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Injection of energy and momentum by stellar winds and supernovae in compact, newly born stellar clusters

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Abstract. The literature is still lacking 3D, realistic studies of the SN feedback in very dense systems such as young GCs. Thanks to two previously awarded class C projects, we started using RAMSES, an hydrodynamical high-resolution code based on the Adaptive Mesh Refinement technique (Teyssier 2002) to study, by means of 3D simulations, the response of the typical gas-rich GC precursor to multiple supernova explosions occurring in stellar associations.

1. Introduction

Nowadays, Galactic globular clusters (GCs) are known to host multiple stellar populations. However, in most GCs such populations are characterised by the same metallicity, as traced by the [Fe/H] measured in their stars (Renzini et al. 2015). The fact that within each GC the different stellar generations share the same metallicity implies that the metals produced by the supernovae of the first stellar generation must not be incorporated in subsequent generations. Understanding if and how the natal, metal-enriched gas was lost during the early evolution of the cluster is key to assess the reliability of formation scenarios proposed so far for GCs and for stellar clusters in general. This question also connects to another majorly debated issue in modern astrophysics, i.e. the importance of stellar feedback on galactic and sub-galactic scales, which consists in the injection of energy, momentum and mass by dying stars. In this case, the question is: what is the role of stellar feedback in the evolution of stellar clusters? The process which contrasts the efficiency of stellar feedback is radiative cooling. In radiative simulations and in a very dense gas distribution the energy deposited by massive stars (MS) in the pre-supernova and supernova phases can be radiated away very quickly, which sometimes renders the stellar feedback highly inefficient. This implies that other assumptions are needed in order to have an appreciable effect of stellar winds and supernovae on the interstellar medium (ISM), i.e. switching off cooling in an appropriate and hopefully realistic fashion, e. g. in some ”spheres of influence” around MS. One problem is that there is no unique way to switch off cooling in a realistic way, nor there is any completely trustworthy, quantitative definition of the extent of the regions where cooling needs to be switched off. By means of hydrodynamical simulations carried on with the RAMSES (Teyssier 2002) hydro-code, in a previous study we have shown that, by injecting thermal energy only ans switching off cooling according to some appropriate, parametrized fashion, the heating of MS is sufficient to expel the residual gas in a young GC of mass $10^7 M_\odot$ and half-mass radius $\sim$ 30 pc (Calura et al. 2015) hereafter [C15]. However, for a more complete understanding of such topics, more feedback schemes need to be tested, in particular the injection of momentum, as well as the combined injection of both momentum and energy by the feedback sources. With this project, we have been able to address quantitatively the impact of the feedback scheme in the removal of the residual gas within a massive proto-GCs as the one studied in C15.

2. Simulation setup

We have started from the same setup of C15, i. e., we have assumed a young cluster with all the stars already in place, distributed according to a Plummer (1911) density profile. The total mass of the cluster is $10^7 M_\odot$, with $3 \cdot 10^6 M$ in stars. The computational box has a volume of $(\sim 162pc)^3$, and the static sources of feedback, which represent OB associations (OBA), have been distributed all over the volume following the same prescriptions as described in C15, i. e. sampling randomly from the mass distribution. The initial metallicity was $Z = 0.001$, representing a typical value for Galactic Globular Clusters. In C15 each OBA was constantly injecting thermal energy and mass within a given volume, which were meant to represent the typical size of an OB association. Radiative cooling was switched off in suitable grids following the prescriptions of Teyssier et al. (2013), i.e. that each OBA can inject in the ISM an amount of non-thermal energy of the same order of magnitude as the thermal energy. A non-thermal velocity dispersion σ_{turb} was computed from the cumulative energy density injected by OBAs, and cooling was switched off in any cell in which $\sigma_{turb} > 10km/s$. In the present work we study the role of σ_{turb}, testing the effect of a different, larger value on the evolution of the system.

