Evolution of stellar-gaseous disks in cosmological haloes

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ABSTRACT

Aims. We explore the growth and the evolution of the bar instability in stellar-gaseous disks embedded in a suitable dark matter halo evolving in a fully consistent cosmological framework. The aim of this paper is to point out the impact of different gas fractions on the bar formation, inside disks of different disk-to-halo mass ratio, and the role of the cosmological framework.

Methods. We perform cosmological simulations with the same disk-to-halo mass ratios as in a previous work where the gas was not taken into account. We compare results of the new simulations with the previous ones to investigate the effect of the gas by analysing the morphology of the stellar and gaseous components, the stellar bar strength and the behaviour of its pattern speed.

Results. In our cosmological simulations, inside dark-matter dominated disks, a stellar bar, lasting 10 Gyr, is still living at $z = 0$ even if the gaseous fraction exceeds half of the disk mass. However, in the most massive disks we find a threshold value (0.2) of the gas fraction able to destroy the bar.

The stellar bar strength is enhanced by the gas and in the more massive disks higher gas fractions increase the bar pattern speed.

Key words. galaxies: spirals, structure, evolution, halos, kinematics and dynamics

1. Introduction

In a pioneering paper Berentzen et al. (1998) presented the numerical results describing the impact of a gas fraction inside a stellar disk on the stellar orbits and on the whole bar instability. Their model galaxy containing stars and gas was compared with a pure stellar model, subject to the same initial conditions, chosen to produce the development of a strong stellar bar.

They showed that dynamical instabilities become milder in the presence of the gas component, and therefore a weakening of the bar itself is observed as a gradual process. Moreover, the overall evolution is accelerated because of the larger central mass concentration and the resulting decrease in the characteristic dynamical time.

The gas behaviour in disk galaxies and its connections with the bar feature was studied in several papers (Friedli & Benz (1993); Fux (1999); Berentzen et al. (2001); Athanassoula (2002); Bottema (2003); Bournaud et al. (2005), Michel-Dansac & Wozniak (2006), Stinson et al. (2006)). However in all these works the evolution of the disk or of the disk+halo simulated system arises in an isolated framework, outside the cosmological scenario, even if progressive efforts for improving the model, accounting for more recent knowledges coming from the cosmological hierarchical clustering scenario of structures formation about density distribution and concentration of the dark matter (DM) halos, have been performed in the last years (Curir & Mazzei (1999); Mazzei & Curir (2001), Athanassoula & Misiriotis (2002)). Here, for the first time, we analyse the growth and the evolution of the bar instability in stellar-gaseous disks embedded in a DM halo evolving in a fully consistent cosmological scenario. Our model cannot be viewed as a general galaxy evolution model, since the gradual formation and growth of the stellar disk has not been taken into account. Thus our work cannot be compared with the more recent papers by Abadi et al. (2003), Governato et al. (2004), Robertson et al. (2004), Sommer-Larsen et al. (2006), where the formation of a realistic disk galaxy within the hierarchical scenario of structure formation in $\Lambda$-dominated cosmologies has been followed self-consistently. However our approach allows us to vary parameters like the disk-to-halo mass ratio and the gas fraction inside the disk, and to analyse the growth of the bar instability and its dependence on such parameters in a self-consistent cosmological framework for the first time.

Following the pioneering study by Berentzen et al. (1998), we compare the results of such new set of simulations with those of a previous set (Curir et al. 2006) including a pure stellar disk in the same scenario and with the same initial conditions.

The plan of the paper is the following: in Section 2, we summarise our recipe for the initial disk + halo system fully described in Paper I. In Section 3 we present the cosmological
simulations and in Section 4 we point out our results. Section 5 is devoted to our discussion and conclusions.

2. Method

We embed a gaseous and stellar disk inside a cosmological halo selected in a suitable slice of Universe and follow its evolution inside a cosmological framework: a \( \Lambda \)CDM model with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \sigma_8 = 0.9, h = 0.7 \), where \( \Omega_m \) is the total matter of the Universe, \( \Omega_\Lambda \) the cosmological constant, \( \sigma_8 \) the normalisation of the power spectrum, and \( h \) the value of the Hubble constant in units of \( 100h^{-1} \) km s\(^{-1}\) Mpc\(^{-1}\).

