



# Star Clusters in the Galactic tidal field, from birth to dissolution

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**Abstract.** We study the evolution of star clusters in the Galactic tidal field starting from their birth in molecular clumps. Our model clusters form according to the local-density-driven cluster formation model in which the stellar density profile is steeper than that of gas. As a result, clusters resist the gas expulsion better than predicted by earlier models.

We vary the impact of the Galactic tidal field  $\lambda$ , considering different Galactocentric distances (3–18 kpc), as well as different cluster sizes. Our model clusters survive the gas expulsion independent of  $\lambda$ .

We investigated the relation between the cluster mass at the onset of secular evolution and their dissolution time. The model clusters formed with a high star-formation efficiency (SFE) follow a tight mass-dependent dissolution relation, in agreement with previous theoretical studies. However, the low-SFE models present a shallower mass-dependent relation than high-SFE clusters, and most dissolve before reaching 1 Gyr (cluster teenage mortality).

**Keywords.** stars: formation, stars: kinematics, (Galaxy:) open clusters and associations: general, galaxies: star clusters

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## 1. Introduction

Star clusters (SC) form in collapsing cold dense clumps formed out of the turbulent gas of molecular clouds (Krumholz *et al.* 2019). Once thermonuclear reactions begin within massive stars ( $>8M_{\odot}$ ), they start to drive effectively the natal gas out of the star-forming region. Their radiation pressure, strong winds, ionizing radiation and eventually explosion as supernovae type II are enough to clear up the cluster from all its gas within a few million years (Rahner *et al.* 2019; Li *et al.* 2019; Wall *et al.* 2019). SCs older than 5 Myr are observed to be gas-free (Leisawitz *et al.* 1989). The star-formation efficiency (SFE), that is the mass fraction of star-forming gas converted into stars, is usually below 30% in star-forming regions of the solar vicinity (Lada & Lada 2003; Higuchi *et al.* 2009). The weakening of the cluster gravitational potential due to the residual gas expulsion drives the SC out of virial equilibrium, possibly causing its expansion depending on the cluster dynamical state during the gas embedded phase (see e.g. Baumgardt & Kroupa 2007). During their violent relaxation, SCs can lose their stars, modify their structures and

masses and even dissolve without reaching a new virial equilibrium (Shukirgaliyev *et al.* 2017; Shukirgaliyev *et al.* 2018). Those SCs surviving the gas expulsion are observed as stable dynamical systems at the end of violent relaxation. However, they are going to be disrupted by several dissolution mechanisms like two-body relaxation driven evaporation, stellar evolutionary mass-loss and tidal stripping by the host galaxy (e.g Baumgardt & Makino 2003; Renaud 2018).

Due to the complexity of the problem, each phase of a SC life has usually been considered separately in the framework of one particular model. These different models and approaches are not always connected with each other. For instance the detailed hydrodynamical simulations of SC formation usually cover the early evolution only and they cannot cover the full parameter space of cluster initial conditions due to their computational cost. The detailed  $N$ -body simulations of the long-term evolution of SCs usually start when clusters are in virial equilibrium, neglecting the violent relaxation phase and, thus, do not bear the information about the birth conditions of SCs. It is worth building a self-consistent model describing the full life of SCs starting from their birth until full dissolution in the tidal field of their host galaxy. Then we will be able to see a whole picture of SC evolution and to test our models by comparing them with observations.

There are a few projects considering the evolution of SCs from formation till dissolution in cosmological simulations (e.g. Pfeffer *et al.* 2018; Li *et al.* 2017). Additionally to them, in this work, we propose a new approach to build a comprehensive model of the life of SCs, including a more detailed picture of their internal dynamics.

