Resolved properties of galaxies as a tracer of their cosmological mass assembly

Frédéric Bournaud

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Chapitre 1

Numerical codes for galactic studies

1.1 Treecode and Particle-Mesh codes : N-body dynamics at high resolution

1.2 Hydrocodes, SPH, and sticky-particles : modelling the turbulent ISM of galaxies

Chapitre 2

A fundamental evolution mechanism : galaxy mergers

2.1 Collisions, mergers, and elliptical galaxy formation

Galaxy collisions and mergers have been known for decades not to be rare events (Zwicky 1959), and have been proposed as a possible formation mechanism for elliptical, spheroid-dominated galaxies : spiral disk galaxies merging together undergo a violent relaxation process (Lynden-Bell 1967) which strongly modifies their shape, concentration and kinematical support, so that they can evolve from rotating disks to pressure-supported spheroids. Real elliptical galaxies have a characteristic "$R^{1/4}$" profile (de Vaucouleurs 1948), or more generally a Sersic profile with a Sersic index $n \simeq 4$. Some elliptical can have $n = 6$ or more (Trujillo et al. 2004), the Sersic index is anyway a useful parameter to distinguish them from disk galaxies characterized by $n \simeq 1$, at most $n = 2$.

Even before the role of mergers in the standard hierarchical-merging paradigm has been fully realized, numerical simulations have been used to study the effect of tidal fields in interacting pair of galaxies (Toomre & Toomre 1972; Barnes 1992), and whether or not the spheroids formed by the merging of two disk galaxies resemble real, observed elliptical galaxies – which observation of late-stage mergers suggest is the case (Schweizer 1982; Chitre & Jog 2002). Nevertheless, the resolution of numerical simulations has been really sufficient to resolve the violent relaxation process only around 2000 - especially when the interstellar gas dynamics is included in the models. These works had focused either on "major" mergers (equal-mass or almost, mass ratios of 1 :1, 2 :1, 3 :1) (Bendo & Barnes 2000; Cretton et al. 2001) or "minor" mergers of a spiral galaxy with a dwarf companion (mass ratios above 10 :1) (Walker et al. 1996). As of 2003, there had been no comprehensive study covering all mass ratios from major (1 :1) to minor (above 10 :1) with the same physical hypothesis, initial conditions, modeling, and in particular mass ratios around 5 :1 to 10 :1 had never been investigated, while they are both very frequent (in the Λ-CDM hierarchical theories) and susceptible to affect the properties of galaxies more fundamentally than the more minor mergers with dwarf companions.

Before realizing a complete census of the properties of galaxy merger remnant for all mass ratios, we have undertaken the first study of the "intermediate" mass ratios, published in 2004 (paper *Merger I*). Studying the properties of galaxy merger remnants for mass ratios like 5 :1 or 7 :1, we have realized that they cannot modify the properties in the same manner as major, equal-mass mergers. The morphology of such merger remnant is still disk-like, even if the bulge is much more massive than in the progenitor spirals. We typically find that 7 :1 mergers starting with Sb/Sc-like spiral galaxies lead to doubling the bulge mass, and the remnants of 5 :1 mergers typically have a bulge almost as massive as their exponential disk component. In the late stages of the merging process, when the two central bodies have merged but the outer parts are not fully relaxed yet, tidal debris make possible to identify merger remnants. The intermediate mass ratio (5 :1-7 :1) are then predicted, in our models, to have atypical properties. Their morphology should be that of an irregular disk, with an azimuthally averaged luminosity profile that has a low Sersic index or even an exponential shape. Their kinematics is however elliptical-like. Such properties corresponds to atypical merger remnants observed by (Jog & Chitre 2002), which are not rare in the sample studied by these authors.

Beside the properties of on-going mergers, a more general question for galaxy formation is to know what the remnants look liked when the merger is completely relaxed and the system has the appearance of a single, isolated galaxy. Important work had been done by Naab & Burkert (2003) (and the following papers by Naab and collaborators) but covering only the major mass ratios, typically from 1 :1 to 3 :1. These authors present convincing evidence that 1 :1 mergers produce somewhat boxy elliptical with little residual rotation, 3 :1

mergers still produce elliptical-like galaxies, but most often with a disky isophotal shape and more residual rotation after the merger.

Our study (Paper Merger II) covers a larger range of mass ratios, from the 1 :1 equal-mass mergers, down to 10 :1 minor mergers, focusing mostly on the intermediate range that had not been covered before. The galaxies formed by these mergers are analyzed on simulated projected density maps, velocity fields, and velocity dispersion fields. We find that the morphological and kinematical properties of the relaxed remnants of binary mergers depend above all on the mass ratio. The orbital parameters (collision velocity, impact parameter, prograde/retrograde orbits) do affect the properties of the merger remnant, but less than a change by a factor of 2 in the mass ratio. For instance, all 1 :1 merger remnant are elliptical-like, and none of the 7 :1 merger remnants is elliptical-like, independently of the orbital parameters. Overall, we have shown that mergers can be classified in three main categories :

- the major mergers produce elliptical-like galaxies, for mass ratios ranging from 1 :1 to 3-4 :1
- intermediate mergers, for mass ratios from 4-5 :1 to 10 :1 produce disk galaxy with a massive spheroid and high stellar velocity dispersions, likely progenitors of S0 lenticular galaxies - other formation mechanisms can contribute too as discussed in the paper.
- minor mergers beyond 10 :1 do not change a initial spiral galaxy into an S0 or E galaxy. They keep it spiral-like, but the disk is thickened, the bulge grows, and some stars are dispersed in a spheroidal halo. The product of such an event is a spiral galaxy of earlier type than its main progenitor. Typically the properties change by 1 or 2 Hubble classes for a 10 :1 merger, for instance an Sc galaxy undergoing a 10 :1 merger will become an Sb or Sa, depending on the orbital parameters.

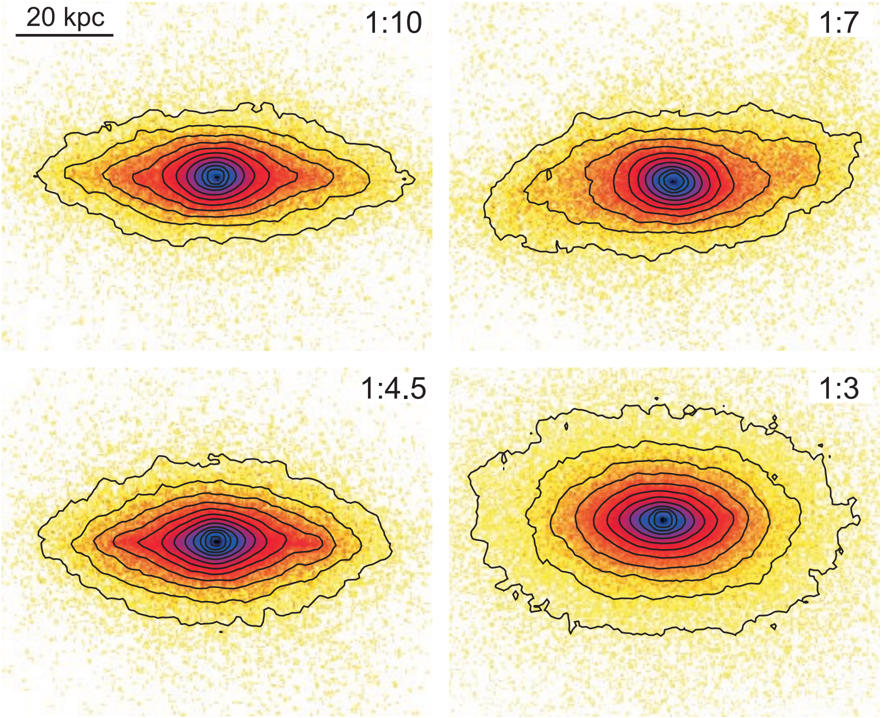

FIG. 2.1 – tbc

As we have seen so far, mergers in the newly explored range of mass ratios (5 :1–10 :1) have an important effect on galaxy morphology. In the $\Lambda - CDM$ paradigm, a given galaxy with a present-day mass around the Milky-Way's one is more likely to encounter several successive mergers of this kind than single single major merger (3 :1-1 :1). This simple remark, made from exploring merger trees from cosmological models, led us to wonder what happens to a galaxy when it undergoes several mergers of 5 :1, 10 :1, or even more minor mass ratios. At this stage, we are not directly considering real merger trees from cosmological simulations, but studying the theoretical question of how affected a galactic disk is when it undergoes N mergers with a mass ratio M :1. In our study we have varied M from 3 to 50, and N from 1 to M. Even if we do not implement cosmological merger trees in this study, it remains relevant and realistic for the following reasons :

- in merger trees, we do find a significant fraction of galaxies that have several successive mergers in the 10 :1–5 :1 range of mass ratios between $z = 2$ and $z = 0$ (see paper merger II)

- the number of successive mergers that we simulate varies from $N = 1$ to $N = M$ where M is the mass ratio : this corresponds up to doubling the initial mass of the main parent galaxy, which is representative of the mass growth rate observed for spirals between z=1-2 and z=0 ; our models then illustrate the case where this mass growth would be achieved mostly by galaxy mergers.

We found in this study (detailed in paper Merger III) that several successive mergers with an intermediate mass ratio can convert a disk galaxy into a spheroid-dominated galaxy with little or no exponential disk component, and overall properties similar to both major merger remnants and real elliptical galaxies (low axis ratios, low diskiness or boxiness, low v/σ,etc..). We show on Figure AJOUTER UNE FIGURE some exemples of multiple 6 :1 mergers, in a recent study at a resolution higher than in our 2007 paper, which confirmed the robustness of this result. We find that, on average, the main parameter that determines the nature of a multiple-merger remnant is the total merged mass. The number of fragments from which the mass is merger, and each individual orbit, induce less variations in the result than the total merged mass. Thus, the remnant of two 3 :1 mergers will, on average, be quite similar to the remnant of four 6 :1 mergers and eight 12 :1 mergers – the main difference actually being that the later cases are cosmologically more likely than the former one.

We show on Figure 2.2 the average number of mergers needed to form an elliptical-like galaxy, as a function of the mass ratio. On the green line or just above, the sequence of mergers will most often produce a disky, somewhat flat and rotating elliptical galaxy (expect at 1 :1). For a merged mass at least doubling the initial mass of the main progenitor (i.e. one 1 :1 merger or six 6 :1 mergers) the final system is (most frequently) a boxy, slowly-rotating elliptical galaxy.

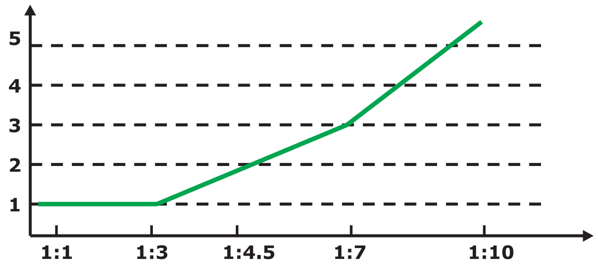

Fig. 2.2 – tbc

Paper Merger I

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Astronomy & Astrophysics

Unequal-mass galaxy merger remnants: Spiral-like morphology but elliptical-like kinematics

F. Bournaud[1,2], F. Combes[1], and C. J. Jog[3]

[1] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, 75014 Paris, France
[2] École Normale Supérieure, 45 rue d'Ulm, 75005 Paris, France
[3] Department of Physics, Indian Institute of Science, Bangalore 560012, India

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Abstract. It is generally believed that major galaxy mergers with mass ratios in the range 1:1–3:1 result in remnants that have properties similar to elliptical galaxies, and minor mergers below 10:1 result in disturbed spiral galaxies. The intermediate range of mass ratios 4:1–10:1 has not been studied so far. Using N-body simulations, we show that such mergers can result in very peculiar systems, that have the morphology of a disk galaxy with an exponential profile, but whose kinematics is closer to that of elliptical systems. These objects are similar to those recently observed by Jog & Chitre (2002). We present two cases with mass ratios 4.5:1 and 7:1, and show that the merging causes major heating and results in the appearance of elliptical-type kinematics, while surprisingly the initial spiral-like mass profile is conserved.

Key words. galaxies: interaction – galaxies: formation – galaxies: evolution – galaxies: kinematics

1. Introduction

Numerical simulations commonly show that the merging of two equal-mass spiral galaxies results in the formation of an elliptical galaxy with an $r^{1/4}$ radial profile consistent with observations (de Vaucouleurs 1953), and which is mainly supported by velocity dispersion rather than rotation (e.g., Barnes 1992). Galaxy mergers with mass ratios of 1:1 to 3:1 and 4:1 have been studied by Bendo & Barnes (2000), Cretton et al. (2001) and Naab & Burkert (2003): these lead to the formation of boxy or disky elliptical galaxies, depending on the mass ratio. On the other hand, minor mergers with mass ratios of more than 10:1 have also been studied in numerical simulations. They correspond to the merging of a spiral galaxy with a dwarf companion, which has visible effects on the morphology and kinematics of the remnant: Walker et al. (1996) have found a significant heating and thickening of the disk. However, the remnant of a minor merger remains an exponential disk supported by rotation.

These numerical works do not account for a recent observational result: Chitre & Jog (2002) have analyzed a set of observed advanced merger remnants, and have classified them in two morphological classes. "Class I" remnants are elliptical-type galaxies with an $r^{1/4}$ radial profile. "Class II" systems have an exponential profile typical of spiral disks (Freeman 1907); a central bulge is present, too, but does not dominate the mass distribution, so that these systems cannot be simply regarded as elliptical galaxies with faint outer disks. Among the class II objects, Jog & Chitre (2002) have pointed out systems with kinematical properties typical of elliptical galaxies: they have velocity dispersions as large or larger than rotation velocity, while spiral disks are usually supported by rotation. We will call these merger remnants with spiral-like morphology and elliptical-like kinematics "hybrid" systems.

In this Letter, we test the hypothesis of Jog & Chitre (2002), that the unexplored range of mass ratios of 4:1 to 10:1 could lead to the formation of these hybrid systems in galaxy mergers. We present N-body simulations of galactic encounters with mass ratios 4.5:1 and 7:1, and show that the remnants reproduce the mixed properties observed in the hybrid systems. Mergers with such unequal-mass ratios are very likely to occur, since low mass galaxies are much more numerous than large-mass ones (e.g., Binney & Tremaine 1987).

2. Numerical simulations

We have used the N-body FFT code described in Bournaud & Combes (2003). The gravitational potential is computed on a cartesian grid of size 256^3 with a resolution of 700 pc. The number of particles is 10^6 for the most massive galaxy, and is proportional to the mass for the other one. The dissipative gas dynamics is included using a sticky-particles scheme, described in detail in the Appendix of Bournaud & Combes (2002), with parameters $\beta_r = \beta_t = 0.8$. Star formation and time-dependent stellar mass-loss are modeled by the code described and the parameters used in Bournaud & Combes (2002).

Send offprint requests to: F. Bournaud,
e-mail: `Frederic.Bournaud@obspm.fr`

Paper Merger II

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Galaxy mergers with various mass ratios: Properties of remnants

F. Bournaud[1], C. J. Jog[2], and F. Combes[1]

[1] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, 75014, Paris, France
e-mail: `Frederic.Bournaud@obspm.fr`
[2] Department of Physics, Indian Institute of Science, Bangalore 560012, India

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Abstract. We study galaxy mergers with various mass ratios using *N*-body simulations, with an emphasis on the unequal-mass mergers in the relatively unexplored range of mass-ratios 4:1–10:1. Our recent work (Bournaud et al. 2004) shows that the above range of mass ratio results in hybrid systems with spiral-like luminosity profiles but with elliptical-like kinematics, as observed in the data analysis for a sample of mergers by Jog & Chitre (2002). In this paper, we study the merger remnants for mass ratios from 1:1 to 10:1 while systematically covering the parameter space. We obtain the morphological and kinematical properties of the remnants, and also discuss the robustness and the visibility of disks in the merger remnants with a random line-of-sight. We show that the mass ratios 1:1–3:1 give rise to elliptical remnants whereas the mass ratios 4.5:1–10:1 produce hybrid systems with mixed properties. We find that the transition between disk-like and elliptical remnants occurs between a narrow mass range of 4.5:1–3:1. The unequal-mass mergers are more likely to occur than the standard equal-mass mergers studied in the literature so far, and we discuss their implications for the evolution of galaxies.

Key words. galaxies: evolution – galaxies: kinematics and dynamics – galaxies: formation – galaxies: interactions – galaxies: structure

1. Introduction

Mergers between galaxies are known to be frequent and can lead to a significant dynamical and morphological evolution of galaxies. Numerical simulations of mergers of two equal-mass spiral galaxies have been studied extensively (e.g., Barnes & Hernquist 1991; Barnes 1992). These have been shown to give rise to pressure-supported remnants with an $r^{1/4}$ radial mass profile, as observed in elliptical galaxies (de Vaucouleurs 1977). These so-called major mergers result in a dramatic violent relaxation leading to the formation of an elliptical galaxy, as was proposed theoretically (Toomre 1977). Recently, mergers of galaxies with comparable masses with the mass ratios in the range 1:1–3:1 or 1:1–4:1 have also been studied by *N*-body simulations (Bendo & Barnes 2000; Cretton et al. 2001; Naab & Burkert 2003). These also mostly result in elliptical-like remnants, but which can be disky or boxy.

These models were largely motivated by the observations of infrared-bright, ultra-luminous galaxies, which appear to be the result of comparable-mass galaxy mergers. A few of these mergers show an $r^{1/4}$ de Vaucouleurs profile typical of elliptical galaxies (e.g., Schweizer 1982; Stanford & Bushouse 1991; Chitre & Jog 2002). Thus, the main aim of these theoretical studies seems to be to show that merger remnants with elliptical-like mass profiles can form.

At the other extreme end of the range of mass ratios, the so-called minor mergers between a large galaxy and a satellite galaxy with a ratio of 10:1 or more have also been studied numerically (Quinn et al. 1993; Walker et al. 1996; Velaquez & White 1999). These result in hot, thickened disk galaxies which still have an exponential mass distribution, as in an isolated spiral galaxy (Freeman 1970).

Surprisingly, the large intermediate range of mass ratios (4:1–10:1) has not been explored in the literature, perhaps because there was no clear observational motivation for doing so. However, given that the observed mass spectrum of galaxies peaks at lower masses (i.e., the Schechter luminosity function, see e.g., Binney & Tremaine 1987), it is obvious that mergers with this mass range are more likely to occur than the equal-mass cases that have been studied commonly in the literature so far. Hence, such unequal-mass mergers need to be studied in detail. Note that these must be even more important in the early evolution of galaxies.

This new mass range (4:1–10:1) was explored recently in numerical simulations by Bournaud et al. (2004) who showed that the above range of mass ratios can result in "hybrid" systems with spiral-like morphology but elliptical-like kinematics. These results explain well the observed properties of a sample of advanced mergers analyzed by Jog & Chitre (2002), and the

Paper Merger III

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Astronomy & Astrophysics

Multiple minor mergers: formation of elliptical galaxies and constraints for the growth of spiral disks

F. Bournaud[1], C. J. Jog[2], and F. Combes[3]

[1] Laboratoire AIM, CEA-Saclay DSM/DAPNIA/SAp – CNRS – Université Paris Diderot, 91191 Gif-sur-Yvette, France
e-mail: `frederic.bournaud@cea.fr`
[2] Department of Physics, Indian Institute of Science, Bangalore 560012, India
[3] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, 75014 Paris, France

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ABSTRACT

Multiple, sequential mergers are unavoidable in the hierarchical build-up picture of galaxies, in particular for the minor mergers that are frequent and highly likely to have occured several times for most present-day galaxies. However, the effect of repeated minor mergers on galactic structure and evolution has not been studied systematically so far. We present a numerical study of multiple, subsequent, minor galaxy mergers, with various mass ratios ranging from 4:1 to 50:1. The N-body simulations include gas dynamics and star formation. We study the morphological and kinematical properties of the remnants, and show that several so-called "minor" mergers can lead to the formation of elliptical-like galaxies that have global morphological and kinematical properties similar to that observed in real elliptical galaxies. The properties of these systems are compared with those of elliptical galaxies produced by the standard scenario of one single major merger. We thus show that repeated minor mergers can theoretically form elliptical galaxies without major mergers, and can be more frequent than major mergers, in particular at moderate redshift. This process must then have formed some elliptical galaxies seen today, and could in particular explain the high boxiness of massive ellipticals, and some fundamental relations observed in ellipticals. In addition, because repeated minor mergers, even at high mass ratios, destroy disks into spheroids, these results indicate that spiral galaxies cannot have grown only by a succession of minor mergers.

Key words. Galaxy: evolution – Galaxy: structure – Galaxy: kinematics and dynamics – galaxies: elliptical and lenticular, cD – Galaxy: formation – galaxies: interactions

1. Introduction

Major mergers between spiral galaxies of similar masses are known to form elliptical-like galaxies. The remnants of such violent events present an $r^{1/4}$ radial mass profile, as observed in elliptical galaxies (de Vaucouleurs 1977), and are mainly pressure-supported. This is the case for equal-mass mergers (e.g. Barnes & Hernquist 1991; Barnes 1992), but more generally for mass ratios ranging from 1:1 to 3:1 and even 4:1, studied by Bendo & Barnes (2000), Cretton et al. (2001), Naab & Burkert (2003) and in Bournaud et al. (2005b, hereafter Paper I). The merger remnant tends to be boxy for 1:1 mergers, while 3:1 and 4:1 mergers mostly result in disky elliptical galaxies – that are not disk galaxies, but elliptical galaxies with a disky isophotal shape. An outer disk-like component appears in particular for mass ratios of 3:1 and higher (Naab & Trujillo 2006). It can be present even in 1:1 or 2:1 merger remnants but is far from being the main contribution to the total stellar mass. The disk component becomes more massive with increasing mass ratios. Beyond 4:1, mergers do not form elliptical galaxies any longer, but early-type disk-dominated systems (Bournaud et al. 2004, and Paper I). They are usually called "minor" mergers, but we have suggested in these earlier works that one should distinguish between "intermediate" mergers (between 4:1 and around 10:1) that form S0-like galaxies[1], and the real "minor" mergers with ratios larger than 10:1, where the remnants can be classified as (disturbed) spiral galaxies (Quinn et al. 1993; Velazquez & White 1999; Walker et al. 1996).

Existing studies of multiple mergers have focused on nearly-simultaneous mergers of several galaxies of comparable masses (Weil & Hernquist 1994, 1996; Bekki 2001). This typically corresponds to the collapse of a compact group into one single giant elliptical galaxy. Weil & Hernquist (1994, 1996) have shown that the elliptical galaxies produced by these events have some kinematical properties that differ from the remnants of pair mergers, and provide a better explanation for observed properties. Bekki (2001) has studied the starbursts occurring when such events involve gas-rich late-type spirals, and the possible connection with ULIRGs. There is observational evidence that some galaxies are remnants of the collapse of compact groups (e.g., Borne et al. 2000) or at least of the simultaneous merging of more than 2 galaxies (Taniguchi & Shioya 1998). However, these studies are limited to situations where the different galaxies merge nearly at the same time, and have comparable masses, so that the merger of only two of them would already have resulted in the formation of an elliptical galaxy.

In this paper, we study a different process: the multiple, sequential mergers of the intermediate and minor types – hereafter both called "minor" for simplicity – i.e. the mass ratios that do not form elliptical-like galaxies after one single merging event. This corresponds to a given spiral galaxy that gradually grows by merging with smaller companions. The mergers are not

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[1] These systems have a disk-like profile, but a massive bulge and their support is dominated by pressure instead of rotation, unlike spirals, making them rather S0-like (Jog & Chitre 2002; Bournaud et al. 2004)

2.2 Mergers and evolution on the Hubble Sequence

2.2.1 Early-type galaxy formation

Even though fashionable in the Λ-CDM hierarhical paradigm, mergers are not the only theoretical mechanism able to form spheroidal galaxies. At least two others could exist : early monolithical collapse (e.g., Larson 1975), and violent internal instabilities in disks (Noguchi 1999; Elmegreen et al. 2005). Can we then find evidence that ellipticals are formed by mergers, at least, for the moment, for the low-redshift ellipticals in the Local Universe ?