A detailed description of our method to produce the cosmological scenario where the disk is evolved has been given in Curir et al. (2006). Here we present a short overview of our recipe. Moreover, Curir et al. (2006) showed that the numerical resolution does not impair their main result: in pure stellar disks, long living bars are a ‘natural’ outcome of the cosmological scenario.

2.1. The DM halo

To select the DM halo, we perform a low-resolution simulation of a “concordance” \( \Lambda \)CDM cosmological model. The initial redshift is 20.

From this simulation we identify the DM halos at \( z=0 \) in the mass range \( 0.5-5 \times 10^{11}h^{-1} \) M\(_{\odot} \), with a standard friends-of-friends algorithm.

We select one suitable DM halo with a mass \( M \sim 10^{11}h^{-1} \) M\(_{\odot} \) (at \( z=0 \)). We resample it with the multi-mass technique described in Klypin et al. (2001). The particles of the DM halo, and those belonging to a sphere with a radius 4\( h^{-1} \) Mpc, are followed to their Lagrangian position and re-sampled to an equivalent resolution of 1024\(^3\) particles. The total number of DM particles in the high resolution region is 1216512 which corresponds to a DM mass resolution of 1.21 \( h^{-1} \) Mpc. The high-resolution DM halo is followed to the redshift \( z=0 \).

After selecting the halo and resampling at the higher resolution the corresponding Lagrangian region, we run the DM simulation, to extract the halo properties in absence of any embedded stellar disk. The mass of our halo at \( z=0 \), \( 1.03 \times 10^{11}h^{-1} \) M\(_{\odot} \), corresponds to a radius, \( R_{\text{vir}} = 94.7h^{-1} \) Kpc, which entails 84720 halo particles. The nearest DM halo, more massive than \( 10^{10}h^{-1} \) M\(_{\odot} \) is \( \sim 1900h^{-1} \) Kpc away from the centre of our halo; the less massive one, having mass of 4.6 \( \times 10^{10}h^{-1} \) M\(_{\odot} \), is \( \sim 215h^{-1} \) Kpc away. Moreover, the behaviour of the density contrast, \( \delta \), is monotonically decreasing with the radius, and \( \delta \) falls below the unity value at \( \sim 550h^{-1} \), 450\( h^{-1} \), 350\( h^{-1} \) physical Kpc away from the centre of our halo at \( z = 0 \), \( z = 1 \), and \( z = 2 \) respectively. Therefore, we conclude that the selected halo is living in an underdense environment. From its accretion history (see Fig. 1 in Curir et al. (2006)) we conclude that our halo undergoes no significant merger during the time it hosts our disk, nor immediately before. The halo density profile is well–fitted by a Navarro, Frenk and White (NFW) form (Navarro et al. (1996); Navarro et al. (1997)) at \( z \leq 2 \). The concentration, \( C_{\text{vir}} \), equal to \( \frac{R_{\text{vir}}}{R_s} \), takes a high value, 18.1, confirming that this halo does “form” at quite high redshift (e.g. Wechsler et al. (2002) for a discussion about the link between concentration and assembly history of the halo). The dimensionless spin parameter of the halo is 0.04 at \( z=2 \), near to the average one for our cosmological model (Maller et al., 2002).

2.2. The baryonic disk

The spatial distribution of particles follows the exponential surface density law: \( \rho = \rho_0 \exp\left(-r/r_0\right) \) where \( r_0 \) is the disk scale length, \( r_0 = 4h^{-1} \) Kpc, and \( \rho_0 \) is the surface central density. The disk is truncated at five scale lengths with a radius: \( R_{\text{disk}} = 20h^{-1} \) Kpc. To obtain each disk particle’s position according to the assumed density distribution, we used the rejection method (Press et al., 1986). We used 56000 star particles and 56000 gaseous particles to describe our disk. The (Plummer equivalent) softening length, the same for DM, gas, and star particles, is 0.5\( h^{-1} \) Kpc in comoving coordinates. The stellar radial velocity dispersion, \( \sigma_{\text{R}} \), is assigned through a Toomre parameter \( Q \). \( Q \) is initially constant at all disk radii and it is defined as \( Q = \frac{\kappa}{\pi \Sigma} \) where \( \kappa \) is the epicyclic frequency, and \( \Sigma \) the surface density of the disk. We plug a value of \( Q \): 1.5, which corresponds to a warm disk. The gas particles share the same velocity field as the stars. The constraint \( Q_s > 1 \) where \( Q_s = \frac{\kappa_s}{\Sigma_{\text{gas}}} \), needed for the gaseous disk stability (Friedli & Benz, 1993) is always verified.

