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Clumpy disc and bulge formation

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ABSTRACT

We present a set of hydrodynamical/*N*-body controlled simulations of isolated gas-rich galaxies that self-consistently include supernova (SN) feedback and a detailed chemical evolution model, both tested in cosmological simulations. The initial conditions are motivated by the observed star-forming galaxies at $z \sim 2$–3. We find that the presence of a multiphase interstellar media in our models promotes the growth of disc instability favouring the formation of clumps which, in general, are not easily disrupted on time-scales compared to the migration time. We show that stellar clumps migrate towards the central region and contribute to form a classical-like bulge with a Sérsic index, $n > 2$. Our physically motivated SN feedback has a mild influence on clump survival and evolution, partially limiting the mass growth of clumps as the energy released per SN event is increased, with the consequent flattening of the bulge profile. This regulation does not prevent the building of a classical-like bulge even for the most energetic feedback tested. Our SN feedback model is able to establish self-regulated star formation, producing mass-loaded outflows and stellar age spreads comparable to observations. We find that the bulge formation by clumps may coexist with other channels of bulge assembly such as bars and mergers. Our results suggest that galactic bulges could be interpreted as composite systems with structural components and stellar populations storing archaeological information of the dynamical history of their galaxy.

Key words: galaxies: bulges – galaxies: evolution – galaxies: formation – galaxies: interactions.

1 INTRODUCTION

The formation of bulges is still a matter of large debate. Observations suggest that the Sérsic index (n) of a large sample of bulges is smaller than what was previously thought, specifically for late-type galaxies, suggesting that secular processes play an important role in the formation of this component. These observations establish a clear dichotomy in bulge properties, classifying them into classical- ($n > 2$) and pseudo- ($n < 2$) bulges (Fisher & Drory 2008). Mergers are considered as one possible mechanism of formation as well as secular evolution. Both formation modes seem to generate bulges with different properties in numerical simulations, the first ones being more prompted to yield de Vaucouleurs (high-n) density profiles compared to the second ones which would favour more exponential ones (low n). However, there is currently no theory to explain the Sérsic index values in bulges. Recently, a third possibility has come out from new observations of high-redshift galaxies and high-resolution, improved numerical models.

The high-redshift observations show that the most intense star formers in the Universe are galaxy discs at $z \sim 2$. Their morphologies are consistent with thick, gas-rich discs, rotationally supported with circular velocities of ~200 km s^{-1}. A peculiar feature of these galaxies is that their discs show the presence of several giant clumps of $\sim 10^8$–10^{10} M$_\odot$ (e.g. Förster Schreiber et al. 2011), where intense star formation is observed (e.g. Förster Schreiber et al. 2009). Gravitational instabilities in gas-rich turbulent discs have been proposed as the fundamental mechanism to account for this fragmentation. This scenario is also able to explain the bulge formation via clump migration (Elmegreen, Bournaud & Elmegreen 2008; Genzel et al. 2008; Bournaud et al. 2011; Guo et al. 2011).

Cosmological simulations (Ceverino, Dekel & Bournaud 2010), analytical works (Dekel, Sari & Ceverino 2009) and simulated idealized discs in isolation (Immeli et al. 2004; Bournaud, Elmegreen

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Table 1. Main parameters of the numerical experiments. $E_{\rm SN}$ is the amount of SN energy release by each event in units of 10^{51} erg s^{-1}. $n_{\rm initial}$ and $n_{\rm final}$ are the initial and final Sérsic indexes of the bulges, and $Re_{\rm initial}$ and $Re_{\rm final}$ are the respective effective radius. *B*/*T* is the final bulge-to-total stellar masses, where the bulge is computed within 2*Re*. The errors correspond to one standard deviation.

Simulations	$E_{\rm SN}$	$n_{\rm initial}$	$n_{\rm final}$	$Re_{\rm initial}$	$Re_{\rm final}$	B/T
S.BasicSPH	–	1.4 ± 0.2	1.6 ± 0.2	0.63 ± 0.01	0.67 ± 0.02	0.24
S.Mu	–	1.3 ± 0.2	3.5 ± 0.1	0.61 ± 0.02	0.33 ± 0.01	0.32
S.FeMu	0.5	1.4 ± 0.1	4.2 ± 0.1	0.65 ± 0.02	0.33 ± 0.02	0.31
S.ModFeMu	0.7	1.3 ± 0.2	3.2 ± 0.1	0.61 ± 0.02	0.40 ± 0.02	0.34
S.StrFeMu	1.0	1.3 ± 0.2	2.9 ± 0.1	0.61 ± 0.02	0.58 ± 0.01	0.29
S.FeMu_Int	0.5	1.3 ± 0.1	2.9 ± 0.3	0.53 ± 0.02	0.51 ± 0.02	0.39
S.FeMu_Bar	0.5	1.6 ± 0.2	2.3 ± 0.2	0.47 ± 0.02	0.30 ± 0.02	0.35

