Hydrodynamic simulations of an isolated star-forming gas cloud in the Virgo cluster

Francesco Calura1⋆, Michele Bellazzini1, Annibale D’Ercole1

1INAF-Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Gobetti 93/3, I-40129 Bologna, Italy

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ABSTRACT

We present a suite of three-dimensional, high-resolution hydrodynamic simulations that follow the evolution of a massive ($10^7 M_\odot$) pressure confined, star-forming neutral gas cloud moving through a hot intra-cluster medium (ICM). The main goal of the analysis is to get theoretical insight into the lifetimes and evolution of stellar systems like the recently discovered star-forming cloud SECCO 1 in the Virgo cluster of galaxies, but it may be of general interest for the study of the star forming gas clumps that are observed in the tails of ram pressure stripped galaxies. Building up on a previous, simple simulation, we explored the effect of different relative velocity of the cloud and larger temperature of the ICM, as well as the effect of the cloud self-gravity. Moreover, we performed a simulation including star-formation and stellar feedback, allowing for a first time a direct comparison with the observed properties of the stars in the system. The survivability of the cold gas in the simulated clouds is granted on timescales of the order of $1 \text{ Gyr}$, with final cold gas fractions generally $>0.75$. In all cases, the simulated systems end up, after $1 \text{ Gyr}$ of evolution, as symmetric clouds in pressure equilibrium with the external hot gas. We also confirm that gravity played a negligible role at the largest scales on the evolution of the clouds. In our simulation with star formation, star formation begins immediately, it peaks at the earliest times and decreases monotonically with time. Inhomogeneous supernova explosions are the cause of an asymmetric shape of the gas cloud, facilitating the development of instabilities and the decrease of the cold gas fraction.

Key words: Galaxies: star formation - methods: numerical - hydrodynamics - galaxies: individual.

1 INTRODUCTION

Within a survey aimed at looking for stellar counterparts in compact HI clouds, Bellazzini et al. (2015a) found ongoing star formation within an isolated gas cloud lying in the Virgo cluster (see also Bellazzini et al. 2015b). The mass budget of this stellar system, named SECCO 1, is dominated by neutral hydrogen ($M_{\text{HI}} \sim 10^7 M_\odot$), while the stellar mass is $M_\ast \sim 10^5 M_\odot$, (see also Sand et al. 2015, 2017, and Adams et al. 2015). The nebular metallicity as measured in several HII regions within the system is $12+\text{log}(O/H)=8.38\pm0.11$, much higher than that of dwarf galaxies of similar mass, implying that the cloud could have been stripped from a larger galaxy (Beccari et al. 2017, Bellazzini et al. 2018, B18 hereafter), but, in fact, SECCO 1 lies several hundreds of kpc apart from any known galaxy within the Virgo cluster (see Sand et al. 2017 and B18).

Indeed, all the known properties of SECCO 1 lie in the range covered by star-forming gas clumps observed in the extended tails of ram pressure stripped gas in the so-called jellyfish galaxies (Poggianti, et al. 2019 and references therein).

The crucial difference with these systems is the extreme isolation of SECCO 1. This cloud could have travelled away from its parent galaxy for a long time ($\gtrsim 1 \text{ Gyr}$) within the Intra Cluster Medium (ICM) of Virgo, preserving the conditions to form stars today, in spite of not being gravitationally bound (B18). Sand et al. (2017) presented a list of five additional candidate siblings of SECCO 1. Hence, SECCO 1 may be the prototype of a new class of stellar systems.

By means of hydrodynamical simulations, Kapferer et al. (2009) showed that in galaxy clusters, ram-pressure stripping episodes are expected to extract from disc galaxies a large number of star-forming blobs, and that such blobs are expected to be long-lived in the cluster medium. In the past, other models have been proposed (Bekki, Koribalski & Kilborn 2005) which showed that large amounts of neutral gas could be removed from the parent galaxy by tidal encounters. Burkhart & Loeb (2016) suggested that small clumps stripped from gas-rich systems can travel for a relatively long time, confined by the pressure of the surrounding hot ICM. They showed that pressure confinement may drive them to density conditions conducive to the ignition of star formation.

In an attempt to verify the plausibility of the survival over long travel times of a cloud like SECCO 1, B18 performed both two-dimensional (2D) and three-dimensional (3D) hy-
dynamical simulations of an initially cold (\(T \sim 5000\) K) gas cloud moving subsonically (but with a large speed, \(\sim 200\) km/s) through a very hot (\(T \sim 10^6\) K) medium. Their results indicated that the cloud was able to preserve \(\sim 75\%\) of its initial content of cold gas during its 1 Gyr-long flight, while the remaining \(\sim 25\%\) was evaporated into the hot medium. The cloud also experienced a considerable morphological evolution, mostly driven by Kelvin-Helmholtz instabilities (KHI).

However, important physical ingredients were missing in the B18 simulations, including, e.g., the self-gravity of the cloud. Additional numerical experiments are needed to test further the role of the environment in determining the survivability of the cloud. In particular, how does the thermal state of the ICM affect the evolution of the cloud? What is the effect of a different relative velocity between SECCO 1 and the ICM in its long-term evolution? Last but not least, what are the effects of star formation and stellar feedback? In order to address these issues, in this paper we present a new suite of high-resolution, 3D simulations aimed at describing the motion of a cold gas cloud similar to SECCO 1 through a hot ICM.

A description of the code, of the initial setup and of the physical ingredients of our simulations are presented in Sec. 2. In in Sec. 3, our results are presented and discussed. Finally, we draw our conclusions in Sect. 4.

## 2 MODEL DESCRIPTION

Our numerical simulations are designed to describe the motion of a cold gas cloud with respect to a background distribution of hot gas, representing the Virgo ICM. The cold gas cloud is assumed to be initially spherical, and it is designed to represent the main body of SECCO 1, which contains a large fraction (\(\sim 80\%\)) of the total gas mass detected in the entire system (B18), which also includes a secondary body, which accounts for the remainder \(\sim 20\%\) of the mass. An H\(\alpha\) intensity map of the main body of SECCO 1 is presented in Fig. 1, whereas a summary of its main observational properties is in Tab. 1.

In the present work, we do not investigate how the cold gas cloud can have originated. We study its evolution after it has abandoned its parent galaxy and is outside the effects of its gravitational field. We focus on a parameter space which includes a few fundamental properties of system and of the external medium, including temperature and relative velocity. After some pure hydrodynamic, radiative runs, we also perform runs which take into account the self-gravity of the gas. Finally, in the most refined model, we consider star formation and stellar feedback and study their effects on the evolution of the gas cloud.

It is important to stress that our idealised, numerical experiments are designed to gain an insight into the physical processes that are expected to play a major role in the evolution of this kind of systems.

### 2.1 Simulation Setup

The code used is a customized version of the grid-based, Adaptive Mesh Refinement (AMR) hydro-code RAMSES (Teyssier 2002). The AMR technique allows one to reduce the computational cost of a simulation by assigning higher resolution to zones of particular interest within the computational box. In our case, the AMR feature is exploited by adopting both geometry-based and discontinuity-based criteria. In our Cartesian Grid, the computational box has a volume of \(V_{\text{box}} = (40 \text{ kpc})^3\), chosen in order to largely contain the whole cloud and, as much as possible, the extent of instabilities. For a given setup, in general more simulations are run at various resolution and starting from the same initial conditions, in order to check numerical convergence. The maximum spatial resolution used in our simulations is of 76 pc.

As in B18, the initial radius of the spherical gas cloud is \(\sim 3.7\) kpc. With this configuration, the side of the box is \(\sim 10\) times the initial radius of the cloud.

Our setup is designed to recreate the fast motion of the cloud in the hot ICM of the Virgo cluster. In our ‘wind tunnel’ numerical experiment (with a basic setup similar to the one of Calura et al. 2019), the reference frame is placed at the centre of the cold gas cloud, and since the start of the simulation the hot ICM gas moves continuously along the x-axis. New, fast hot gas is continuously allowed to flow inside our computational box from one of the boundaries and again moving parallel to the x-axis, from left to right.

The parameters describing the initial conditions of the models investigated in this paper are reported in Table 2 (columns 2-8).

