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Research Note

Binaries in Open Clusters

II. Discrimination Between Double and Rotating Stars

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Summary. Rotating stars and binaries, both of which fall above the normal main sequence in an HR diagram, can, in principle, be distinguished using Strömgren four-color photometry. We here attempt to make this distinction for unevolved stars in six young open clusters. A straightforward interpretation of the data implies that the $\sim$45–50% of A and F stars lying more than $0\overset{\mathrm{m}}{.}07$ above the main sequence are about equally divided between binaries with $M_2/M_1 \gtrsim 0.5$ and stars rotating $\gtrsim 30\%$ ($\gtrsim 75\,\mathrm{km\,s^{-1}}$) faster than their cluster averages. This is in reasonable agreement with other determinations of binary incidence in young clusters and the field. But, because the six clusters do not define the same main sequence in a c_0, $b-y$ diagram (Praesepe especially being discordant), we wish to leave open the possibility that some other parameter may be influencing colors of main sequence stars in young clusters at the $0\overset{\mathrm{m}}{.}05$ level. As a result, it may not be practical to determine binary incidence from photometry of distant, young clusters.

Key words: binary stars – stellar rotation – open clusters – photometry

I. History of the Problem

Several years ago, we remarked (Trimble and Ostriker, 1978, hereinafter Paper I) that efforts to identify binaries in star clusters and to determine their mass ratios from positions in HR diagrams would fail because of the effects of stellar rotation. Rotational velocities of the size seen in unevolved A and F stars in young clusters (~ 100–$200\,\mathrm{km\,s^{-1}}$) suffice to move the stars to the right of (hence above) the single-star, non-rotating main sequence by about the same amount as a companion would. Thus double and rotating stars cannot be distinguished from HR diagram data alone. The fact that binaries are typically slower rotators than single stars of the same mass in the same cluster (Abt, 1970) additionally makes it difficult to deduce just where the unperturbed MS ought to be drawn if further analysis is to be done. Thus distribution functions for binary system mass ratios should not be trusted if they are derived from HR diagrams alone.

Paper I also noted that additional color data, e.g. c_0 vs. $b-y$ (which is sensitive to Balmer discontinuity strength and so to surface gravity and luminosity) should allow binary and rotating stars to be distinguished. This paper reports an attempt to make the distinction in the suggested way.

Our original goal was to calibrate the method on nearby clusters, for which measurements of $v \sin i$ and searches for spectroscopic binaries have already been carried out, so that it could be applied to distant ones for which spectroscopy on the main sequence is difficult. This goal has not entirely been achieved. Although correlations of colors with rotation and duplicity in the expected directions are seen, there appear to be other parameters affecting c_0 at a level which prevents the distinction from being made cleanly enough to yield new information on other clusters.

II. Theory

The expected positions of binaries in a c_0, $b-y$ diagram can readily be predicted by combining various pairs of stars from the Crawford (1975, 1978, 1979, for F, B, and A stars respectively) mean main sequence. Figure 1 shows examples. Two stars (with $M_v = 2.30$ and 3.14; X's in the figure) were paired successively with stars further and further down the main sequence, producing trajectories as shown (loops in the directions of the arrow heads) in the figure. Notice that the loops never diverge very much from the single-star main sequence ($\delta c_0 \leqq 0\overset{\mathrm{m}}{.}02$ for most trajectories and $\leqq 0\overset{\mathrm{m}}{.}04$ for the most extreme ones). Thus, stars that fall above the MS in a normal HR diagram owing to duplicity should not fall above in a c_0, $b-y$ diagram.

Rotation affects both $b-y$ and c_0. The star is redder (cooler); and c_0 increases because rotational support lowers the effective surface gravity, decreasing the Balmer jump, as well. The theoretical trajectory (from Collins and Sonneborn, 1977) is almost perpendicular to the main sequence (Fig. 1). Thus, stars that fall above the MS in a normal HR diagram because they rotate more rapidly than the average of their clusters should also fall above in c_0, $b-y$. Crawford (1970) has calibrated the effect for A stars of known $v \sin i$ and finds $\delta_{c_0}/\delta v \sin i = +0\overset{\mathrm{m}}{.}04/100\,\mathrm{km\,s^{-1}}$ over the range 0–$250\,\mathrm{km\,s^{-1}}$. This is in the same direction, but smaller than, the theoretical trajectory value (The X toward the end of this trajectory in Fig. 1 represents $v = 150\,\mathrm{km\,s^{-1}}$.) The discrepancy increases when the difference between v and $v \sin i$ is taken into account. This follows because the relationship between rotation velocity and distance from the MS in c_0 is nearly independent of $\sin i$ (Collins and Sonneborn, 1977), while the width of rotationally broadened line profiles clearly is not. Thus, the Crawford calibration implies $\delta c_0/\delta v = 0\overset{\mathrm{m}}{.}04/150\,\mathrm{km\,s^{-1}}$, but the theoretical trajectory gives $0\overset{\mathrm{m}}{.}14/150\,\mathrm{km\,s^{-1}}$. It is possible that the discrepancy is due to neglect of differential rotation in the calculations, although Maeder and Peytremann (1972) expected the effect to go the other way. We use the empirical relation in the following analysis.

