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Effects of rotation on the colours and line indices of stars : 4—The effect on broad band UBV colours

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Abstract. Analysis of the available observational data for the members of Alpha Persei, Pleiades, and Scorpio-Centaurus association shows that rotation effects on the broad band colour indices $(U-B)$ and $(B-V)$ are considerable. These effects are found to have a spectral type dependance as in intermediate band indices. For Alpha Persei and Pleiades B stars, which are mostly of spectral type B5-B9, the observed effect in $(U-B)_0$ and $(B-V)_0$ is 0.042 and 0.011 magnitudes per 100 km s^{-1} of rotation respectively. For Scorpio-Centaurus association which contains an equal number of early and late B stars, the effect found in $(U-B)_0$ and $(B-V)_0$ is 0.032 and 0.007 magnitudes per 100 km s^{-1} of rotation. These observed effects in broad band colours are found to be consistent with theoretical predictions by Collins & Sonneborn but are much larger than the prediction by Maeder & Peytremann.

Key words : stellar rotation—colour indices—UBV

1. Introduction

We have already discussed the need for determining the effects of rotation on the colours and line indices of stars. (Rajamohan & Mathew 1988 ≡ Paper 1; Mathew & Rajamohan 1989 ≡ Paper 2). In this paper we analyse the effects of rotation on UBV and Hβ for α-Persei, Pleiades and the Scorpio-Centaurus association. A comparison of the observed effects is made with the theoretical photometric effects due to rotation predicted by Maeder & Peytremann (1970) and Collins & Sonneborn (1977).

2. The data and analysis

The factors other than rotation that affect the colours of stars are differential reddening across the cluster, binary nature, peculiarity, evolutionary effects, and systematic errors in photometry. A detailed discussion of these is given in paper 1. These are taken into account before analysing for rotation effects. The B type stars alone were considered and the colour indices were dereddened using the Q-method originally set up by Johnson & Morgan (1953). Double lined spectroscopic binaries and close visual doubles with a

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magnitude difference less than two magnitudes were excluded. Emission lined objects and known peculiar stars were in general excluded and only luminosity class IV and V stars are included for data analysis so that the reddening effect found can be completely attributed to rotation alone. References to the cluster data used in this study is given in table 1.

Table 1. References to *UBV*, *Hβ*, *V* sin *i* data for clusters

Cluster	Data	Reference
α-Persei	*UBV*	Mitchell (1960)
	Hβ	Crawford & Barnes (1974)
	V sin *i*	Kraft (1967)
Pleiades	*UBV*	Johnson & Mitchell (1958)
	Hβ	Crawford & Perry (1976)
	V sin *i*	Anderson, Stoeckly & Kraft (1966)
Sco-Cen	*UBV*, *Hβ*	Moreno & Moreno (1968)
	V sin *i*	Rajamohan (1976)
		Slettebak (1968)
		Uesugi & Fukuda (1982)

3. Results

3.1 *The effect of rotation on the colours of α-Persei stars*

Amongst the 23 B stars used for the analysis of *uvby* photometry four stars having $V \sin i$ values < 50 km s^{-1} are excluded from the analysis of *UBV* photometry. For the rest of the 19 B stars $\Delta(U-B)_0$, the colour excess in $(U-B)_0$ derived from the mean relationship between β and $(U-B)_0$, is plotted against $V \sin i$ in figure 1 and is represented by open circles. For the α-Persei members alone a least square solution for