& Elmegreen 2007; Bournaud et al. 2011) have succeeded to explain most of the observed clump properties. However, a remaining aspect should be addressed, that is, the ability of clumps to survive the effect of supernova (SN) feedback. Several works have disregarded clump disruption by SN thermal heating, claiming radiation pressure to play a more dominant role (Dekel et al. 2009; Murray, Quataert & Thompson 2010). Hydrodynamical simulations including radiation pressure models have found that clumps disrupt before coalescing the bulge (Hopkins et al. 2012; Genel et al. 2012). However, Krumholz & Dekel (2010) use analytical models to conclude that radiation pressure would not be efficient to disrupt clumps in high-redshift galaxies. The strongest pieces of evidence suggesting that clumps survive long enough to reach the bulge are the observational estimations of clump ages (Genzel et al. 2011) and the radial gradients detected in the clump properties (Guo et al. 2011).

In this paper, we revise the clump survival problem within the context of our adopted SN feedback and multiphase model and analyse the impact that clumps might have on bulge formation. For this purpose, we use hydrodynamical simulations of isolated gas-rich discs and a realistic physically motivated SN feedback model implemented with a multiphase treatment of the interstellar medium (ISM; Scannapieco et al. 2005, 2006). We also explore how different mechanisms of bulge formation (clumps migration, mergers and bars) compete with each other, and trace their structural and stellar population properties. These last results could help to unravel the dynamical galactic history contained in the archaeological information of bulges.

2 NUMERICAL SIMULATIONS AND CLUMP IDENTIFICATION

We analysed a set of simulations run by using an extended version of the GADGET-2 code which includes a realistic SN feedback model, implemented with a multiphase treatment of the ISM (Scannapieco et al. 2005, 2006). This code allows the coexistence of gas clouds with different thermodynamical properties and is able to describe the injection of energy into the ISM producing the self-regulation of the star formation and the triggering of mass-loaded galactic outflows, without the need to introduce mass-dependent parameters or to change discontinuous particle momentum to start a wind or temporary suppression of the radiative cooling. The radiative cooling rates are estimated according to the metallicity of the gas.

We studied a set of hydrodynamical simulations of pre-prepared disc galaxies initially composed of a dark matter halo (following an NFW profile), a Hernquist bulge and an exponential disc, with a total baryonic mass of $M_{\rm b} \sim 5 \times 10^{10}\,{\rm M}_{\odot}$. All experiments were run with 50 per cent of discs in the form of gas in order to reproduce observations of $z \sim 2$ gas-rich galaxies (Daddi et al. 2010). We use 200 000 dark matter particles, 100 000 stars initially distributed in the stellar disc and bulge, and 100 000 initial gas particles in the disc component with a mass resolution of $\approx 2 \times 10^5\,{\rm M}_{\odot}$. A gravitational softening of $\epsilon_{\rm G} = 0.16$ kpc was adopted for the gas particles, $\epsilon_{\rm S} = 0.20$ kpc for the stars and $\epsilon_{\rm DM} = 0.32$ kpc for the dark matter. The initial metallicity of the gas had been set so that the simulated discs lie on the mass–metallicity relation at $z \sim 2$, as explained in Perez, Michel-Dansac & Tissera (2011).

We analysed five simulations of the isolated gas-rich disc varying the ISM and the SN feedback models. Three simulations, S.FeMu, S.ModFeMu and S.StrFeMu, have the same multiphase ISM model but explore different SN feedback efficiencies, parametrized by their energy release, $E_{\rm SN}$. The other two simulations, S.Mu and S.BasicSPH, do not include SN feedback. The former includes the multiphase ISM model of Scannapieco et al. (2005) but without SN feedback and the latter has star formation but with no SN feedback nor multiphase ISM. We also study the clump growth during galaxy interaction and bar formation using two simulations: S.FeMu_Int and S.FeMu_Bar, respectively. We note that the interacting case and its associated isolated simulation (S.FeMu_Int and S.FeMu) were previously used by Perez et al. (2011) to investigate the evolution of metallicity gradients in high-z galaxies.[1] S.FeMu_Bar is a version of S.FeMu with a shorter radial scalelength in order to have a centrally dominating disc prone to bar instability. The main parameters of the analysed simulations are summarized in Table 1 for the initial conditions and the conditions after ≈3.5 Gyr of evolution.

Consistently with previous works, our simulated discs fragment into large clumps. In order to identify them, we use a morphological criterion similar to that used by Bournaud et al. (2007), based on the fact that clumps represent local overdensities. First, we compute the face-on projected surface density on a polar grid, defined to control the particle noise. Then, we keep the pixels which represent overdensities compared to the average density at the same radius. This overdensity criterion is controlled by a free parameter, set to eliminate extended connected regions as spiral arms. Selected clumps have masses ranging from $\approx 10^7$ to $\approx 10^9\,{\rm M}_{\odot}$ with a mean at $\sim 10^8\,{\rm M}_{\odot}$ (see Fig. 2), which are in agreement with previous observational and numerical works.

