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Effects of Rotation on the Colours and Line Indices of Stars 6. The Reality of the Blue Straggler Phenomenon

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Abstract. The effect of rotation on the observed colours of stars has been considered as a possible cause for the blue straggler phenomenon in clusters listed by Mermilliod (1982). It appears that this phenomenon is definitely not real in the case of the late B and early A spectral type blue stragglers that are intrinsic slow rotators. Among clusters containing the early B type blue stragglers it is found that the anomalous position of the stragglers in NGC 6633, NGC 6475 and NGC 2516 cannot be accounted for by rotation effects alone.

Key words: stars, rotation—stars, colours—star clusters, individual—stars, blue stragglers

1. Introduction

Blue stragglers are stars that occupy a position in a cluster colour magnitude diagram above and to the left of the cluster main sequence. They appear bluer than the presumed cluster turn off, obviously contradicting the assumption that all cluster members are coeval. Various theories have been put forward to explain their anomalous position with respect to the cluster main sequence.

Williams (1964a) in his delayed formation theory suggested that these objects were formed later than other cluster members and that the assumption that cluster members are coeval is erroneous. This theory is not favoured any longer since there is no independent observational evidence especially in old open clusters for ongoing star formation such as the occurrence of T-Tauri stars, emission or reflection nebulae and differential reddening due to clumps of dusty gas (Wheeler 1979a).

Williams (1964b) proposed the theory of accretion in which a main sequence star accretes matter from high density regions and moves along the main sequence to become a bluer star. The interaction of the interstellar matter already present in the cluster with the mass ejected by supergiant members is supposed to produce such regions. For this mechanism to be operative such clusters must be fairly old while blue stragglers seem to occur in clusters of all ages.

Mass transfer in close binaries proposed by McCrea (1964) and quasi homogenous evolution proposed by Wheeler (1979b) are more viable but the evidence in support of them is not conclusive. While some blue stragglers do show radial velocity

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variations, an equal number have constant radial velocity indicating that duplicity is not a necessary condition for their existence.

Maeder (1987) hypothesized extra-mixing by rotationally induced turbulent diffusion in OBN stars giving rise to nearly homogeneous evolution. This suggestion is analogous to the extensive mixing hypothesis proposed by Wheeler. Another mechanism that may lead to homogenous evolution is extensive core overshooting as suggested by Stothers & Chin (1979). Stellar coalescence suggested by Leonard (1989) attributes the formation of blue stragglers to binary–binary collisions in globular clusters. A blue straggler formed from the above mechanism must not be a slow rotator as the merger of binaries should produce a rapidly rotating star. Blue stragglers on the other hand have a wide range of observed $V \sin i$ values.

Mermilliod (1982) compiled a list of blue stragglers in clusters younger than the Hyades which show a large spread in properties indicating that no unique model would be able to explain all the observations.

Mermilliod (1982) has shown that there are no observable differences between the blue stragglers and corresponding normal main sequence stars, except for the distribution in their rotational velocities. He also found that the blue stragglers cannot be identified spectroscopically and can only be discovered from their position in the colour-magnitude diagram.

An interesting feature that has emerged out of the work on blue stragglers (Pendl & Seggewiss 1975; Mermilliod 1982) is that more than half of them belong to the class of chemically peculiar (CP) stars of spectral types B7 and later. This group, in general consists of slow rotators. The blue stragglers earlier than B5, in general, have a range in their observed rotational velocities and some of them are also Be stars. This marked characteristics in the rotational velocity distribution of the blue stragglers and the fact that even in the old galactic cluster M 67 (Mathys 1991) they are all slow rotators have led us to investigate the possibility of rotation effects on colours of cluster stars as a primary cause for their observed positions. We have already established in a series of papers (Rajamohan & Mathew 1988; Mathew Rajamohan 1990 a,b; 1991) that such rotation effects are discernible in the observed data of star clusters and also that the effects are fully consistent with the theoretical prediction of Collins & Sonneborn (1977).

The blue stragglers that fall in the early A-type domain the intrinsic slow rotators – are discussed in Section 2, and the B-type stragglers with a wide range in rotational characteristics are discussed in Section 3. A summary of the results is given in Section 4.

2. The A-type blue stragglers

The early B type stars in a cluster have maximum observed rotational velocities close to their break-up speeds, while the maximum observed rotational velocity for stars in the spectral range B5–FO is close to $\omega = 0.9$ (Rajamohan 1978; Kawaler 1987). The effect of rotation on the main sequence of a cluster, is to displace it from its non-rotating counterpart and broaden it by about twice the displacement (Collins & Smith 1985). The maximum displacement that a main sequence star would suffer, depends directly on the maximum rotational velocity that it can have; this corresponds to the balance between centrifugal force and gravity at the equator. The observed distribution of main sequence stars in a cluster between the zero rotation main sequence curve and the main sequence curve for $\omega = 1.0$ therefore, depends on the spread in the true rotational velocities of the stars. Also the observed dispersion along the main sequence would be a function of mass as the effects on different indices peak in different mass ranges.

The maximum effects predicted for the $(u - b)$ index are for stars in the B7–A0 spectral range (Collins & Sonneborn 1979). The presence of a slow rotator in any cluster where the turn-up occurs for stars in the above spectral range, would make the slow rotator appear bluer than other normally rotating main sequence stars. Since the effects of rotation and evolution both act in the same direction, this observed colour difference would make the stars on the main sequence appear more evolved than the blue straggler itself. We have in the following analyses, taken this differential reddening effect due to rotation into account in judging how blue the blue stragglers really are, and how much really are the nearby cluster members evolved.

Table 1 gives the theoretically predicted changes for inclinations $i = 0°$ and $i = 90°$ in the various photometric indices for a non-rotator and a star of the same spectral type rotating with $\omega = 0.9$. This table was derived from the work of Collins and Sonneborn (1977). They have listed the values of $(b - y)$, c, m, β, M_v and $(u - b)$ for various values of i ranging from 0° to 90° and fractional velocities $\omega = 0.0$, 0.5, 0.8, 0.9 and 1.0. These values have been tabulated for the mass range that corresponds to the main sequence stars in the spectral type domain B0 to A7. Table 1 shows that the effects of rotation on the colour indices are almost independent of i in the B0 to A2 spectral domain.

Table 2, lists the blue stragglers belonging to the class of slow rotators taken from a list compiled by Mermilliod (1982). Column 2 lists the clusters to which the blue straggler belongs, Column 3 its HD number, Column 4 its spectral type and Column 5 its observed $V \sin i$ value. The last column contains remarks, if any, on the binary nature, membership probability, radial velocity variations etc. of the blue stragglers under consideration. The $V \sin i$ values of the stragglers in NGC 6633 and NGC 6281 have been taken from Abt (1985). The spectral type, $V \sin i$ values and other remarks for the clusters in the table are as given by Mermilliod.

Mermilliod's listing contains a few more clusters. We have considered only those for which intermediate and narrow-band photometric data along with $V \sin i$ values for the blue straggler were readily available. The membership probability of star no. 161 (HD 170563) in NGC 6633 (Abt 1985) and star no. 9 (HD 153947) in NGC 6281, (Feinstein & Forte 1974) is low.

From Table 1, it can be seen that rotation effects on the $(u - b)$ index are larger than on $(b - y)$ in the B7–A0 spectral range. In a given cluster the members in these spectral ranges, rotating with an average velocity typical of their spectral class should suffer a large change in both the $(u - b)$ and $(b - y)$ indices due to rotation and be pushed away from the zero rotation main sequence. This rotational reddening in $(u - b)$ is especially large for this spectral range. Most of the blue stragglers listed in Table 2, being peculiar, are intrinsic slow rotators (Abt 1979) and have anomalously low observed $V \sin i$ for their spectral type. They fall in the above mentioned spectral range where rotation effects on the $(u - b)$ index reach a maximum.

A plot in the M_v versus $(b - y)$ or M_v versus $(u - b)$ plane of any of these clusters containing an intrinsic slow rotator in the B9–A0 spectral range would, therefore, show the slow rotators in a position that is blue when compared to other stars in the same spectral range rotating with an average velocity of the order of 150 km s^{-1}. The slow rotator would thus appear as a blue straggler, the effect being more pronounced in the M_v versus $(u-b)$ plane since rotation affects the $(u-b)$ index considerably.