The parameters of our Standard model are the same as the ones of the simulations carried on in B18, with an initial density of the cloud and of the ICM of \(3 \times 10^{-26}\) and \(2.5 \times 10^{-29} \text{ g/cm}^3\) respectively. As discussed in B18, the parameters of the Standard run were derived from the available observations. The temperature of the hot gas \(T_{\text{ICM}}\) was derived from the radial velocity dispersion of the ICM as determined by Boselli et al. (2014). The density of the ICM was derived from the total mass (dark and baryonic matter) of the low velocity cloud substructure of the Virgo cluster, assuming that the hot gas density distribution follows the dark matter density profile (Navarro et al. 1996). As for the cloud, for its initial temperature a value comparable to the mean temperature of the diffuse HI was assumed (e.g. Wolfire et al. 2003), whereas its density was computed from the observed radius and mass of SECCO 1 reported in Tab. 1 and considering a mass abundance of HI with respect to all elements at the temperature of the cloud of \(\sim 0.16\) (B18). Note that, with this choice, at the beginning of the simulation the cloud is almost in pressure equilibrium with the surrounding environment.

It may be interesting to estimate how far out of equilibrium the cloud is initially, e. g. by computing the radius it needs to have to be in equilibrium. This has important consequences for the suggestion of Burkhart & Loeb (2016) that pressure confinement can explain the survival of clouds similar to SECCO 1. This was tested also in Taylor, Wünsch & Palouš (2018), but only in clouds where dynamic pressure dominates over thermal pressure. The much lower line width of the cloud explored here potentially gives this study greater similarity to the original pressure confinement model. The equilibrium radius can be estimated from the initial conditions shown in Tab. 2, suggesting that the ratio between the initial pressure of the cloud of the standard run and the one of the hot ICM is of 2.4. Considering \(\rho_d \propto R_{\text{HI}}^{-3}\), a condition of...
Hydrodynamic simulations of SECCO 1

Figure 1. Hα image of the main body of SECCO 1 as obtained from MUSE data (see Beccari et al. 2017). The black contour lines represent the flux at 0.5, 1.0, 2.0, 4.0, 8.0 and 16.0 × 10^-18 erg cm^-2 s^-1.

Table 1. Summary of the main observational properties of the main body of SECCO.

| Quantity       | SECCO Main Cloud Observed value or range | References              |
|----------------|----------------------------------------|-------------------------|
| Distance [Mpc] | 17                                     | Boselli et al. (2014)   |
| $M_*$ [$M_\odot$] | 4 × 10^4 - 1.2 × 10^5^a                 | Sand et al. (2017), Beccari et al. (2017) |
| $M_{HI}$ [$M_\odot$] | 1.5 × 10^7                            | Adams et al. (2015)    |
| $R_*$ [kpc]    | 1.2                                    | Beccari et al. (2017)  |
| $R_{HI}$ [kpc] | 3.7                                    | Adams et al. (2015)    |
| $\sigma_*$ [km s^-1] | 3.5±2.1                                | Beccari et al. (2017)  |
| $\sigma_{HI}$ [km s^-1] | 9 ±3                                   | Adams et al. (2015)    |
| SFR [$M_\odot$ yr^-1] | $\sim$1 × 10^{-3} b                | Sand et al. (2017)    |

^a The reported range includes the value derived from CMD analysis and the upper limit derived from the integrated light.

^b Derived from CMD analysis.

complete equilibrium requires a radius of the cloud $\sim$ 1.3R_{HI}. The model in which the deviation from initial pressure equilibrium is the smallest is the T1E7K, with an initial ratio between cloud pressure and ICM pressure of 1.2.

The default value chosen for the relative velocity between the cloud and the ICM is 200 km/s, but we will also test a larger value (400 km/s). Initially, both the cold cloud and the external medium are homogeneous and characterised by a uniform temperature. The cloud and the ICM have uniform initial metallicity values of 0.5Z_\odot and 0.1Z_\odot, respectively. Initially, the isothermal cloud temperature is of 10^4 K, whereas for the hot gas we test two different values, 5 × 10^6 K, and 10^7 K. In most of the simulations without star formation, the effects of gravity are neglected. This is based on the fact that in B18, from the calculation of the virial ratio of the cloud, it was shown that the system is not bound grav-
in the paper, we investigate this aspect further and run one simulation in which the self-gravity of the gas is taken into account, with the aim of testing its effects on the motion of the gas cloud in absence of star formation. All the simulations without SF have been run for 1 Gyr. Finally, we will also present one simulation in which the effects of star formation and stellar feedback will be included.

In Tab. 2, columns 9-11, we present a few global quantities computed from different simulations. The cloud half-mass radius $R_{c,hm}$ (column 9 of Tab. 2) is computed from the two-dimensional mass density profile of the cold (i.e. with temperature $T<20000$ K) gas. In each cell, the projected 2D density profile is computed in the $y$-$z$ plane and with respect to an origin placed at initial centre of the box. In all models but the Supersonic ones, initially the centre of the cloud coincides with the centre of the box. In the Supersonic models, initially the cloud is at $x=-10$ kpc, $y=0$ and $z=0$. This choice is done in order to delay the leakage of gas from the boundaries lying in the back of the cloud, which will occur at earlier times in case of supersonic velocity.

In column 10 of Tab. 2 we report the estimated line width $σ_l$. This quantity was computed from the 1D density-weighted velocity dispersion of the cold gas

$$σ^{2}_{l,1D} = \frac{1}{3} \sum \rho \left[ (v_x - \bar{v}_x)^2 + (v_y - \bar{v}_y)^2 + (v_z - \bar{v}_z)^2 \right]$$

(e. g., Shetty et al. 2010), where $\rho$, $v_x$, $v_y$ and $v_z$ are the density, the $x$-, $y$- and $z$-component of the velocity of the cold gas in a cell, respectively, whereas $\bar{v}_x$, $\bar{v}_y$ and $\bar{v}_z$ are the average $x$-, $y$- and $z$-component velocity values, respectively.

Besides $σ^{2}_{l,1D}$, the observed line width will include also a contribution from the sound speed $c_s$:

$$σ^{2}_{l} = σ^{2}_{l,1D} + c^{2}_{s}$$

The minimum temperature value adopted in this work is $5000$ K, hence the sound speed in the cold gas as defined here will range between $8$ km s$^{-1}$ and $16$ km s$^{-1}$. This implies that, for the temperature range considered here, $σ_l$ will always be higher than the observed line width, for which we consider the value of $σ_{HII} = 9$ km/s reported in Tab. 1 and which is very likely to trace gas with $T<5000$ K and lower sound speed. For these reasons, in Tab. 2 for the line width we provide upper limit values computed assuming in Eq. 2 $c_s = 16$ km s$^{-1}$, which correspond to the maximum temperature value in our definition of cold gas, i.e. $T=20000$ K.

Finally, in the last column of Tab. 2 we report the average star formation value for the simulations that include star formation and feedback. All the quantities presented in columns 9-11 have been computed from the results of the runs obtained at epochs between 0.25 Gyr and 1 Gyr.

### 2.2 Cooling and heating

Radiative cooling of the gas is computed assuming photoionization equilibrium as a function of temperature for different values of the gas density and metallicity. The cooling function implemented in RAMSES takes into account H, He and metal cooling (see Few et al. 2014). At the beginning of our simulations the metallicities of the cloud and of the ICM are uniform, but during the evolution of the systems metals are advected, and can also be newly produced if new stars are born. At each timestep and in each cell the metallicity value is stored and continuously updated into a passive tracer, which is used by the radiative cooling routine to take into account the evolution of the metal content of the gas.

The contribution from metals is accounted for by means of a fit of the difference between the cooling rates calculated at solar metallicity and those at zero metallicity using the photoionization code CLOUDY (Ferland et al. 1998). The temperature threshold for radiative cooling adopted in this work is $5000$ K, i. e. anywhere in the volume the gas is not allowed to cool down to a temperature below this value. The aim of this choice is to model a two-phase medium, consisting of a neutral one, representing the coldest regions of the cloud, and an ionised one which includes the ICM and the gas continuously exchanged between the cloud and the external medium.

In our simulations, we do not take into account thermal conduction. The effects of a uniform ultraviolet (UV) background are also taken into account. The RAMSES cooling routine includes...
functional fits for the photo-heating and photoionisation rates of the Haardt & Madau (1996) ionizing background spectrum, as formulated in Theuns et al. (1998). Besides radiative cooling and heating from a UV background, in our star formation simulation we also include stellar feedback as further heating source (see Sect. 3.2.1).

