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Bimodal regime in young massive clusters leading to subsequent stellar generations

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Abstract. Massive stars in young massive clusters insert tremendous amounts of mass and energy into their surroundings in the form of stellar winds and supernova ejecta. Mutual shock-shock collisions lead to formation of hot gas, filling the volume of the cluster. The pressure of this gas then drives a powerful cluster wind. However, it has been shown that if the cluster is massive and dense enough, it can evolve in the so–called bimodal regime, in which the hot gas inside the cluster becomes thermally unstable and forms dense clumps which are trapped inside the cluster by its gravity. We will review works on the bimodal regime and discuss the implications for the formation of subsequent stellar generations. The mass accumulates inside the cluster and as soon as a high enough column density is reached, the interior of the clumps becomes self-shielded against the ionising radiation of stars and the clumps collapse and form new stars. The second stellar generation will be enriched by products of stellar evolution from the first generation, and will be concentrated near the cluster center.

Keywords. globular clusters: general, galaxies: starburst, galaxies: star clusters: general, galaxies: star formation, stars: winds, outflows, hydrodynamics, radiative transfer

1. Introduction

It has been found by photometric observations that globular clusters contain two or more populations of stars differing by age and/or the chemical composition (see e.g. Pancino *et al.* 2000; Bedin *et al.* 2004; Piotto *et al.* 2007, 2015, and references therein). Furthermore, spectroscopic observations found anticorrelations between abundances of Na and O and other pairs of elements (Carretta *et al.* 2009; Mucciarelli *et al.* 2012) suggesting that a certain fraction of stars in globular clusters contain products of hydrogen burning at high temperatures. Several hypotheses were suggested to explain the above observations (Decressin *et al.* 2007; D'Ercole *et al.* 2008; Bastian *et al.* 2013; de Mink *et al.* 2009). Here we propose a cooling winds scenario in which the second stellar generation is formed out of fast stellar winds enriched by products of hydrogen burning in massive stars, that cool down inside the cluster evolving in the so–called bimodal regime.

Young massive clusters with masses $10^5 - 10^7$ M$_\odot$ and ages $< 10^7$ yr include a high number of massive stars ($\sim 2 \times 10^4$ per 10^6 M$_\odot$ of the cluster stellar mass assuming the standard IMF) concentrated in a small volume of several pc in radius (see e.g. Portegies Zwart *et al.* 2010; Larsen 2010). These stars insert through stellar winds large amounts of gas moving with velocities several thousands km s^{-1} into their surroundings. As the winds collide with each other, their kinetic energy is thermalised and the gas is heated

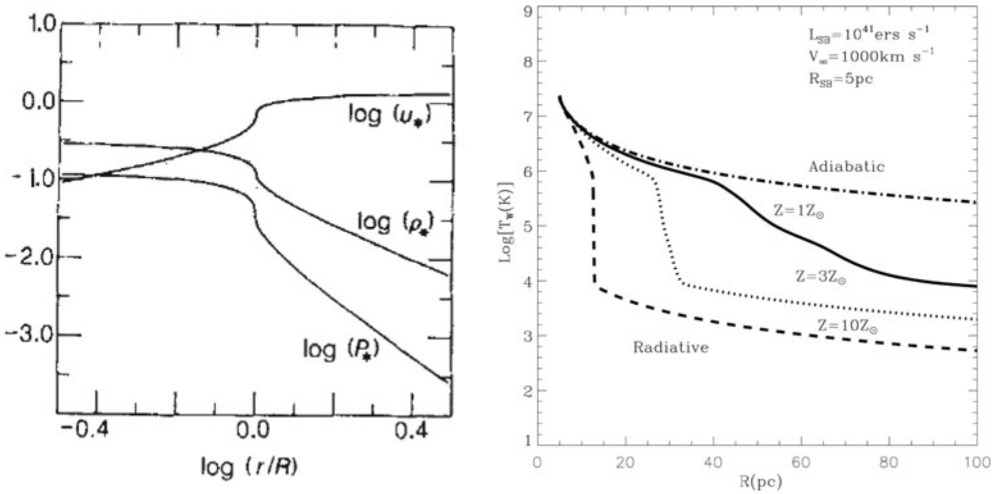

Figure 1. Left: Cluster wind solution by Chevalier & Clegg (1985, Fig. 1, reprinted by permission from Nature Publishing Group), it shows radial profiles of the wind density ($\rho_\star$), pressure ($P_\star$) and velocity ($u_\star$) in logarithmic scale. Right: Radial profile of the wind temperature, comparison of the adiabatic solution to the radiative solution by Silich *et al.* (2003, Fig. 1, reprinted by permission from AAS) for three different metallicities.

to temperatures $\sim 10^7$ K. The high pressure of this hot gas then drives the star cluster wind.