3 CLUMPS SURVIVAL

Our simulated gas-rich discs fragment into large clumps, where an intense star formation activity is detected. In good agreement with

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[1] This simulation was referred to as SimVI by Perez et al. (2011).

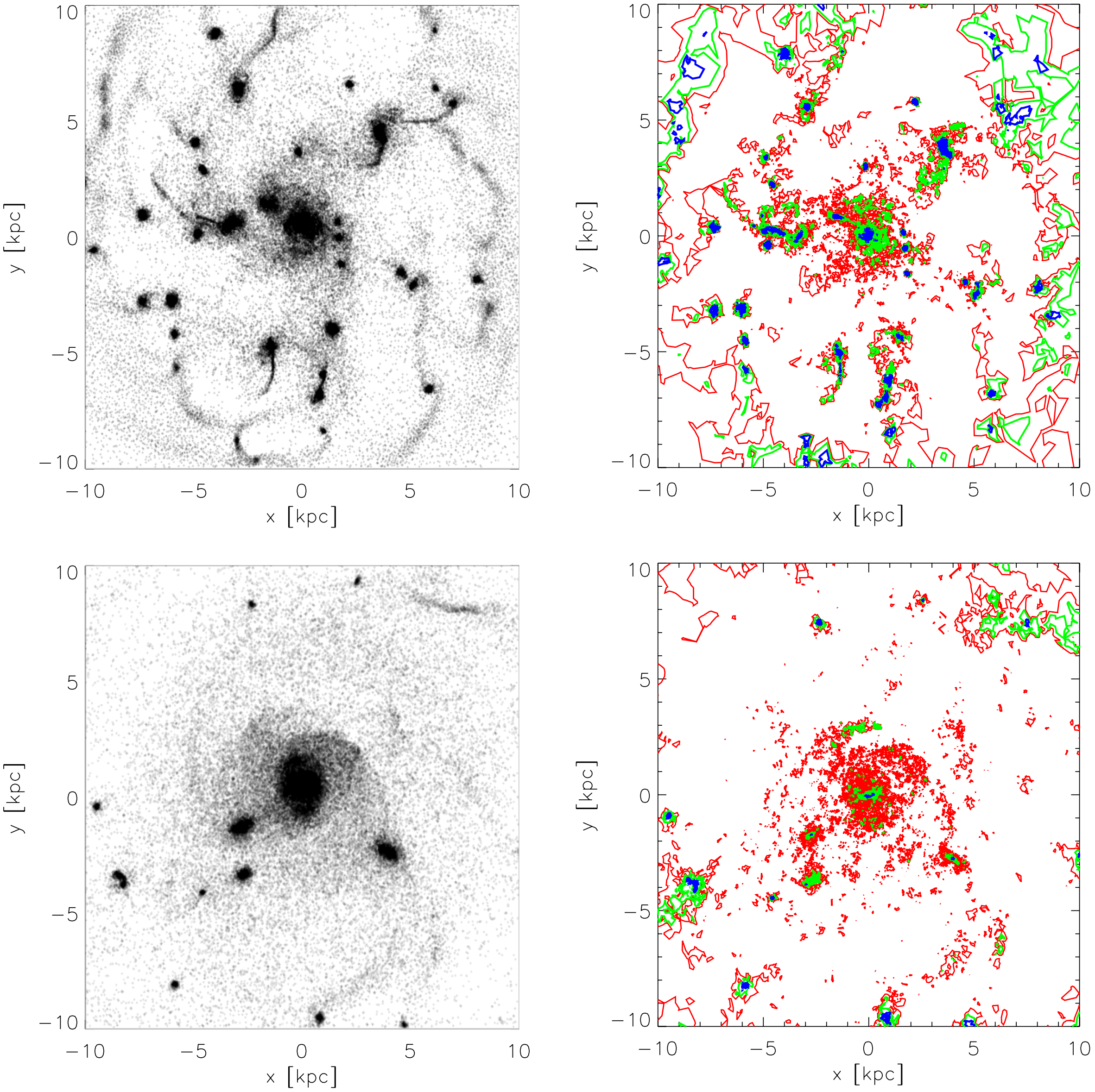

Figure 1. Projected baryonic mass distributions (left-hand panels) and colour contours of stellar ages (right-hand panels) for the simulated galaxy disc in the S.FeMu experiment at an early and advanced stage of evolution (lower and upper panels). Old, intermediate and young populations are indicated by red, green and blue lines, respectively.

observations (Guo et al. 2011), we find that the individual contribution of clumps to the global star formation rate (SFR) of the host galaxy is in general lower than 10 per cent, with a collective contribution of ≈45 per cent on average and a maximum of ∼60 per cent. Even with active star formation in clumps, the rate at which they form stars is less than 1 per cent of the clumps mass per free-fall time, which determines a dimensionless SFR efficiency, e_{ff}, to be lower than 0.01 (see equation 6 of Krumholz & Dekel 2010).