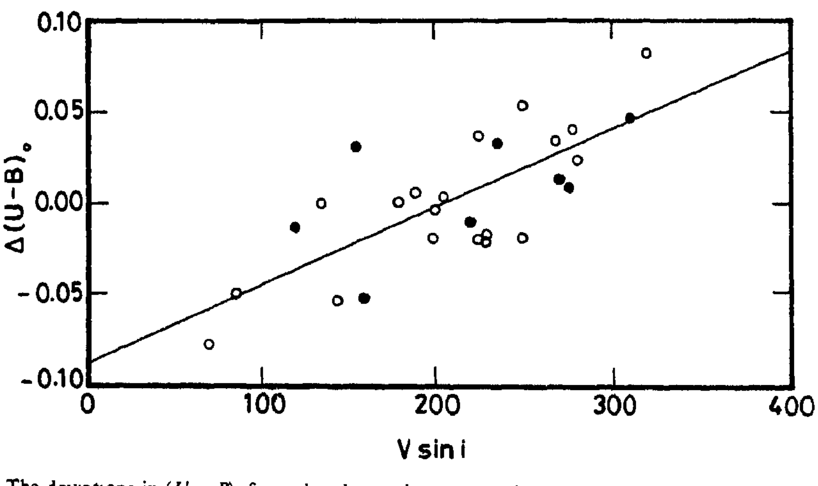

Figure 1. The deviations in $(U-B)_0$ from the observed mean relation between β and $(U-B)_0$ of Alpha Persei and Pleiades B-stars are plotted against $V \sin i$, Open circles: α-Persei members, filled circles: Pleiades members.

the residuals give·

$$\Delta(U-B)_0 = 0.486(\pm 0.059) \times 10^{-1}\ V \sin i - 0.102(\pm 0.013)$$

$$\Delta\beta = -0.164(\pm 0.020) \times 10^{-1}\ V \sin i + 0.034(\pm 0.004).$$

From β, $(B-V)_0$ we derive

$$\Delta(B-V)_0 = 0.130(\pm 0.016) \times 10^{-1}\ V \sin i - 0.027(\pm 0.003)$$

$$\Delta\beta = -0.164(\pm 0.020) \times 10^{-1}\ V \sin i - 0.034(\pm 0.004).$$

The colour excess $\Delta(B-V)_0$ derived from this is plotted against $V \sin i$ and is shown in figure 2a as open circles.

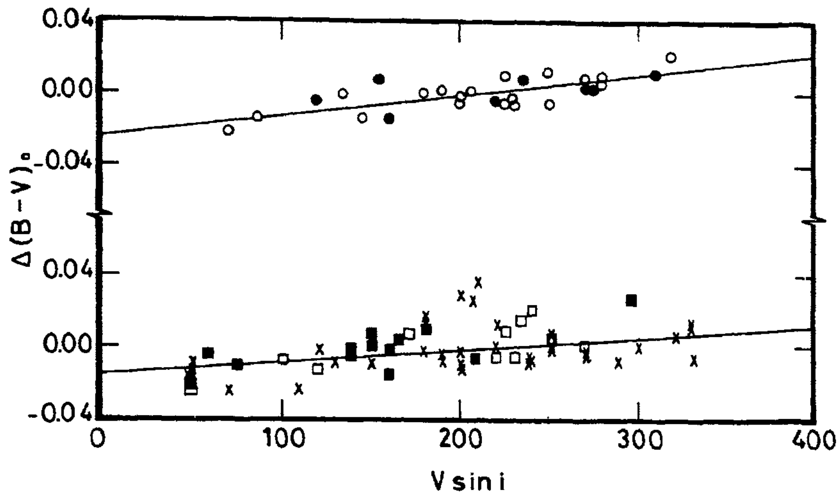

Figure 2. The deviations in $(B-V)_0$ derived from β, $(B-V)_0$ for (a) Alpha Persei and Pleiades and (b) Scorpio-Centaurus association are plotted against $V \sin i$ for B stars, filled squares: lower-Centaurus, Open squares upper-Centaurus, Crosses upper-Scorpius.

The $\Delta\beta$ values derived from β, $(U-B)_0$ and β, $(B-V)_0$ relationships are shown as open circles in figures 3a and 4a respectively. From a plot of $(U-B)_0$ versus $(B-V)_0$ for B stars in α-Persei cluster, we find that the deviations $\Delta(U-B)_0$ are not related to the rotational velocity of the star. The residuals in $(U-B)_0$, β and $(B-V)_0$ for the α-Persei B stars are listed in table 2. The identification numbers given in column 1, for the stars are from Heckmann, Dieckvoss & Kox (1956).

