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The effect of stellar rotation on colour–magnitude diagrams: on the apparent presence of multiple populations in intermediate age stellar clusters

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ABSTRACT

A significant number of intermediate age clusters (1–2 Gyr) in the Magellanic Clouds appear to have multiple stellar populations within them, derived from bimodal or extended main-sequence turn-offs. If this is interpreted as an age spread, the multiple populations are separated by a few hundred million years, which would call into question the long-held notion that clusters are simple stellar populations. Here, we show that stellar rotation in stars with masses between 1.2 and 1.7 $M_\odot$ can mimic the effect of a double or multiple population, whereas in actuality only a single population exists. The two main causes of the spread near the turn-off are the effects of stellar rotation on the structure of the star and the inclination angle of the star relative to the observer. Both effects change the observed effective temperature, hence colour, and flux of the star. In order to match observations, the required rotation rates are 20–50 per cent of the critical rotation, which are consistent with observed rotation rates of similar mass stars in the Galaxy. We provide scaling relations which can be applied to non-rotating isochrones in order to mimic the effects of rotation. Finally, we note that rotation is unlikely to be the cause of the multiple stellar populations observed in old globular clusters, as low-mass stars ($<1\,M_\odot$) are not expected to be rapid rotators.

Key words: stars: rotation – galaxies: star clusters.

1 INTRODUCTION

Due to the increase in spatial resolution and photometric accuracy, colour–magnitude diagrams (CMDs) of star clusters have become more refined in recent years, which has led to the discovery of unexpected phenomena. Arguably, the most exciting recent discovery in cluster research has been that clusters often appear to contain structure in their observed CMDs which cannot be accounted for by current evolutionary isochrones for a single age/metallicity (see Piotto 2008 for a recent review). Of particular interest has been the discovery that intermediate age (1–2 Gyr) clusters in the Magellanic Clouds often have bi- or multimodal distributions in their main-sequence turn-off (Mackey & Broby Nielsen 2007; Mackey et al. 2008; Glatt et al. 2008; Milone et al. 2009). This spread has been interpreted as an age difference of 200–300 Myr between multiple co-existing stellar populations, which is much longer than the age spread inferred in currently forming clusters (<3 Myr, e.g. Massey & Hunter 1998). This potentially large age spread has called into question whether intermediate age star clusters are indeed simple stellar populations (i.e. all stars have similar ages and metallicities).

Various models have been put forward to explain how a cluster can contain multiple populations with age differences of a few hundred million years. Three recent models are: (i) the formation of a second generation of stars from the ejecta of first generation asymptotic giant branch (AGB) stars (D'Ercole et al. 2008; Goudfrooij et al. 2009), (ii) the merging of two (or more) star clusters with large age differences (>200 Myr; Mackey & Broby Nielsen 2007) and (iii) star cluster – giant molecular clouds (GMC) collisions, from which the newly formed stars in the GMC are retained in the existing star cluster (Bekki & Mackey 2009). Each of these rather exotic models have problems explaining certain observations. In the Model 1 scenario, the second generation can never have as many or more stars than the first (without drastically changing the stellar initial mass function between the two generations), which is in contrast with observations (Milone et al. 2009). Additionally, this model predicts that the younger clusters (100–500 Myr) should contain dense pockets of gas that are forming new stars. The main drawback of Model 2 is that collisions between clusters with large age differences are quite rare, and therefore would not be expected to affect a large fraction of clusters. In the third scenario, the newly

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formed stars are expected to form in a disc-like structure in the centre of the cluster, which is at odds with the observations that the two populations have similar spatial distributions (unless very rapid relaxation is invoked).

Alternatively, the observed spread near the turn-off may be due to stellar evolutionary effects. Mackey et al. (2008) demonstrate that this spread cannot be explained by unresolved binaries. In this work, we investigate how stellar rotation affects the CMD of these clusters.

