Report about project
"Three-dimensional hydrodynamical simulations of supernova explosions in the smallest Milky Way satellites"
(INA17_C1B01)

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Allocated CPU time: 300,000 hr (100,000 on Galileo, 200,000 on Marconi KNL)

This project is part of the first PI's study requiring HPC resources. It is meant to allow the PI to get familiar with HPC and with the adopted hydrodynamic code (RAMSES, Teyssier 2002 [A&A, 385, 337]). The ultimate goal is to access PRACE HPC systems. The results obtained in the framework of this specific project will add to results obtained from previous ISCRA projects and will also be complemented by another simulation; they will then be submitted for publication all together in the coming six months. The advantages of the MoU CINECA-INAF have mainly been a reduced waiting time between the proposal submission and the allocation of the necessary CPU time. However, the recent advent of SLURM has significantly slowed down the runs, most likely due to the relatively old version of RAMSES adopted. We are now planning to use the latest release of the code available from https://bitbucket.org/rteyssie/ramses

SUMMARY OF THE RESEARCH

Introduction

In the ΛCDM concordance cosmology, large halos form from the merging and accretion of smaller building blocks (White & Rees 1978); however, a large number of sub-halos is predicted to survive the digestion processes and inhabit the main galaxy halo. In the past dozen years, the number of known Milky Way (MW) companions has increased apace, thanks to the commitment of hundreds of scientists around the world to deep large-area sky imaging surveys, such as the Sloan Digital Sky Survey (York et al. 2000), the VST ATLAS Survey (Shanks et al. 2015), the Dark Energy Survey (DES Collaboration 2016), the Pan-STARRS1 3π Survey (Chambers et al. 2016), and the Hyper Suprime-Cam Subaru Strategic Program Survey (Aihara et al. 2018). A new class of galaxy has been discovered, one made of extremely faint, dark-matter dominated, scarcely evolved stellar systems, that have been given the name of ultrafaint dwarf galaxies (UFDs; see, e.g., Willman et al. 2005; Belokurov et al. 2006, 2007, 2014; Bechtol et al. 2015; Laevens et al. 2015; Homma et al. 2016, 2018).

All of this has dramatically impacted our understanding of the way the halo of our Galaxy came into being. The continuing discovery of more and more UFDs, even at the detectability limits of the surveys (see Torrealba et al. 2016, their figure 9), pulls the trigger on studies aimed at establishing how star formation and chemical enrichment proceed in small dark matter halos.

Semi-analytical models and pure chemical evolution models rely on simple, yet physically motivated, parameterizations and heuristic prescriptions to trace the evolution of several elements in the interstellar medium (ISM) of systems with structural properties similar to those of observed UFDs. They generally agree that these galaxies formed stars very inefficiently, converting into stars less than 1–3 per cent of their baryons, but there is no consensus about the mechanism(s) that truncate(s) the star formation, with either reionization, galactic winds or tidal stripping being suggested (e.g. Salvadori & Ferrara 2009; Vincenzo et al. 2014; Romano et al. 2015). Chemical evolution models have been very successful in explaining many observed properties of galaxies but, when moving to stellar systems with lower and lower dynamical masses, the parameterizations adopted to treat the thermal feedback from stars, the conditions imposed on the onset of galactic-scale outflows, the assumed mass loading factors for the neutral ISM, all introduce degeneracies in the proposed solutions. Furthermore, there are severe limitations in the treatment of spatial inhomogeneities. That is why chemical evolution models can not put firm constraints to the physical processes regulating the evolution of the lowest mass systems (see, e.g., the discussion in Romano et al. 2015). The natural outcome is to turn to hydrodynamical simulations.

