Disc formation and the origin of clumpy galaxies at high redshift

Oscar Agertz,1⋆ Romain Teyssier1,2 and Ben Moore1

1 Institute for Theoretical Physics, University of Zürich, CH-8057 Zürich, Switzerland
2 CEA Saclay, DSM/IRFU/SAp, Batiment 709, 91191 Gif-sur-Yvette Cedex, France

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ABSTRACT

Observations of high-redshift galaxies have revealed a multitude of large clumpy rapidly star-forming galaxies. Their formation scenario and their link to present-day spirals are still unknown. In this Letter, we perform adaptive mesh refinement simulations of disc formation in a cosmological context that are unrivalled in terms of mass and spatial resolution. We find that the so-called ‘chain-galaxies’ and ‘clump-clusters’ are a natural outcome of early epochs of enhanced gas accretion from cold dense streams as well as tidally and ram-pressured stripped material from minor mergers and satellites. Through interaction with the hot halo gas, this freshly accreted cold gas settles into a large disc-like system, not necessarily aligned to an older stellar component, that undergoes fragmentation and subsequent star formation, forming large clumps in the mass range \(10^7–10^9\) \(M_\odot\). Galaxy formation is a complex process at this important epoch when most of the central baryons are being acquired through a range of different mechanisms – we highlight that a rapid mass loading epoch is required to fuel the fragmentation taking place in the massive arms in the outskirts of extended discs, an accretion mode that occurs naturally in the hierarchical assembly process at early epochs.

Key words: galaxies: evolution – galaxies: formation – galaxies: haloes.

1 INTRODUCTION

The morphology and star formation properties of high-redshift galaxies are very different from present-day quiescent spirals and ellipticals. Large clumpy irregular discs with kpc-sized star forming clumps as massive as \(M_\text{cl} \sim 10^7–10^9\) \(M_\odot\) are observed in the Hubble Ultra Deep Field (UDF; e.g. Elmegreen et al. 2007, 2009), a population that is very rare today. ‘Chain galaxies’, first identified by Cowie, Hu & Songaila (1995), are believed to be high-redshift discy galaxies seen edge-on, while ‘clump cluster’ galaxies are their face-on counterparts (Dalcanton & Shectman 2009), a population that is very rare today. ‘Chain galaxies’ and ‘clump-clusters’ are a natural outcome of early epochs of gas accretion.

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for gas of temperature $T \sim 10^4$ K is shorter than the time-scale of gas compression and shocks are unable to develop. In haloes above this mass, cold accretion persists as gas is supplied by cold streams penetrating through hot massive haloes at $z \gtrsim 2$ (Ocvirk et al. 2008; Dekel et al. 2009) whilst the classical hot mode of gas accretion dominates at lower $z$. Because of insufficient spatial resolution, these studies could not follow the evolution of the accreting gas and how the cold streams connect to the central galaxies. The purpose of this Letter is to look in detail at the gas accretion and disc formation process using state-of-the-art numerical simulations.

2 NUMERICAL SIMULATION

We use the adaptive mesh refinement (AMR) code RAMSES (Teyssier 2002) to simulate the formation of a massive disc galaxy in a cosmological context including dark matter, gas and stars. The gas dynamics are calculated using a second-order unsplit Godunov method, while collisionless particles (including stars) are evolved using the particle-mesh technique. The modelling includes realistic recipes for star formation (Rasera & Teyssier 2006), supernova feedback and enrichment (Dubois & Teyssier 2008). Metals are advected as a passive scalar and are incorporated self-consistently in the cooling and heating routine, as in Agertz et al. (2009), and we adopt an initial metallicity of $Z = 10^{-3} Z_\odot$ in the high-resolution region. The refinement strategy is based on a quasi-Lagrangian approach, so that the number of particles per cell remains roughly constant, avoiding discreteness effects (e.g. Romeo et al. 2008). The computational domain is a 40 Mpc cube containing nested AMR grids of particles and gas cells down to a Lagrangian region containing dark matter particles of mass $m_p = 2.2 \times 10^5 M_\odot$. The effective resolution of our initial grid is therefore 2048$^3$. We then refine this base grid according to our refinement strategy, so that the maximum resolution is $\Delta x \sim 40$ pc in physical units at all times.