3.2. *The effect of rotation on the colours of Pleiades stars*

After excluding the giants, double lined binaries, emission lined stars, and close visual pairs with $\Delta m < 2.0$ mag we are left with only eight stars which can be considered as normal main sequence objects whose colours are free from effects other than that due to rotation. Even though this sample is small, we have analysed it independently and derived the residuals in β, $(U-B)_0$ and $(B-V)_0$. The residuals are listed in table 2. The identification numbers for the stars are from Hertzprung (1947).

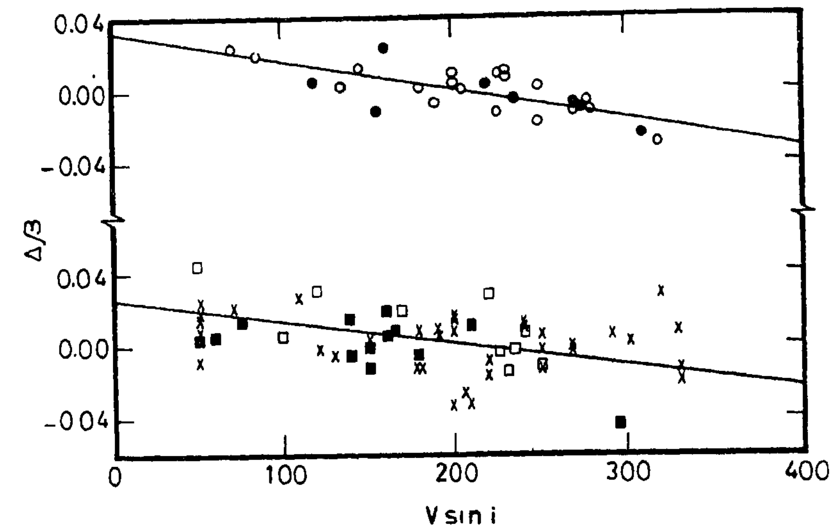

Figure 3. The deviations in β derived from observed β, $(U-B)_0$ for B stars of (a) Alpha Persei and Pleiades (b) Scorpio-Centaurus association

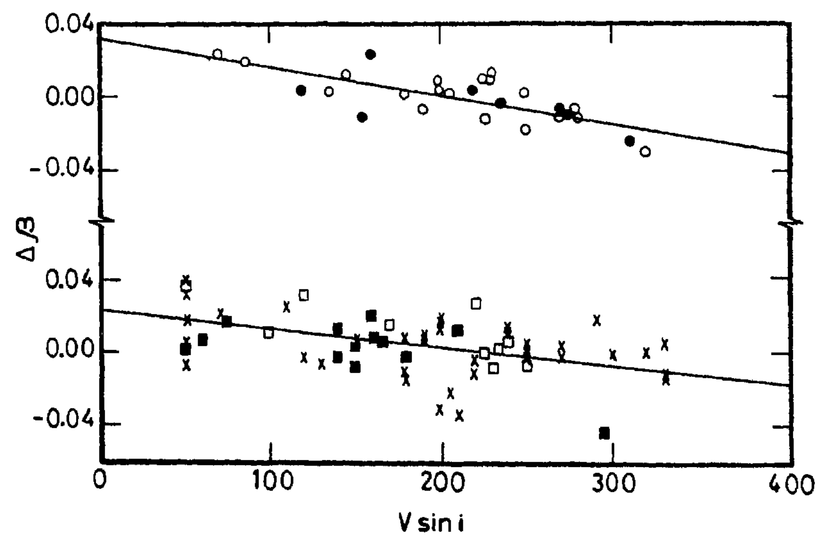

Figure 4. Same as figure 3. $\Delta\beta$ derived from β, $(B-V)_0$ relation is plotted against $V \sin i$.