2.3 Star formation and stellar feedback

The star formation (SF) model used in this work relies mostly upon the native RAMSES implementation, which is described in detail in Rasera & Teyssier 2006. In each cell where the flow is converging, we assume that the gas with temperature $T < 2 \times 10^4$ K can form one star particle. In each cell where these criteria are met, the gas, characterised by density $\rho$, can be converted into star particles with density $\rho_*$ according to:

$$\dot{\rho}_* = \frac{\rho}{t_\star},$$

i.e. according to the Schmidt (1959) law.

The star formation timescale $t_\star$ is proportional to the local free-fall time $t_{ff}$, and computed as

$$t_\star = t_{ff}/\epsilon_{ff},$$

where $t_{ff} = \sqrt{3 \pi/32 G \rho}$ and $\epsilon_{ff}$ is the star formation efficiency per free-fall time. As described later in Sect. 3, various values for $\epsilon_{ff}$ have been tested in lower resolution simulations, in order to account for some observational features of SECCO 1.

For purposes of numerical stability, the code allows that no more that 90% of the gas in a cell can be used for star formation. Star particles are spawned stochastically as detailed below. The mass of each collisionless stellar particle is $M_p = N \ m_0$, where $m_0 = 25 \ M_\odot$ is the minimum particle mass and $N$ is determined by sampling from a Poisson distribution, characterised by a probability $P$ given by

$$P(N) = \frac{\lambda P}{N!} \exp(-\lambda P),$$

where the mean value is calculated as:

$$\lambda P = \left( \frac{\rho \Delta x^3}{m_0} \right) \frac{\Delta t}{t_\star}.$$

In this equation $\Delta t$ represents the timestep, whereas $\Delta x$ is the cell size.

The formation of single stars cannot be resolved in our simulations, hence one star particle is meant to describe a stellar association or a group of stars. The collisionless star particles are placed at the centre of their parent cell, with a velocity equal to the local fluid velocity. The corresponding mass, momentum, energy and density are conservatively removed from the ones of the parent cell. Once formed, star particles are allowed to move as an N-Body particles in the gravitational potential of the system, which is computed from its total mass. Each star particle can inject energy, mass and metals into the surrounding gas. Once born, each particle immediately deposits in the cell an amount of mass equal to $\eta \ M_p$, with $\eta = 0.1$, and an amount of energy

$$E_p = \frac{\eta \ M_p}{10 \ M_\odot} \times 10^{51} \text{erg},$$

as well as a mass of metals which can be computed directly from its initial mass and the metallicity of the gas out of which it has originated. The ejection of $\sim 10\%$ of the initial mass of stellar particles is expected if each of them represents a simple stellar population with a standard (e. g., Salaro 1955 or Kroupa 2001) initial mass function, and if each massive star (i.e. the stars with mass $M > 8 \ M_\odot$) ejects most of its mass during its lifetime, leaving behind a remnant of a few solar masses. In the case in which SF and feedback have been taken into account, the simulation has been terminated at 2 Gyr.

3 RESULTS

The origin of SECCO 1 and, in particular, the candidate parent galaxies have been thoroughly discussed in B18. In all the considered cases, a travel time $\sim 1$ Gyr through the Virgo ICM is required for SECCO 1 to reach its current position. Based on this argument, as in B18, most simulations are run for at least 1 Gyr, to study if the system can have retained its cold gas and survived within this environment for such a long time.

The stability of the gas cloud and the general behaviour of the system is studied at various evolutionary epochs by means of various diagnostics, i.e. two-dimensional density and temperature maps, radial profiles for density, temperature and pressure and three-dimensional gas distribution. All the profiles discussed in this section are computed by assuming an origin placed at the centre of the computational box. The temporal checkpoints for our analysis are 0.25, 0.5, 0.75 and 1 Gyr, which are the epochs at which the features of the systems are studied and discussed.

3.1 Hydrodynamical Evolution of the gas cloud

Figures 2 and 3 show two-dimensional density and temperature maps, respectively, computed at four different evolutionary times for four of the models described in Sect. 2. The models we consider in this section are the ’Standard’ one (in which the initial parameters are the same as the ones of B18), the T1E7K, the Supersonic and the Gravity ones, i.e. all the models in which star formation and stellar feedback within the cloud are not taken into account. Each map represents a section of the computational domain in the x-y plane; the maps have been calculated by selecting all the grids crossed by a plane centered at the middle of the computational volume and perpendicular to the z-axis. In all the cases shown in Figures 2 and 3, the evolution of the system is mostly driven by the different degrees of compression attained in various cases, and by the growth of Kelvin-Helmholtz instabilities. To complement our description of the physical properties of the cloud in these four cases as visible from the 2D maps, for each one of them we also show the 3D volume-rendering maps (see Pomarède, et al. 2008) of the gas density at different times (Fig. 4) and the evolution of the density, pressure and temperature profiles (Fig. 5).

3.1.1 The Standard model

The first columns from the left of Figures 2 and 3 show the time evolution of the density and temperature, respectively, of the cold gas cloud in the x-y plane in the case of
Figure 2. Two-dimensional gas density maps in the x-y plane in our simulations at various time steps for the Standard (first column), T1E7K (second column), supersonic (third column) and gravity (fourth column) simulations. In each column, the first, second, third and fourth row describe the model at 250 Myr, 500 Myr, 750 Myr and 1 Gyr, respectively.

the Standard model, for which the initial setup is the same of the 3D simulation set described in B18.

As in the 3D model of B18, even if an overall stability of the cloud was found across a time interval of 0.25 Gyr, already at this time the cloud presents a shape significantly different than the initial, spherical one, visible from various aspects. First of all, a compression in the back of the cloud causes a flattening of its rightmost edge and a central overdensity, as visible also from the density profile in Fig. 5.

The shape of the cloud also changes significantly because of the Kelvin-Helmholtz or shear instabilities, which are caused by the velocity difference between the cloud and incoming fast hot intra-cluster gas. Symmetric, tiny filaments are visible at the upper and lower edges of the cloud and at the extremes of its back. As visible from the temperature map (Fig. 3), such filaments are surrounded by gas layers which have intermediate temperature between the gas cloud and the ICM.

The velocity field (gray arrows in Fig. 3) shows that at large distances from the centre the motion of the incoming gas is weakly perturbed by the presence of the cloud, with nearly parallel arrows in the leftmost side of the plot and at y-distances > 10 kpc. On the left side of the temperature map (i.e. at negative values of the x-coordinate), the arrows are tilted by the rise of a few parcel of unstable cold gas, which from the cloud protrude outwards. In proximity of the cloud, the inclination of the arrows is gradually increasing along the y-axis, to become parallel to the y-axis at Y∼ 10 kpc. Moreover, downstream of the cloud some of the hot gas presents an inverted velocity field with respect to the overall flow. This feature is visible from the inclination of the filaments, which increases progressively as one moves towards higher values of both the x- and y- coordinates, to become parallel to the x-axis at |Y| ∼ 9 kpc. At the same value of the y-coordinate and at X ∼ 10, the instability curls up and some of the gas moves parallel to the flow but in opposite direction, which explains the negative x-component of the velocity. The curling-up of the extended unstable wings far from the cloud is barely visible in the maps also because of the AMR, which uses low resolution at large distances from the cloud centre (where the density contrast is not significant), but more curled-up extended filaments and smaller rippled structures are visible in other maps (e.g. in the temperature map of the T1E7K and supersonic models at 0.75 and 1 Gyr).

After 0.5 Gyr, the cloud has significantly expanded, the ripples which were barely visible at earlier times are now much more prominent in both the front and rear profile and distributed in a symmetric fashion with respect to the x-axis. The two overdense bent filaments at the two upper and lower sides have grown considerably, and now extend up to the rightmost edge of the 2D maps. The velocity field reveals a complex pattern, with parcels of cold gas which, from front of the cloud, expand forward and with an inverse velocity with respect to the bulk flow of the ICM.

A more elongated shape of the cloud is also visible in the 3D map, which shows that the rear part has undergone more
The results described in this section have shown how a timescale of $\sim0.5$ Gyr is enough for a system such as SECCO 1, to evolve from an initial spherical shape (as assumed here) to an umbrella-like or jellyfish-like shape. In the Standard model, the cloud has typical size (as measured by its half-mass radius $R_{c,HM}$ in Tab. 2) between 3.3 and 6.4 kpc, where in general lower values are found at earlier times, and line with $\sigma_1 < 20.8$ km/s, which corresponds to a maximum 1D velocity dispersion $\sigma_{1D} = 4.8$ km/s.

