J. Astrophys. Astr. (1988) **9,** 107–116

# Effects of Rotation On The Colours and Line Indices of Stars 1. The Alpha Persei Cluster

R. Rajamohan & Annamma Mathew *Indian Institute of Astrophysics, Bangalore 560034*

Received 1987 November 23; accepted 1988 March 25

**Abstract.** Analysis of the available observational data for the $\alpha$-Persei cluster members shows that rotation effects on the intermediate-band indices $c_1$ and $(u - b)$ are considerable. In $c_1$, rotation produces a reddening of 0.040 magnitudes per 100 km $s^{-1}$ In $(u - b)$ the effect for B stars is found to be 0.06 magnitudes per 100 km $s^{-1}$ of $V \sin i$.

The binaries and peculiar stars are found to behave differently in the colour excess (due to rotation) versus $V \sin i$ diagrams. These empirical effects can be utilised to recalibrate these colour indices and also to separate members that are either chemically peculiar or in binary systems.

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

## 1. Introduction.

The effects of rotation on colours and line indices of stars is a subject of some controversy though not actually appreciated as such. Empirical calibrations of *uvby* and H$\beta$ system in terms of intrinsic colour and absolute magnitudes have been carried out (Crawford 1978) on the assumption that differences in rotational velocities of stars does not substantially affect their colours. Theoretical work by Collins & Sonneborn (1977) and Collins & Smith (1985) seems to indicate that such effects are appreciable only for stars that rotate close to their break-up speeds. Warren (1976) discussed the proposed effects of rotation in some detail for B stars in the Orion region and showed that no systematic effects are present for $V\sin i$ less than 250 km $s^{-1}$. Similar conclusions were reached by Petrie (1965) based on H$\gamma$ equivalent-width data. Dickens, Kraft & Krzeminski (1968) found no large systematic effects in $(U - B)$ colours at a fixed $(B - V)$ for stars in Praescepe. Crawford & Barnes (1974) found that no rotation effect can be discerned in the data for B stars in $\alpha$-Persei cluster, whereas the data for A stars indicated that the $c_1$ index may be affected by as much as 0.035 magnitudes per 100 km $s^{-1}$ of $V \sin i$.

On the other hand, Kraft & Wrubel (1965) found that the ultraviolet excess is related to $V \sin i$ in the Hyades. Rajamohan (1978) showed that the $c_1$ index in $\alpha$-Persei and the Scorpio-Centaurus association is correlated with $V \sin i$. The work by Maeder & Peytremann (1970, 1972) seems to indicate that predicted theoretical effects are still smaller than the observed effects. However due to other parameters that affect the observed colours, no consistent picture has emerged. A systematic study of this effect would be needed for not only calibrating the indices, but also for comparison with existing theories that could then be used for differentiating between uniform solid-body rotation and differential rotation.

We have decided to reinvestigate this problem systematically and determine empirically whether the colours and line indices of stars are affected by rotation at all values of $V$ sin $i$. Cluster members provide the best homogeneous data since the members can be assumed to be coeval. We begin with the $\alpha$-Persei cluster since it has a low binary frequency (Kraft 1967; Heard & Petrie 1967). We plan to analyse each cluster separately and later take the effects of rotation into account in recalibrating the line indices as a function of absolute magnitude and spectral type. Comparison with theory will become feasible and easy once the analysis is extended to all clusters.

## 2. The data and analysis

The basic observational data for $u,v,b,y$ and H$\beta$ are taken from Crawford & Barnes (1974). The $V$ sin $i$ data are taken from Kraft (1967). The identification numbers for the stars are from Heckmann, Dieckvoss & Kox (1956). Only early-type stars (earlier than F5) are considered here. There are totally 34 stars of type B and 28 of type A and early F (Tables IV, V, VI of Crawford & Barnes 1974).

Before the data for these objects can be analysed for rotation effects, the following factors that affect their colours have to be taken into account.