The reduced gravity in rotating stars results in lower luminosities and effective temperatures (e.g. Faulkner, Roxburgh & Strittmatter 1968; Meynet & Maeder 1997). Also the orientation of the star with respect to the line of sight is important: a star deformed by fast rotation appears brighter and hotter if viewed pole-on. Various authors have demonstrated that these effects can significantly alter the colour and magnitude of stars (e.g. Collins & Smith 1985; Gray & Garrison 1987; Townsend, Owocki & Howarth 2004), and therefore the CMD of a cluster (D'Souza, Mathew & Rajamohan 1992; Pérez Hernández et al. 1999). In addition, mixing processes induced by rotation modify the composition of the stellar envelope and effectively increase the size of the stellar core, resulting in higher luminosities and cooler temperatures for turn-off stars (Palacios et al. 2003).

The stars near the turn-off in the intermediate-age Large Magellanic Cloud (LMC) clusters, with masses above about $1.2\,\mathrm{M}_\odot$, are expected to be fast rotators. Many of their galactic counterparts, late A and early F type stars are found to rotate rapidly, both in the field (e.g. Royer, Zorec & Gómez 2007) and in open clusters (e.g. Boesgaard 1987; Gaige 1993). One might expect even higher rotation rates for stars in clusters with respect to field stars (Huang & Gies 2006, however see Huang & Gies 2008) and for stars in the lower metallicity environment of the LMC (Hunter et al. 2008). Only stars near and just below the turn-off, which have radiative envelopes, are expected to rotate fast. Lower mass stars are found to be slow rotators, probably due to the magnetic fields they can generate in their convective envelopes (e.g. Cardini & Cassatella 2007).

In the present work, we explore how the shape of the observed CMD of an intermediate-age (∼1–2 Gyr) cluster is affected by rotation. We employ a simple method using non-rotating isochrones and correction factors to account for rotational effects. We note that we use the standard B, V and I filter notation, although all results correspond to the *Hubble Space Telescope* (*HST*) filters F435W, F555W and F814W, respectively.

2 METHOD

To model the effects of rotation on the shape of the CMD of an intermediate age cluster, we apply a simple method starting from a standard isochrone based on non-rotating stellar models. We adopt a Salpeter (1955) stellar initial mass function, and sample 50 000 stars stochastically between 0.8 and $5\,\mathrm{M}_\odot$. We use the BaSTI isochrones (Pietrinferni et al. 2004) to find the *HST*-ACS F555W and F814W magnitudes (hereafter V and I, respectively) for each star, assuming an age of 1.25 Gyr and metallicity of $Z = 0.008$, relevant for intermediate age clusters in the LMC.

We assume that the distribution of rotation rates is described by a Gaussian distribution with a peak at $\omega = 0.4$ and a standard deviation of 0.25, where ω is the fraction of the critical break-up rotation rate. We do not allow extreme rotation rates by excluding $\omega > 0.7$. The precise shape of the distribution does not affect our conclusions and we will return to this point in Section 3. Below $1.2\,\mathrm{M}_\odot$ (at LMC metallicity) stars exhibit a convective envelope, in which they may generate a magnetic field. The braking torque of winds magnetically coupled to the surface can efficiently slow down the rotation rate (Schatzman 1962; Mestel & Spruit 1987). Also, stars that evolve off the main sequence expand and slow down their rotation rate due to conservation of angular momentum. Therefore, we assume no rotation for stars evolved beyond the end of the main sequence and for stars with masses smaller than $1.2\,\mathrm{M}_\odot$.[1]

Below we derive how rotation changes the (apparent) luminosity and effective temperature of a rotating star. To convert these corrections to changes in colour, we use that the dependence of the $V - I$ colour on effective temperature in the region of interest is well described by the relation $\Delta(V - I) = -3.3\Delta\log T_{\mathrm{eff}}$ (Eldridge, Mattila & Smartt 2007), based on the BaSeL-2.2 atmosphere library by Westera, Lejeune & Buser (1999).

