Star Clusters: From the Milky Way to the Early Universe
Proceedings IAU Symposium No. 351, 2019
A. Bragaglia, M. Davies, A. Sills & E. Vesperini, eds.

doi:10.1017/S1743921319006732

Hydrodynamic simulations of second generation star formation in a young globular cluster

Francesco Calura

INAF - OAS, Osservatorio di Astrofisica e Scienza dello Spazio di Bologna,
via Gobetti 93/3, I-40129 Bologna, Italy
email: `francesco.calura@inaf.it`

Abstract. I will present results obtained by means of three-dimensional hydrodynamic simulations of the formation of second generation (SG) stars in a young globular cluster (GC). Our setup includes the mass return from Asymptotic Giant branch (AGB) stars, the accretion of pristine gas as well as star formation of SG stars, three ingredients which have never been simultaneously taken into account in previous 3D numerical studies of GC formation. The cluster is set in motion with respect to a distribution of gas and allowed to accrete mass from it. Formation of SG stars occurs out of the gas shed by AGB stars and from the gas accreted during the motion of the cluster. We consider two models characterised by different densities of the external gas. In both cases, we find that a very compact SG subsystem with central density $>10^5 M_\odot/pc^3$ forms in the innermost regions of the cluster.

Keywords. Hydrodynamics; methods: numerical; globular clusters: general; galaxies: star formation.

1. Testing the AGB scenario with hydrodynamic simulations

Several models have been proposed to explain the origin of multiple populations (MP) in globular clusters (GCs). In the asymptotic giant branch (AGB) scenario for MPs, a second generation (SG) of stars start to form from the ejecta of first generation (FG) AGB stars (e.g. D'Ercole *et al.* 2008). As FG and SG stars generally present a low metallicity spread, as traced by their [Fe/H] (typically of 0.1 dex, e.g., Renzini *et al.* 2015), the formation of SG stars must occurr after FG massive stars have expelled the gas enriched by FG supernovae (e.g. Calura *et al.* 2015 [C15]; D'Ercole *et al.* 2016). If one assumes a standard stellar initial mass function, the mass return from aging stellar populations is in general too scarce to form a large SG population (e.g. Calura, Ciotti & Nipoti 2014). For this reason, in order to account for the present-day mass and predominance of SG stars as observed in GCs, at its formation the FG has to be substantially more massive than at the present day, and dilution of the AGB ejecta with pristine gas occurring during SG formation must be invoked.

By means of hydrodynamic simulations carried on with RAMSES (Teyssier 2002, A&A, 385, 337) C15 have shown that the heating of massive stars may be sufficient to expel the residual gas in a young GC of mass $10^7 M_\odot$ and half-mass radius of 30 pc. The effects of the heating of FG stellar winds and SNe on the gas in which they are embedded is shown in Fig. 1, where two-dimensional density (left panels) and temperature (right panels) maps at two different evolutionary times (0.5 Myr and 1.6 Myr after the birth of the cluster) are shown. In this simulation, all the massive stars have been grouped into OB associations (OBAs) and distributed in the volume occupied by the cluster as described in C15.