Figs 1 to 5 show the clusters listed in Table 2 plotted in the $(M_v, b-y)$; $(M_v, u-b)$, and $(u-b)$, $(b-y)$ planes. The observed $(b-y)$ index of each of the

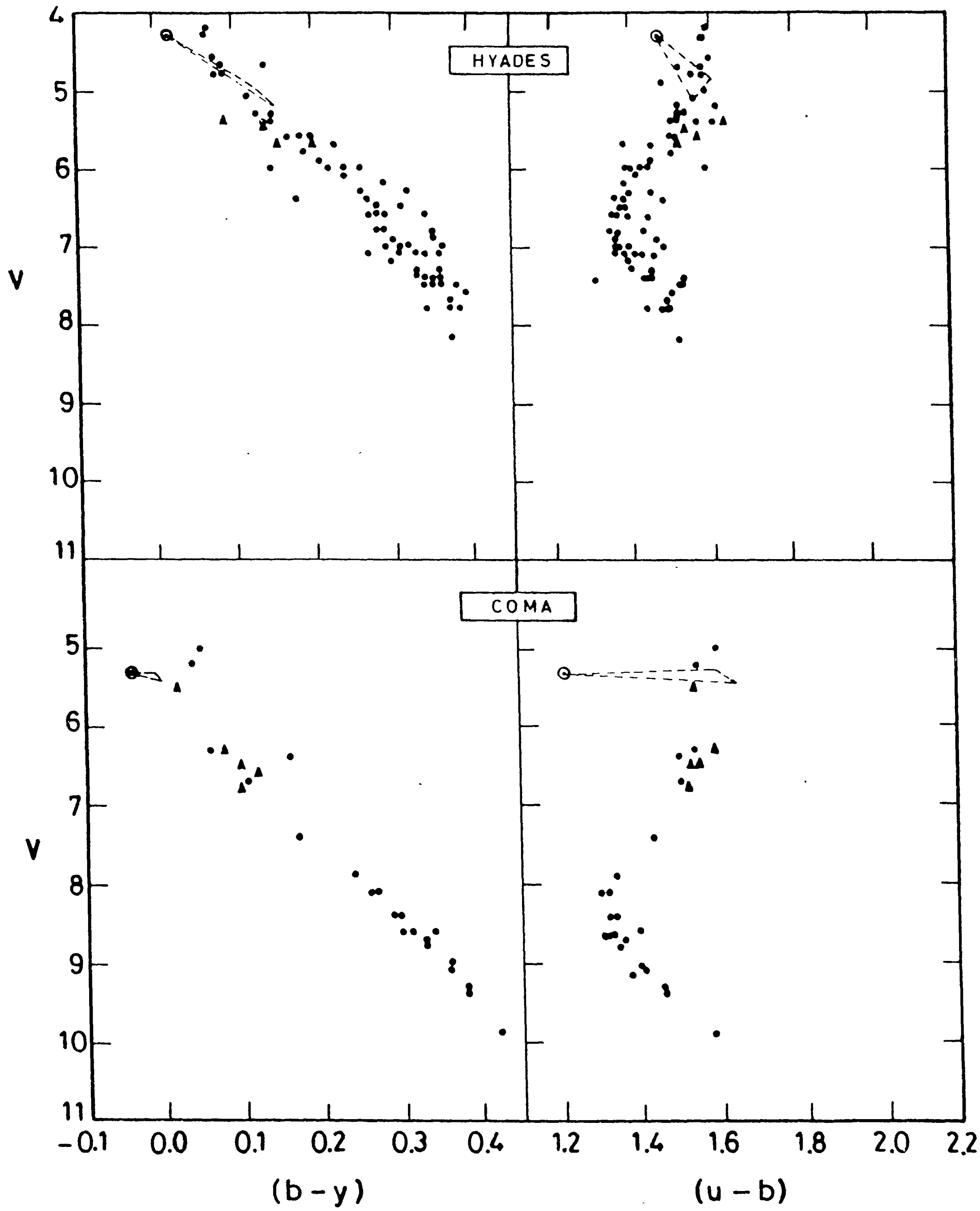


Figure 1(a). Hyades and Coma in the V versus $(b-y)$ and V versus $(u-b)$ planes. The filled circles represent the cluster members and the filled triangles the Ap and Am stars in the cluster. The blue straggler is denoted by a dot inside an open circle. The triangle with one apex as the blue straggler represents the correction for $\omega = 0.9$ for angles of inclination $i = 0$ and $i = 90$.

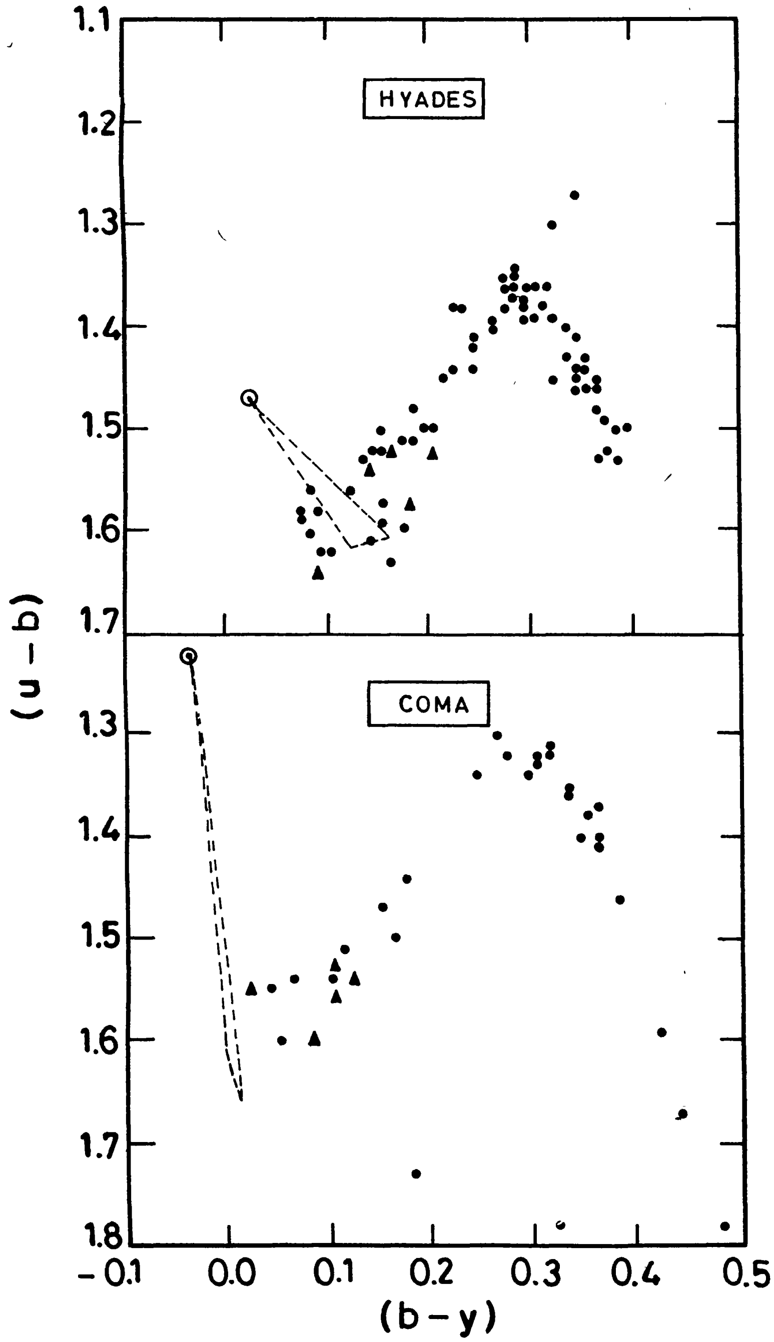


Figure 1(b). Hyades and Coma clusters in the $(u-b)$ versus $(b-y)$ plane. Symbols are the same as in Fig. 1(a).