In Fig. 1, we show the projected baryonic mass distributions for S.FeMu at two different times (after 0.25 and 0.60 Gyr of evolution, upper and lower panels). We also display colour contours defined according to star particle ages. It is clear from this figure that the youngest stellar populations are located mainly in clumps. We can also see a stellar age gradient which is consistent with a migration scenario (Guo et al. 2011). Effectively, by inspecting the time evolution of the galaxy, we find that clumps migrate to the central region of the galaxy on time-scales that, on average, are about 0.5 Gyr, in agreement with previous analytical and observational results (Dekel et al. 2009; Genzel et al. 2011; Guo et al. 2011).

In order to study the origin and survival of clumps in our simulations, we explore the ability of different ISM and SN feedback models to form and preserve clump structures in disc simulations. We find that in the basic smoothed particle hydrodynamics (SPH) model, the formation of clumps is prevented because gravitational instability on the gaseous discs is more difficult to be developed due to the oversmoothing of the density and temperature distributions. Conversely, in all our simulations with a multiphase ISM model, gravitational disc instabilities (Toomre 1964) are promoted as a consequence of a better description of density and temperature gradients (Scannapieco et al. 2006). The growth of this instability drives the fragmentation of discs into clumps which locally match $Q_{\mathrm{Toomre}} < 1$.

We compare the density and temperature distributions of gas particles in our basic SPH simulation (S.BasicSPH) with those in the

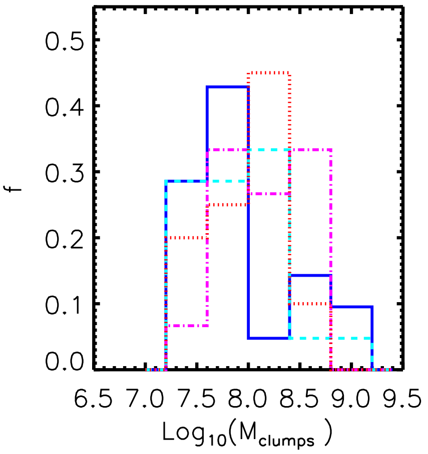

Figure 2. Histograms of stellar masses for clumps in S.FeMu (blue, solid line), S.Mu (magenta, dot–dashed line), S.ModFeMu (cyan, dashed line) and S.StrFeMu (red, dotted line).

multiphase model (S.Mu). The multiphase ISM produces a more 'clumpy' and concentrated gas distribution with at least three orders of magnitude larger densities than the basic SPH. As expected, these larger overdensities are found to match the clump distribution and are formed by cold gas ($\simeq 10^4$ K). Within these clumpy gas concentrations, densities are so large that their cooling times are significantly shorter compared to their dynamical time. Consequently, gaseous clumps in our multiphase ISM model are transformed into bound stellar systems which, capable to survive the disc shearing, migrate and coalesce to the galactic centre. The inclusion of SN feedback regulates their stellar masses by heating the gas and triggering outflows as shown below. Hence, our main analysis will be focused on simulations with the multiphase ISM model (S.Mu, S.FeMu, S.ModFeMu, S.StrFeMu), unless specifically stated.

Fig. 2 shows the clump-mass distributions for experiments with the multiphase ISM model and different SN feedback energy parameters: without SN feedback (magenta), with our mild SN feedback model ($E_{\rm SN} = 0.5 \times 10^{51}$), with a moderate ($E_{\rm SN} = 0.7 \times 10^{51}$) and a strong ($E_{\rm SN} = 1 \times 10^{51}$) SN feedback at a reference time as an example. We find that clumps can survive SN winds even in the simulation with strong SN feedback. However, their growths are limited by the SN energy release: the highest mass clumps are found in the simulation without SN feedback and in the mild SN feedback run. The increase of the SN energy event produces the decrease in the average clump mass as expected as the gas is heated up and partially blown away. Also note that clumps are continuously accreting new material along their evolutionary path; they are not close systems, but they highly interact with their surrounding ISM. Stronger SN outflows also contribute to the formation of less gravitationally bound clumps which can be more easily disrupted. We find that the mean bound energy for the strong SN feedback run is ~58 per cent of that corresponding to our mild SN feedback model.