The residuals in $(U-B)_0$ for Pleiades B stars are superposed (in figure 1) over those derived for the members of the α-Persei cluster. Similarly $\Delta\beta$ for B stars in Pleiades are superposed (in figure 3a) over those derived for the members of the α-Persei cluster. From the combined data points, we derive

$$\Delta(U-B)_0 = 0.418(\pm 0.052) \times 10^{-3}\ V \sin i - 0.087(\pm 0.011)$$

$$\Delta\beta = -0.156(\pm 0.018) \times 10^{-3}\ V \sin i + 0.032(\pm 0.004).$$

Table 2. Effect of rotation for α-Persei and Pleiades B stars

Hz	HD	Sp.	$V \sin i$	From β, $(U-B)_0$		From β, $(B-V)_0$	
				$\Delta(U-B)_0$	$\Delta\beta$	$\Delta(B-V)_0$	$\Delta\beta$
α-Persei							
212	49 876	B9V	280	0.041	−0.012	0 011	−0.012
333	50 731		230	−0.016	0.008	−0.004	0 008
383	49 899	B3V	145	−0.054	0 012	−0.014	0 012
401	49 902	B5V	320	0.082	−0.031	0.022	−0 031
423	48 886	A0Vn	280	0.024	−0.007	0.006	−0.007
557	48 899	B5V	250	−0.018	0.002	−0 005	0 002
575	51 728	A0V	85	−0.049	0.019	−0.013	0 019
581	48 903	B9V	200	−0.003	0 003	−0.001	0.003
675	48 913	B7V	70	−0.078	0 024	−0.021	0.024
729	47 826	B9V	225	−0.021	0 009	−0 005	0.009
775	47 831	B8 5V	200	−0.019	0.009	−0 005	0.009
780	49 938	A1Vn	230	−0.024	0.010	−0 006	0.010
817	48 927	A1Vn	270	0.035	−0.012	0 009	−0.012
831	47 835	B9V	135	−0.001	0.002	0 000	0.002
835	49 945	B3V	190	0.006	−0 007	0.002	-0.007
868	48 933	A1IVn	180	0.001	0.001	0.000	0.001
875	47 840	A0Vn	250	0 053	−0.018	0.014	−0 018
965	48 943	B8V	225	0.038	−0.012	0 010	−0 012
1082	48 949	B9V	205	0 003	0.001	0.001	0.001
Pleiades							
255	23432	B8V	220	−0.011	0.003	−0 003	0 003
323	23480	B6V	75	0.008	−0.011	0.002	−0 011
722	23753	B8V	270	0.011	−0.008	0.003	−0.008
910	23873	B9.5V	120	−0.012	0 004	−0.003	0 004
977	23923	B9V	310	0.045	−0.024	0.012	−0.024
1129	24076	A2V	155	0.031	−0.011	0.008	−0.011
508	23629	A0V	160	−0.051	0.023	−0.014	0 023
510	23632	A1V	235	0.032	−0.004	0.008	−0 004

Similarly from the combined data for Pleiades and α-Persei, B stars (figure 2a and 4a) we derive from β, $(B-V)_0$ relation