blue stragglers in the clusters was corrected for interstellar reddening using the average $E(b-y)$ given for each of these clusters in the original papers giving photometric data. References to the cluster data along with the $E(b-y)$ value used are given in Table 3. The rotational correction for $\omega = 0.9$ at the observed $(b-y)_0$ was taken for $i = 0°$ and $i = 90°$ from Table 1. We have indicated by means of a triangle in each of these figures the change in position of the blue straggler if it were to be rotating with velocity ranging anywhere from zero to a maximum velocity corresponding to $\omega = 0.9$. Rotation effects in the $(u-b,\ b-y)$ plane push the stars along the

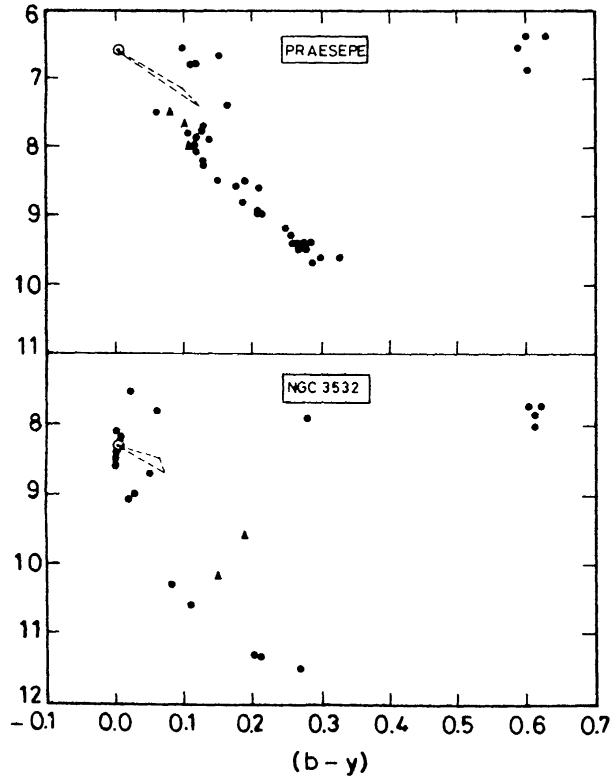


Figure 2(a). Praesepe and NGC 3532 in the V versus $(b - y)$ plane. Symbols are the same as in Fig. 1(a).

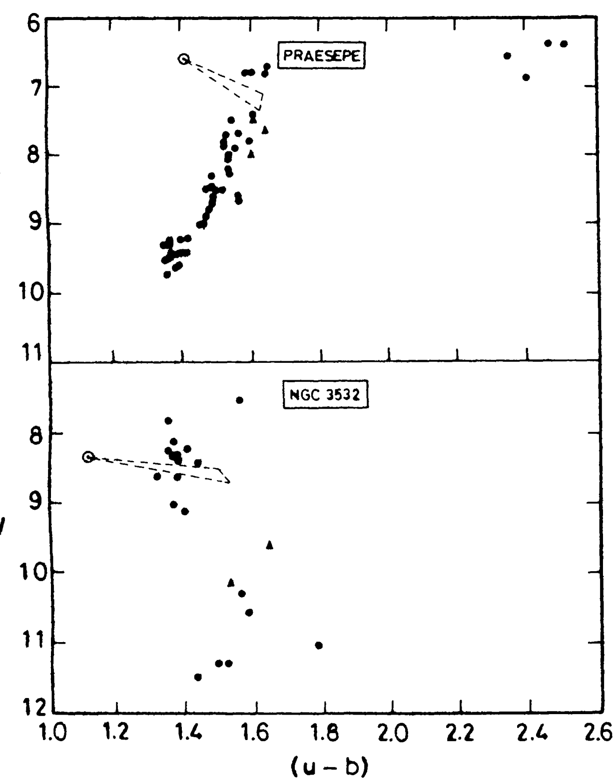


Figure 2(b). Praesepe and NGC 3532 in the V versus $(u - b)$ plane. Symbols are the same as in Fig. 1(a).

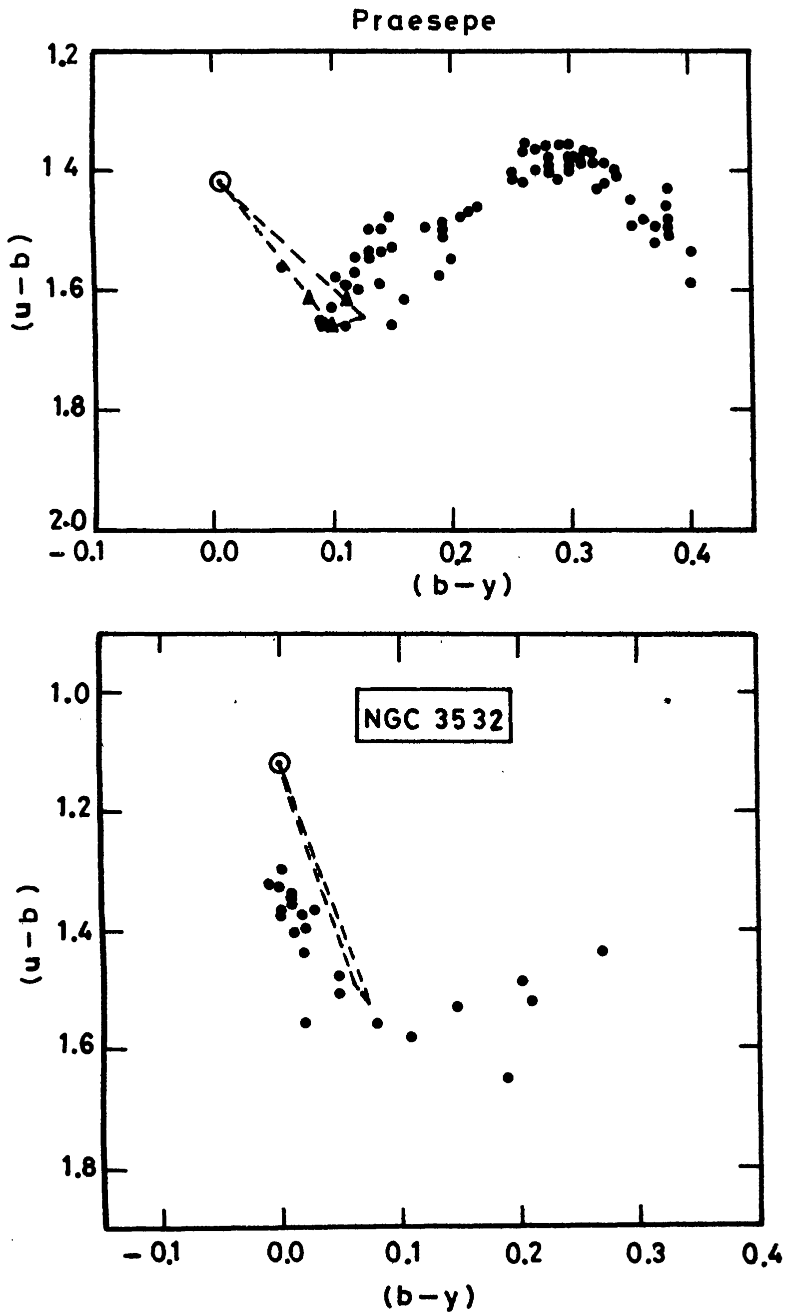


Figure 2(c). Praesepe and NGC 3532 in the $(u-b)$ versus $(b-y)$ plane. Symbols are the same as in Fig. 1(a).

main sequence curve. For the B0 to A2 stars the $(u-b)$ index is affected by a larger extent than the $(b-y)$ index. A slow rotator in this plane would therefore, maintain its position on the curve, whereas the other normally rotating stars would be pushed downwards. This would cause a large gap between the slow rotators and the others. Correction of the blue straggler in this plane causes a significant reduction in this gap as shown in Fig. 1(b) for Hyades and Coma and in Fig. 2(c) for Praesepe and NGC 3532. An exception to these results is the cluster NGC 6633. The blue stragglers in this cluster are discussed in the next section.