1. Binary nature: This makes the star generally lie above the main sequence defined by non-rotating single stars. This factor, first suggested by Atkinson (1937) for identifying binaries from colour-magnitude diagrams depends on the mass ratio and evolutionary status of the components. Binaries in general rotate synchronously and hence have lower rotational velocities than single stars of the same spectral type. This effect leads to the inverse correlation between mean rotational velocities and binary frequency of clusters found by Abt & Hunter (1962).

2. The chemically peculiar stars are likely to have their colours affected by line-blanketing. These are in general slow rotators and some of them are magnetic and spectrum variables. The binary frequency amongst magnetic stars is very low, whereas almost all Am stars are likely to be in binary systems (Abt 1965)

3. Evolutionary effects: If the sample does not conform to a homogeneous coeval group, then evolutionary effects (even within the main-sequence lifetime) have to be taken into account as this would introduce a spread in the observed colour–magnitude diagrams. The advantage of analysing cluster data is that this effect would be a minimum, though in some clusters and associations it is known that not all members are coeval.

4. Differential reddening across the cluster: Since rotation effect is also to redden the stars, it is not clear whether the stars must be dereddened for this effect before analysing the data. The two effects being similar, we have decided to analyse the observed data as though the interstellar reddening is uniform across the cluster.

5. Large systematic errors in photometry: Eventhough there is no evidence that such systematic observational errors exist, it is worth noticing that Trimble & Ostriker (1978, 1981) found that some unknown effect exists which complicates the analysis of cluster data for discriminating between double and rotating stars. We plan to overcome this problem by analysing each cluster independently.

In order to minimize the first two effects, we decided to eliminate stars which are already known to be binary, variable or chemically peculiar. This we assume leaves a sample of single main-sequence normal stars at the same stage of evolution and only differing in their rotational velocities. Any reddening effect found then can be confidently attributed to the effect of rotation alone.

## 3. The effect of rotation on colours

### 3.1 *The Effect on* $c_1$: *B-Stars*

Tables 1 and 2 list the relevant data for the B and A stars. Because of the various factors listed in the previous section, which affect the colour indices, we cannot hope to derive