We embed the disk in the high resolution cosmological simulation, at redshift 2, in a plane perpendicular to the angular momentum vector of the halo and in gravitational equilibrium with the potential. Its centre of mass corresponds to the minimum potential well of the DM halo. The initial redshift corresponds to 10.24 Gyr down to \( z = 0 \) in our chosen cosmology.

3. Simulations

We performed eight cosmological simulations of a disk+halo system. We also performed one simulation in an isolated framework, using a NFW halo, to disentangle the effects of the dynamical state of the halo, and in particular of the evolutionary framework, on the growth of the bar instability (§3.1).

We exploited the public parallel N-body treecode GADGET-2 (Springel, 2005).

\footnote{In the following, we refer to the mass as the virial mass i.e. that enclosed in a sphere with overdensity \( \delta = \rho/\rho_{\text{crit}} = 178 \cdot \Omega_m^{0.44} \) (Navarro et al., 2000).}

\footnote{Halos have been identified using the friends of friends algorithm with a linking length \( l = 0.15 \), i.e. the mean interparticle distances, and with more than 8 particles}
I col: simulation number and simulation type (c: cosmological simulation, i: isolated simulation)
II col: mass of the disk in code units (i.e. $5 \times 10^9 M_\odot$)
III col: fraction of gas, i.e. gas–to–disk mass ratio
IV col: DM mass inside the disk radius in code units
V col: halo–to–disk mass ratio inside the disk radius
VI and VII cols: Efstathiou et al. (1982) parameters: $\alpha = r_0^{-1}$, $v_{\text{max}}$ is the maximum rotational velocity, $r_m$ the corresponding radius
VIII col: type of halo used

The simulations run on the SP4 and CLX computers located at the CINECA computing centre (BO, Italy; grant inato003) and on OATo Beowulf-class cluster of 32 Linux-based PC (16 processor AMD K7, clock 700 MHz, and 16 Pentium 4, clock 1700 MHz) at the Osservatorio Astronomico di Torino. The main parameters and the initial properties of our set of simulations are listed in Table I.

| N     | $M_{\text{disk}}$ | gas fraction | $M_{\text{DM}}$ | $R_{\text{DM}}$ | $\alpha r_m$ | $\frac{M_{\text{DM}}}{m_{\odot}}$ | halo |
|-------|------------------|--------------|-----------------|-----------------|-------------|-------------------------------|------|
| c1    | 0.77             | 2.39         | 0.68            | 0.43            | 8.4         | y                             | n    |
| c2    | 0.78             | 2.01         | 0.01            | 0               | n           | n                             | n    |
| c3    | 0.78             | 2.4          | 0.07            | 0               | n           | n                             | n    |
| c4    | 0.73             | 2.4          | 0.58            | 0.32            | 5.8         | n                             | y    |
| c5    | 0.73             | 2.4          | 0.0             | 0.3             | 5.4         | n                             | n    |
| c6    | 0.73             | 2.6          | 0.46            | 0.23            | 5.6         | n                             | n    |
| c7    | 0.73             | 2.6          | 0.46            | 0.2             | 5.4         | n                             | n    |
| c8    | 0.73             | 2.6          | 0.42            | 0.21            | 5.8         | n                             | n    |
| i1    | 1.00             | 3.03         | 0.36            | 0.0             | 1.08        | cosmological                  | NFW  |

The results of the simulations are given in Table II. All the results in Table II can be compared with those of the homologous simulations performed with a pure stellar disk, presented in Curir et al. (2006). We repeated, indeed, one of the simulation of Curir et al. (2006) with the GADGET-2 code, since the time–stepping criterion we used is not present any more in the current version of the code. A comparison with the previous run does not show any significative change. In such a paper we also performed several numerical tests on the stability of the results. Here we summarise our findings:

