Mass Loss from Stars and the Evolution of Stellar Clusters
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The Impact of Selective Mass Loss on the Age Determination of Star Clusters

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Abstract. Dynamical models and observations of star cluster evolution show clear signs of mass segregation (in the sense that high-mass stars tend to be found towards the cluster center, and low-mass stars preferentially occupy the cluster outskirts). The low-mass stars in the cluster outskirts get stripped off more easily by interaction with the gravitational potential of their host galaxy. This alters the stellar mass function within the cluster, therefore changes its spectrophotometry, altering the cluster ages determined when the new spectrophotometry is compared to standard evolutionary synthesis models. These age changes can amount up to a factor of ten (in the most extreme cases).

1. Introduction

1.1. Star Clusters

Globular clusters (GC) are dense, massive and round-shaped groups of stars present in the vast majority of galaxies. By virtue of their old age ($\simeq$ 12 billion years [Gyr]), they provide valuable insights into the formation and the early evolution of their host galaxy. Furthermore, the refurbished Hubble Space Telescope (*HST*) has discovered young and intermediate age compact stellar clusters with typical GC masses in merging and interacting galaxies. The formation of such massive stellar clusters is a subject of very broad relevance, as it is related either to the very early phase of the host galaxy formation or to galaxy merging processes, the two most actively star-forming phases in a galaxy's lifetime.

By comparing a cluster's spectral energy distribution with the predictions of spectrophotometric models one can determine this cluster's physical parameters, e.g. age, metallicity and mass. In principle this method can determine the violent star formation history of galaxies by determining the age distributions of cluster samples, it is straightforward and has been applied extensively (see e.g. reviews by Kennicutt 1998 and Larsen 2004).

However, recently it has become clear that there are two major problems with this method:

(a) *many clusters have been already disrupted since their formation:* This can happen on surprisingly short timescales, 10^7 to 10^8 years, and affects the age distribution of older clusters dramatically (a large fraction of the old clusters may have disappeared because their stars are dispersed) and leads to errors in the derived star formation histories. The most prominent observational example of a disrupting star cluster is the Milky Way GC Palomar 5 with its extended tidal tails (Odenkirchen et al. 2003). From simulations several disruption mechanisms are studied, like slow mass loss by evaporation due to two-body relaxation (e.g. Spitzer 1940, Hénon 1960, Baumgardt & Makino 2003), shocks by disc passage (Spitzer & Chevalier 1973), interactions with spiral arms (Gieles et al. 2007) or interactions with giant gas clouds (Spitzer 1958, Gieles et al. 2006).

(b) *the mass distribution of the stars in a cluster (the stellar mass function, MF) changes with time:* this affects both the high mass stars (due to stellar evolution) and the low mass stars (due to dynamical effects, see next section). These changes in the MF change the spectrophotometric model predictions, and, if these models are used to determine physical parameters from observations, change the derived parameter distributions, like star formation histories. This proceedings contribution will show the first results on the latter issue.

1.2. Mass Segregation and Selective Mass Loss

The term "mass segregation" in a star cluster describes the effect that high-mass stars (stars with mass higher than the median stellar mass) are preferentially found in the cluster center (or "core"). The low-mass stars are preferentially found in the outskirts of the cluster.

The effect is found both in simulations and in observations. It emerges dynamically by energy equipartition between stars of different masses, causing the more massive star to slow down and sink towards the cluster center while the less massive star is accelerated to an orbit further out than its original orbit. Examples from simulations and analytical investigations include, to name only a few, Lynden-Bell (1967), Spitzer (1969), Meylan & Heggie (1997). Also observationally this effect has been known for quite some while already (e.g., Da Costa 1982, Kontizas et al. 1987, King et al. 1995). Recent observations are hinting at some mass segregation being present even during the formation of the cluster (e.g., Hillenbrand & Hartmann 1998, de Grijs et al. 2002, Gouliermis et al. 2004, Bragg & Kenyon 2005). However, the amount of such *primordial* mass segregation seems to vary between clusters, for reasons not yet understood. Theoretically, primordial mass segregation is a natural outcome of the "competitive accretion" star formation scenario of Bonnell et al. (see e.g., Bonnell & Bate 2006). However, the validity of this scenario is currently under debate (see Krumholz et al. 2005). To summarize, in a mass segregated cluster high-mass stars are preferentially slowly moving and found in the cluster core, while low-mass stars are mainly fast moving and found in the outer parts of the cluster.

