Disk Formation In Hierarchical Hydrodynamical Simulations: A Way Out Of The Angular Momentum Catastrophe

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ABSTRACT

We report results on the formation of disk-like structures in two cosmological hydrodynamical simulations in a hierarchical clustering scenario, sharing the same initial conditions. In the first one, a simple and generic implementation of star formation has allowed galaxy-like objects with stellar bulges and extended, populated disks to form. Gas in the disk comes from both, particles that survive mergers keeping in part their angular momentum content, and new gas supply by infall, once the merger process is over, with global specific angular momentum conservation. The stellar bulge forms from gas that has lost most of its angular momentum. In the second simulation, no star formation has been included. In this case, objects consist of an overpopulated central gas concentration, and an extended, underpopulated disk. The central concentration forms from particles that suffer an important angular momentum loss in violent events, and it often contains more than 70% of the object’s baryonic mass. The external disk forms by late infall of gas, that roughly conserves its specific angular momentum. The difference between these two simulations is likely to be due to the stabilizing character of the stellar bulge-like cores that form in the first simulation, which diminishes the inflow of gas triggered by mergers and interactions.

Subject headings: galaxies: formation - observations - cosmology: theory - dark matter - methods: numerical
1. INTRODUCTION

The standard model of disk formation has been set by Fall and Efstathiou (1980) following and extending previous work by White and Rees (1978). According to this scheme, extended disks resembling those observed in spiral galaxies can be formed from the diffuse halo gas component provided that it conserves its specific angular momentum \( (j) \) during collapse. This scheme has served as a basis to build-up theoretical models of galaxy formation (Lacey et al. 1993; Kauffmann 1996; Dalcanton et al. 1997; Mo et al. 1998; van den Bosch 1998, hereafter vdB98), but it has the shortcoming of not being able to treat the effects of mergers in disk formation. Merger effects are naturally taken into account in numerical simulations. However, so far, no hydrodynamical simulation of galaxy formation in fully consistent hierarchical cosmological scenarios had been able to produce extended disks, with structural and dynamical properties similar to those of observed spirals. The problem was the excessive loss of angular momentum by the gas clumps as they merge inside the dark haloes, resulting in too concentrated disks (the so-called angular momentum catastrophe problem, hereafter AMC, see Navarro & Benz 1991; Evrard et al. 1994; Vedel et al. 1994; Navarro et al. 1995; Navarro & Steinmetz 1997; Weil et al. 1998). No star formation processes have been considered by these authors. By contrast, the effects of star formation have been considered by Katz (1992) and Steinmetz & Müller (1995) in a semi-cosmological modelling of the collapse of an isolated constant density perturbation in solid-body rotation, getting in both cases a three component system that resembles a spiral galaxy.

A realistic implementation of the star-forming processes in a simulation is beyond present possibilities. However, turning on the star formation process could have important consequences in building up galaxy-like objects in hierarchical scenarios, since stellar bulge-like cores would be formed at high redshifts, modifying substantially the fate of the
subsequently formed disk-like objects relative to that of their bulgeless counterparts (Mihos & Hernquist 1994, 1996, hereafter MH94, MH96). In fact, both theoretical studies and numerical simulations have shown that a disk can develop violent instabilities leading to bar formation, followed by inward material transport due to non conservation (Toomre & Toomre 1972; Ostriker & Peebles 1974; Toomre 1981; Efstathiou et al. 1982; Athanassoula & Sellwood 1986; Binney & Tremaine 1987; Barnes & Hernquist 1991, 1992; Friedli & Benz 1992; Martinet 1995 and references quoted therein; MH94, MH96). However, Athanassoula & Sellwood 1986, MH94, MH96, Christodoulou et al. (1995) and vdB98, have shown that bulges, if present, play a fundamental role in stabilizing disk galaxies against the bar instability mode, diminishing the inflow of gas triggered by interactions and mergers.