- a simulation performed with a mass resolution increased by a factor 8, i.e. with a force resolution increased by a factor 2 (for a disk–to–halo mass ratio 0.1; see section A.2 in Curir et al. 2006), gives rise to a long living bar (10 Gyr old) as in the case of the lower mass and force resolution; note that in this test the mass and force resolution are respectively $M_{\text{DM}} = 2 \times 10^9 M_\odot$ and $\epsilon = 250 h^{-1} \text{pc}$, thus comparable to the resolution of recent works on galaxy formation simulations, e.g. (Sommer-Larsen et al., 2006; Stinson et al., 2006; Governato et al., 2006);
- embedding adiabatically a classically stable stellar disk in a isolated DM halo having a NFW profile, while keeping the mass and force resolution constant, brings to no bar instability, thus ruling out the possibility that the embedding procedure is the main driver of the bar instability (see Section 5 in Curir et al. 2006);
- varying the stellar softening, at fixed mass resolution, from $0.36 h^{-1} \text{Kpc}$ to $0.65 h^{-1} \text{Kpc}$ does not result in any significative changes as far as the bar instability is concerned (see section A.3 in Curir et al. 2006);
the same holds when the stellar mass resolution is reduced by a factor of 1/6 and increased up to 10 times the value adopted in our set of simulations (see A.2 in Curir et al. 2006). These results guarantee that, in the dynamical range currently reached with tree–code N–body simulations, no mayor numerical shortcoming is expected, at least under the point of view of the gravitational evolution. Moreover, as a final test, we re-run simulation c2 using two times more gaseous particles, 112000 instead of 56000. We find that the final bar dissolution and the gas inflow are the same as in the previous case.

4. Results

In this section we present the final (i.e. at z=0) isodensity contours for stars and gas of simulations in Table 1. All such figures have been built up with the same box-size, number of levels, and density contrast (see caption of Fig. 1).

We define as a measure of the bar strength the value of the ellipticity, $\epsilon = 1 - b/a$ (Table 2); a strong bar corresponds to $\epsilon \geq 0.4$.

A more dynamical measure of the bar strength at radius R has been defined by Combes & Sanders (1981) by using the parameter: $Q_b(R) = \frac{F_{\parallel}^{\text{max}}(R)}{F_{\perp}^{\text{max}}(R)}$ where $F_{\parallel}^{\text{max}}(R) = \frac{\partial \Phi(R, \theta) / \partial \theta}{m = 0}$ is the maximum amplitude of tangential force at a given radius R and $< F_{\parallel}^{\text{max}}(R) >= R(\partial \Phi_0 / \partial R)$ is the mean axisymmetric radial force derived from the $m = 0$ component of the gravitational potential at the same radius. The maximum value of $Q_b(R)$ provides a measure of the bar strength $Q_b$ for the whole galaxy. We evaluated the components of the gravitational force directly from the masses and the radii of the system produced by the simulations. We then represented the matrix $Q_b(i, j) = \frac{F_{\parallel}(i, j)}{F_{\perp}(i, j)}$ on a suitable two-dimensional grid in analogy with the method outlined by Buta & Block (2001). Naming $Q_{bk}$ the maximum value of $Q_b(i, j)$ in quadrant k of the map, according with Buta & Block (2001), we define: $Q_b = \sum_{k=1}^{4} Q_{bk}$.

We listed the final values of the parameter $Q_b$ in Table 2. The values of the bar strength derived with both methods are consistent.

In all our cosmological simulations, with the exception of simulations c2 and c3, a stellar bar is still living at z=0.