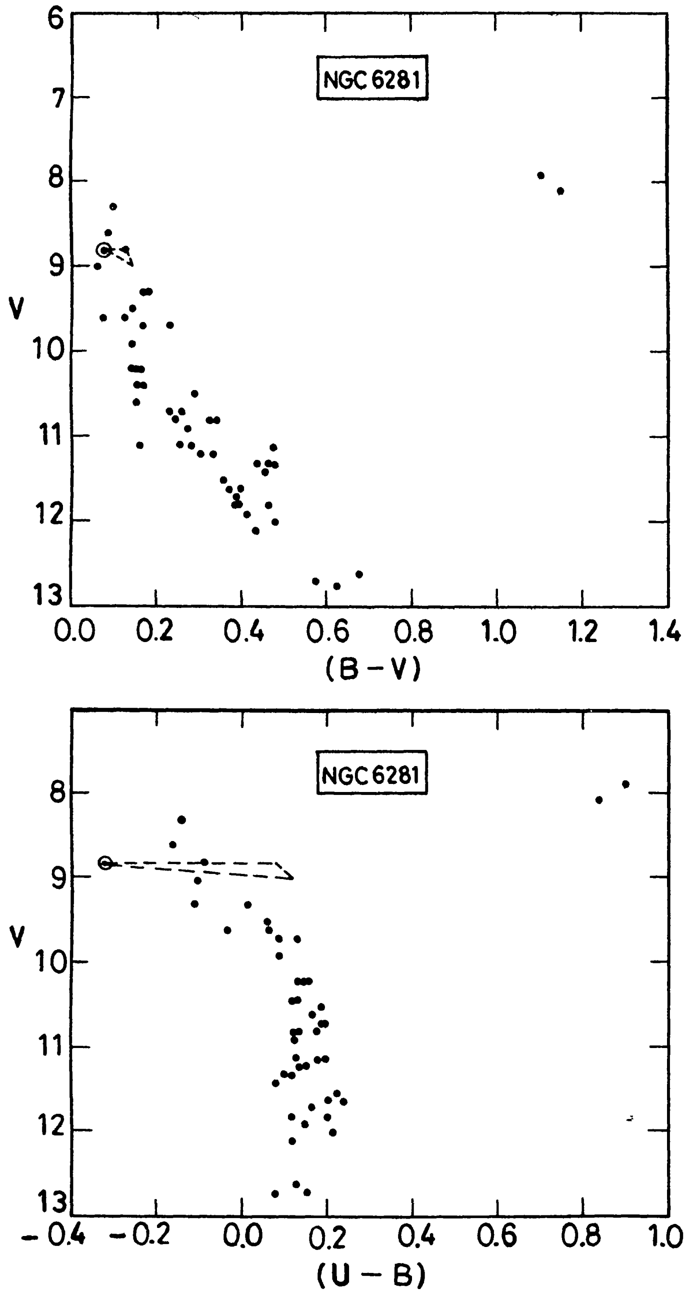
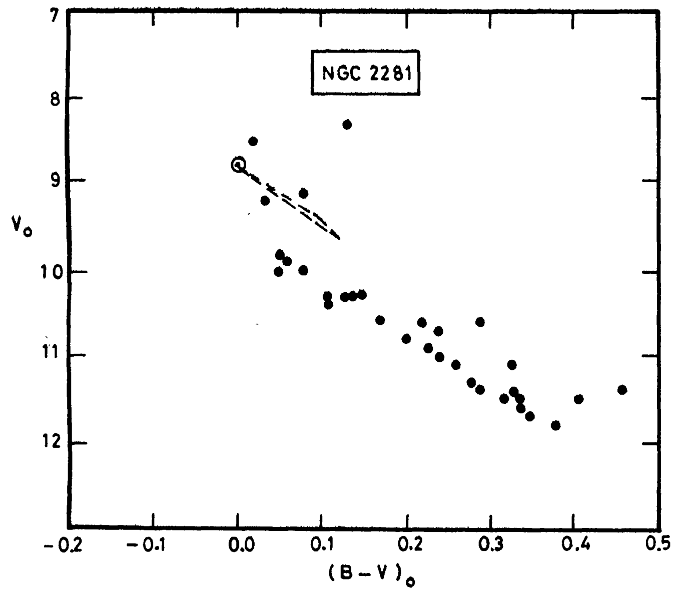


Figure 3. NGC 6281 in the V versus $(B-V)$ and V versus $(U-B)$ planes. Symbols are the same as in Fig. 1(a).

NGC 2281 has been analysed using *UBV* data since narrow-band data for this cluster is not available. Similarly, for NGC 6281 broad-band indices have been plotted as narrow band data for the blue straggler in this cluster is not available. The corrections applied to the blue stragglers in these cases would be underestimated since larger effects due to rotation on the broad-band colours are predicted (Collins & Smith 1985). The analysis of rotation effects on the broad-band *UBV* colours of the α-Persei and Pleiades cluster (Mathew & Rajamohan 1991) show that the effects are of the order of 0.05 mag. per 100 km s^{-1} in $(U-B)$.

The cluster colour–colour and colour–magnitude diagrams show clearly that the



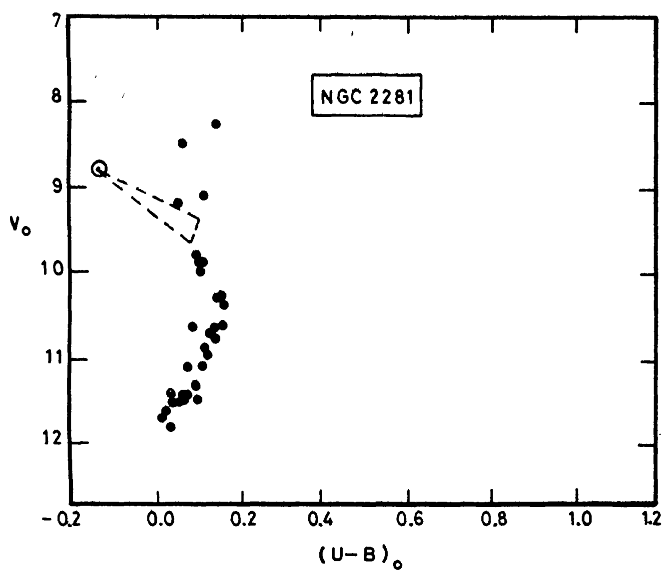


Figure 4. NGC 2281 in the V_0 versus $(B-V)_0$ and V_0 versus $(U-B)_0$ planes. Symbols are the same as in Fig. 1(a).

anomalous position of all the blue stragglers listed in Table 2, with the exception of the blue stragglers in NGC 6633, can be explained purely by differences in the rotational velocities between the straggler and its nearest main sequence neighbours. The fact that blue stragglers in the *B* and early *A* spectral type domain appear bluer because of their low rotation seems to have been noted by Strittmatter & Sargent (1965) more than 25 years ago! They corrected the metallic-line stars in the Hyades, Praesepe and Coma clusters for blanketting effects and found that they lie to the left of the main sequence. They suggested that this was because they were slow rotators and that other stars of similar masses have been shifted to the red due to rotation.

We would also like to draw attention here to the blue stragglers in IC 4756, IC 4651, NGC 752 and M67. The stragglers studied by Pendl & Seggewiss (1975) in IC 4756 are all spectroscopically peculiar and these authors were the first to suggest

