FORMATION OF GALAXIES IN A HIERARCHICAL CLUSTERING MODEL

P.B. TISSERA[1,2], A. SÁIZ[1] and R. DOMÍNGUEZ-TENREIRO[1]
[1] *Dpt. Física Teórica, UAM, Cantoblanco, 28049 Madrid, Spain*
[2] *IAFE, Casilla 67, Suc. 28, 1428 Buenos Aires, Argentina*

Abstract. We present results on the formation and evolution of galaxy-like objects in hydrodynamical cosmological simulations.

1. Introduction

For decades astronomers have devoted great efforts to understanding how galaxies have formed and evolved to have the astrophysical characteristics observed today. In particular, the so-called standard model for the formation of discs has been set up by Fall and Efstathiou (1980, hereafter FE). These authors show that a disc-like structure with observational counterparts could be formed from the diffuse gaseous component in a dark matter halo with a certain initial angular momentum, provided that this gas cools and collapses *conserving its specific angular momentum*. This last hypothesis is the key point in the successful formulation of FE. However, this model assumes that the gas and dark matter are initially distributed in an isolated sphere, suffering no mergers or close encounters. This is an unrealistic situation in a hierarchical clustering model, the favourite scenario nowadays for the formation and evolution of structure.

Several semi-analytical studies have adopted the FE model and applied it successfully to the study of general properties of the disc population (e.g. Dalcanton, Spergel and Summers, 1997; Mo, Mau and White, 1998). However, they take for granted the condition of specific angular momentum conservation. Unfortunately, serious problems arise in this regard when hydrodynamical simulations are used. These numerical experiments have the great advantage of being able to introduce the physics in a general way and not as recipes (even if they are in the early stages of their development and much work still needs to be done). In this case, in cosmological hierarchical clustering models, it has been shown that gaseous discs form but are too small and concentrated.

Later studies showed that the main problem is the loss of angular momentum by the gaseous component during mergers (e.g. Navarro and Steinmetz, 1997; Weil, Eke and Efstathiou, 1998). Because in these kinds of scenarios, mergers are ubiquitous at all epochs, these angular momentum losses translate into a catastrophic

Astrophysics and Space Science **276:** 1079–1086, 2001.
© 2001 *Kluwer Academic Publishers. Printed in the Netherlands.*

effect: the resulting gaseous discs have at least *one* order of magnitude less angular momentum than their host dark matter haloes. The condition of conservation of the specific angular momentum by the gas component is no longer satisfied. On the other hand, when star formation is included, because of its high efficiency, most of the gas is transformed into stars at high redshift, depleting the reservoir to form discs at lower z (e.g. Steinmetz and Navarro, 1998). The obvious suggested solution has been the inclusion of supernova effects. However, there is hitherto no numerical code that treats this effect satisfactorily. Moreover, there exist other physical processes that may play a non trivial role. In particular, the formation of stellar bulges could have important consequences in building up galaxy-like objects in hierarchical scenarios. This is so since stellar bulge-like cores would be formed at high redshifts, modifying substantially the fate of the subsequently formed disc-like objects relative to that of their bulgeless counterparts.

In fact, both theoretical studies and numerical simulations have shown that a disc can develop violent instabilities leading to bar formation, followed by inward material transport due to specific angular momentum (j) non conservation (e.g. Toomre, 1981; Binney and Tremaine, 1987; Barnes and Hernquist, 1991, 1992, 1996; Mihos and Hernquist, 1994, 1996). Athanassoula and Sellwood (1986) and Mihos and Hernquist (1996), among others, have shown that bulges, if present, play a fundamental role in stabilizing disc galaxies against these bar instability modes. A compact stellar bulge provides for stability by assuring the axisymmetric character of the potential well, preventing angular momentum losses. Many questions still have to be answered about gas inflows and the physics related to them, but observational studies have started to give hints in favour of these hypotheses (e.g. Chapelon, Contini and Davoust, 2000).