### 3.1.2 The effects of different initial conditions on the evolution of the cloud

Some of the values assumed for a few fundamental initial parameters of the SECCO 1 Standard simulation are clearly uncertain. For instance, the temperature assumed for the external medium is of $\sim 5 \times 10^6$ K, but considering the temperature profile of the Virgo cluster (Urban et al. 2011) and that SECCO 1 could lie at a distance of $\sim 1.1$ Mpc from the centre of the cluster, in principle the ICM temperature could also be higher, of the order of $10^7$ K. Moreover, in B18 a velocity of 200 km/s was assumed from the estimated projected value. It may be interesting to study the effects of a larger velocity, and in particular of a supersonic motion, on its stability. Also gravity could influence its evolution, in particular by increasing its stability against the development of filamentary structures or instabilities. In this
Figure 4. Three-dimensional gas density distribution in our simulations at various time steps for the Standard (first column), T1E7K (second column), supersonic (third column) and gravity (fourth column) simulations. In each column, the first, second, third and fourth row describe the model at 250 Myr, 500 Myr, 750 Myr and 1 Gyr, respectively. The assumed rotation angle with respect to the x- and y-axis is of 30 degrees.

### Effects of a larger ICM temperature value
The second columns from the left of Figures 2 and 3 show the time evolution of the x-y density and temperature maps, respectively, of the gas cloud when a larger temperature value of $10^7$ K is assumed for the Virgo ICM gas. In this case, at the beginning of the simulation the cloud is in a state of quasi-equilibrium of pressure with the ICM (blue thick dashed lines in the second row of Fig. 4). At early times, the cloud appears much more compressed than in the Standard model. This is clearly visible from its size at 0.25 Gyr as shown in the density map. In the innermost regions, the density profile is not much different than the one of the Standard model (solid lines in the second row from top in Fig. 5), but in this case it is truncated at $R \sim 5$ kpc, whereas with lower ICM temperature it decreases more slowly up to $R \sim 10$ kpc. Despite the different aspect, the instabilities at the edges of the cloud are still visible also in the case of a larger ICM temperature.

From the pressure profile, we can see how 0.25 Gyr of evolution are enough for the cloud to move out of equilibrium of pressure with the ICM.

The stronger compression of the cloud with respect to the Standard model is more visible at 0.5 Gyr. At this time, both the density and pressure in the cloud have increased with respect to the previous epoch (dashed lines in Fig. 5), at variance with the Standard model in which these two quantities generally decrease at later epochs. Several filaments behind
the cloud are visible in the 3D rendered map in Fig. 4, as well as in Fig. 3.

At a later time (0.75 Gyr), the x-y cross-section of the cloud is considerably denser and thinner than the one of the Standard model (and the thinnest of all the cases considered here). Due to the strong compression in all directions, the 3D structure of the cloud appears considerably flat (Fig. 4).

A thinner x-y cross section with respect to the Standard model and a flat shape of the cloud is visible also later at 1 Gyr, although significant expansion has occurred at this stage. At variance with the Standard model, one striking feature of the system emerging from the pressure profile is that,
after 1 Gyr, it has not reached pressure equilibrium with the external environment. Although the pressure profile increases smoothly outwards, the pressure value in the central regions of the cloud is by a factor $\sim 3$ lower than the one of the ICM.

Fig. 7 shows the time evolution of the cold gas fraction in the cloud in the Standard model and in the other cases discussed here. As in B18, the cold gas fraction has been computed considering the gas with temperature $< 20000$ K. At a given time, the gas fraction is the ratio between the total mass of gas with temperature below such value, divided by the initial mass of cold gas, i.e. by the initial mass of the cloud. Overall, the assumption of a high temperature in the ICM causes the system to retain larger fractions of cold gas with respect to the Standard model. This occurs as a higher ICM pressure causes a stronger contraction of the cloud, hence higher gas density and consequently a higher cooling rate, which on the long term evolution of the cloud facilitates the retention of the cold gas. Assuming a larger ICM temperature affects also the size of the cloud, with maximum values of its half-mass radius of 4.2 kpc (Tab.2).

i. Effects of a higher relative velocity. In the case of a supersonic relative velocity between the cloud and the ICM, initially the cloud has been placed closer to the leftmost boundary than in the Standard case. The reason is that with a larger speed, the cloud undergoes a significantly larger expansion along the direction of motion. Had not we adopted such an initial position, a considerable fraction of the cold gas would have leaked out of the computational box after $\sim 0.5$ Gyr$^2$. A slightly larger expansion of the back of the cloud and a larger curvature of its front profile with respect to the previous models is visible at 0.25 Gyr in the case of the Supersonic model in Figures 2 and 3 (third column from left), as also the presence of a bow shock upstream the cloud. In Fig. 3, we can appreciate that the velocity field of the ICM gas behind the cloud but in proximity (i.e. within a few kpc) of its upper and lower edges appears less distorted than in the Standard model. The two main ripples at the upper and lower edges are now less developed. The 2D density map and the 3D map (third column from left in Fig. 4) emphasise the strong compression occurring at the front of the cloud in the supersonic model.

At 0.5 Gyr, the cloud is still characterised by a central density comparable to the initial one but by a larger pressure (third row from top in Fig. 5). A striking feature is the strong growth of two filaments in the back of the cloud as visible in the x-y density map. At a later time (0.75 Gyr), the cold filaments have curled up, their extent has reached the right boundary and they appear significantly less expanded along the y-axis than in the Standard model. The top of the cloud is still highly dense. The high velocity causes the baricenter of the cloud to shift along the x-axis and towards right.

At 1 Gyr, the elongated filaments have moved out of the computational box and the front of the cloud has expanded. The overall expansion of the cloud as traced by its 3D map is smaller than the one of the previous two models. The pressure profile gently decreases from the central regions of the cloud to the outermost regions of the computational volume.

Fig. 7 evidences that even in the supersonic case, the decrease of the cold gas fraction as a function of time is lower than in the Standard model, and the general behaviour of this quantity is similar to the one of the T1E7K model. One conclusion of our study is that both a large ICM temperature and a large velocity of the cloud help increasing its capability to retain its initial cold gas reservoir across a 1 Gyr period. The sharp decrease of the cold gas fraction of the Supersonic model at $\sim 0.9$ Gyr is partly due to effective loss of cold gas from the simulation volume, as we have seen that at this time its cold filaments have already reached one of the boundaries and some of the cold gas is leaking out of the box. The assumption of a supersonic motion affects the size of the cloud as derived from its 2D profile in a plane perpendicular to the x-axis, with maximum values of its half-mass radius of 4.4 kpc, i.e. lower than in the Standard model, and causes line width values larger than in the Standard case, $\sigma < 22.6$ km/s, corresponding to maximum $\sigma_{1D} = 6.6$ km/s.

In principle, the assumption of a velocity $> 400$ km/s will lead to a faster cloud crushing. In adiabatic conditions, this can be understood by considering that the cloud crushing timescale scales with the inverse of the relative velocity between the hot medium and the cloud (Klein et al. 1994). In a non-star forming cloud, radiative cooling can delay this disruption by a few cloud crushing timescales, but not prevent it (Scannapieco & Brüggen 2015 and references therein).

The effects of supersonic motion on a star-forming cloud will be discussed later in Sect. 3.2.3.

iii. Effects of the self-gravity of the cloud. In the simulations presented in B18 and run to assess the stability of the cloud during its motion, the self-gravity was neglected. The reason was the low density of the cloud which, as discussed in B18, implies that the system is unbound, stable against collapse and pressure-confined by the external medium. As mentioned in B18, the global effect expected by gravity on the cloud is to limit the growth of hydrodynamical instabilities (see also Murray et al. 1993).

To directly assess the role of gravity in the evolution of SECCO 1, we run one simulation with same initial conditions as in the Standard Model but also taking into account the self-gravity of the gas.

In presence of gravity, the two-dimensional density map indicates that at 0.25 Gyr the central density of the cloud is larger than the one of the Standard model. The cloud also appears slightly more compressed than in the Standard model. An increased central density at this time is indicated also by the density profile shown in Fig. 5. At this time, the 3D map computed for this model is barely distinguishable from the one of the Standard model.

