	−0.003	−0.003	0.023	−0.004	0.003	−0.003	0.001

main-sequence stars, 32 are of type B5 to B9 and 32 are of spectral type B0 to B3. Among them the $V\sin i$ values of 9 stars of type B5 to B9 are not known.

In order to compare the results of analysis of the data for these clusters with predictions of Collins & Sonneborn (1977), the theoretical line indices were divided into B0 to B3 and B5 to B9 groups (see Section 3.4). In Table 10, the slopes of the observed relation between colour excess and $V\sin i$ are tabulated.

For Δc_0, the observed slope for α-Persei and Pleiades members is 0.040 ± 0.003 magnitudes per 100 $\mathrm{km\,s^{-1}}$ of $V\sin i$. This can be compared with the expected theoretical value for B5 to B9 stars in Table 7. The value of the slope for Δc_0 ranges from 0.038 ± 0.004 for $i=90°$ to 0.058 ± 0.007 for $i=30°$. We have no specific reason to believe that the rotation axes in clusters are randomly distributed (Rajamohan 1978). Therefore, the observed value of 0.04 for the slope of Δc_0, $V\sin i$ relation for α-Persei and Pleiades members can be deemed to be in excellent agreement with theoretical predictions of Collins & Sonneborn (1977).

Similarly in $(u-b)_0$, the observed effect of 0.044 ± 0.005 per 100 $\mathrm{km\,s^{-1}}$ of $V\sin i$ is in excellent agreement with the average predicted value of about 0.05 for B5 to B9 stars. From β, $(b-y)$ we derive that the effect in $(b-y)$ is 0.004 per 100 $\mathrm{km\,s^{-1}}$ of $V\sin i$ for α-Persei and Pleiades in agreement with the value of 0.003 predicted by theory. In a colour-colour plot of c_1, $(b-y)$ no effect is found, again in excellent agreement with theoretical predictions. Comparison of the various observed slopes given in Table 9 for α-Persei and Pleiades are found, in general, to be in excellent agreement with predictions made from theory for B5 to B9 stars.

The Scorpio-Centaurus association consists of B0 to B9 stars and the average slope derived for various colour indices are in good agreement with the average value predicted for B0 to B9 stars. We tested this, in particular, by deriving the reddening in c_0 independently for upper Centaurus stars which are mostly B2 and B3 stars. The derived value of 0.017 ± 0.005 for this subgroup is in excellent agreement with that predicted by theory for B2 and B3 stars (see Fig. 16). The value derived from Collins & Sonneborn (1977) predicted colour indices lead to a value for Δc_1 of 0.018 ± 0.002 for B2 and B3 stars.

Rotation also affects the observed spectral types at a given mass. However, this effect is considerable only when the stars rotate close to their break-up speeds. Such objects have already been eliminated as most of them would appear as emission-lined

Table 9. Observed reddening due to rotation for 100 $km\,s^{-1}$ of $V \sin i$ in B stars.

Sp.	No. of stars	from β, c_0		from β, $(u-b)_0$		from β, $(b-y)_0$		from c_0, $(b-y)_0$	
		c_0	β	β	$(u-b)_0$	β	$(b-y)_0$	c_0	$(b-y)_0$
α-Persei									
B0–B3	2	0.044	−0.015	−0.013	0.053	−0.016	0.004	0.000	0.000
B5–B9	14	±0.003	±0.001	±0.001	±0.005	±0.001	±0.000	±0.000	±0.000
A0–A2	7								
α-Persei + Pleiades									
B0–B3	2	0.040	−0.015	−0.011	0.047	−0.016	0.004	0.000	0.000
B5–B9	19	±0.003	±0.001	±0.001	±0.005	±0.001	±0.000	±0.000	±0.000
A0–A2	10								
Sco-Cen									
B0–B3	31	0.028	−0.007	−0.006	0.033	−0.008	0.003	0.000	0.000
B5–B9	22	±0.003	±0.001	±0.001	±0.004	±0.001	±0.000	±0.000	±0.000
				Theoretical means					
B5–B9		0.046	−0.011	−0.010	0.054	−0.009	0.005	0.002	0.000
B0–B3		0.017	−0.003	−0.003	0.023	−0.004	0.003	−0.003	0.001
B0–B9		0.032	−0.007	−0.007	0.039	−0.007	0.004	0.000	0.000

Table 10. Theoretical reddening due to rotation for 100 $km\,s^{-1}$ of $V \sin i$ in A stars.

i	from β, c_1		from c, $(b-y)$		from β, $(b-y)$	
	c_1	β	$(b-y)$	c_1	$(b-y)$	β
30	0.035	−0.016	0.020	0.041	0.003	0.003
	±0.004	±0.002	±0.003	±0.006	±0.002	±0.002
45	0.027	−0.012	0.013	0.026	0.000	0.000
	±0.003	±0.001	±0.002	±0.005	±0.001	±0.001
60	0.022	−0.011	0.009	0.019	−0.001	−0.002
	±0.003	±0.001	±0.002	±0.004	±0.001	±0.001
90	0.016	−0.008	0.006	0.012	−0.002	−0.002
	±0.003	±0.001	±0.002	±0.003	±0.001	±0.001
mean	0.025	−0.012	0.012	0.025	0.000	0.000