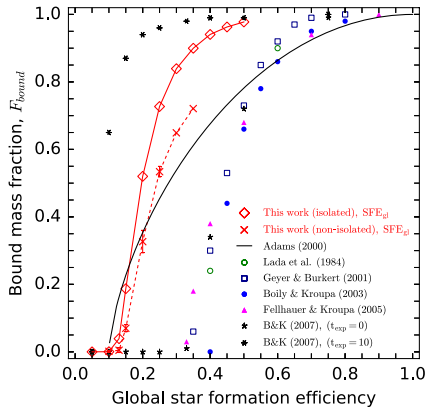
## 2. Our model

Instead of performing hydrodynamical simulations, we assume that our SCs form according the semi-analytical local-density-driven cluster formation model of Parmentier & Pfalzner (2013). That is, stars form in centrally concentrated, spherically symmetric clump with a constant SFE per free-fall time. Therefore, as it was observed by Gutermuth *et al.* (2011), stars are more concentrated to the center of the cluster-forming clump than the gas (see e.g. Fig. 1 in Parmentier & Pfalzner (2013) and Fig. 2 in Shukirgaliyev *et al.* 2017). We use the adapted program MKHALO program from `falcON` package (McMillan & Dehnen 2007) to generate stellar systems in virial equilibrium within the residual gas potential (Shukirgaliyev *et al.* 2017). Then, assuming that gas expulsion is instantaneous we perform the direct  $N$ -body simulations of gas-free SCs orbiting in the Galactic disk plane on circular orbits. The parallelized high-precision direct  $N$ -body code `phi-GRAPE/GPU` (Berczik *et al.* 2013) is used for our simulations.

We consider not only the short-term violent relaxation, but also follow the long-term evolution (aka secular evolution) of our model clusters until they dissolve in the Galactic tidal field. This way we are able to cover a large parameter space with high precision.

## 3. Results

We perform  $N$ -body simulations of SCs evolving in the solar neighborhood (i.e. at the Galactocentric distance  $R_{\text{orb}} = 8.0$  kpc) covering different global SFEs ( $\text{SFE}_{\text{gl}}$ , the total SFE measured within dense gas clumps) from 0.1 to 0.25 (0.35) and different cluster birth masses ( $M_{\star}$ , the cluster stellar mass before gas expulsion) from 3k to 300k  $M_{\odot}$ . We find that the violent relaxation duration (i.e. the time span over which SCs lose mass in response to gas expulsion) of our model clusters depends neither on the cluster birth mass nor on the  $\text{SFE}_{\text{gl}}$ . We find that our model clusters can survive instantaneous gas expulsion with a minimum  $\text{SFE}_{\text{gl}}$  of 15% (Fig. 1). This is a factor of two lower than previous estimates of 33% (Shukirgaliyev *et al.* 2017). Figure 1 presents the bound mass fraction of model SCs at the end of violent relaxation as a function of  $\text{SFE}_{\text{gl}}$ , where we

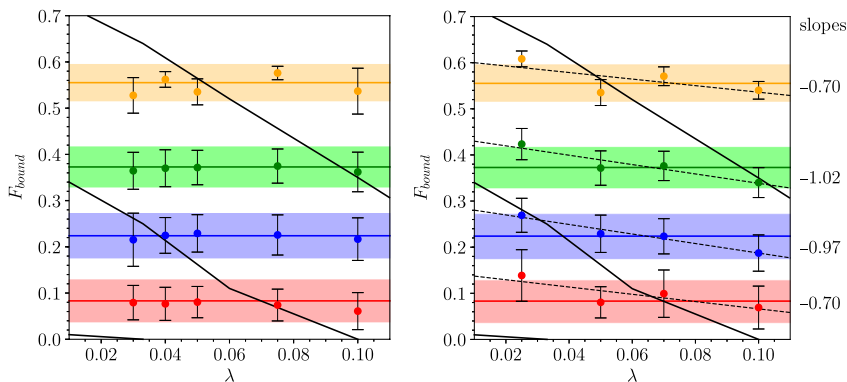


**Figure 1.** Bound fraction as a function of  $SFE_{g1}$ . We compare our results (red lines) with previous works. The isolated models are depicted by red diamonds, and non-isolated models by red crosses. (Top panel of Fig. 8 in Shukirgaliyev *et al.* 2017).

also compare our results with previous works. We have improved the survival likelihood of SCs after instantaneous gas expulsion. This is caused by the difference in density profiles between the embedded cluster and its residual gas, namely, the stellar density profile has a steeper slope than that of the residual gas (see Parmentier & Pfalzner 2013 for details). We also report that there is no dependency between  $M_*$  and the final bound fraction in our models (see Fig. 3 of Shukirgaliyev *et al.* 2018).

