PRODUCING DISC-LIKE OBJECTS WITH OBSERVATIONAL COUNTERPARTS FROM HIERARCHICAL HYDRODYNAMICAL SIMULATIONS

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Abstract. We report some results on the formation of disc-like objects in hierarchical hydrodynamical simulations with characteristics compatible with observed spirals.

1. Introduction

Even if still at its beginnings, the numerical approach to the study of galaxy formation and evolution from primordial fluctuations using hierarchical hydrodynamical simulations seems promising, because the physics is introduced at a very general level. This approach has been made possible thanks to some recent developments in theoretical cosmology, in numerical computation techniques and in the power and velocity of computers, and, contrary to other methods, it has the advantage that merger and interaction effects are naturally accounted for. However, so far, no hydrodynamical simulation of galaxy formation in fully consistent hierarchical cosmological scenarios had been able to produce extended discs similar to those observed in spirals. The problem was either the excessive loss of angular momentum by the gas clumps as they merge inside the dark haloes, when no star formation processes are considered, resulting in over-concentrated discs (see Navarro, Frenk and White, 1995; Navarro and Steinmetz, 1997; Weil, Eke and Efstathiou, 1998, and references quoted therein), or the over-rapid gas exhaustion into stars as the gas cools and collapses, leaving no gas to form discs at low z (Steinmetz and Navarro, 1998; Tissera and Domínguez-Tenreiro, 1998). As reported in Domínguez-Tenreiro, Tissera and Sáiz (1998, and references therein) and Tissera, Sáiz and Domínguez-Tenreiro (these proceedings), excessive angular momentum losses can be avoided by stabilizing discs with bulges, which are unavoidably formed when star-forming processes are considered. So even a simple implementation of these processes, provided that it does not lead to an excessive gas depletion at high z, could be enough to ensure the formation of discs and their stability.

In this paper we report some results on the formation of disc-like structures, with characteristics similar to those observed in spirals, in a hierarchical hydro-

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TABLE I

Some characteristics of DLOs[a]

DLO	1	2	3	4	5	6	7	8	9	10	HRS
N_{gas}	348	359	307	311	210	151	227	189	108	109	1713
N_{star}	278	240	211	215	95	69	79	157	99	47	1380
n_{opt}	1	1	2	1	2	1	1	2	1	2	2
B/D	1.19	1.19	1.55	1.60	1.15	1.22	2.02	1.31	2.95	1.30	0.86
r_{b}	0.74	0.74	0.85	0.74	0.54	0.53	0.99	0.49	0.54	0.40	1.13
r_{d}	7.33	5.66	10.90	9.98	6.50	5.61	6.56	5.29	7.07	9.75	9.58
$V_{2.2}$	257	271	220	227	197	176	207	213	167	148	178
r_{max}	6.36	8.64	7.20	5.74	9.45	6.93	7.80	5.88	6.48	7.80	49.70
$V_{\mathrm{cir}}^{\mathrm{max}}$	279	278	251	254	203	179	217	215	181	156	188
LS	−.17	−.16	−.11	−.09	−.14	−.09	−.19	−.18	−.15	−.18	.04
$\log \kappa$	3.33	3.48	3.02	3.08	3.15	3.11	3.19	3.30	2.97	2.72	2.90
λ	.069	.049	.079	.023	.063	.063	.011	.039	.074	.045	.042

[a] Distances are given in kpc, velocities in km s^{-1} and κ is in $M_{\odot}$ pc^{-2}

dynamical simulation (I.2, see Table I in Tissera *et al.* (these proceedings). The low η value used in this simulation allowed us to have available gas to form discs at low z. To some extent, this condition could mimic the effects of energy injection from supernova explosions.

2. Structural Properties. Bulge–Disc Decomposition

Baryonic objects forming disc-like structures (DLOs) identified in I.2 have external extended populated discs, mostly consisting of gas, a central stellar bulge-like concentration and also stars in a thick disc. Some characteristics of those with $N_{\mathrm{baryon}} > 150$ are given in Table I.