If the cluster is in a tidal field (usually the tidal field of the host galaxy), this tidal field imposes a limiting radius on the cluster. This radius, the tidal radius, is where the cluster potential equals the external tidal potential. Stars which get scattered in an orbit larger than the tidal radius will get more attracted by the external tidal field than by the tidal field of the cluster, and hence will be lost from the cluster. As in a mass-segregated cluster the outer regions are preferentially occupied by low-mass stars, these stars will be lost preferentially, therefore changing the global stellar mass function. We will refer to this effect as "selective mass loss". Possibly the strongest observational evidence for selective mass loss is the unusual stellar mass function of the Arches cluster close to the Galactic center (Stolte et al. 2002), as the cluster core is severely depleted in low-mass stars. Portegies Zwart et al. (2002) conclude from N-body modelling that this mass function can have evolved from a normal mass function under the effects of dynamical cluster evolution.

1.3. Evolutionary Synthesis Modelling

All evolutionary synthesis models are based on the fundamental work done by B. Tinsley (see e.g., Tinsley 1968, 1972, 1980). For evolutionary synthesis models the composition of the stellar population is computed at each time step, i.e. the number of stars of a given mass, age, and metallicity. The corresponding spectra of all stars are summed up, to give a model grid of integrated spectra as a function of the age of the stellar population and its metallicity. By convolving the integrated spectra with filter response functions, artificial magnitudes and colours are synthesised, to be compared with observed magnitudes and colours.

The basic ingredients for a model are therefore: information on the stellar evolution (in terms of isochrones [for each age the basic quantities of stars of different masses are given]), a library of stellar spectra, a set of filter response functions. In addition, a fixed stellar mass function must be assumed. These quantities define the evolutionary synthesis model of a star cluster completely (for a composite stellar population, like a galaxy, star formation and chemical enrichment history have to provided in addition). However, as we have seen in the previous section, the stellar mass function of a cluster in a tidal field is time-dependent and not fixed as usually assumed for evolutionary synthesis modelling.

Here we want to present the first evolutionary synthesis models which take this time-dependent stellar mass function from N-body simulations into account.

2. Input for the New Models

The GALEV code was developed by U. Fritze-v.Alvensleben (Fritze-v. Alvensleben et al. 1989) and maintained and constantly extended since in her working group (see e.g., Schulz et al. 2002, Anders & Fritze-v. Alvensleben 2003, Bicker et al. 2004).

The time dependence of the stellar mass function is based on Baumgardt & Makino (2003). Their N-body simulations of clusters at different galactocentric distances in the Galaxy and with different orbits (circular vs. eccentric) show that mass segregation and selective mass loss becomes important when a cluster has lost a certain fraction of its mass (approximately 70%), almost independent of the dissolution time-scale.