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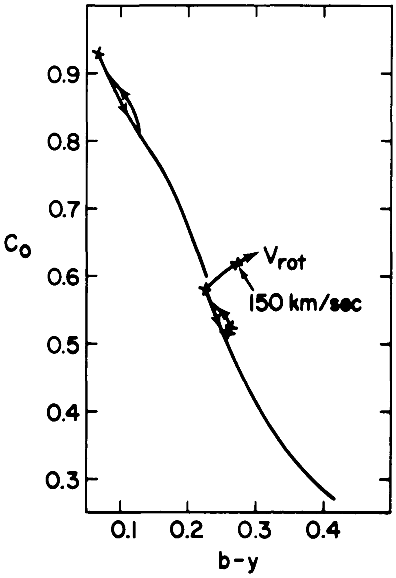

Fig. 1. Effects of duplicity and rapid rotation on c_0 vs. $b-y$. The trajectory perpendicular to the main sequence (from Collins and Sonneborn 1977) applies to rotating stars almost independent of aspect angle. The X away from the MS represents a star rotating at $v=150\,\mathrm{km\,s^{-1}}$. The loop trajectories close to the MS represent binaries formed by pairing the stars marked X with stars successively further down the MS. The direction of the arrows indicates decreasing mass of the companion

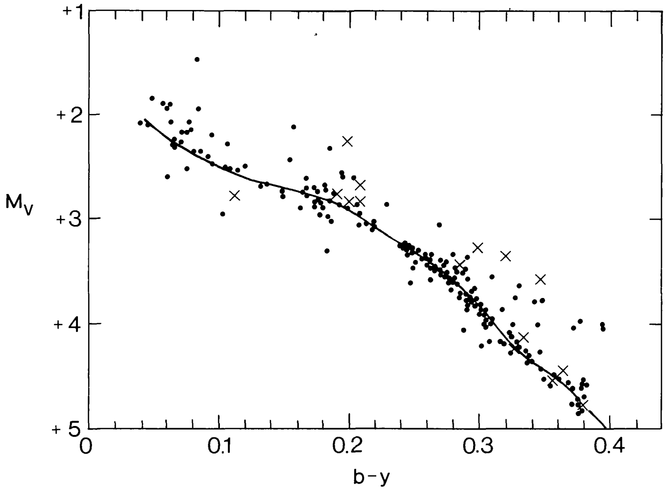

Fig. 2. 195 stars redder than $b-y=0.05$ (in the Pleiades, M 34, ζ Scl, and α Per) or 0.17 (in Coma and Praesepe) in the M_v, $b-y$ plane, using *ubvy* photometry by Crawford and his colleagues and the distance moduli from Paper I. Stars more than $0^m_.07$ above the line shown (which is intermediate between MS 1 and MS 2 of Paper I) constitute the B/R sample. X's are the binaries known at the time the photometry was done

III. The Data and Their Analysis

The clusters studied and the sources of the photometry are Coma, Praesepe, and Alpha Persei (Crawford and Barnes, 1969a, b, 1974), Pleiades (Crawford and Perry, 1976), ζ Scl (Perry et al., 1978), and M 34 (Canterna et al., 1978). A total of 195 stars in these six clusters falls within the useful color range ($b-y=0.05-0.40$ for Pleiades, α Per, ζ Scl, and M 34; $b-y=0.07-0.40$ for Coma and Praesepe). Stars bluer than this show some evidence of evolution and cannot be analyzed in the way proposed here.