Hence, stellar bulges could be critical to ensure global conservation in the assembly of disks in hydrodynamical cosmological simulations. The inclusion of a star formation algorithm leads unavoidably to stellar bulge formation, regardless of its details. So even a simple implementation, that takes into account only its gross physical properties, provided that not all the gas is depleted at high redshifts, could be enough to ensure the formation of disks and their stability. In this Letter we discuss the problem of the $j$ conservation in connection with disk formation in the hierarchical clustering scenario. We analyze the role played by central compact bulges as a critical component to prevent the AMC.

2. DISK FORMATION

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 code coupled to the high resolution AP3M code (Thomas & Couchman 1992), either including a star formation algorithm (S1 simulation) or not (S2 simulation). The initial distribution of positions and velocities is the same in both S1 and S2, and is consistent with a standard flat CDM cosmology, with $\Omega_m = 0.1, \Lambda = 0$.
and $b = 2.5$. All, dark, gas and star particles have the same mass, $m = 2.6 \times 10^8 \, \text{M}_\odot$. The integrations were carried out only gravitationally from $z \simeq 50$ to $z = 10$, and from there on the SPH forces were also taken into account up to $z = 0$ using fixed time steps of $\Delta t = 1.3 \times 10^7$ years. The gravitational softening length is 3 kpc and the minimum allowed smoothing length is 1.5 kpc. In S1, cold and dense ($\rho_{\text{gas}} > 7 \times 10^{-26} \, \text{g/cm}^3$) gas particles which also satisfy the Jeans instability criterion are transformed into stars according to:

$$dp_{\text{star}}/dt = -c\rho_{\text{gas}}/t_\star,$$

with star formation efficiency $c = 0.01$ and $t_\star$ a characteristic time scale (for details, see Tissera et al. 1997). No supernovae explosion effects have been considered. The low $c$ value used implies that star formation occurs mainly in the very dense regions, and so it allowed us to have available gas to form disk-like structures at low $z$. To some extent, this could mimic the effects of energy injection from supernovae explosions. Haloes formed in S1 are identical to those formed in S2 (Tissera & Domínguez-Tenreiro 1998, hereafter TDT98). The baryonic disk-like objects (DLOs) that they host have been identified using a friend-of-friends algorithm. Only those DLOs whose total baryon number (i.e., star, $N_{\text{star}}$, plus gas, $N_{\text{gas}}$, number) satisfies $N_{\text{baryon}} > 150$ have been considered. The number of particles per DLO is essentially the same in the S1 and S2 simulations. Ten disks (and three spheroids, not considered in this paper) have been found in S1 following this criterion. Their general characteristics are given in Table 1. DLOs #5 and #6 form a pair in S1, while in S2 they cannot be resolved as two distinct objects.

DLOs that form in S1 have central star concentrations and extended, populated disks, while those in S2 present an inner, rather disordered gas concentration and, also, extended disks, but with a much lower surface mass density than their S1 counterparts. The mass density profiles of baryons, projected on the disk plane, are well fit in both S1 and S2 by a double exponential (Courteau et al. 1996; Courteau 1997) whose bulge and disk scale lengths, $R_b$ and $R_d$, respectively, are given in Table 1. As a measure of the central baryonic concentrations, in Table 1 we also give the corresponding mass $B/D$ ratios. These are
larger for S2 versions of the DLOs, although the differences vary from DLO to DLO.