Their configurations at $z = 0$ can be described as follows (where $\vec{r_i}$, $\vec{v_i}$ are the position and velocity vectors of particle i; R_i is its distance on the equatorial plane; and $\vec{J_i}$, $\vec{J}_{\mathrm{dis}}$ are the i-th particle and disc angular momentum vectors, respectively):

a) Gas: Disc gas particles, that is, those at $r_i < 30$ kpc, are highly ordered. These particles move on the equatorial plane, so that $\cos(\vec{J_i}, \vec{J}_{\mathrm{dis}}) \simeq 1$, where they follow circular trajectories ($\cos(\vec{r_i}, \vec{v_i}) \simeq 0$ (Figure 1*a*). Then, $J_{z,i} \simeq |\vec{J_i}| = R_i v_c(R_i)$, i.e. it only depends on the position of the particle ($v_c(R) = GM(< R)/R$). Halo gas particles, that is, those with $r_i > 30$ kpc, are disordered (Figure 1*b*).

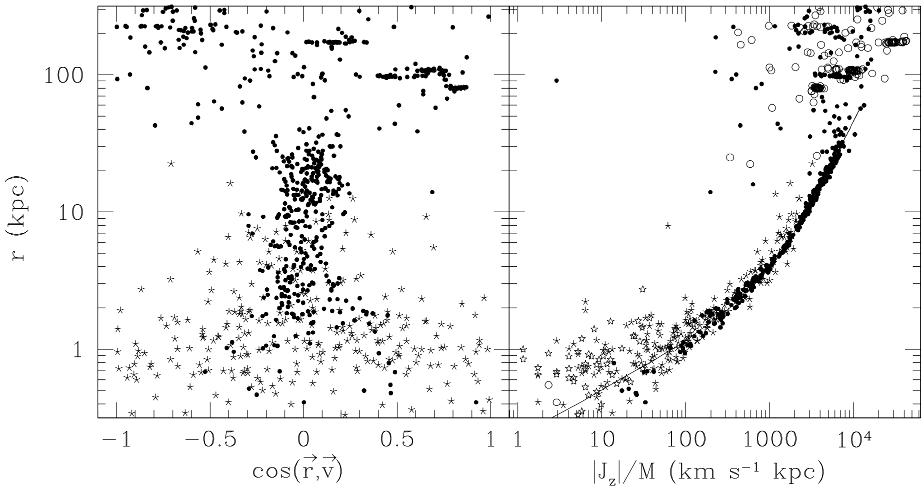

Figure 1. DLO #1 in I.2 at $z = 0$. *Points:* Gas particles. *Stars:* Star particles. *Open symbols in b):* Counterrotating particles. *a)* Angle formed by the position and velocity vectors of each particle. *b)* Specific angular momentum in the direction of $\vec{J}_{\rm dis}$. The *full line* is $v_c(R)R$.

b) Stars: Most stars form a central compact bulge (at $r_i \leq 2$ kpc they are relaxed, disordered); some of them stay in a thick disc at $r_i \geq 2$ kpc (see Figures 1*a* and *b*).

Observationally, the structural parameters of spirals are obtained from a fit to the shape of the surface *brightness* profile. A bulge–disc decomposition proves convenient:

$$\Sigma(R) = \Sigma_{\rm b}(R) + \Sigma_{\rm d}(R), \quad \text{with} \quad \Sigma_{\rm c}(R) = \Sigma_{\rm c}(0) \exp\left[-\left(\frac{R}{r_{\rm c}}\right)^{1/n}\right] \qquad (1)$$

both for $c = b$ (bulge) and $c = d$ (disc), and where n is the *shape parameter* (Sérsic, 1968) ($n = 1$ gives a *pure exponential law*, $n = 4$ gives a *de Vaucouleurs profile*), R is the projected radial distance, $r_{\rm b}$ and $r_{\rm d}$ are the bulge and disc scale lengths, respectively, and $\Sigma_{\rm b}(0)$ and $\Sigma_{\rm d}(0)$ are the bulge and disc central surface brightness, respectively. It has recently been shown that the bulges of most spirals are better described by an exponential law rather than the widely used de Vaucouleurs profile (see Andedakis, Peletier and Balcells, 1995; de Jong, 1995; Courteau, de Jong and Broeils, 1996; Courteau, 1997).