At 0.5 Gyr the front profile of the cloud appears considerably smoother than the one of the Standard model. A few instabilities which cause symmetric ripples on the front surface are absent, whereas the two symmetric filaments lying behind the cloud and which extend backwards are still present, with an aspect and size very similar to the one of the Standard model. Also in presence of gravity the cloud has expanded by an amount similar to our Standard simulation, which further supports the argument that gravity does not play a dominant role in its large-scale evolution.

At 0.75 Gyr, the prominent, curled up instabilities present on
the front of the cloud in the Standard model are now absent, but the filaments on the back have reached out to the boundary. Also the 3D figure shows that the front surface is overall smoother than the one of the Standard model, but also that the back instabilities do not seem to be underdeveloped. At 1 Gyr the only frontal instability which has grown is the bar at the centre of the cloud. A sharp structure at the cloud front is evidenced also by the 3D map. The cloud is in pressure equilibrium with the ICM.

Fig. 7 shows how globally, gravity helps further in retaining the cold gas at all times, with differences in the gas fraction with respect to the Standard model which are less than 10%. One conclusion of our study is that gravity hinders the development of small-scale instabilities all over the surface of the cloud, in particular on its front, but it does not prevent the growth of large scale instabilities such as the elongated filament along its trail. The addition of self-gravity causes smaller cloud size values than in the Standard model, with $R_{c,HM}$ between 2.7 kpc and 5.8 kpc.

### 3.2 The effects of star formation and feedback

#### 3.2.1 Star formation history

As described in Sect. 2, in simulations which include star formation, the star formation timescale $t_s$ represents an unknown quantity. To assess the role of this quantity in shaping the properties of SECCO 1, we have run a set of star formation simulations with spatial resolution of $\sim$150 pc (corresponding to maximum refinement level = 8), taking also into account stellar feedback, in which we considered three initial values for the SF timescale: 0.4 Gyr, 1 Gyr and 40 Gyr.

The constraints we considered for our models were the observed stellar mass, the gas mass and the star formation rate (SFR) value, compared to the values of the models at 1 Gyr, regarded as a reference value for SECCO 1’s age, i.e. the time spent in-flight once departed from its parent galaxy, clearly with the knowledge that this value is uncertain.

At this time, it was impossible to reproduce at the same time these three constraints. We came to this conclusion by noticing that with the largest SF timescale value (i.e. with the lowest SF efficiency), although the stellar mass and gas mass values were acceptable, the SFR at 1 Gyr was always lower than the observed one by one order of magnitude. On the other hand, the lowest SF timescale produces too a large stellar mass (of the order of $10^6 M_\odot$) in a short time. In the light of these results, we chose for the SF timescale the intermediate value of 1 Gyr. Once again, we stress that several unknown quantities may play an important role in our study, including the original gas mass and the current age of the system.

The peculiar nature of SECCO 1 is outlined by its unusual combination of isolation and recent star formation activity. We believe that the setup discussed in this section defines a realistic framework, surely more complete as for its physical ingredients, than the simulations of Sect. 3.1.2, to describe the motion of a star-forming, massive gas cloud in the hot ICM. It is important to bear in mind that the aim of the present simulations is to explore the evolution, and not the formation, of SECCO 1, and that to investigate how it was originated requires a much different setup, e.g. describing the motion of an entire galaxy through the ICM (Kapferer et al. 2009).

The value assumed for $t_s$ is to be regarded as a representative one, likely reliable as order-of-magnitude estimate. Figure 6 shows the star formation history of the cloud, computed with the prescriptions about SF and stellar feedback as described in Sect. 3.2.1. The two different curves are for simulations computed at different maximum spatial resolution values (76 pc and 152 pc), and are helpful to appreciate the convergence of our numerical test. Numerical convergence seems satisfactory, considering the notorious difficulty of achieving numerical convergence in AMR simulations (e.g., Calura et al. 2015 and references therein).

In our simulations, SF begins immediately and, through the whole history, it presents maximum SFR values at the earliest times, showing a monotonical decrease and a value at 1 Gyr which is very similar to the observed estimate. The total stellar mass at 1 Gyr is of $10^6 M_\odot$ and the cold gas mass is $4 \times 10^6 M_\odot$.

#### 3.2.2 Evolution of the gas and stellar component

In Figure 8 we show the effects of star formation and stellar feedback on the evolution of SECCO 1, as traced by 2D density maps, temperature maps and three-dimensional gas distribution computed at different times. At 250 Myr (top panels) the system still presents its symmetric shape, with the presence of Kelvin-Helmholtz instabilities already visible on its sides. Inside the gas cloud, several hot, rarefied and approximately circular regions are visible which are due to the effects of stellar feedback. SNe exploding in various regions of the cloud carve cavities, whose extent depends on the local conditions, in particular on the local density. SNe exploding in regions far-away from the centre generate larger cavities, whereas the local medium is strongly affected by the compression induced by the growth of the instabilities. This is in agreement with other grid-based studies of the local effects of stellar feedback in different environments, i.e. in globular clusters (Calura et al. 2015) and in dwarf spheroidal galaxies (Romano, et al. 2019).

The density inside the SN-driven bubbles is a few orders of magnitude lower than the one in the centre of the cloud, whereas the temperature is of the order of $10^6$ K, which is a typical value for the cavity generated by a SN explosion (e.g., Cioffi & Shull 1991). Although the global profile of the gas cloud is similar to the one of the Standard model (Fig. 2), in this case it presents a larger amount of small scale distortions. A few SN-driven cavities are visible along both the front and rear profile of the cloud. In front of such cavities, chimneys of hot gas extending towards the left and right boundaries are visible in the temperature map. These features are made of parcels of hot gas moving away from the cloud and, once again, are the product of SN explosions, which clearly represent an additional mechanism though which the initially cold gas is heated and can leave the cloud. A confined stellar component is already visible, completely embedded in the cold gas. The velocity field, plotted in the temperature map, presents a pattern which at this time is not strikingly different than the one of the Standard model (Fig. 3). A more perturbed front profile of the cloud is visible also in the 3D map, which shows an irregular pattern of scattered overdensities, which are due to the
local accumulation of gas generated by the expansion of the
SN-driven bubbles and the multiple encounters of their dense
shells. At this epoch, the density, pressure and temperature
profiles (Fig. 9) of the model with SF+feedback are very
similar to the ones of the Standard model, confirming that,
on the largest scales, the effects of SF are negligible.
At t=500 Myr, significant differences with respect to the
Standard case are already visible in the 2D density and tem-
perature maps of Fig. 8, in particular in the fact that they
both appear asymmetric. This is visible for instance from the
extent of the two instabilities on the front of the cloud and at
its centre, with the lower one (i.e. the one at negative Y val-
ues) which is more structured, developed and curled than the
upper one, i.e. at positive X-values. Other signs of asymmetry
are in the different extent of the instabilities at the sides of
the cloud as well as along the rear profile. These asymmetries
are due to inhomogeneous SN explosions, occurring in sparse
locations within the cloud. Multiple SN explosions have sensi-
tible effects also on the shape of the large cavity at the centre
of the cloud. At this time, such cavity is globally bell-shaped,
but it is considerably regular in the Standard and ‘gravity’
cases (Fig. 2 and 3), with limited extension along the x-axis,
whereas in the SF+feedback simulation it appears distorted and
slightly more extended along the x-axis. Moreover, the
density contrast between the inner cavity and its edges is
larger in the SF+feedback case than in the Standard. SN ex-
plosions are visible only along the outer shell, as the gas flow
in the inner parts is globally divergent (see the velocity field
plotted in Fig. 3), hence the conditions for SF (and sub-
sequent SN explosion) are not satisfied. The 3D map shows
that the rear of the gas cloud presents more developed fila-
ments than in the Standard case. Once again, each SN explo-
sion occurring in various position along the edge of the cloud
pushes the gas in different directions, including outwards of
the cloud, thus enhancing the growth of the instabilities, such
as the filaments in the back. At this time, the stellar com-
ponent is more compact than at the previous time, as visible
from the density profile of Fig. 9, steeper than the one com-
puted at 250 Myr.
After 750 Myr, the cloud has undergone considerable evo-
lution, in particular its x-y cross-section has considerably
reduced. After having expanded, the central regions of the
cloud have now re-contraction. At this time, its asymmetric
shape is particularly marked, with a visibly different aspect
of the two longest filaments in its back. The combined effects
of the gravity of the stars and of the compression of the cloud
in its centre as due to stellar feedback have a strong influence
on the properties of the cloud. Its central density presents a
value considerably higher (nearly by a factor 10) than the one
of the Standard case (see Fig. 9), whereas its strong central
compression is outlined by the pressure profile. At this time,
the central gas density is still of the same order of magnitude
of the average density of the real system. In the x-y plane,
a few hot cavities generated by SNe are still visible, which
have exploded in a very narrow region of the cloud, and with
small sizes due to the average high density. The spatial extent