In Fig. 1 we plot the specific total angular momentum at \( z = 0 \) versus mass for dark haloes in S1 or S2, \( j_{\text{dh}} \), for the inner 83\% of the gas mass for S1 and S2 DLOs (i.e., the mass fraction enclosed by \( R_{\text{opt}} = 3.2 R_{\text{d}} \) in a purely exponential disk), \( j_{\text{g}} \), and for the stellar component in S1, \( j_{\text{s}} \). We see that \( j_{\text{g}} \) is of the order of \( j_{\text{dh}} \) for S1 DLOs, so that these gas particles have collapsed conserving, on average, their angular momentum, while those in their S2 counterparts have suffered a strong loss, in agreement with previous results. Moreover, DLOs formed in S1 are inside the box defined by observed spiral disks in this plot (Fall 1983), while DLOs in S2 are not. The stellar component in S1 has formed from gas that had lost a substantial fraction of its \( j \). To make these points clearer, in Fig. 2a we plot, for each baryon particle of halo hosting DLO #1 in S1, its angular momentum component per unit mass \( j_{z,i} \) (parallel to the total angular momentum of the disk, \( \vec{j}_{\text{dis}} \)) versus \( R_i \), the projected radial distance from \( i \) to the mass center, at \( z = 0 \). The full line is \( v_c(R)R \), where \( v_c(R) \) is the circular velocity at \( R \) in the potential well of both the dark matter and baryons (see TDT98). We see that most gas particles placed at \( R_i \lesssim 30 \) kpc follow circular trajectories on the equatorial plane, that is, they have \( j_{z,i} \approx \vec{j}_i \approx v_c(R_i)R_i \), with a small dispersion around this value, so that they form a cold thin disk. In contrast, those at \( R_i \gtrsim 30 \) kpc (hereafter, halo gas particles) are disordered, with their \( |j_{z,i}| \) taking any value under the full line. Roughly half halo gas particles have \( j_{z,i} < 0 \) (counterrotating particles, open circles). Stars at \( R_i \lesssim 2 \) kpc form a compact central relaxed core, with \( \vec{j}_i \) without any preferred direction and very low \( |\vec{j}_i| \), while those at \( R_i \gtrsim 2 \) kpc roughly follow a (thicker) disk. These same plots for DLO #1 in S2 (Fig. 2b), show that their gas particles placed at 6 kpc \( \lesssim R_i \lesssim 30 \) kpc form, also in this case, an extended, thin, ordered disk, but now most gas particles are at \( R_i \lesssim 6 \) kpc and show an important dispersion around small \( j_{z,i} \) values, even with negative ones. Halo gas particles show similar properties in both simulations. The behaviour patterns for baryons at \( z = 0 \) described so far are common to
the other DLOs identified either in S1 or S2. In any case, gas particles in the cold disk component have globally conserved their $j$, while most of those in the central regions (in S2) or those giving rise to stars in the bulge (in S1) have been involved in an inflow event with high $j$ loss, i.e., in an AMC.

The first of these two processes can be understood as follows: the net effect of shocks and cooling on disordered halo gas particles in the stages of quiescent evolution is that the fluid is forced to a coherent rotation with global specific angular momentum conservation. Consequently, gas particles tend to settle at the halo center, moving on a plane (the equatorial plane) on circular orbits if the gravitational potential at the inner regions is axisymmetric. The axisymmetric character of the potential is self-regulatory, as in the inner regions baryons are dynamically dominant (see TDT98). So, cold thin disks naturally appear in the non-violent phases of evolution, as in Fall & Efstathiou (1980).

However, as previously stated, cold disks are known to be strongly unstable against the bar instability mode. Massive dark haloes can stabilize disks, but some analytical works on disk stability (Christodoulou et al. 1995; vdB98) suggest that not every halo is able to stabilize any amount of baryons as a pure exponential disk, and a bulge is needed to ensure stability. In the absence of a bulge, the disk would develop a bar instability, that implies a loss of the axial character of the gravitational field produced by the baryon component and so, $j_{z,i}$ is no more conserved and the gas particles can fall to the center. This could be the process at work in the angular momentum losses observed in S2 (and the star forming gas in S1) and other author’s simulations. Global disk stability is usually studied through the $X_2(R)$ parameter (Toomre 1981, Binney & Tremaine 1987). We have calculated $X_2(R)$ for the disk component of our DLOs at different $z$. Moreover, to find out whether haloes formed in S1 or S2 need a bulge to stabilize pure exponential disks with baryon masses as deduced from Table 1, 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 disk, whose scalelength is determined assuming specific angular momentum conservation. In Fig. 2a (2b) we plot $X_2(R)$ for the S1 (S2) version of DLO #1 at $z = 0$. The same plots for the same DLO are given after its last major event in Fig. 2c (2d) for its S1 (S2) version, and previous to this event in Figs. 2e (for S1) and 2f (for S2). Moreover, the $X_2(R)$ for their bulgeless counterpart at $z = 0$ is plotted in Fig. 2b. Recalling the $X_2(R)$ stability criterion, if we define $R_{\text{inst}}^{\text{rad}}$ and $R_{\text{inst}}^{\text{pot}}$ as the points where $X_2(R) = 3$ (stability thresholds) for actual and pure exponential disks, respectively, it is apparent from these Figures that disks, when present, are stable: they are detected at $R > R_{\text{inst}}^{\text{rad}}$ if they have had enough time to form after the last merger (see below). By contrast, the bulgeless version of DLO #1 at $z = 0$ would be stable only at larger $R$ ($R > R_{\text{inst}}^{\text{pot}} \approx 21 \text{kpc}$). This behaviour is common to any DLO in S1 or S2, and so central mass concentrations are needed to stabilize these disks.