Winds of young massive star clusters were studied analytically by Chevalier & Clegg (1985) who derived a stationary solution of spherically symmetric hydrodynamic equations. They assumed that sources of mass and energy are distributed uniformly in a sphere with a given radius and they neglected radiative cooling of the hot gas. A remarkable property of their solution is that the wind velocity reaches the sound speed always exactly at the cluster border. Radial profiles of the basic hydrodynamic quantities given by their solution are shown on the left panel of Fig. 1.

The Chevalier&Clegg wind solution was later tested and further explored by e.g. Cantó *et al.* (2000); Raga *et al.* (2001) and many other authors. An important field of research is an interaction of the cluster with the ambient gas, in particular with the remnant of the parent molecular cloud. This subject is not covered here and we refer e.g. to Tenorio-Tagle *et al.* (2006); Harper-Clark & Murray (2009); Krause *et al.* (2012, 2013); Rogers & Pittard (2013); Herrera & Boulanger (2015) and references therein. Another interesting problem is the interaction of cluster winds with each other. It was studied by Tenorio-Tagle *et al.* (2007a) who show that it can lead to the formation of the super galactic wind as observed for instance in M82 galaxy.

The influence of the radiative cooling on the star cluster wind was studied by Silich *et al.* (2003) who included cooling into the spherically symmetric wind solution similar to the one by Chevalier & Clegg (1985). They show that the wind rapidly cools at some distance from the cluster, which depend on the cluster parameters, in particular on its mass and the wind metallicity (see Fig. 1). The radiative solution was compared to X-ray observations of young clusters by (Silich *et al.* 2004), for instance it was shown that it is in good agreement with measured X-ray fluxes of the nuclear cluster NGC 4303 (Jiménez-Bailón *et al.* 2003).

It has also been found that if the cluster is massive and compact enough, *i.e.* if its wind mechanical luminosity $L_{\rm crit}$ exceeds a certain value, no stationary wind solution exists

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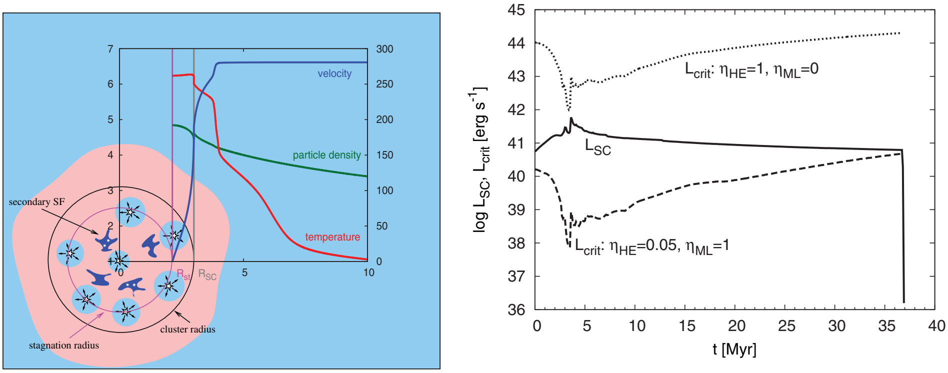

Figure 2. Left: schematic view of the cluster evolving in the bimodal regime. Individual stars are surrounded by free wind regions, however, most of the cluster volume is filled by the hot gas heated up the wind reverse shock. The hot gas is thermally unstable and forms dense warm clumps in some regions inside the cluster. The graph shows the wind density, temperature and velocity in the outer part of the cluster where the stationary solution exists. Right: time evolution of the wind mechanical luminosity (for cluster with mass 10^7 $M_\odot$, solid) compared to the critical luminosity calculated for heating efficiency 1 and no mass loading (dotted) and heating efficiency 5% and mass loading 1 (dashed).