**Table 1.** Rotation effect on $c_1$ and $(u - b)$ for B stars.

| Star No. | BD | $\beta$ | $c_1$ | $u-b$ | $V \sin i$ | $\Delta c_1$ | $\Delta(u-b)$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| 167 | 48°862 | 2.887 | 0.945 | 1.367 | 20 | −0.051 | −0.080 | |
| 212 | 49 876 | 2.807 | 0.865 | 1.169 | 280 | 0.052 | 0.063 | |
| 285 | 47 792 | 2.848 | 0.999 | 1.557 | 35 | 0.074 | 0.242 | Ap |
| 333 | 50 731 | 2.794 | 0.762 | 1.054 | 230 | −0.014 | 0.006 | |
| 383 | 49 899 | 2.683 | 0.356 | 0.514 | 145 | −0.026 | −0.015 | |
| 401 | 49 902 | 2.668 | 0.393 | 0.549 | 320 | 0.076 | 0.094 | |
| 423 | 48 886 | 2.856 | 0.990 | 1.358 | 280 | 0.056 | 0.040 | |
| 557 | 48 899 | 2.688 | 0.407 | 0.563 | 250 | 0.059 | 0.028 | SB ? |
| 575 | 51 728 | 2.886 | 0.965 | 1.377 | 85 | −0.030 | −0.066 | |
| 581 | 48 903 | 2.813 | 0.821 | 1.099 | 200 | −0.008 | −0.033 | |
| 601 | | 2.597 | 0.356 | 0.802 | | 0.323 | 0.673 | non-member |
| 625 | 47 817 | 2.875 | 0.940 | 1.368 | 25 | −0.014 | −0.071 | velocity var. |
| 675 | 48 913 | 2.726 | 0.462 | 0.616 | 70 | −0.089 | −0.120 | |
| 692 | 47 821 | 2.856 | 0.947 | 1.275 | 340 | 0.032 | −0.084 | SB ? |
| 729 | 47 826 | 2.868 | 0.962 | 1.374 | 225 | 0.002 | 0.006 | |
| 735 | 47 828 | 2.766 | 0.795 | 1.039 | 375 | 0.105 | 0.117 | |
| 774 | 48 920 | 2.702 | 0.407 | 0.543 | 65 | −0.041 | −0.116 | velocity var. |
| 775 | 47 831 | 2.804 | 0.786 | 1.100 | 200 | −0.018 | 0.007 | |
| 780 | 49 938 | 2.888 | 1.005 | 1.513 | 230 | 0.007 | 0.062 | |
| 810 | 49 944 | 2.688 | 0.495 | 0.687 | 385 | 0.147 | 0.096 | SB ? |
| 817 | 48 927 | 2.866 | 0.998 | 1.438 | 270 | 0.043 | 0.078 | |
| 831 | 47 835 | 2.828 | 0.831 | 1.125 | 135 | −0.037 | −0.073 | |
| 835 | 49 945 | 2.678 | 0.373 | 0.497 | 190 | 0.012 | −0.007 | |
| 861 | 46 760 | 2.735 | 0.579 | 0.975 | 150 | 0.006 | 0.158 | non-member |
| 868 | 48 933 | 2.858 | 0.930 | 1.344 | 180 | −0.008 | 0.018 | |
| 875 | 47 840 | 2.858 | 1.008 | 1.418 | 250 | 0.070 | 0.092 | |
| 904 | 47 844 | 2.745 | 0.683 | 0.889 | 380 | 0.074 | 0.220 | shell star |
| 955 | 47 846 | 2.743 | 0.718 | 0.964 | 215 | 0.116 | 0.120 | velocity var. |
| 965 | 48 943 | 2.747 | 0.662 | 0.892 | 225 | 0.036 | 0.058 | |
| 985 | 47 847 | 2.695 | 0.369 | 0.511 | 50 | −0.062 | −0.076 | |
| 1082 | 48 949 | 2.829 | 0.847 | 1.167 | 205 | −0.024 | −0.035 | |
| 1153 | 46 773 | 2.766 | 0.648 | 0.888 | 25 | −0.042 | −0.034 | |
| 1164 | 47 857 | 2.491 | 0.379 | 0.503 | 385 | −0.243 | 0.055 | non-member |
| 1259 | 47 865 | 2.850 | 0.873 | 1.189 | 45 | −0.048 | −0.103 | |

**Table 2.** Rotation effect on $c_1$ for A stars.

| Star No. | BD | $\beta$ | $c_1$ | $V \sin i$ | $\Delta c_1$ | $\Delta\beta$ | Remarks |
|---|---|---|---|---|---|---|---|
| 151 | 47°780 | 2.765 | 0.763 | 140 | 0 | 0 | |
| 220 | 48 865 | 2.792 | 0.805 | 85 | −0.010 | 0.005 | |
| 228 | | 2.759 | 0.727 | | −0.024 | 0.012 | |
| 314 | 50 728 | 2.736 | 0.754 | 110 | −0.045 | −0.033 | SB ? |
| 386 | 49 900 | 2.901 | 1.013 | 260 | 0.025 | −0.020 | |
| 481 | 47 808 | 2.763 | 0.772 | 180 | 0.013 | −0.007 | |
| 501 | 48 894 | 2.770 | 0.741 | 75 | −0.032 | 0.016 | |
| 522 | 51 723 | 2.868 | 0.936 | 200 | −0.111 | −0.004 | velocity variable |
| 595 | | 2.790 | 0.978 | | 0.067 | −0.105 | non-member |
| 606 | 48 905 | 2.775 | 0.765 | 50 | −0.018 | 0.009 | A 8 m ? |
| 609 | 49 918 | 2.755 | 0.789 | 175 | 0.046 | −0.023 | |
| 612 | 48 906 | 2.911 | 0.987 | 85 | −0.014 | −0.010 | |
| 635 | 49 921 | 2.758 | 0.721 | 20 | −0.028 | −0.014 | |
| 639 | 48 907 | 2.896 | 1.007 | 210 | 0.026 | −0.020 | |
| 651 | 48 909 | 2.862 | 0.993 | 250 | 0.061 | −0.043 | |
| 658 | 47 819 | 2.850 | 0.888 | 85 | −0.130 | 0.005 | non-member |
| 694 | 47 822 | 2.902 | 0.956 | 75 | −0.033 | 0.024 | |
| 721 | 47 825 | 2.730 | 0.686 | | −0.005 | 0.002 | |
| 756 | 47 830 | 2.908 | 1.002 | 145 | 0.005 | −0.004 | |
| 802 | 48 924 | 2.893 | 0.976 | 200 | −0.001 | 0.001 | |
| 885 | 48 934 | 2.856 | 0.867 | 80 | −0.164 | 0.023 | velocity variable |
| 906 | 47 842 | 2.872 | 0.939 | 150 | −0.008 | 0.006 | |
| 921 | 49 953 | 2.880 | 0.970 | 200 | 0.011 | −0.008 | |
| 931 | 49 954 | 2.894 | 0.960 | 90 | −0.018 | 0.013 | |
| 958 | 49 858 | 2.739 | 0.741 | 155 | 0.031 | −0.015 | |
| 970 | 48 944 | 2.886 | 0.938 | 120 | −0.029 | 0.020 | |
| 1050 | 49 967 | 2.834 | 0.893 | 60 | −0.098 | −0.014 | SB ? |
| 1218 | 46 780 | 2.729 | 0.733 | 120 | −0.051 | −0.028 | SB ? |