In this paper, we study the effects of the presence of compact stellar bulges in the formation of disc-like structures in a hierarchical scenario using *fully consistent cosmological hydrodynamical simulations*. The same initial condition has been run twice: in run I.2 stellar bulges have been allowed to form and in run I.4 only gas and dark matter have been followed. A comparison of the properties and histories of formation of the galactic objects in I.2 and of their pure gaseous counterparts in I.4, has been carried out. This paper is organized as follows. Section 1 describes the numerical experiments, in Section 2 we analyse the galactic objects and their history of formation and Section 3 summarizes the findings.

2. Numerical Experiments

We have followed the evolution of 64^3 particles in a periodic box of 10 Mpc ($H_0 = 50$ km s^{-1} Mpc^{-1}) using a SPH+AP3M code (see Tissera, Lambas and Abadi, 1997, for details), either including a star formation algorithm (I.2 simulation) or not (I.4 simulation). The initial condition is consistent with a standard CDM cosmology, with $\Omega_b = 0.1$, $\Lambda = 0$ and $b = 2.5$. All dark gas and star particles have the same mass, $m = 2.6 \times 10^8\ M_\odot$ (the gravitational softening length is 3 kpc and the minimum smoothing length, 1.5 kpc). In I.2, cold and dense gas particles which also satisfy the Jeans instability criterion are transformed into stars according to the Schmidt law (for details, see Tissera *et al.*, 1997; simulations I.2 and I.4 correspond to I.2 and I.4 in Tissera *et al.*, these proceedings). No supernova explosion effects have been considered. A low star formation efficiency has been used in I.2 so that star formation occurs mainly in the *very dense regions*, allowing us to have gas available to form disc-like structures at low z. To some extent, this could mimic the effects of energy injection from supernova explosions. Dark haloes formed in I.2 are identical to those formed in I.4 (Tissera and Domínguez-Tenreiro, 1998). The baryonic disc-like objects (DLOs) that they host have been identified using a friend-of-friends algorithm. Only those DLOs whose total baryon number satisfies $N_{\rm baryon} > 150$ have been considered. Ten discs (and three spheroids, not considered in this paper) have been found in I.2 following this criterion (see Domínguez-Tenreiro, Tissera and Sáinz, 1998, for more details).

3. Analysis

DLOs identified in I.2 have central bulge-like concentrations and extended discs. A detailed comparison with observations is discussed by Domínguez-Tenreiro, Sáiz and Tissera (these proceedings). A double exponential decomposition was applied to the *mass* density of baryons projected on to the disc plane for the DLOs in I.2 and I.4. It is found that for DLOs in I.2, the bulge and disc scale parameter distribution, $R_{\rm b}$ vs. $R_{\rm d}$, is consistent with observations (e.g. Courteau, 1997). For the same DLOs in the pure-gas run, the bulge scale lengths change considerably (the mean value for DLOs in I.2 is $< R_{\rm b} >= 0.59$, and for those in I.4, $< R_{\rm b} >= 1.31$). This fact indicates that a larger fraction of gas has fallen into the central regions.

The j distribution of the different components (dark matter, gas and stars) shows clearly if there have been angular momentum losses during the process of formation by any of these components. In Figure 1 we plot j at $z = 0$ versus mass for dark haloes in I.2 or I.4, $j_{\rm dh}$, for the inner 83% of the gas mass for I.2 and I.4 DLOs (i.e. the mass fraction enclosed by $R_{\rm opt} = 3.2R_{\rm d}$ in a purely exponential disc), $j_{\rm g}$, and for the stellar component in I.2, $j_{\rm s}$. We see that $j_{\rm g}$ is of the order of $j_{\rm dh}$ for I.2 DLOs, so that these gas particles have collapsed, conserving on average their angular momentum, while those in their I.4 counterparts have suffered a strong loss, in agreement with previous results. Moreover, DLOs formed in I.2 are inside the box defined by observed spiral discs (Fall, 1983), while DLOs in I.4 are not. The stellar component in I.2 has formed from gas that has lost a substantial fraction of its j. Another way of seeing this is to construct a histogram where baryonic particles are sorted according to their j. Figure 2 shows the histograms for DLO #1 (see Table I of Domínguez-Tenreiro, Sáiz and Tissera, these proceedings, and