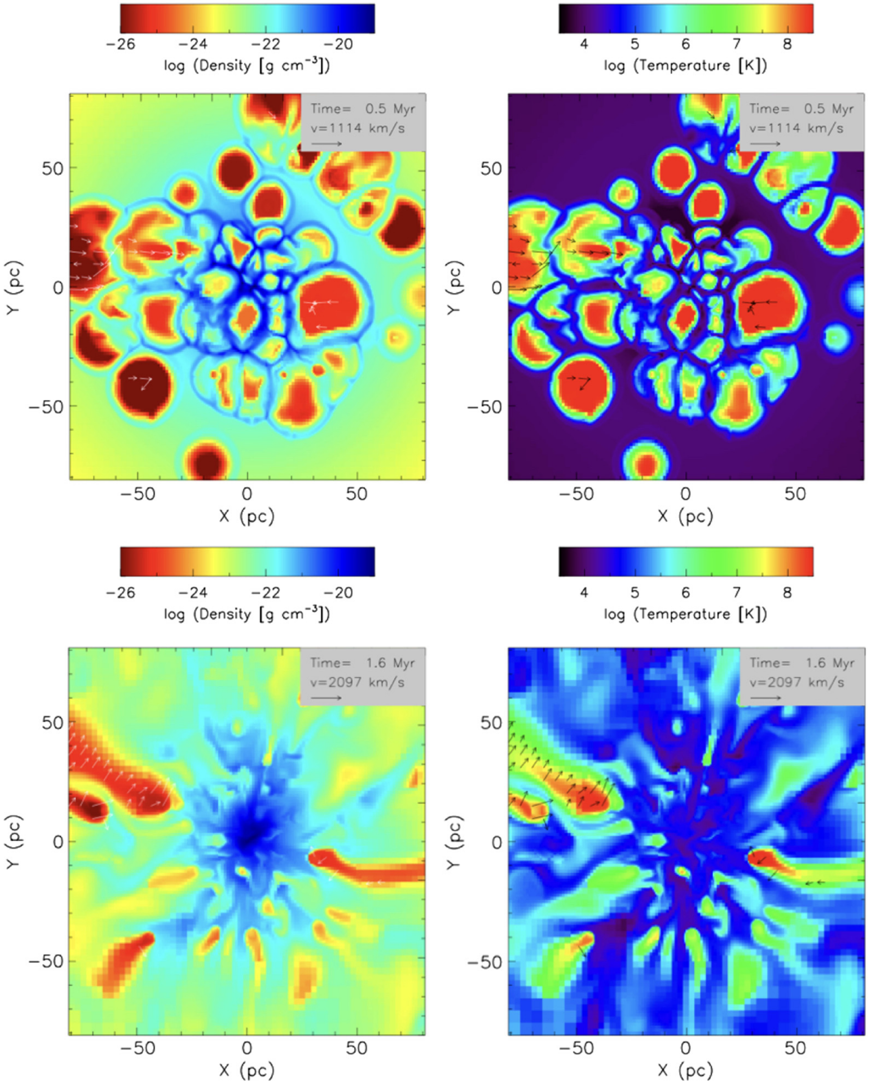

Figure 1. Effects of the feedback of stellar winds blown by massive stars in a young globular cluster, as shown by two-dimensional density (left panels) and temperature (right panels) maps in a simulation at two different evolutionary times (0.5 Myr and 1.6 Myr) from Calura *et al.* (2015). The arrows represent the velocity field of the most acceleareated gas portions, with maximum speed of ∼2000 km/s.

Several hot cavities have been carved in the gas by stellar winds already at 0.5 Myr, when some of the superbubbles expanding in the unperturbed medium still conserve a nearly round shape. This is mainly true for the most isolated ones, located in the lowest density regions. On the other hand, bubbles originating from sources with one or more OBAs nearby show strong distortions and are asymmetrically compressed already at early times. At 1.6 Myr most of the bubbles have merged, their dense shells have dissolved and a high-density, low-temperature region is visible in the center of the cluster, created by the combined action of multiple OBAs which push material in opposite directions, and by the gravity of the system. At later times the residual gas is progressively heated and expelled by the system, with less than 1% of the initial amount ($\sim 7\ 10^6\ M_\odot$) still present at 14 Myr.