meaningful results by defining a standard main sequence, or a zero age main sequence (ZAMS) or zero rotation main sequence (ZAZRMS) (see also Trimble & Ostriker 1978,1981). We have therefore decided to use the data for each cluster to define its own relationship between different indices. Fig. 1 is a plot of $\beta$ versus $c_1$ for all members listed in Tables 1 and 2. A second-order polynomial was fitted to the data and for each star, a calculated $c_1$ value was derived using the polynomial coefficients for its observed $\beta$. We define $\Delta c_1$ as the observed minus computed value of $c_1$ for its observed value of $\beta$. We have plotted $\Delta c_1$ versus $V \sin i$ using different symbols for B and A stars. It was found that strong rotation effects are present independently for B and A stars and that a single polynomial fit is not appropriate for B and A stars taken together.

Fig. 2 shows the result for the B stars analysed independently, omitting the probable binaries and peculiar stars. The $c_1$ indices were represented by an equation of the type.

$$c_1 = f + g\beta + h\beta^2$$

The $(O - C)$ values in $c_1$ for each star derived using the above coefficients are given in Columns 6 and 7 of Table 1. These $(O - C)$ values in $c_1$ are denoted by $\Delta c_1$. A linear fit

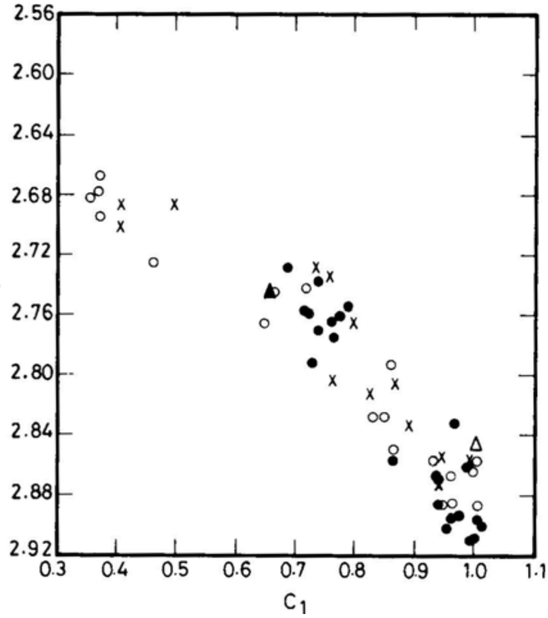


**Figure. 1** The $\beta$, $c_1$ plot for B stars (open circles) and A stars (filled circles) in the $\alpha$-Persei cluster. Stars with variable radial velocities, and suspected binaries are plotted as crosses. A peculiar star is plotted as an open triangle, and a shell star by a filled triangle.