Baumgardt & Makino (2003) calculated the dynamical evolution of a large grid of clusters in the tidal field of the Galaxy by means of N-body simulations. This grid consists of: different initial cluster masses (4 000 to 70 000 $M_{\odot}$), different initial density distributions (King profiles with central concentration parameters $W_0 = 5.0$ or 7.0), different galactocentric distances (from 2.8 to 15 kpc), in circular or elliptical orbits. An initial Kroupa (2001) MF was adopted. Baumgardt & Makino (2003) defined the dissolution time of their models as the age at which only 5% of the initial mass remains due to stellar evolution and dis-

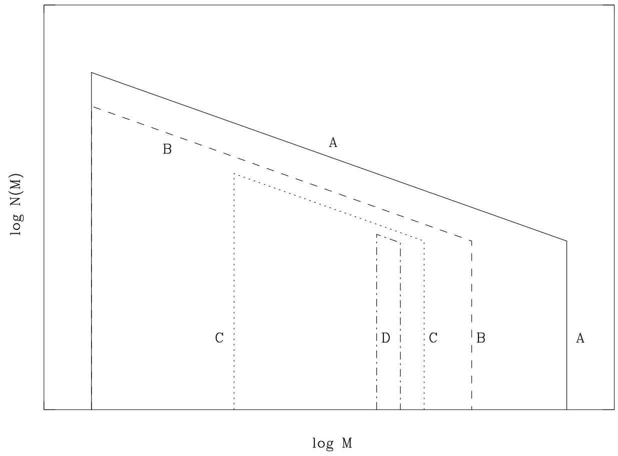

Figure 1. Schematic changes in the stellar MF, $\log(N)$ versus $\log(M)$, of a cluster due to stellar evolution and dissolution. The initial MF is assumed to be a power law. A: the inital MF. B: Stellar evolution has removed the most massive stars and dynamical effects, before cluster-wide mass segregation, have reduced the number of stars of all masses with equal probability. C: after mass segregation has occurred dynamical effects have removed the lowest-mass stars. D: the MF just before the cluster is completely dissolved.

solution. The dissolution times of these models are in the range $2.3 < t_{\rm dis}^{\rm BM} < 40$ Gyr.

The N-body simulations of Baumgardt & Makino (2003) show several remarkable features:
(a) Despite significantly different initial conditions the preferential loss of low-mass stars starts at about the same fractional age of the cluster, i.e. at $t_{\rm segr} \simeq 0.20\ t_{\rm dis}^{\rm BM}$.
(b) Before this age the fractional decrease of the number of stars is almost independent of mass (except for the most massive stars whose number decreases because of stellar evolution). This is because stars of almost all masses can be kicked out by encounters with the most massive ones.
(c) After $t_{\rm segr}$ the cluster mainly loses high-mass stars, due to stellar evolution, and low-mass stars due to evaporation, but almost no stars of intermediate mass.
(d) The changes in the mass function at the low mass end, $M \leq 2M_{\odot}$, as a function of $t/t_{\rm dis}$ are very similar for all models, despite large differences in the initial cluster mass, dissolution time and ellipticity of the orbit of the cluster.

2.1. The Philosophy of our Simplified Models

Based on the results of the N-body simulations, we can derive a simple model that agrees with the basic results of Baumgardt & Makino (2003) and that allows us to subsequently calculate the photometric evolution of dissolving clusters.

We describe the effects of stellar evolution and cluster dissolution on the stellar MF by the following approximations:
(1) Stellar evolution removes stars at the high-mass end of the MF but leaves the

rest of the mass distribution unchanged. The stellar upper mass limit decreases with time during all phases. (In fact, the evolution of stars of all masses is fully taken into account in our method because we use the results from the GALEV cluster evolution models.)
(2) Initially, dissolution will remove stars of all masses with about equal probability. This means that the number of stars of all masses will decrease but the slope of the mass distribution will remain unchanged. This agrees with the results of the N-body simulations.
(3) When mass segregation has occurred (for $t > t_{\rm segr}$), dissolution preferentially removes the stars with the lowest remaining mass from the cluster. Thus, the lower mass limit of the cluster stars will increase to higher values.