Numerical set-up

We have run our simulations with a customized version of the Adaptive Mesh Refinement (AMR) code RAMSES (Teyssier 2002) that solves the Euler equations of gravito-hydrodynamics with a second-

order, unsplit Godunov scheme. The initial configuration is designed to mimic a well-studied system, the Boötes I UFD (see, e.g., Romano et al. 2015, and references therein), and foresees a non-rotating distribution of gas and stars embedded in an isolated dark matter halo. The initial baryonic and dark masses are $M_{gas} = 6 \times 10^6$ $M_\odot$ and $M_{DM} = 3.5 \times 10^7$ $M_\odot$ and follow, respectively, a Plummer (1911) density profile, with a characteristic radius of 200 pc, and a Burkert's (1995) profile, with cut-off radius of 1.2 kpc. The dark matter component is modeled as a static external potential and added to the solution of the Poisson equation; the self-gravity of the gas is neglected for simplicity. The initial pressure profile is set by solving the hydrostatic equilibrium equation. A population of coeval stars, $M_{stars} = 10^5$ $M_\odot$, is set in place at the beginning of the simulation. Assuming a Kroupa (2001) stellar initial mass function, 650 of these stars are assigned initial masses in excess of 8 $M_\odot$. The massive stars are grouped in ten OB associations 8 pc wide scattered across the computational volume, following the procedure outlined in Calura et al. (2015), to whom we refer the reader for details. Each association is allowed to inject mass and energy in its surroundings at a constant rate for an uninterrupted period of 30 Myr (roughly corresponding to the lifetime of a 8 $M_\odot$ star) through both stellar winds and supernova (SN) explosions (cf. Mac Low & McCray 1988). The mass and energy injection rates during the pre-SN phase (lasting 3 Myr) and SN phase (from 3 to 30 Myr) for each OB association are computed after Leitherer et al. (2014). Mass and energy are spread on the volume occupied by the OB association. The computational box is L = 2 kpc on a side, with a maximum refinement level corresponding to a minimum cell size of $\Delta x_{min} = 0.95$ pc. The refinement strategy is geometry and discontinuity-based. In particular, at each time step a number of cells at the highest refinement level is set up to cover the regions occupied by the OB associations. This assures that every OB association is adequately spatially resolved –stellar ejecta and SN energy are added to the gas within a sphere that is four grid cells in radius, which prevents the occurrence of square-shaped shock fronts. We use free outflow boundary conditions and create a passive scalar to trace the evolution of the metallicity of the gas in each cell, starting from a primordial (zero) metallicity value. We ran both an adiabatic and a cooling model. The first was run from 0 to 30 Myr, the second from 0 to 18 Myr. To minimize numerical problems, we set a temperature floor of $T_{min} = 3900$ K.