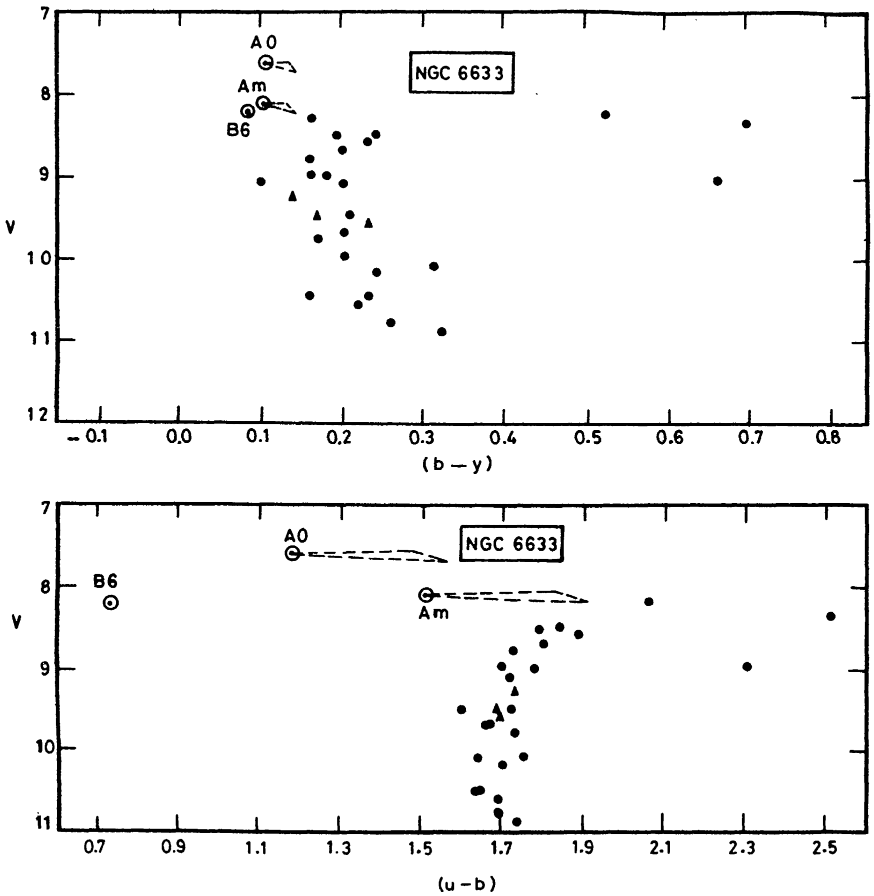


Figure 5. NGC 6633 in the V versus $(b-y)$ and V versus $(u-b)$ planes. Symbols are the same as in Fig. 1(a).

Table 1. Change in the indices from $\omega = 0.0$ to $\omega = 0.90$.

$M/M_\odot$	Sp. Type	ΔM_v		$\Delta(b-y)$		$\Delta(u-b)$		Δc_1	
		$i=0$	$i=90$	$i=0$	$i=90$	$i=0$	$i=90$	$i=0$	$i=90$
14.5	B0	0.07	0.23	0.025	0.029	0.149	0.158	0.097	0.098
11.0	B1	−0.01	0.15	0.027	0.031	0.208	0.085	0.152	0.156
8.3	B2	−0.05	0.12	0.028	0.033	0.247	0.265	0.185	0.193
6.3	B3	−0.07	0.10	0.028	0.034	0.291	0.314	0.229	0.242
4.9	B5	−0.09	0.09	0.029	0.035	0.347	0.379	0.281	0.300
3.9	B7	−0.06	0.12	0.032	0.039	0.391	0.430	0.311	0.336
2.8	B9	0.23	0.43	0.056	0.068	0.374	0.401	0.246	0.247
3.3	B8	0.03	0.21	0.039	0.047	0.401	0.442	0.303	0.324
2.5	A0	0.55	0.32	0.091	0.117	0.237	0.217	0.077	0.025
2.3	A1	0.64	0.93	0.104	0.137	0.152	0.114	−0.004	−0.082
2.1	A2	0.68	0.97	0.115	0.153	0.086	0.026	−0.078	−0.172
1.9	A3	0.72	1.01	0.129	0.174	−0.009	−0.086	−0.173	−0.290
1.8	A5	0.45	0.74	0.119	0.173	−0.107	−0.189	−0.239	−0.367
1.7	A7	0.31	0.59	0.120	0.179	−0.146	−0.217	−0.274	−0.403

Table 2. List of the *A*-type blue stragglers.

S. no.	Cluster	Star no. HD(E)	Spectral type	$V \sin i$	Remarks
1.	Hyades	27962	AIVm	< 30	Constant Vr, D 1″.4, $3^m.3$
2.	Coma	108662	AOp (Sr, Cr)	15	Constant Vr, α CVn type var.
3.	Praesepe	73666	AIV	10	Constant Vr
4.	NGC 3532	96213	AOIV		D 0″.4, $0^m.5$
5.	NGC 6281	153947	AOp(Si)	~ 30	Probable non member
6.	NGC 6633	169959	AOIII	< 40	
		170563	Am		Probable non member
7.	NGC 2281	49010	Ap		

Table 3. References to cluster data for the A-type stragglers.

S. no.	Cluster	Data	Reference
1.	Coma	*uvby*	Crawford & Barnes (1969)
2.	Hyades	*uvby*	Crawford & Perry (1966)
3.	Praesepe	*uvby*	Crawford & Barnes (1969)
4.	NGC 2281	*UBV*	Pesch (1961)
5.	NGC 3532	*ubvy*	Eggen (1981)
6.	NGC 6281	*UBV*	Feinstein & Forte (1974)
7.	NGC 6633	*uvby*	Schmidt (1976)

strongly that the two phenomena appear to be related. What is actually common to the two phenomena is slow rotation. Slow rotation is indirectly responsible for these objects to appear bluer and it is well known that almost all chemically peculiar stars on the upper main sequence are slow rotators.

In M 67 Mathys (1991) finds that all the blue stragglers are slow rotators and the blue straggler phenomenon seems to be related to the Am phenomenon even though only two of the eleven stragglers are known Am stars (Pesch 1967). As noted by Pendl & Seggewiss (1975) the blue stragglers have not been studied carefully to recognise Ap, Am characteristics and it would not be surprising if a large fraction of the M 67 stragglers turn out to be Ap stars of the Hg–Mn type. A comparison of IC 4651 and M 67 in the M_v versus $(B - V)$ plane also indicates that the stragglers in IC 4651 could possibly be explained in terms of rotation effects if they were to be intrinsic slow rotators. The position of the blue straggler in NGC 752 however does indicate that it cannot be explained by rotation effects alone.

3. The B-type blue stragglers

A listing of the blue stragglers in the B0–B6 spectral range is given in Table 4. The third coloum gives the HD number of the blue straggler, followed by its spectral type and observed $V \sin i$ values in Columns 4 and 5 respectively. The last column is similar to that in Table 2 and gives details regarding duplicity etc. The nine clusters listed in Table 4 along with the above data have been taken from Mermilliod's (1982) listing of blue stragglers. Unlike the A-type stragglers discussed in Section 2, the B-type stragglers have a random $V\sin i$ distribution. Out of the nine clusters listed in the table, NGC 6633 and NGC 6475 stragglers have low observed $V\sin i$'s. The rotational velocities of the stragglers in NGC 6025 and NGC 2439 are not available. Out of the remaining five clusters, four contain emission-line objects, indicating rotation at a velocity close to their break-up speeds, while the blue straggler in IC 2602 has a $V\sin i$ typical of stars belonging to the spectral type B0.

The effect of rotation, in general, on the early B type (B0–B3) stars, is small in comparison with the effect on the late B type (B5–B9) stars. The reddening due to rotation in the $(u-b)_0$ and c_0 indices in particular shows a steep increase in the B5–B9 spectral range relative to the early B type stars. The blue stragglers that are fast rotators, except for Alcyone in Pleiades fall in the B0–B3 mass domain where the rotation effects are not pronounced. It is therefore possible that in a few of these clusters, differential rotational reddening, may cause the stars that are of slightly lower mass than the straggler, to appear redder and therefore more evolved.

To check that the above effect may be a possible cause for some of the stars to be designated blue stragglers we attempted to correct the brightest cluster stars on the main sequence for the effects of rotation. We do find that the bright main sequence stars close to the stragglers are indeed fast rotators and fall in the spectral type range where the rotational effects on their colours are large.

To correct each star for rotation effects, we need to know the individual values of V and i. We have assumed a value of $i = 45°$ to get an approximate estimate of the velocity V with which the star is rotating from the observed $V\sin i$ value. Table 5 contains the average corrections for $100\,\mathrm{km\,s^{-1}}$ of rotation that have to be applied in the M_v, $(u-b)_0$ and M_v, $(b-y)_0$ plane calculated from the work of Collins & Sonneborn (1977). These corrections have been listed as a function of $(u-b)_0$ since masses of the stars are unknown. The ZRZAMS values of $(u-b)_0$ as a function of mass is taken from Mathew & Rajamohan (1991). The observed $(u-b)_0$ for each star was used to get the first set of corrections in $(u-b)_0$ and M_v. These corrected indices were then used to derive the second set of corrections in M_v and $(u-b)_0$. The average of these two sets was used to correct the stars in the M_v range 0.0 to -2.0 magnitude for which rotation velocity data are available. Some of the stars in this magnitude range have low observed $V\sin i$ ($< 50\,\mathrm{km\,s^{-1}}$). These appear considerably displaced from the ZRMS and are probably fast rotators seen pole-on. The velocities obtained from the $V\sin i$ values in these cases are obviously underestimated leaving these star uncorrected.