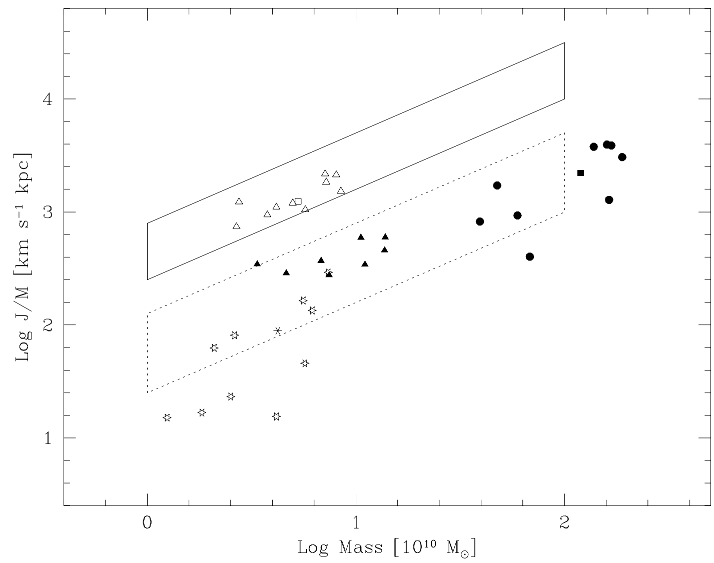

Figure 1. The specific angular momentum at $z = 0$ versus mass for haloes in I.2 or I.4 (*filled circles*), the inner 83% of the gas component in discs I.2 (*open triangles*) and I.4 (*filled triangles*) and the stellar component in I.2 (*open stars*). *Filled and open squares* and the *asterisk* are the corresponding results for a high-resolution run. The *solid* and *dotted* boxes show the regions occupied by spiral and elliptical galaxies, respectively.

Domínguez-Tenreiro *et al.*, 1998) in I.2 [*left panel*] and I.4 [*right panel*]; both distributions have their y-axes cut off at $N = 50$ for the sake of clarity). It can be seen that the differences in the distributions show the existence of a high-j tail in I.2 that is barely present in I.4, together with more prominent and broad distribution for $j \leq 3$ in the latter. The high angular momentum tail particles form the disc in I.2. An important fraction of these particles have lost angular momentum in I.4 and fallen into lower j bins.

Global disc stability is usually studied through the $X_2(R)$ parameter (Toomre, 1981; Binney and Tremaine, 1987). We have calculated $X_2(R)$ for the disc component of our DLOs at different z. According to Fall and Efstathiou (1980) and Dalcanton *et al.* (1997), among others, if the diffuse gas in the halo collapses with j conservation, then baryons will settle on to a disc with an exponential surface density profile. So to find out whether haloes formed in I.2 or I.4 need a bulge to stabilize the pure exponential discs that would be formed from the diffuse gas, we have also calculated $X_2(R)$ for bulgeless versions of our DLOs, i.e. putting all the baryonic mass of each DLO in a pure exponential disc whose scale length is determined assuming specific angular momentum conservation. In Figure 3*c* (3*f*) we plot $X_2(R)$ for the I.2 (I.4) version of DLO #1 at $z = 0$. The same plots for the same DLO are given after its last major event in Figure 3*b* (3*e*) for its I.2 (I.4)