4.1. Star and gas morphologies

The strongest and the longest bar arises from simulation c1 (Fig. 1). In this case, the “geometrical” strength of such a bar, namely the ellipticity, $1 - b/a$, evaluated through the isodensity plots, is higher (0.68) than the one measured in the homologous case (0.52 Curir et al. 2006). The strength measured through the $Q_b$ parameter is also higher than the corresponding one in the non-dissipative homologous case as shown in Fig. 2 which compares the maps of $Q_b(i, j)$ final values of the stellar bars. The enhancement of the stellar bar strength is due to the gaseous bar which is superimposed, i.e. coupled, to the stellar one along all the evolution. (see Fig. 1 bottom panel). In the simulation c2, the gas develops a “grand-design” spiral structure, more evident than in simulation c1 (Fig. 3). Such an effect can contribute to destroy the stellar bar, in agreement with recent findings by Bournaud et al. 2005. In the same simulation, c2, the gas produces a barred feature from the earlier stages, lasting until $z \approx 1.2$. After such a redshift, the gaseous central condensation contributes to the bar destruction, according to the claim of Berentzen et al. 1998. These authors show that the growth of a gas mass concentration in the disk dissolves the regular orbits in the stellar bar. In such a simulation, the stellar bar decreases its strength and disappears completely at $z \approx 0.15$, whereas in the c3 case, which corresponds to a larger initial gas fraction, the bar disappears at $z \approx 0.6$. Fig. 4 shows the gas and star morphologies of simulation c2 at $z=0$. Simulation c4 shows a stronger stellar bar than in Curir et al. 2006.
Fig. 1. Face-on, edge-on and side-on isodensity contours (from left to right) of simulation c1 at z=0 (see text); top panel shows the stellar component, bottom panel the gaseous component. Spatial resolution is always $0.5h^{-1}$ physical Kpc and the box size is 40 times the spatial resolution. Contours are computed at 11 fixed levels ranging from $2 \times 10^{-4}$ to 0.015 in term of density fraction of stars (gas) within the spatial resolution to the total star (gas) density in the map.

Fig. 3. Gas isodensity contours, x-y projection, of simulation c1 (left panel) and c2 (right panel) at z=1.

(2006) (ellipticity 0.58 from Table 2 instead of 0.3 from their Table 3) and bar-in bar features along the whole evolution until z=0 (see Fig. 5). Simulations from c5 to c8, which correspond to increasing gas fractions, show the same but less enhanced features during the system evolution, so that at z=0 no bar-in-bar appear, and for simulation c8 (Fig. 5) the final bar is the weaker one. In this set of DM dominated disk simulations, the action of the increasing gas mass is not enough to destroy the bar. We note that, also in these cases, the gaseous bar is coupled with that of the stars from the beginning, however simulations with the larger gas fraction restore the gaseous disk earlier, so that gas and star distributions decouple from z=1 (Fig. 7).

In Fig. 8 we show the behaviour of the ellipticity and of the $Q_b$ as a function of the increasing mass fraction in disks of different masses. It is remarkable the agreement we recover between the trends: the dynamical evaluation of the bar strength and the geometrical evaluation of it through ellipticities.

Fig. 9 compares the gas and star morphologies of the non-cosmological simulation, i1, with those of the homologous non-dissipative case (simulation i4 in Tables 2 and 3 of
Fig. 4. As in Fig. 1 for simulation c2.

Fig. 8. Behaviour of the bar strength and ellipticity at z=0 for our set of cosmological simulations with increasing gas fraction. $Q_b$ (dotted line) and ellipticity (full line) of our more massive disks (i.e. disk-to-halo mass ratio 0.33); $Q_b$ (dot-dashed line) and ellipticity (dashed line) of our less massive, DM dominated, disks (i.e. disk-to-halo mass ratio 0.1).

Curir et al. (2006) after 10.24 Gyr. In simulation i1 the bar forms approximately at the same time as in the pure stellar case. However the presence of the gas destroys the bar after 7.5 Gyr instead of 8.3 Gyr as in simulation c2. Thus the cosmological framework fuels a longer living bar, moreover, when the disk-to-halo mass ratio is 0.33, in such a framework we find a critical value of the gas fraction, 0.2, able to destroy the bar.

In the case of DM dominated disks, all the simulations here performed show a bar feature still present at z=0. This is enhanced for the lower gas percentage, 0.1, and slightly weakened for the higher ones, compared with the corresponding no dissipative case (Curir et al., 2006), but the bar cannot be destroyed by the gas presence.

4.2. Mass inflow and circular velocities

The gas, initially distributed over all the disk surface with the same density distribution as the stars, evolves by increasing its concentration depending on the disk-to halo mass ratio and on its initial mass fraction. Both such parameters affect the life and the strength of the bar, as discussed above.

One crucial parameter to monitorate the ability of the central gas condensation to destroy the bar, is indeed the ratio of the central gas mass over the total disk mass, that we show in Fig. 10 and 11. Fig. 10, for DM dominated disk simulations, show that the rate of inflow at each radius decreases for higher gas fractions: from 65% to 37% at 2 Kpc and from 56% to 35% at 5 Kpc as we go from simulation c4 to c8. Fig. 11, for our more massive disks, show the same trend but with a stronger decrease: from 75% to 35% at 2 Kpc and from 66% to 41% at 5 Kpc as we go from simulation c1 to c2. In particular, for simulation c2, where the gas fraction is able to destroy the bar, the accretion rate at the outer radii becomes quasi stationary after $z = 1$ (Fig. 11 middle panel) since with the weakening
of the bar, the gas inflow is no longer forced. In simulation c3, such a behaviour appears earlier (Fig. 1 middle panel) as well as the bar disappears earlier than in the c2 case.