The first step is to plot all the stars in a color-magnitude diagram (M_v, $b-y$). The result, after distance moduli have been adjusted to bring all the main sequences together ($V_0-M_v=5^m_.54$ for the Pleiades; $6^m_.1$ for α Per; $5^m_.95$ for Praesepe; $4^m_.60$ for Coma; $8^m_.2$ for M 34; and $6^m_.9$ for ζ Scl) is Fig. 2. Next, stars significantly ($\delta M_v \geqq 0^m_.07$) above the main sequence must be selected. There is no unique best way to do this because there is no unique best way to draw the MS (as discussed in Paper I). We have (somewhat arbitrarily) chosen the MS shown in Fig. 2, which is intermediate between MS 1 and MS 2 of Paper I and puts 77 stars significantly above. The level $\delta M_v \geqq 0.07$ corresponds to a main sequence binary with mass ratio $M_2/M_1 \geqq 0.5$ or rotation with $v \sin i \geqq 20\,\mathrm{km\,s^{-1}}$ faster than average, using calibrations from Strömgren (1963) and Crawford (1970), which are further discussed below. This sample of 77 stars will hereinafter be called the B/R stars, meaning (we hope) binary and/or rotating. No further attention will be paid to stars falling below our nominal main sequence. Some of them are undoubtedly rotating more slowly than their cluster averages and others may be the result of larger-than-average observational error.

Next, we must plot all the stars in a c_0, $b-y$ diagram and decide which of the B/R stars lie in its main sequence and which significantly above. "Significantly above" in this context might be defined in several ways. We have chosen for it to mean $\delta c_0 \geqq 0^m_.035$, the approximate maximum possible from duplicity alone. Neither this nor any other choice of δc_0 can unambiguously separate the B/R stars into binaries (B) and rotating single stars (R) even in principle. The R sample will be contaminated by double stars with components in rapid rotation (because the system is too wide or too young for synchronism to have been achieved, or because the companion is compact). And the B sample will be contaminated by single stars rotating only slightly faster ($\delta v \sin i = 20$–$80\,\mathrm{km\,s^{-1}}$) than average. We shall return shortly to the issue of how serious this contamination is, making use of stars whose $v \sin i$ has been measured spectroscopically.

A potentially more serious problem appears when the stars are plotted and identified by cluster (Fig. 3). They clearly do not all define the same c_0, $b-y$ main sequence. Praesepe particularly is about $0^m_.05$ brighter in c_0 than the average of the other clusters (which also do not quite agree, but less conspicuously). The discrepancy is largest at reddest colors, but noticeable everywhere. It cannot be due to errors in distance modulus (which does not enter into c_0 or $b-y$ at all) or reddening (which is small for all six clusters and has been removed where appropriate). Other factors which might affect c_0 include evolutionary effects (but Praesepe is neither old enough nor young enough for its A and F stars to be mostly pre or post MS objects), rotation itself [but Praesepe stars on average rotate rather slower than those in the younger clusters α Per and Pleiades, as one might expect, cf. Abt (1970, and references therein)], strong magnetic fields and accompanying surface abundance peculiarities (but Praesepe is not excessively

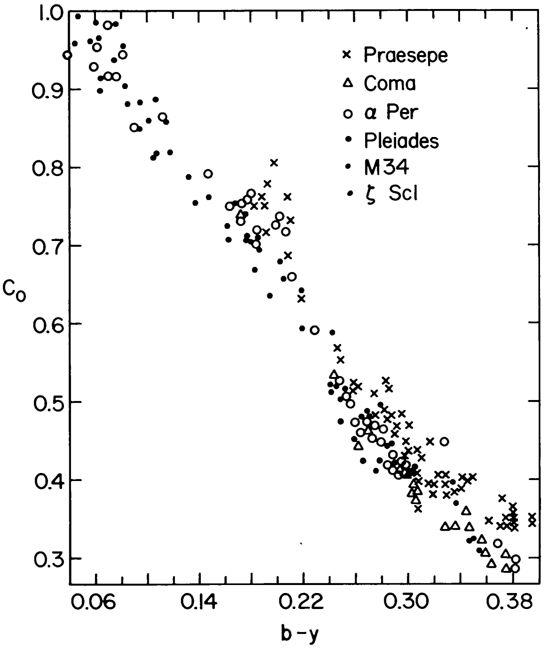

Fig. 3. The 195 stars of Fig. 2 in the c_0, $b-y$ plane. Symbols distinguish members of the several clusters. Not all the clusters define the same main sequence, Praesepe especially being discordant by about $0^{m}.05$ in c_0