We have tested the above relation by creating blackbody spectra of various effective temperatures and convolving them with the filter response functions of the *HST*-ACS F555W and F814W filters. This simple derivation agrees well with the results from detailed atmosphere models of Eldridge et al. (2007). A cubic polynomial of the form $\Delta(V - I)/\Delta(\log T_{\mathrm{eff}}) = a + bx + cx^2 + dx^3$, where $x = \log(T_{\mathrm{eff}})$, provides a good fit to the $\mathrm{d}(V - I)/\mathrm{d}(\log T_{\mathrm{eff}})$ distribution when $a = -406.350$, $b = 263.140$, $c = -57.1160$ and $d = 4.1519$. Carrying out the same analysis for $\mathrm{d}(B - V)/\mathrm{d}\,(\log T_{\mathrm{eff}})$ (where B is the *HST* ACS F435W filter) results in $a = -214.177$, $b = 132.886$, $c = -27.5868$ and $d = 1.9145$. All fits were carried out over the range $3.6 < \log(T_{\mathrm{eff}}) < 4.5$.

Effect on the structure. To quantify the effects of rotation on the structure due to the reduced gravity and mixing we use the one-dimensional hydrodynamic stellar evolution code described by Heger, Langer & Woosley (2000) and Yoon, Langer & Norman (2006), which takes into account the effects of rotation on the structure and mixing induced by rotation. We use the same choices for the mixing parameters as De Mink et al. (2009), which were calibrated by Brott et al. (in preparation). Assuming an initial composition relevant for the LMC, we evolve stellar models with an initial mass of $1.5\,\mathrm{M}_\odot$ from the onset of hydrogen burning, beyond the end of the main sequence, assuming initially uniform rotation rate ω of 0, 0.23, 0.35, 0.48, 0.63 and 0.77. For not too extreme rotation rates ($\omega < 0.7$), the effective temperature of these models can be described with a simple fit

$$T_{\mathrm{eff}}(\omega)/T_{\mathrm{eff}}(0) = 1 - a\omega^2,$$

where $T_{\mathrm{eff}}(0)$ is the effective temperature of the non-rotating model and a is the fit coefficient which changes from 0.17 at zero age to 0.19 at the end of the main sequence. Similarly, for the luminosity we fit

$$L(\omega)/L(0) = 1 - b\omega^2,$$

where b varies from 0.11 to 0.03 over the main-sequence evolution. These relative changes are consistent with results of the Geneva group (G. Meynet, private communication) for a $4\,\mathrm{M}_\odot$ star, the lowest in their model grid. As we are interested in the turn-off, where stars no longer resemble zero-age stars, we adopt the corrections for the end of the main sequence. We note that differences between the rotating and non-rotating model tracks for the post-main-sequence

[1] This gives a mass range of 1.2–$1.65\,\mathrm{M}_\odot$ where rotation is considered. We note, however, that the development of a convective envelope depends merely on the T_{eff} (e.g. Talon & Charbonnel 2004), which may be a better proxy for investigating when magnetic braking is most efficient.

evolution are much smaller than on the main sequence, further justifying our assumption that only the main sequence and the turn-off are strongly affected by rotation.

Effect of inclination. Depending on the inclination angle between the rotation axis and the line of sight, a star deformed by rotation may appear brighter and hotter if viewed pole-on. To estimate the importance of this effect, we assume that the star is deformed according to the Roche model. To obtain the flux emitted towards the observer for various inclinations and rotation rates, ω, we integrate the flux of each surface element, which depends on the local effective gravity according to von Zeipel (1924). We take into account that each surface element is stretched and inclined with respect to the line of sight. Furthermore, we adopt a simple limb-darkening law (assuming a plane–parallel grey atmosphere using the Eddington approximation). We compute the apparent effective temperature by averaging the effective temperature of each surface element given by the von Zeipel theorem, weighted by the flux emitted by this element towards the observer. We emphasize that the adopted approach is simplified, but the level of sophistication is sufficient for the objective of this paper.