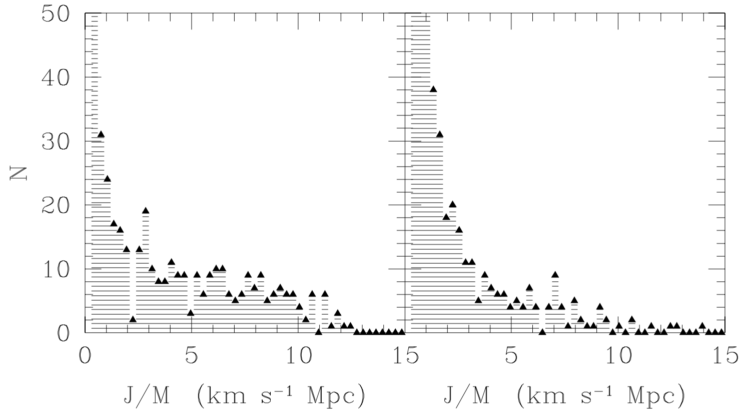

Figure 2. Histograms of the specific angular momentum of baryonic particles in a typical DLO in I.2 (*left panel*) and in its counterpart in I.4 (*right panel*).

version, and prior to this event in Figures 3*a* (for I.2) and 3*d* (for I.4). Moreover, the $X_2(R)$ for their bulgeless counterpart at $z = 0$ is plotted in Figure 3*f*. Recalling the $X_2(R)$ stability criterion, it is apparent from these figures that discs, when present, are stable: they have $X_2(R) > 3$ for $R > 3$ kpc. By contrast, the bulgeless version of DLO #1 at $z = 0$ would be stable only at larger R ($R > \simeq 21$ kpc). This behaviour is common to any DLO in I.2 or I.4, and so central mass concentrations are needed to stabilize these discs.

Let us now analyse how these DLOs formed in both runs in order to understand where the differences in their properties have originated. Their assembly in I.2 is an inside-out process with different episodes. i) First, dark-matter haloes collapse at high z forming a first generation of (small) discs and stars. ii) Then, the first destabilizing mergers at high z occur, resulting in disc disruption and rapid mass inflow to the central regions with j loss and violent star formation, mainly in the central regions. Also, most pre-existing stars will concentrate in the centre of the new object through violent relaxation. These two processes help build up a central stellar bulge-like structure. iii) After the first mergers, a disc is regenerated through an infall of gas particles, either belonging to the baryonic merging clumps or diffuse. For example, a compact stellar bulge and an almost cold disc in I.2 DLO #1 at $z = 0.57$ are apparent in Figure 3*a*. iv) After disc regeneration, the system can undergo new major merger events at lower z (see Tissera, Goldschmidt and Domínguez-Tenreiro, 2000, for details). During the orbital decay phase, prior to the actual fusion of the DLOs, most of their orbital angular momentum is transported to (the particle components of) each host halo, spinning it up (Barnes, 1992; Barnes and Hernquist, 1991, 1992, 1996). Because, now, the discs involved in the merger are stabilized by their bulges, no strong gas inflow occurs in this phase (Mihos and Hernquist, 1994, 1996). As the discs approach one another, they are heated and finally disrupted, but the high efficiency of gas shocking and cooling, and the