The circular velocity, $v_{\text{circ}}$, computed assuming a spherical mass distribution and therefore having the expression $(GM/r)^{1/2}$ where $M$ is the mass of a component of the system, gives a measure of the absolute concentration of such a component. In Figs. 12 and 13 (left panels) we show its behaviour at $z = 0$ for gas, stars and dark matter in simulations c4 and c6. In the same Figs. (right panels) we also show the behaviour of the $v_{\text{circ}} = r(\partial \Phi / \partial r)$ evaluated from the force field of the stellar and DM components. The difference of these values from the previous ones is due to the deviation from the spherical isotropy of the mass distribution. In particular, the wide spread we observe for the DM component indicates a wide anisotropy, wider at large radii.

The impact of a central mass concentration (CMC) on the bar evolution has been discussed in detail by Shen & Sellwood (2004). Their study is not directly comparable with ours, since the growth of the CMC is modelled with an analytic potential instead of being the result of gas inflow like in our simulations. In their work it was shown that the destruction power depends on the CMC, given as a fraction of the disk mass, and on the ‘softening’ of its potential, $r_s$, a parameter which controls the compactness of the CMC. Shen & Sellwood (2004) find that for a hard CMC (namely with $r_s$ very small) only few percent of the disk mass is able to destroy the bar, whereas for a soft CMC ( $r_s = 0.3$ Kpc) a fraction larger than 0.1 plays the job. In our scenario, $r_s$ qualitatively translates into the radius, $r_g$, where we set the evaluation of the gas mass concentration. We deduce that for our more massive disks (i.e. when $R_{DM} = 1.94$ in Table 1) a gas mass greater than 9% of the disk mass inside $r_g = 2$ Kpc is needed to destroy the bar. However for DM dominated disks, (i.e. with $R_{DM} = 6.4$ in Table 1) a value of 18% of the disk mass in the same $r_g$ cannot destroy the bar.

Therefore, our cosmological simulations point out that also the value of $R_{DM}$ is a crucial parameter in this play.

4.3. Bar pattern speed

The bar pattern speed, $\Omega_p$, is the angular speed of the bar-like density wave as viewed from an inertial frame. Here it is evaluated following the position angle of the major bar axis during the disk evolution, where the major axis is selected with the same criterion E1 quoted in Michel-Dansac & Wozniak (2006), namely as the radius where the ellipticity profile reaches a maximum. In Fig. 14 the values of $\Omega_p$ as function of the redshift are shown for the two sets of our simulations: the more massive disks and the lighter disks respectively. Since the behaviour of $\Omega_p$ is rather noisy, we provided also the error bars calculated with the running average method, i.e. they are obtained averaging three consecutive values and computing their standard deviations. This error bar is more representative of the fluctuations of the quantity $\Omega_p$ than of the real errors on the measurements. On the other hand, the uncertainty in the measure of the position angle of the semimajor axis is always less than 10°. Such a limit leads to a maximum error of 6%
Fig. 6. As in Fig. 1 for simulation c8.

Fig. 7. Gas isodensity contours (top panel), x-y projection, of simulation c4 (left panel) and c8 (right panel) at z=1; bottom panels show that corresponding contours for stars.
Fig. 9. Isodensity contours of simulation i1 at 10.24 Gyr (top and central panels) compared with the stellar isodensity contours of the same case without gas (bottom panel, simulation c4 of Curir et al. (2006)) at $z=0$.

In the evaluation of $\Omega_p$, the error bar related to such a maximum error is presented at the bottom of each panel in Fig.14. For the more massive disks, the stronger decrease is observed in simulation c1. This is also the simulation with the longer and the stronger stellar bar (see Table 2), usually coupled with the higher decrease of the pattern speed during the evolution (Athanassoula, 2002). Simulation c2 shows the same trend, the decrease of $\Omega_p$ is slightly lower, and the bar disappears before $z=0$, as in simulation c3. However in such a simulation, the pattern speed increases by decreasing the redshift.