(Silich *et al.* 2003). This can be easily understood from basic scaling relations. The energy available for driving the wind is directly proportional to the total energy of stellar winds which is directly proportional to the cluster mass. On the other hand, energy losses due to cooling are proportional to the square of the wind density, and therefore to the square of the cluster mass. As a result, the energy losses will always dominate if the cluster is massive and compact enough. This led Tenorio-Tagle *et al.* (2005) to suggest that the star formation feedback in massive clusters takes an extreme positive form leading to a high star formation efficiency.

2. Bimodal regime and secondary star formation

Tenorio-Tagle *et al.* (2007b) studied winds of clusters with mechanical luminosities higher than $L_{\rm crit}$. They found a new, so–called bimodal regime, for the wind solution, in which the volume of the cluster is divided into two regions (see Fig. 2 left). In the outer region, the stationary solution still exists with the wind velocity starting from zero at the stagnation radius, $R_{\rm st}$, and reaching the sound speed at the cluster border $R_{\rm SC}$. In the inner region below $R_{\rm st}$, random parcels of hot gas become thermally unstable, cool down and get compressed by the ambient hot gas into dense clumps. These dense clumps may stay warm, maintained at temperature $T \sim 10^4$ K by the stellar ionising radiation, however, if their column densities become large enough, they can self-shield themselves (see Section 3), cool to lower temperatures and feed the secondary star formation inside the cluster. The existence of the bimodal regime was confirmed by 2D hydrodynamic simulations by Wünsch *et al.* (2008) where also the estimates of the mass accumulated inside the cluster were provided. This prediction of the mass accumulation and the secondary star formation is particularly interesting in context of formation of globular clusters and their observed multiple stellar populations.

There is an observational evidence that the temperature of the hot gas inside young massive clusters is lower than several times 10^7 K which correspond to the thermalisation of all the kinetic energy of individual stellar winds. It led to the introduction of the so–called heating efficiency, $\eta_{\rm HE}$, denoting a fraction of the stellar wind kinetic energy

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that is converted into the hot gas internal energy (Silich *et al.* 2007). For instance, hydrogen recombination lines of super star clusters in the Antennae galaxies exhibit moderately supersonic widths (Gilbert & Graham 2007), larger than individual velocities of stars, but smaller than typical velocities of stellar winds. They were interpreted in terms of the bimodal wind solution by Tenorio-Tagle *et al.* (2010) who suggest that the line profiles are consistent with $\eta_{\mathrm{HE}} \lesssim 0.2$. Silich *et al.* (2009) found a similarly small values $\eta_{\mathrm{HE}} \lesssim 0.1$ by measuring and analysing sizes of HII regions coinciding with super star clusters in M82 galaxy. On the other hand, Strickland & Heckman (2009) found relatively high values of the heating efficiency, $\eta_{\mathrm{HE}} = 0.3 - 1.0$ by comparing X-ray observation of M82 with a set of 1D and 2D hydrodynamic models. Another effect that can decrease the temperature of the hot gas is mass loading of the wind with the primordial gas. Strickland & Heckman (2009) estimate the mass loading factor, η_{ML}, having a moderate values between 1 and 2.8. Additionally, there is evidence coming from observations of the Li abundance (Decressin *et al.* 2007), that stars in subsequent generations in globular clusters contain approximately 30% of the primordial gas. In summary, the heating efficiency and the mass loading are important parameters of the wind solution, however, they are not yet very well constrained.

Evolution of the star cluster wind for the first 40 Myr was computed by Wünsch *et al.* (2011) by combining output from the stellar population synthesis code Starburst99 (Leitherer *et al.* 1999) with a semi-analytic code calculating the spherically symmetric wind solution. Fig. 2 (right) shows the evolution of the wind mechanical luminosity for a cluster with mass $M_{\mathrm{SC}} = 10^7\ \mathrm{M}_{\odot}$and radius $R_{\mathrm{SC}} = 3\,\mathrm{pc}$ compared to the evolution of the the critical luminosity L_{crit} given for two combinations of the heating efficiency and the mass loading. It can be seen that the most conservative and rather unrealistic values $\eta_{\mathrm{HE}} = 1$ and $\eta_{\mathrm{ML}} = 0$ represent a marginal case for which the wind is not bimodal for all the period shown. On the other hand, a more realistic case with $\eta_{\mathrm{HE}} = 0.05$ and η_{ML} gives a solution in the bimodal regime (and hence mass accumulation) for the whole period of the existence of massive stars.