Some galaxies show direct evidence for recent merging, like the NGC7252 late-state merger (cf Fig xxx) its two long tidal tails and several shorter arcs and shells. As the central body in this system has elliptical-like morphology (including an azimuthally averaged "$r^{1/4}$" profile) and kinematics, it certainly confirms that major mergers of spirals can form ellipticals. But it does not probe that most ellipticals were formed by merger, as the vast majority of Local ellipticals do not show very obvious signs of past mergers. This is of course expected if most mergers are older than the timescale during which tidal debris are easily detected (around 1Gyr after the central coalescence of the merging pair for $M*$ galaxies at $z = 0$). Even recent interactions may not be easy to identify when the two protagonist have significantly different masses : see for instance our paper Merger IV on a possible recent collision between M32 and M31, which leaves little evidence in the optical data.

Some signs of past mergers can nevertheless last long in the morphology and kinematics of elliptical galaxies. This is the case, for instance, of Kinematically Decoupled Cores (KDCs). These are rather frequently observed in Local ellipticals (e.g., McDermid et al. 2007; Krajnović et al. 2008). Equal-mass mergers produce them rather easily, too, when simulated at high-enough resolution (a first, rough estimate from our on-going study may be around 20% in 1 :1 mergers). An example is show on Figure 2.3. They seemed less frequent in our study of multiple minor mergers (although a comparison at fixed resolution and other parameters is needed (work in progress)). Alternative scenarios (for instance spheroid formation by violent disk instabilities, Section XXX) do not seem to produce KDCs frequently, if not at all. The high fraction of KCDs, and other kinds of morphology/kinematic misalignments in early-type galaxies, likely indicates that a at least significant part is the produce of past galaxy mergers – those galaxies that have KCDs should even have undergone their last merger when the gas fraction was relatively high (∼10% of higher).

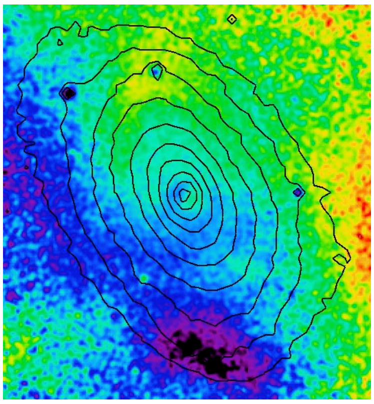

Fig. 2.3 – tbc

Some other signs for past mergers could lie in the population of Globular Clusters (GCs) around elliptical galaxies. There is strong evidence that elliptical galaxies have a higher specific fraction of GCs than later-type spirals. There is also some (relatively disputed) evidence that the population of GCs around early-type galaxies is bimodal, with some old, low-metallicity GCs and some young, higher-metallicity ones. The standard interpretation is that the former population is formed early in the Universe (?) and present around galaxies of all types. The younger population would be formed during major galaxy mergers, thus present around today's early-type galaxies. This has long been a putative interpretation, though. Starbursting mergers are observed to have many super star clusters (SSCs) that could be the progenitor of GCs (e.g., Mengel et al. 2008) but whether or not they are long-lived, bound structures depends on their mass, which observationally depends on the IMF. Hydrodynamical simulations had shown that the pressure in galaxy mergers could be high enough to theoretically enable the formation of massive bound star clusters (Li et al. 2004). However the formation of GCs had not been resolved directly ; also these models (SPH) computed the thermal pressure while standard theories indicate that the turbulent pressure is the driver of star formation and star-cluster formation (Elmegreen 2002).

We have performed a wet major merger simulation with unprecedented spatial and mass resolution of 32 pc and 7×10^3 $M_\odot$ (the later is the particle mass ; at least 10-20 particles are required to resolve the formation of a bound self-gravitating structure). Here we directly resole the formation of massive, self-gravitating and tightly bound star clusters (see paper Merger V). These clusters form in regions with enhanced gas turbulent speeds (tidal tails and other gas flows) where high densities and velocity dispersions ensure a high Jeans mass. They are strongly bound, and compact (< 100 pc in diameter). We show in the paper that at infinite resolution they would be even more compact. These clusters are thus robust candidate as long-lived GCs, and this extends to the observed super star clusters in on-going major mergers. Our results thus confirm that the large, and likely bimodal, population of GC around elliptical galaxies is fully consistent with a merger origin. A low redshift, no other know mechanism could form GCs so efficiently (but there might be some at higher-z). Thus, at least for the "not too old" ellipticals, their GC population can be seen as another probe of their merger origin.

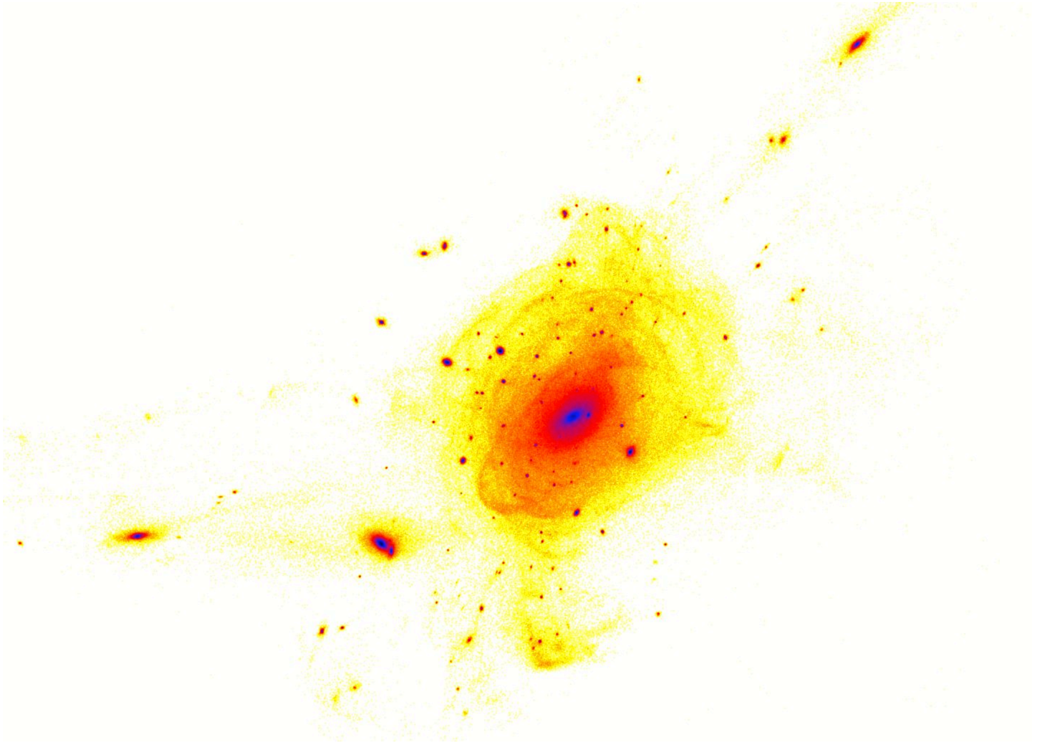

Fig. 2.4 – tbc

Paper Merger IV

An almost head-on collision as the origin of two off-centre rings in the Andromeda galaxy

D.L. Block[1], F. Bournaud[2,3], F. Combes[2], R. Groess[1], P. Barmby[4], M.L.N. Ashby[4], G.G. Fazio[4], M.A. Pahre[4], S.P. Willner[4]

[1] Anglo American Cosmic Dust Laboratory, School of Computational and Applied Mathematics, University of the Witwatersrand, Private Bag 3, WITS 2050, South Africa
[2] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, F-75014, Paris, France
[3] Present Adress: DSM/DAPNIA/Service d'Astrophysique, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France
[4] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts

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Abstract. The unusual morphology of the Andromeda Spiral (Messier 31, the closest spiral galaxy to the Milky Way) has long been an enigma. Although regarded for decades as showing little evidence of a violent history, M 31 has a well-known outer ring[1-7] of star formation at a radius of 10 kpc whose center is offset from the galaxy nucleus. In addition, the outer galaxy disk is warped as seen at both optical[8] and radio[9] wavelengths. The halo contains numerous loops and ripples. Here we report the discovery, based on analysis of previously-obtained data[10], of a second, inner dust ring with projected dimensions 1.5 by 1 kpc and offset by $\sim$ 0.5 kpc from the center of the galaxy. The two rings appear to bedensity waves propagating in the disk.Numerical simulations offer a completely new interpretation for the morphology of M 31: both rings result from a companion galaxyplunging head-on through the center of the disk of M 31. The most likely interloper is M 32. Head-on collisions between galaxies are rare, but it appears nonetheless that one took place 210 million years ago in our Local Group of galaxies.

Newly-acquired images[10] of M 31 secured by the Infrared Array Camera[11] (IRAC) onboard the Spitzer Space Telescope span the wavelength regime of 3.6 to 8.0 microns. These images offer unique probes of the morphologies of the stellar distribution and interstellar medium with no interference from extinction. Figure 1 shows the emission map of the interstellar medium at 8 microns, generated by subtracting a scaled 3.6 micron image (dominated by starlight) from the 8 micron image. The subtraction removes the contribution from stellar photospheres and leaves only the emission from dust grains[10], which trace the interstellar medium of M 31. What is most striking in Figure 1 (and in the enlarged inset) is the presence of a complete though asymmetric inner ring of dust 6.9 by 4.4 arcmin in extent, translating to linear dimensions of about 1.5 by 1 kpc (assuming a distance[12] of 780 kpc). The inner ring lies between the two well known Baade spiral dust arms[13], both of which are clearly seen in emission. The inner ring is elongated in a direction close to the minor axis and belongs to the central gas disk, which appears to be more face-on[14]. It is therefore not possible to know the inner rings precise ellipticity, but it is unlikely to be circular. IRAC imaging thus reveals two rings. The outer ring is offset by approximately 10 percent of its radius, while the inner ring is offset by about 40 percent or 0.5 kpc. The inner elliptical ring has been alluded to in earlier studies[15,16], but all investigators have hitherto believed it to be a mini-spiral, related to a bar. Published Spitzer 24 micron images5 of M 31 show centrally-concentrated dust emission; the ring morphology is therefore disguised at these longer wavelengths. The IRAC images beautifully show the inner ring at high spatial resolution and furthermore confirm that this feature is a complete and continuous ring, even though offset and asymmetrical. There are two known scenarios whereby disk systems form rings: by head-on galaxy collisions or by rotating bars. Head-on collisions differ from common tidal interactions between galaxies because the pericentric distance of the orbit of the companion is small and its orbit is almost perpendicular to the target disk. Such collisions produce expanding ring-shaped waves[17]. Rotating bars in spiral disks produce inner, outer, and sometimes nuclear rings in barred spiral galaxies. The rings occur at orbital resonancesand arise from the galaxys internal dynamics (unlike collisional rings). Many examples of bar-induced rings are known[18].

Send offprint requests to: D.L. Block e-mail: `block@cam.wits.ac.za`

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High-resolution simulations of galaxy mergers: Resolving globular cluster formation

F. Bournaud[1,2⋆], P.-A. Duc[2,1] & E. Emsellem[3]
[1] *CEA, IRFU, SAp, F-91191 Gif-sur-Yvette, France*
[2] *Laboratoire AIM, CNRS, CEA/DSM, Université Paris Diderot. F-91191 Gif-sur-Yvette, France.*
[3] *Université de Lyon, Lyon, F-69003, France ; Université Lyon 1, Observatoire de Lyon, 9 avenue Charles André, Saint-Genis Laval, F-69230, France CNRS, UMR 5574, Centre de Recherche Astrophysique de Lyon ; Ecole Normale Supérieure de Lyon, Lyon, F-69007, France*

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ABSTRACT

Massive star clusters observed in galaxy mergers are often suggested to be progenitors of globular clusters. To study this hypothesis, we performed the highest resolution simulation of a gas-rich galaxy merger so far. The formation of massive star clusters of 10^5 to 10^7 $M_{\odot}$, triggered by the galaxy interaction, is directly resolved in this model. We show that these clusters are tightly bound structures with little net rotation, due to evolve into compact long-lived stellar systems. Massive clusters formed in galaxy mergers are thus robust candidates for progenitors of long-lived globular clusters. The simulated cluster mass spectrum is consistent with theory and observations. Tidal dwarf galaxies of 10^{8-9} $M_{\odot}$ can form at the same time, and appear to be part of a different class of objects, being more extended and rotating.

Key words: globular clusters: general – galaxies: star clusters – galaxies : interactions

1 INTRODUCTION

Globular clusters (GCs) are an important fossil record of the evolution of physical conditions in galaxies (Bekki et al. 2008), because the formation of massive clusters is triggered by shocks and high pressures in the interstellar medium (van den Bergh 1979; Ashman & Zepf 2001). Fundamental properties along the Hubble sequence are a higher frequency of GCs around elliptical than disk galaxies (Harris 1991) and a bimodal population in particular around early-type galaxies, with a population of low-metallicity GCs and a population of younger, higher-metallicity ones (Ashman & Zepf 1992).

Since the works of Schweizer (1987) and Whitmore et al. (1993), there has been increasing evidence that young massive star clusters (YMC) form in interacting and merging galaxies, and these are often proposed to be GC progenitors. Theoretically, massive clusters form in mergers because of shocks and high turbulent pressure in interacting galaxies, which favors the formation of tightly bound clusters rather than unbound associations (Elmegreen & Efremov 1997). If GCs can form this way, given that most elliptical galaxies formed by galaxy mergers (Naab & Burkert 2003, Bournaud et al. 2005), this mechanism could account for the youngest and most metallic GCs that are more frequent around early-type galaxies (Ashman & Zepf 2001). These GCs would come in addition to those formed early in the Universe as a result of thermal instabilities in protogalaxies (Fall & Rees 1985), strong shocks at the epoch of the Reionization (Cen 2001), or stripping of nucleated dwarf galaxies (Freeman 1990; Gao et al. 2007). Nevertheless, that an important population of GCs formed in galaxy mergers is still challenged by some observations (Spitler et al. 2008). Whether or not YMCs formed during mergers contribute to the present-day GC populations is still an open question also because the long-term evolution of such YMCs is uncertain (see de Grijs 2007). A requirement for YMCs to become long-lived GCs is that they should be gravitationally bound, which is difficult to assess observationally, as the velocity dispersion of a cluster does not directly trace its mass because of mass segregation (Fleck et al. 2006). The survival issue is further complicated by the the mass-loss of clusters if their IMF is too shallow, and by the tidal field of the parent galaxy which may progressively disrupt these clusters (Miocchi et al. 2006).

Numerical simulations are a powerful tool to study galaxy mergers, but resolving the formation of star clusters in self-consistent models requires a huge dynamical range, because structures smaller than 100 pc should be resolved in a simulated volume larger than 100 kpc. Models by Bekki et al. (2002) and Kravtsov & Gnedin (2005) have shown that the pressure and density required to form massive bound star clusters could be reached in galaxy mergers. They could

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[⋆] E-mail: frederic.bournaud@cea.fr

2.2.2 (Tidal) dwarf galaxy formation

Tidal dwarf galaxies are another class of structures form in galaxy mergers. A large number of merging galaxies exhibit massive gas accumulations in the outermost regions of their tidal tails (see examples on Fig. 2.5). As these structures host molecular gas and star formation, and can be as massive as a few 10^9 M$_\odot$ of baryons, they ave long been considered as candidate for newly formed dwarf galaxies of second generation.

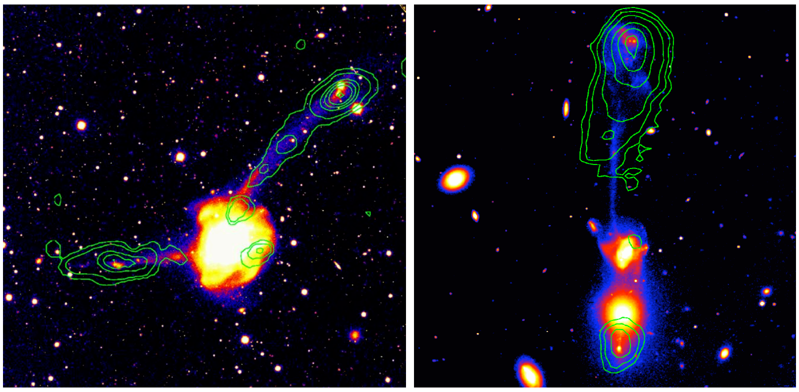

Fig. 2.5 – tbc

Our early work on this topic (Bournaud et al. 2004) has shown that, at least a large number of these objects were not chance alignments of tidal filaments along the line-of-sight, with high densities only in 2-D projections on the sky, but genuine accumulations of matter with high 3-D densities. A first argument was from the detection of molecular gas (Braine et al. 2000, 2001) but the issue had remained open (?). Our study based on the kinematics of tidal tails to restore their 3-D morphology has helped solve this concern. Observed "Tidal Dwarf Galaxy" (TDG) candidates are indeed genious accumulations of matter. We also provided some new evidence that these objects could be self-gravitating and possibly long-lived – not just diffuse gas clouds, so that the "Tidal Dwarf" naming was fully justified.

Studying how these objects could form in numerical simulations (Bournaud et al. 2003; Duc et al. 2004) we realized that their observed location frequently near the tip of tidal tails is not anecdotic. It actually results from large gas masses being pilled-up here (a characteristic of tidal tails tat requires very extended, ∼150-kpc-sized haloes for a Milky-Way like disk) and these firstly kinematically generated gas accumulations then becoming self-gravitating and dynamically decoupled from the rest of the system. A largely similar mechanism had been proposed by (Elmegreen et al. 1993), where giant molecular clouds become self-gravitating when they are expulsed into tidal tails during a galaxy interaction. The increased velocity dispersion and Jeans mass then allow structures as massive as dwarf galaxies to collapse in this process. Our mechanism slightly differs by having the whole outer disk, or a whole part of it, pilled-up in the outer tidal tails, without even requiring a precursor substructure : the overdense gas region that eventually collapses into a tidal dwarf can arise naturally from the kinematical response of a tidally disturbed disk.

Another mechanism for the formation of bound structures in tidal tails had been proposed by Barnes & Hernquist (1992). It consist of local gravitationnal (Jeans) instabilities in dense and gas-rich tidal tails. This mechanism however fails to account for the highest mass tidal dwarfs, observed to form preferentially near the tip of the tails. In our recent high-resolution simulation resolving SSC/GC formation as described above, we found that the mass distribution is likely bimodal, with SSCs up to $\sim 10^7$ M$_\odot$ and TDGs of a few $\sim 10^{8-9}$ M$_\odot$. The idea that two different families of objects does not come only from the suspected bimodal mass distribution : these objects also form at different location, and more importantly they have very different properties : the SSC/GC in our classification are very compact, pressure supported spheroids that converted their gas into stars with a high efficiency, while TDGs have large radii (even when rescaled to their mass) and are rotating disks forming stars at a lower rate. [RENVOYER AU PROCEEDINGS PLUS LOIN ?]. The objects studied by Barnes & Hernquist, and more recently at higher resolution by (Wetzstein et al. 2007), are probably the high mass end of the SSC distribution – or SSCs biased to higher masses in the case of early low resolution models. The most massive one can reach a few 10^7 M$_\odot$ in both their model and ours : these could indeed evolve into dwarf galaxies once the tidal tails have dissolved, but they will be another class (lower-mass and more compact ones) than the most striking TDGs forming at large distances from their parent galaxies. Our Figure 2.6 illustrates a typical case with high-mass, rotating disk TDGs forming near the end of tails (objects A, B and perhaps F) and a few lower mass objects forming at smaller radii. Our high-resolution merger simulation show earlier on Fig. 2.4 also has three massive tip-of-tails TDGs, and more than 100 of SSCs, the most massive of which may evolve into supermassive GCs (or small TDGs).

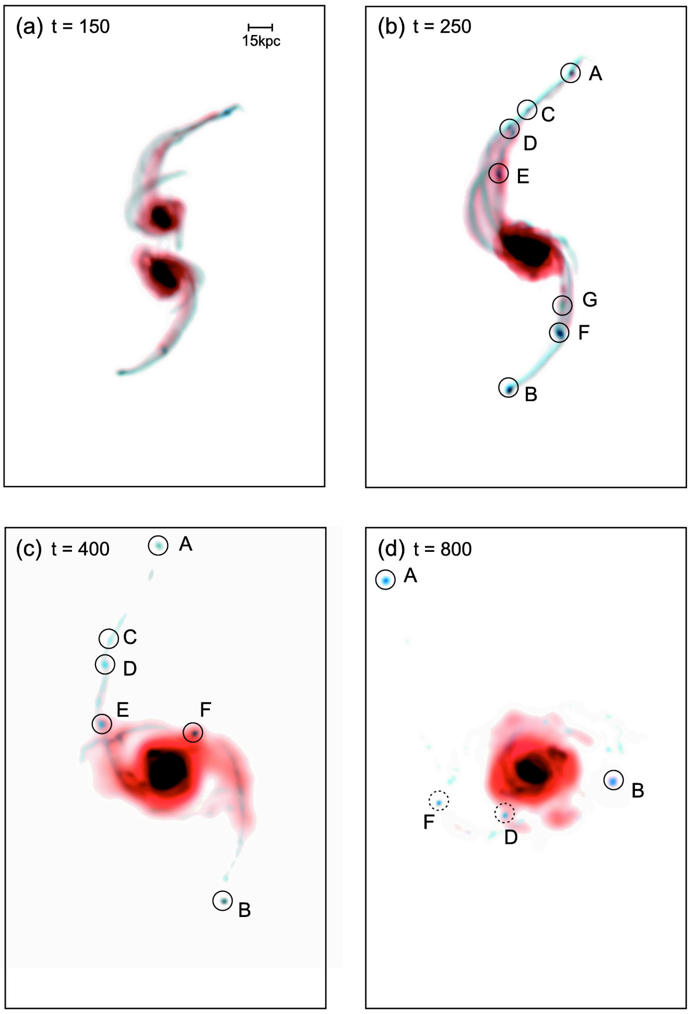

Fig. 2.6 – tbc

An important question for general galactic studies is whether Tidal Dwarfs can significantly contribute to the global population of dwarf galaxies in the Universe. We have performed an extensive, statistical study to study this issue (paper Merger VI). Major mergers (1 :1–3 :1) are required to form tidal dwarfs efficiently. More minor mergers around 5 :1 or 7 :1, only the low mass companion is affected in a strong way and can have its material forming TDG-like objects (but of lower mass and more limited lifetime), the most massive progenitor does not form long tidal tails and tidal dwarfs. At higher mass ratios (10 :1 and above) the small galaxy is too severely disrupted, and no gravitationally bound structure can form in the intense tidal field, so no tidal dwarf form at all in these cases.

In our sample of almost 100 simulations of major mergers, we have studied how frequently TDGs form and whether or not they can survive. We find that a large fraction can survive more than 2 Gyrs, appearing as "normal" dwarf satellite galaxies around the early-type merger remnant (see examples on Figs. 2.6 and 2.7). Some (of low masses in general) are disrupted by the tidal field in which they are embedded, some others fall back rapidly onto their massive progenitor. But that actually limits the contribution of TDGs to the global dwarf satellite galaxies is not their lifetime, but rather the fact that no more than 1-2 TDG can be formed per major merger (on average). Our statistical results indeed imply that only a few percent of dwarf galaxies at $z = 0$ could have been formed during past galaxy mergers. Nevertheless, the contribution could be much higher around early-type galaxies, and in particular around elliptical major merger remnant : there the contribution could be a few tens of percents. Note also that, if the high mass end of the Super Star Clusters formed in mergers evolve into compact spheroidal dwarfs rather than globular clusters, they could form an additional family of lower mass tidal dwarfs, and increase the contribution. It has hence been suggested that, if this process was efficient in gas-rich mergers at high redshift, the intriguing Great Planes of dwarf galaxies could be alignments of tidal dwarfs formed at high redshift, along the planes in which their progenitor tidal features lied (Metz et al. 2007).

