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INVITED REVIEW

The Baltimore and Utrecht models for cluster dissolution

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Abstract The analysis of the age distributions of star cluster samples of different galaxies has resulted in two very different empirical models for the dissolution of star clusters: the Baltimore model and the Utrecht model. I describe these two models and their differences. The Baltimore model implies that the dissolution of star clusters is mass independent and that about 90% of the clusters are destroyed each age dex, up to an age of about a Gyr, after which point mass-dependent dissolution from two-body relaxation becomes the dominant mechanism. In the Utrecht model, cluster dissolution occurs in three stages: (i) mass-independent infant mortality due to the expulsion of gas up to about 10^7 yr; (ii) a phase of slow dynamical evolution with strong evolutionary fading of the clusters lasting up to about a Gyr; and (iii) a phase dominated by mass-dependent dissolution, as predicted by dynamical models. I describe the cluster age distributions for mass-limited and magnitude-limited cluster samples for both models. I refrain from judging the correctness of these models.

Keywords Star clusters · Star cluster systems · Star cluster evolution · Dynamical evolution

1 Introduction

The dissolution of star clusters in external galaxies can in principle be derived empirically from the analysis of the age distribution of detected clusters. If the clusters are destroyed rapidly in their host galaxy, the number of clusters will decrease rapidly with age, in the sense that there will be many fewer old than young clusters. If cluster destruction is slow, the decrease with age will be more gentle.

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In practice, this method is more complicated than suggested here. This is for several reasons:

1. One has to assume (or determine) a cluster formation history, because changes in the cluster formation rate with time will affect the shape of the age distribution of the observed clusters.
2. Clusters fade with age due to stellar evolution. If the cluster sample is magnitude limited, older clusters will drop out of the sample because they are fainter than the detection limit.
3. For both magnitude-limited and mass-limited samples, the samples have to be corrected for incompleteness. This implies that the study needs to be restricted to the age and mass range over which reliable completeness corrections can be done.
4. The accuracy of the age and mass determinations, which are based on the fitting of the photometric spectral energy distributions with cluster models, has to be taken into account.

The dissolution of star clusters has been derived from the age distribution of cluster samples. These studies have resulted in two empirical models for cluster dissolution, which I will refer to as the 'Baltimore model' and the 'Utrecht model'.

For the interpretation of the age distribution using the Baltimore model, see Fall et al. (2005), Whitmore et al. (2007; Antennae, solar neighbourhood, SMC), Chandar et al. (2006; SMC) and Chandar (these proceedings). For interpretations based on the Utrecht model, see Boutloukos and Lamers (2003, hereafter BL03; solar neighbourhood, SMC, M33, M51), Gieles et al. (2005; M51), Lamers et al. (2005a)