It is important to note that the SN feedback models used in this work are capable to reproduce the observed galactic mass-loading factors (Scannapieco et al. 2006) as well as those of individual clumps such that the mass-loss rates typically exceed the SFRs by a factor of a few (Genzel et al. 2011). For clumps in the strong SN feedback model, we report the highest extreme mass-loading factors of ~7, which nevertheless are within observed values (Genzel et al. 2011).

Clumps in our simulations are not fully disrupted by the action of SN feedback as reported by other authors. This discrepancy could stem from differences in the numerical codes, which might lie on the details in the ISM and feedback models. First, we note that our code does not include other sorts of feedback apart from thermal heating from SNe. Radiation pressure has been claimed to be the dominant mechanism over other sources of feedback, including the SN thermal heating (Dekel et al. 2009; Murray et al. 2010). Numerical results from Hopkins et al. (2012) and Genel et al. (2012) support this claim. However, its role in disrupting clumps remains debated (Krumholz & Dekel 2010; Krumholz & Thompson 2012; Bournaud et al. 2013). Since we do not have a physically motivated radiative pressure so far implemented in our code, we follow Bournaud et al. (2011) and explore a stronger SN feedback model (S.StrFeMu) as a way to somehow mimic an extra energy contribution for other possible sources, finding no significant variations in our conclusions.

The SN feedback model developed by Scannapieco et al. (2005, 2006) is one of the most physically motivated currently available models. In this model, the SN energy is fractionally distributed into the gaseous neighbours of two different ISM phases, denoted as *hot* and *cold*. The energy injected into the hot phase is instantaneously thermalized and that received by the cold phase is stored in a *reservoir*, defined for each gas particle in this phase. This energy is accumulated until it is enough to modify the thermodynamical properties of these particles so they match the corresponding ones of the hot phase. When this happens, the cold particle is promoted to the hot phase dumping its reservoir energy into its internal energy. This scheme prevents artificial losses of SN energy by the cold phase and ensures the triggering of mass-loaded galactic winds which are capable to reproduce the observations (Genzel et al. 2011).

Beyond differences in the feedback schemes, our simulations distinguish themselves by the adopted multiphase scheme (Scannapieco et al. 2006) as discussed before. In S.Mu experiments which include the multiphase ISM but not the SN feedback, clumps consume their gas into stars, persisting (~0.5 Gyr) as a bound stellar system until they coalesce in the galactic centre. The inclusion of SN feedback in our models (S.FeMu, S.ModFeMu and S.StrFeMu) partially limits their mass growth and weakly reduces their lifetimes, even though it is able to reproduce the observed mass-loading factor of clumps. The survival of clumps for these experiments could be explained because the SN feedback in our model self-regulates the conversion of gas into stars in such a way that the dimensionless SFR efficiency, $e_{\rm ff}$, is found to be within the survival regime (Krumholz & Dekel 2010). In brief, all our simulations with a multiphase ISM model promote disc instabilities driving the formation of clumps which migrate and shape a classical bulge.

3.1 The structure of the bulges

In order to quantify the role of SN feedback in the bulge formation via clumps, we analyse the final structure of bulges for S.BasicSPH, S.Mu, S.FeMu, S.ModFeMu and S.StrFeMu discs by computing their stellar density profiles and performing a disc–bulge decomposition by using an exponential profile for the disc and a Sérsic law for the bulge. The decomposition was carried out in radial range internally limited by the gravitational softening and extended up to 8 kpc. Note that we use the relation $bn = 2 \times n + 0.32$ (Mac Arthur et al 2003), reducing the degree of Sérsic parameter space in order to make the fitting process more efficient.

Fig. 3 shows these stellar density profiles plotted as a function $r^{1/4}$ with the aim of emphasizing deviations from classical bulges,

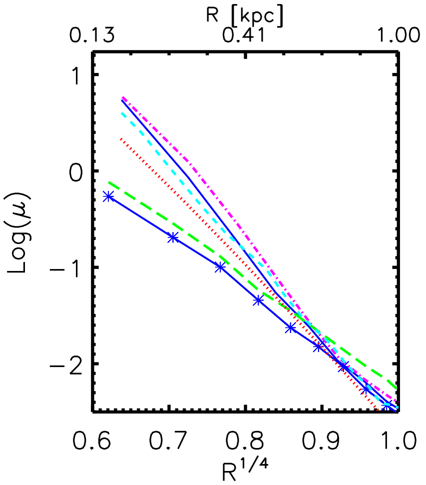

Figure 3. Stellar surface density profiles in the central region of simulated galaxies in S.BasicSPH (green, long dashed line), S.FeMu (blue, solid line), S.Mu (magenta, dot–dashed line), S.ModFeMu (cyan, dashed line) and S.StrFeMu (red, dotted line). The initial stellar density profile is plotted for comparison (asterisks and blue solid line). See Table 1 for initial and final Sérsic indexes.

principally, in the central regions (Fisher & Drory 2008). According to this figure and the derived Sérsic indexes (Table 1), we find that pseudo-bulges ($n < 2$) are only formed when using the basic SPH technique (with no multiphase ISM or SN feedback model). Classical bulges ($n > 2$) are always formed when our multiphase ISM model is switched on. We analysed the gas and temperature distributions of the run without and with the multiphase ISM model, finding that this is capable of reproducing much better density and temperature gradients allowing the coexistence of clouds with different entropies, generating a turbulence medium which better represents the underlying physics (Scannapieco et al. 2006).