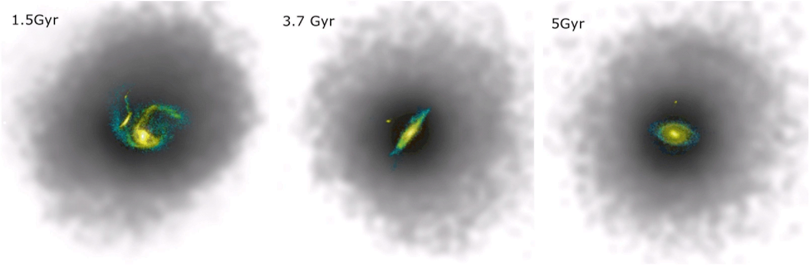

Fig. 2.7 – tbc

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From tidal dwarf galaxies to satellite galaxies*

F. Bournaud[1] and P.-A. Duc[2]

[1] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, 75014 Paris, France
e-mail: `Frederic.Bournaud@obspm.fr`
[2] CNRS UMR 7158, AIM, & CEA/DSM/DAPNIA, Service d'Astrophysique, Saclay, 91191 Gif-sur-Yvette Cedex, France

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ABSTRACT

The current popular cosmological models have granted the population of dwarf satellite galaxies a key role: their number, location, and masses constrain both the distribution of dark matter and the physical evolution of their hosts. In the past years, there has been increasing observational evidence that objects with masses of dwarf galaxies can form in the tidal tails of colliding galaxies, as well as speculations that they could become satellite-like galaxies orbiting around their progenitors and thus be cosmologically important. Yet, whether the so-called "Tidal Dwarf Galaxy" (TDG) candidates are really long-lived objects and not transient features only present in young interacting systems is still largely an open question to which numerical simulations may give precise answers. We present here a set of 96 N-body simulations of colliding galaxies with various mass ratios and encounter geometries, including gas dynamics and star formation. We study the formation and long-term evolution of their TDG candidates. Among the 593 substructures initially identified in tidal tails, about 75% fall back onto their progenitor or are disrupted in a few 10^8 years. The remaining 25% become long-lived bound objects that typically survive more than 2 Gyr with masses above 10^8 $M_\odot$. These long-lived, satellite-like objects, are found to form in massive gaseous accumulations originally located in the outermost regions of the tidal tails. Studying the statistical properties of the simulated TDGs, we infer several basic properties that dwarf galaxies should meet to have a possible tidal origin and apply these criteria to the Local Group dwarfs. We further found that the presence of TDGs would foster the anisotropy observed in the distribution of classical satellite galaxies around their host. Identifying the conditions fulfilled by interacting systems that were able to form long-lived tidal dwarfs – a spiral merging with a galaxy between 1/4 and 8 times its mass, on a prograde orbit, with an orbital plane inclined up to 40 degrees to the disk plane – and estimating their fraction as a function of redshift, we roughly estimate their contribution to the overall population of dwarfs. We conclude that a small but significant fraction of them – a few percent – could be of tidal origin. This number may be underestimated in particular environments such as the vicinity of early-type galaxies or in groups.

Key words. galaxies: interactions – galaxies: kinematics and dynamics – galaxies: formation – galaxies: evolution – galaxies: structure

1. Introduction

The properties of dwarf satellite galaxies that surround spirals and ellipticals are often used to constrain cosmological models. Their number has been actively debated since cosmological simulations have shown that the low-mass dark halos are much more numerous around their massive hosts than the dwarf galaxies identified around the Milky Way (e.g., Klypin et al. 1999; Moore et al. 1999). Moreover, the spatial distribution of satellites can provide information on the mass and shape of dark haloes (Zaritsky et al. 1997; Brainerd 2005; Lee & Kang 2006). Finally, as building blocks, they play a major role on the physical evolution of massive galaxies with which they will eventually merge. It is generally assumed in such studies that dwarf galaxies have a cosmological primordial origin and were not formed recently. However, there is growing evidence that objects with masses typical of dwarf galaxies form in the tidal tails that surround colliding and merging spiral galaxies (e.g., Duc & Mirabel 1994, 1998; Hibbard et al. 2001; Mendes de Oliveira et al. 2001; Temporin et al. 2003; Knierman et al. 2003). Many of these so-called Tidal Dwarf Galaxies (TDGs) appear to be self-gravitating objects (Braine et al. 2000; Bournaud et al. 2004). If these tidal objects are long-lived, they could contribute to the total population of dwarf satellites in addition to primordial dwarfs. Their statistical properties would then be modified and the possible constraints on cosmological models would have to be updated.

Dwarf galaxies presently observed to form in tidal tails could, however, be short-lived. Indeed, dynamical friction may cause a rapid orbital decay. Hibbard & Mihos (1995) have shown that a large part of the once expelled tidal material falls back onto the parent spiral galaxies in a few hundreds of Myr, but the timescale increases to Gyr in the outer regions; thus, the tidal dwarfs formed there may have a significant lifetime. Also, dwarf galaxies may be disrupted by the tidal field of their progenitor even if the internal orbits of their stars are not resonant with their orbital period (e.g., Fleck & Kuhn 2003); this disruption process can take a few billion years depending on their mass, orbit, and concentration. Thus, the lifetime of tidal dwarfs is a priori rather uncertain and their cosmological importance far from being proven.

Actually, no real old TDGs, still surviving after the merger of their progenitors and the vanishing of the umbilical cord linking them to their parents, has yet been unambiguously found, although candidates were discussed in the literature (Hunter et al. 2000; Duc et al. 2004b, and references therein). Because of the difficulties in identifying a tidal origin in evolved galaxies, numerical simulations appear to be unavoidable in

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* The appendix is only available in electronic form at `http://www.edpsciences.org`

Chapitre 3

Low redshift galaxies : towards other formation mechanisms

3.1 Barred galaxies

3.1.1 Bar dissolution

Most disk galaxies in the Local Universe are barred, especially when observed in the near-infrared where the stellar disk is unveiled from dust (e.g., Eskridge et al. 2000). This is surprising given many theoretical works in the 90's that were showing that bars should be short lived (Hasan & Norman 1990, Pfenniger & Norman 1990, Friedly & Benz 1993, Berentzen et al. 1998). The bar dissolution mechanism described in these works was the following : bar exert gravity torques on the gas disk, and gas inside the corotation falls into a central mass concentration (CMC). Orbits are cahotic during the growth of the CMC, which strongly weakens or dissolves the bar.

In this context, we had published our 2002 work (here paper Bar II) weeking for re-formation mechanisms to explain the ubiquity of bars at $z = 0$. Later-on, the hypothesis of bar dissolution by the growth of CMCs has been challenged : Shen & Sellwood (2004) have shown that the effect of CMCs had been over-estimated by the first models, because of a too low resolution. Regan & Teuben (2004) also point out that a too viscous ISM model induces artificial torques that can accelerate the growth of the CMC and bar weakening.

I will thus present first our 2005 study (here paper Bar I) where we argue that the dissolution of bars in our models is robust, and that the initial disagreement with other authors does not come from different numerical results, but from the role of the CMC having been over-estimated in the 90's. In this paper, we do agree with others like Shen & Sellwood that a "realistic" CMC is not massive enough to strongly weaken the bar, but we show that another mechanism participates to the bar dissolution in self-consistent simulations.

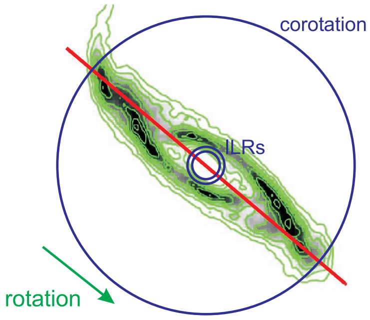

Fig. 3.1 – tbc

First of all, what initiates the whole bar weakening processes is the response of gas to the barred potential. Between the ILRs (if any) and the corotation (CR) resonance, the gas is concentrated on the leading side of the bar (e.g., Athanassoula 1992, and Fig. 3.1 for our models). We checked in our models that the gas response is realistic compared to observed nearby barred spirals : inside the CR, gas looses typically $\simeq 5-10\%$ of its angular momentum per rotation in our simulations, which is also what is estimated in observations (our paper bar I, see also Boone et al. 2007, Hunt et al. 2008, etc..). Viscous torques in our simulations are negligible compared to the gravitational forces. As a result of the gravity torques between the stellar bar and the gas dust-lanes, two processes weaken or dissolve the bar :

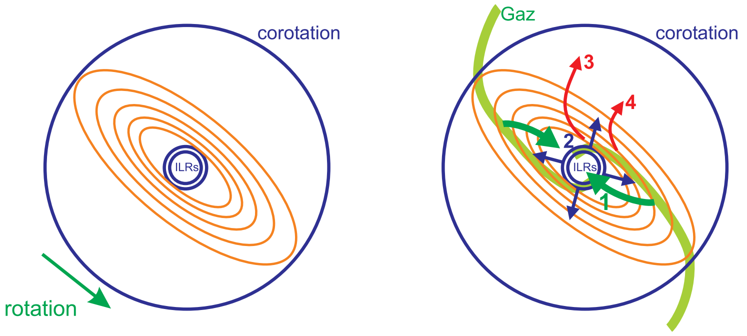

Fig. 3.2 – tbc

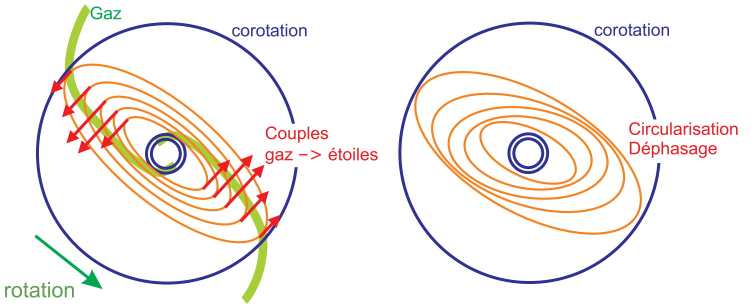

Fig. 3.3 – tbc

- The gas on the leading side of the bar undergoes negative gravity torques, looses angular momentum and falls into the CMC. The growth of the CMC increases the ILR radius, or creates an ILR if none was initially present. The innermost X1 orbits are affected by the change of orbit, become cahotic and do not participate to the bar structure anymore. This mass redistribution affects the rest of the bar which is weakened too (see Fig. 3.2).
- Gas on the leading side of the stellar bar exerts positive gravity torques on the stars in the bar. Stars on X1 orbits gain most angular momentum around the apocenter of their orbit ; this tends to circularize the orbits, and to apply a phase shift that varies with radius : rounder and unaligned orbits directly weaken or dissolve the bar (see Fig. 3.3).

We performed test models including only the same CMC as the full simulation, but where the second effect (poistive gas torques on the stellar bar) is suppressed ; we then find that the CMC alone is generally unsufficient to fully dissolve the bar, and the resulting bar weakening is much more modest than in the complete simulation. This is in agreement with the result of Shen & Sellwood (2004) that studied the response of a purely stellar bar to the growth of an imposed CMC. The strong weakening or full dissolution of bars observed in our models with 10% of gas is a result of the two processes above.

Depending on the bulge/disk/halo parameter, we typically find that a gas mass fraction of 5% in the disk leads to significant weakening, but not full dissolution, and gas fractions around 10% or above lead to a strong weakening is not full dissolution. Quite often, an $m = 2$ mode remains present in the form of a lens (see Fig. 3.4) ; which by the way resembles many observed galaxies. We call this a "dissolved" bar in our model in the sens that the strong bar present before is not seen anymore ; some other authors would probably called this a "weakened" bar in the sens that an $m = 2$ mode still exist. In the present discussion, I use the "dissolved bar" wording to allude to a galaxy that has been strongly barred (SB in the de Vaucouleur's classification) and is not strongly barred anymore (can be SA or SAB).

To ensure of the reliability of the results, we had compared the gravity torques to some observed cases (paper bar I + other references above). I also performed simulations with an hydrodynamical scheme (BGK kinetic scheme, following the work of REF–Slyz 2003). The paper is in preparation, but I find similar results compared to the sticky-particle simulations, namely that a gas fraction of 10% strongly weakens or dissolves bars in most spiral galaxies, in a few Gyrs. ADD A FIGURE SHOWING EXAMPLES.

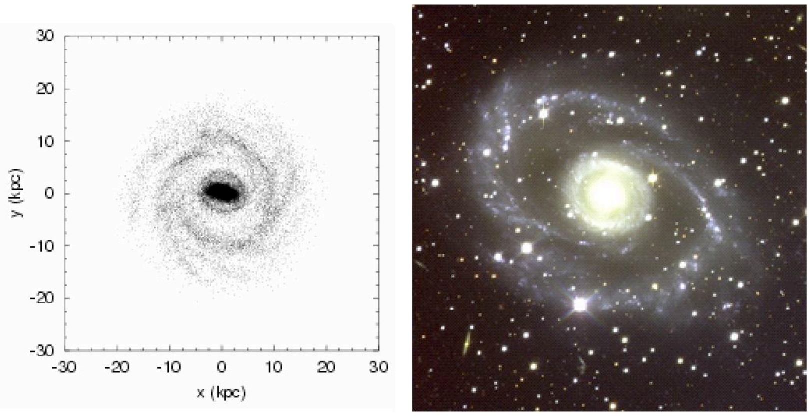

FIG. 3.4 – tbc

Nevertheless, other authors using self-consistent simulations find galactic bars that survive 10 Gyrs or more : for instance Curir et al. 2006, Berentzen et al. 2006, Martinez-Valpuesta et al. 2006.. The difference needs to be explained. It does not seem to result from different modelling (SPH vs. sticky-particles) as our paper bar I shows that star/gas gravity torques are the same in our sticky-particle models, in SPH models, and in observations.

In fact the difference more likely comes from different hypothesis on the dark matter halo. We use cored dark matter profiles, with a relatively low dark to visible mass ratio inside the disk radius (not a maximum disk, but not far from it). The other authors above have used more massive, more concentrated dark halos, with a cuspy NFW profile or a similar one. We may argue that our choice is supported by observations (REF-Bosma, REF-Things : Trachternach et al. 08, de Blok et al. 08), but other choices would be supported by cosmological models. In particular the work by Curir et al. directly uses dark matter haloes produced in cosmological simulations. A more massive/concentrated dark matter halo will incerase the lifetime of bars :

- by diluting the gravity torques in the axisymetrical halo potential
- by removing angular momentum from the bar in a dynamical friction process (Athanassoula 2002).

and Curir et al. (2006) simulation indeed show that bars are much easier to weaken for high disk/halo mass ratios. We even note that the highest disk/halo ratio in Curir et al's simulations correspond to the lowest one in some of our models, and our results are then in agreement regarding the lifetime of the bar and the mass fraction of gas needed to dissolve it.

It would be difficult to conclude on the lifetime of bars for gas fraction between 5 and 10% without speculating on the dark matter fraction. WIth 5% of gas, bars can be short-lived, transient features for almost maximum disk models, and can be long-lived, robust, with NFW-like halos. But for gas fraction of 10% and above, if the dark matter mass within the disk radius is kept compatible with observational contraints, bars will be dissolved or at least strongly weakened (SB → SAB) in less than a Hubble time. It is then difficult to know if the bars seen in today's spiral will be long-lived or not, but this is not the most interesting question anyway. Bars seen at $z > 0.5$, with gas fraction higher than in today's spiral, can hardly be long lived and survive until $z = 0$. This is why the high fraction of barred galaxies both in the Local Universe (Eskridge et al. 2000, White et al. 2002) and at $z = 0.5 - 1$ (Sheth et al. 2003, Elmegreen et al. 2004, Jogee et al. 2004) is posing a theoretical challenge.

Note : Recent results are questioning how "constant" the bar fraction is between $z = 1$ and $z = 0$. I will come back in more detail to the discussion on bar evolution with redshift in the "Perspective" Chapter-XXX, after studying the nature of high-redshift galaxies. For the moment, I will discuss, based mostly on our 2002 paper, how a high fraction of bars can be maintained over a Hubble Time if bars cannot be long-lived structures in gas-rich spiral galaxies.

3.1.2 Bar reformation

A first possibility to re-form bar in order to keep the bar fraction high over Gyrs and/or prevent their weakening, could be galaxy interactions. For instance Gerin et al. (1990) have shown that the interaction with a companion on a direct orbit (co-rotating with the bar) can strengthen the bar. But at the opposite, an interaction on a retrograde orbit would weaken the bar. No strong net effect on the bar fraction is then expected. In more detail, as there are more barred galaxies than unbarred/wekly-barred ones, the destruction of a pre-existing bar due a a retrograde encounter should be more frequent than the formation of a bar in a previously unbarred galaxies during a prograde encounter. The net effect, as detailed by Elmegreen (2004), would be a slightly decreasing bar fraction with decreasing redshift. This mechanism is not compatible with the observations that show a constant or increasing bar fraction with decreasing redshift. van den Bergh (2002) has also shown that the presence of companions does not affect the presence of bars in spiral galaxies. Even worse, while interactions can strengthen an existing bar (under some conditions), Berentzen et al. (2004) show that they cannot reform a new bar after the dissolution of a previous bar, and not even re-strengthen the oval-shaped structure left over after bar dissolution into a new SB bar. the disk is too stable after the dissolution of the first bar, it can be distorted when a companion is present by no strong $m = 2$ mode will persist when the companion is further away. Galaxy interactions alone cannot thus explain why most spirals are barred today, while they were already barred 10 Gyrs ago.

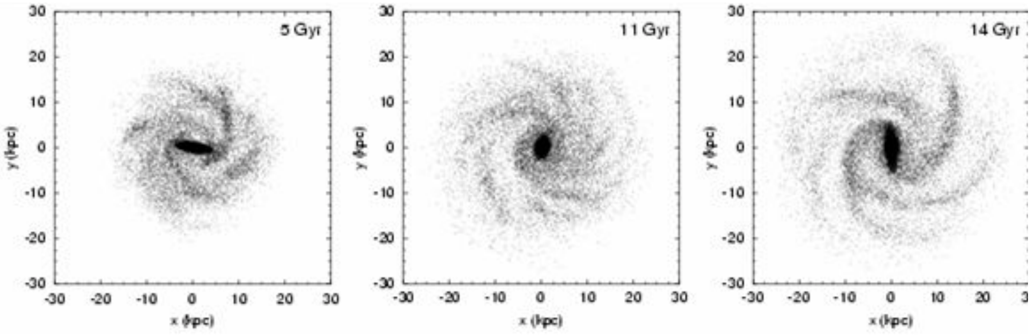

FIG. 3.5 – tbc

As shown in our 2002 paper (paper Bar II), strong bar reformation can be achieved if the mass of the disk is increased, without increasing its V/σ ratio. This decreases the Toomre Q parameter, by reducing the stabilizing influences of the bulge and the previously formed CMC. This is the case in particular when a galactic disk accretes large amounts of cold gas, for instance from cosmic infall. This gas is gradually converted into low-velocity-dispersion stars in the disk. A new strong bar can then appear a few Gyrs after the first bar episode, and up to three or four bars can be formed/dissolved within a Hubble Time. We show on Fig. 3.5 and example of a strong SB bar that is dissolved into a faint SAB lense, and a strong SB bar is reformed again. The properties of the reformed bars can differ from the previous one (pattern speed, etc..) in a way that usually depends from the accretion parameters (angular momentum of the accreted material), as detailed in the paper.

The reformation of strong bars by external gas accretion requires accretion rate of a few M$_\odot$/yr for M$_*$ galaxies. This is somewhat larger what can be observed for Local spirals (e.g., Fraternali & Binney 2008) and the Milky-Way. It could thus be that present-day galaxies cannot reform their bars anymore by this process. But as discussed earlier, the gas fraction of today's spiral may not be high enough to dissolve their bars (depending on the dark halos concentration). At higher redshift however, the gas fraction was higher, making the lifetime of bars definitely shorter than a Hubble Time. At the same time the accretion rate of spirals was easily several M$_\odot$/yr, if not a few tens of M$_\odot$/yr at $z \sim 1$ (e.g., Katz et al. 2005) : this according to our models is sufficient to reform strong bars a couple of Gyrs after the previous bar is dissolved.

If present-day spirals were already mostly barrred at the $z1$ epoch (which several observations support), then the fact they most are still barred today can be explained by the internal evolution of bars, and by galaxy interactions/mergers. This property of spiral galaxies implies that substantial amount of gas have been accreted by disks between $z \simeq 1$ and $z = 0$. For a Milky-Way like galaxy, our model would imply a typical infall rate of 10 M$_\odot$/yr over the last 8 Gyrs : the newly accreted mass would then be $\simeq 8 \times 10^{10}$M$_\odot$/yr below $z \simeq 1$. This is globally compatible with the stellar populations of the thin disk, as well as the average mass growth of spirals in cosmological models (about doubling their baryonic mass from $z = 1$ to 0).

Paper Bar I

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The lifetime of galactic bars: central mass concentrations and gravity torques

F. Bournaud,[★] F. Combes and B. Semelin
Observatoire de Paris, LERMA, 61 av. de l'Observatoire, F-75014, Paris, France

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ABSTRACT

Bars in gas-rich spiral galaxies are short-lived. They drive gas inflows through their gravity torques, and at the same time self-regulate their strength. Their robustness has been subject of debate, as it was thought that only the resulting central mass concentrations (CMCs) were weakening bars, and only relatively rare massive CMCs were able to completely destroy them. Through numerical simulations including gas dynamics, we find that with the gas parameters of normal spiral galaxies, the CMC is not sufficient to fully dissolve the bar. But another overlooked mechanism, the transfer of angular momentum from the infalling gas to the stellar bar, can also strongly weaken the bar. In addition, we show that gravity torques are correctly reproduced in simulations, and conclude that bars are transient features, with lifetime of 1–2 Gyr in typical Sb-Sc galaxies, because of the combined effects of CMCs and gravity torques, while most existing works had focussed on the CMC effects alone.

Key words: galaxies: evolution – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure.

1 INTRODUCTION

In most barred galaxies, gas is concentrated on the leading side of the bar (e.g. de Vaucouleurs & de Vaucouleurs 1963), which is reproduced in numerical simulations (e.g. Athanassoula 1992). Then, the bar gravity torques make gas lose angular momentum, which initiates a gas inflow and fuels a central mass concentration (CMC). The bar is weakened by the CMC growth, because of escaping orbits (Hasan & Norman 1990; Pfenniger & Norman 1990). Friedli & Benz (1993), Berentzen et al. (1998) and Hozumi & Hernquist (1999) report the dissolution of galactic bars with CMCs of mass 0.5 to 2 per cent of the disc mass. To explain the large fraction of barred galaxies observed both at $z \simeq 0$ (e.g. Eskridge, Frogel & Pogge 2002) and at $z > 0.7$ (Sheth et al. 2003), we have proposed that bars are dissolved and reformed (Bournaud & Combes 2002, hereafter Paper I): our N-body simulations showed that bars are dissolved in 1–4 Gyr in most galaxies, which we had attributed to the CMC growth. Yet, whether bars are really transient is still debated. Resonant rings are often observed in barred galaxies, which implies that gravitational torques are much larger than viscous torques (e.g. Buta & Combes 1996). For a long time, gaseous simulations were too limited in resolution, induced too large viscous torques, so that such rings did not form. If viscous torques are still over-estimated, this may induce unrealistic inflows of gas, so that CMCs are more massive and/or fueled more rapidly, and the lifetime of bars may be much under-estimated (Regan & Teuben 2004). Moreover, even if the CMC fueling is realistic, the effects of the CMC may not be enough to fully dissolve the bar: recent simulations with more spatial resolution by Shen & Sellwood (2004) – which do not include the whole gas response – have shown that bars are more robust against the growth of CMCs than was believed before.

Thus, the limited lifetime of bars found in Paper I and other works could be an artifact of viscous torques or an over-estimation of the effects of the CMC. In this Letter, we show that the gas inflow in our simulations is actually initiated by gravitational torques, that are much larger than viscous torques. While most existing works had focused on the effects of the CMC growth, we show that another phenomenon can also lead to the destruction of galactic bars in a few Gyr: the torques between the stellar bar and the gaseous arms also disturb the bar and can dissolve it. We then find that galactic bars are transient, even when the gas infall and the effects of the CMC are correctly treated and do not destroy the bar themselves: the growth of the CMC is not the only factor of bar dissolution.

2 NUMERICAL SIMULATIONS

We employ the N-body fast Fourier transform (FFT) code described in Paper I, including star formation. The gravitational potential is computed on a Cartesian grid of size $512 \times 512 \times 64$. The softening length and cell size are 75 pc, and the number of particles is 10^6 for each component (gas and stars).