Six of the nine clusters listed in Table 4 are shown in the M_v versus $(u-b)_0$ plane in Figs 6 to 11. Table 6 gives the references to the cluster data along with the distance modulus and $E(b-y)$ value used. The straggler in NGC 2287 is considered a non-member by Mermilliod (1982), as it lies outside the cluster radius and its membership based on available radial velocities is difficult to assess. Intermediate-band photometric indices are not available for NGC 2439. The stragglers in the remaining seven clusters are discussed below in relation to the rotational reddening effects as a possible cause contributing to their erroneous designation as blue stragglers. More detailed discussion on other properties of these stragglers have been listed by Mermilliod (1982).

(a) *HD 93030 in IC 2602*: This bright southern object has been found by Walborn (1979) to be a short period binary ($P = 1.7788$ days) with a relatively low mass companion. Mass transfer phenomenon is supposed to account both for its spectral

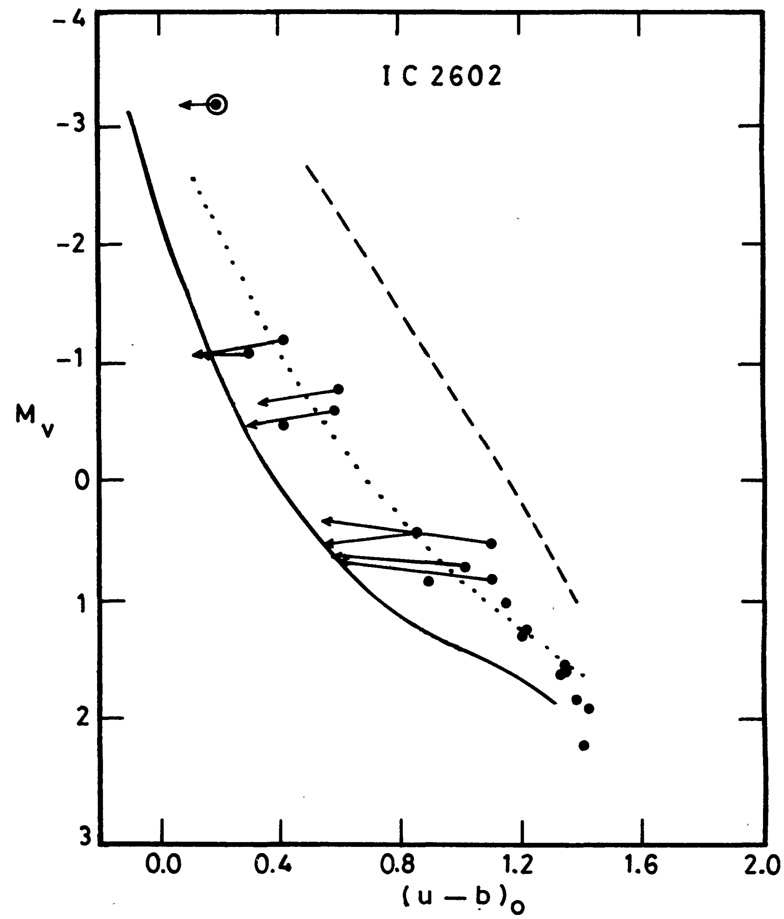


Figure 6. IC 2602 in the M_v versus $(u-b)_0$ plane. The blue straggler is denoted by a dot inside an open circle. The continuous line represents the zero rotation main sequence used by us. The theoretical sequence for $\omega = 0.9$ and 1.0 are denoted by the dotted and broken lines respectively. The arrow heads indicate the position of the stars, when corrected for rotation.

peculiarity and observed location in the HR diagram. The upper main sequence of the IC 2602 stars is shown in Fig. 6. Also shown, are the zero rotation zero age main sequence (ZRZAMS) from Mathew & Rajamohan (1991), the zero age main sequence (ZAMS) for $\omega = 0.9$ and the ZAMS for $\omega = 1.0$. The reddening effects predicted by Collins & Sonneborn (1977) for $\omega = 0.9$ and 1.0 were appropriately combined with the adopted ZRZAMS to derive the two ZAMS curves. The arrow heads indicate the position which the stars indicated would occupy if they were to be non-rotators. The rotationl velocities for these stars were taken from Levato (1975) and were corrected using Table 5. It can be noticed that the majority of the stars scatter around the ZAMS for $\omega = 0.9$ and would lie along the ZRZAMS if rotational reddening can be properly taken into account. The position of the blue straggler shows it is slightly evolved and cannot be considered anomalous.

(b) *HD 60855 in NGC 2422*: The upper main sequence of the stars in NGC 2422 is shown in Fig. 7. Rotational reddening corrections for the brightest members are indicated by arrows. Rotational velocities were taken from Dworetsky (1975). These corrections are a lower estimate if these stars have fractional velocities greater than $\omega = 0.9$. The reddening effect due to rotation is highly nonlinear for $\omega > 0.9$ (Collins &

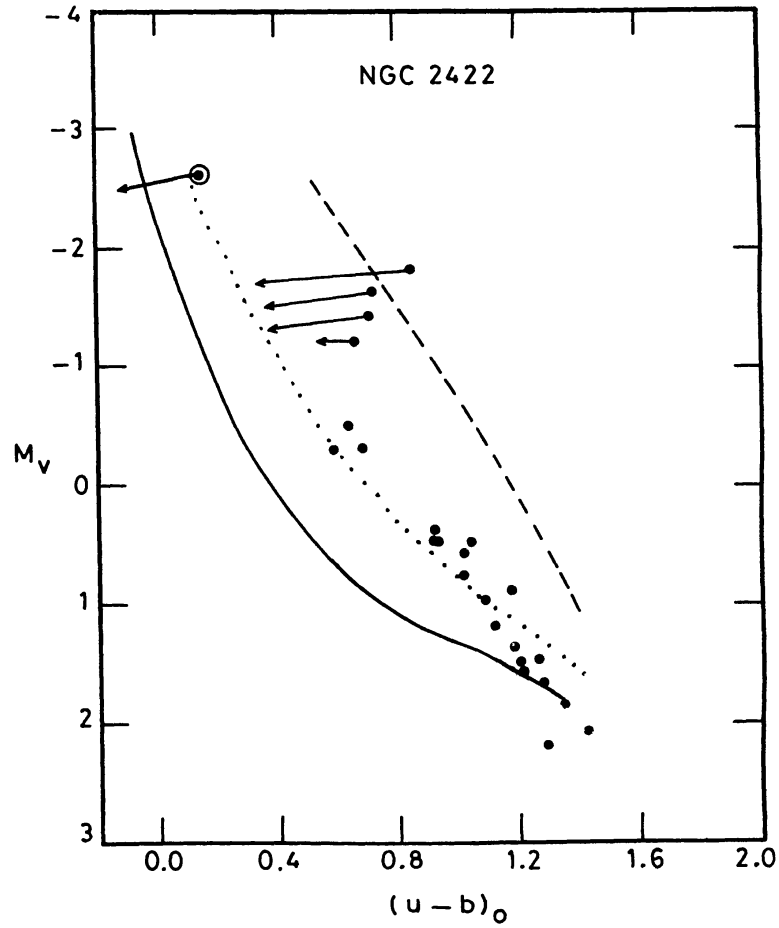


Figure 7. NGC 2422 in the M_v versus $(u-b)_0$ plane. Symbols are the same as in Fig. 6.

Sonneborn 1977; Collins & Smith 1985). On the other hand, if the stars on the upper main sequence are evolved, then they would be rotating with less than 0.9, as an increase in the radius would diminish the rotational velocity of the star. Our corrections in this case would be slightly overestimated. However, an ultraviolet excess of 0.15 magnitudes is not unusual for Be stars (Mermilliod 1982; Feinstein 1968). Therefore HD 60855 should be considered only as a probable blue straggler until detailed evolutionary tracks that take rotation into account become available.

(c) *HD 23630 in Pleiades:* The Pleiades data are plotted in Fig. 8, and the observed position of the stars appear to be consistent with the fact that they are fast rotators. (Anderson, Stoeckly & Kraft 1966). The rotation corrections applied to the bright stars indicate that the age has to be revised downwards by a larger amount than that estimated by Maeder (1970). Remarks similar to the ones made in connection with NGC 2422 regarding the estimates for these corrections also apply to Pleiades. Given the uncertainties in the position of the bright members, HD 23630 should not be considered a blue straggler.