Figure 6. Star formation history of our Standard and Supersonic simulations. As for the Standard model, the black thick solid line is the
SFH computed in our maximum resolution simulation, whereas the thin dashed line has been computed at lower resolution. The thick
solid cyan line is the SFH of the Supersonic simulation at maximum resolution. In the latter case, the simulation has been stopped at 1
Gyr.
of the stellar component is not much different from the one seen at the previous time. However, among the times considered for our plots of Fig. 9, this is the one at which the average stellar density is the largest, a factor of ~ 8 lower than the one of the gas, and remarkably comparable to the central gas density in the Standard case at the same epoch. After 1 Gyr, the gas cloud has undergone significant disruption. This is visible from its scattered aspect in the density and temperature maps, and from its density profile, which in the centre is considerably lower than at the previous time, and also an order of magnitude lower than in the Standard case. This proves that although self-regulated star formation have caused a contraction of the cloud at previous times, on a timescale of 1 Gyr the gas cloud is dispersing under its effects. The pressure profile shows that also in this case, large-scale pressure equilibrium has been reached at this time. At this time the scattered, partially disrupted aspect of the cloud is probably more similar to the one of the real system. In our simulation, star formation is still present and SNe are still exploding, but the stellar component has undergone considerable expansion with respect to the previous time, with a factor 10 decrease in the central density value. The scattered stellar component visible in the density map underlines its disgregation, as a result of the disruption of the gas cloud. The presence of star formation and stellar feedback does not seem to affect large-scale properties of the gas cloud, such as its half-mass radius and velocity linewidth, with values similar to the ones calculated in the Standard simulation without star formation (Table 2). On the other hand, in the Standard simulation with SF, the evolution of the cold gas fraction is considerably different than the one presented by all the other cases, with a much stronger decrease but with 50% still present inside the computational volume after 1 Gyr (Fig. 7). A fraction of the order of 10% of the gas initially present inside the box has leaked out. Such fraction is increasing with time and at 2 Gyr, 80% of the initial amount of gas has abandoned the simulated box. This prevents us to make quantitative predictions on the physical properties of SECCO 1 at times larger than 1 Gyr, however, our study indicates that at this time SECCO 1 is expanding, hence its likely final fate is to be completely disrupted and disperse in several pieces.

### 3.2.3 Supersonic simulation with star formation

In Sect. 3.1.2 we have tested the effects of a supersonic motion on the hydrodynamic evolution of the cloud in a simulation without star formation. In this section, we investigate the effects of a supersonic velocity in a more realistic case, i.e. in presence of star formation and stellar feedback. The results are shown in Fig. 10, where we present 2D density and temperature maps and 3D rendered images of the density profile computed at various times. Also in this case, initially the cloud has been placed closer to the left boundary than in the Standard simulation, in order to reduce the early leakage of gas from the rightmost boundary. The density maps computed at 250 Myr show the bow shock already seen in Fig. 1 and 2, which is a typical signature of a supersonic motion. The back of the cloud is stretched along the x-axis and the extent of the rear filaments is visibly larger than in the Standard model. Also in this case star formation...
sets in immediately and the supersonic motion causes a high contraction of the cloud, which produces a compact stellar component, highlighted by the orange contour in the top-left panel of Fig. 10. Hot cavities are visible scattered around the cloud as the result of multiple SN explosions, with a visible concentration at the centre of the cloud, where the gas is particularly dense.

At 500 Myr the stars occupy a small region on the head of the cloud, whereas the filamentary tail is stretched out to the boundary. At 750 Myr the gas is decoupled from the stars, with a distance between the compact stellar component and the most prominent filaments lying on the head of the cloud of a few kpc. Such separation grows at later times, to reach a value of $\sim 20$ kpc at 1 Gyr. At this epoch, some stars are still forming at the head of the cloud. The remainder of the cloud lies close to the right boundary, and a significant fraction of its initial mass is leaking out of the box; this is the reason why this simulation was terminated at 1 Gyr. Overall, the supersonic, star forming simulation is characterised by higher star formation rate with respect to the Standard model. Such enhancement in the star formation rate with is visible in Fig. 6, where the star formation history of the Standard and Supersonic simulations are compared.

As in the Standard simulation, the presence of stellar feedback does not affect much the line width and size of the cloud (see Tab. 2), whereas the evolution of the cold gas fraction is very similar to the one computed in the Standard model discussed in Sect. 3.2.1.

### 3.3 Comparing the simulated stellar system with observations

Are the observed properties of SECCO 1 compatible with those of the ensemble of stars of our simulation with SF at the end of the simulation? To try to answer this question we took the $t=1$ Gyr snapshot of the stars in the SF simulation and we attached to each particle a value of the luminosity appropriate for its age, interpolating on the theoretical model of a Simple Stella Population (SSP) with Z=0.008, from the BASTI dataset (Pietrinferni et al. 2004)$^3$.

Then we computed several quantities that may be useful for the comparison with the observed system, like, for example, the velocity dispersion, the half-mass radius (computed, for each particle age slice, with respect to the median values of the three spatial coordinates), the surface brightness within the half-mass radius, etc., for the entire synthetic sample and for remarkable age slices. For instance, the most appropriate subsample to compare with SECCO 1 is the age slice 0.0 Myr $\leq$ Age $\leq$ 50 Myr, since all the observed stars of the real system lie in this age range (Sand et al. 2017; B18). Another useful quantity we computed is the virial ratio $\alpha_{\text{vir}}$, that, for a spherically symmetric stellar system$^4$ with isotropic velocity distribution we define as

$$\alpha_{\text{vir}} = 2.32 \times 10^5 \left( \frac{3\sigma^2 R_{hm}}{M} \right)$$

where $\sigma$ is the velocity dispersion in one direction (in real life along the line-of-sight) in km s$^{-1}$, $R_{hm}$ is the 3D half-mass radius in kpc, and M is the mass in solar masses. According to the Virial Theorem an idealised system like that envisaged above, if gravitationally bound and in virial equilibrium should have $\alpha_{\text{vir}} \sim 1.0$. In practice, given all the involved assumptions and the uncertainties, as a general criteria we can consider a system as gravitationally bound if $\alpha_{\text{vir}} \lesssim 1.0$ and unbound if $\alpha_{\text{vir}} \gg 1.0$. As a sanity check we used the new dataset for Galactic Globular Clusters (GCs) by H. Baumgardt and collaborators$^5$ (see, Baumgardt et al. 2019, Hilker et al. 2020, and references therein) to compute $\alpha_{\text{vir}}$ for 152 clusters for which both the 3D half mass radius and the 2D half-light radius ($R_h$: the observable that is typically available in most cases) are provided. The median $\alpha_{\text{vir}}$ of this sample is 0.63, with semi-interquartile intervals as small as $\pm 0.05$. There is only one cluster with $\alpha_{\text{vir}} > 1.0$, i.e. the remote and anomalous cluster NGC 2419 (Ibata et al. 2011, Mucciarelli et al. 2012), having $\alpha_{\text{vir}} = 1.67$. The observed mean $R_{hm}/R_h$ for the Galactic GCs is $\sim 1.5$. Adopting this calibration we can obtain a version of Eq. 8 as a function of $R_h$, instead of $R_{hm}$ just by replacing the constant 3.0 with $3.0 \times 1.5 = 4.5$, assuming that mass approximately follows light in systems where the contribution of dark matter to the potential should be negligible or null, like GCs or the star forming clouds considered here.

The entire set of simulated stars in the considered snapshot has $\alpha_{\text{vir}} = 103$, hence it is clearly unbound, albeit the contribution of the cold gas to the potential may help the system to hold their stars stronger than what measured by the stellar $\alpha_{\text{vir}}$. In this context it is important to note that $\alpha_{\text{vir}}$ is driven to values as low as $\approx 100$ by the oldest stars, that at the end of the simulation have left most of the gas distribution to lag behind (see Fig. 8, lower right panel). The stars with 900 Myr $< \text{Age} \leq 1$ Gyr have $\alpha_{\text{vir}} = 69.3$ while those with 0 Myr $< \text{Age} \leq 50$ Myr have $\alpha_{\text{vir}} = 2712$.