For our initial conditions, we take the Via-Lactea II simulation (Diemand et al. 2008) which forms a Milky Way sized dark matter halo that accretes most of its mass ($M_{\text{vir}} = 2 \times 10^{12} M_\odot$ at $z = 0$) by redshift $z = 2$. We evolved the entire simulation to $z = 0$ at a coarser resolution; here, we report on the high-redshift evolution to $z = 2$ at which point it hosts a disc that is massive enough to be compared to the observations in e.g. Bournaud et al. (2008) and Genzel et al. (2006). We use standard galaxy formation ingredients, with a star formation efficiency of 2 per cent (as defined in Rasera & Teyssier 2006), a star formation density threshold $n_H = 4$ cm$^{-3}$ and a supernovae mass loading factor $f_w = 10$ (as defined in Dubois & Teyssier 2008). In order to prevent artificial fragmentation, we use a pressure floor $P \simeq 3 G \Delta x^2 \rho^2$, so that we satisfy the Truelove et al. (1997) criterion at all times.

3 RESULTS

Fig. 1 shows a large-scale view of the galactic disc at $z \sim 3$. At this time, the dark matter halo has reached a mass of $M_{\text{vir}} \sim 3.5 \times 10^{11} M_\odot$, while the total baryonic mass in the disc (disregarding the bulge) is $M_{\text{bary}} \sim 2.4 \times 10^9 M_\odot$ out of which 50 per cent is gas, putting it in a regime where both cold flows and stable shocks can exist (Kereš et al. 2005; Dekel & Birnboim 2006; Ocvirk et al. 2008). This striking image ties together many aspects present in modern theories of galaxy formation and highlights new complexities. Cold streams of gas originating in narrow dark matter filaments effectively penetrate the halo and transport cold metal-poor gas right down to the protogalactic disc to fuel the star-forming region. A comparable amount of metal-enriched material reaches the disc in a process that has previously been unresolved – material that is hydrodynamically stripped from accreting satellites, themselves small discy systems, through the interaction with the hot halo and frequent crossings of the cold streams.

Streams of cold gas flow into the halo on radial trajectories eventually forming orderly rotational motion in an extended disc. This gas is in approximate pressure equilibrium with the hot halo that has a rotational velocity of $v_{\text{rot}} \sim 30 \text{ km s}^{-1}$ close to the virial radius, increasing smoothly to $v_{\text{rot}} \sim 200 \text{ km s}^{-1}$ to match the rotation at the edge of the disc ($r \sim 10 \text{kpc}$). The ram pressure is significant close to the disc, forcing the streams to curve around it. At early times, when the interaction region close to the disc is tenuous, streams can ‘swing’ past the protodisc before being decelerated completely. At later times, the turbulent accretion region carries significant mass and infalling cold gas quickly decelerates by plowing through it. We detect compression and radiative shocks that quickly dissipate since the cooling times are very short, resulting in a denser configuration for the cold gas. The global outcome of this interaction is a turbulent gas heavy disc prone to fragmentation. Fig. 2 shows a

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**Figure 1.** An RGB-image of the gas showing the disc and accretion region at $z \sim 3$. The image is constructed using $R =$ temperature, $G =$ metals and $B =$ density. We can clearly distinguish the cold pristine gas streams in blue connecting directly on to the edge of the disc, the shock-heated gas in red surrounding the disc and metal-rich gas in green being stripped from smaller galaxies interacting with the halo and streams of gas. The disc and the interacting satellites stand out since they are cold, dense and metal rich.
time sequence of the complicated and asymmetric gas flows around
the gas disc at \( z \sim 3 \). The figure reveals that many of the large-scale
spiral arms at large radii are not waves but material arms that can
survive for an orbital time, and that these arms are gravitationally
unstable and can fragment into clumps. Gravitational instability has
been used by E93 to explain the formation of massive clumps, as
large as dwarf galaxies, in the tidal tails of merging galaxies. The
typical mass of objects that form within the arms is \( M_1 \sim \frac{\sigma^2_{1D}}{G^2} \),
where \( \Sigma \) is the surface density of gas within the arm and the
effective mass-weighted one-dimensional velocity dispersion is defined
as \( \sigma^2_{1D} = c_s^2 + \sigma_{ID}^2 \) where \( c_s \) is the local sound speed. Using the
small region highlighted by the grey square in Fig. 2, we have mea-
sured \( \Sigma = 60 \, \text{M}_\odot \, \text{pc}^{-2} \) and \( \sigma_{eff} \sim 25 \, \text{km} \, \text{s}^{-1} \), giving \( M_1 \sim 2 \times 10^8 \, \text{M}_\odot \) which agrees well with the mass of the forming clump.
The internal dispersion velocity is roughly equal to the divergent
motions across the curved gas filament. The typical velocity disper-
sion across a \( \lambda \sim 1 \, \text{kpc} \) patch of the filament will be of the order of
\( \sigma \sim \frac{\lambda v_{orb}}{R_c} \sim 20 \, \text{km} \, \text{s}^{-1} \), where the orbital velocity \( v_{orb} \sim 200 \, \text{km} \, \text{s}^{-1} \) and the curvature radius \( R_c \) of the filament equals the
radius of the extended disc. This value agrees well with the domi-
nating turbulent component of \( \sigma_{eff} \). As the interaction region grows
in mass and develops a more symmetric disc-like morphology, we
also observe massive clump formation in fragmenting spiral waves
at intermediate radii.