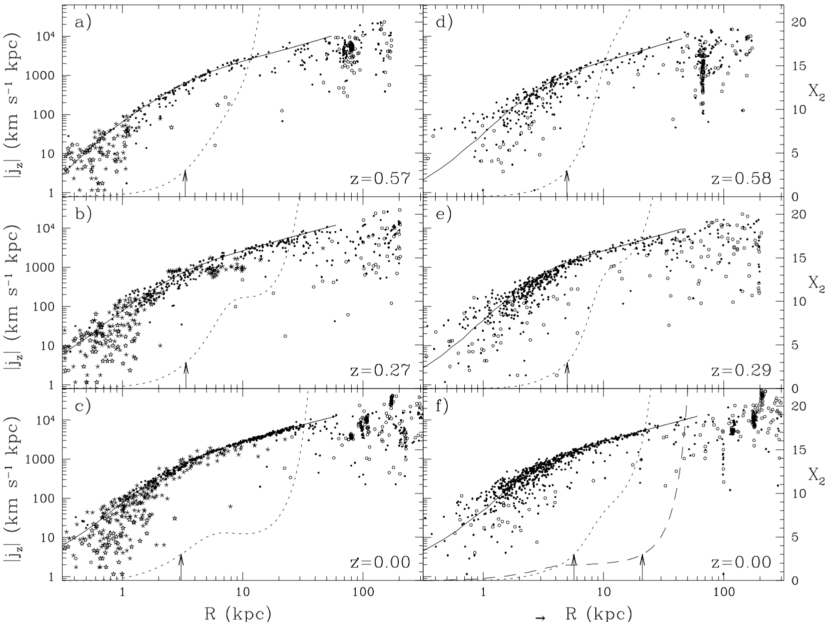

Figure 3. Specific angular momentum component along $\vec{J}_{\rm dis}$ for each baryon particle of halo #1, versus their positions at different z. *Points:* Gas particles; *stars:* stellar particles; *open symbols:* counter-rotating particles. *Left panels:* I.2 version at different z; *right panels:* I.4 version at approximately the same z. *Full lines:* $v_c(R)R$; *dotted lines:* $X_2(R)$ for actual discs at each z; *dashed line:* $X_2(R)$ for the pure exponential version at $z = 0$. *Arrows* mark $R_{\rm st}^{\rm ad}$ and $R_{\rm st}^{\rm ped}$, where $X_2(R) = 3$.

symmetry of the central potential, quickly puts those of their gas particles with high j into a *new intermediate disc*, while their low-j particles sink to the centre, where most of them are transformed into stars feeding the bulge. The stellar bulge of the smaller DLO is eventually destroyed and incomplete orbital angular momentum loss puts most of its stars on the remnant disc (Figure 3*b*, note the incomplete relaxation). These particles construct the final disc from the intermediate one so that, in the end, the final disc is well populated. v) Relaxation and disc regeneration are completed. Most of disc external particles are supplied by infall, as in iii) [Figure 3*c*].

The assembly of galaxy-like objects in I.4 follows the same stages. It should be recalled that in both simulations, haloes and merger trees are identical. The main difference is that in I.4, stages i) and ii) do not result in a stellar core, and, consequently, in stage iii) an unstable gas disc is formed, susceptible to growing a bar. In particular, during the orbital decay phase in iv), strong gas inflow and j loss are induced (Figure 3*d*; see also Mihos and Hernquist, 1994, 1996). Most of the j is lost during this period, so that when the actual fusion occurs (Figure 3*e*) most of the gas particles originally in the discs are already at the centre. The rest of j is lost during the fusion. Few particles are left for disc regeneration, so that, in phase v), discs are formed almost only from halo gas particles (Figure 3*f*). These particles, although settling into a disc-like structure according to their j (Figure 2), are not enough to regenerate a full disc with the correct total j. Small satellites that orbit around DLOs may also trigger, in this case, a further gas inflow, while in I.2 they are accreted without any major damage.

Concerning numerical resolution, DLOs in I.2 and I.4 are resolved with a relatively low number of particles. In contrast, dark-matter haloes are described with a much better resolution. An inappropriately low gas resolution would result in an unphysical gas heating that could halt the gas collapse (Navarro and Steinmetz, 1997). However, some studies suggest that it is an inadequate resolution in the dark-matter halo component that may produce the larger undesired numerical artefacts (Steinmetz and White, 1997). Therefore, to make sure that the populated and extended discs in I.2 do not result from unphysical gas heating, we have run a higher-resolution simulation (64^3 particles in a periodic box of 5 Mpc, with cosmological and star formation parameters similar to those in I.2; hereafter HRS). Only one disc with mass comparable to those in I.2 forms. Its analysis has shown that it is populated and extended, that its structural and dynamical characteristics are compatible with observations (see Figure 1 and Domínguez-Tenreiro, Sáiz and Tissera, these proceedings), and that the physical processes leading to its formation are essentially the same as those at work in I.2. In addition, a comparison between the distributions of the ratios $t_{\rm dyn}/t_{\rm cool}$ for gas particles belonging to the DLOs in I.2, and to their counterparts in I.4, shows no difference. These results indicate that the infall of gas in I.2 has not been artificially heated by the decrease in numerical resolution due to the transformation of gas particles into stars.