In Fig. 11 we show the distribution of the stellar particles at the end of the simulation in the x,y plane that we take as the plane of the sky, for convenience, while the z direction, consequently, is considered as approximately aligned with the hypothetic line of sight (in computing $\alpha_{\text{vir}}$ we adopt $\sigma = \sigma_z$). The particles are color coded according to their age (left panel) and to their velocity in the direction of the mean motion of the cloud (x; right panel). A few density contours illustrate the position and the morphology of the density peak of the overall structure. It is interesting to note that a significant fraction of the oldest stars maintain a relatively compact and symmetric configuration, reminiscent of the spherical symmetry of the original cloud, while the others are diffused over a nearly spherical halo out to more than 10 kpc from the center of the system. Stars younger than $\approx 600$ Myr keep memory of the jellyfish shape of the cloud.

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$^3$ The quantity that is actually interpolated from the model is the V-band mass to light ratio in solar units, $M/L_V$. Multiplying the inverse of this number for the mass of the particle we obtain the V-band luminosity of each individual particle, according to its age.

$^4$ The formula for $\alpha_{\text{vir}}$ we used in B18 is appropriate for gas clouds.

$^5$ people.smp.uq.edu.au/HolgerBaumgardt/globular/parameter.html
at the epoch of their birth, and finally the youngest stars traces the dense gas filaments of the legs of the jellyfish at the end of the simulation. The mean motion in the directions perpendicular to the systemic motion (Y and Z) is an overall expansion, following the axial expansion of the umbrella and the legs of the jellyfish. When integrated, for instance along the Z direction, this motion appears as non ordered, since in any given direction one sees approximately the same number of stars approaching and receding from us, once the systemic motion is subtracted. Note that the velocity dispersions ranges from $\simeq 3 \text{ km s}^{-1}$ to $\simeq 8 \text{ km s}^{-1}$ depending on the age slice and the direction considered (the gradient shown in Fig. 11 makes the dispersion in the X direction larger than that in Y and Z), corresponding to 3-8 kpc Gyr$^{-1}$.

Now, focusing on the comparison with SECCO 1 (main properties from Tab. 1 by B18), based on Fig. 11 and the quantities we computed for the various age slices, in particular the $0 \text{ Myr} < \text{Age} \leq 50 \text{ Myr}$ (“youngest” hereafter) and the $900 \text{ Myr} < \text{Age} \leq 1000 \text{ Myr}$ (“oldest” hereafter) slices, we can summarise our main conclusions as follows:

- The velocity dispersion ($\sigma_z = 4.4 \text{ km s}^{-1}$) and the half-mass radius ($r_{hm} = 4.3 \text{ kpc}$) of the youngest population are similar to those of SECCO 1. The amplitude of the velocity gradients along the direction of motion is compatible with that of the observed gradients (Beccari et al. 2017). In the simulation, the youngest stars form along the legs of the gaseous jellyfish, in filamentary structures similar to SECCO 1 as well as the other candidate SECCO 1-like systems identified by Sand et al. (2017).
The overall distribution of the simulated stars, on the other hand, seems quite different. Even when only the stars younger than 10 Myr are considered, they are distributed over a very large area, of the order of 20 kpc × 20 kpc, while the distance between the two pieces of SECCO 1 (main body and secondary body, see B18) is only 7.3 kpc, and B18 were able to find only one additional candidate H II region possibly associated to SECCO 1 over a surveyed circular area of radius = 20 kpc around the system.

The total luminosity of the youngest population is $4.4 \times 10^5 \, L_{\odot}$, that is ≈ 2.6 times smaller than the total luminosity of SECCO 1. Even rescaling the luminosity of the youngest population by this factor the average surface brightness within the 2D half-mass radius is $\mu_{V,e} = 30.5 \, \text{mag/arcsec}^2$, a factor of $\sim 4 - 12$ lower than what observed in SECCO 1 secondary body ($\mu_{V,e} = 28.9 \, \text{mag/arcsec}^2$) and main body ($\mu_{V,e} = 27.8 \, \text{mag/arcsec}^2$).

The SFR in the last 50 Myr of the simulation is $0.6 \times 10^{-3} \, M_{\odot} \, \text{yr}^{-1}$ in excellent agreement with the current SFR measured in SECCO 1.

As said, the oldest stars are able to preserve a spheroidal morphology, and display the smallest size ($r_{hm} = 2.1 \, \text{kpc}$), the lowest velocity dispersion ($\sigma_z = 4.4 \, \text{km} \, \text{s}^{-1}$), and the brightest average surface brightness ($\mu_{V,e} = 29.7 \, \text{mag/arcsec}^2$) of any other age slice of the final snapshot of the simulation. On the other hand, for a combination of the spatial diffusion and of the behaviour of $M/L_V$ with age, the intermediate-age slices are those with the faintest surface brightness (e.g., $\mu_{V,e} = 33.5 \, \text{mag/arcsec}^2$ for the slice 450 Myr < Age ≤ 550 Myr), hence they would be the hardest to detect observationally.

In the context emerging above, it is intriguing to note that there is a low-surface brightness (SB) dwarf spheroidal (dSph) in the vicinity of SECCO 1, at a projected distance compatible with that between the density peak of the oldest stars and the youngest stars of the simulation (Sand et al. 2017; B18). Much deeper observations than those currently available are required to verify if SECCO 1 and the nearby dSph are immersed into a wedge-shaped low-SB distribution of intermediate age stars as the one we see in the end state of our simulation.

3.4 Discussion and comparison with other results

So far, several theoretical studies have been dedicated to the evolution of ultra-diffuse systems with some of the features presented by SECCO 1 in various environments (e.g., Ploeckinger, et al. 2015; Taylor, Wünsch & Palouš 2018; Hausammann, Revaz & Jablonka 2019 and references therein, Silk 2019). However, there were not many previous attempts to model the evolution of isolated, diffuse, initially unbound objects with no dark matter content and with size and mass comparable to the ones of SECCO 1. In this Section, we discuss a few of such extant studies and, where possible, compare their results to ours.

By means of an analytic approach, Burkhart & Loeb (2016) discussed the possibility that starless, dark HI clumps might be supported by external pressure in the surrounding inter-cluster medium. From their surface density, they predicted...
that some of the HI dark clumps detected in the Virgo Cluster by the ALFALFA HI Arecibo survey might be on the cusp of forming stars. This conclusion was based on the fact that many systems were lying above the HI-H2 transition threshold density, which in principle might mark the threshold for star formation, estimated to be between 4 and 10 $M_\odot/pc^2$. The average surface density of SECCO 1 is well below such values (B18). The fact that SECCO 1 is forming new stars puts into question that a threshold value for star formation may really exist.

Past works have shown that the adoption of a density threshold of 100 cm$^{-3}$ was necessary to produce bulgeless dwarf galaxies in simulations (e.g., Governato et al. 2010; Pilkington et al. 2011). Since then, in a great multitude of paper star formation was modelled through the adoption of a density threshold criterion, sometimes with much lower values (0.1 cm$^{-3}$) and with resolution lower than the maximum resolution used here (e.g., Pilkington et al. 2012; Few et al. 2014). At the scales probed by our simulations (76 pc), most of the times the gas is compressed to density values lower than 0.1 cm$^{-3}$. In simulations where star formation occurs mostly in gravitationally bound regions, such density value can be reached easily on large scales, e.g. even a few hundred pc (e.g., Pilkington et al. 2011). We cannot exclude that at higher resolution larger density values could be reached, however another possibility is that, in an unbound system such as SECCO 1 where star formation is activated by external compression from an external, hot medium, it can occur at lower average density values than in typical star-forming galaxies.