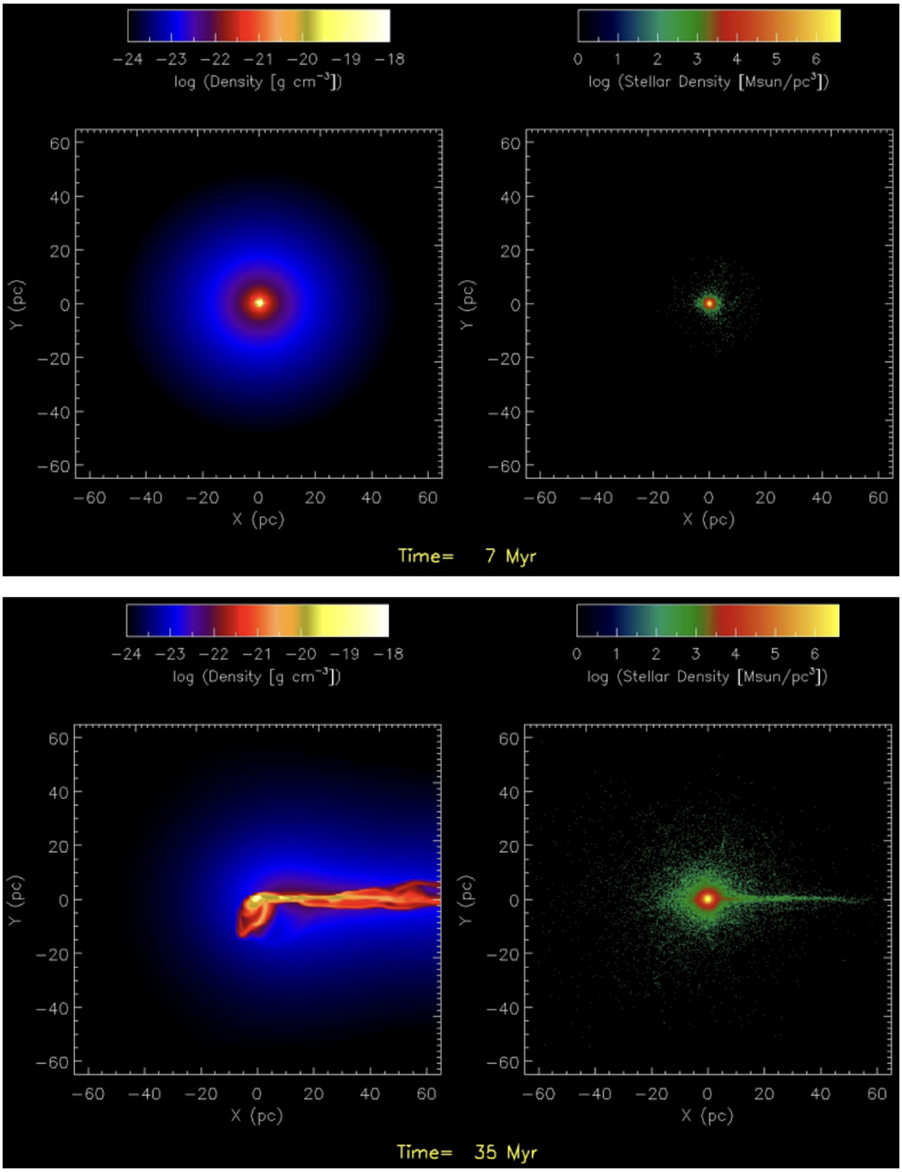

Figure 2. The birth of second generation stars in a young globular clusters. Shown are two-dimensional gas density (left panels) and stellar density (right panels) maps in a simulation at two different evolutionary times (7 Myr and 35 Myr; see Calura *et al.* 2019).

2. The birth of second generation stars

In a subsequent study, Calura *et al.* (2019; [C19]) have simulated the formation of SG stars in a 40 Myr old GC, where all the FG SNe have already exploded and as AGB stars start restoring their ejecta. The cluster has a FG stellar mass of 10^7 $M_\odot$. The 3d hydro-simulations performed with the RAMSES code (Teyssier 2002) include mass return from SG stars, gravity, star formation, SG stellar dynamics computed by a N-body solver, radiative cooling, and dilution from an external medium. The setup is designed to recreate the physical conditions described in D'Ercole *et al.* (2016), in which the cluster is assumed to lie within the disc of a galaxy at high redhift. The simulations are aimed at describing the motion of a cluster with respect to a background uniform gas distribution.

The cluster is assumed to be moving in a large cavity carved by FG stellar winds and SNe, and starting from a time $t_w > t_{AGB} = 40$ Myr, pristine gas starts to flow inside the computational box from one of the boundaries. We assume that a single star particle is allowed to form in each cell with a temperature $T < 2\ 10^4$ K and where the gas flow is converging. The mass of each collisionless stellar particle is $M_p = N m_0$, with $m_0 = 0.1\ M_\odot$ the minimum allowed mass and N drawned from a Poisson distribution (e.g., Rasera & Teyssier 2006). Star formation is assumed to stop 100 Myr after the birth of FG stars, as the first FG Type Ia SNe start to explode.

In Fig. 2 we show the results of our simulation, in which the density of the diluting gas is $10^{-24} g/cm^3$. The time at which such dilution starts depends on both the density of the gas and on FG stellar mass (D'Ercole *et al.* 2016), and in this case it is ∼60 Myr after the birth of FG stars.

The two top panels at 7 Myr show how the system looks like when it is still isolated, i.e. when the infall of pristine gas has still to start. As the ejecta of the AGB stars give rise to a cooling flow directed towards the cluster centre, enough gas can collect and give place to SG star formation. The already formed, compact stellar component is visible in the top-right stellar density map. At this time, the mass which has been turned into stars is $\sim 5\ 10^4\ M_\odot$, with an half-mass radius < 1 pc. These stars are highly He-rich, with $Y > 0.34$ (C19). At the later time of 35 Myr (bottom panels of Fig. 2), a subsonic front of pristine gas has crossed the cluster and a narrow, dense and cold tail has emerged, visible in the gas density map (left bottom panel). The tail has grown as the ram-pressure-stripped gas from the head of the bow shock was channelled behind the cluster centre, generating an an 'accretion column' (e.g. Bondi & Hoyle 1994), through which matter continuously flows onto the cluster and mix with the AGB ejecta. The stellar component in the core appears more diffuse than at 7 Myr, but the mass outside the innermost ∼3 pc is negligible.

We also run a model with a factor 10 higher density of the infall, characterised by a less concentrated SG of stars. At the end of the star formation, for the FG-to-SG stellar mass ratio we find values of 12.8 and ∼2 for the low-density and high-density infall model, respectively.

In future studies we will improve our investigation of the parameter space, e.g. exploring how the mass of FG stars and how energetic sources, such as type Ia SNe and stellar winds, can regulate mass accretion and SG star formation.

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