In the present work, we have assumed that the size of each OBA is 1.5 pc. All the new simulations include radiative cooling as well, and different prescriptions are made on how such process is treated in the grids enclosing OB associations. The self gravity of the gas is taken into account, and a static potential describes the gravitational effects of the stellar component on the gas. The assumed temperature floor is $T_{floor} = 1000K$. The main aspect which was dealt with in this project and which represents an improvement with respect to the previous work is that various assumptions were made regarding how feedback was deposited by OB associations within a sphere 1.5 pc wide. In particular, we have tested the following cases:

- A: radiative cooling is never switched off, and thermal energy is continuously deposited with in a sphere of radius 1.5 pc
- B: radiative cooling is never switched off, no thermal energy is injected but momentum is continuously deposited with a rate $\dot{p} = L_{mec}/v_{wind}$, where L_{mec} is the mechanical luminosity of associations as due to winds and supernovae, defined as in C15, and $v_{wind} \sim 2000km/s$ is the terminal velocity of the matter injected by OBAs (Weaver et al. 1977).
- C: both momentum and energy are deposited without switching off cooling.
- D: thermal energy is deposited and cooling is turned off in each grid characterised by $\sigma_{turb} > 10km/s$ (as in C15).
- E: thermal energy is deposited and cooling is turned off in each grid characterised by $\sigma_{turb} > 50km/s$.

The last case gives us the opportunity to test one fundamental parameter of the prescriptions adopted in C15, i. e. the turbulent velocity a grid should have for being regarded as adiabatic.

3. Preliminary results

A few very preliminary results of our study are presented in Fig. 1, which shows 2D density and temperature maps calculated at the same evolutionary time and assuming various feedback implementations. At the evolutionary time chosen for the maps of Fig. 1, the OBAs have already carved several hot, rarefied cavities in the ISM, which are progressively expanding and, in some cases, of the verge of

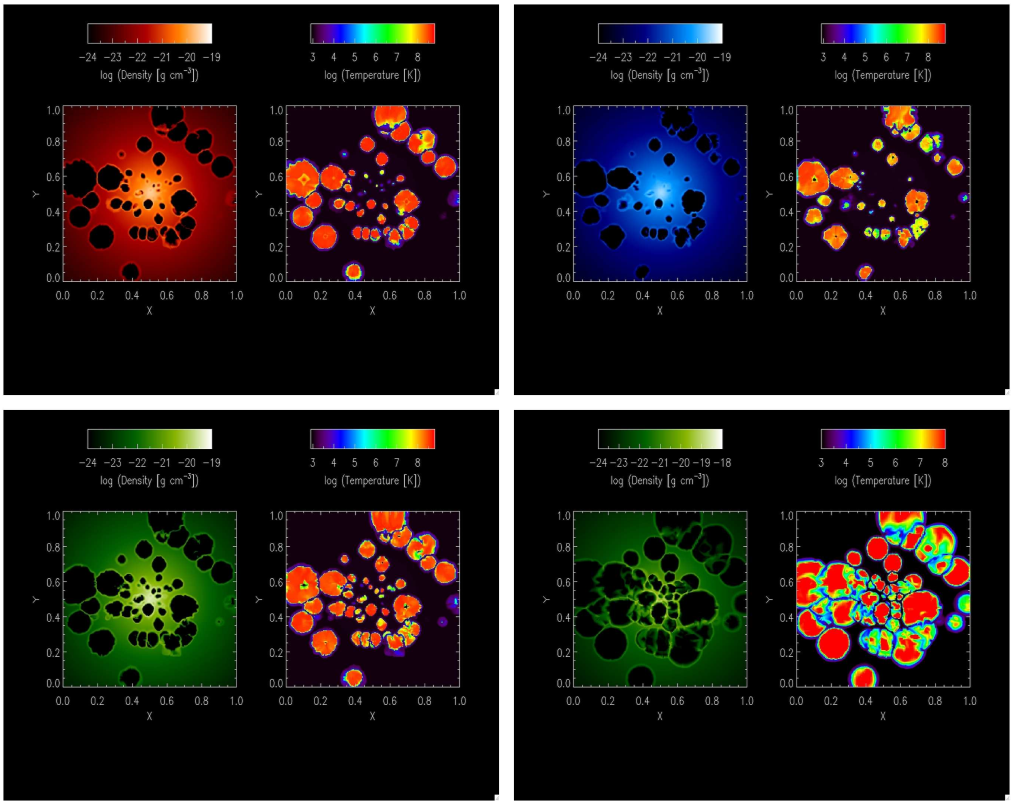

Fig. 1. Density and temperature maps of our simulations at the same evolutionary time and for different feedback implementations. Top-left: case A. Top-right: Case B. Bottom-left: case C. Bottom-right: Case E.

merging or crashing one onto the other. The cases A and B are similar in terms of extent of the cavities. One remarkable note is that, despite the large initial density of the gas ($> 10^{-20} g/cm^3$), OBAs are able to carve cavities in most of the cases by injecting either thermal energy only or momentum only. In these two cases, the sizes of the cavities and their covering factor into the computational volume seem comparable.