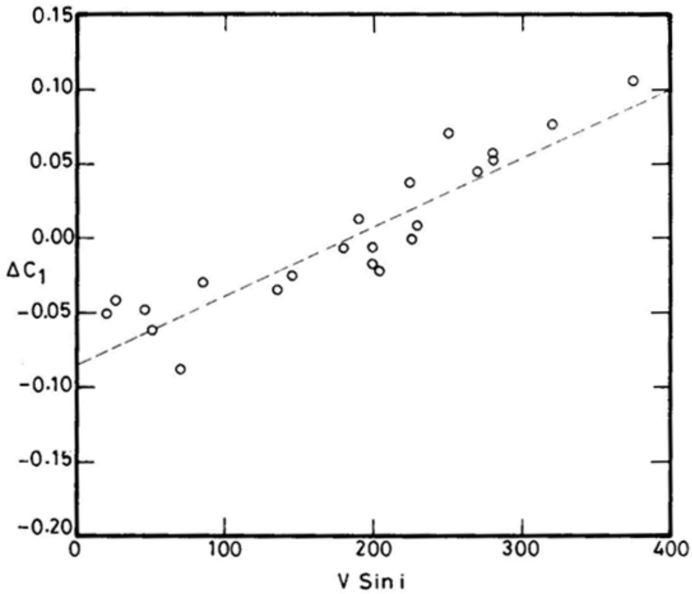


**Figure 2.** The deviation in $c_1$ is plotted against $V$ sin $i$ for B stars.

to the data points in Fig. 3 gives

$$\Delta c_1 = 0.454(\pm 0.032) \times 10^{-3} V \sin i - 0.084(\pm 0.006).$$

### 3.2 *The Effect on* $c_1$ : *A Stars*

A similar analysis was done for the A stars in Table 2. The deviations are given in Column 6 of Table 2 and are plotted against $V \sin i$ in Fig. 3. A linear fit to the data points given for the A stars.

$$\Delta c_1 = 0.326(\pm 0.038) \times 10^{-3} V \sin i - 0.044(\pm 0.006).$$

The effect of rotation on $c_1$ for the B and A stars taken together (Fig. 4) is of the order of 0.040 magnitudes per 100 km $s^{-1}$ of $V \sin i$.

### 3.3 *The Effect on* ($u$   $b$)

The $\beta$, $(u - b)$ relation was also represented by a second-order polynomial for the B stars.

The deviations in $(u - b)$ are given in Column 8 of Table 1. These are plotted against $V \sin i$ in Fig. 5. It is obvious that the effect of rotation on the $(u - b)$ colour at a given $\beta$ is considerable. A linear fit to the data points in Fig. 5 gives