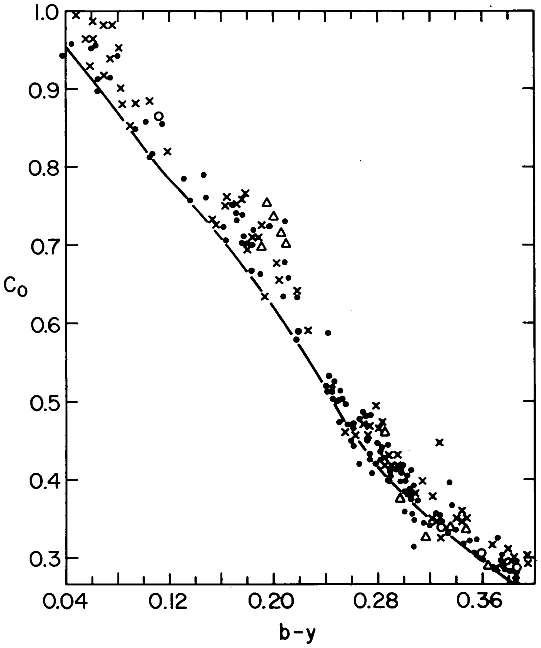

Fig. 4. The stars of Fig. 3, redrawn with Praesepe shifted down $0^{m}.05$ in c_0. The line is our assumed single-star, minimum-rotation main sequence. X's are the B/R stars and open symbols are known binaries (triangles those above the Fig. 2 MS and open circles those on it). Notice that both the B/R stars and the binaries are scattered fairly uniformly through the thickness of the MS

endowed with Am or Ap stars), and initial helium abundance. Changing Y affects both luminosity and color (primarily via mean molecular weight) and so shifts the main sequence in a complicated way, which depends somewhat on the color system in use. How large a difference in Y is required? For A and F stars, $\delta M_v \sim 10\,\delta c_0$ (Strömgren, 1963), implying $\delta M_v \sim 0^{m}.5$ for Praesepe. This would not show up in the HR diagrams as the cluster distances are derived by assuming that all the MS's coincide. Thus, according, eg, to models given by Strömgren (1965) and many others and homology relations compiled by Terlevich (1980), to displace the Praesepe main sequence $0^{m}.5$ from the others would take a ΔY of 0.1–0.15. There is no evidence, spectroscopic or otherwise, for a difference of this sort between Praesepe and other young, open clusters. There is also not much evidence against such a difference, but we regard it as exceedingly improbable on any reasonable model of galactic evolution and star formation. Two possibilities remain – unexpectedly large systematic errors in the photometry (for which, again, there is no evidence) or some other physical parameter affecting c_0 that we have not been able to think of.

In order to be able to proceed with the analysis, we will make the (perhaps incorrect) assumption that, whatever the problem is, it is not strongly correlated with duplicity or rotation. On this assumption, we can safely draw separate lower envelope main sequences in the c_0, $b-y$ diagram for Praesepe and the other clusters. Next, we go back and identify the B/R stars in a new c_0, $b-y$ diagram (Fig. 4), in which Praesepe has been shifted down $0^{m}.05$ in c_0 to match the other clusters. The B/R stars are shown as X's, and known binaries as O's (if on MS) or open triangles (if above MS in HR diagram). The line is our nominal "minimally-rotating, single star" MS. It naturally falls lower than the Crawford (1975, 1978, 1979) main sequence, which is fitted through the average of all the stars in several clusters.

The separation of the 77 B/R stars into those less than $0^{m}.035$ from the lower envelope MS (supposedly binaries) and those further away (supposedly fast rotators) yields roughly equal groups, 41 B's and 36 R's. The implication that 41/195 = 21% of the cluster stars are binaries with $M_2/M_1 \geqq 0.5$ is in good accord with other data for clusters and field stars (Abt, 1979). The positions of the 41 B's above the main sequence in M_v, $b-y$ can be interpreted (after the manner of Paper I) to yield the distribution of mass ratios shown in Table 1. Not surprisingly, it closely resembles those found for the total sample of stars above similar MS's in Paper I. Other choices of main sequence in Fig. 2 would have yielded different numbers of B stars and different distributions of mass ratio.