$$\Delta(B-V)_0 = 0.111(\pm 0.014)\times 10^{-3}\ V \sin i - 0.023(\pm 0.003)$$

$$\Delta\beta = -0.156(\pm 0.018)\times 10^{-3}\ V \sin i + 0.032(\pm 0.004).$$

3.3. *The effect of rotation on colours of Scorpio-Centaurus association stars*

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 paper 2. 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. Among the 35 stars from lower Centaurus for which β values are given by Moreno & Moreno (1968), 28 are of luminosity class IV and V. Removing the known binaries, peculiar and emission lined stars whose colours may be affected due to reasons other than rotation, we are left with 19 stars. Out of these HD 93163, HD 93607 and HD 108483 deviate considerably in $\Delta(U-B)_0$ vs $V \sin i$ diagrams. They may probably belong to peculiar, variable or emission lined stars (Rajamohan & Mathew ≡ paper 3). The rest of the 16 stars from lower Centaurus subgroup are used in the analysis. Amongst the 36 stars in upper Centaurus subgroup for which β values are available, HD 120908 is classified as B5V by de Vaucouleurs while in *Bright star catalogue* (Hoffleit & Jaschek 1982) it is given as B5 III. This object deviates considerably in $\Delta(U-B)_0$ vs $V \sin i$ plot indicating that the classification as giant is probably appropriate. We are left with 24 stars of luminosity class IV and V of which only 11 belong to the sample of probable normal single stars and single lined spectroscopic binaries at the same stage of evolution. From the upper Scorpius subgroup β values of 68 stars are known. Two stars HD 144661 and HD 170523 appear to be giants from their position in the colour-magnitude diagram which agrees with the classification given in the Bright star catalogue. Amongst these 57 are of luminosity class IV and V and 36 out of the 57 seem to be normal single stars and single lined spectroscopic binaries.

The colour excesses $\Delta(U-B)_0$, $\Delta(B-V)_0$ and $\Delta\beta$ due to rotation are derived independently for lower Centaurus, upper Centaurus and upper Scorpius subgroups and are given in table 3. The deviations $\Delta(U-B)_0$ for the 16 lower-Centaurus, 11 upper-Centaurus and 36 upper-Scorpius members are plotted in figure 5 using different symbols for the three subgroups. A least square fit excluding HD 142114 and HD 143600 yields

$$\Delta(U-B)_0 = 0.323(\pm 0.052) \times 10^{-1}\ V \sin i - 0.068\ (\pm 0.011).$$

Similarly $\Delta\beta$ derived from β, $(U-B)_0$ relation is plotted in figure 3b. From this we derive

$$\Delta\beta = -0.121(\pm 0.029) \times 10^{-3}\ V \sin i + 0.255(\pm 0.006).$$

For the same sets of stars the relationship between β and $(B-V)_0$ was derived. The deviations $\Delta(B-V)_0$ are plotted in figure 2b. A least square fit gives

$$\Delta(B-V)_0 = 0.070\ (\pm 0.013) \times 10^{-3}\ V \sin i - 0.015(\pm 0.003)$$

$\Delta\beta$ is also derived from $\beta,(B-V)_0$ and is plotted in figure 4b. We derive

$$\Delta\beta = -0.108(\pm 0.029) \times 10^{-3}\ V \sin i - 0.024(\pm 0.006).$$

The slopes of the observed relation between colour excess and $V \sin i$ for the α-Persei, Pleiades and Scorpio-Centaurus association are given in table 4.

4. Discussion

Maeder & Peytremann (1970) have computed the energy distribution of uniformly rotating stars for 5, 2 and 1.4 solar masses, for various rotational velocities and orientations. The 5.0, 2.0 and 1.4 $M_\odot$ models approximately correspond to spectral type B4, A0, and A9 respectively. The $(U-B)$, $(B-V)$ predicted colours from Maeder & Peytremann (1970) together with the β values taken for the corresponding spectral types from Collins & Sonneborn (1977) were analysed the same way as we did our cluster data. The β values for $i = 30°$ and $60°$ models were used for $i = 36°$ and $54°$ model predictions of colours by Maeder & Peytremann (1970). For each model and for different ω values 0,