The dissipative dynamics of the interstellar medium (ISM) is modelled by the 3D sticky-particles code described in Paper I (we use an elasticity parameter for cloud–cloud collisions $\beta_r = \beta_t = 0.75$ in this paper). Star formation and stellar mass-loss

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[★] E-mail: Frederic.Bournaud@obspm.fr

Paper Bar II

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Astronomy & Astrophysics

Gas accretion on spiral galaxies: Bar formation and renewal

F. Bournaud[1] and F. Combes[2]

[1] École Normale Supérieure, 45 rue d'Ulm, 75005 Paris, France
[2] Observatoire de Paris, DEMIRM, 61 Av. de l'Observatoire, 75014 Paris, France

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Abstract. The effects of gas accretion on spiral disk dynamics and stability are studied through *N*-body simulations, including star formation and gas/stars mass exchange. The detailed processes of bar formation, bar destruction and bar re-formation are followed, while in the same time the disk to bulge ratio is varying. The accreted gas might be first prevented to flow inwards to the center by the bar gravity torques, which maintains it to the outer Lindblad resonance. While the first bar is weakening, the accreted gas replenishes the disk, increasing the disk-to-bulge ratio, and the disk self-gravity. A second bar is then unstable, with a higher pattern speed, due both to the increased mass, and shorter bar length. Three or four bar episodes have been followed over a Hubble time. Their strength is decreasing with time, while their pattern speed is increasing. Detailed balance of the angular momentum transfer and evolution can account for these processes. The gas recycled through star formation, and rejected through stellar mass loss plays also a role in the disk dynamics. Implications on the spiral galaxy dynamics and evolution along the Hubble sequence, and as a function of redshift are discussed.

Key words. galaxies: evolution – galaxies: spiral – methods: *N*-body simulations

1. Introduction

Bars are an essential feature in galaxy evolution. About two-thirds of spiral galaxies are barred (de Vaucouleurs 1963), one third being strongly barred (SB), the other third mildly barred (SAB). In the near-infrared, where the central structure is unveiled from dust, the fraction is even higher (Eskridge et al. 2000).

In the last decade, it has been realized that bars are not long lived features, in particular in gaseous spiral disks, and that galaxies are not frozen for a Hubble time in their morphological class: a bar can be destroyed by large radial gas inflow and mass accumulation in the center (Hasan & Norman 1990; Pfenniger & Norman 1990; Hasan et al. 1993; Friedli & Benz 1993). The mass concentration destroys the orbital structure that supported the bar, and this begins through the creation of two strong inner Lindblad resonances (ILR). The process is initiated by the strong gravity torques exerted by the bar on the gaseous spiral arms, which decrease afterwards as the bar weakens. It can lead to the decoupling of a secondary bar, embedded into the primary, just inside its ILR (Friedli & Martinet 1993; Combes 1994), and this is likely to weaken the primary bar.

The bar phenomenon can then be a self-regulated process (e.g. Combes 2000). A tantalizing scenario is that a galaxy may have several bar episodes in its life, and that the fraction of barred galaxies in the de Vaucouleurs classification only reflects the time percentage that a spiral galaxy spends as a barred object. How can a bar be revived after a destruction or weakening event? The disk self-gravity must be enhanced to counteract the stabilizing influence of the bulge and central mass concentration, enforced by the first bar episode. This may be obtained through external gas accretion, that settles in the disk. Significant amounts of matter can be accreted in the life-time of the galaxy (e.g. Katz et al. 1996), and we consider realistic that the mass of a galaxy could double in a few Gyrs. The presence of gaseous warps in practically every spiral galaxy (Sancisi 1983; Briggs 1990) has been interpreted as a sign that a spiral galaxy accretes mass and angular momentum: the amount accreted is such that it changes completely orientation in a typical time-scale of a few Gyrs (Jiang & Binney 1999).

During its life, a bar changes its pattern speed, and this could be a possible way to trace its age. In dissipationless simulations, the pattern speed decreases in a time-scale of a few Gyrs (Combes & Sanders 1981). This is also related to the length of the bar. The early bar instability involves central orbits, where the orbital precession rate is higher, then more and more orbits become trapped in the bar, at larger radii, and the bar lengthens and slows down, The transient spiral waves formed in the stellar component transfer the angular momentum outwards. This process is also accelerated by escaping chaotic orbits, around corotation (Pfenniger & Friedli 1991). If there is a massive spheroidal dark matter halo, concentrated enough to perturb the bar dynamics, the pattern speed of the bar could decrease even further, owing to the dynamical friction (Debattista & Sellwood 1998). According to the density of dark matter, the time scale could be estimated down to a few 10^8 yr.

Send offprint requests to: F. Bournaud,
e-mail: `bournaud@clipper.ens.fr`

3.2 Lopsided galaxies

Lopsided galaxies have one half of there disk that is more extended / more massive than the other half ; giving them an egg-like shape. Even though this characteristic is not as striking as bars and spiral arms, a large fraction of low-redshift spirals are lopsided. These asymetries are easily seen in extended HI gas disks, but are also visible in the stellar mass distribution and in the near-infrared light.

We have determined in our Paper m1 that two third of spiral galaxies in a low-redshift sample are "significantly" lopsided, in the sense that their asymetry cannot just result from noise, irregularities in the spiral arm densities, etc.. This corresponds to an asymetry parameter A_1 larger than 5%, while internally evolving disk do not spontaneously get $A_1 > 5\%$ (except in the very central regions not considered here). These asymmetries thus require an external triggering factor. Once again, two mechanisms can be figured out for such external causes : interactions/mergers, or accretion of external gas onto the disk.

To trigger disk lopsidedness, mergers should be minor ones – otherwise they would destroy the stellar disk into a spheroid. Equal-mass interactions should be interactions without mergers, i.e. distant fly-bys. These are most efficient to trigger lopsidedness when they occur on retrograde orbits, because the $m = 1$ mode in galactic disk is counter-rotating ($\Omega - \kappa/m < 0$ for $m = 1$, κ being the epicyclic frequency). We have studied the effect of both distant major fly-bys and minor mergers, and find that they cannot account for the observed statistical properties of disk lopsidedness :

- interactions make galaxies become earlier-type (more concentrated) at the same time as they trigger the $m = 1$ mode. Late-type disks are observed to be more lopsided than early-type ones.
- interactions cannot explain the observed correlation of the $m = 2$ mode (bars, pairs of arms) with the $m = 1$ intensity, as retrograde orbits trigger the $m = 1$ mode but weaken the $m = 2$ one (and vice-versa for prograde orbits).
- and above all, the existence of many strongly lopsided galaxies that are very isolated, with no sign of recent merging, cannot be explained by past interactions/mergers. We do find that lopsidedness are somewhat long-lived, but not long lived enough so that the asymetry parameter A_1 should correlate with the Tidal Parameter measuring the presence of a tidally-interaction companion (see Fig. 3.6). No correlation of this type is found for our observed sample, at the opposite there is evidence that the expected correlation for interactions/mergers is not observed.

At the same time, external gas infall does explain why lopsidedness are more frequent and stronger in later-type galaxies, in barred galaxies, and do not correlate with the presence of companions. It is thus a required mechanism to account for the observed properties of disk lopsidedness in low-redshift spirals. As for bars, the required accretion rates are a few $M_\odot$/yr on average over the last few Gyrs.

We note that recently Angiras et al. (2006, 2007) have found a reversal of the asymetry/Hubble type correlation in dense groups, where interactions are of course a more frequent trigger of asymetries. These results support our interpretation of the reversed correlation in the field and loose groups, where a different triggering mechanism must dominate. The role of external gas infall compared to interactions and mergers has also been emphasized recently by Mapelli et al. (2008). We are now performing other comparison of models and observations, regarding the phase of the $m = 1$ mode, and its radial variations. The phase tends to be constant with radius, which both our models and those from Mapelli et al. 2008 can better reproduce with external gas accretion than with interactions as the triggering mechanism of disk lopsidedness. This study is still in progress, but would bring further confirmation of the origin of these spiral disk asymmetries.

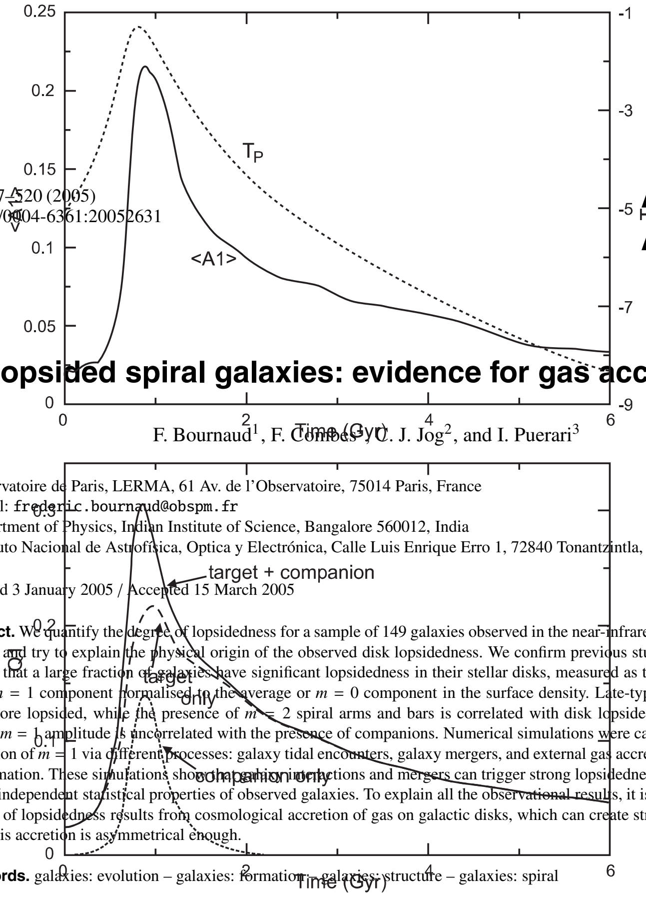

FIG. 3.6 – tbc

Paper m1

A&A 438, 507–520 (2005)
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Astronomy & Astrophysics

Lopsided spiral galaxies: evidence for gas accretion*

F. Bournaud[1], F. Combes[1], C. J. Jog[2], and I. Puerari[3]

[1] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, 75014 Paris, France
e-mail: `frederic.bournaud@obspm.fr`
[2] Department of Physics, Indian Institute of Science, Bangalore 560012, India
[3] Instituto Nacional de Astrofísica, Optica y Electrónica, Calle Luis Enrique Erro 1, 72840 Tonantzintla, Puebla, Mexico

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Abstract. We quantify the degree of lopsidedness for a sample of 149 galaxies observed in the near-infrared from the OSUBGS sample, and try to explain the physical origin of the observed disk lopsidedness. We confirm previous studies, but for a larger sample, that a large fraction of galaxies have significant lopsidedness in their stellar disks, measured as the Fourier amplitude of the $m = 1$ component normalised to the average or $m = 0$ component in the surface density. Late-type galaxies are found to be more lopsided, while the presence of $m = 2$ spiral arms and bars is correlated with disk lopsidedness. We also show that the $m = 1$ amplitude is uncorrelated with the presence of companions. Numerical simulations were carried out to study the generation of $m = 1$ via different processes: galaxy tidal encounters, galaxy mergers, and external gas accretion with subsequent star formation. These simulations show that galaxy interactions and mergers can trigger strong lopsidedness, but do not explain several independent statistical properties of observed galaxies. To explain all the observational results, it is required that a large fraction of lopsidedness results from cosmological accretion of gas on galactic disks, which can create strongly lopsided disks when this accretion is asymmetrical enough.

Key words. galaxies: evolution – galaxies: formation – galaxies: structure – galaxies: spiral

1. Introduction

It has been known for a long time that the gaseous component (HI) in galaxies is often strongly asymmetric and lopsided. Baldwin et al. (1980) have first studied this remarkable phenomenon in detail and proposed that the perturbations are $m = 1$ waves built from off-centered elliptical orbits that may persist a long time against differential precession. However, they have derived a lifetime that is still not sufficient to explain the high frequency of lopsidedness in neutral gas disks. Richter & Sancisi (1994) have compiled a sample of 1700 galaxies from the literature and noticed on resolved maps of nearby galaxies (like M101) that there is a correspondence between lopsidedness and the global HI velocity profile of the galaxy. It is therefore possible to study the asymmetries directly on the global HI spectrum, for a much larger sample. They derive a lower limit of 50% for the fraction of lopsided galaxies, and conclude that HI asymmetries in disk galaxies are the rule rather than the exception. Lopsidedness is more frequent in late-type galaxies, where Matthews et al. (1998) found a frequency of 77% of HI-distorted profiles. However, it is difficult to get a precise quantitative indicator of the degree of lopsidedness with HI profiles without any spatial resolution.

The ubiquity of lopsidedness may not be the privilege of HI disks. The stellar disk potential, traced by near-infrared light, can be strongly lopsided, even in isolated galaxies, like the spectacular case of NGC 1637 (Block et al. 1994). The stellar light is definitely affected by the phenomenon, as shown by the studies of Rix & Zaritsky (1995) and Zaritsky & Rix (1997) with a total sample of 60 galaxies. They computed the $m = 1$ Fourier amplitude of the density, and found that at least one third of these galaxies are significantly lopsided. Kornreich et al. (1998) quantify the asymmetry by comparing the optical light contained within trapezoidal sectors of galactic disks, and find also that 30% of galaxies are very lopsided. In addition to the spatial asymmetry discussed above, some galaxies also display kinematical lopsidedness though this has been less studied (Schoenmakers et al. 1997; Swaters et al. 1999).

To explain the high frequency of lopsidedness, two kinds of arguments have been proposed. First the perturbation might be longer-lived than previously thought, either because the winding out by differential precession is quite long in the outer parts of galaxies (Baldwin et al. 1980), because of weakly damped modes (Weinberg 1994), because of the amplification of density waves (Shu et al. 1990; Syer & Tremaine 1996), or alternatively that the disk is distorted in a lopsided halo (Jog 1997, 2002) or else off-centered with respect to a massive halo (Levine & Sparke 1998; Noordermeer et al. 2001). Second, the perturbations could be forced by tidal interactions

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[*] Appendix A is only available in electronic form at
`http://www.edpsciences.org`

3.3 Polar rings

Paper PRG I

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Astronomy
&
Astrophysics

Formation of polar ring galaxies*

F. Bournaud[1,2] and F. Combes[1]

[1] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, 75014 Paris, France
[2] École Normale Supérieure, 45 rue d'Ulm, 75005 Paris, France

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Abstract. Polar ring galaxies are peculiar systems in which a gas-rich, nearly polar ring surrounds an early-type or elliptical host galaxy. Two formation scenarios for these objects have been proposed: they are thought to form either in major galaxy mergers or by tidal accretion of the polar material from a gas rich donor galaxy. Both scenarios are studied through *N*-body simulations including gas dynamics and star formation. Constraints on physical parameters are drawn out, in order to determine which scenario is the most likely to occur. Polar ring galaxies from each scenario are compared with observations and we discuss whether the accretion scenario and the merging scenario account for observational properties of polar ring galaxies. The conclusion of this study is that the accretion scenario is both the most likely and the most supported by observations. Even if the merging scenario is rather robust, most polar ring galaxies are shown to be the result of tidal gas accretion events.

Key words. galaxies: formation – galaxies: kinematics and dynamics

1. Introduction

A polar ring galaxy (PRG) is made up of an early-type, lenticular, or elliptical host galaxy, surrounded by a ring of gas and stars orbiting in a plane that is nearly polar (Whitmore et al. 1990). The presence of two dynamical planes is thought to give an insight into the shape of dark halos in such systems, which explains why PRGs are interesting peculiar systems. The prototype polar ring galaxy, NGC 4650A, has been the target of several kinematical studies: Whitmore et al. (1987) concluded that the dark matter halo is nearly spherical. Sackett & Sparke (1990) and Sackett et al. (1994) have proposed a dynamical model that indicates that the dark halo is flattened, with its major axis along the equatorial plane of the host galaxy. More recently, Combes & Arnaboldi (1996) have built a different model in which the dark matter is only needed to explain velocities at large radii in the polar ring, while the velocities in the host galaxy are accounted for by the visible mass; thus they concluded that the dark halo of NGC 4650A may be flattened towards the polar ring. In all these studies the common conclusion was that PRG were embedded in a dark halo, for the visible mass is not enough to account for the observed velocities in rings. According to a different approach based on the Tully-Fisher relation, applied to several PRGs, Iodice et al. (2002c) have argued that the dark halo may be flattened along the polar ring plane in most PRGs.

From the shape of the dark matter distribution in PRGs, we would like to get information on dark halos around spiral galaxies in general. At least for this reason, it seems fundamental to know how polar rings form. Polar rings are usually thought to be formed during a secondary event around a pre-existing galaxy. The collapse of a protogalactic cloud could create two misaligned systems (Curir & Diaferio 1994), thus the polar ring and the host galaxy might be formed at the same time. However, polar rings appear to be younger than host galaxies: they are gas-rich (see HI surveys from Richter et al. 1994 and van Driel et al. 2000, 2002), while the host galaxy is generally depleted of gas; moreover polar rings contain a young stellar population while host galaxies contain old stars, as indicated by their color indices (Iodice 2002b,c). Thus, it seems reasonable to admit that PRGs are made up of a previously-formed host galaxy and a more recent polar structure.

Two kinds of scenarios have then been proposed to account for the formation of a polar ring around a preexisting galaxy (Iodice 2001):

- the merging scenario: proposed by Bekki (1997, 1998), this scenario assumes a head-on collision between two orthogonal spiral galaxies (see Fig. 1). The first one is called the intruder, the second one the victim. When the relative velocity of colliding galaxies is large, such collisions are known to form cartwheel-like rings (Horellou & Combes 2001) that are not polar rings for they do not surround a host galaxy and are transient expanding features. When the relative velocity is lower, Bekki (1997, 1998) has shown that the two galaxies merge, owing to dynamical friction: the intruder becomes the host galaxy, while the gas content of the victim galaxy forms the polar ring;

Send offprint requests to: F. Bournaud,
e-mail: `Frederic.Bournaud@obspm.fr`

* Appendices A and B are only available in electronic form at `http://www.edpsciences.org`

Paper PRG II

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POLAR RING GALAXIES AND THE TULLY-FISHER RELATION: IMPLICATIONS FOR THE DARK HALO SHAPE

E. IODICE AND M. ARNABOLDI
INAF–Osservatorio Astronomico di Capodimonte, via Moiariello 16, 80131 Naples, Italy;
iodice@na.astro.it, magda@na.astro.it

F. BOURNAUD AND F. COMBES
Observatoire de Paris, LERMA, 61 Avenue de l'Observatoire, F-75014 Paris, France;
frederic.bournaud@ens.fr, Francoise.Combes@obspm.fr

L. S. SPARKE
Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706-1582;
sparke@astro.wisc.edu

W. VAN DRIEL
Observatoire de Paris, Section de Meudon, GEPI, CNRS FRE 2459, 5 place Jules Janssen, F-92195 Meudon Cedex, France;
Wim.vanDriel@obspm.fr

AND

M. CAPACCIOLI
INAF–Osservatorio Astronomico di Capodimonte, via Moiariello 16, 80131 Naples, Italy; capaccioli@na.astro.it

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ABSTRACT

We have investigated the Tully-Fisher relation for polar ring galaxies (PRGs), based on near-infrared, optical, and H I data available for a sample of these peculiar objects. The total *K*-band luminosity, which mainly comes from the central host galaxy, and the measured H I line width at 20% of the peak line flux density, which traces the potential in the polar plane, place most polar rings in the sample far from the Tully-Fisher relation defined for spiral galaxies, with many PRGs showing larger H I line widths than expected for the observed *K*-band luminosity. This result is confirmed by a larger sample of objects, based on *B*-band data. This observational evidence may be related to the dark halo shape and orientation in these systems, which we study by numerical modeling of PRG formation and dynamics: the larger rotation velocities observed in PRGs can be explained by a flattened polar halo, aligned with the polar ring.

Subject headings: galaxies: kinematics and dynamics — galaxies: peculiar

1. INTRODUCTION

Polar ring galaxies (PRGs) are peculiar objects composed of a central spheroidal component, the host galaxy, surrounded by an outer ring made up of gas, stars, and dust that orbits nearly perpendicular to the plane of the gas-poor central galaxy (Whitmore et al. 1990). Previous papers (Arnaboldi et al. 1995, 1997; Iodice et al. 2002a, 2002b, 2002c) found that even when the morphology of the host galaxy resembles that of an early-type system, PRGs show many similarities with late-type galaxies. The PRGs are characterized by a large amount of neutral hydrogen (H I), always associated with the polar structure (Schechter et al. 1984; van Gorkom, Schechter, & Kristian 1987; Arnaboldi et al. 1997), and by a gas-to–total luminosity ratio in the *B* band typical of late-type galaxies.

The connection between PRGs and spirals is important for two of the best-studied systems: NGC 660 (van Driel et al. 1995) and NGC 4650A, for which the new surface photometry (Iodice et al. 2002a; Gallagher et al. 2002), based on near-infrared (NIR) and optical *Hubble Space Telescope* (*HST*) data, has confirmed that the polar structure appears to be a disk of a very young age. By exploring the properties of the host galaxy and ring in the optical and NIR for a sample of PRGs, Iodice et al. (2002a, 2002b, 2002c) found that the connection with spirals is tighter. Iodice and collaborators found that in almost all PRGs (1) the host galaxy is bluer (even NIR and optical colors are similar to those of late-type galaxies) and younger (age vary between 1 and 5 Gyr) than normal early-type galaxies, and it is characterized by a "compact," nearly exponential bulge, with a brighter and smaller disk than those found in standard S0 galaxies; and (2) the polar structure is even bluer than the host galaxy, and it has colors similar to those of dwarf irregular and spiral galaxies.

The Tully-Fisher (TF) relation is the most important scaling relation for disks (Tully & Fisher 1977): this is an empirical relationship between the disk rotational velocity ($V_{\rm rot}$) and its absolute luminosity (L), where $L \propto V_{\rm rot}^4$, approximately. The TF relation is extensively used to estimate extragalactic distances (see, e.g., Sakai et al. 2000; Tully & Pierce 2000 and references therein). Furthermore, this relation is considered a critical constraint in galaxy formation theories (Dalcanton, Spergel, & Summers 1997; McGaugh & de Blok 1998; Mo, Mao, & White 1998; Steinmetz & Navarro 1999, van den Bosch 2000). Several studies have addressed the origin of the TF relation (Kauffmann, White, & Guiderdoni 1993; Cole et al. 1994; Silk 1997; Avila-Reese, Firmani, & Hernández 1998; Heavens & Jimenez 1999; Elizondo et al. 1999; van den Bosch 2000), but a definitive conclusion is yet to be found.

In the past few years, several studies have asserted the validity of the TF relation for some classes of disk galaxies that show different photometric and kinematical properties

3.4 Summary – Evidence for cosmic infall from low redshift galaxy properties

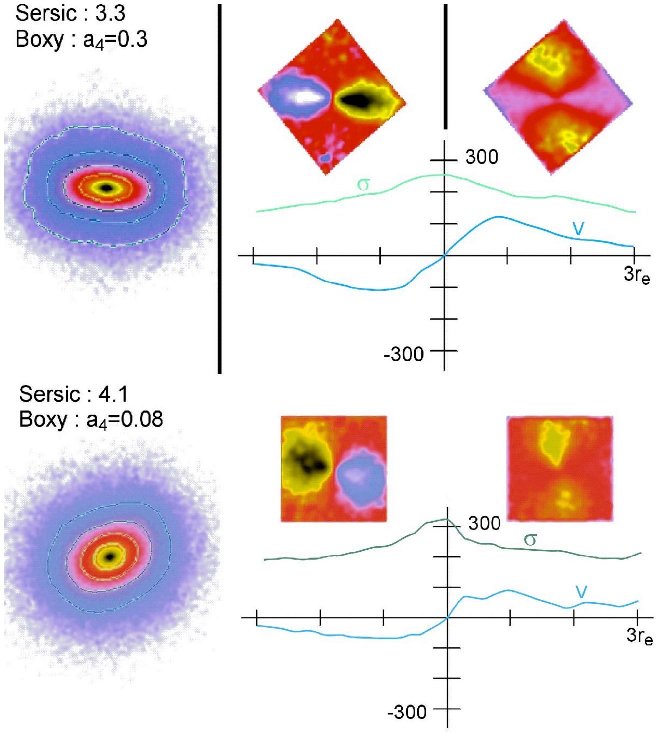

Fig. 3.7 – tbc

Chapitre 4

High redshift galaxies : witnessing mass assembly

4.1 New challenges for observers and theorists

When the studies summarized in the first chapters were undertaken (2002-04), little was know yet about the internal properties of galaxies at high redshift.