Table 1. Distribution of mass ratios, M_2/M_1, for the 41 stars in sample B (stars above the MS in M_v, $b-y$, but close to it in c_0, $b-y$) as deduced from their distances δM_v above the MS in an HR diagram

δM_v	M_2/M_1	No.
$\leqq 0.07$	$\leqq 0.5$	154
0.07–0.13	0.5–0.6	12
0.13–0.23	0.6–0.7	9
0.23–0.37	0.7–0.8	7
0.37–0.55	0.8–0.9	4
0.55–0.75	0.9–1.0	5
>0.75	>1.0	4

How pure are the B and R samples? Four of 15 known binaries fall too close to the M_v, $b-y$ MS to appear in B/R at all, and 5 of the remainder had δc_0's that put them into the R sample. Three of these are known independently to show large spectroscopic $v \sin i$'s ($\geqq 100\,\mathrm{km\,s^{-1}}$). Thus only 6 of 15 known binaries end up in the B sample. This is at least more than would have appeared there if we had chosen 41 stars at random from the 195 and called them B; especially as some of the known binaries probably have $M_2/M_1 < 0.5$, and so never made it into B/R.

The number of interlopers is more difficult to estimate, as one cannot say with certainty that any particular star does not have a companion. At the cluster distances, systems with $P = 50$–100 yr and velocity amplitudes of 3–5 $\mathrm{km\,s^{-1}}$ would be detected neither as visual nor as spectroscopic binaries. But they would still fall significantly above the HR diagram MS and would be (correctly) placed in the B/R sample as a result. But, if only about half of the real binaries get into the B sample, the fact that its total size is plausible suggests that up to one-half of the B stars may be interlopers of various kinds.

Stellar rotation velocities have been published for four of the clusters (though not necessarily for all the stars in each): Coma (Kraft, 1965), α Per (Kraft, 1967), Pleiades (Anderson et al., 1966), and Praesepe (Dickens et al., 1968). Thirty-seven of our 195 stars are known rapid rotators ($v \sin i \geqq 100\,\mathrm{km\,s^{-1}}$). Of these, 15 fall on and 22 above the main sequence in M_v, $b-y$; and 14 on and 23 above the MS in c_0, $b-y$. There is considerable, but not perfect, overlap between the groups falling "above" in the two cases. Thus, the method here investigated correctly puts about half the known rapid rotators (including some binaries) into the R sample, puts a few into B, and leaves the rest completely outside the B/R sample. What about interlopers in the R sample? Because not all stars have had their rotation velocities measured, and because $\sin i$ can be small, we cannot prove that any particular star in the R group does not belong there. But, if $\sin i$ is randomly distributed and if stars without $v \sin i$ data rotate as fast as those with data on average, then about 1/3 of the R stars do not really belong in the group.

IV. Discussion and Conclusions

Why is this seemingly straightforward approach only 40–70% successful in sorting out binary and rotating stars? Some mixing of the classes is inherent in the method: double stars that are also rapid rotators will automatically end up in the wrong sample. This applies to 3 of 15 known binaries, but as rapid rotation makes velocity variaton harder to detect, 20% is probably a lower limit to the binaries lost this way. A (probably) similar fraction of moderately rotating single stars ends up among the B's. But we seem to be doing even worse than expected. The most likely explanation is that whatever it is that has separated the Praesepe main sequence from the others in c_0, $b-y$ also moves individual stars up and down in c_0, relative to their cluster averages, enough to mingle the R and B samples in the way we find. Random jitter of $\sim 0\overset{\mathrm{m}}{.}02$ in c_0 would suffice.

It would be tempting to blame observational errors for the problems. Their magnitudes are somewhat difficult to assess, as no other comparably complete set of *ubvy* colors has been published for any of the clusters under consideration. But they are probably smaller than would be required to explain the random and systematic variations we find. Crawford and Barnes (1969a) report, for instance, that, using data obtained both by themselves and by Strömgren over a seven year period, the mean errors of one observation of a Coma star as determined from the internal scatter are $\pm 0\overset{\mathrm{m}}{.}008$ in $b-y$ and $\pm 0\overset{\mathrm{m}}{.}012$ in c_1. As each star was observed many times, the errors of the mean colors reported should be even smaller.

We are, therefore, forced to conclude that, until all the conditions that affect c_0 have been understood, our method, though theoretically appropriate, is not clean enough to provide new information on binaries and/or rotation velocities in distant clusters. There is, in other words, no substitute for spectroscopy. Advice on parameters affecting c_0 would be welcomed by the authors.

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