The profile given by Equation (1) has been fitted to the *mass* density of baryons projected in the disc plane for the DLOs in our sample. Integrated mass densities have been used instead of the mass densities themselves to circumvent noise problems. Disc projected mass densities have been taken to be exponential, i.e. with $n = 1$ in Equation (1) (Delcanton, Spergel and Summers, 1997). Bulge shape

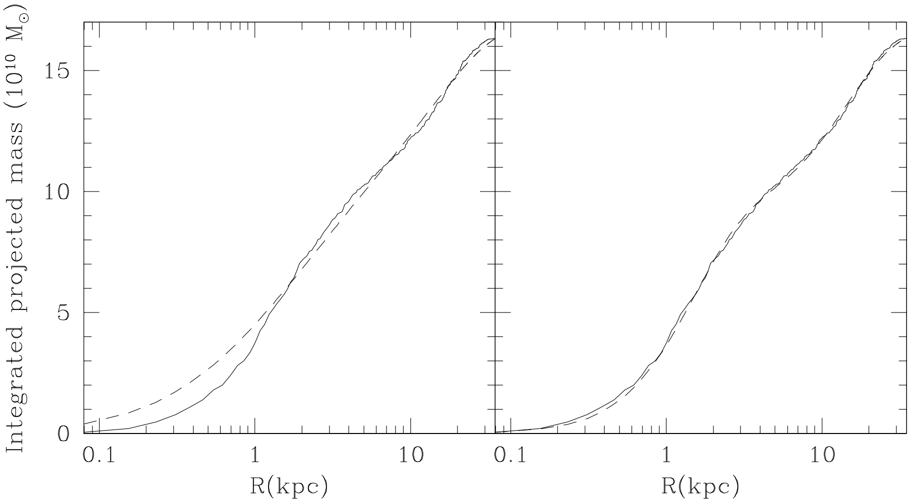

Figure 2. Fits to the integrated mass, projected on the disc plane for a DLO in our sample (*full lines*) to the curves given by Equation (1) (*dashed lines*). *Left:* De Vaucouleurs bulge profile. *Right:* Exponential bulge profile.

parameters have been left free. Only integer values have been tested. The resulting optimal bulge shape parameters for different DLOs, n_{opt}, are given in Table I. As for observed spiral bulges, in most cases $n = 1$ is the best fit. In Figure 2 we show one such fit, with a de Vaucouleurs profile (*left*) and an exponential one (*right*). As noted by Adredakis *et al.* (1995), the shape parameter is correlated with the spiral type. The objects in our sample would be $T \geq 1$ in the RC2 classification scheme.

The scale parameters, r_{b} and r_{d}, corresponding to a double exponential fit, are given in Table I and plotted in Figure 3. For comparison, we also plot the values given by Courteau (1997) and Courteau *et al.* (1996) from D1 surface brightness decompositions of Sb–Sc spirals. From this figure we see that the scales are consistent with the values found by these authors. Moreover, we get a scale length ratio of $r_{\mathrm{b}}/r_{\mathrm{d}} = 0.09 \pm 0.03$, to be compared with the values found by Courteau (1997) and Courteau *et al.* (1996) in the r band, 0.08 ± 0.05, and de Jong (1995) at R, 0.09 ± 0.04. Note, however, that we miss DLOs having small values of r_{b} and/or r_{d} as compared with the range of values obtained by these authors.

The *mass* B/D ratios, corresponding to a double exponential fit, are given in Table I. They are rather high as compared to the *luminosity* B/D ratios for spirals. But it is difficult to answer at this time whether or not the central baryon concentrations found in DLOs are excessive, as disc and bulge mass-to-light ratios, Υ_{d} and Υ_{b}, would be required to compare with observed *luminosity* B/D ratios. Some estimations give: $\Upsilon_{\mathrm{d}} = 2.1h$, $\Upsilon_{\mathrm{b}} = 6.6h$ (van den Bosch, 1998) and $\Upsilon_{\mathrm{d}} = 1 - 2$ (Courteau and Rix, 1998). To ascertain if the baryon mass distributions we have