When the SN feedback model is switched on, the growth of the clumps is regulated by the SN energy released by an event as already shown in Fig. 2. As a consequence, when the SN energy is increased, the bulge profiles get flatter, but even in the strong SN feedback run the resulting bulge has $n > 2$. We also find that the ratio B/T decreases significantly in the case of the strong SN feedback model as the outflows are more violent and can remove gas or even prevent new gas infall more easily. These results suggest that our SN feedback model can regulate the growth of clumps, but it does not preclude the building of a classical bulge if sensitive SN energy values are adopted. Hence, classical bulges could emerge in a secular scenario by clump migration and not only from mergers.

4 MULTICHANNEL BULGE FORMATION

As mentioned in the previous section, clump migration should be considered as an alternative channel of bulge formation. In order to disentangle its contribution, we investigate how clumps are able to modify the final density profiles of our S.FeMu disc. Fig. 4 shows how the different stellar components contribute to the final density profile of the galaxy. Note that the stellar population initially distributed in the bulge component will be hereinafter referred to as old bulge, and, analogously, the old disc. These old stars can be followed along the galaxy evolution and thus, separated from the younger stellar population formed out from the gaseous disc and located in the emerging new bulge and disc components.

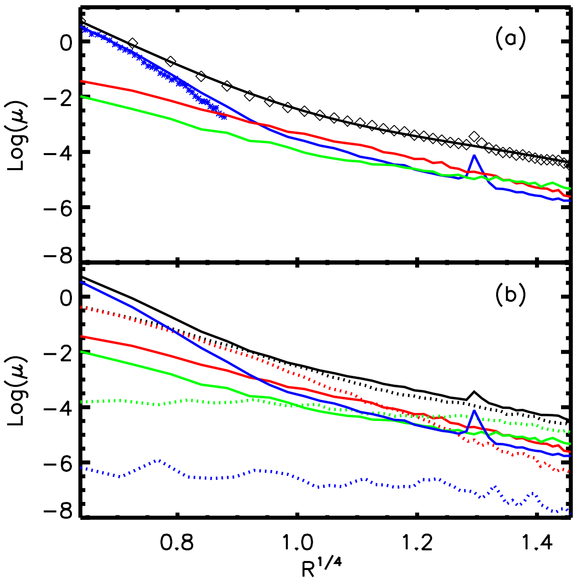

Figure 4. (a) Final density profiles of the simulated disc for the S.FeMu experiment. The total stellar component (i.e. old bulge, old disc and new stellar population) produces a profile shown by black diamonds, fitted by an $n \sim 4$ Sérsic-exponential function (solid black line). Contributions from the old bulge, old disc and from the new stellar population were discriminated (red, green and blue lines, respectively). The blue asterisks show new stars identified at the final stage within the bulge, but formed in any of the clumps along the galaxy evolution. (b) Time evolution of density profiles for each stellar component in S.FeMu: total stellar components (black), old disc (green), old bulge (red) and new stars (blue). The solid (dotted) lines show the final (initial) profiles. The dotted blue line represents the new stars formed during the initial snapshot.

Fig. 4(a) shows that the new stellar populations (solid blue line) significantly contribute to the final density profile in the central region, but also indicates that the new stars formed in clumps (blue asterisk) are those which have the major role in shaping the bulge. Note, however, that we specifically exclude the new stars formed in any clump eventually developed in situ in the bulge, i.e. we consider only the new stars formed in clumps identified on the disc[2] (blue asterisk).

In agreement with previous works (e.g. Elmegreen et al. 2008; Ceverino et al. 2010), our results indicate that a secular process of bulge formation, i.e. the clump migration, allows the formation of a classical-like bulge with a Sérsic index of $n \sim 3$–4 (see Table 1). Note that thisresult seems to be in tension those of Bournaud et al. (2011), where a central bulge but with less steeper profile, $n \sim 1.7$, is reported. This discrepancy likely emerges from the fact that their kinetic feedback might be more efficient destroying clumps which, on the other hand, is consistent with the relatively young stellar population of clumps found in the latest phases of their merging experiments. Also note that they find the Sérsic index by fitting the profile from 1.6 kpc ($0.3 \times R_{1/2}$), much further out than our fitting range.