$$\Delta(u - b) = 0.618(\pm 0.046) \times 10^{-3} V \sin i - 0.114(\pm 0.009).$$

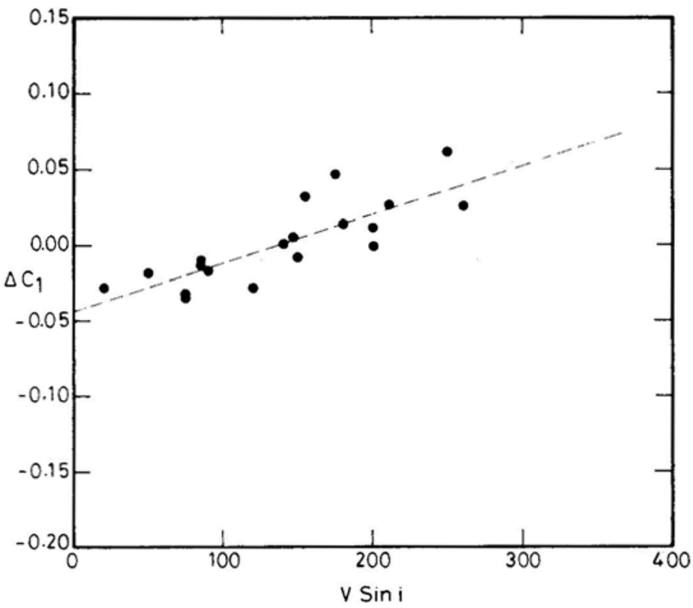


**Figure 3.** The deviation in $c_1$ is plotted against $V \sin i$ for A stars.

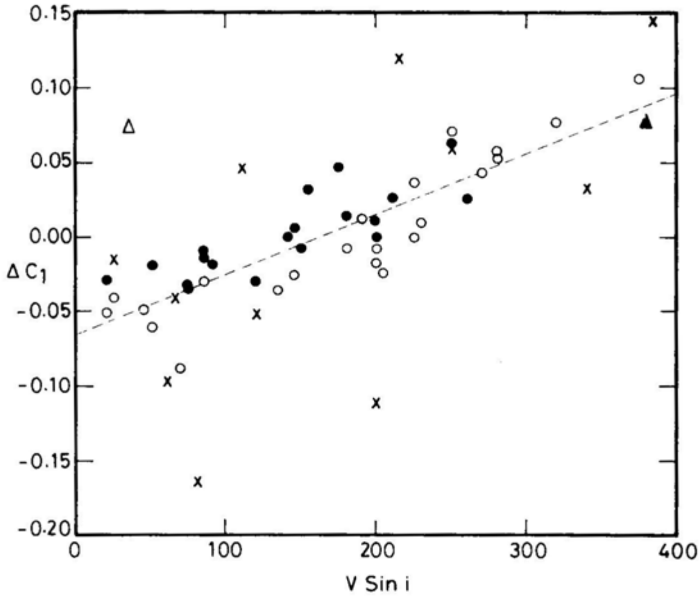


**Figure 4.** The deviation in $c_1$ for all stars. Symbols are the same as in Fig. 1

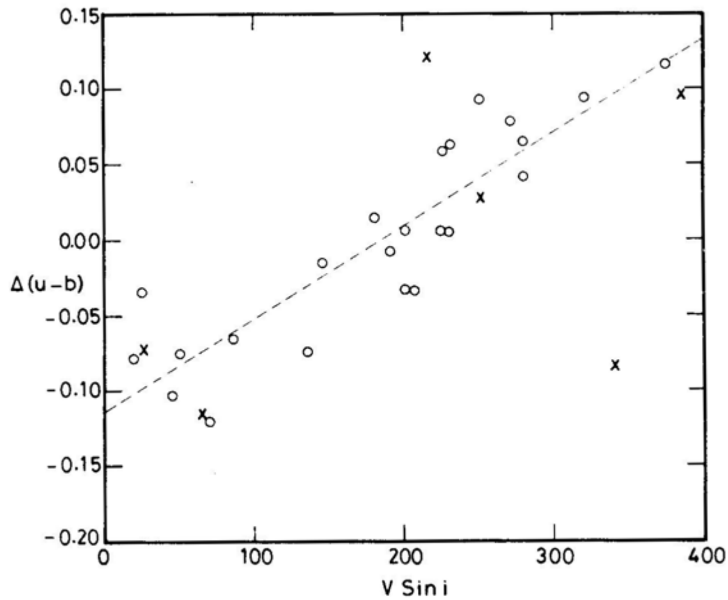


**Figure 5.** The deviation in $(u-b)$ is plotted against $V \sin i$ for B stars.

### 3.4 *The Effect on* $(b-y)$, $m_1$

No striking correlation is found with excess in $(b-y)$ or $m_1$, when these quantities are interrelated with $\beta$, $c_1$ or $(u-b)$ except in the case of $c_1$ versus $(b-y)$ relation for A stars. This effect is shown in Fig. 6. The procedure adopted is probably not best-suited