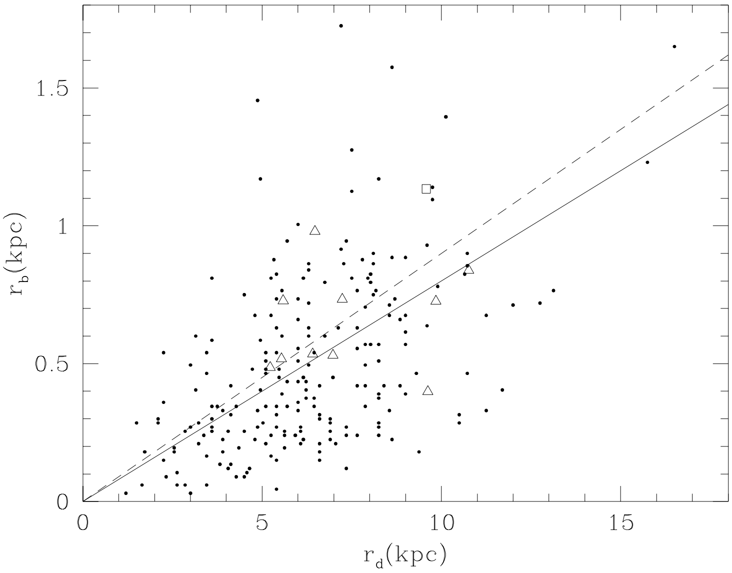

Figure 3. The scale parameters r_b versus r_d for DLOs in I.2 (*open triangles*), and HRS (*open square*). *Points* are from 1D decompositions of surface brightness profiles given by Couteau (1997). The *dashed (solid)* line is a fit to the I.2 values (data).

found are consistent with observations, or if bulges are too prominent, one must instead look at their dynamical observable manifestations, namely at the RCs.

3. Rotation Curves

The RCs of the simulated objects have been constructed by adopting a softened Plummer potential with an effective gravitational softening of $\epsilon_g = 3$ kpc (Evrard, Summers and Davis, 1994). These RCs fit the tangential velocity of the baryonic particles very well, suggesting that they are in rotationally supported equilibrium within the potential well produced by both the dark haloes and the baryons themselves (Tissera and Domínguez-Tenreiro, 1998).

Their shapes are declining beyond $r = 2.2 r_d$ and some of them have central spikes produced by the bulge, similar to those found in some observed galaxies with *mass* B/D ratios of about 1 (i.e. NGC 6674 and NGC 7331; see Rhee, 1996). The shapes of spiral RCs are determined by the 3D mass distributions of their three components (i.e. bulge, disc and halo).

These distributions, however, cannot be inferred from observed RCs, as different decompositions yield equally good agreement with the data (van Albada *et al.*, 1985). So one has to resort to a rather descriptive characterization of RCs to compare simulations to observational data. In this work, their shapes have been quantified through parameters related to:

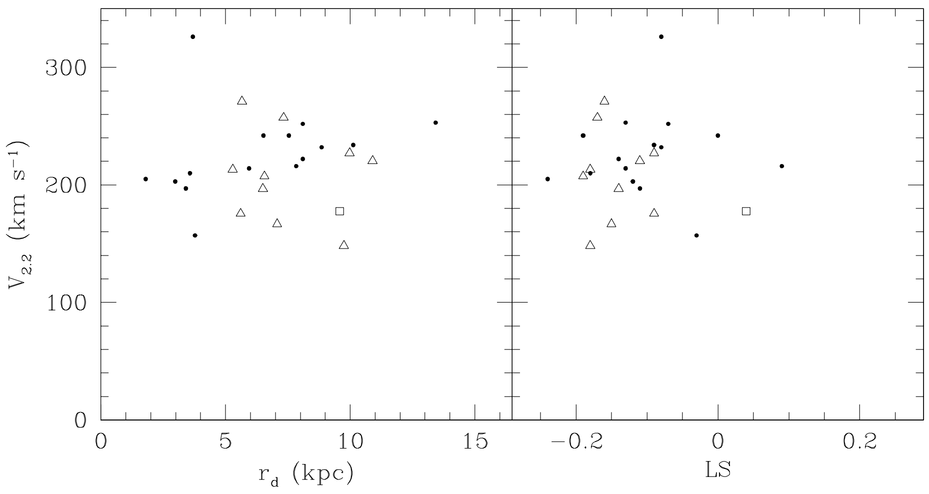

Figure 4. Plots of GLOBAL parameters that quantify rotation curves (see text). *Points:* Values measured in extended HI RCs in the sample of Casertano and van Gorkom's (1991) and Broeils' (1992) compilation. *Open triangles:* Idem id in DLOs identified in I.2 simulation. *Open square:* HRS DLO.

i) Their global properties: r_d, see above; the rotation velocity at $r = 2.2r_d$, $V_{2.2}$, and

ii) Their central mass concentration: the maximum or peak rotation velocity, $V_{\rm cir}^{\rm max}$, and the radius where this is reached, $r_{\rm max}$, (see Rhee, 1996, for a discussion about RC decomposition in principal components).