We extend our simulations by varying the impact of the Galactic tidal field,  $\lambda = r_h/R_J$ , measured by the ratio between the half-mass radius and the Jacobi radius of clusters immediately after gas expulsion (Shukirgaliyev *et al.* 2019). We vary  $\lambda$  in two ways: either by varying the Galactocentric distance of SCs (and therefore the Jacobi radius), by varying the radius of SCs while keeping them in the solar neighborhood ( $R_{orb} = 8.0$  kpc). In the first case, we adopt  $R_{orb} = 2.9, 4.64, 8.0, 10.95, 18.0$  kpc, yielding  $\lambda = [0.1, 0.07, 0.05, 0.04, 0.03]$  (left panel of Fig. 2). In the second case we adopt  $\lambda = [0.1, 0.075, 0.05, 0.025]$  (right panel of Fig. 2). Figure 2 shows the bound mass fraction of our model clusters at the end of violent relaxation as a function of  $\lambda$ . The dependency seen in the right panel of Fig. 2 is weak and stays within the error-bars. Therefore, we conclude that the survivability after instantaneous gas expulsion of SCs formed with a centrally peaked SFE profile is independent of the impact of the tidal field of the Galaxy (Fig. 2, Shukirgaliyev *et al.* 2019).

In Shukirgaliyev *et al.* (2018) we consider the long-term evolution of model solar neighborhood SCs, continuing our simulations until full their dissolution in the Galactic tidal field. We have found that SCs formed with a high  $SFE_{g1}$  ( $\geq 0.20$ ) dissolve in a tight mass-dependent dissolution time (MDD) regime, in agreement with earlier works. In contrast, model clusters formed with low  $SFE_{g1}$  ( $= 0.15$ ) dissolve more quickly than high-SFE clusters, most dissolving within 1 Gyr, and present a shallower MDD relation (see Figs. 5-7 in Shukirgaliyev *et al.* 2018). We find that the relation between the SC dissolution time and “initial” mass (i.e. cluster mass after violent relaxation, initial for long-term evolution) becomes close to that observationally found by Lamers *et al.* (2005) for the solar neighborhood if the SC population is dominated by low-SFE ones. Therefore, in this study, we propose to recover the cluster dissolution time for the solar neighborhood found by Lamers *et al.* (2005) in a way that is alternative to that proposed by Gieles *et al.* (2006).



**Figure 2.** The final bound mass fraction as a function of the impact of the tidal field for different Galactocentric distances (left) and different cluster central densities at  $R_{\text{orb}} = 8.0 \text{ kpc}$  (right panel). The colors code  $\text{SFE}_{\text{gl}} = 0.15$  (red), 0.17 (blue), 0.20 (green), and 0.25 (yellow). Each point corresponds to the mean and standard deviation of model clusters with the same  $\text{SFE}_{\text{gl}}$  and  $\lambda$ . Colored solid lines and shaded areas show the mean bound fraction and standard deviation for all models with a given  $\text{SFE}_{\text{gl}}$ . The black dashed lines are the linear fits to the final bound fractions of a given  $\text{SFE}_{\text{gl}}$  as a function of  $\lambda$ . The black solid lines correspond to the results of Baumgardt & Kroupa (2007) for models with an SFEs of 0.33, 0.4 and 0.5 from bottom to top, respectively. (Based on Figs. 3-5 of Shukirgaliyev *et al.* 2019)

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