The Hubble Deep Field (HDF) survey had been completed in 1995. It covered only galaxies with a median redshift $z_{med} \simeq 0.3$ (Cowie et al. 1996, Cohen et al. 1996). Very few sources have a redshift larger than one, and galaxies at $z \simeq 1$ in the HDF are unresolved and/or particularly massive galaxies – not the progenitors of the spirals like the Milky Way or M31. Morphological studies with increasing redshift were performed (e.g., Abraham 1996), but future deeper surveys discussed below would show how difficult lockback time studies can be when a relatively complete sample is not available up to a redshift of almost 1, because of the limited amount of time that can be covered, in addition to several other biases (completeness, bandshifting, etc..). A new morphological class of galaxies was nevertheless unveiled in the Hubble Deep Fields and Hawaiian Deep Field (Williams et al. 1996, Volonteri et al. 2000, Cowie et al. 1995, van den Bergh et al. 1996), the ?chain galaxies ?. The main achievements from the HDF surveys actually concerned the integrated properties of galaxies, for instance the downsizing (Cowie et al. 1996).

The GEMs survey imaging data were taken in 2003, and have enabled much more robust studies of the morphological evolution of galaxies up to $z/simeq8$, which already represents a substantial amount of time. One of the main morphological studies in GEMs has been performed by Jogee et al. 2004, finding a constant bar fraction with redshift. This result and others on the bar fraction evolution will be discussed later, regarding also our simulations, in XXX.

A deeper survey, and a more important one for resolved properties of galaxies (firstly morphology, but also spectroscopic follow-up) is the Hubble Ultra Deep Field (UDF), imaged in 2003-04 with the ACS and NICMOS cameras, covering the BVizJH bands, with a resolution of 0.05" in the optical and 0.25" in the infrared. In the ACS optical images, some galaxies with masses not larger than the present mass of the Milky Way are resolved (over a few pixels) up to $z = 5$, and the vast majority of sources with known spectroscopic redshifts $1 < z < 2$ are well resolved – even their minor axis for edge-on systems.

On the theoretical and numerical side, most achievements are even more recent in terms of *resolved*, internal galaxy properties. The Millenium simulation, published in 2005, was a dark-matter only simulation.. On large volumes, covering statistically significant samples, only the recent MareNostrum run (Ocvirck et al. 2008) includes baryonic physics and a somewhat relevant resolution (2kpc), but stopped at redshift z=2xxxxxxx. Higher resolution in cosmological models has been obtained using ?zoom ? techniques (REFs ? ?). This technique remains quite expensive if a resolution better than a kpc is reached, and statistically significant studies including, say, a few tens of targets have not been performed yet. Another issue remains that the ?zoom ? itself should include the whole area in which all progenitors of the final galaxy are found. As a consequence, ?zooming ? on a galaxy due to merge with a companion initially very far away would require a prohibitively large computing time. The technique is thus mostly used to simulate calm, isolated galaxies, in low density regions, which is dramatically biased to study the formation of the Hubble Sequence. Only Naab and collaborators (2007) have obtained an early-type (elliptical) galaxy with this technique ; this elliptical if formed at very high redshift. To my knowledge, ellipticals formed by major mergers at redshift $z < 2$ have never been modeled so far in cosmological simulations. A more focused discussion about how to simulate galaxies at high resolution in their cosmological environment will be found in the next chapters. For the moment, we wanted to illustrate how recently studies of resolved galaxy properties became possible, both in observations and in cosmological simulations. In simulations, another option is to neglect or simplify the cosmological context and use galaxy-sized models. This has extensively been done in the low redshift context in the previous chapters and by a large number of a other authors. These simulations do not tell anything on what the Λ-CDM cosmology predicts, but they enable to study the dynamical processes in disks with given physical conditions, which is crucial to fully understand what is being observed at high-redshift, and how the young galaxies seen at $z > 1$ are evolving. This is what will be done in the following sections.

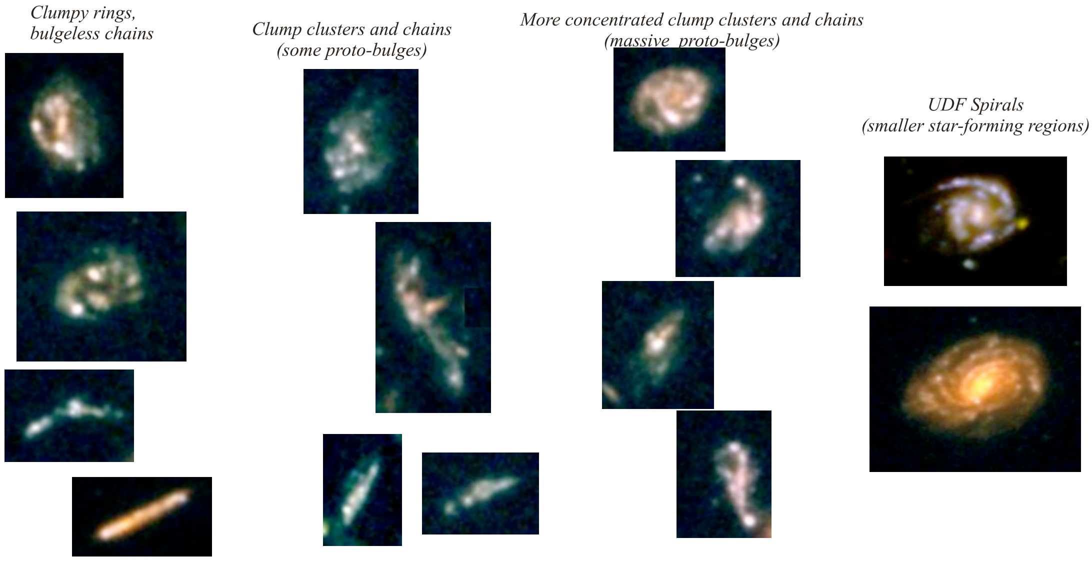

Fig. 4.1 – tbc

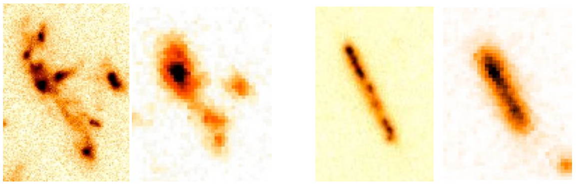

Fig. 4.2 – tbc

4.2 High redshift galaxies : Mergers or massive disks ?

The Hubble and Hawaiian Deep Fields (ref. above) have shown that galaxies at redshift around 1 and above often have non-classical morphologies, not seen in the Local Universe. The most striking non-classical galaxies are the "chain galaxies", remarkable by their linear morphology and the alignment of bright, large clumps on a more diffuse background light. Other types like the "tadpoles" and "doubles", somewhat less frequent, could be more asymmetrical versions, or versions where two main clumps dominate the system. While these system are increasingly frequent with increasing redshift (REF) whether they are the precursor of today's "normal" galaxy types, or more anecdotic, transient objects in a peculiar phase has long been unclear, and is still discussed today. REF-Ven den Bergh 1996 suggested that chain galaxies are primordial "proto-spiral" disks in a very early stage, but Taniguchi & Shioya (2001) argue that these could be merging units along filaments, observed under a peculiar projection angle. Overzier et al. (2008) also claim the similarity of clumpy galaxies with merging systems.

The high linearity of chain galaxies and the strong confinement of their clumps to the mid-plane favors an edge-on disk nature (e.g., EES04, Dalcanton 96). The face-on counterpart was nevertheless missing, until EEH04 point out the "clump-cluster" morphology, which could be face-on clumpy disk rather than compact groups of merging, initially-independent galaxies. The continuity of the axis ratio distribution of chains and clump-clusters, together with the similar photometrical properties of their substructures, support this interpretation. The clumps would then not correspond to several proto-galaxies, formed each inside a separate dark matter halo, but would be substructures formed inside single proto-galaxies by a disk-fragmentation process, namely, the well-known Jeans instability.

Spectroscopic observations also support this scenario. First, high redshift disks are found to be highly turbulent by REFs SINS. Although these results account only for the ionized gas, the neutral and molecular phases could then be much less turbulent, they indicate large velocity dispersions than in the ionized gas of local, normal disk galaxies. As a result from this enhanced turbulence, together with high gas densities (inferred from high gas masses REF-Daddi), the Jeans Mass is expected to be as high as a few 10^8 $M_\odot$, which indeed corresponds to the typical mass of the clumps in high-redshift chain galaxies and clump clusters.

Many galaxies in the SINS survey are also found to have the kinematical properties expected for rotating disks rather than major galaxy mergers (REF-Shapiro). If these galaxies are clumpy, then it would imply that clumpy galaxies are indeed rotating disks, but this survey lacks deep imaging to identify galaxy morphologies. Ionized gas density maps often show giant Hα clumps (REF-genzel06) but identifying their mass from their velocity dispersion is quite approximate. In our models below, uncertainties of a factor 5-10 occur for massive clumps, and such mass estimates could be more uncertain for low-mass star-forming regions, whose mass may be strongly overestimated if supernovae winds affect them. And indeed, some known giant Hα blobs, estimated to the very massive from their velocity dispersion, are actually absent from the K-Band stellar light distribution (REF-messenger).

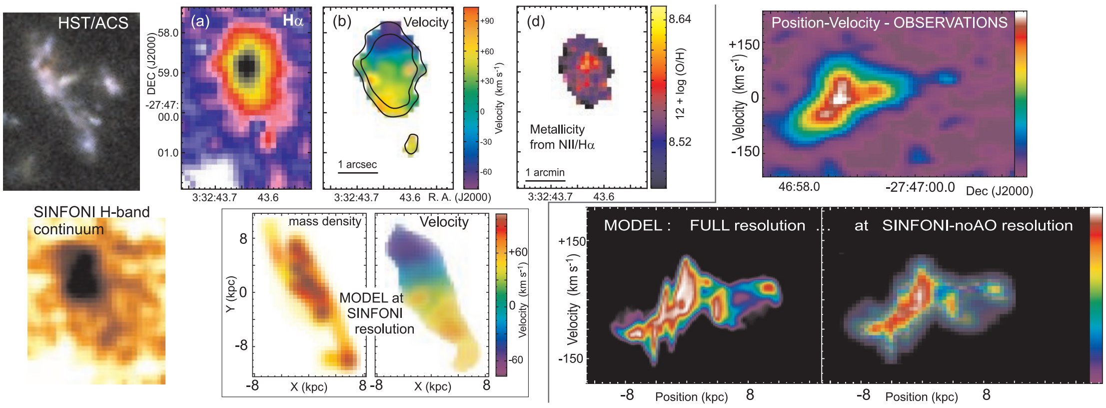

Fig. 4.3 – tbc

Whether or not highly clumpy galaxies are rotating disk remains unclear, and we have then undertaken observations of a very irregular system in the UDF, using the VLT/Sinfoni instrument. This system, UDF 6462 at $z = 1.57$, is one of the most clumpy and irregular clump-cluster in the UDF (Elmegreen et al. 2007). But while the morphology may suggest a merger origin, we found a rotation-like velocity field. Local disturbances are found, but these are expected in our models of internally fragmented disks, as the clumps interact with each other and exchange angular momentum. Merging galaxies are not expected to exhibit similar signatures : for instance tidal tails have ample velocity gradients, often inverting their sign along the tails, not resembling disk rotation curves (our paperXXX in chapter XXX).

More observations are really needed to firmly probe the contribution of disk fragmentation and galaxy merger processes in the formation of these clumpy galaxies. Larger samples are needed, and should be observed at higher resolution (with adaptive optics). Ideally one should aim at resolving the clumps internal kinematics : disk fragmentation models (shown below) predict each clump has an internal spin aligned with the initial disk spin axis ; this prediction could be observed for the largest clumps with adaptive optics and high signal-to-noise ratios. More of a technical challenge would be the observations of spatially-resolved CO lines, enabling a direct measurement of the turbulent speed in the cold ISM, which should translate into the Jeans length and mass of the clumps, if formed by local gravitational instabilities.

In the following we will nevertheless assume that (most) clumpy galaxies are massive gas-rich disk that fragmented via local gravitational instabilities, ie a Toomre parameter $Q < 1$. Indeed, most observations so far favor this mechanism, both from the morphology (continuity of axial ratio distribution from edge-on chains to face-on clump clusters ; confinement of clumps to the mid-plane of edge-on chains) and the spectroscopy (rotation with only local disturbances ; disk-like metallicity gradients). Within this context, the numerical models presented in the next sections and paper study the evolution of these clumpy galaxies.

4.3 Formation of spiral disks and bulges

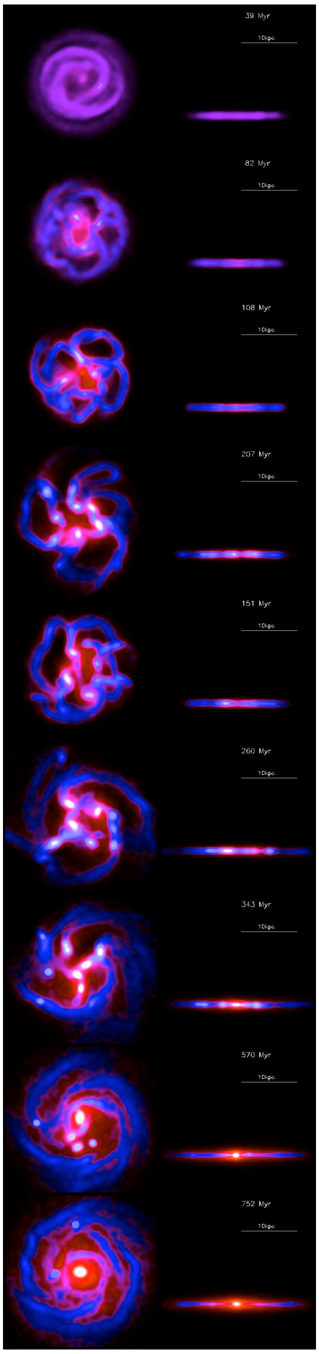

Fig. 4.4 – tbc

The simulations published in papers *HighZ II, III and IV* study the evolution of a massive, gas rich, unstable disk. We do not aim at modeling how a massive gas-rich disk has formed, for instance by gas cooling inside a single dark matter halo, or accretion from cosmic filaments along cold flows. We assume such a disk has formed and study its internal evolution, when it gets unstable (with a Toomre parameter $Q < 1$) and fragments into a few massive clumps, with clumps masses up to 10^{8-9} $M_\odot$ owing to a large turbulent speed (large Jeans mass). After, say, 200 Myr of initial evolution and fragmentation, these systems resemble the clumpy galaxies observed in the UDF, in terms of clump individual mass, number and total mass fraction in the clumps, and in term of spectroscopic/kinematic properties (see for instance the comparison with UDF 6462 above). We then study the time evolution of these systems following their internal, dynamical evolution.

The parameters are detailed in the papers ; typically our systems have gas mass fraction of 50%, baryonic (gas+stars) masses of $\sim 5{\times}10^{10}$ $M_\odot$, and initial gas turbulent speeds of 10-30km/s providing the high Jeans mass (these initial turbulent speeds are increased by the local instabilities during the formation of clumps).

The face-on and edge-on evolution of a typical case is shown on Fig. 4.4. It justifies the "evolutionnary sequence" built from observed UDF galaxies on Fig. 4.1. Indeed, the clumps form at large radii in a bulgeless system, recalling the observed clumpy rings. Then the clumps interact together and undergo friction on the diffuse disk component and dark matter halo ; the system takes the sahpe of a more irregular clump-cluster (when seen face-on) or chain galaxy (when observed edge-on). Later-on, clump coalescence in the central kpc grow a proto-bulge (a central spheroid redder than the rest of the galaxy) and the system resemble the late-stage clump-cluster in our evolutionary sequence. At the end, a spiral disk, with an exponential radial profile plus a central spheroidal bulge has been formed. It has no giant clump anymore – only lower mass star forming regions, just like the smooth UDF spirals. The internal evolution from irregular clump-clusters (that may have no bulge and no regular exponential profile yet) to regular spiral disks, with an exponential disk and a central bulge, is fast : it takes only half a billion year on average, in our models, and never more than 1 Gyr. Considering that on-going mass accretion onto the disk (for instance from cosmic flows) may form new clumps, the clumpy phase may be recurrent or last somewhat longer. In any case, we have shown in paper HighZ-II that the timescale of clump-driven internal evolution is much faster than the timescale of internal evolution from spiral arms and/or bar. Although the later could theoretically contribute to form exponential disk profiles and bulges, the dominant mechanism at high redshift must then be the clump-driven evolution (as also suggested from observations REF). This new mode of "secular" evolution is faster than the classical secular evolution at low redshift, as it is based on stronger disk instabilities.

As the clump interact with each other, and undergo dynamical frcition on the rest of the disk and the dark matter halo, they gradually migrate towards the center, on non-ciruclar orbits and with individual clump velocity different from the initial disk circular velocity. Theis result is kinematical perturbations up to 40-30km/s for circular velocities of 150km/s, over scales of 1-2kpc (the typical clump diameter). At larger scales, the global reoation-like velocity field of the initial proto-disk is preserved. An example on Fig. 4.5 shows large kinematical disturbances, some other projection can also show less perturbations, with an almost regular disk-like velocity field ; this depends on the line-of sight, and the age of the clumps too : young clumps still match the underlying disk velocity field, old clumps have increasing velocity anomalies. Some cases closely resemble our observation of the UDF 6462 clump-cluster (previous section) as well as some high-redshift disk in the SINS survey (REF-FS06). Large velocity dispersions in primoridla disks from long-slit spectroscopy observations (REF$_Weiner06)arealsoconsistentwithourhigh-redshiftdiskmodels.$

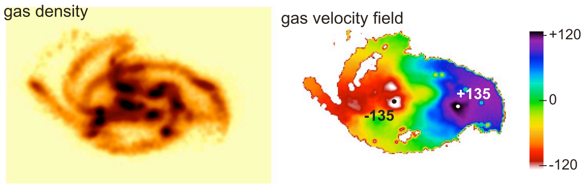

Fig. 4.5 – tbc

The disk of spiral galaxies formed by clump-driven evolution gets an exponential profile as a result of :

- gravity torques exerted by the clumps on the diffuse, inter-clump disk. The outer parts undergo positive torques, increasing their radial sacle-lentgh and decreasing their density. The inner regions get more concentrated.
- clump radial migration towards the center, and clump dissolution : clumps typically release 30–70% of their initial mass into the disk before they reach the central bulge ; this also contributed to shaping a more concentrated disk.

when they reach the central kpc, which takes a few 10^8 yr, the clumps still contain a significant fraction of their mass, and they merge into a spheroidal component, which older (redder) than the rest of the system. Violent relaxation takes place during the clump coalescence, even if the system is hosted by a single dark matter halo, without any merger of dark matter haloes. As a result, the Sersic index of this spheroid is high (typically 3–5 at radii smaller than 500 pc, Fig. 4.7), and the velocity dispersions are high too (Fig. 4.6). As detailed in paper HighZ III, such bulges resemble the classical bulge that dominate early-type (Sa) spirals, more than the pseudo-bulges more frequent in later-type (Sc) spirals and can be formed by other processes, including bar instabilities.

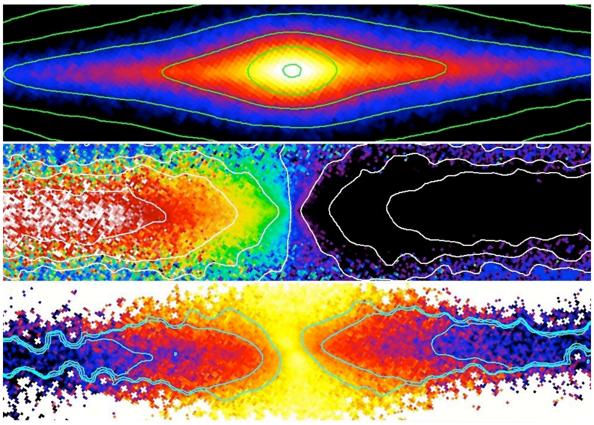

Fig. 4.6 – tbc

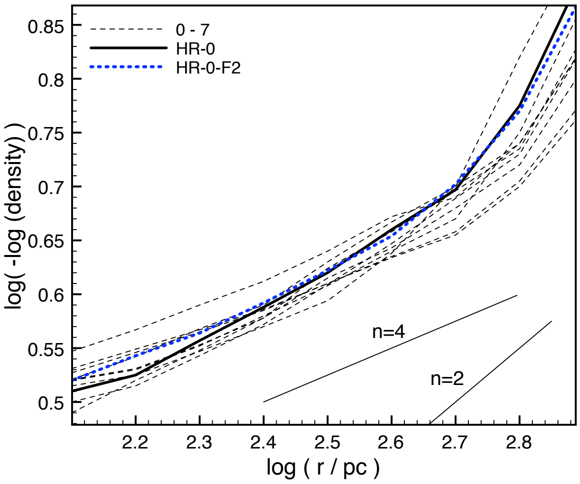

Fig. 4.7 – tbc

As the clumps are initially gas-rich, an important wonder is whether supernovae feedback (winds...) could disrupt them, and release their whole mass in the disk before they coalesce into the bulge, which might even prevent the bulge-forming mechanism to take place at all. We have conducted runs with an increasing intensity of feedback (Fig. 4.8 and paper HighZ III) and find that the clumps are not disrupted by the supernovae winds, unless the disk itself is disrupted. To keep the gas layer thick but disk-like, the supernovae feedback intensity has to be low enough, so that clumps are not strongly affected. Observed edge-on chain galaxies to not have disk much thicker than the clumps themselves, suggesting that the most realistic cases in our models are the ones with the lowest intensities of feedback (runs HR-0 and HR-O-F1 on Fig. 4.8). In these runs the influence of feedback is marginal, only slightly increasing the mass released by the clumps into the disk and somewhat regulating the bulge growth, but never more than a moderate modification of the initial parameters.

The clumps observed in many galaxies at redshift $z \geq 1$ and reproduced in our model are thus bound, long-lived entities, that can survive a few 10^8 yr before they coalesce into the central bulge. This bulge has the properties of the classical bulges of spirals, but is formed without galaxy merger : clump coalescence differs from galaxy mergers by not implying the merging of several dark matter haloes, which can be tested at low redshift. Our model is then supported by observations showing that present-day spiral galaxies do not have a specific dark matter component associated to the bulge (REF REF Corsini2007, Noordemeer+07). More direct observations support this model of bulge formation from internal evolution at $z > 1$: REF Genzel+08, Elmegreen+08.

An observational constraint for this disk+bulge formation scenario is that a classical bulge is always observed

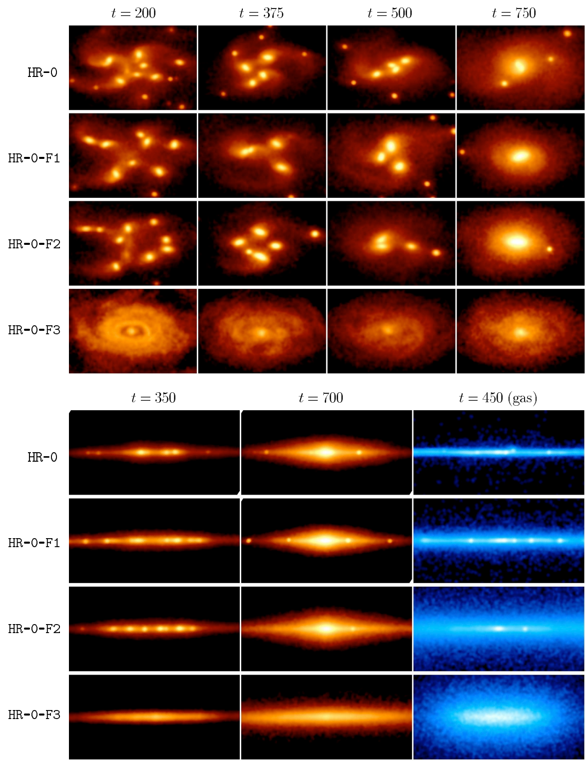

FIG. 4.8 – tbc

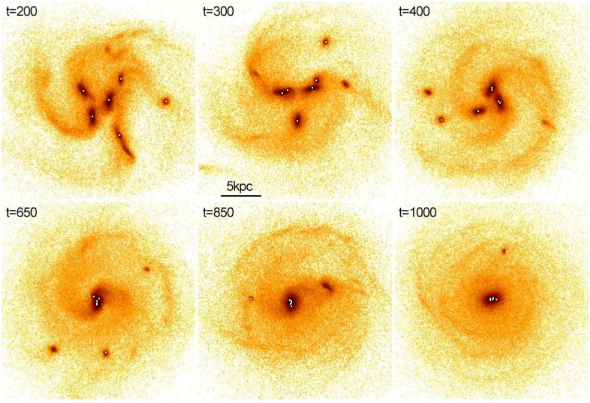

FIG. 4.9 – tbc

to host a supermassive black hole, following some scaling relations. Any model of bulge formation must then offer a theoretical possibility to form these black holes. In the case of our model, this comes from the clumps being very dense. If we assume that they are not fragmented into multiple, lower-mass structures (which is true in our simulations and is supported by the high Jeans masses inferred from Hα observations), then these clumps are dense enough for runaway stellar collisions to form intermediate-mass black holes in their core. Clumps do release a large fraction of their mass before they reach the central kpc, but new models on Fig. 4.9 show that these intermediate mass black holes would not escape the clumps before reaching the very central regions, where they could merge into a single supermassive black hole hosted by the bulge. The merging of black holes could be accompanied by a large velocity kick, which in our model is solved by the IMBHs having similar masses (resulting from the clumps similar masses, all about the Jeans mass) and the IMBHs spins being aligned (the clumps all having an internal spin aligned with the whole disk). Then the velocity kick is minimal (typically < 100km/s) and the SMBH will rapidly settle back to the center by dynamical friction. In the merger-driven model for spheroid formation, nuclear black hole mergers are also assumed. Given that the mass and spin axes are more likely to be different from each other in this context, coming from initially independent galaxies, an extra mechanism is needed to prevent large velocity kick to expulse the SMBH from the spheroid center. Theoretical solutions have been proposed (REF-Bogdanovic) in the case of wet mergers, but the case of dry mergers remains more questionable. This issue is directly solved in our model. No observation so far can directly support or question this model : no study of the nuclear activity in large samples of galaxies of different clumpiness has ever been performed, and the resolution of observations cannot really tell if clumps have a single super-dense core of are fragmented in many lower-density substructures.