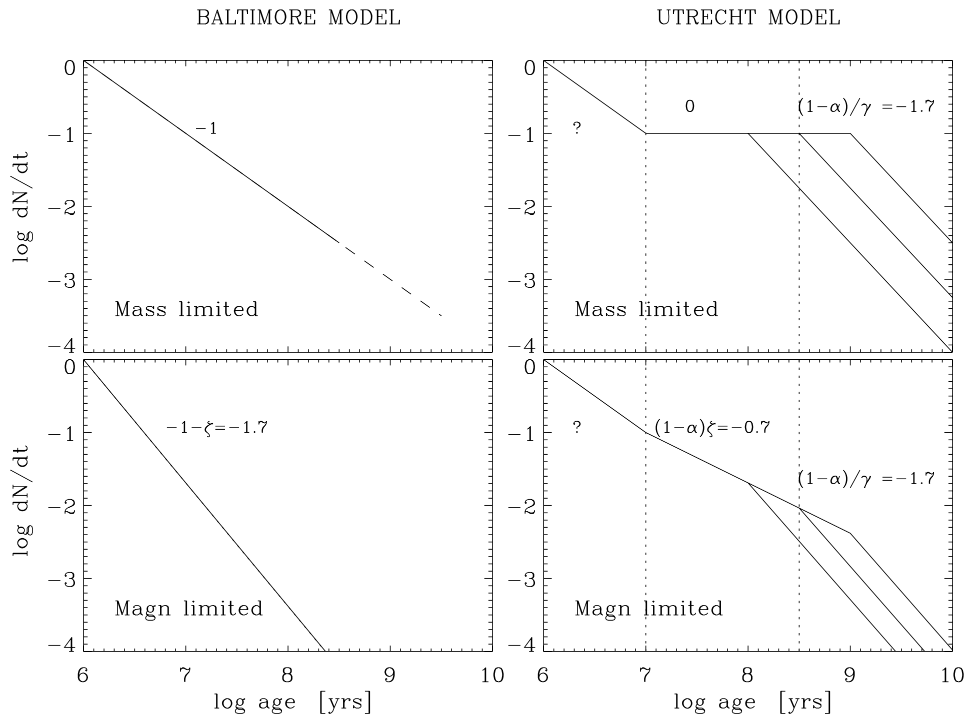

Fig. 1 Schematic representation of the age distributions of cluster samples which are mass limited (*upper panels*) or magnitude limited (*lower panels*) for the Baltimore and Utrecht models for cluster dissolution. In the Baltimore model cluster dissolution is mass independent, and removes 90% of the clusters each age dex up to about 1 Gyr. The *dashed line* indicates that the Baltimore group finds it impossible to extend the analysis of their data sets beyond this point, where they assume that two-body relaxation becomes important. The Utrecht dissolution model occurs in three phases: (i) mass-independent infant mortality, (ii) slow dynamical evolution with evolutionary fading, and (iii) mass-dependent dissolution. The transition between (ii) and (iii) depends on the conditions in the host galaxy. In an environment with a strong tidal field or a high density of GMCs, the transition will occur at younger ages than in a quiescent galaxy. The slopes of the relations are indicated. The parameters are $\alpha \simeq 2$ for the cluster initial mass function, $\zeta \simeq 0.6$ to 1 for evolutionary fading, and $\gamma \simeq 0.6$ for mass-dependent dissolution of the form $t_{\rm dis} \propto M^{+\gamma}$. (The predicted bends of the Utrecht model will be less sharp and more gentle than shown in this systematic picture.) See text for explanation

and Lamers and Gieles (2006; solar neighbourhood), Gieles et al. (2007; SMC), and Gieles (these proceedings).

In this paper, I will explain the differences between the two models. I will try to give an unbiased description of the two models and refrain from judging the correctness of the models. This implies that the reader may find different interpretations of the same data sets.

The age distributions of both magnitude-limited samples and mass-limited cluster samples are compared in Fig. 1, and described below. The main observable difference between the two interpretations is the presence (Utrecht) or absence (Baltimore) of a bend in the age distributions, and the presence (Utrecht) or absence (Baltimore) of a flat part in the age distribution of mass-limited cluster samples.

2 The Baltimore model for cluster dissolution

The Baltimore model for cluster dissolution is based on the observed age distribution of cluster samples in the Antennae, the solar neighbourhood, the SMC and the LMC (Whitmore et al. 2007; Chandar et al. 2006; Chandar, these proceedings).

In this model, the age distribution of a *mass-limited cluster sample* is a straight line with a slope of -1 in a $\log(\mathrm{d}N/\mathrm{d}t)$ versus log(age) plot, where $\mathrm{d}N/\mathrm{d}t$ is the number of clusters in a logarithmic age bin divided by the linear age range of that bin. The same slope is also found when different mass cuts are applied to the data sets. This implies that dissolution is independent of the mass of the clusters up to approximately 1 Gyr, at which point incompleteness limits set in. I will refer to this as mass-independent dissolution, MID.[1] The steep slope, i.e., -1, of the logarithmic age distribution implies that 90% of the clusters are dissolved in each age dex, independent of their mass.

[1] Mass-independent dissolution is sometimes called 'infant mortality'. However, I suggest that this name be reserved for the dissolution of star clusters due to the gas expulsion during the first 10^6 to 10^7 yr, as originally proposed by Lada and Lada (2003).