Table 3. Effect of rotation for Sco-Cen Association B stars

HD	Sp	$V \sin i$	From $\beta,(U-B)_0$ $\Delta(U-B)_0$	$\Delta\beta$	From $\beta,(B-V)_0$ $\Delta(B-V)_0$	$\Delta\beta$
			Lower-Cen			
76161	B6Vn		0.078	−0.014	0.020	−0.013
80094	B7IV		0.065	−0.003	0.018	−0.001
85980	B4V	165	−0.006	0.010	0.003	0.005
93194	B5Vn	295	0.100	−0.042	0.027	−0.045
93845	B3V	60	−0.030	0.007	−0.006	0.007
99264	B2IV		−0.030	−0.012	−0.012	−0.009
103079	B4IV	140	−0.036	0.016	−0.007	0.013
103884	B3V	150	0.008	0.001	0.000	0.003
105937	B3V	210	−0.027	0.013	−0.005	0.012
106983	B2.5V	140	−0.010	−0.004	−0.002	−0.004
108257	B5Vn	150	0.034	−0.011	0.007	−0.009
109026	B5V	180	0.033	−0.004	0.009	−0.003
110956	B3V	75	−0.032	0.014	−0.011	0.016
113703	B5V	160	−0.056	0.020	−0.016	0.019
113791	B2IV	50	−0.100	0.005	−0.022	0.002
115823	B6V	160	0.009	0.007	−0.001	0.008
			Upper-Cen			
120307	B2IV	100	0.044	0.006	−0.008	0.010
121743	B2IV	120	0.062	0.030	−0.014	0.031
124367	B2V	270	0.006	−0.110	0.000	−0.108
124771	B4IV	240	0.091	0.009	0.020	0.005
125238	B3V	235	0.070	−0.001	0.015	0.001
126981	B6IV	225	0.023	−0.002	0.008	−0.003
129116	B2.5V	170	0.027	0.019	0.007	0.015
132955	B3V	50	0.088	0.045	−0.023	0.037
136664	B3V	220	−0.006	0.029	−0.005	0.027
138690	B2V	250	0.012	−0.011	0.004	−0.008
143118	B2V	230	−0.027	−0.014	−0.005	−0.008
			Upper-Sco			
138764	B6IV	50	−0.046	0.016	−0.013	0.017
139094	B8IV	180	0.038	−0.011	0.015	−0.016
139160	B7IV	200	0.040	0.014	−0.009	0.012
141637	B2V	270	−0.007	−0.003	−0.001	−0.004
142114	B3Vn	330	−0.040	0.009	−0.006	0.005
142165	B6IVn	250	0.043	−0.012	0.006	−0.004
142315	B8V	250	0.008	0.006	0.001	0.003
142378	B3V	240	0.035	0.010	−0.009	0.009
142669	B2IV-V	120	0.021	−0.001	−0.002	−0.003
142883	B3V	110	0.094	0.027	−0.023	0.025
142990	B8V	150	0.018	0.004	−0.009	0.007
143567	B9V	290	0.007	0.006	−0.007	0.018
143600	B9V	320	−0.043	0.029	0.006	0.000

(Continued)

Table 3. (Continued)

HD	Sp	$V \sin i$	From $\beta, (U-B)_0$: $\Delta(U-B)_0$	From $\beta, (U-B)_0$: $\Delta\beta$	From $\beta, (B-V)_0$: $\Delta(B-V)_0$	From $\beta, (B-V)_0$: $\Delta\beta$
143699	B5V	180	0 047	−0 011	0.012	−0 011
144294	B3IVn	300	−0.016	0 003	0 000	−0 001
144470	B1V	130	−0 043	−0 004	−0 007	−0 006
145353	B9V	220	0 051	−0 016	0 012	−0 012
145482	B3Vn	220	0.019	−0 007	0 000	- 0 004
145554	B9V	180	−0 003	0 008	−0 001	0 008
145631	B9 5Vn	200	0 007	0 009	−0 004	0 015
145792	B5V	50	−0 051	0 016	−0 015	0 017
146001	B7IV	240	−0.038	0.013	0 009	0 013
146285	B8IV	200	−0 034	0 017	−0 010	0 018
146416	B9V	330	0 055	−0 018	0 013	−0 014
147010	B9P	50	−0 068	0 024	−0 023	0 030
148579	B9V	250	0 018	−0 001	0 002	0 003
148605	B2V	270	−0 007	−0 001	−0.007	0 002
148703	B2IV	50	−0.047	0 005	−0 009	0 003
149438	B0V	50	−0 048	−0.010	−0 017	−0 007
149711	B3IV	—	−0 072	0 018	−0 023	0 021
153716	B5V	190	−0 013	0 005	−0.004	0 005
156325	B6IV	−	0 250	−0 064	0 067	− 0 064
168905	B3Vn	330	0 049	−0 013	0 012	−0 012
172910	B3V	70	−0 098	0 022	−0 024	0 020
175362	B8IV	190	−0 042	0.010	−0 010	0 008
186837	B5V	−	0 038	−0 009	0 009	−0 008