The role played by stellar cores will be better clarified through a description of how galactic-like objects are built-up in our simulations. Their assembly in S1 is an inside-out process with different episodes. i) First, dark matter haloes collapse at high $z$ forming a first generation of (small) disks and stars. ii) Then, the first unstabilizing mergers at high $z$ happen, resulting in disk disruption and rapid mass inflow to the central regions with $j$ loss and violent star formation, mainly at the central regions. Also, most preexisting stars will concentrate at the center 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 disk is regenerated through an infall of gas particles, either belonging to the baryonic merging clumps or diffuse, as previously described. For example, a compact stellar bulge and an almost cold disk in S1 DLO #1 at $z = 0.57$ are apparent in Fig. 2e. iv) After disk regeneration, the system can undergo new major merger events at lower $z$ (see Tissera et al. 1998 for details). During the orbital decay phase, previous 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 & Hernquist 1996, hereafter BH96).

Because, now, the disks involved in the merger are stabilized by their bulges, no strong gas inflow occurs in this phase (MH96). As the disks approach one another, they are heated and finally disrupted, but the high efficiency of gas shocking and cooling, and the symmetry of the central potential, quickly puts those of their gas particles with high $J_i$ into a new intermediate disk, while their low $J_i$ particles sink to the center 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 disk (Fig. 2c, note incomplete relaxation). v) Relaxation and disk regeneration are completed. Most of disk external particles are supplied by infall, as in iii) (Fig. 2a).

The assembly of galactic-like objects in S2 follows the same stages. We recall that in both simulations, haloes and merger trees are identical. The main difference is that in S2, the i) and ii) stages do not result in a stellar core, and, consequently, in iii) stage an unstable gas disk is formed, susceptible to grow bars. In particular, during the orbital decay phase in iv), strong gas inflow and $j$ loss are induced (Fig. 2f, see also MH96 and BH96). The actual fusion completes the gas inflow (Fig. 2d), involving most of the gas particles originally in the disks. Few of them are left for disk regeneration, so that, in phase v), disks are formed almost only from halo gas particles (Fig. 2b). Small satellites that orbit around DLOs may also trigger, in this case, a further gas inflow (as in MH94), while in S1 they are accreted without any major damage. We recall that for a given choice of the star formation parameters, the final characteristics of one object in a simulation are determined by its merger tree as well as the particular values that the parameters describing mergers and interactions take in each event (Barnes 1992, MH94, BH96, MH96). This explains the dispersion in the $B/D$ values among the different DLOs in S1 (or S2).

Concerning numerical resolution, DLOs in S1 and S2 are resolved with a relatively
low number of particles. In contrast, dark matter haloes are described with a much better resolution. An inappropriate low gas resolution would result in an unphysical gas heating that could halt the gas collapse (Navarro & Steinmetz 1996). However, some works suggest that it is an inadequate resolution in the dark matter halo component that may produce the larger undesired numerical artifacts (Steinmetz & White 1997). Therefore, to make sure that the populated and extended disks in S1 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 S1; hereafter HRS). Only one disk with mass comparable to those in S1 forms. Its analysis has shown that it is populated and extended, that its structural and dynamical characteristics are compatible with observations (see Table 1 and Fig. 1) and that the physical processes leading to its formation are essentially the same as those that are at work in S1. In addition, a comparison between the distributions of the ratios $t_{\text{dyn}}/t_{\text{cool}}$ for gas particles belonging to the DLOs in S1 and to their counterparts in S2 shows no difference. These results indicate that the infall of gas in S1 has not been artificially affected by the decrease of numerical resolution due to the transformation of gas particles into stars.