We take this effect into account by assigning a random orientation to each star in the CMD and applying the correction computed as described above to the luminosity and effective temperature. The effect of the inclination is small for moderately rotating stars ($\omega < 0.5$): less than 1 per cent on the effective temperature for most viewing angles, compared to ~5 per cent due to structural effects.

3 RESULTS

Panel (a) in Fig. 1 shows the sampled CMD affected by rotation as described in the previous section. The horizontal dashed line indicates the location of a $1.2\,\mathrm{M}_{\odot}$ star, below which we do not consider rotation. The dominant effect responsible for the spread is the reduction of the temperature due to reduced centrifugal force. Although the change in effective temperature is small, the steep dependence of the $V - I$ colour on the effective temperature magnifies the spread in the CMD. The effect of the inclination is only significant for those stars viewed nearly pole- or equator-on and is always about a factor of 6 smaller than the change due to structural effects of rotation, but it is responsible for the stars located on the blue side of the non-rotating isochrone. In panel (b), we include typical observational errors, taken to be normally distributed with a standard deviation of 0.01 and 0.014 in magnitude and colour, respectively. These errors are derived from the spread in the main-sequence band of observed clusters. We note that these errors may

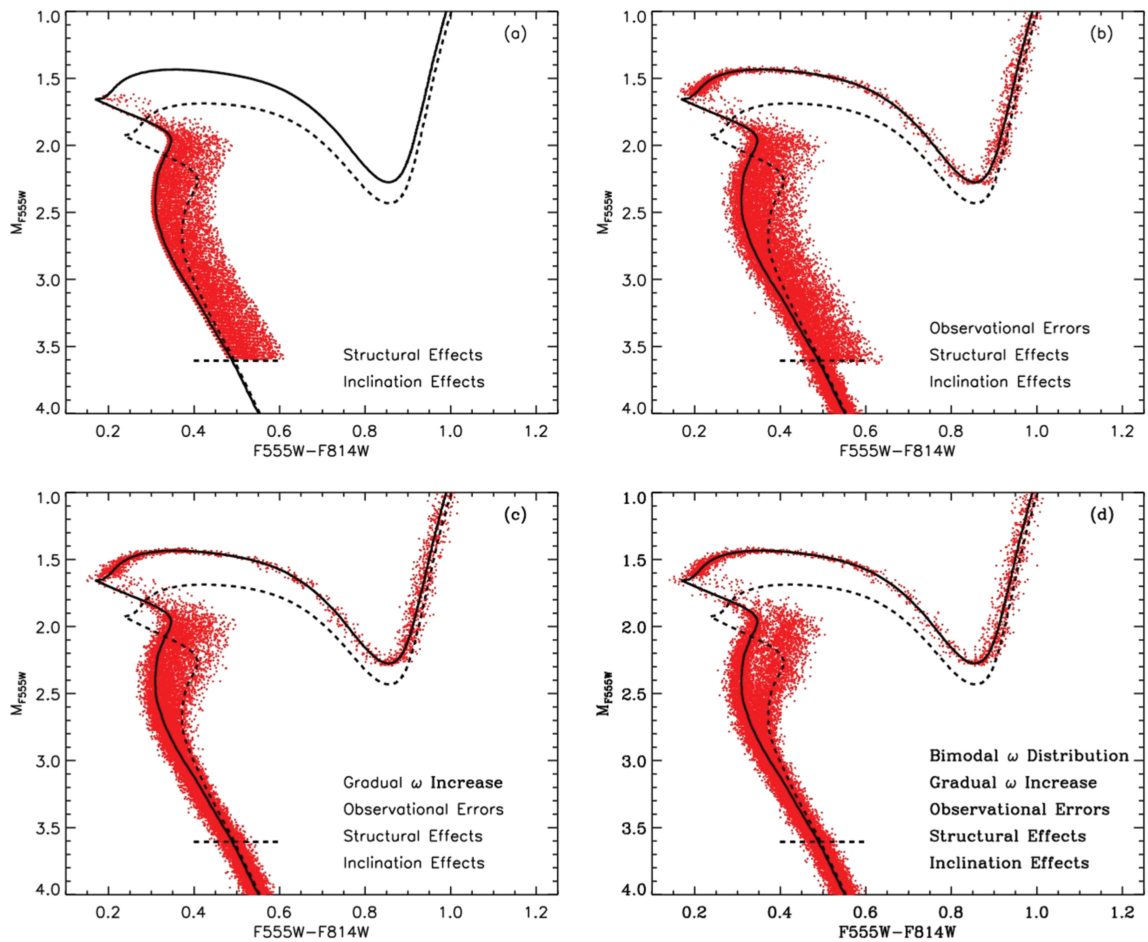

Figure 1. Simulated CMDs including the effects of rotation. The isochrone for an age of 1.25 Gyr is shown as a solid line. In each panel, the effects that are included in the simulation are given (see text for details). The horizontal dashed line marks the position of a $1.2\,\mathrm{M}_{\odot}$ star. Note that in panel (a) all stars with masses outside the range allowed for rotation (see text) are located behind the isochrone. In all panels, we also show an isochrone with an age of 1.5 Gyr and metallicity of $Z = 0.008$ as a dashed line for reference.

be overestimated as a part of this spread may be caused by rotational broadening of the main sequence.