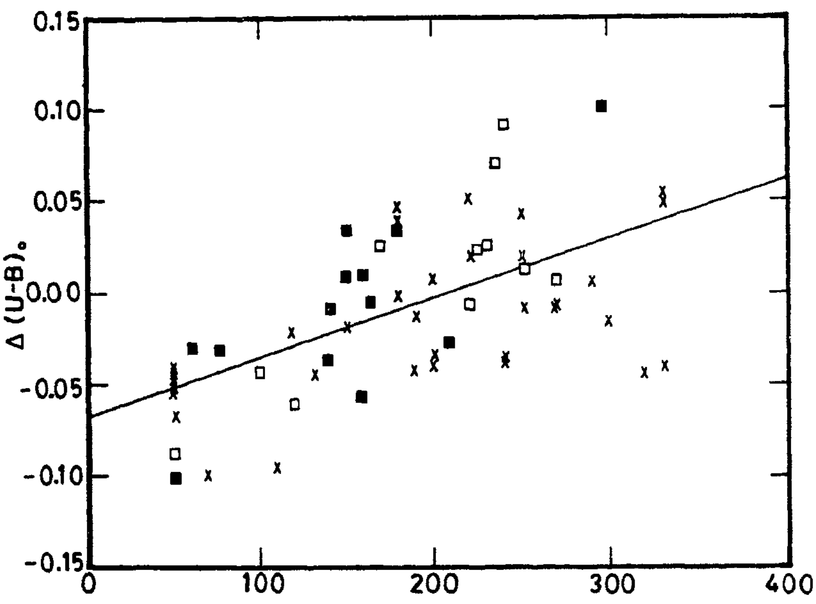

Figure 5. The deviations in $(U-B)_0$ are plotted against $V \sin i$ for Scorpio-Centaurus members. Symbols have the same meaning as in figure 2b.

Table 4 Observed reddening due to rotation for 100 km s⁻¹ of V sin i in B stars

Cluster	Sp	No of stars	From β, $(U-B)_0$: $(U-B)_0$	β	From β, $(B-V)_0$: $(B-V)_0$	β
α-Per	B0-B3	2	0.049	−0.016	0.013	−0.016
	B5-B9	10	±0.006	±0.002	±0.002	±0.002
	A0-A2	6				
α-Per + Pleiades	B0-B3	2	0.042	0.016	0.011	−0.016
	B5-B9	15	±0.005	±0.002	±0.001	±0.002
	A0-A2	9				
Sco-Cen	B0-B4	33	0.032	−0.012	0.007	−0.011
	B5-B9	33	±0.005	±0.003	±0.001	±0.003

0.5, 0.8, 0.9, 0.99 and i values 0, 36, 54 and 90, a second order polynomial fit was determined for the β, $(U-B)$ and β, $(B-V)$ relations and the deviations $\Delta(U-B)$, $\Delta(B-V)$ and $\Delta\beta$ were determined. The slopes of the relation between $V \sin i$ and the colour excess derived for the two models corresponding to the spectral types B4 and A0 are given in table 5, which can be compared with table 4. It can be noticed that the theoretical predictions of Maeder & Peytremann (1970) do not agree with the observed results and that they are much lower than the observed results.