Paper HighZ I

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Astronomy & Astrophysics

Observations and modeling of a clumpy galaxy at $z = 1.6$[*]

Spectroscopic clues to the origin and evolution of chain galaxies

F. Bournaud[1,2], E. Daddi[1,2], B. G. Elmegreen[3], D. M. Elmegreen[4], N. Nesvadba[5], E. Vanzella[7], P. Di Matteo[5,6],
L. Le Tiran[5], M. Lehnert[5], and D. Elbaz[1,2]

[1] CEA, IRFU, SAp, 91191 Gif-sur-Yvette, France
e-mail: `frederic.bournaud@cea.fr`
[2] Laboratoire AIM, CEA-Saclay – CNRS – Université Paris Diderot, France
[3] IBM Research Division, T.J. Watson Research Center, PO Box 218, Yorktown Heights, NY 10598, USA
[4] Vassar College, Dept. of Physics & Astronomy, PO Box 745, Poughkeepsie, NY 12604, USA
[5] Observatoire de Paris, GEPI, 92195 Meudon, France
[6] Observatoire de Paris, LERMA, 75014 Paris, France
[7] INAF - Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, 40131 Trieste, Italy

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ABSTRACT

We investigate the properties of a clump-cluster galaxy at redshift 1.57. In optical observations, the morphology of this galaxy is dominated by eight star-forming clumps, and its photometric properties are typical of most clump-cluster and chain galaxies. Its complex asymmetrical morphology has led to the suggestion that this system is a group merger of several initially separate proto-galaxies. We performed Hα integral field spectroscopy of this system using SINFONI on VLT UT4. These observations reveal a large-scale velocity gradient throughout the system, but with large local kinematic disturbances. Using a numerical model of gas-rich disk fragmentation, we find that clump interactions and migration can explain the observed disturbed rotation. On the other hand, the global rotation would not be expected for a multiply merging system. We also find that this system follows the relations of stellar mass versus metallicity, star formation rate, and size that are expected for a disk at this redshift. Furthermore, the galaxy exhibits a disk-like radial metallicity gradient. A formation scenario of internal disk fragmentation is therefore the most likely one. A red and metallic central concentration appears to be a bulge in this proto-spiral clumpy galaxy. A chain galaxy at redshift 2.07 in the same field also shows disk-like rotation. Such systems are likely progenitors of present-day bright spiral galaxies, which shape their exponential disks through clump migration and disruption, a process that in turn fuels their bulges. Our results show that disturbed morphologies and kinematics are not necessarily signs of galaxy mergers and interactions, but may instead be produced by the internal evolution of primordial disks.

Key words. galaxies: formation – galaxies: kinematics and dynamics – galaxies: evolution
– galaxies: interactions

1. Introduction

Giant molecular clouds and star formation complexes in present-day spiral galaxies have masses that rarely exceed 10^{-3} of the disk mass, and the total mass in these low-mass star-forming regions does not dominate the disk mass. At high redshift ($z \simeq 1$ and above), the clumpiness and asymmetry of galaxies increases (Conselice 2003; Conselice et al. 2004; Daddi et al. 2004), which affects both the light fraction inside the clumps and the individual clump masses. Clumps at high redshift can be as wide as about a kpc, and as massive as $10^9\ M_\odot$ (Elmegreen 2007, and references therein). In particular, the so-called "chain galaxies" have striking morphologies that are dominated by the alignment of massive clumps (Cowie et al. 1996; van den Bergh et al. 1996; Moustakas et al. 2004). Dalcanton & Shectman (1996) first proposed that these chain galaxies could be edge-on low surface brightness galaxy (LSB) progenitors at high redshift; however their clumps are an order of magnitude brighter than the star-forming regions of LSBs (Smith et al. 2001), and are not only bright star-forming complexes but are massive structures also visible in the near infrared (Elmegreen & Elmegreen 2005, hereafter EE05; see also NICMOS observations by Dickinson 2000). "Clump-cluster" galaxies have the appearance of highly clumpy disks. Some are bulgeless, while others have small red central concentrations that resemble primordial bulges. Because the photometrical properties of their clumps are similar to those of chain galaxies, Elmegreen et al. (2004) suggested that chains are the edge-on counterpart of clump-clusters, which solves the problem of the face-on counterpart of chains being missing (O'Neil et al. 2000). The fraction of chains and clump-clusters increases with redshift. Since these galaxies do not have an exponential profile already established, Elmegreen et al. (2005) proposed that they could be the progenitor of $z \sim 1$ spirals that further evolved into present-day bright spirals. They could therefore represent a crucial stage in the formation of massive disk galaxies.

The origin of the massive clumps in chains and clump-cluster galaxies, however, remains uncertain and largely debated. Noguchi (1999) and Immeli et al. (2004a,b) proposed

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Paper HighZ II

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RAPID FORMATION OF EXPONENTIAL DISKS AND BULGES AT HIGH REDSHIFT FROM THE DYNAMICAL EVOLUTION OF CLUMP-CLUSTER AND CHAIN GALAXIES

Frédéric Bournaud
Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot Dapnia/Service d'Astrophysique, CEA/Saclay, F-91191 Gif-sur-Yvette Cedex, France; frederic.bournaud@cea.fr

Bruce G. Elmegreen
IBM Research Division, T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598; bge@watson.ibm.com

and

Debra Meloy Elmegreen
Department of Physics and Astronomy, Vassar College, Box 745, Poughkeepsie, NY 12604; elmegreen@vassar.edu

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ABSTRACT

Many galaxies at high redshift have peculiar morphologies dominated by 10^8–10^9 $M_\odot$ kpc-sized clumps. Using numerical simulations, we show that these "clump clusters" can result from fragmentation in gravitationally unstable primordial disks. They appear as "chain galaxies" when observed edge-on. In less than 1 Gyr, clump formation, migration, disruption, and interaction with the disk cause these systems to evolve from initially uniform disks into regular spiral galaxies with an exponential or double-exponential disk profile and a central bulge. The inner exponential is the initial disk size, and the outer exponential is from material flung out by spiral arms and clump torques. A nuclear black hole may form at the same time as the bulge from smaller black holes that grow inside the dense cores of each clump. The properties and lifetimes of the clumps in our models are consistent with observations of the clumps in high-redshift galaxies, and the stellar motions in our models are consistent with the observed velocity dispersions and lack of organized rotation in chain galaxies. We suggest that violently unstable disks are the first step in spiral galaxy formation. The associated starburst activity gives a short timescale for the initial stellar disk to form.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift

Online material: color figures

1. INTRODUCTION

Galaxies at redshifts larger than $z \sim 1$ become increasingly clumpy with star formation in kpc-size complexes containing 10^7–10^9 $M_\odot$ that are several hundred Myr old (see review in Elmegreen 2007). A remarkable morphology is that of "chain galaxies" with large visible clumps aligned along one axis (Cowie et al. 1995; van den Bergh et al. 1996; Moustakas et al. 2004). These are rare in the local universe (e.g., Abraham et al. 1996) but much more frequent at redshift ~1 (Elmegreen et al. 2005c, hereafter EERS05). Dalcanton & Shectman (1996) suggested that chain galaxies could be edge-on low surface brightness galaxies. However, the clumps are much more massive than those observed in the UV in nearby edge-on disks (e.g., Smith et al. 2001), and the actual face-on counterparts of chain galaxies at high redshift are observed to be starburst disks with kpc-sized clumps—the so-called "clump-cluster galaxies" (Elmegreen et al. 2004; see the example of UDF 1666 in Fig. 1 from EERS05). Both clumpy types are found up to the bandshifting limit of $z \sim 5$ (Elmegreen et al. 2007b, hereafter EERC07). Ring (Elmegreen & Elmegreen 2006b) and interacting (Elmegreen et al. 2007a) galaxies at high redshift are also very clumpy. Distant ellipticals can be clumpy too, as found in the Tadpole and A1689 cluster fields (Menanteau et al. 2004, 2005) and the Ultra Deep Field (UDF; Elmegreen et al. 2005b). Clumpiness in high-redshift galaxies has been quantified with the *S*-parameter by Conselice (2003) and Conselice et al. (2004).

O'Neil et al. (2000) suggested that chains could be knotty disks seen edge-on; otherwise, the edge-on counterparts of face-on disks would be missing at high redshift. Taniguchi & Shioya (2001) proposed that chains are filaments of clumps about to merge into elliptical remnants. Detailed observations actually confirm that *chain* and *clump-cluster* galaxies are mostly a single class of objects that are clumpy disks viewed in different orientations: the two types have equivalent sizes, magnitudes, and redshift ranges, and their clumps have similar properties (Elmegreen & Elmegreen 2005, hereafter EE05; EERC07). Their combined distribution of axial ratios is flat, as it is for a single disk population (EE05). In a sample of 10 extremely clumpy galaxies in the UDF, the fraction of the light in the clumps was found to be ~40% and the fraction of the total stellar mass was ~10% (EE05). On average in the UDF, the luminosity fraction of the clumps in 178 clump-cluster galaxies is ~20%, and the luminosity fraction of the clumps in 269 spiral galaxies is ~5%, not counting the bulges in the latter (EERS05). Comparisons between ACS and NICMOS images of clump-cluster and chain galaxies confirm that the clumps are intrinsic to the mass and are not rest-frame blue patches on a smooth underlying disk (EERC07). The clumps therefore represent a large fraction of the mass in these galaxies, unlike the clumps in modern spirals.

Clump clusters and chains have irregular and somewhat flat luminosity profiles—different from spirals, which have bulges and exponential disks. However, the azimuthally averaged number density of clumps as a function of radius in UDF clump clusters, when normalized to the galaxy sizes, is similar to that of the (smaller) clumps in the spirals, and both distributions are close to exponential (Elmegreen et al. 2005a, hereafter EEVFF05). This equivalence suggests that exponential disks and bulges in spiral galaxies generally form by the dissolution of clumps in clump-cluster and chain galaxies. Consistent with this scenario is the

Paper HighZ III

Bulge Formation by the Coalescence of Giant Clumps in Primordial Disk Galaxies

Bruce G. Elmegreen

IBM Research Division, T.J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA

`bge@us.ibm.com`

Frédéric Bournaud

Laboratoire AIM, CEA-Saclay DSM/IRFU/SAP - CNRS - Université Paris Diderot, F-91191 Gif-sur-Yvette Cedex, France

`frederic.bournaud@cea.fr`

Debra Meloy Elmegreen

Vassar College, Dept. of Physics & Astronomy, Box 745, Poughkeepsie, NY 12604

`elmegreen@vassar.edu`

ABSTRACT

Gas-rich disks in the early universe are highly turbulent and have giant star-forming clumps. Models suggest the clumps form by gravitational instabilities, and if they resist disruption by star formation, then they interact, lose angular momentum, and migrate to the center to form a bulge. Here we study the properties of the bulges formed by this mechanism. They are all thick, slowly rotating, and have a high Sersic index, like classical bulges. Their rapid formation should also give them relatively high $\alpha-$element abundances. We consider fourteen low-resolution models and four high-resolution models, three of which have supernova feedback. All models have an active halo, stellar disk, and gaseous disk, three of the models have a pre-existing bulge and three others have a cuspy dark matter halo. All show the same basic result except the one with the highest feedback, in which the clumps are quickly destroyed and the disk thickens too much. The coalescence of massive disk clumps in the center of a galaxy is like a major merger in terms of orbital mixing. It differs by leaving a bulge with no specific dark matter component, unlike the merger of individual galaxies. Normal supernova feedback has little effect because the high turbulent speed in the

Paper HighZ IV

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NUCLEAR BLACK HOLE FORMATION IN CLUMPY GALAXIES AT HIGH REDSHIFT

Bruce G. Elmegreen
IBM Research Division, T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598; bge@watson.ibm.com

Frédéric Bournaud
CEA, IRFU, SAP, F-91191 Gif-sur-Yvette, France; and Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, France;
frederic.bournaud@cea.fr

and

Debra Meloy Elmegreen
Department of Physics and Astronomy, Vassar College, Box 745, Poughkeepsie, NY 12604; elmegreen@vassar.edu
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ABSTRACT

Massive stellar clumps in high-redshift galaxies interact and migrate to the center to form a bulge and exponential disk in $\lesssim 1$ Gyr. Here we consider the fate of intermediate-mass black holes (BHs) that might form by massive-star coalescence in the dense young clusters of these disk clumps. We find that the BHs move inward with the clumps and reach the inner few hundred parsecs in only a few orbit times. There they could merge into a supermassive BH by dynamical friction. The ratio of BH mass to stellar mass in the disk clumps is approximately preserved in the final ratio of BH to bulge mass. Because this ratio for individual clusters has been estimated to be $\sim 10^{-3}$, the observed BH-to-bulge mass ratio results. We also obtain a relation between BH mass and bulge velocity dispersion that is compatible with observations of present-day galaxies.

Subject headings: instabilities — galaxies: bulges — galaxies: nuclei — galaxies: star clusters — stellar dynamics

1. INTRODUCTION

Numerical simulations have reproduced the massive clumpy structures of star formation in high-redshift galaxies and followed the migration of these clumps into the galaxy centers where they merge to form bulges (Noguchi 1999; Immeli et al. 2004a, 2004b; for a review of clumpy structures, see Elmegreen 2007). The clumps result from gravitational instabilities in a gas-rich, highly turbulent disk, and the central migration results from clump interactions and angular momentum losses to the disk, halo, and clump debris. In a series of papers, we have shown that the resulting disk has the characteristic double-exponential profile of modern spiral galaxies (Bournaud et al. 2007, hereafter BEE07), and that the bulge has a classical form, with high Sersic index, three-dimensional random motions, little rotation, and a rapid formation (Elmegreen et al. 2008, hereafter EBE08). We have also reproduced in detail the peculiar morphology and kinematics of a galaxy in the *Hubble Space Telescope* Ultra Deep Field, UDF 6462, with this model (Bournaud et al. 2008). Other spectroscopic observations also indicate, less directly but over a larger sample, that high-redshift disk and bulge evolution is characterized by giant clump interactions and high turbulence (e.g., Förster Schreiber et al. 2006), which is consistent with our models.

This paper considers another aspect of clumpy disk evolution, the formation of nuclear black holes (BHs). Models of bulge formation should be able to explain how BHs form at the same time, why the BH-to-bulge mass ratio is $\simeq 0.002$ (McLure & Dunlop 2002; Marconi & Hunt 2003), and why the BH mass and bulge central velocity dispersion are related by $\log (M_{\rm BH}/M_\odot) = 8.13 + 4.02 \log (\sigma_{\rm bulge}/200\ {\rm km\ s^{-1}})$ (Ferrarese & Merritt 2000; Tremaine et al. 2002). Here we model all of these observations by considering that each clump forms an intermediate-mass black hole (IMBH) by stellar coalescence. We follow the evolution of these IMBHs as their clumps move in the disk. We find that the IMBHs migrate inward along with the clumps and that the final central BH-to-bulge mass ratio is approximately the same as the initial BH-to-clump ratio. This is about the observed value for bulges. The velocity dispersion relation for BHs in bulges is also reproduced approximately in our simulations.

In the following, § 2 outlines our model for nuclear BH formation, § 3 describes the numerical simulations, § 4 gives the results, and § 5 contains a brief discussion.

2. BLACK HOLE FORMATION MODEL

Nuclear BHs are an important aspect of galaxy and bulge formation. Malbon et al. (2007) summarized BH models by suggesting that gas accretion during starbursts forms relatively low mass BHs at high redshift, while BH coalescence during galaxy mergers forms supermassive BHs at low redshift (see also works by Di Matteo et al. 2005, 2008; Johansson et al. 2008). Disk density waves are less efficient in fueling nuclear black holes (Younger et al. 2008). In a very different type of model, Ebisuzaki et al. (2001) suggested that IMBHs grow by stellar coalescence in dense young clusters that form in the central regions of galaxies. Dynamical friction then forces these IMBHs to the center, where they merge into a nuclear BH. Here we determine whether a model like this can also apply to IMBHs that form in dense disk clusters, far from the nucleus. We know from clumpy disk models that the disk clusters migrate to the center to form a bulge, so the primary question here is whether IMBHs that form in these clusters follow them inward to the nucleus. The BH-to-cluster mass ratio was found in the simulations by Ebisuzaki et al. (2001) to be $\sim 10^{-3}$, which is the same as the BH-to-bulge mass ratio. Thus, what we primarily need to determine is whether this mass fraction is preserved during the clump/BH migration. There are two important differences from the Ebisuzaki et al. model: (1) the clusters here are much more massive than they considered,

Chapitre 5

Star formation history

The standard idea about star formation in the hierarchical context is that galaxy mergers trigger bursts of star formation, and that a large fraction of today's stars could have been formed during these merger-induced starbursts. For instance, in their model of the formation of a massive spiral galaxy by the merger of smaller gas disks, ? report that almost 50% of the stars in this spiral formed during two interaction-triggered starbursts. The dynamical processed of star formation triggering in major mergers has been studied in detail by ???... Observationally, the deep first infrared surveys (?) has also suggested that a large fraction of today's stars had formed in dusty starbursts, likely merger-driven ones. More recent results from Spitzer (?) could likely question this, as the star formation activity of a galaxy depends mostly on its stellar mass, rather than its dynamical state (interacting or not). Nevertheless, ? find that the star formation rate of galaxies also correlate with environments. At redshift zero galaxies in dense regions of the Universe do not form much stars : they indeed are in rich groups and clusters, where the cold gas has been removed by a variety of processes including ram pressure stripping (??). But at redshift ~ 1 when groups and proto-clusters only begin to form, galaxies in these relatively dense environments have a higher specific star formation rate than field galaxies. This cannot only come from mergers being more frequent, but we have suggested that this could come from mergers being more efficient when they take place in a group or near a cluster, than if they just occur between two field galaxies. Our paper SFR II studies a statistical sample of major mergers, and we find that, on average, merger-induced starbursts are significantly more efficient when they occur near a large, dense cosmological structure. This come mostly from the orbit of the interacting galaxies being different when a large-scale tidal field is present (with, in particular, a gravitational focussing effect). This could contribute to explain the star formation – environment relation observed at high redshift by Elbaz et al., while the reversal of the relation at z=0 would arise when quenching factors become more important (gas exhaustion, virialization of the large structures and stripping, etc..). More generally this process can increase the efficiency of interactions and mergers in driving the formation of stars in galactic disks.

Nevertheless the basic idea of a star formation that would be mostly driven by interaction and mergers is conflicting with some observations mentioned, including those in the previous part and others, in particular at high redshift. The most actively star-forming galaxies in the Local Universe are almost exclusively involved in a major interaction (??). It probably remains true that the strongest starbursts at high redshift are also triggered by interactions : on average, an inteaction or merger will always trigger the star formation efficiency of a galaxy, by concentrating a substantial fraction of its gas. But this does not necessarily dominate the star formation density in the young Universe. And indeed, high-redshift star formation as observed in the UDF does not appear to be merger-driven. Among UV (star-forming) galaxies that are spatially resolved by the ACS camera (which resolves a large number of galaxies down to $M_* 10^1 0$ solar masses), not many seem to be on-going mergers. They are actually disks, or more precisely clumpy disks (?), these clumpy galaxies are internally fragmented disks and not on-going mergers with several star formating blobs (previous chapter, ?????). These disks may have been hierarchically formed by previous mergers (?), but these mergers would be relaxed, hence not driving the star formation activity anymore (note that in simulations, merger-induced starbursts are short-lived, and do not last longer than the main morphological signatures or mergers). The duty cycle of high-resfhit star forming disks seems to be low ??, these disks form stars at a high rate (tens or hundreds of $M_\odot \cdot yr^{-1}$, (?)) but this comes from them having giant gas reservoirs rather than a particularly high star formation efficiency (?). All this clearly suggest that most star formation in the Early Universe occurs by gravitational instability in turbulent gas disks, the differences with Milky-Way like galaxies being mostly a scale-up of the process : gas fractions are much higher (and fo is the SFR), the turbulence is much stronger, and the star-forming regions are massive, giant clumps that can drive the dynamical evolution.

Do these observational fact falsify simulations, since the later show that mergers can trigger strong bursts of star formation ?

Paper SFR I

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On the frequency, intensity and duration of starburst episodes triggered by galaxy interactions and mergers

P. Di Matteo[1,2], F. Bournaud[3], M. Martig[3], F. Combes[1], A.-L. Melchior[1,4], and B. Semelin[1,4]

[1] Observatoire de Paris, LERMA, 61, Avenue de L'Observatoire, 75014 Paris, France
[2] Observatoire de Paris, Section de Meudon, GEPI, 5 Place Jules Jannsen, 92195, Meudon, France
[3] Laboratoire AIM, CEA-Saclay/DSM/IRFU/SAp – CNRS – Université Paris Diderot, 91191 Gif-sur-Yvette, France
[4] Université Pierre et Marie Curie - Paris 6, 4 Place Jussieu, 75252 Paris Cedex 5, France

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ABSTRACT

We investigate the intensity enhancement and the duration of starburst episodes, triggered by major galaxy interactions and mergers. To this aim, we analyze two large statistical datasets of numerical simulations. These have been obtained using two independent and different numerical techniques to model baryonic and dark matter evolution, that are extensively compared for the first time. One is a Tree-SPH code, the other one is a grid-based N-body sticky-particles code. We show that, at low redshift, galaxy interactions and mergers in general trigger only moderate star formation enhancements. Strong starbursts where the star formation rate is increased by a factor larger than 5 are rare and found only in about 15% of major galaxy interactions and mergers. Merger-driven starbursts are also rather short-lived, with a typical duration of the activity of a few 10^8 yr. These conclusions are found to be robust, independent from the numerical techniques and star formation models. At higher redshifts where galaxies contain more gas, gas inflow-induced starbursts are neither stronger neither longer than their local counterparts. In turn, the formation of massive gas clumps, results of local Jeans instability that can occur spontaneously in gas-rich disks or be indirectly favored by galaxy interactions, could play a more important role in determining the duration and intensity of star formation episodes.

1. Introduction

The role played by galaxy interactions in affecting star formation was realized by Larson & Tinsley (1978), who showed that disturbed galaxies in the Arp Catalogue (Arp 1966) have a larger dispersion in their colors and a bluer envelope in the (U-B, B-V) plane than normal systems taken from the Hubble Atlas (Sandage 1961). Using evolutionary synthesis models, they suggested that the features found in UBV colors of interacting galaxies were caused by bursts of star formation lasting a few $10^7 - 10^8$ years. The large amount of observational works that followed (see Kennicutt et al. (1996) for a complete review) showed that in the Local Universe, the response of galaxies to mutual interactions and mergers is quite varied.