For clarity and simplicity, we have assumed so far that an abrupt transition occurs at $1.2\,M_{\odot}$; lower mass stars are assumed to be non-rotating due to magnetic braking (however, see Footnote 1). In reality, the transition is more gradual. For example, in solar-type stars in our own Galaxy, magnetic fields are detected up to $\sim 1.5\,M_{\odot}$ (Donati & Landstreet 2009). Due to the large distance to the LMC, magnetic fields and rotation rates for low-mass stars are hard to detect directly. To show the effect of a more gradual transition, we multiply ω for each star by a factor, which depends linearly on the mass, such that there is no rotation at $1.2\,M_{\odot}$ and at $1.5\,M_{\odot}$ each star has the full rotation assigned to it. Under this assumption the spread in the CMD of an intermediate-age cluster is limited to the turn-off region, as shown in panel (c), which is similar to what is observed for many intermediate-age LMC clusters (cf. Milone et al. 2009). Although the resemblance is striking, we warn the reader that the assumed mass dependence of the velocity distribution here is ad hoc.

Royer et al. (2007) claim that the observed distribution of rotational velocities for A-type stars is bimodal. Tidal torques in close binaries and magnetic torques in Ap stars will cause some stars to be slow rotators ($\omega < 0.1$) while many stars have considerable rotation rates ($\omega \geq 0.5$). Therefore, we simulate a cluster assuming a bimodal ω distribution, namely two Gaussians with equal number of stars with peaks at 0.1 and 0.6 with standard deviations of 0.1 (again not allowing any stars to have $\omega > 0.7$). Panel (d) shows that a bimodal ω distributions may result in bimodal turn-off. We emphasize that the precise shape depends on the assumed distribution. In particular, the assumed width of the 'fast rotator' peak determines the spread in the CMD of the 'red sequence': a narrow 'fast rotator' peak in the ω distribution is needed to obtain a well-defined bimodal spread around the turn-off.

4 DISCUSSION AND CONCLUSIONS

As discussed above, stars that rotate can have significantly different effective temperatures and luminosities compared to their non-rotating counterparts, even for moderate rotation rates (20–50 per cent of the critical break-up rotation rate). The general effect of this is to shift stars to the red in the CMD which causes a spread to occur which is detectable with high-precision photometry.