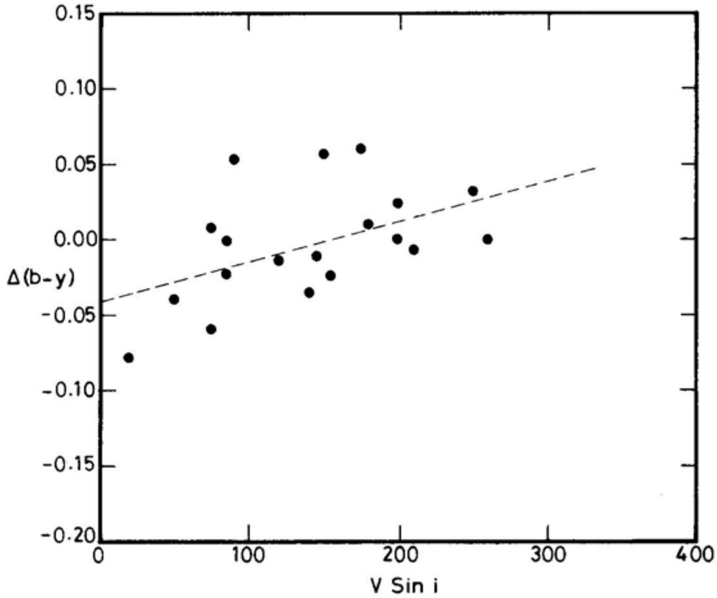


**Figure 6.** The deviation in $(b - y)$ is plotted against $V \sin i$ for A stars.

to find the effects of rotation on these colour indices. We defer the conclusions regarding the indices to a later paper.

## 4. Discussion

The effect of rotation on the observed intermediate-band indices $c_1$ and $(u - b)$ seems to be considerable. The complicating factors that introduce scatter in the colour colour and colour magnitude diagrams are the incidence of peculiar and binary stars, evolutionary effects, and reddening. If these are taken into account by eliminating peculiar and binary stars and confining ourselves to the analysis of main sequence normal single stars in a cluster, the rotation effect comes out strikingly for $c_1$ and $(u - b)$. Hence in the calibration of these indices with spectral type and absolute magnitude or the $\beta$ index, we must make allowance for rotation effects; this has not been done in earlier work (*e.g.* Crawford 1978).

Trimble & Ostriker (1978, 1981) tried to derive the binary frequency in clusters by analysing the displacement of stars in the colour-magnitude diagrams and taking into account the expected effects of rotation. The effort was not fully successful since they found that different clusters do not define a unique zero rotation main sequence According to them, an unknown parameter influenced the observed colours up to a 0.05-magnitude level. We avoid this problem by analysing clusters individually, eventhough this leaves us with a smaller sample of stars for analysis.

In $\Delta c_1$ and $\Delta(u - b)$ versus $V \sin i$ diagrams the binaries seem to be displaced to a position below the mean relationship while the peculiar stars seem to lie considerably above this relationship. The region above this mean relationship can also be occupied by stars whose indices are affected by incipient emission in *β*. These objects, in general, would occur at high values of *V* sin *i* excepting those that are seen pole on. However, emission occurs in general in very early B stars and hence it should be possible, in principle by the position of the objects in $\Delta c_1$, $\Delta(u-b)$ versus *V* sin *i* diagrams, to identify these three different kinds of objects.

The tight relationship found for $\Delta c_1$ and $\Delta(u-b)$ with *V sin i* leads to some interesting questions. Collins & Sonneborn (1977) found that the relationship between rotational velocity and the rotational displacement of an object from the main sequence is almost independant of sin *i*. Low values of *V* sin *i* could be a combination of high *V* and very low sin *i* or a low value of *V* itself. In that case we must expect a large spread in the observed values of $\Delta c_1$ at low values of *V* sin *i.* The spread would be expected to be low at large values of *V* sin *i*, since the spread in *V* itself would be expected to be small at high values of *V* sin *i*. Two possibilities exist. For a random distribution in *V* and *i,* the expected number of stars at low values of *V* sin *i* would be small. However we find in Fig. 3 and 4 the distribution of stars for different values of *V* sin *i* is more or less uniform. The other possibility is that the effect of differing inclination is much larger than that predicted by theory. In that case, these results seem to support the arguments by Rajamohan (1978) that the normal single stars of a given mass arrive on the main sequence with a small spread in their angular momentum. We will address this question in greater detail after the analysis of data on other clusters is completed.