In case C, when both thermal energy and momentum are injected in the gids without switching off cooling, the size of the cavities is appreciably larger than in the previous cases, and in several cases the shells sorrounding the cavities are in contact. Such features are even more clearly visible in the maps computed for case (E) (bottom-right of Fig. 1), i.e. when cooling is switched off when $\sigma_{turb} > 50 km/s$.

Our results are summarised in Fig. 2. The stellar winds drive the fluid to large velocities which, in order to comply with the Courant condition for numerical convergence, may require very small time steps and large computational times. For this reason, in some cases the simulations have been interrupted before 30 Myr, i. e. the time which marks the end of SN activity within a single stellar population. Our results indicate that a non-negligible amount of the gas present initially is blown out of the computational volume also if either only energy or only momentum are injected in the system. The only cases in which all the gas is ejected is when we switch of cooling in a fash-

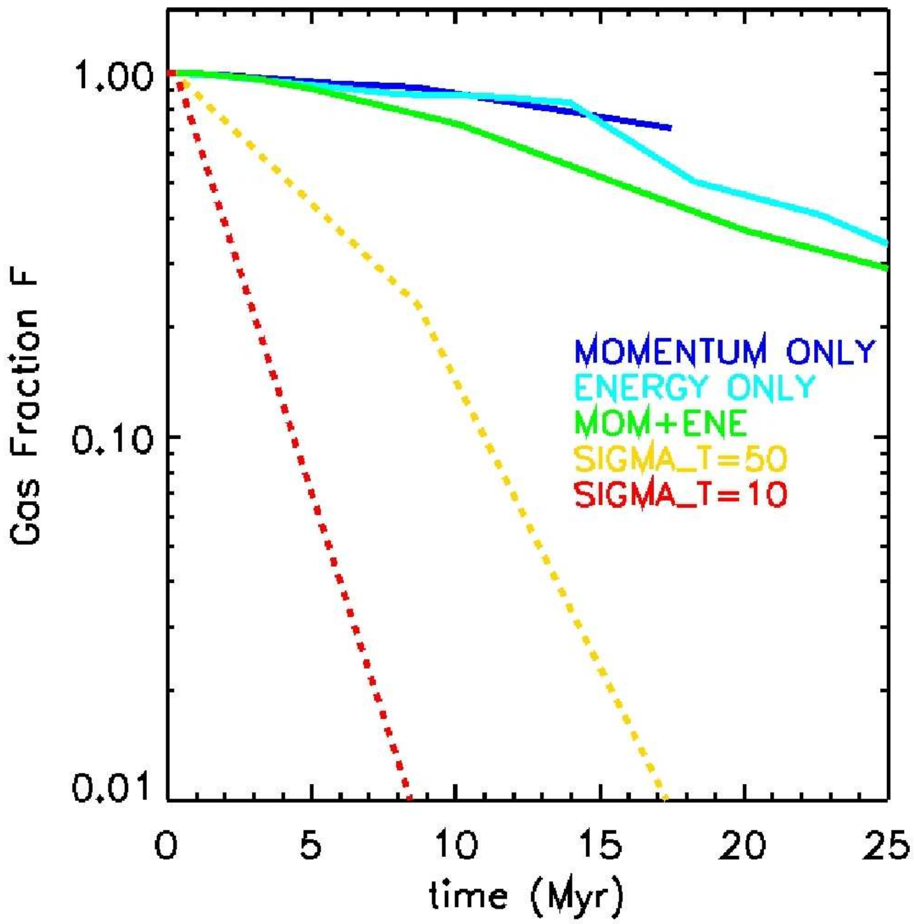

Fig. 2. Evolution of the gas fraction in the system as a function of time for various feedback prescriptions.

ion similar to the one of C15, but also for a larger value of σ_{turb}.

4. Hydrodynamical simulations of a pressure-confined gas cloud

Part of the CPU hours of the budget related to this project were used for performing 3D hydro-simulations aimed at studying the evolution of a new class of objects, i. e. pressure-confined gas clouds recently detected in the Virgo cluster (Bellazzini 2015).