Many starbursts in the Local Universe take place in the central regions of interacting/merging galaxies, as it is the case for instance for NGC 7714 studied by Weedman et al. (1981), and the protoype starburst galaxy M 82 (de Grijs 2001a,b). Another well-studied example is the NGC 4038/4039 system (the Antennae): this early stage merger presents an extended star formation, the most intense star forming regions being located between the two galaxies (Wang et al. 2004). Actually, the vast majority of UltraLuminous Infrared Galaxies (ULIRGs) at low redshift, i.e. the strongest starbursts in the Local Universe, are found in interacting and merging galaxies (Sanders & Mirabel (1996), see also Duc et al. (1997)). This is however not reciprocal. Indeed, Bergvall et al. (2004) among others have shown that, in a magnitude-limited sample of 59 interacting and merging galaxies, only a weak enhancement of star formation (a factor of 2-3 in the galaxy centers) is found when compared to a reference sample of non-interacting galaxies, so that the contribution of interactions and mergers to the global star formation activity at low redshift could on average be much less efficient than suggested by the strongest examples of starbursts.

At high redshift, the role of mergers in the star formation history of galaxies is debated, too. In a pioneering study of distant infrared galaxies, Elbaz & Cesarsky (2003) showed that the majority of present-day stars were formed in dusty starbursts, and suggested that the later were triggered by galaxy interactions. Conselice et al. (2003) also suggested that about two thirds of submillimeter galaxies at $z > 1$ are undergoing a major merger. In a study of the Spitzer First Look Survey, Bridge et al. (2007) argued that close pairs are major contributors to the star formation density at $z > 0.7$, about half of the star formation rate density at $z \sim 1$ being attributed to major mergers and interactions. However, an important part of the infrared luminosity of galaxies could be caused by AGN heating (e.g. Daddi et al. 2007a,b). Bell et al. (2005) find that less than one third of actively star forming galaxies at $z \sim 0.8$ are actually interacting or merging, the majority having undisturbed disk morphologies. Similarly, selecting interacting galaxies in the GEMS survey, Jogee et al. (2007, 2008 in preparation) find that over the redshift interval z~0.24 to 0.80 (corresponding to lookback times 3 to 7 Gyr), the average SFR of strongly distorted interacting/merging massive galaxies is only modestly enhanced with respect to normal undisturbed galaxies. At even higher redshift ($z \sim 2$) in GOODS, Daddi et al. (2007a) find that the star formation activity of ULIRGS is long lived (at least half a Gyr) which might be longer than expected for merger-induced starbursts.

In the last decade, a lot of progress has been made in our theoretical understanding of the role played by galaxy interac-

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Send offprint requests to: P. Di Matteo

Paper SFR II

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Triggering of merger-induced starbursts by the tidal field of galaxy groups and clusters

M. Martig[1]* and F. Bournaud[1]
[1] *Laboratoire AIM, CEA/DSM - CNRS - Université Paris Diderot. Dapnia/SAp, 91191 Gif-sur Yvette, France*

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ABSTRACT
Star formation in galaxies is for a part driven by galaxy mergers. At low redshift, star formation activity is low in high-density environments like groups and clusters, and the star formation activity of galaxies increases with their isolation. This star formation – density relation is observed to be reversed at $z \sim 1$, which is not explained by theoretical models so far. We study the influence of the tidal field of a galaxy group or cluster on the star formation activity of merging galaxies, using N-body simulations including gas dynamics and star formation. We find that the merger-driven star formation is significantly more active in the vicinity of such cosmological structures compared to mergers in the field. The large-scale tidal field can thus enhance the activity of galaxies in dense cosmic structures, and should be particularly efficient at high redshift before quenching processes take effect in densest regions.

Key words: galaxies: evolution – galaxies : interactions – galaxies: starburst – galaxies: clusters: general

1 INTRODUCTION

In the Local Universe ($z \simeq 0$), the strongest starbursts occur in interacting systems; luminous and ultraluminous infrared galaxies are usually found in major mergers involving at least two galaxies of comparable masses (e.g., Duc et al. 1997). At redshift $z \simeq 1$ and above, an important fraction of starbursts still seem associated with interactions and mergers (Conselice et al. 2003; Bridge et al. 2007), even if the bulk of star formation may not be simply merger-driven (Bell et al. 2005; Daddi et al. 2007; Jogee et al. 2007). Theory and numerical simulations succeed in explaining the triggering of starbursts by galaxy interactions and mergers (e.g., Mihos & Hernquist 1996). However, supernovae feedback can regulate the star formation in mergers (Cox et al. 2006) and Di Matteo et al. (2007) showed from a statistical study of a large sample of galaxy interactions and mergers that the maximal star formation rate (SFR) in interacting galaxies is rarely higher than a few times that of isolated galaxies even in equal-mass mergers – the activity decreases significantly with increasing mass ratios (Cox et al. 2007). This suggests that some factors contributing to the triggering of high SFRs in mergers could have been neglected.

At low redshift, the star formation activity in a given galaxy is anti-correlated to the density of galaxies that surround it (Lewis et al. 2002; Kauffmann et al. 2004), galaxies in or near groups forming less stars than galaxies in poorer regions of the field. In clusters, star formation is even less active, which is explained by a variety of phenomena including the ram-pressure stripping (Quilis et al. 2000), galaxy harassment (Moore et al. 1996), and galaxy strangulation (Kawata & Mulchaey 2007).

Cosmological ΛCDM models (Millenium, Springel et al. 2005) explain the Local star formation activity – environmental density relation, but predict that it gets reversed only at very high redshift $z > 2$. Yet, it has been recently discovered that the star formation – density relation is already reversed at $z \simeq 1$, where the star formation activity of galaxies increases with the local density of the surrounding galaxies, except in the very densest regions (Elbaz et al. 2007, Cooper et al. 2007). This reversal of the star formation-density relation at $z \sim 1$ is theoretically unexplained by hierarchical models and cannot simply result from major mergers being more frequent in dense environments (see Elbaz et al. 2007). This suggests that unknown environmental mechanisms can trigger the star formation activity further than what mergers do. These environmental processes may still take place during mergers, at least for a part, since the later remain a major driver of star formation.

In this Letter, we study the influence of the tidal field of galaxy groups and clusters on the star formation activity of isolated and merging galaxies. While the tidal field of such structures alone only triggers a weak activity in a single galaxy, we show that it can strongly enhance the SFR of merger-induced starbursts. Mihos (2004) has shown that an external potential can modify the morphology of gaseous

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* E-mail: marie.martig@cea.fr

Chapitre 6

Dark matter from galaxy formation

6.1 Cold Dark Matter and mass assembly : the old and new paradigms

6.2 From cold flows to proto spirals

6.3 Dark matter and dark baryons

Paper DM I

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TIDAL DEBRIS FROM HIGH-VELOCITY COLLISIONS AS FAKE DARK GALAXIES: A NUMERICAL MODEL OF VIRGOHI 21

Pierre-Alain Duc and Frederic Bournaud
Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, Dapnia/Service d'Astrophysique,
CEA-Saclay, 91191 Gif-sur-Yvette Cedex, France

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ABSTRACT

High-speed collisions, although current in clusters of galaxies, have long been neglected, as they are believed to cause little damages to galaxies except when they are repeated, a process called "harassment." In fact, they are able to produce faint but extended gaseous tails. Such low-mass, starless, tidal debris may become detached and appear as free-floating clouds in the very deep H I surveys that are currently being carried out. We show in this paper that these debris possess the same apparent properties as the so-called dark galaxies, objects originally detected in H I, with no optical counterpart, and presumably dark matter–dominated. We present a numerical model of the prototype of such dark galaxies—VIRGOHI 21—that is able to reproduce its main characteristics: the one-sided tail linking it to the spiral galaxy NGC 4254, the absence of stars, and above all the reversal of the velocity gradient along the tail originally attributed to rotation motions caused by a massive dark matter halo, which we find to be consistent with simple streaming motions plus projection effects. According to our numerical simulations, this tidal debris was expelled 750 Myr ago during a flyby at 1100 km s^{-1} of NGC 4254 by a massive companion that should now lie at a projected distance of about 400 kpc. A candidate for the intruder is discussed. The existence of galaxies that have never been able to form stars had already been challenged on the basis of theoretical and observational grounds. Tidal collisions, in particular those occurring at high speed, provide a much more simple explanation for the origin of such putative dark galaxies.

Subject headings: galaxies: individual (NGC 4254, VIRGOHI 21) — galaxies: interactions — galaxies: kinematics and dynamics

Online material: color figures

1. INTRODUCTION

With the availability of unprecedented deep H I blind surveys, a population of apparently free-floating H I clouds without any detected stellar counterpart has become apparent (Meyer et al. 2004; Davies et al. 2004; de Blok et al. 2005; Giovanelli et al. 2007; Kent et al. 2007). It has been suggested that a fraction of them could be "dark galaxies," a putative family of objects that would consist of a baryonic disk rotating in a dark matter halo, but that would differ from normal galaxies by being free of stars, having all their baryons in the form of gas. They would thus be "dark" in the optical and most other wavelengths but visible through their H I emission, contrary to pure "dark matter" halos. Such dark galaxies would be extreme cases of low surface brightness galaxies, a class of objects that have a particularly faint stellar content compared to their gaseous and dynamical masses (e.g., Carignan & Freeman 1988). The formation of low-mass dark galaxies is actually predicted by ΛCDM models (e.g., van den Bosch et al. 2003; Tully 2005). Taylor & Webster (2005) provided theoretical arguments against the existence of galaxies that would have remained indefinitely stable against star formation, unless they are of very low mass, at least a factor of 10 below that of classical dwarf galaxies.

If they exist, the dark galaxies are predicted to have a low dynamical mass and H I content. In the Local Group, some possibly rotating, high-velocity clouds were speculated to be dark galaxies (Simon et al. 2004, 2006). Furthermore, Davies et al. (2006) argued that most previous H I blind surveys were not sensitive enough to rule out the existence of dark galaxies. And indeed, while the HIPASS survey failed at detecting H I clouds without optical counterparts (Doyle et al. 2005), deeper recent H I observations, in particular with the Arecibo telescope, have revealed a number of dark galaxy candidates (Kent et al. 2007). Among these free-floating low-mass H I clouds, one object located in the outer skirts of the Virgo Cluster has attracted much attention and discussion: VIRGOHI 21 (Davies et al. 2004; Minchin et al. 2005; see Fig. 1). Despite a H I mass of only $\sim 10^8\ M_\odot$, this elongated gaseous structure, mapped with the Westerbork Synthesis Radio Telescope (WSRT) by Minchin et al. (2007, hereafter M07), exhibits a velocity gradient as large as 220 km s^{-1} (see Fig. 2). *Assuming* that the observed H I velocities trace rotation, the inferred dynamical mass would be as large as $\sim 10^{11}\ M_\odot$. The object shows no optical counterpart, even on deep *Hubble Space Telescope* (*HST*) images (M07). With such extreme properties, VIRGOHI 21 has become the prototype for dark galaxies, although its high dynamical mass is atypical even in models predicting the existence of dark galaxies. If real, an object like VIRGOHI 21 could tidally disturb the galaxies in their neighborhood, as investigated by Karachentsev et al. (2006). Actually, VIRGOHI 21 itself lies at $\sim$150 kpc from the massive spiral galaxy NGC 4254 (M99), to which it is connected by a faint H I filament. This structure could, in principle, be a bridge linking the two galaxies and would then appear as a sign of a tidal interaction between them (M07).

However, starless, isolated gas clouds showing a large velocity spread are not necessarily genuine dark galaxies. Ram pressure can strip gas away from spirals in the vicinity of clusters, a process that does not affect stars. Interaction with an external field, for instance, that of another galaxy, can expulse large amounts of material from the disk in the form of gas-rich tidal tails and debris. In that vein, Bekki et al. (2005a, hereafter B05) have suggested that interactions among flyby (i.e., interacting without merging) galaxies orbiting in a potential well similar to the one produced by the Virgo Cluster form tidal tails that after some

Paper DM II

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Materials and Methods
Figs. S1 to S7
Tables S1 to S10
References

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REPORTS

Missing Mass in Collisional Debris from Galaxies

Frédéric Bournaud,[1]* Pierre-Alain Duc,[1] Elias Brinks,[2] Médéric Boquien,[1] Philippe Amram,[3] Ute Lisenfeld,[4,5] Bärbel S. Koribalski,[6] Fabian Walter,[7] Vassilis Charmandaris[8,9,10]

Recycled dwarf galaxies can form in the collisional debris of massive galaxies. Theoretical models predict that, contrary to classical galaxies, these recycled galaxies should be free of nonbaryonic dark matter. By analyzing the observed gas kinematics of such recycled galaxies with the help of a numerical model, we demonstrate that they do contain a massive dark component amounting to about twice the visible matter. Staying within the standard cosmological framework, this result most likely indicates the presence of large amounts of unseen, presumably cold, molecular gas. This additional mass should be present in the disks of their progenitor spiral galaxies, accounting for a substantial part of the so-called missing baryons.

When galaxies collide, gravitational forces cause the expulsion of material from their disks into the intergalactic medium. In this debris, dense self-gravitating structures form. Because they can reach masses typical of those of dwarf galaxies and they show ordered rotation and active star formation (*1*–*8*), they deserve to be considered galaxies in their own right, albeit "recycled" ones. Whether these recycled dwarf galaxies contain dark matter can put strong constraints on the nature and distribution of this enigmatic constituent of the Universe. Indeed, standard theory (*9*–*11*) predicts that they differ from classical galaxies by being nearly free of nonbaryonic dark matter (*5*, *7*, *12*). According to the widely accepted ΛCDM (cold dark matter with cosmological constant) model (*13*), the matter density of the Universe is dominated by nonbaryonic dark matter. This matter is expected to surround galaxies in the form of large halos supported by random motions (*9*). Recycled galaxies are expected to have little, if any, dark matter of this type, because only material from rotating disks is involved in the galactic recycling process. In addition to nonbaryonic dark matter, part of the baryonic component is "dark" as well [i.e., it is known to have existed in the early Universe (*14*), but it is hard or impossible to detect locally today]. It has been speculated to be cold gas (*15*, *16*) but is most widely thought to reside in a diffuse warm-hot intergalactic medium (WHIM) that surrounds galaxies (*10*, *11*) and that cannot be substantially accumulated in collisional debris. Hence, recycled dwarf galaxies are predicted by conventional views to be mostly free of both baryonic and nonbaryonic dark matter. We put these views to the test, measuring the mass of three galaxies formed in the collisional debris around galaxy NGC5291 (*17*, *18*).

The galaxy NGC5291 is surrounded by a large, gas-rich ring of collisional debris (*17*). In several places, gas has gathered into self-gravitating, rotating dwarf galaxies where new stars form (Fig. 1). We studied the kinematics of atomic hydrogen in the ring through its 21-cm emission line, using the National Radio Astronomy Observatory (*19*) Very Large Array (VLA) interferometer in a high-resolution configuration. We estimated the mass actually present in the dwarf galaxies and compared this to their visible mass (*6*, *18*, *20*, *21*). We used *N*-body simulations that model the gravitational dynamics of stars, gas, and dark matter halos, with 1 million particles for each component. The model also accounts for energy dissipation in the interstellar gas, and the onset of star formation (*22*), reproducing both the global morphology of the NGC5291 system and the formation of recycled dwarf galaxies in it. These simulations enable us to date the formation of the system and to study its three-dimensional morphology. According to our model (*23*), the ring formed during a galaxy collision 360 million years ago and is seen inclined by 45° from the line of sight (Fig. 1 and figs. S1 and S2).

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[1] Laboratoire Astrophysique des Interactions Multi-Echelles, Commissariat à l'Energie Atomique (CEA) Direction des Sciences de la Matière–CNRS–Université Paris Diderot, Laboratoire de recherches sur les lois fondamentales de l'Univers (Dapnia)/Service d'Astrophysique, CEA/Saclay, F-91191 Gif-sur-Yvette Cedex, France. [2] Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield, AL10 9AB, UK. [3] Observatoire Astronomique Marseille-Provence, Laboratoire d'Astrophysique de Marseille UMR 6110, 2 place Le Verrier, F-13248 Marseille Cedex 4, France. [4] Departamento Física Teórica y del Cosmos, Universidad de Granada, Spain. [5] Instituto de Astrofísica de Andalucía (CSIC), Post Office Box 3004, 18080 Granada, Spain. [6] Commonwealth Scientific and Industrial Research Organisation (CSIRD), Australia Telescope National Facility (ATNF), Post Office Box 76, Epping NSW 1710, Australia. [7] Max Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany. [8] Department of Physics, University of Crete, GR-71003 Heraklion, Greece. [9] Foundation for Research and Technology (IESL), Hellas, GR-71110, Heraklion, Greece. [10] Observatoire de Paris, F-75014, Paris, France.

*To whom correspondence should be addressed. E-mail: frederic.bournaud@cea.fr

Chapitre 7

Perspectives

7.1 Understanding high-redshift galaxies

7.2 Linking cosmology and galaxy properties

The Galaxy Disk in Cosmological Context
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Numerical simulations of galaxy evolution in cosmological context

Marie Martig^{1,2}, Frédéric Bournaud^{1,2} and Romain Teyssier^{1,2}
^{1}CEA, IRFU, SAp. F-91191 Gif-sur-Yvette,France.
^{2}Laboratoire AIM, CNRS, CEA/DSM, Université Paris Diderot. F-91191 Gif-sur-Yvette, France.

Abstract. Large volume cosmological simulations succeed in reproducing the large-scale structure of the Universe. However, they lack resolution and may not take into account all relevant physical processes to test if the detail properties of galaxies can be explained by the CDM paradigm. On the other hand, galaxy-scale simulations could resolve this in a robust way but do not usually include a realistic cosmological context.

To study galaxy evolution in cosmological context, we use a new method that consists in coupling cosmological simulations and galactic scale simulations. For this, we record merger and gas accretion histories from cosmological simulations and re-simulate at very high resolution the evolution of baryons and dark matter within the virial radius of a target galaxy. This allows us for example to better take into account gas evolution and associated star formation, to finely study the internal evolution of galaxies and their disks in a realistic cosmological context.

We aim at obtaining a statistical view on galaxy evolution from z $\simeq$ 2 to 0, and we present here the first results of the study: we mainly stress the importance of taking into account gas accretion along filaments to understand galaxy evolution.

Keywords. galaxies: evolution, galaxies: interactions

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1. Introduction

The morphology of galaxies in the Local Universe is well constrained by observations, but is still largely unexplained. Indeed, large volume cosmological simulations fail to reproduce realistic galaxies. For instance, the disks formed are often too concentrated : it is the “angular momentum problem”, well known since the early work of Navarro & Benz (1991). It is still unclear whether this is an intrinsic problem of the ΛCDM paradigm or if something (i.e. resolution, physical processes...) is missing in these simulations.

Another puzzle is the question of disk survival till z=0 (Koda et al., 2007). For instance, Kautsch et al. (2006) study a large sample of edge-on spiral galaxies in the SDSS and find that a significant fraction of them (i.e. roughly one third) are bulgeless or “superthin”. This is still unexplained by cosmological models. Indeed, ΛCDM predicts that galaxy interactions are frequent (see e.g. the recent work by Stewart et al., 2007). More exactly, major mergers, that are well known to destroy disks to form ellipticals (Barnes & Hernquist, 1991) are rather rare, but minor mergers are much more common. These minor mergers can thicken disks, and if frequent enough could even form elliptical galaxies (Bournaud et al., 2007). The problem is then to find whether ΛCDM predicts too many mergers, or if the satellites have properties and orbital parameters such that they have little influence on the galactic disks. Also, gas accretion along filaments could fuel a thin disk and counteract the effect of mergers (Dekel & Birnboim, 2005, Keres et al., 2005, Ocvirk et al., 2008).

To study the properties of galaxies at low and high redshift, it thus seems necessary to take the full cosmological context into account. Large scale cosmological simulations could of course achieve this goal and give a statistical view on galaxies at each redshift, but for now they mainly lack resolution at the galactic scale. On the contrary, small volume cosmological simulations like the one performed by Naab et al. (2007) can resolve galactic scales in detail but are so time-consuming that obtaining a statistical sample is for now a challenge.

A first method to solve these problem is to use semi-analytical models, i.e. extracting merger trees from cosmological simulations and using different recipes to infer physical properties of galaxies (Somerville et al., 2001, Hatton et al., 2003, Khochfar & Burkert, 2005). The drawback is that approximations are necessary.

Another possibility has been explored by Kazantzidis et al. (2007), Read et al. (2007) and Villalobos & Helmi (2008) : they extract merger histories from cosmological simulations and re-simulate these histories at higher resolution. Nevertheless, they perform collisionless simulations with no gas component, neither in the main galaxy, nor in satellites, nor in filaments.

We here present a new approach where we re-simulate at high resolution a history given by a cosmological simulation, using self consistent realistic galaxies (the main galaxy and the satellites have a gas disk, a stellar disk and a dark matter halo), and we also take into account gas accretion from cosmic filaments. Our goal is to obtain a statistical sample of merger and accretion histories in a ΛCDM context to simulate the resulting galaxies and to compare our results to observations at various redshifts.

After a description of the technique used, we will present our first results and emphasize the importance of gas accretion along filaments to understand galaxy evolution.

2. Method

2.1. *Analysis of the cosmological simulation*

Merger histories and accretion data are extracted from a dark matter only cosmological simulation performed with the AMR code RAMSES (Teyssier, 2002). This simulation has an effective resolution of 512^3 and a comoving box length of 20 h^{-1} Mpc. The mass resolution is 6.9×10^6 $M_\odot$, so that a Milky Way type halo is made of a few 10^5 particles. The cosmology is set to ΛCDM with Ω_m=0.3, Ω_Λ=0.7, H_0=70 km.s^{-1}.Mpc^{-1} and σ_8=0.9.

In this simulation, halos are detected with the HOP algorithm (Eisenstein & Hut, 1998), with $\delta_{\rm peak}$=240, $\delta_{\rm saddle}$=200 and $\delta_{\rm outer}$=80 (the minimal number of particles per halo is fixed to 10). In the following, we also take into account particles that do not belong to a halo, and we consider them as diffuse accretion.

The halo of which we want to build the merger and accretion history is then chosen in the final snapshot of the simulation (at $z = 0$) and is traced back to higher redshift (typically $z \simeq 2$) : we will call it the main halo. From $z \simeq 2$ to $z = 0$, each halo or particle (in the case of diffuse accretion) entering a sphere around the main halo (the radius of this sphere is the virial radius of the main halo at z=0) is recorded, with its mass, position, velocity and spin (spin is of course omitted for diffuse accretion).

2.2. *High resolution re-simulation*

2.2.1. *The PM code*

The history that has been extracted from the cosmological simulation is re-simulated with a particle-mesh code (Bournaud & Combes, 2002). Gas dynamics is modeled with a

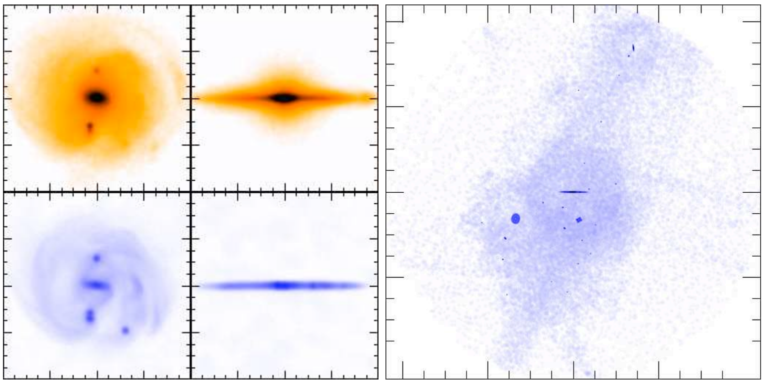

Figure 1. Left : Initial distribution of stars (top panel) and gas (bottom panel) for the main galaxy, seen face-on and edge-on (each panel is 40 kpc x 40 kpc in size). Right : large scale view of the gas distribution in a simulation box (the panel is 440 kpc x 440 kpc in size).

sticky-particle scheme with β_r=0.8 and β_t=0.7, and star formation is computed according to a Kennicutt law with an exponent 1.5.

The maximum spatial resolution is 130 pc. For the two simulations shown hereafter, the mass resolution varies from 1.2×10^4 $M_\odot$ to 2.1×10^4 $M_\odot$ for gas particles, from 6×10^4 $M_\odot$ to 1.4×10^5 $M_\odot$ for stellar particles and from 1.2×10^5 $M_\odot$ to 4.4×10^5 $M_\odot$ for dark matter particles. This allows to have a total number of particles of the order of 15×10^6 at the end of both simulations.