The resulting galaxy is shown in Fig. 3 at \( z \sim 2.7 \), after many large
clumps have formed through the above mechanisms. We detect 14
clumps with masses between \( M_{cl} \sim 5 \times 10^7 \) and \( 10^9 \, \text{M}_\odot \), of which
only the two smallest did not form in situ but were infalling satel-
lites. The three most massive clumps have \( M_{cl} \sim 7-8 \times 10^8 \, \text{M}_\odot \).
In total, \( \sim 15 \) per cent of the baryons are in clumps. In the interac-
tion region between the disc and the cold streams, the typical arm
surface density and velocity dispersion can both be estimated using
mass-average quantities within cylindrical shells. At \( r \sim 8 \, \text{kpc} \),
we measure \( \langle \Sigma \rangle \sim 20 \, \text{M}_\odot \, \text{pc}^{-2} \) and \( \langle \sigma \rangle \sim 30 \, \text{km} \, \text{s}^{-1} \), giving rise to
clump masses as large as \( M_1 \sim 10^9 \, \text{M}_\odot \). Even though we satisfy the

Truelove criterium, convergence in the details of the clump proper-
ties can be influenced by numerical fragmentation and may require
more cells per Jeans length. In addition, numerical diffusion from
bulk flows can lead to an underestimation of the turbulent veloc-
ity dispersion. Quantifying this is beyond the scope of this Letter.
The detected clumps are located in the interaction region between
the inner disc and the cold streams. In our case, this region is not
aligned with the initial galactic disc, giving rise to a misalignment
of the clumps with respect to the inner galactic disc (see edge-on
images in Fig. 3). Although we believe that this misalignment is
not typical, it is an elegant explanation for the formation of 'bent'
chains, such as the one reported in Bournaud et al. (2008a). In-
deed, Elmegreen & Elmegreen (2006) report that the typical chain
galaxy has clumps mostly aligned in the mid-plane, while in some
cases clumps are seen above and below the mid-plane (outer and
inner disc misaligned). In our case, the misalignment is due to a
third cold stream that is perpendicular to the main filament seen
in Fig. 1. In a similar scenario, this process has also been invoked
to explain the formation of large polar rings (Macciò, Moore &
Stadel 2006).

The simulated galaxy is sharing many properties with observed
chain and clump cluster galaxies (Elmegreen et al. 2007). Viewed
edge-on, the misaligned disc morphology is clearly seen and the
overall structure resembles a large chain galaxy. Viewed face-on,
the spiral-like structure has a similar morphology as clump clusters
or clumpy spirals. Elmegreen & Elmegreen (2005) report that UDF
clumpy galaxies at \( z \sim 1.5-3 \) have a stellar mass \( \gtrsim 6 \times 10^{10} \, \text{M}_\odot \)
and a radius \( \sim 10 \, \text{kpc} \), in striking agreement with our simulated galaxy.
Not only does the cosmological simulation reproduce the observed
clump morphology and global rotation of these systems but we
also find a realistic metallicity gradient and star formation rate of
\( 20 \, \text{M}_\odot \, \text{yr}^{-1} \). The inner disc has an average solar metallicity, while
that in the clump-forming region is only \( \sim 1/10 \, Z_\odot \), due to the
accretion of pristine gas in the cold streams mixing with stripped
satellite gas. This has the important observational consequence that

\( \text{Figure 2. A time sequence spanning 40 Myr of the projected gas density at } z \sim 3 \text{ in a } 18 \times 18 \, \text{kpc}^2 \text{ region. The box shows the formation of a } \sim 10^8 \, \text{M}_\odot \text{ clump via gravitational instability.} \)

\( \text{Figure 3. Density projection of the stars (left-hand panels) and gas (right-hand panels) at } z \sim 2.7 \text{ illustrating the fragmentation process and the formation of large clumps of mass } \sim 10^7-10^9 \, \text{M}_\odot. \)
these massive clumps might be devoid of dust, making them easier to detect.