We derive that in the more massive disks the increasing gas fraction produces a speed up of the stellar bar pattern since the gas presence both shortens the bar and decreases its ellipticity. Moreover such a behaviour is consistent with the findings of Berentzen et al. (1998), i.e. an accelerated evolution of the whole system when the gas is included.

On the other hand, the DM dominated disks show the strongest decrease of $\Omega_p$ with the redshift. The lower dynamical support of these light disks compared to the more massive cases indeed enhances the role of the gas which slows down the pattern speed more quickly.

5. Discussion and conclusions

We presented eight cosmological simulations with the same disk–to–halo mass ratios as in Curir et al. (2006). In order to study the impact of the gaseous component, here we included and varied its percentage inside disks with different disk–to–halo mass ratios.

Between the more massive disks, simulation c1, with the smaller gas percentage, shows a long lasting bar, 10 Gyr old, stronger than the one developed in the pure stellar case. In
Fig. 12. Left panel: circular velocities obtained assuming a spherical mass distribution of gas (red dashed line), stars (yellow continuous line) and DM (blue long dashed line) at $z=0$ for simulation c4. Right panel: circular velocities deduced from the radial force (upper curve: dark matter, lower curve: stars) at $z=0$ for simulation c4.

Fig. 13. The circular velocities as in Fig. 12 for simulation c6.

Simulation c2, a gas percentage of 20% appears as a threshold value for the bar life as far as such disk mass is concerned. In such a simulation, indeed, the gas is able to destroy the bar at the very end of the evolution ($z=0.15$). By increasing the gas percentage, as in simulation c3, the bar disappears earlier than in c2 (at $z=0.6$). We find that a gaseous mass concentration equal to 9% of the total mass of the disk inside a radius of 2 Kpc, is a lower limit for the bar dissolution. In our more massive disks, where the baryons gravitational field is compelling with that of the DM halo (i.e. disk-to-halo mass ratio 0.33), we find a threshold value of the gas fraction, 0.2, able to destroy the bar.

The gas shows a trend to be more widely distributed by increasing its fraction, for a given disk mass. Moreover, for the same gas fraction, the mass inflow is larger in more massive disks. These effects contribute to weakening the bar which, however, in our cosmological framework, cannot be destroyed in DM dominated disks. In these cases, indeed, the cosmological evolution of the DM halo drives the growth of the bar insta-
The DM dominated disks show indeed a behaviour which is strongly driven by the cosmology as in Curir et al. (2006). In these cases: i) we do not find any value of the gas fraction, in the range 0.1–0.6, able to destroy the bar, ii) even a high value of central gas concentration does not succeed in dissolving the bar. The bars in these disks are not a classical product of the self–gravity, which is very weak, or of angular momentum exchanges, since the disk rotates very slowly, but they are features that strongly depend on the dynamical state and evolution of the cosmological halo. Therefore the classical results emphasising the gas impact obtained outside the cosmological scenario are no longer applicable. This confirms the results of Curir et al. (2006), where in the DM dominated disks the bar feature is triggered and maintained by the dynamical characteristics of the halo, namely its triaxiality and its dynamical state.

Therefore the whole set of cosmological simulations we present here is suggesting a play between three parameters which drive the bar formation and dissolution in cosmology: the gas fraction inside a suitable disk radius, $r_g$, the $r_g$ value itself, and the halo-to-disk mass ratio inside the disk radius.

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Fig. 14. Evolution of the bar pattern speed with the redshift. Left panel: simulation c1 (red full line), c2 (black dashed line), c3 (magenta dotted line). Right panel: simulations c4 (blue full line), c5 (light blue dotted line), and c6 (green dashed line). The error bars on the curves are obtained with the running average method, and the error bar at the bottom of each panel represents the uncertainty in the measure of the position angle of the bar (see text).
Fig. 10. Gas–to–disk mass ratio at different disk radii: 2 Kpc (magenta dashed-dotted line), 3 Kpc (blue dashed line), 4 Kpc (red dotted line), and 5 kpc (black full line) as function of redshift for simulation c4 (top panel), c5 (middle panel), and c8 (bottom panel).

Fig. 11. As in Fig 10 for simulation c1 (top panel), c2 (middle panel), and c3 (bottom panel).

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