We also study the relative contribution of the new stars and a preexisting bulge and a disc component to the final bulge structure, including the time evolution of the different stellar density profiles in S.FeMu (Fig. 4b). The result indicates that stars distributed initially

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[2] Note that we use a morphological bulge–disc decomposition, defining the radius of bulge as twice the effective radius as obtained from the Sérsic-exponential fitting of profiles.

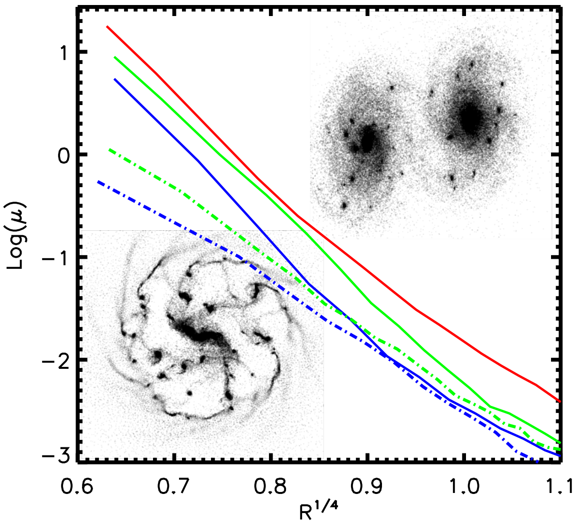

Figure 5. Final stellar density profiles (solid lines): S.FeMu (isolated disc, blue), S.FeMu_Int (merger remnant, red) and S.FeMu_Bar (bar, green). The initial profiles are shown for reference (dash–dotted lines). Note that for construction, the initial profile of the merger remnant coincides with that of the isolated disc. It is remarkable that models with similar Sérsic index values like S.FeMu and S.FeMu_Int ($n \sim 3–4$) come out of very different dynamical histories.

in the old bulge gradually become less dominant, while new stars (formed primarily in clumps) have a more prominent role. This suggests a dynamical interaction between both stellar populations, which is sculptured in their final relative mass distribution.

Besides clump migration, other processes such as bars and mergers are well known to shape the bulge mass distribution. Several numerical works have contributed to show that mergers are able to form classical bulges ($n \sim 3$) and bars induce pseudo-bulge ($n \leq 2$) formation. However, the presence of clumps in these processes has been little explored. Particularly, our motivation, as a first approach to the subject, is to contribute to answer the question: If clump migration by itself develops classical bulges, does the combination with other mechanisms make it even more difficult to explain bulge formation in a Λ cold dark matter cosmology? That is, it will produce an even large excess of classical bulges in spiral galaxies at low redshift [see Bournaud et al. (2011) and Zavala et al. (2012) for a more detail discussion].

In order to explore this topic, we investigate how these mechanisms might compete with each other or reinforce the action of clumps by studying their contributions to the density profiles. In Fig. 5, we show final profiles of the isolated disc of S.FeMu, of its associated model with bars (S.FeMu_Bar) and of the merger remnant in S.FeMu_Int. The bulge growth can be followed by comparing final density profiles (solid lines) with their respective initial ones (dash–dotted lines), or more quantitative, by their Sérsic indexes (see Table 1).

Our results indicate that clump migration in isolated discs can be as effective as mergers in developing a classical bulge (high Sérsic index), but with a less extended bulge growth than mergers, i.e. lower effective radius and bulge-to-total stellar masses (see Table 1).

Our model with a more dominant disc (S.FeMu_Bar) presents a different evolution compared with the S.FeMu. As all the simulated cases, the gas-rich disc fragments generating clumps, but the model also develops relatively soon a large-scale bar-like structure, similar to that observed in some barred galaxies with a clumpy stellar distribution (Hernández-Toledo et al. 2011). The gas distribution and motion is affected by this bar triggering an inflow, which in turn weakens the large-scale bar. This behaviour is not unusual in gaseous bar simulations (Norman, Sellwood & Hasan 1996; Immeli et al. 2004).

It is well known that bar robustness is highly sensitive to the numerical time step (Shen & Sellwood 2004; Klypin et al. 2009). In order to check the robustness of this trend, we rerun the model S.FeMu_Bar with a smaller time step. In both of our experiments a large-scale bar forms and weakens. The overall result of our barred experiments is that bar formation produces a less compact pseudo-bulge with index $n \sim 2.3$, even when clumps form. Our result could be explained as the dominant effect of the large-scale bar which induces a mass redistribution over the contribution of clump migration. The pictures emerging out of our analysis may provide an explanation to the study recently reported by Okamoto (2012), where bar formation and clumpy star formation coexist in a simulated galaxy within a cosmological context, with a final bulge with a low Sérsic index and a dominant mass contribution from a central starburst (also see Inoue & Saitoh 2012). It is important to say that a systematic scan of the parameter space is required in order to accurately characterize this evolution channel.