(d) *HD 143448 in NGC 6025:* The data for this cluster is plotted in Fig. 9 which seems to indicate that the majority of the stars are fast rotators. No rotational velocity data is available for this cluster. The cluster appears similar to that of NGC 2422 and the same remarks as before apply to this cluster.

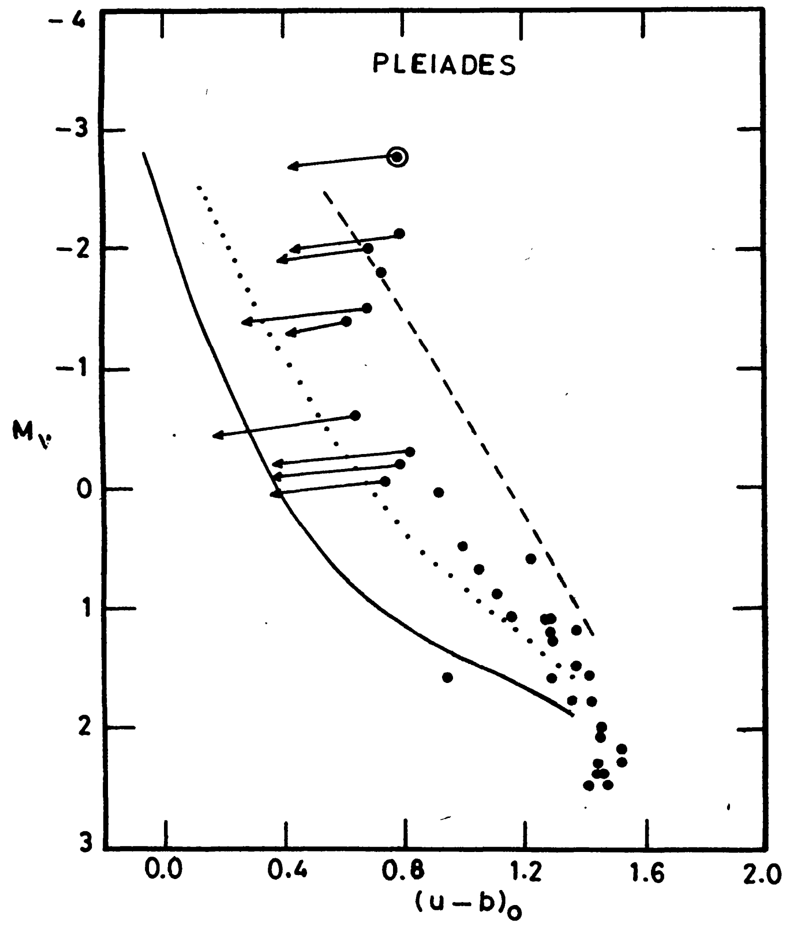


Figure 8. The Pleiades cluster in the M_v versus $(u-b)_0$ plane. Symbols are the same as in Fig. 6.

(e) *HD 66194 in NGC 2516:* The data for this cluster is plotted in Fig. 10. The large scatter of the stars in the M_v, $(u-b)_0$ plane appears to be directly correlated to the large spread in their rotational velocities. The $V\sin i$ values were taken from Abt *et al.* (1989). The slowly rotating peculiar stars in this cluster are found closer to the ZRZAMS. This fact has already been noted by Eggen (1972) and Snowden (1975). Both of them call the CP stars in this cluster as stragglers! We find that a large number of slow rotators lie well above the main sequence indicating that they are probably fast rotators seen pole-on. For a few of the bright members, rotational velocities are not available. The age estimates for this cluster by Eggen (1972) and Snowden (1975) must be considered highly uncertain due to the large observed spread in the rotational velocity distribution for this cluster. However, the position in the colour-magnitude diagram of one of the evolved giants in this cluster indicates that HD 66194 should be considered as a blue straggler, as the giant appears to have evolved from a star less massive than the blue straggler itself.

(f) *HD 162374 and HD 162586 in NGC 6475:* The data for this cluster is plotted in Fig. 11. As both are slow rotators we can consider what would be their position if their rotational velocities were to be high as we have done for the A-type stragglers. If HD 162586 is an intrinsic slow rotator, a fact which we cannot prove, then it cannot be considered as a blue straggler. HD 162374 appears to be a definite blue straggler

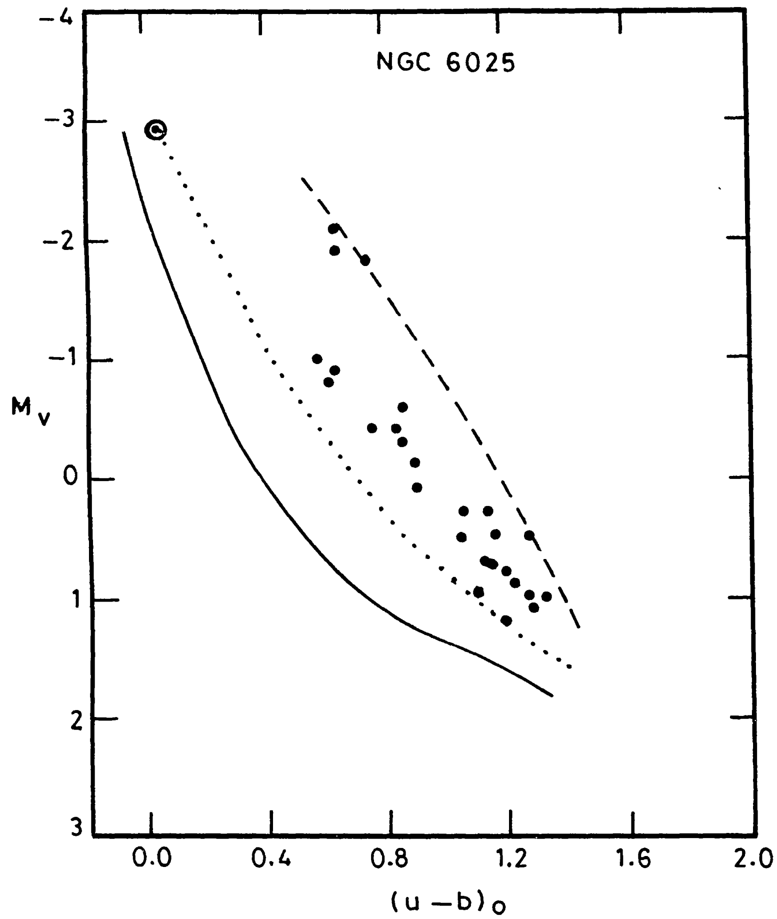


Figure 9. NGC 6025 in the M_v versus $(u-b)_0$ plane. Symbols are the same as in Fig. 6.

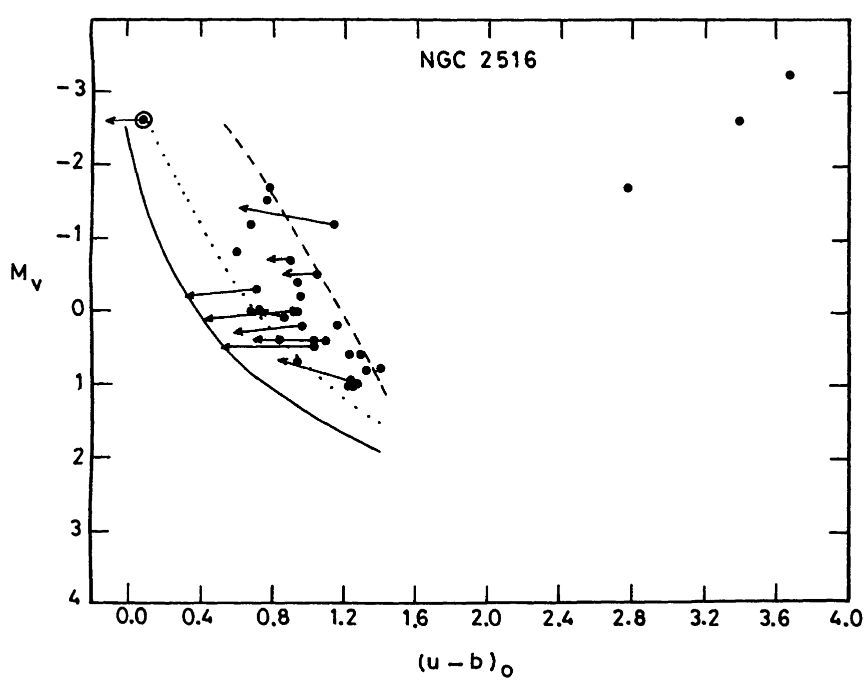


Figure 10. NGC 2516 in the M_v versus $(u-b)_0$ plane. Symbols are the same as in Fig. 6.