We have completely left out the late-type stars from our analysis. The colours of these stars, with outer convection zones, are likely to be affected not only by rotation but also by chromospheric phenomenon and star spots. Chromospheric activity enhanced by duplicity (Young & Koniges 1977) would further complicate the analysis of their data. They belong to a separate class of interesting objects and the role of rotation in these objects is a totally different problem. Also some young Pleiades K dwarfs have been found to have very high values of *V* sin *i* (Stanffer & Hartmann 1987). We plan to analyse only the data for early-type stars in different clusters where the rotation effects on colours and line indices seem much less complicated than in their late-type counterparts.

## 5. Conclusion

For the *α*-Persei cluster members the effect of rotation is found to be + 0.04 magnitudes per 100 km $s^{-1}$ in $c_1$ and + 0.06 magnitudes per 100 km $s^{-1}$ of *V* sin *i* in $(u-b)$.

Binaries, peculiar stars and emission-line objects seem to occupy different regions in the $\Delta c_1$, $\Delta(u-b)$ versus *V* sin *i* diagrams. This fact can be used as a criterion for selecting the most probable peculiar and binary stars in distant young clusters.

These effects were fairly easy to determine in *α*-Persei since the cluster has a low frequency of spectroscopic binaries and has been fairly extensively studied both photometrically and spectroscopically. In fact, no confirmed short period binaries exists in the *α*-Persei cluster.

We plan the comparison of empirically-determined rotation effects on colours with available model calculations after analysing the data for other clusters for which extensive observational material exists.

**Acknowledgements**

The data analysis in this paper was carried out with the TDC-316 computer of the Indian Institute of Astrophysics, we are thankful to Mr. A. V. Raveendran for lending his computer programmes.

## References

Abt, H. A. 1965, *Astrophys. J. SuppL.*, **11,** 429.
Abt, H. A., Hunter, J. H. Jr. 1962, *Astrophys. J.*, **136,** 381.
Atkinson, R. d'E 1937, *Observatory*, **60,** 299
Collins, G. W., Smith, R. C. 1985, *Mon.Not.R.Astr.Soc,* **213**, 519.
Collins; G. W., Sonneborn, G. H. 1977, *Astrophys. J. SuppL.*, **34,** 41.
Crawford, D. L. 1978, *Astr. J.,* **83,** 48.
Crawford, D. L., Barnes, J. V. 1974**,** *Astr. J.*, **79,** 687.
Dickens, R. J., Kraft, R. P., Krzeminski, W. 1968, *Astr. J.,* **73,** 6.
Heckmann, O., Dieckvoss, W., Kox, H. 1956, *Astr. Nachr.,* **283,** 109.
Kraft, R. P. 1967, *Astrophys. J.*, 1**48,** 129.
Kraft. R. P., Wrubel, M. 1965, *Astrophys. J.,* **142,** 703.
Maeder, A., Peytremann, E. 1970, *Astr. Astrophys.* **7,** 120.
Maeder, A., Peytremann, E. 1972. *Astr. Astrophys.,* **21,** 279.
Petrie, R. M. 1965, *Publ. Dominion Astrophys. Obs.,* **12,** 317.
Heard, J. F., Petrie, R. M. 1967, *IAU Symp. No*: 30: *Determination of Radial Velocities and their Applications,* Eds A. H. Batten & J. F. Heard, D. Reidel, Dordrecht, p. 179.
Rajamohan, R., 1978, *Mon. Not. R. Astr. Soc,* **184,** 743
Stauffer, J. R., Hartman, L. W. 1987, *Astrophys. J.*, **318,** 337
Trimble, V. L.; Ostriker, J. P. 1978, *Astr. Asjrophys.,* **63,** 433.
Trimble, V. L., Ostriker, J. P. 1981, *Astr. Astrophys*., **97,** 403.
Warren, W. H. 1976 *Mon. Not. R. Astr. Soc,* **174,** 111.
Young, A., Koniges, A. 1977 *Astrophys. J.*, **211,** 836.