To illustrate ‘how discs acquire their baryons’, we have plotted the mass accretion rate in different gas phases measured around our simulated galaxy at $z = 5, 3$ and $2$ in Fig. 4. We define the phases as cold diffuse ($T < 2 \times 10^4$ K, $n < 0.05$ cm$^{-3}$), dense ($n > 0.05$ cm$^{-3}$), hot diffuse ($T > 2 \times 10^4$ K, $n < 0.05$ cm$^{-3}$) and stripped ($Z > 0.01 Z_\odot$, $n < 0.05$ cm$^{-3}$). Indeed, at $z = 3$ and $5$ the mass accretion rates in cold streams is very high ($\dot{M} \sim 20 M_\odot$ yr$^{-1}$). A significant amount of baryons are also accreted from stripped satellites, although quantifying this amount is difficult in Eulerian schemes since this metal-rich material can mix with the other gas phases that have never been part of the satellites. After $z \sim 2$, the hot mode of accretion dominates, making large clump formation at large radii only possible through galaxy mergers, c.f. Barnes & Hernquist (1992) and E93. At $z \sim 2$, the galaxy has a thin and extended spiral disc component. Although the gas velocity dispersion is still rather high in the disc, the Jeans mass in the spiral arms is of the order of $\sim 10^7 M_\odot$, closer to the largest giant molecular clouds (GMCs) in present-day spiral galaxies. The corresponding gas $Q_g$-parameter (Goldreich & Lynden-Bell 1965) is $Q_g \simeq 1.5–2$ in the star-forming region, indicating that the disc is marginally stable and the galaxy has reached a quiescent phase with no further large clump formation.

Fig. 5 shows the dark matter mass accretion rate in the simulated galaxy, as a function of time. At $z = 2$, the accretion rate is significantly lower than the average, explaining why the disc has reached this quiescent phase. A global analytical approach for understanding high-$z$ disc fragmentation can be applied (Dekel, Sari & Ceverino 2009), based on simple stability arguments and the disc fraction $\delta \equiv M_d/M_{td}(R_d)$. Here, $M_d$ is the baryonic mass in the disc and $M_{td}(R_d)$ is the total mass within the disc radius $R_d$. A $\delta \sim 0.25–0.5$ should give rise to large clumps involving a few per cent of the disc mass, and $\delta \sim 0.3–0.35$ is predicted for a steady-state fragmentation from moderately clumpy streams. The disc in our simulation at $z = 5, 3$ and $2$ has $\delta = 0.47, 0.33$ and $0.33$, respectively, which is in excellent agreement with the above prediction (see also Fig. 2 in Dekel et al. 2009). Using only the gas in $M_d$ renders a lower bound of $\delta = 0.17, 0.17$ and $0.1$. We point out that the stellar fraction increases significantly towards lower redshifts and this ‘hotter’ component stabilizes the disc at $z \sim 2$.

4 CONCLUSIONS

We have followed the formation and accretion history of a Milky Way-sized galaxy using state-of-the-art AMR techniques. Most of the baryons are in an orderly rotating disc by a redshift $z = 2$, but how they attain this equilibrium is very complex and the focus of this work. One of the most important points of this Letter is that we can answer the question in detail of ‘how galaxies get their baryons’. Extending recent work on the impact of cold streams on galaxy formation (Kereš et al. 2005; Dekel & Birnboim 2006; Ocvirk et al. 2008; Dekel et al. 2009), we analyse for the first time how single-phase narrow cold streams and ram pressure stripped debris assemble an extended turbulent rotating disc. Complex gas interactions take place in an extended accretion region in which infalling gas is decelerated through compression/radiative shocks and from the pressure gradients arising from a hot halo component.

Prior to $z \sim 2$, the accretion rate of cold gaseous material on to the disc is the highest and we resolve the gravitational instabilities responsible for the formation of many very massive clumps within an extended $\sim 10$ kpc disc. This is about two times larger than the theoretical expectations of disc sizes at this epoch (Mo, Mao & White 1998). The observed morphology, star-forming rate,
global rotation and metallicity of the system are in good agreement with the observed clump-cluster and chain galaxies (Elmegreen & Elmegreen 2006; Elmegreen et al. 2007; Bournaud et al. 2008). This scenario is an extension of the disc fragmentation scenario proposed by B07 and Elmegreen et al. (2008), although here studied more consistently within the current cosmological framework, and more specifically related to cosmological accretion. Therefore, clumpy galaxies should be most frequent at this epoch since massive clump formation stops during the remaining slow-accretion phase and the disc evolves quiescently until $z = 0$ which will be reported on in a forthcoming paper.