Some combinations of these parameters have also been used, such as: the compactness parameter, $\kappa = V_{2.2}^2/Gr_d$, which is proportional to the average total mass surface density inside r_d and seems to correlate with the central mass concentration (Rhee, 1996), and the logarithmic slope, LS (Casertano and van Gorkom, 1991; Persic and Salucci, 1991; Broeils, 1992; de Blok, McGaugh and van der Hulst, 1997).

These parameters have been measured in the RCs of discs formed in the simulation. The values we have obtained are given in Table I. They have been compared with the values measured from extended HI RCs in the sample of Casertano and van Gorkom (1991) and the compilation of Broeils (1992; see also de Blok *et al.*, 1997). r_d and $V_{2.2}$ are consistent with observations (Figure 4). DLOs identified in I.2 have $V_{2.2} > 150$ km s^{-1} and $r_d > 5.25$ kpc; that is, they are large bright spirals. Their LS and κ parameters take values that are found in observed spirals with the same range in $V_{2.2}$ and r_d (see Figure 4). $V_{\rm cir}^{\rm max}$ and the $r_{\rm max}/r_d$ ratio are consistent with Broeils' (1992) data. We conclude that *RCs of DLOs have observational counterparts*. However, again, we miss some variability such as objects with LS between, say, 0.0 and -0.1 at a given $V_{2.2}$ and r_d value, and objects with somewhat less massive bulges at a given LS.

4. Angular Momentum Content

The total specific angular momentum content has been measured in DLOs for their different components: halo, disc and stars.

In the halo component, it is usually measured through the spin parameter $\lambda = J_\mathrm{tot}|E_\mathrm{tot}|^{1/2}/GM_\mathrm{tot}^{5/2}$. The results for our simulations are given in Table I. They are compatible with observations. As gas follows dark matter in virialized halos, $(J/M)_\text{dark matter} \simeq (J/M)_\text{halo gas}$.

Concerning the disc component, Figure 1 of Tissera *et al.* (these proceedings) indicates that the $(J/M)_\text{disc gas}(z = 0)$ values are consistent with observed values of normal spirals (Fall, 1983), and that $(J/M)_\text{dark matter}(z = 0) \simeq (J/M)_\text{disc gas}(z = 0)$. This indicates that gas infall in the quiescent phases of evolution, i.e. after the last merger event, has occurred with *global* J/M *conservation*, as in Fall and Efstathiou's (1980) scenario for disc formation (see also Tissera *et al.*, these proceedings).

Bulge stars have been formed from gas particles that had lost angular momentum. Most disc stars come from the bulge of the satellite involved in the last merger event. Their angular momentum content results from incomplete orbital angular momentum loss (see Domínguez-Tenreiro *et al.*, 1998, and Tissera *et al.*, these proceedings, for details).

5. Summary, Discussion and Conclusions

A simple implementation of star formation that prevents early gas depletion as it is transformed into stars at high redshifts has allowed extended and populated discs with stellar bulges to form at later times. In a more realistic model, supernovae should play this part, leading to self-regulating star formation. The generality and simplicity of the implementation we have used suggests that *extended discs are generic*: they easily form when gas is available and they last provided that their tendency to instability is offset with a stellar bulge, for example.

It is a priori unclear whether unphysical gas heating could have artificially halted the gas collapse. To make sure, we have run a higher-resolution simulation, hereafter HRS (64^3 particles in a periodic box of 5 Mpc, with cosmological and star formation parameters similar to those in I.2). Only one disc forms with a mass comparable to those in I.2. Its analysis has shown that it is populated and extended, that its structural and dynamical characteristics are compatible with observations (see Table I and Figures 3 and 4) and similar to those of DLOs formed in I.2, and that the physical processes leading to its formation are essentially the same as those at work in I.2 (see Tissera *et al.*, these proceedings, and discussion therein). We are led to the conclusion that DLOs in I.2 are resolved with a number of gas and dark matter particles that suffices to ensure that disc formation results from physical processes.

The comparison of the structural and dynamical properties of simulated DLOs to discs of observed spirals indicates that they have observational counterparts. However, some variability is also missing in DLOs. Not surprising, since resolution and dynamical limitations imply a narrow range in mass and, in addition, we cannot estimate the effects of different environments. Moreover, some processes that would add variability, such as energy injection from supernova explosions, are not considered in this study. Despite these shortcommings, we can conclude that hydrodynamical simulations are a promising tool for learning about the physical processes leading to galaxy formation and evolution in a cosmological framework.

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