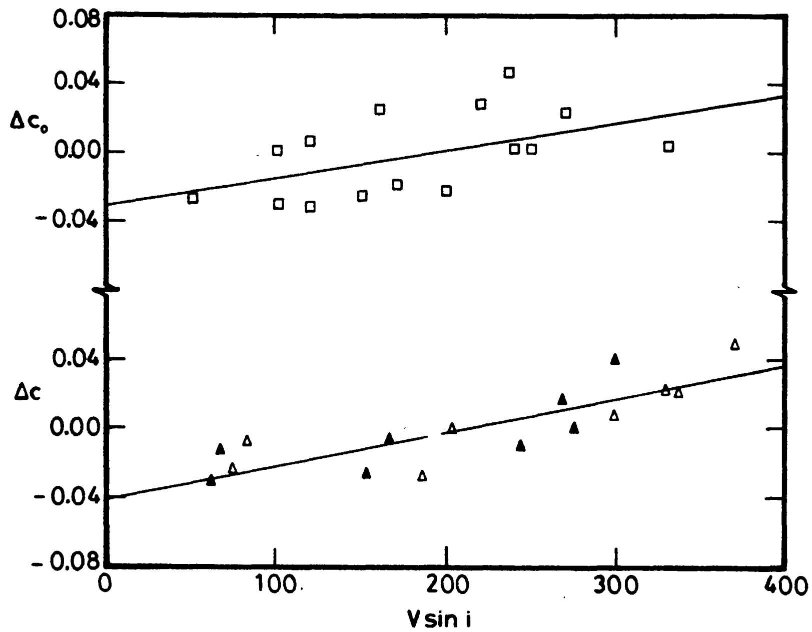

Figure 16. The deviations in c_0 derived from β, c_0 of B2, B3 stars in (a) Upper-Centaurus, (b) theoretical predictions for $i=45°$ and 60° are plotted against $V \sin i$.

objects. Only few stars rotate near break-up limits (see also Collins & Sonneborn 1977). For the large majority of the stars in Table 2–4 this effect would not be more than one or two spectral subdivisions. The results in Tables 8 and 10 should be highly representative for the observed spectral type groups given.

These results suggest that the main-sequence stars of type B are probably rigid rotators and that differential rotation for these objects can be ruled out. Gray & Garrison (1987) suggested that the A stars in the field are probably rotating differentially. We discuss this in the next subsection on A-stars.

Table 11. Observed reddening due to rotation for 100 $km s^{-1}$ of $V \sin i$ in A stars.

Cluster	from β, c_0		from c_0, $(b-y)_0$		from β, $(b-y)_0$	
	c_0	β	$(b-y)_0$	c_0	$(b-y)_0$	β
α-Persei	0.031	−0.016	0.012	0.020	−0.005	−0.004
	±0.004	±0.003	±0.005	±0.004	±0.003	±0.001
Pleiades	0.027	−0.011	0.011	0.035	0.001	0.002
	±0.004	±0.002	±0.002	±0.005	±0.002	±0.002

4.2 *A Stars*

The reddening for various colour indices derived for α-Persei and Pleiades A stars together with that derived from colour indices predicted by Collins & Sonneborn (1977) are given in Table 11. The majority of the stars analysed for the A-group in α-Persei and Pleiades are in the spectral type range A3 to FO. The theoretical predictions for this spectral type range for $i = 45°$ and 60° are in excellent agreement with the observed values.

In fact it is a bit surprising that in spite of the various uncertainties the agreement is excellent between observations and predictions of Collins & Sonneborn (1977) for rigidly rotating stars. We believe that this became possible because we eliminated all that scatter in the diagrams that would have been introduced by including double-lined binaries, emission-lined objects and highly peculiar objects. Further, by analysing each cluster separately, and each subgroup in Scorpio-Centaurus separately we were able to eliminate most of the uncertainties that would have otherwise been introduced.

Gray & Garrison (1989) derived a higher slope for the effect in c_0 for field F-type stars. They suggested that field F stars may be rotating differentially but that no firm conclusion can be drawn and that the different slopes derived may also be due to evolutionary effects. We find that differences in the evolutionary stage of the stars even on the main sequence will introduce a large scatter in the observed effect. This is amply demonstrated by the Scorpio-Centaurus association where we find that the two subgroups, if analysed together, produces a large scatter in the Δc_0, $V \sin i$ and $\Delta(u-b)_0$, $V \sin i$ diagrams. Even though F stars have much longer main sequence lifetime than B-stars, evolutionary effects may be important for field F-stars.

5. Conclusion

The reddening effect due to rotation on various colour indices and H_β is firmly established. These effects as observed in α-Persei, Pleiades and Scorpio-Centaurus association members, having a range in spectral type in B0 to F0, are in excellent agreement with theoretical calculations of photometric effect due to rigid rotation by Collins & Sonneborn (1977).

We emphasize that evolutionary effects even on the main sequence can lead to scatter in the reddening effects if not properly taken into account. This is amply demonstrated by our analysis of different subgroups in the Scorpio-Centaurus association.

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