4. Conclusions

The formation of compact stellar bulges prior to the last main mergers of the galactic objects helps gaseous discs to conserve a fraction of their angular momentum during mergers and interactions by assuring the axisymmetric character of the potential well at all times. The formation of a (small) intermediate disc after a merger is a key point in the process. A low star formation efficiency has only allowed the formation of a compact stellar bulge without depleting the gas reservoir, which has provided the right conditions for the FE model to remain valid. Future papers will deepen in this analysis in order to better understand the physical processes and the numerical effects involved in this problem.

Acknowledgements

We acknowledge useful comments from J.F. Navarro and J. Barnes. We are grateful to S.D.M. White for fruitful discussions during the summer workshop 1998 at the Aspen Center for Physics.

References

Athanassoula, E. and Sellwood, J.: 1986, *Mon. Not. R. Astron. Soc.* **221**, 213.
Barnes, J.E.: 1992, *Astrophys. J.* **341**, 425.
Barnes, J.E. and Hernquist, L.: 1991, *Astrophys. J. Lett.* **370**, L65.
Barnes, J.E. and Hernquist, L.: 1992, *Annu. Rev. Astron. Astrophys.* **30**, 705.
Barnes, J.E. and Hernquist, L.: 1996, *Astrophys. J. Lett.* **471**, 115.
Binney, J. and Tremaine, S.: 1987, *Galactic Dynamics*, Princeton Univ. Press, Princeton.
Chapelon, S., Contini, T. and Davoust, E.: 1999, *Astron. Astrophys.* **345**, 18.
Courteau, S.: 1997, in: D. Block and M. Greenber (eds.), *Morphology and Dust Content in Spiral Galaxies*, Kluwer, Dordrecht.
Dalcanton, J.J., Spergel, D.N. and Summers, F.J.: 1997, *Astrophys. J.* **482**, 659.
Domínguez-Tenreiro, R., Tissera, P.B. and Sáiz, A.: 1998, *Astrophys. J. Lett.* **508**, L123.
Fall, S.M.: 1983, in: E. Athanassoula (ed.), IAU Symp. **100**, *Internal Kinematics and Dynamics of Galaxies*, Reidel, Dordrecht.
Fall, S.M. and Efstathiou, G.: 1980, *Mon. Not. R. Astron. Soc.* **193**, 189.
Mihos, J.C. and Hernquist, L.: 1994, *Astrophys. J. Lett.* **425**, L13.
Mihos, J.C. and Hernquist, L.: 1996, *Astrophys. J.* **464**, 641.
Mo, H.J., Mao, S. and White, S.D.M.: 1998, *Mon. Not. R. Astron. Soc.* **295**, 319.
Navarro, J.F. and Steinmetz, M.: 1997, *Astrophys. J.* **438**, 13.
Steinmetz, M. and Navarro, J.F.: 1998, *Astrophys. J.* **513**, 555.
Steinmetz, M. and White, S.D.M.: 1997, *Mon. Not. R. Astron. Soc.* **289**, 545.
Tissera, P.B. and Domínguez-Tenreiro, R.: 1998, *Mon. Not. R. Astron. Soc.* **297**, 177.
Tissera, P.B., Goldschmidt, P. and Domínguez-Tenreiro, R.: 2000, *Mon. Not. R. Astron. Soc.*, submitted.
Tissera, P.B., Lambas, D.G. and Abadi, M.G.: 1997, *Mon. Not. R. Astron. Soc.* **286**, 384.
Toomre, A.: 1981, in: S.M. Fall and D. Lynden-Bell (eds.), *The Structure and Evolution of Normal Galaxies*, Cambridge Univ. Press, Cambridge, p. 111.
Weil, M.L., Eke, V.R. and Efstathiou, G.: 1998, *Mon. Not. R. Astron. Soc.* **300**, 773.