Table 5. Theoretical reddening due to rotation for 100 km s⁻¹ of V sin i in B stars (Maeder & Peytremann, 1970)

Sp	From β, $(U-B)_0$: $(U-B)_0$	β	From β, $(B-V)_0$: $(B-V)_0$	β
B4	0.019	0.000	0.006	0.006
	±0.004	±0.003	±0.001	±0.004
A0	0.008	0.056	0.009	−0.015
	±0.004	±0.006	±0.004	±0.006

In order to compare with predictions by Collins & Sonneborn (1977) who have given the intermediate band photometric indices as a function of rotational velocity we derived the relation between $(U-B)$ and $(u-b)$ and also $(B-V)$ and $(b-y)$. The indices for B star standards of various spectral types taken from the ephemerides lead to the relation.

$$(U-B) = -0.134(u-b)^2 + 0.7777(u-b) - 0.9223$$
$$(B-V) = 1.891(b-y) - 0.028.$$

A detailed discussion of the theoretical predictions of Collins & Sonneborn for the intermediate band uvby indices is given in paper 2. Using the relationship given above, the predicted slopes from narrow band indices (table 7a and 7b of paper 2) were used to derive the expected effects in broad band UBV colours. This for two different spectral type ranges are given in table 6.

The observed slope of the rotation effect in $(U-B)_0$ for α-Persei and Pleiades members, where majority belong to B5 to B9 stars, is 0.042 ± 0.005 per 100 km s⁻¹ of

Table 6. Theoretical reddening due to rotation for 100 km s^{-1} of $V \sin i$ (Collins & Sonneborn 1977)

Sp.	From $\beta,(U-B)_0$		From $\beta,(B-V)_0$	
	$(U-B)_0$	β	$(B-V)_0$	β
B5-B9	0.042 $\pm$0.007	−0.010 $\pm$0 002	0 010 $\pm$0.001	−0.009 $\pm$0 002
B0-B9	0 030 $\pm$0.005	−0.007 $\pm$0 002	0 008 $\pm$0.001	−0 007 $\pm$0 002

$V \sin i$ in excellent agreement with the calculated theoretical value for B5 to B9 stars For Scorpio-Centaurus association the reddening due to rotation in $(U-B)_0$ is 0.032 ± 0.005 which is in agreeement with the calculated average theoretical value of 0.030 ± 0.005 for B0 to B9 stars.

In $(B-V)_0$ too the slopes are in excellent agreement. For α-Persei and Pleiades the slope is 0.011 ± 0.001 while the theoretical prediction is 0.010 ± 0.001 for B5 to B9 stars. For Scorpio-Centaurus association reddening in$(B-V)_0$ is 0.007 ± 0.001 which agrees very well with the theoretical predictions of 0.008 ± 0.001 for B0 to B9 stars. It should be noted that the predicted values were first derived for *uvby* indices (paper 2). These slopes were related to broad band colours through standard stars. In spite of such uncertainities the agreement seems to be excellent.

5. Conclusion

The effect of rotation on UBV photometry is estimated. The relationship between $(U-B)$ and $(u-b)$ and also $(B-V)$ and $(b-y)$ were established using the standard stars photometry to compare the observed effects with the theoretical predictions of Collins & Sonneborn. The observed effects of rotation in α-Persei, Pleiades, and Scorpio-Centaurus association is in excellent agreement with models of Collins & Sonneborn (1977) but disagrees with the calculations by Maeder & Peytremann (1970). The slope of the observed reddening per 100 km s^{-1} of $V \sin i$ in $(U-B)$ and $(B-V)$ for B5 to B9 stars is 0.042 ± 0.005 and 0.011 ± 0.001 respectively.

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Discussion

Mohan : Do you have the spectral classes for the stars that you have considered? If so, what are the calibrations that you have used to get the intrinsic colours?
Rajmohan : For the intermediate band indices like C1, $(u - b)$, $(b - y)$ etc. we followed Crawford to determine the intrinsic colour indices.