3. Influence of stellar ionising radiation

If the cluster evolves in the bimodal regime, a certain fraction of the gas reinserted within the cluster by massive star in a form of their winds gets thermally unstable, cools down and accumulates inside the cluster. However, the stellar ionising radiation can still maintain the gas warm and ionised if the column density of dense warm clumps does not exceed the value necessary for self-shielding. The minimum mass, m_{self}, of a spherical clump which is able to self-shield against the ionising radiation was estimated analytically by Palouš *et al.* (2014):

$$m_{\mathrm{self}} = \dot{N}_{\mathrm{UV,SC}} \frac{\mu m_{\mathrm{H}}}{\alpha_{\star}} \frac{kT_{\mathrm{ion}}}{P_{\mathrm{hot}}} \tag{3.1}$$

where $\dot{N}_{\mathrm{UV,SC}}$ is the total production rate of ionising photons, T_{ion} is the temperature of the warm ionised gas, P_{hot} is the pressure in the hot gas, $\alpha_{\star}$ is the recombination coefficient to the second and higher levels, μ is the average molecular weight of particles in the hot gas, m_{H} is the hydrogen nuclei mass and k is the Boltzmann constant.

If the gravity of the cluster is taken into account, dense clumps start to sink into the cluster centre and evolve in more or less steady streams, as shown by the hydrodynamic simulations (see below). The gas streams collide in the centre forming a massive central clump. If self-shielding occurs, it may happen either in both streams and the central clump, or only in the central clump. It has interesting implications for the second stellar

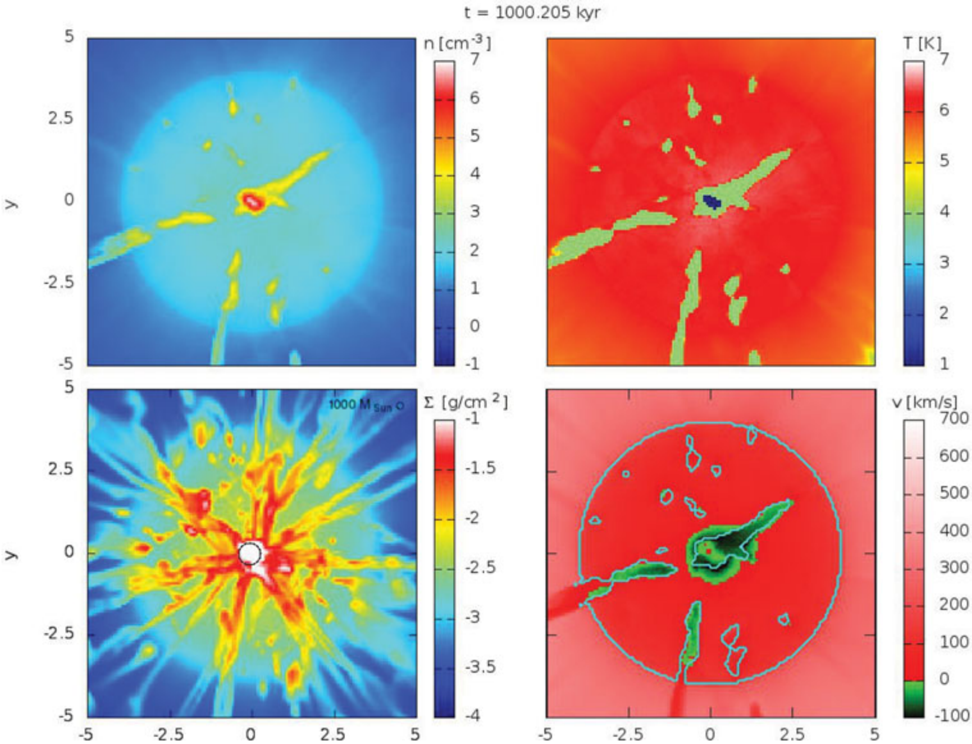

Figure 3. A frame from the 3D radiation-hydrodynamic simulation of a cluster in the bimodal regime at age 1 Myr. Cluster parameters are given in Tab. 1. Individual panels show: logarithm of the gas volume density at plane $z = 0$ (top left), logarithm of the gas temperature (top right) at $z = 0$, logarithm of the gas column density integrated in z-direction (bottom left), and the gas radial velocity (bottom right). In the last panel in the color version of this figure, the red/green color shows the outward/inward velocity and the cyan line marks the points where the flow changes from subsonic to supersonic. (see online edition for the colour version)