These assumptions have the advantage that *the slope of the mass distribution remains constant* during all phases of a cluster's evolution. Only the maximum and minimum stellar mass (due to effects 1 and 3, respectively), and the constant describing the total number of stars (due to effect 2) change as a function of time. This is the only simplifying difference to the data by Baumgardt & Makino (2003). With these simplifications, we can study and understand the expected changes in the photometry of star clusters during their evolution. Fig. 1 shows the concept of our approximations. In this simple description the MF gets narrower with time and reaches a single mass just before the cluster is fully dissolved.

3. The Changes in Photometry Due to our New Models

The time-dependent mass functions (with lower mass cutoffs due to selective mass loss) were implemented into the GALEV code to predict the spectrophotometric properties of dissolving star clusters.

One example of our new photometry is shown in Fig. 2. In this example for $t_{\rm dis} = 1$ Gyr the changes in cluster colours are of the order of several tenths of magnitude towards the end of cluster disruption. Such magnitude changes translate into age errors of several tenths in $\log(t)$, as can be seen in Fig. 3.

The general results can be summarized as follows:

1. During the first part of the lifetime of the cluster, i.e. during the first $\sim$ 40%, irrespective of the total life time $t_{\rm dis}$, the photometric evolution is the same as predicted for the standard models if the decreasing mass is taken into account. The dissolution of the cluster makes it fainter in all bands, but the colours are unaffected.

2. Between $\sim$ 40 and $\sim$ 80% of its total lifetime the cluster is *bluer* than predicted by the standard models. This is due to the fact that the cluster has lost a large fraction of its (red) low-mass stars. This effect is small: $\Delta(V - I) \simeq 0.03$ mag for clusters with $t_{\rm dis} = 1$ Gyr, but increases steeply with increasing $t_{\rm dis}$. The maximum deviation is about 0.1 mag for $t_{\rm dis} = 10$ Gyr. This implies that the age of the clusters will be *underestimated* when standard models are used. The maximum error in the age estimate is about 0.15 dex in $\log(t)$ if $t_{\rm dis} = 3$ Gyr, 0.30 dex if $t_{\rm dis} = 10$ Gyr and 0.5 dex if $t_{\rm dis} = 30$ Gyr. Thus, the age of clusters with a total lifetime of 20

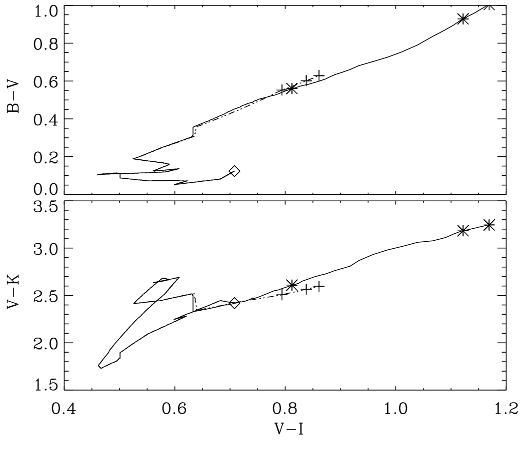

Figure 2. The evolution of dissolving star clusters in the colour-colour diagram of the *HST*/WFPC2 broad-band filters $B-V$ vs $V-I$ and $V-K$ vs $V-I$, for clusters without initial mass segregation ($t_{\rm segr}=0.2$)and $t_{\rm dis}=1$ Gyr. The solid line shows the colour-colour evolution with mass segregation and the preferential loss of low-mass stars and the dashed lines show the evolution without the loss of low-mass stars, i.e. the evolution of the standard GALEV models. The diamond shows the colours in the beginning, at $t=12$ Myr. The three asterisks show the colours of the cluster at three different ages: $t/t_{\rm dis}=0.80$, 0.90 and 0.95 (reddest point). The three crosses show the colours of the standard GALEV models at the same time. Notice that the colours get much redder than the standard models near the end of the lifetime of the clusters.