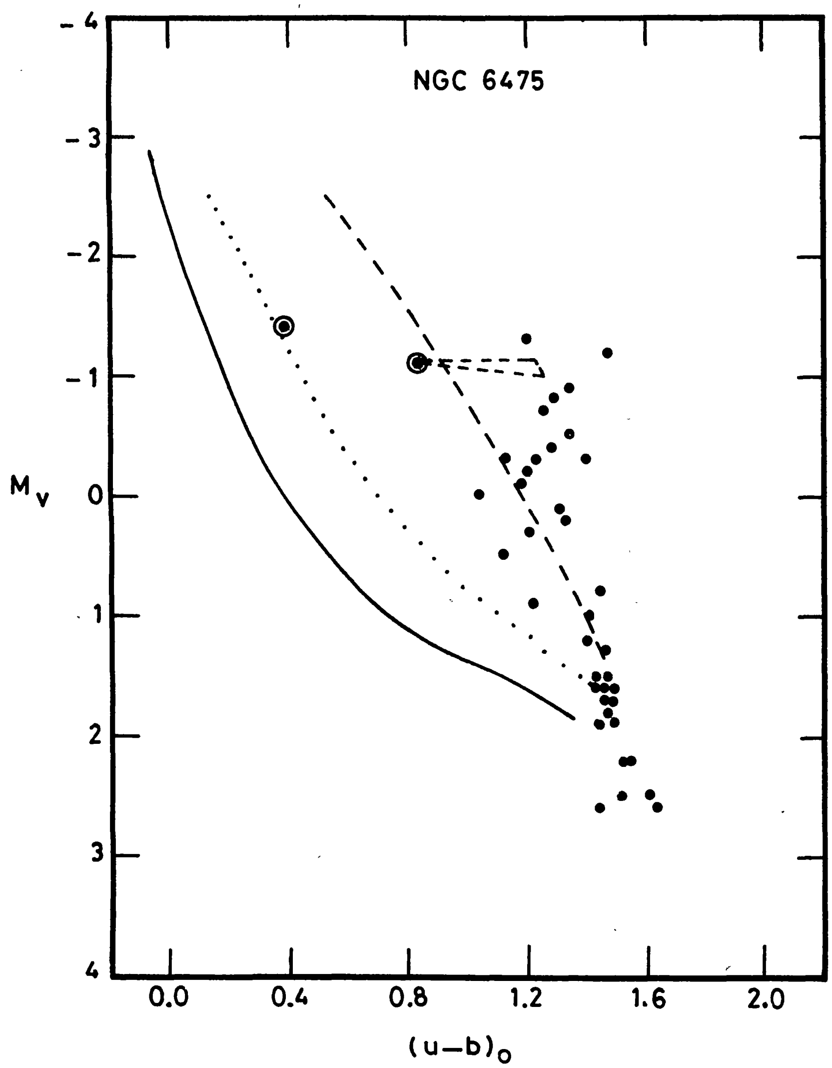


Figure 11. NGC 6475 in the M_v versus $(u-b)_0$ plane. Symbols are the same as in Fig. 6. The triangle with one apex as the blue straggler (HD 162586) represents the correction for $\omega = 0.9$ for angles of inclination $i = 0°$ and $i = 90°$.

Table 4. List of the *B*-type blue stragglers.

S. no.	Cluster	Star no. HD(E)	Spectral type	$V \sin i$	Remarks
1.	NGC 6633	170054	B6IV	< 20	Constant Vr
2.	NGC 6475	162374	B5IVp	< 40	He weak, constant Vr
		162586	B6V	< 40	D 0″5, $0^{m}0$
3.	NGC 2287	49333	B4p	100	He weak, probable non-member
4.	NGC 2516	66194	B2IVne	250	
5.	NGC 6025	143448	B3IVne		
6.	Pleiades	23630	B8IIIe	230	Alcyone
7.	NGC 2422	60855	B2IVe	320	D 5″2, $6^{m}8$
8.	IC 2602	93030	B0IVp	195	SB1
9.	NGC 2439	DM31° 4911	B1.5Ib		

Table 5. Average change in indices for change in velocity of $100\,\mathrm{km\,s^{-1}}$.

$(u-b)_0$	ΔM_v	$\Delta(b-y)$	$\Delta(u-b)$
−0.058	−0.009	0.005	0.045
0.185	−0.019	0.006	0.059
0.436	−0.026	0.007	0.078
0.654	−0.034	0.007	0.103
0.830	−0.027	0.008	0.122
0.926	0.000	0.011	0.129
1.129	0.062	0.016	0.122
1.301	0.170	0.028	0.072
1.379	0.200	0.031	0.043
1.488	0.206	0.035	0.020

Table 6. References to cluster data for *B*-type stragglers.

S. no.	Cluster	Data	Reference	Distance modulus	$E(b-y)$
1.	IC 2602	*uvby*	Hill & Perry (1969)	5.92	0.021
2.	NGC 2422	*uvby*	Shobbrook (1984)	8.01	0.060
3.	Pleiades	*uvby*	Crawford & Perry (1976)	5.54	0.040
4.	NGC 6025	*uvby*	Kilambi (1975)	9.40	0.110
5.	NGC 2516	*uvby*	Snowden (1975)	8.01	0.088
6.	NGC 6475	*uvby*	Snowden (1976)	7.01	0.067

whatever be its true rotational velocity unless its helium weak nature can account for its large observed excess in the $(u-b)_0$ index. The ultraviolet excess may not be able to account for the observed $(u-b)_0$ index for HD 162374 unless it is also an intrinsic slow rotator while the other members of the cluster are fast rotators.

(g) *HD 170054 in NGC 6633*: This cluster has two blue stragglers in the A-type domain and one blue straggler in the B-domain. Fig. 5 in Section 2 shows that the position of the Am star (HD 170563) can easily be accounted for in terms of rotation effects. This star is a probable non-member. There are six red giants in the cluster, whose membership has been established from radial velocity measures by Mermilliod & Mayor (1989). The observed position of the giants in the colour-magnitude diagram of this cluster surely indicates that HD 169959 and HD 170054 are definite blue stragglers.

If some of the stragglers in the B0–B3 class are real, then they are probably produced by the mechanism of mass-exchange in binary stars proposed by McCrea (1964). Quasi-homogenous evolution proposed by Wheeler (1979b) appears ruled out as these few candidate stragglers, which are all in the early B-spectral range have a wide range in their observed $V\sin i$ distribution.

4. Conclusions

The effect of rotation on observed colours of stars was considered as a possible cause for the observed position of blue stragglers in star clusters. We find that the observed blueness of the blue stragglers which are intrinsic slow rotators, in the B7–A2 type range can easily be accounted for by such effects. The reddening caused by rotation shifts the entire cluster main sequence away from the zero rotation main sequence leaving the slow rotators behind. The rotation effect in $(u-b)_0$ index reaches a maximum in the B7–A0 spectral type range where all the slowly rotating blue stragglers are also concentrated. It is also therefore not surprising that the majority of these A-type stragglers are found to be CP stars.

There are at least 6 blue stragglers which fall in the spectral type domain B0–B3 with the exception of the straggler in Pleiades. Amongst these objects, it is found that the dispersion in the $(u-b)_0$ index due to rotation can account for the blue stragglers in Pleiades and IC 2602. The position of the stragglers in NGC 6025 and NGC 2422 can probably be accounted for by a combination of rotation effects and the expected ultraviolet excess in Be stars. The position of two stragglers in NGC 6633, one in NGC 6475 and the NGC 2516 straggler cannot be accounted for by rotation effects alone.

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