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REFERENCES

Agertz O., Lake G., Teyssier R., Moore B., 2009, MNRAS, 392, 294
Barnes J. E., Hernquist L., 1992, Nat, 360, 715
Birnboim Y., Dekel A., 2003, MNRAS, 345, 349
Bournaud F., Elmegreen B. G., Elmegreen D. M., 2007, ApJ, 670, 237 (B07)
Bournaud F. et al., 2008a, A&A, 486, 741
Bournaud F., Duc P.-A., Emsellem E., 2008b, MNRAS, 389, L8
Brooks A. M., Governato F., Quinn T., Brook C. B., Wadsley J., 2009, ApJ, 694, 396
Cowie L. L., Hu E. M., Songaila A., 1995, AJ, 110, 1576
Daddi E., Cimatti A., Renzini A., Fontana A., Mignoli M., Pozzetti L., Tozzi P., Zamorani G., 2004, ApJ, 617, 746
Dalcanton J. J., Shectman S. A., 1996, ApJ, 465, L9
Dekel A., Birnboim Y., 2006, MNRAS, 368, 2
Dehnen W., Heliönen J., 2008, MNRAS, 389, 325
Dekel A. et al., 2009a, Nat, 457, 451
Dekel A., Sari R., Ceverino D., 2009b, preprint (arXiv:0901.2458)
Diemand J., Kuhlen M., Madau P., Zemp M., Moore B., Potter D., Stadel J., 2008, Nat, 454, 735
Dubois Y., Teyssier R., 2008, A&A, 477, 79
Eisenstein D. J., Hut P., 1998, ApJ, 498, 137
Elmegreen B. G., Elmegreen D. M., 2005, ApJ, 627, 632
Elmegreen B. G., Elmegreen D. M., 2006, ApJ, 650, 644
Elmegreen B. G., Kaufman M., Thomasson M., 1993, ApJ, 412, 90 (E93)
Elmegreen D. M., Elmegreen B. G., Hirst A. C., 2004, ApJ, 604, L21
Elmegreen D. M., Elmegreen B. G., Ravindranath S., Cee D. A., 2007, ApJ, 658, 763
Elmegreen B. G., Bournaud F., Elmegreen D. M., 2008, ApJ, 688, 67
Elmegreen B. G., Elmegreen D. M., Fernandez M. X., Lemonias J. J., 2009, ApJ, 692, 12
Förster Schreiber N. M. et al., 2006, ApJ, 645, 1062
Genzel R. et al., 2006, Nat, 442, 786
Genzel R. et al., 2008, ApJ, 687, 59
Goldreich P., Lynden-Bell D., 1965, MNRAS, 130, 97
Jogee S. et al., 2008, in Funes J. G., Corsini E. M., eds, ASP Conf. Ser. Vol. 396, Formation and Evolution of Galaxy Disks. Astron. Soc. Pac., San Francisco, p. 337
Kereš D., Katz N., Weinberg D. H., Davé R., 2005, MNRAS, 363, 2
Kereš D., Katz N., Fardal M., Davé R., Weinberg D. H., 2009, MNRAS, 395, 160
Macciò A. V., Moore B., Stadel J., 2006, ApJ, 636, L25
Mo H. J., Mao S., White S. D. M., 1998, MNRAS, 295, 319
Neistein E., van den Bosch F. C., Dekel A., 2006, MNRAS, 372, 933
Ocvirk P., Pichon C., Teyssier R., 2008, MNRAS, 390, 1326
Overzier R. A. et al., 2008, ApJ, 677, 37
Rasera Y., Teyssier R., 2006, A&A, 445, 1
Robertson B. E., Bullock J. S., 2008, ApJ, 685, L27
Romeo A. B., Agertz O., Moore B., Stadel J., 2008, ApJ, 686, 1
Shapiro K. L. et al., 2008, ApJ, 682, 231
Taniguchi Y., Shioya Y., 2001, ApJ, 547, 146
Teyssier R., 2002, A&A, 385, 337
Truelove J. K., Klein R. I., McKee C. F., Holliman II J. H., Howell L. H., Greenough J. A., 1997, ApJ, 489, L179
Zheng W. et al., 2004, ApJS, 155, 73

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