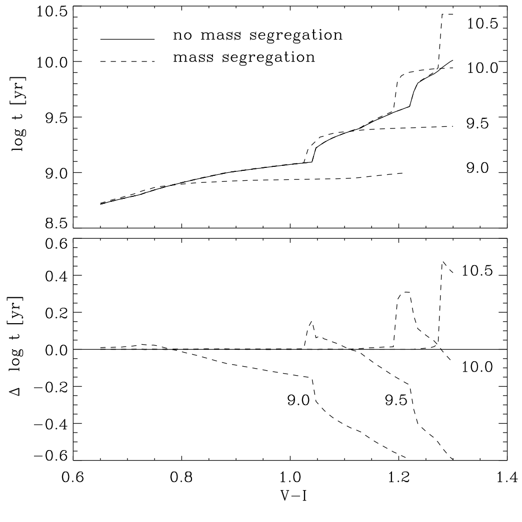

Figure 3. *Upper panel:* the relation between $V-I$ and the corresponding age of a cluster. The solid line is for clusters without mass segregation. The dashed lines are for clusters with mass segregation and the preferential loss of low-mass stars, for different dissolution times. The parameters $\log(t_{\rm dis})$ are indicated in the panel. *Lower panel:* the logarithmic age correction to be made to ages derived from standard cluster evolution models.

Gyr and a real age of 14 Gyr, will erroneously be estimated as about 4 Gyr on the basis of the $V-I$ and $V-K$ photometry.

3. Between about ~ 0.80 and $1.0\ t_{\mathrm{dis}}$ the clusters are much *redder* than predicted by the standard models. At those ages the AGB stars are the dominant contributors to the photometry at long wavelengths. These AGB stars are redder than the stars at the low-mass end of the main sequence. So the removal of the lowest mass main-sequence stars will make the cluster redder than predicted by standard models. This effect increases from $\Delta(V-I) \simeq 0.0$ mag at $t \simeq 0.8\,t_{\mathrm{dis}}$ to 0.3 mag at $0.95\ t_{\mathrm{dis}}$. This reddening will result in an *overestimate* of the age of clusters based on broad-band photometry from $B-V$ to $V-K$ colours if standard cluster evolution models are used. The effect is large and can grow to an overestimate of a factor ~ 4 near the end of the cluster's life.

4. The changes in colour due to mass segregation and the preferential loss of low-mass stars occurs almost along the same lines in the colour-colour plots as the photometric evolution of the standard models. This makes it difficult to distinguish this effect from reddening due to the age of clusters.

5. The predicted photometric history of clusters with inital cluster-wide mass segregation is indistinguishable from that of clusters without initial mass segregation. This is due to the fact that mass segregation will occur quite rapidly (within $\sim$0.20 t_{dis}), even if there were no initial mass segregation. Because both the total lifetime of a cluster and the time for mass segregation depend on the half-mass relaxation time, mass segregation will occur at about a constant fraction of t_{dis}.

The complete results can be found in Lamers et al. (2006).

4. Application and Outlook

A promising application would be to study the star cluster system of the inconspicuous elliptical galaxy NGC 4365. This galaxy harbours a population of star clusters with colours between the peaks of the typical colour bimodality of GCs (Larsen et al. 2005). This could be hinting at an intermediate-age population of star clusters. However, high-resolution spectra obtained and analysed by the same group argue strongly for genuinely old star clusters (Larsen et al. 2005). This discrepancy could originate from the effects of selective mass loss, in which case the suspicious clusters had ages between ~ 40 and $\sim 80\%$ of the clusters total lifetime. The clusters are concentrated towards the center of the galaxy, where dynamical cluster evolution is expected to have strong effects.
Upcoming topics include:

- a more realistic description of the changing mass function.
- further exploration of the parameter space governing the mass function changes, i.e. extending the work by Baumgardt & Makino (2003). This will include the effects of primordial mass segregation, primordial binaries and the interactions with GMCs and spiral arms.

- identification of observables to disentangle the effects of selective mass loss from other parameters.
- comparison with observations, and if necessary refinement of the models.

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