2.2.2. *Model galaxies*

Each halo of the cosmological simulation (i.e. the main halo as well as all the interacting satellites) is replaced with a realistic galaxy, having a disk, a bulge and of course a dark matter halo. The total mass of the galaxy is divided in 20% of baryons and 80% of dark matter (the mass of dark matter being given by the cosmological simulation). The dark matter halo follows a Burkert profile extended to its virial radius, with a core radius chosen to follow the scaling relations given in Salucci & Burkert (2000). The disk radius of each galaxy is proportional to the square root of its mass so that the surface density is constant from one galaxy to another.

The gas fraction in the disk is 30% for galaxies that have a halo mass lower than 10^{11} $M_\odot$. For galaxies that have a greater halo mass, the gas fraction is set to 30% at high redshift (z>0.8) and 15% at low redshift.

Figure 1 (left side) shows for example the initial distribution of gas and stars in the main galaxy.

2.2.3. *Diffuse accretion*

Each dark matter particle that is considered as diffuse accretion in the cosmological simulation is replaced with a small blob of particles, containing in mass 20% of gas and 80% of dark matter.

The right side of figure 1 shows an example of simulation where the main galaxy (edge-on) is surrounded by accreted gas (clearly in a filament) and a few satellite galaxies.

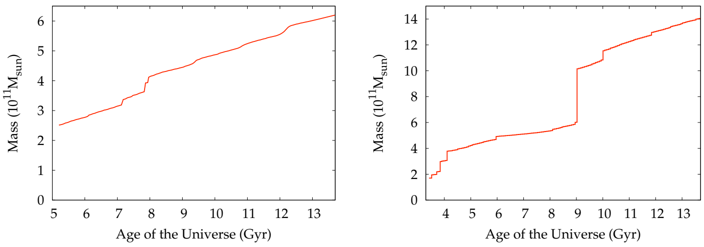

Figure 2. Evolution of the total mass of dark matter in the simulation box as a function of time for the two simulations studied here : in the left case, the mass growth is dominated by accretion, and in the right one by mergers

2.3. *Two examples*

We present here the first results concerning two simulations, that have been chosen to have a mass at z=0 of the order of magnitude of the mass of the Milky Way. They have very different histories.

In the the first one, the mass growth of the galaxy is dominated by diffuse accretion (at a mean rate of $\sim$ 5 $M_{\odot}$/yr). Only some very minor mergers take place, the most important of these mergers having a mass ratio of 12:1 (see on the left panel of figure 2 the mass evolution as a function of time). We will call this simulation *"the calm case"*.

The other simulation also contains diffuse accretion, but is mainly dominated by mergers. There is a first period of repeated minor and major mergers (mass ratios 8:1, 10:1, 3:1 and 4:1) at the very beginning of the simulation, then a calm phase and finally a major merger (mass ratio 1.5:1) at low redshift (see right panel of figure 2). We will call it *"the violent case"*.

3. Results

3.1. *The calm case*

The evolution of the distribution of gas and stars is shown in figure 3. Gas is smoothly accreted around the galaxy and falls onto the disk. Minor mergers are not strong and frequent enough to destroy the stellar disk. They only slightly heat it, and a thin stellar disk is rebuilt thanks to gas from diffuse accretion along the filaments. The thin disk is mainly formed from stars younger than 4 Gyr, and has a well-defined structure with two spiral arms.

3.2. *The violent case*

In this case, the evolution of the morphology of the galaxy is totally different (see figure 4). The disk is destroyed early by the first series of mergers. In fact, after the first of these mergers (which has a mass ratio of 8:1) the disk is already very perturbed, and the following mergers contribute to the transformation of the galaxy into an elliptical.

Nevertheless, thanks to gas accretion that takes place along a filament, a gas disk is gradually re-built into the elliptical galaxy (this would not happen if only mergers were taken into account in the simulation). New stars form in this disk, forming a young stellar disk inside the old spheroid (see figure 5), this disk being in a perpendicular plane with respect to the initial disk. Finally, the last major merger (with a mass ratio of 1.5:1) destroys this disk and the galaxy becomes elliptical again.

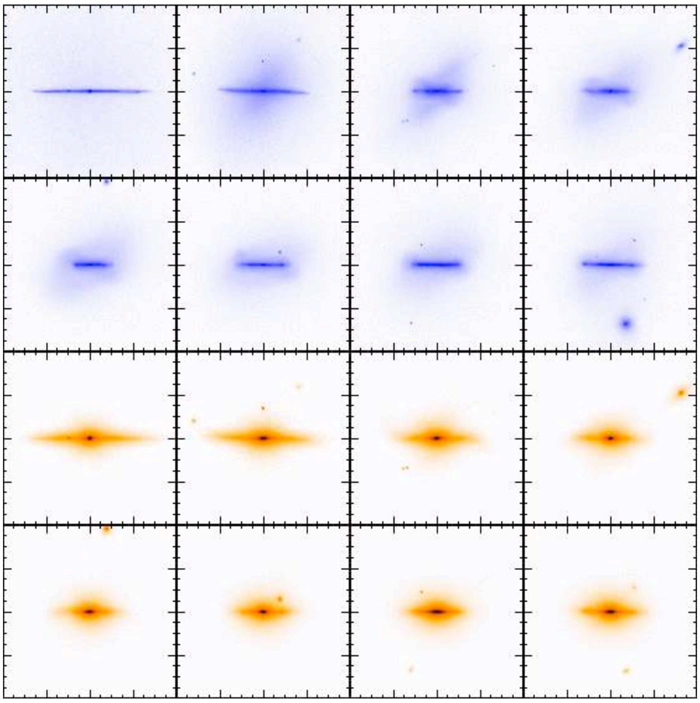

Figure 3. Evolution of the distribution of gas (top panels) and stars (bottom panels) for the calm case. Snapshots are taken every Gyr and each panel is 40 kpc x 40 kpc in size.

4. Conclusion

In order to study galaxy evolution in cosmological context, we have successfully developed a technique that allows us to perform high resolution simulations taking into account realistic merger and gas accretion histories.

The first two simulations shown here do not allow us to draw any general conclusion on galaxy evolution in a ΛCDM context. Nevertheless, we can already confirm that even low mass satellites can thicken disks and that ellipticals from both through repeated minor mergers and major mergers. We also emphasize that gas accretion from filaments can allow to rebuild a thin disk in a galaxy, which proves the absolute necessity to take this accretion into account to understand galaxy evolution.

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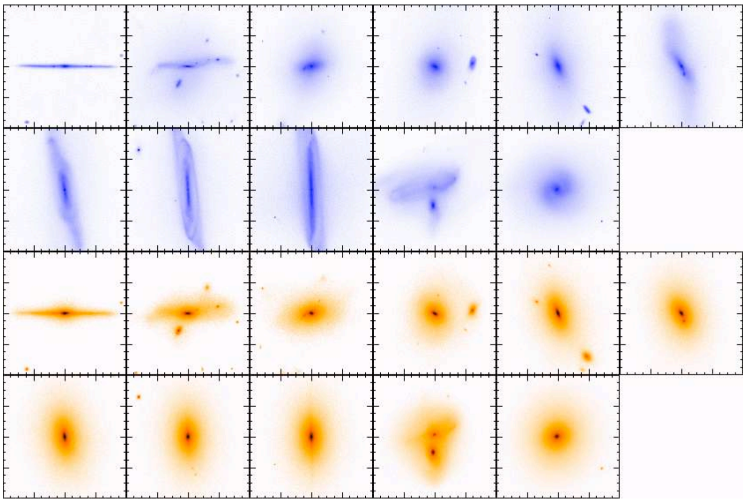

Figure 4. Evolution of the distribution of gas (top panels) and stars (bottom panels) for the violent case. Snapshots are taken every Gyr and each panel is 40 kpc x 40 kpc in size.

Figure 5. Projected stellar mass density at z = 0.2 for the violent case.

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7.3 Deep studies at low redshift

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Galaxy mergers at high resolution: From elliptical galaxies to tidal dwarfs and globular clusters

F. Bournaud[1,⋆], **M. Bois**[2], **E. Emsellem**[2], **P.-A. Duc**[3]

[1] CEA, IRFU, SAP. F-91191 Gif-sur-Yvette, France.
[2] Université de Lyon, Université Lyon 1, Lyon, Observatoire de Lyon, 9 av. Charles André, Saint-Genis Laval, F-69230; CNRS, UMR 5574, Centre de Recherche Astrophysique de Lyon ; Ecole Normale Supérieure de Lyon, France
[3] Laboratoire AIM, CEA/DSM – CNRS – Université Paris Diderot. CEA Saclay, IRFU/SAp, F-91191 Gif-sur-Yvette, France.

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Key words galaxies: interactions – galaxies: evolution – galaxies: elliptical – globular clusters: general

Numerical simulations of galaxy mergers are a powerful tool to study these fundamental events in the hierarchical built-up of galaxies. Recent progress have been made owing to improved modeling, increased resolution and large statistical samples. We present here the highest-resolution models of mergers performed so far. The formation of a variety of substructures ranging from kinematically decoupled cores to globular-like clusters is directly resolved. In a resolution study, we show that the large-scale structure of elliptical-like merger remnants can be affected by the resolution, and a too modest resolution may affect the numerical predictions on the properties of major merger remnants: understanding precisely which kind of event or succession of events has formed the various types of elliptical galaxies remains an open challenge.

1 Introduction

For more than two decades, numerical simulations have been a powerful tool to study the dynamics of interacting galaxies and the properties of galaxy merger remnants. Some of the main results obtained from numerical models range from the formation of elliptical-like galaxies with realistic $r^{1/4}$ density profiles in major mergers of massive spirals (Barnes 1992, Naab & Burkert 2003, Bournaud et al. 2005), the effect of minor mergers of spiral galaxies with small companions (e.g., Walker et al. 1996), and the triggering of star-formation by galaxy interactions and mergers (Mihos & Hernquist 1994, Cox et al. 2006, di Matteo et al. 2007).

Recent progress have been made by studying galaxy interactions in a wider range of physical conditions including more complex (and more realistic) cases like: the (re-)merging of early-type galaxies that are themselves remnants of past major mergers (Naab et al. 2006), sequences of repeated minor mergers (Bournaud et al. 2007a), or merging galaxies embedded in a larger-scale group or cluster environment, showing a significant influence of the ram-pressure and large-scale gravity field on interacting galaxies (Kapferer et al. 2008, Martig & Bournaud 2008).

We present here recent progress in terms of numerical resolution, in simulations of "standard" mergers of two massive spiral galaxies merging together, with no multiple mergers and no large-scale environment accounted for (see Section 2). While the remnants of major mergers in numerical simulations do globally resemble elliptical galaxies, whether the major merger scenario can really explain the exact properties of most real elliptical galaxies or not is still an open question (see Burkert et al. 2007). This raises the question of whether or not most simulations of galaxy mergers have a high-enough resolution to predict accurately the detailed properties of merger remnants: this is studied in Section 3, where we show that a too modest resolution may significantly affect the properties of numerical merger remnants. Our recent very-high resolution simulations also enable to study the smallest structures formed in galaxy mergers, like decoupled cores, tidal dwarfs, and super star clusters: results on these aspects will be presented in Section 4.

2 The simulations and resolution

The simulations presented here were performed with a particle-mesh code based on a FFT Poisson solver for the gravity. The gas dynamics is modeled with a sticky-particle scheme, and a Schmidt law is used for star formation. A thorough description of the code and initial conditions can be found in Bournaud et al. (2008) and references therein. The stellar disks have initial masses of 2×10^{11} $M_\odot$ and we use Burkert (core) profiles for the dark halos. In the following we present simulations obtained at three different resolutions, all with the same 0.5 Gyr timestep:

- the *low* resolution has a softening of 180 pc (up to 25 kpc from each galaxy center, and degraded at larger

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[⋆] Corresponding author: e-mail: frederic.bournaud@cea.fr

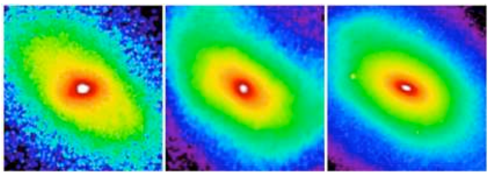

Fig. 1 Projected stellar density maps for a major merger between two spiral galaxies. The *low*, *medium* and *high* resolution models of the same merger are viewed with the same projection angle. These snapshots show an area of 16x16 kpc.

distances) and uses 10^5 particles/galaxy/component (the components are: stars, gas, and dark matter; this implies a total of 6×10^5 particles).

- the *medium* resolution has a softening of 80 pc and 10^6 particles/galaxy/component (total of 6×10^6 particles).
- the *high* resolution has a softening of 32 pc and uses 6×10^6 particles/galaxy/component (total of 36×10^6 particles). Too our knowledge, this is the highest resolution ever achieved so far in this kind of simulations (see comparison with other works in Bournaud et al. 2008).

3 Global properties of elliptical galaxies: a resolution study

To test the standard proposal that ellipticals have been formed by galaxy mergers, and explore in more detail which sort of merger has formed them (binary major mergers, repeated minor or major merger, wet/dry mergers, etc..), recent works have measured in detail the properties of such numerical merger remnants (references above). This raises the question of whether or not numerical simulations with typically a few 10^5 particles per galaxy have converged in terms of the detailed properties of these "ellipticals".

Here we present a wet 1:1 merger model: the two spiral progenitors contain 83% of stars and 17% of gas (plus a dark halo with a Burkert profile), and they have the same mass. The simulation was run at the *low*, *medium* and *high* resolutions defined above. The morphology of the relaxed merger remnant under the very same projection is shown for each resolution on Figure 1. Among the many quantitative parameters measured (which will all be presented in Bois et al. 2009, in preparation), we show on Figure 2 the radial variations of the robust tracer of angular momentum λ_R, defined by Emsellem et al. (2007), measured for a set of isotropically distributed projections.

Our main conclusions follow, and we made sure (Bois et al. 2009) that these effects are not artifacts caused by somewhat different initial conditions (defining the very same initial conditions at different resolution is not trivial), do not affect only the gas dynamics and star formation but also the stellar and dark matter dynamics (sizeable results are found for dry mergers), and do not result simply from a change in the orbit (because the dynamical friction would not be equally resolved in the three cases), but really result from the way the violent relaxation processes are resolved:

- At the three resolutions, the merger remnant resemble an elliptical galaxy, with about the same flattening (axis ratio) except in the central 3 kpc, and a similar $r^{1/4}$-like density profile. The effective (half-mass) radius is 2–2.5 kpc, depending on the projection angle, in the three cases.
- In more detail, significant variations can be seen in the isophotal shape (Fig. 1). The *low* resolution case is overall disky with a major ($\sim 70^\circ$) isophotal twist. The *medium* and *high* resolution cases are boxy under the same projection, with little isophotal twist.
- Important kinematical variations are seen (Fig. 2), the angular momentum profile of the *low* resolution case differs dramatically from the *medium* and *high* resolution ones – even the two later cases differ from each other, but in a more modest way and the shape of their λ_R profiles is more comparable. In particular, within their effective radius, the *low* resolution model would be classified as a fast-rotator (as defined by Emsellem et al. 2007) while the *medium* and *high* ones appear to be slow-rotators: this is a major difference as this typically defines two different classes of early-type galaxies (Emsellem et al. 2007), and the origin of the slowly-rotating ellipticals is a particular challenge for merger scenarios (as pointed out by Naab & Ostriker 2007).

Overall, our *low* resolution model (180 pc, 10^5 particles/galaxy /component), which is not so "low" compared to recent works in the field, gives only a gross prediction of the properties of the merger remnant, and the merger/relaxation processes are insufficiently resolved to accurately predict the detailed properties of this "elliptical". Our *medium* resolution (80 pc, 10^6 part/gal/comp), which is quite high compared to several recent works, gives more accurate predictions of the morphology and kinematics. It generally compares favorably to the *high* resolution case (32 pc, 6×10^6 part/gal/comp – the highest to date), but some results may still vary with resolution, in particular the advanced parameters used to deeply explore the structure of ellipticals like λ_R. This shows that resolution issues are a significant concern in attempts to compare in detail the properties of observed ellipticals with prediction of merger models, even in recent simulations with a rather high number of both stellar and gaseous particles.

4 Structure formation in galaxy mergers: from decoupled cores to tidal dwarfs and globular clusters

While the total stellar mass density of merger remnants is dominated by smooth spheroids (Fig. 1), interstellar gas fuels the formation of many substructures of gas and young stars. Kinematically decoupled cores (KDCs) are frequently seen in our medium- and high-resolution simulations of

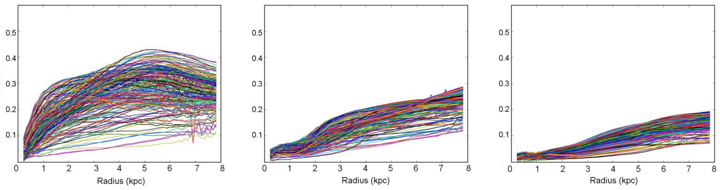

Fig. 2 Radial profiles of the angular momentum tracer λ_R of a relaxed merger remnant, for the *low*, *medium* and *high* resolution models respectively. The many curves in each plot correspond to different projection angle, that were chosen to be isotropically distributed.

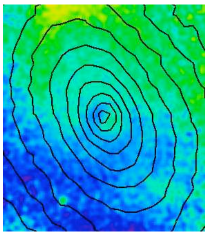

Fig. 3 Stellar velocity field in a high-resolution wet 1:1 merger remnant, showing a counter-rotating KCD. The black contours show the projected stellar mass density (log spacing), this snapshot shows a 10x12 kpc area.

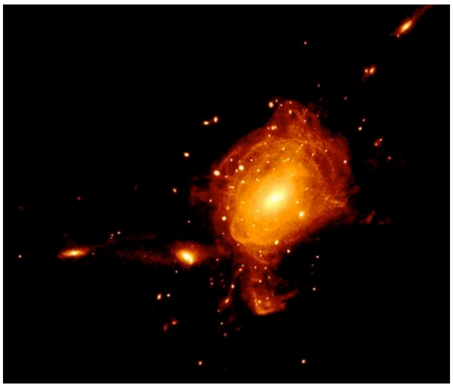

Fig. 4 Projected mass density of the "young" stars, i.e. those formed during or after the merger, in a wet 1:1 high-resolution merger remnant.

galaxy mergers (see Fig. 3). They form when a merger-driven gas inflow triggers the formation of a dense concentration of young stars inside, typically, the central kpc. Such stellar systems formed during/after the merger largely contribute to the total stellar kinematics in the central regions, while the larger-scale system is dominated by stellar populations older than the merger. Torques that act on the gas structures during the galaxy collision frequently cause the central component to have a kinematic axis misaligned with the older stellar system, and the KDC can even sometimes be counter-rotating w.r.t. the rest of the elliptical. Although our statistics are limited for the moment, we do not find KDCs to be preferentially associated to morphological decoupling like large isophotal twists. Note that major wet mergers are not necessarily the only mechanism producing kinematically decoupled components in early-type galaxies (Naab et al. 2007, di Matteo et al. 2008).

The outskirts of merger remnants also contain a variety of young stellar substructures. Figure 4 displays the density map of the "young" stars formed during/after the merger, in a relaxed high-resolution merger remnant (see also Bournaud et al. 2008) : one can notice streams and shells, and more than one hundred of small stellar objects. The three most massive stellar objects have masses of 10^{8-9} $M_{\odot}$ radii of about a kpc and are supported by rotation ($V > \sigma$ – see objects A and B on Fig. 5): they resemble Tidal Dwarf Galaxies (TDGs). The many other, smaller objects have lower masses, ranging from 10^5 $M_{\odot}$ (the resolution limit) to a few 10^7 $M_{\odot}$. They are very compact with radii from $\sim$30 pc (the softening limit) to $\sim$150 pc, and are tightly bound ($E_G/2E_K < -1$, see Bournaud et al. 2008), supported by random motions with little rotation ($V/\sigma < 1$, see Fig. 5). These Super Star Clusters (SSCs) are thus likely progenitors of Globular Clusters (GCs). The formation of such SSCs/GCs in major mergers had been predicted for instance by Li et al. (2004) and is here directly resolved.

TDGs are SSCs/GCs appear to be two different kind of objects: TDGs are large, rotating, found in the outer tidal tails. Their formation occurs when a giant molecular cloud or a dense region of the progenitor spiral disk is moved into a tidal tail by the interaction, following the mechanism proposed by Elmegreen et al. (1993). With large dark haloes, large regions of the outer disk can even be displaced into the outer regions of a tidal tail without being disrupted, and can form a new self-gravitating objects here (Duc et al. 2004).

The SSCs/GCs are formed in the outer tidal tails and other dense streams of gas at smaller radii, they have a much lower specific angular momentum and are more compact. This, together with a dip in the mass function between SSCs/GCs and TDGs (Fig. 6), implies that these are two different categories of objects, and the three large TDGs in our

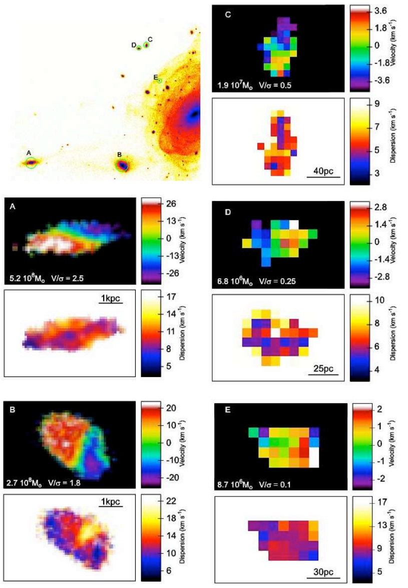

Fig. 5 Line-of-sight velocity and dispersion fields for several young stellar objects formed in the mergers: two TDGs (A, B) and three SSCs/GCs (C, D, E).

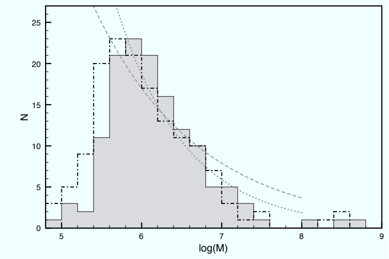

Fig. 6 Mass function of the young bound stellar objects (SSCs/GCs and TDGs) formed in the major merger displayed on Fig. 4. A significant dip separates SSCs/GCs and the three massive TDGs. The dashed histogram corresponds to a test simulation with modified gas dissipation parameters (see Bournaud et al. 2008).

simulation are not just the high-mass end of the SSC distribution. The SSCs are formed by the fragmentation of dense gaseous structures, following the mechanism studied in particular by Wetzstein et al. (2007). In that vein, the "tidal dwarfs" in Wetzstein et al. models do not resemble the three massive TDGs in our model, but rather to the high-mass end of the more compact SSCs. This does not mean that they should never be considered as tidal dwarfs: indeed, with masses of a few 10^7 $M_\odot$, they are really as massive as some dwarf galaxies. There could thus be two types of tidal dwarf galaxies: the high-mass end of SSCs/GCs, which would be compact spheroidal galaxies, and the larger, more massive and rotating TDGs, formed by a different mechanism and resembling the kpc-sized rotating TDGs observed in several interacting systems like NGC 5291 (Bournaud et al. 2007b). TDGs of this later type may still evolve into smaller dwarf spheroidals over a few Gyrs (Metz & Kroupa 2007).

5 Conclusions

High spatial and mass resolution enables the formation of small objects to be resolved in numerical models of galaxy mergers. In recent simulations, even the internal properties of small objects can be resolved – like the rotation curves of tidal dwarfs (see Bournaud et al. 2007b). The results of such high-resolution models is overall in agreement with theoretical expectations, in particular regarding the formation of a population of GCs during major wet mergers.

High resolution is also a must to study accurately the large-scale structure of spheroidal galaxies formed in major mergers. Our recent resolution study shows that even simulations with a total of one million particles and a spatial resolution of a hundred of parsec can still be significantly affected by the resolution. Whether major mergers can explain the detailed properties of elliptical galaxies (boxyness, angular momentum distribution, anisotropy, etc..) is still largely unsolved, and understanding which type of merger would have formed the various kind of ellipticals remains an important challenge.

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7.4 Local morphology and bar evolution in the (new) context of high-resdhift spiral formation

7.5 Comparing simulations and observations

7.6 Modelling the ISM dynamics and star formation processes at high resolution

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