For *magnitude-limited cluster samples*, the slope of the age distribution must be steeper. This is because both cluster dissolution and evolutionary fading remove clusters from a sample below a certain brightness limit. The fading of the clusters due to stellar evolution is described by cluster evolution models, such as the models of Bruzual and Charlot (2003), the STARBURST99 models (Leitherer et al. 1999), the GALEV models (Anders and Fritze-v. Alvensleben 2003), etc. After the first ∼10 Myr, the fading of clusters of constant mass can be approximated by $L_\lambda \propto t^{-\zeta}$ with $\zeta \simeq 0.69$, 0.85 and 1.0 for the V, B, and U filters, respectively. This implies that the predicted age distribution of the Baltimore model for the magnitude-limited samples will be steep, with a slope of $-1-\zeta$, i.e., between about -1.7 and -2. (The Baltimore group has thus far not studied the age distribution of magnitude-limited samples.)

3 The Utrecht model for cluster dissolution

The Utrecht model for cluster dissolution is based on the analysis of magnitude-limited cluster samples of the solar neighbourhood, the SMC, M33 and M51, originally started by Boutloukos and Lamers (2003, hereafter BL03). In this first paper, cluster dissolution was assumed to be instantaneous, but the analysis has been refined for gradual cluster dissolution as described by Lamers et al. (2005a). See review by Gieles (2007).

In this model, the dissolution of clusters occurs in three steps, in agreement with some predictions based on the dynamical evolution of clusters.

1. During the first 10 to 20 Myr, clusters dissolve due to the expulsion of the remaining gas. This dissolution is assumed to be independent of mass (e.g. Goodwin and Bastian 2006). The fraction of the clusters that dissolve at such an early phase is called the 'infant mortality rate' which may be as high as 30 to 90% (Lada and Lada 2003; Fall et al. 2005; Bastian et al. 2005; Lamers and Gieles 2006).
2. During the next 10^8 to 10^9 yr, the number of observable clusters in a magnitude-limited sample decreases due to evolutionary fading. The slope of the logarithmic dN/dt distribution will be about $\zeta(1-\alpha)$ or about -1 to -0.6, where $-\alpha \simeq -2$ is the slope of the initial cluster mass function (BL03).
3. At ages older than about a Gyr, but dependent on the local conditions in the host galaxy, cluster dissolution by tidal effects due to the galactic tidal field and due to shocks by spiral arms and passing giant molecular clouds becomes important. These dissolution effects are mass dependent, approximately as $t_{\mathrm{dis}} = M^{+\gamma}$, with $\gamma \simeq 0.6$ (BL03; Baumgardt and Makino 2003; Gieles et al. 2006b, 2007). During this phase, low-mass clusters are more easily destroyed than massive clusters.

The resulting age distribution of *magnitude-limited cluster samples* correspondingly consists of three parts: (i) the steep decrease due to infant mortality (the shape of this decrease is not known), (ii) a slower decrease between 10^7 and about 10^9 yr with a slope of $(1-\alpha)\zeta \simeq -0.6$ to -1 due to evolutionary fading, and (iii) a steeper slope of $(1-\alpha)/\gamma \simeq -1.7$ due to dynamical effects (BL03). The onset of this decrease depends on the local conditions. In an environment with a strong tidal field or a high density of giant molecular clouds, dynamical dissolution is faster than in more quiescent environments, and so the transition between regions (ii) and (iii) will be at younger age (BL03 and Lamers et al. 2005b).

The age distribution of *mass-limited cluster samples* will also show the three regimes. (i) The slope due to infant mortality will be the same as for magnitude-limited samples if infant mortality is mass independent; (ii) evolutionary fading does not affect the age distribution of mass-limited samples, so the age distribution will be flat for mass-limited samples; and (iii) in the last phase, where dynamical dissolution is more important than evolutionary fading, the age distribution will show a steep slope of approximately $(1-\alpha)/\gamma \simeq -1.7$ (BL03).

Gieles et al. (2006a) and Gieles (these proceedings) has shown that the age distribution of the brightest clusters in a galaxy can also be used to derive information about the dissolution.

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