Within a survey aimed at looking for stellar counterparts in compact HI clouds Bellazzini (2015) found ongoing star formation within one of such clouds. A tiny stellar system was detected with a stellar mass of $10^5 M_\odot$ and neutral gass mass $M_{HI} \sim 10^7 M_\odot$, extremely isolated and with a relatively high metallicity, indicating that the cloud was likely stripped from a large galaxy. This object, which was named SECCO 1, can be the defining prototype of a new class of stellar systems, the so-called pressure confined galaxies. Other candidates

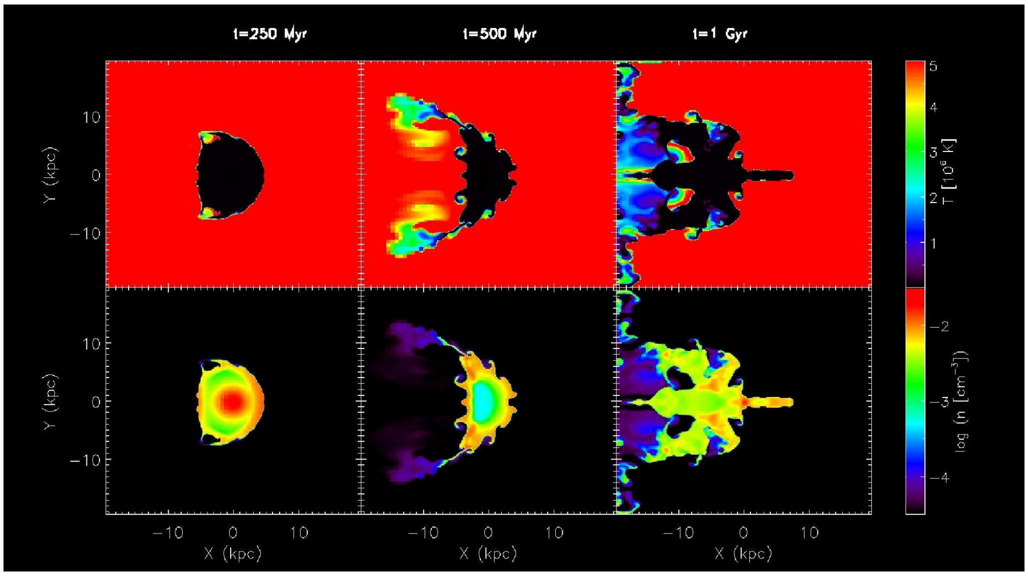

Fig. 3. Temperature (top panels) and number density (bottom panels) snapshots of the SECCO 1 simulation at $t = 250 Myr$ (left panels), $t = 500 Myr$ (middle panels) and $t = 1 Gyr$ (right panels).

in Virgo are being currently followed up with HST and MUSE.

In Bellazzini et al. (2018) we have presented a study based on 3D hydrodynamical simula- tions of an initially cold ($T = 5000K$) gas cloud moving subsonically (but with a large speed, 200km/s) through a very hot ($T \sim 5e6K$) medium. The simulations were carried on by means of the RAMSES hydro-code, and included radiative cooling and heating from a UV background. Our results indicated that in a period of 1 Gyr, nearly 25% of the initial cold gas mass was evaporated into the hot medium. The cloud also experienced a considerable morphological evolution, mostly driven by Kelvin-Helmoltz instabilities (KHI). The results of our study are presented in Fig. 3. Throughout the evolutionary time considered here (1Gyr), from the initially spherical shape, the cold cloud evolves into an umbrella-like or jellyfish-like shape. After 1 Gyr the majority of the initial cloud mass is still cold, with temperatures $T < 20000K$. The 3D simulations have confirmed that the gas cloud can survive a travel of 1 Gyr and that it is likely that SECCO has been ram-pressure stripped from a galaxy pair located a few $\sim$ 100 kpc away from it.

5. Other remarks

The present project was not meant as a pilot for larger projects (such as ISCRA or PRACE). It is currently being complemented by one CHIPP project, aimed at studying gas removal in a smaller cluster, assuming the same feedback prescriptions described in this paper and for a sub-set of cases, namely the most extreme cases (A) and (E). After these runs the results of our study are going to be presented in a future paper. The present project has already led to one publication on a peer-reviewed journal (Bellazzini et al. 2018). The advantages of having obtained the CPU time by means of the MoU CINECA-INAF agreement instead of applying to a generic call is mainly the fast, positive answer which came very soon after our application, as well as the possibility of having promptly both the CPU hours and the requested facilities ready for our use.

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