Models of cluster CMDs that include rotation can explain the spread observed near the turn-off of intermediate age clusters in the LMC (Mackey & Broby Nielsen 2007; Goudfrooij et al. 2009; Milone et al. 2009). Additional support for this model comes from the observations of Milone et al. (2009). From their table 3, it is clear that all clusters older than 1.5 Gyr do not show a spread in the observed turn-off, and all but one cluster[2] below this age have a significant spread in their turn-off. The models developed here are for stars with radiative envelopes, as stars with convective envelopes are thought to have magnetic fields which will slow down any primordial rotation. Hence, older clusters with turn-off masses lower than the mass, where the stellar envelopes become convective, are not expected be significantly affected by stellar rotation.

We emphasize that a large spread around the turn-off can be explained without assuming extreme rotation rates (we assumed a Gaussian distribution in ω with a peak at 0.4 and a standard deviation of 0.25 – with an imposed maximum of 0.70). The number of fast-rotating stars may be larger than what we have assumed. Royer et al. (2007) find that the distribution of F0–F2 stars ($\sim 1.4\,M_{\odot}$) is bimodal with peaks of ω at 0.1 and 0.5, with the 0.5 peak being significantly stronger (their fig. 10). If we would include such a distribution in our model, the spread in the turn-off becomes even larger.

The model that we have introduced makes specific predictions which, in principle, can be tested. The clearest prediction is that the stars farthest from the main sequence should be fast rotators. However, as the effect of inclination is smaller than the effect on the stellar structure, fast-rotating stars far from the nominal main sequence may appear to be slow rotators if they are observed nearly pole-on, so large samples will be required. Stars near the turn-off of intermediate age LMC clusters, with $V = 20.5$–21.5, are near, but within the observational limits of current 8–10 m class facilities. Alternatively, these effects should also be visible in intermediate-age clusters in the Galaxy where the turn-off is more readily accessible. Measurements by Fossati et al. (2008) for stars in the Praesepe cluster ($\sim$700 Myr) show some evidence for rapidly rotating stars to lie redwards of the nominal main sequence, consistent with the results presented here.

Additionally, fast-rotating stars near the turn-off are expected to have modified surface abundances: fragile elements such as Li, B and Be will be depleted (Charbonnel & Talon 1999) and in very fast rotators N may be enhanced and C depleted.

Due to the steep dependence of $(V - I)$ on effective temperature, we do not expect all young clusters to show broadened turn-offs. For younger clusters, the main sequence turn-off occurs at higher temperatures, where the relation between $\Delta(V - I)$ and $\Delta(\log T_{\rm eff})$ is much shallower. However, in these young clusters we would predict that the main sequence (in the mass range of ~ 1.2–$1.7\,M_{\odot}$) would be broader than that expected from observational errors (in the same way that the turn-off is broader in intermediate age clusters).

We emphasize that a number of simplifications and assumptions have been adopted in order to estimate the effect of rotation on observed CMDs. We have adopted an ad hoc treatment of magnetic braking for lower mass stars. This assumption affects the shape of the spread below the turn-off, but it does not affect our main conclusion that the effects of rotation are important near the turn-off. We have also ignored that rotation can slightly prolong the lifetime of the star, which would cause an additional spread around the turn-off. Furthermore, we limited this investigation to effects of rotation on turn-off and main-sequence stars. Just beyond the end of the main-sequence stars contract and will rotate even faster. This evolutionary phase is fast compared to the main-sequence evolution and not many stars are expected to be in this stage. Also we emphasize that interacting binaries can complicate the picture. These effects will be discussed in more detail in a forthcoming paper.

However, the results obtained clearly demonstrate that the rotation can significantly affect the observational properties of an intermediate age cluster, hence detailed modelling of rotational effects and magnetic braking of stars in the mass range considered (1.2–$1.7\,M_{\odot}$) would provide valuable insight in the interpretation of observed CMDs and possible biases in age derivations based on CMD fitting.

Finally, we note that rotation is unlikely to be the cause of the multiple stellar populations observed in old globular clusters, as low-mass stars ($<1\,M_{\odot}$) are not expected to be rapid rotators.

[2] The exception being NGC 1975 whose CMD is not very populated, making it difficult to ascertain whether or not there is an intrinsic spread.

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