generation, because in the latter case, it should be very compact, because the stars are formed out of gas with a very small velocity dispersion. To decide which of the two cases takes place, time $t_{\rm SS}$ needed for self-shielding of the stream can be estimated and compared to the free fall time $t_{\rm ff}$ of the dense clump into the cluster centre. The self-shielding time is

$$t_{\rm SS} = \frac{4\pi^2}{9} N_{\rm UV}^2 R_{\rm SC}^{-1} R_{\rm st}^{-2} (1+\eta_{\rm ML})^{-1} \dot{M}_{\rm SC}^{-1} \mu m_{\rm H} \alpha_*^{-2} \left(\frac{kT_{\rm ion}}{P_{\rm hot}}\right)^3 . \qquad (3.2)$$

In order to test the above model and to explore it in more detail, we run 3D radiation hydrodynamic simulations of the cluster wind in the bimodal regime. It is based on the publically available hydrodynamic code Flash Fryxell *et al.* (2000), regions that are kept warm by the ionising radiation are determined by our code TreeRay, which works in this setup in a similar way as the TreeCol algorithm (Clark *et al.* 2012). The numerical model includes radiative cooling, the background gravitational field of the cluster and self-gravity of the gas. The mass and energy are inserted smoothly in a spherical volume with a radial distribution given by the Schuster profile (Palouš *et al.* 2013). More details will be given in the forthcoming publication (Wünsch *et al.*, 2015).

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quantity	symbol	value
cluster half mass radius	$R_{\rm h}$	2.67 pc
stellar mass of the 1st generation	$M_{\rm SC}$	10^7 M$_\odot$
mass inserted by stellar winds	$M_{\rm sw}$	4×10^5 M$_\odot$
heating efficiency	$\eta_{\rm HE}$	0.05
mass loading	$\eta_{\rm ML}$	1
mass loaded	$M_{\rm ML}$	4×10^5 M$_\odot$
mass of the 2nd stellar generation at 3.5 Myr	$M_{\rm 2G}$	7×10^5 M$_\odot$
mass of the warm gas remaining inside cluster at 3.5 Myr	$M_{\rm warm}$	1.4×10^4 M$_\odot$

Table 1. Parameters of the star cluster model for which the presented RHD simulation was carried out. The last two lines show simulation results: mass of the 2nd stellar generation, *i.e.* mass of all sink particles and the mass remaining in the simulation in a form of warm gas.

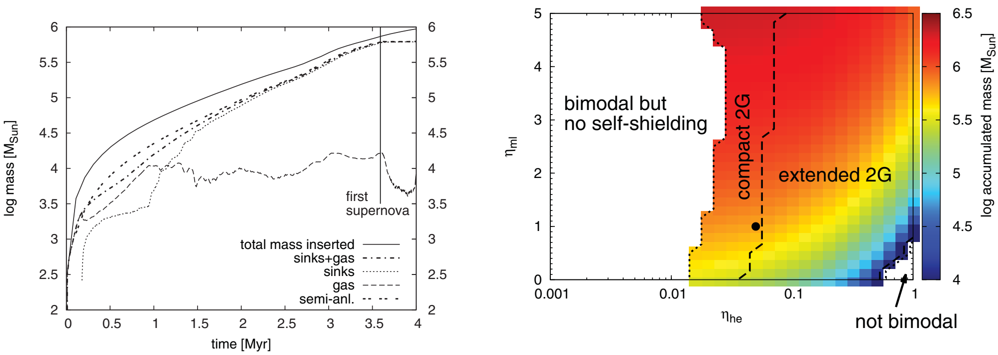

Figure 4. Left: evolution of the total mass inserted into the simulation (solid) and its fraction that stays in the simulation (dash-dotted). The latter can be split into mass of sink particles (thin dotted) and the mass in the cold/warm clumps (thin dashed). Prediction of the accumulated mass by the semi-analytic code is shown by the double dashed line. Right: mass of the second stellar generation calculated by the semi-analytic code as a function of the heating efficiency, $\eta_{\rm HE}$, and mass loading, $\eta_{\rm ML}$. The second stellar generation is predicted to be extended if the thermally unstable gas is able to self-shield against ionising radiation before it falls into the centre, and compact if it is not. The black circle marks parameters used in the presented RHD simulation. (see online edition for the colour version)