Observationally, the spatial properties of local star form-
ing galaxies are studied by means of the Schmidt-Kennicutt (SK) relation (Schmidt 1959; Kennicutt 1998) between SFR and gas surface density in entire galaxies or in sub-galactic region. The resolved SK law (e.g. Kennicutt 1989; Martin & Kennicutt 2001) involves the gas and the SFR surface densities measured either in kpc- or sub kpc-scale regions or their radial profiles and shows a break of correlation in low density environments, such as dwarf galaxies and the outskirts of spirals (Kennicutt et al. 2007) which was interpreted as a drop in the star formation efficiency at a surface density threshold density of $\sim 10 \, M_\odot/pc^2$. By using a sample of local disc galaxies, from the study of the volume gas and SFR densities, Bacchini, et al. (2019a) showed that a single-slope, volumetric SK law is recovered down to a density value of $0.04 \, cm^{-3}$ at scales of a few $100 \, pc$. This implies that the break observed from the classic, two-dimensional SK law could due to a flaring effect which is common in disc galaxies (Elmegreen 2015; Bacchini, et al. 2019b), and argues against the existence of a star formation density threshold, at least down to a density value $< 0.1 \, cm^{-3}$, i.e. lower than the ones previously regarded as reference threshold values. To shed further light on this fundamental aspect, more studies are needed of the spatial star formation properties of low-density systems, of which SECCO 1 surely represents a prototype, perhaps of a peculiar subclass. Another interesting aspect concerns the presence of molecular gas as a necessary ingredient to ignite star formation (Krumholz 2012; Glover & Clark 2012; Bacchini, et al. 2019a). In a comprehensive study of the Schmidt-Kennicutt SF law in local galaxies, Bigiel, et al. (2008) evidenced a transition from HI-dominated SF galaxies to molecular-dominated ones at $9 \, M_\odot/pc^2$. SECCO 1’s gas reservoir is most likely dominated by HI, and it lies well below this density value. The existence of an extreme system such as SECCO 1 might be the proof that SF can occur and be sustained even in systems with no (or very little) molecular gas. In order to have a final proof and to have constraints on the molecular gas content, very deep infrared observations will be required. Regarding theoretical studies of the possible origin of systems like SECCO 1 and their star formation activity, Kapferer et al. (2009) performed smoothed-particle hydro-

dynamical simulations with radiative cooling, star formation and stellar feedback, of the effects of ram-pressure stripping of the motion of a large disc galaxy in a cluster environment. They have tested various values for the relative velocity of the galaxy and the ICM and for the density of the ICM. In general, they found that the effects of the ram-pressure is to strip several gas clouds, lying in extended wakes downstream of the parent galaxy. The gas stripped from the disc can reach distances of several hundreds kpc from the parent galaxy in a few hundred Myr. Star formation occurs at any time in the stripped gas clouds and some of these clouds, at any distance from the parent galaxy along the wake, may be still forming stars after 500 Myr, and hence they may host ionized cavities such as the HII regions observed in SECCO 1 and found in this study. Also in this study, the star-forming knots are generally associated with underlying older stellar populations.

4 CONCLUSIONS

In this work, we have presented a novel suite of 3D, high-resolution hydrodynamic simulations of the motion of a cold gas cloud throughout a background, uniform distribution of hot gas, representing the intra cluster medium (ICM) in Virgo. In our simulations, the cold gas cloud was assumed to be initially spherical and uniform. Our focus was to study its evolution after the cloud is already far away from its parent galaxy, not anymore subjected to the effects of any external gravitational field. The results presented in this work expand the study presented in B18 in which one simulation was run, with only one reference value for a few key parameters was adopted, i. e. an external ICM temperature of $5 \times 10^{6}$ K and a cloud speed of 200 km/s. In the present study, we have tested the effects of a hotter ICM (i. e. $T_{ICM} = 10^7$ K), of a larger relative speed ($v = 400$ km/s) between SECCO 1 and the ICM on the evolution of the system, and of the self gravity of the gas, which is expected to stabilise further the cloud against the development of hydrodynamic instabilities. To address all of these issues, first we have run a few hydro
simulation without taking into account star formation and stellar feedback, but including the effects of a hotter ICM, a larger cloud speed with respect to the 3D model presented in B18 (regarded as the Standard model), and finally one simulation with the same parameters as in B18 but including the self gravity of the gas. After such pure hydrodynamic, radiative runs, we have improved our model and considered star formation and stellar feedback to study their effects on the evolution of the gas cloud.

Our main results can be summarised as follows.

- We have deepened our study of our Standard simulation (with parameters same as in B18), presenting new 3D rendered images of the gas distribution at various evolutionary times. Our results have shown that a timescale of \( \sim 0.5 \) Gyr is enough for a system such as SECCO 1, to evolve from an initial spherical shape (as assumed here) to an umbrella-like or jellyfish-like shape. Our study of the evolution of density and pressure profiles have outlined an oscillating evolution of the central density value, and that pressure equilibrium with the external environment was reached already after 0.5 Gyr of evolution.

- With respect to the Standard model, a larger temperature value \((10^7 \text{ K})\) assumed for the ICM produced, at any time, a more compressed gas cloud. In the first 0.5 Gyr, the progressive increase of the inner density and pressure is stronger. The aspect of the instabilities at the edges of the cloud is different, in that they appear more elongated, spatially separated and curled with respect to the Standard case.

- In the case of a supersonic relative velocity between the cloud and the ICM, the cloud undergoes a strong compression at its front, and its stretching mostly occurs along the direction of motion, which in our reference frame is along the \( x \)-axis, whereas the expansion of its back is much more limited along the two \( y \)- and \( z \)-axis. Similar to the assumption of a large ICM temperature, the choice of large velocity of the cloud helps increasing its capability to retain its initial cold gas reservoir on long timescales, of the order of 1 Gyr.

- In our hydrodynamic simulation in which the self-gravity of the gas cloud was taken into account, on large scales and on a long timescale the properties of the cloud are very similar to the ones of the Standard model. This experiment was thus important to directly show that the role of gravity in the long-term evolution of the cloud and at the largest scales is negligible. Gravity does not prevent the growth of large scale instabilities, such as the elongated filament along its trail, but it hinders the development of small-scale instabilities, in particular on the front of the cloud.

- For each model, the cloud size and line width were computed, expressed by half-mass radius as obtained from the two-dimensional density profile and as the square root of the sum of squares of the 1D velocity dispersion and sound speed, respectively. Since the temperature floor assumed here is characterised by sound speed comparable to the observed line width, for the latter quantity only upper limits were calculated. All models show similar sizes, and supersonic models show upper limits on the line width higher than the subsonic ones.

- All the models which do not include star formation show a similar evolution of the cold gas fraction with time, and similar values after 1 Gyr. Final values range between 0.75 and \( \sim 0.8 \), consistent with the Standard model.

- In our simulation with star formation, SF begins immediately, it presents its maximum values at the earliest times and decreases monotonically with time. After 1 Gyr, the SFR value is comparable with the observed estimate, but the total stellar mass is of \( 10^6 \text{ } M_\odot \), larger than what observed in SECCO 1. The end state of the resulting (unbound) stellar system presents both differences as well as intriguing similarities with the observed structure. Throughout its entire evolution, due to inhomogeneous SN explosions, the appearance of the cloud is much more asymmetric than in the previous cases. The combined effects of the gravity of the stars and of the compression of the cloud in its centre due to stellar feedback have a strong influence on the properties of the cloud. Due to an enhanced compression of the gas in the outskirts, stellar feedback has the global effect of facilitating the development of instabilities. After 1 Gyr, 50% of the initial cold gas is still present in the box.

Also a supersonic, star forming model was presented. In the case of supersonic motion, star formation is enhanced with respect to the Standard case. Moreover, the spatial separation between the stellar component and the gas reaches values of several kpc already after 0.5 Gyr.

In summary, our simulations confirm that in a variety of plausible conditions, the survivability of SECCO 1 is granted on timescales of the order of several hundreds Myr. Although our simulations do not allow us to quantitatively address the evolution of SECCO 1 on a timescale larger than 1 Gyr (mostly because most of the gas leaks out of the volume), the most likely final fate of both the stellar and gas components is to expand further and to be dispersed in the Virgo cluster.

The James Webb Space Telescope will provide the first opportunity to test if the SF scenario and the distribution of stars envisaged in our simulations are (at least partially) similar to those of the real systems, as a significant part of them may lie buried below the sensitivity limits of the presently available observations.

In the future, it will also be important to investigate further on the formation of SECCO 1. A plausible hypothesis is that it was pressure-stripped from a parent galaxy. Such a scenario can be investigated in a model by means, e. g., of a wind tunnel simulation in which a disc galaxy is exposed to a fast, low-density gas such as the one modeled here (Kapferer et al. 2009; Ruggiero & Lima Neto 2017).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, F. C., upon reasonable request.

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