Some results
At the beginning of the simulation, because of the relatively low densities ($n_H \sim 7$ cm$_{-3}$ at the centre and ~ 1 cm$_{-3}$ at the Plummer radius) the radiative cooling is fairly ineffective. Large cavities filled with tenuous hot gas are carved out around the OB associations already during the pre-SN phase (0–3 Myr), *both in the adiabatic run and in the simulation with radiative cooling* (Figs. 1 and 2, respectively, upper panels), without any need for switching off cooling artificially. During the SN phase (3–30 Myr; Figs. 1 and 2, middle and lower panels; shown here is only the behavior up to 13 Myr), in the presence of radiative cooling multiple SN explosions dig superbubbles smaller than those moulded in the adiabatic case, filled with hotter and more rarefied gas. These bubbles also take more time to lose their individuality, disrupt, and merge. We note that, in spite of the growth of Rayleigh-Taylor instabilities at the borders, the bubbles preserve ovoid shapes delimited by thin, dense, cold shells, until they do not interact with each other. Fig. 3 depicts the gas velocity field at the end of the adiabatic simulation. Pockets of tenuous, heated gas around individual OB associations expand at supersonic velocity. SN debris are channeled in hot structures, that resemble chimneys and fountains, and can either be entrained in an outflow or 'rain back' to the galaxy centre with velocities up to several hundreds of km s$_{-1}$. The cooler ambient medium is largely unaffected by the SN activity and likely to remain bound; however, a part of it (mostly in the outermost regions) is swept up and steadily moves outwards with velocities that exceed the local escape velocity (see inset in Fig. 3, where the black areas highlight regions where the velocity is lower than the escape velocity from the system). In the adiabatic run most of the mass and energy injected by massive stars in the ISM escape the system.
The evolution of the gas density profile is shown in Fig. 4. For the simulation with cooling, the profile at t = 18 Myr (green solid curve) differs only slightly form the initial one (black solid curve), which means that, to a large extent, the ambient medium is basically unaffected by the mass return from SNe. On the other hand, the final profile (at t = 30 Myr) for the adiabatic simulation (red solid curve) deviates considerably from the initial one: it is shallower, with densities two order of magnitudes lower at the centre and slightly higher at radii beyond 400 pc.
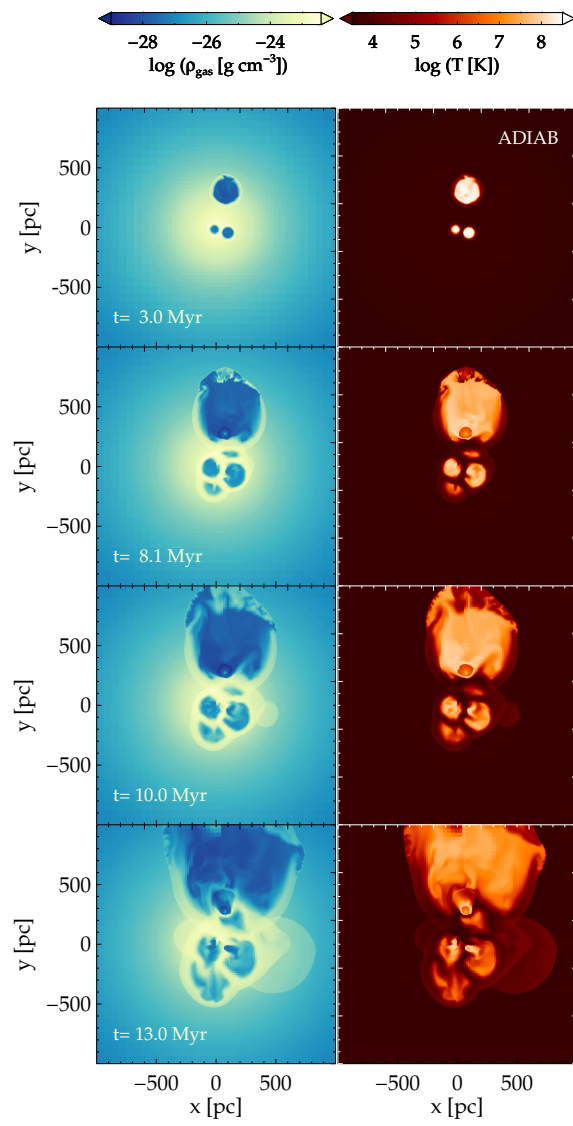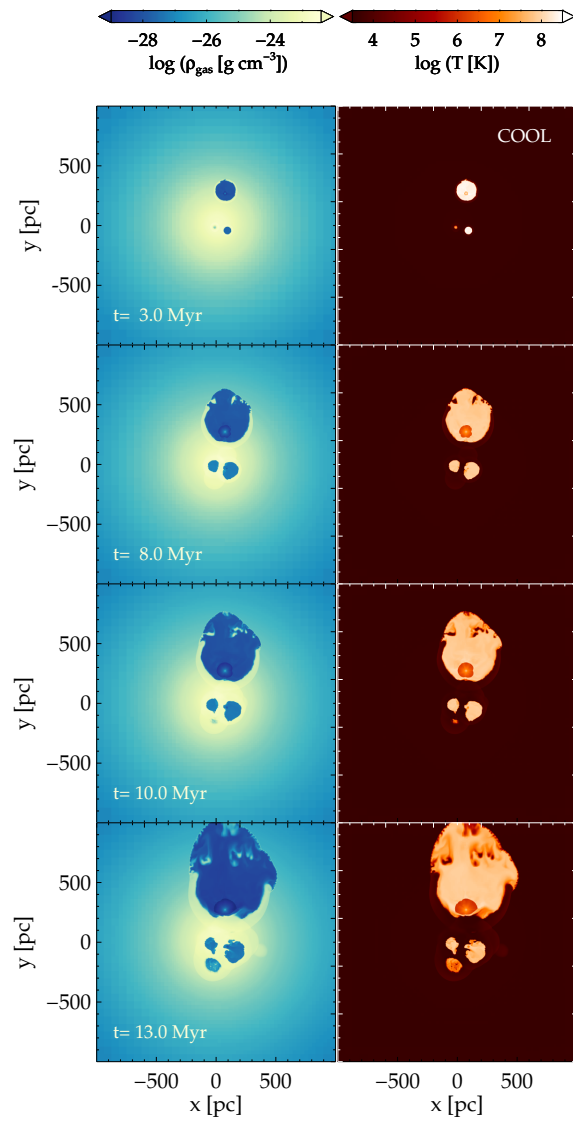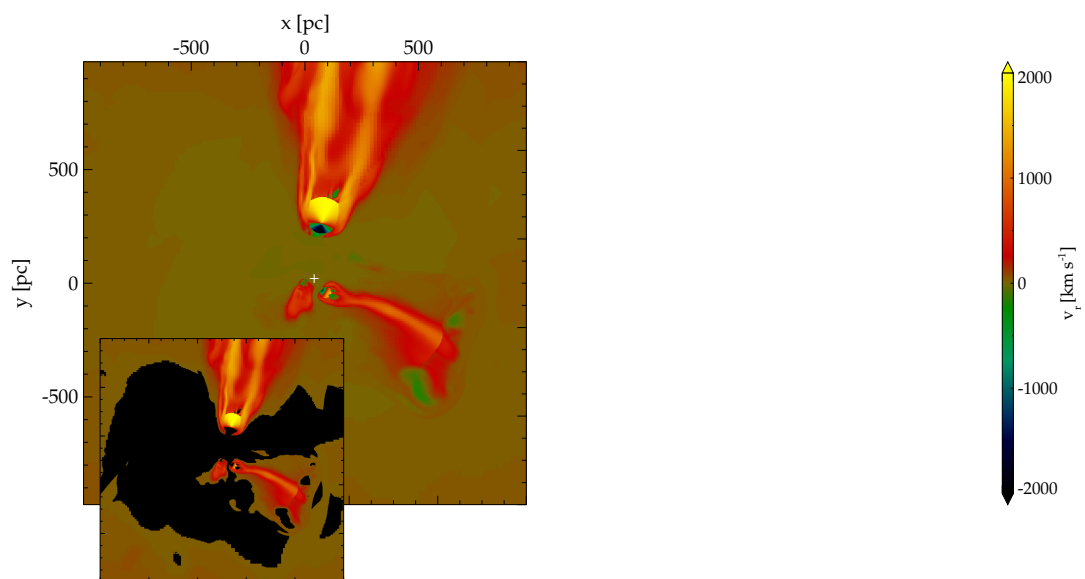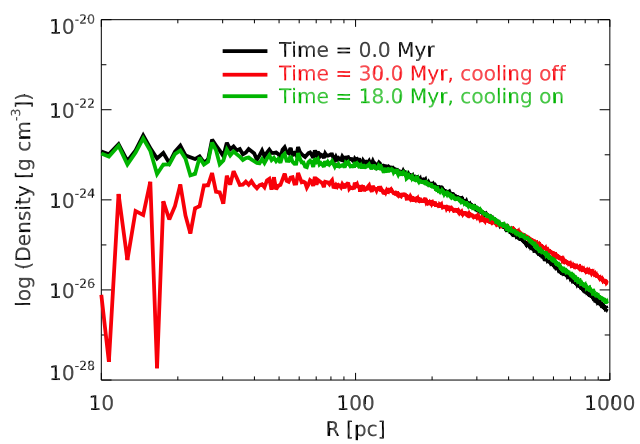
Fig.1

Fig.2

Fig.3

Fig.4