Fig. 3 shows a snapshot from the simulation with parameters given in Tab. 1 at time 1 Myr. It can be seen that thermally unstable gas evolves into dense streams that flow into the cluster centre forming there a massive clump. The streams are fully ionised and stay at $T = 10^4$ K, however, the central clump cools to much lower temperatures in its central part. There, the gas becomes gravitationally unstable and forms sink particles. Due to relatively poor spatial resolution due to missing proper treatment of thermal and chemical processes taking place at low temperature, only a few unrealistically massive sink particles are formed. Therefore, the model is able to predict only the total mass of the second stellar generation, $M_{\rm 2G}$, and the approximate position where the second generation stars are formed. The latter is interesting in terms of mass loss of the first generation stars, because if the second stellar generation is highly concentrated, preferential removal of the first generation stars will be easier independently of the removal mechanism.

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Evolution of the mass accumulated in the simulation is shown in Fig. 4 (left) where it is compared to the total mass inserted into the simulation. The accumulated mass is divided into mass in sink particles and mass in warm clumps/streams, and it is also compared to the calculation by the semi-analytic code. It can be seen that the agreement between the complex RHD simulation and the semi-analytic code is very good. The simulation also includes a short period after 3.5 Myr when supernovae start to explode. As a result, mass of sink particles stops to grow, *i.e.* star formation is stopped, and the amount of the warm gas decreases by almost one order of magnitude, *i.e.* most of the warm gas is removed.

Finally, we explore how properties of the second stellar generation depend on the heating efficiency $\eta_{\rm HE}$ and mass loading $\eta_{\rm ML}$. Fig. 4 (right) shows whether the second generation stars are formed and if they are, what is their total mass and whether they are formed only in the central clump (concentrated 2G) or also in the infalling streams (extended 2G). The mass of the first generation is 10^7 $M_\odot$and the metallicity of the stellar winds is assumed to be solar. The $\eta_{\rm HE} - \eta_{\rm ML}$ plane includes four qualitatively different regions defined mainly by the heating efficiency. If $\eta_{\rm HE}$ is very low, the wind solution is bimodal, however, the accumulated gas is unable to self-shield against ionising radiation due to its relative low density (given by a low hot gas pressure). For $0.02 \lesssim \eta_{\rm HE} \lesssim 0.07$, self-shielding is possible only in the central clump and a concentrated second stellar generation is formed. If $\eta_{\rm HE} \gtrsim 0.07$, self-shielding is possible also in infalling streams and the extended second generation is formed. In the small region around $\eta_{\rm HE} = 1$ and $\eta_{\rm ML} = 0$, the wind solution is not bimodal, and no mass accumulation occurs.

4. Summary

We have reviewed properties of the so–called bimodal star cluster wind solution which are interesting in terms of secondary star formation in young massive clusters. We have shown that if the cluster is massive enough, the thermal instability in the hot gas inside the cluster is inevitable. The exact mass limit depends on the cluster parameters, in particular, on the poorly constrained heating efficiency $\eta_{\rm HE}$ and mass loading $\eta_{\rm ML}$. However, with the most conservative values $\eta_{\rm HE} = 1$ and $\eta_{\rm ML} = 0$, the thermal instability and the bimodal regime should always occur for clusters with masses above 10^7 $M_\odot$.

We suggest the cooling winds model as the possible explanation of the multiple stellar generations in massive star clusters. Numerical simulations show that clusters evolving in the bimodal regime accumulate inside them mass reinserted by massive stars in a form of stellar winds. With realistic cluster parameters (particularly $\eta_{\rm HE}$ being not extremely low), the accumulated gas is able to self-shield against the ionising radiation of massive stars and it highly probably leads to secondary star formation. The heating efficiency, $\eta_{\rm HE}$, also determines where the accumulated gas becomes self-shielding and by that whether the second stellar generation is concentrated (low $\eta_{\rm HE}$) or extended throughout the whole cluster (high $\eta_{\rm HE}$). This is interesting in terms of the so–called mass budget problem, because all models explaining the subsequent stellar populations observed in globular clusters as stars formed out of winds and outflows of the first generation stars have to assume that a substantial fraction of the first generation is removed from the cluster. If the second generation is concentrated near the cluster centre, the preferential removal of the first generation is more probable.

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