5 CONCLUSIONS

We used hydrodynamical simulations of isolated gas-rich discs crafted to mimic star-forming galaxies at $z\sim 2–3$. The simulations include a realistic SN feedback model implemented with a multiphase treatment of the ISM (Scannapieco et al. 2005, 2006), which has been proven to be able to describe galactic global properties comparable to observations (Scannapieco et al. 2008, 2009; De Rossi, Tissera & Pedrosa 2011).

We find that the presence of the inhomogeneous, turbulent multiphase medium in our simulations promotes the formation and growth of gravitational disc instability favouring stellar clump formation. For our specific multiphase ISM and SN feedback model, the gas in clumps is transformed into stars at a rate of less than 1 per cent of the clump mass per free-fall time, producing bound systems within the survival regime (Krumholz & Dekel 2010), and stellar age spreads of the order of 500 Myr. This indicates that the survival of clumps is not strongly affected by our SN feedback model, if sensitive values are adopted for the SN energy released. Our SN feedback model is also able to reproduce the observed mass-loading factors of clumps (Genzel et al. 2011).

The picture which emerges out from the analysis of our numerical experiments is that bulge formation by clumps may coexist with other channels of bulge assembly producing realistic values of Sérsic index and bulge-to-total stellar mass ratios. As a consequence, clump coalescence becomes a viable channel for bulge formation. In this scenario, bulges could be interpreted as compound systems similar to those observed in the Milky Way (Babusiaux et al. 2010) and some external galaxies (Fisher & Drory 2008), with different relative contributions of the preexisting bulge, old disc and new stars, which may store archaeological information of the galaxy assembling.

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REFERENCES

Babusiaux C. et al., 2010, A&A, 519, 77
Bournaud F., Elmegreen B. G., Elmegreen D. M., 2007, ApJ, 670, 237
Bournaud F. et al., 2011, ApJ, 730, 4
Bournaud F. et al., 2013, preprint (arXiv:1307.7136)
Ceverino D., Dekel A., Bournaud F., 2010, MNRAS, 404, 2151
Daddi E. et al., 2010, ApJ, 713, 686
De Rossi M. E., Tissera P. B., Pedrosa S. E., 2011, Bol. Asoc. Argentina Astron. La Plata Argentina, 54, 373
Dekel A., Sari R., Ceverino D., 2009, ApJ, 703, 785
Elmegreen B. G., Bournaud F., Elmegreen D. M., 2008, ApJ, 688, 67
Fisher D. B., Drory N., 2008, ApJ, 136, 773
Förster Schreiber N. M. et al., 2009, ApJ, 706, 1364
Förster Schreiber N. M. et al., 2011, ApJ, 739, 45
Genel S. et al., 2012, ApJ, 745, 11
Genzel R. et al., 2008, ApJ, 687, 59
Genzel R. et al., 2011, ApJ, 733, 101
Guo Y. et al., 2011, ApJ, 735, 18
Hernández-Toledo H. M., Cano-Díaz M., Valenzuela O., Puerari I., García-Barreto J. A., Moreno-Díaz E., Bravo-Alfaro H., 2011, AJ, 142, 182
Hopkins P. F., Keres D., Murray N., Quataert E., Hernquist L., 2012, MNRAS, 427, 968
Immeli A., Samland M., Gerhard O., Westera P., 2004, A&A, 413, 547
Inoue S., Saitoh T. R., 2012, MNRAS, 422, 1902
Klypin A., Valenzuela O., Colín P., Quinn T., 2009, MNRAS, 398, 1027
Krumholz M. R., Dekel A., 2010, MNRAS, 406, 112
Krumholz M. R., Thompson T. A., 2012, ApJ, 760, 155
Murray N., Quataert E., Thompson T. A., 2010, ApJ, 709, 191
Norman C. A., Sellwood J. A., Hasan H., 1996, ApJ, 462, 114
Okamoto T., 2012, AIP Conf. Ser. Vol. 1480, First Stars IV – From Hayashi to the Future. Am. Inst. Phys., New York, p. 403
Perez J., Michel-Dansac L., Tissera P. B., 2011, MNRAS, 417, 580
Scannapieco C., Tissera P. B., White S. D. M., Springel V., 2005, MNRAS, 364, 552
Scannapieco C., Tissera P. B., White S. D. M., Springel V., 2006, MNRAS, 371, 1125
Scannapieco C., Tissera P. B., White S. D. M., Springel V., 2008, MNRAS, 389, 1137
Scannapieco C., White S. D. M., Springel V., Tissera P. B., 2009, MNRAS, 396, 696
Shen J., Sellwood J. A., 2004, ApJ, 604, 614
Toomre A., 1964, ApJ, 139, 1217
Zavala J., Avila-Reese V., Firmani C., Boylan-Kolchin M., 2012, MNRAS, 427, 1503

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