To summarize, a simple implementation of star formation that prevents gas depletion at high redshifts, but permits the formation of stellar bulges, has allowed extended and populated disks to form at later times. In a more realistic model, supernovae should play this part, leading to a self-regulating star formation. These disks have masses and specific angular momenta compatible with observed spirals, and their bulge and disk scales are also consistent with their observable values (Courteau, de Jong & Broeils 1996; Courteau 1997). On the contrary, if the implementation of star formation had resulted in an early gas depletion into stars as it cools and collapses, no gas would have been left to form new disks (TDT98; Steinmetz & Navarro 1998). The generality and simplicity of the implementation we have used suggests that extended, populated disks are generic (Silk & Wyse 1993), and
that they easily form when loss in gas collapse and mergers is prevented by stabilizing the disks with a stellar bulge.

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REFERENCES


Table 1. SOME CHARACTERISTICS OF DLOS\textsuperscript{a}

<table>
<thead>
<tr>
<th>DLO</th>
<th>$N_{\text{gas}}$</th>
<th>$N_{\text{star}}$</th>
<th>$B/D$</th>
<th>$R_b$</th>
<th>$R_d$</th>
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<tr>
<td>1</td>
<td>348</td>
<td>278</td>
<td>1.19(3.66)</td>
<td>0.74(1.29)</td>
<td>7.33(6.99)</td>
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<tr>
<td>2</td>
<td>359</td>
<td>240</td>
<td>1.19(2.17)</td>
<td>0.74(1.29)</td>
<td>5.66(7.08)</td>
</tr>
<tr>
<td>3</td>
<td>307</td>
<td>211</td>
<td>1.55(1.75)</td>
<td>0.85(1.41)</td>
<td>10.90(14.04)</td>
</tr>
<tr>
<td>4</td>
<td>311</td>
<td>215</td>
<td>1.60(4.20)</td>
<td>0.74(1.19)</td>
<td>9.98(9.02)</td>
</tr>
<tr>
<td>5</td>
<td>210</td>
<td>95</td>
<td>1.15</td>
<td>0.54</td>
<td>6.50</td>
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<tr>
<td>6</td>
<td>151</td>
<td>69</td>
<td>1.22</td>
<td>0.53</td>
<td>5.61</td>
</tr>
<tr>
<td>7</td>
<td>227</td>
<td>79</td>
<td>2.02(2.87)</td>
<td>0.99(1.27)</td>
<td>6.56(5.87)</td>
</tr>
<tr>
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<td>189</td>
<td>157</td>
<td>1.31(5.43)</td>
<td>0.49(1.32)</td>
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<td>1380</td>
<td>0.86</td>
<td>1.13</td>
<td>9.58</td>
</tr>
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</table>

\textsuperscript{a}Distances are given in kpc; quantities in parentheses correspond to S2 DLOs. DLO masses are given by $M_{\text{DLO}} = m \times (N_{\text{gas}} + N_{\text{star}})$. 
Fig. 1.— The specific angular momentum at $z = 0$ versus the mass, for haloes in S1 or S2 (filled circles), and HRS (filled square); the inner 83% of the gas component in S1 DLOs (open triangles), S2 DLOs (filled triangles) and the HRS disk (open square); and the stellar component in S1 (open stars) and HRS (asterisk). The solid (dotted) box shows the region occupied by the spiral disks (ellipticals).

Fig. 2.— Specific angular momentum component along $\mathbf{J}_{\text{dis}}$ for each baryon particle of halo #1, versus their positions at different $z$. Circles: gas particles, stars: stellar particles; open symbols: counterrotating particles. Left panels: S1 version at different $z$; right panels: S2 version at approximately the same $z$. Full lines: $v_c(R)R$; dotted lines: $X_2(R)$ for actual disks at each $z$; dashed line: $X_2(R)$ for the pure exponential version at $z = 0$. The arrows mark the point where $X_2(R) = 3$, i.e., $R_{\text{ad}}^\text{st}$ and $R_{\text{ped}}^\text{st}$. 