Star formation and bar instability in cosmological halos

A. Curir¹, P. Mazzei², and G. Murante¹

¹ INAF – Osservatorio Astronomico di Torino, Strada Osservatorio 20, 10025 Pino Torinese, Torino, Italy
e-mail: curir@oato.inaf.it

² INAF – Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, 35122 Padova, Italy

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ABSTRACT

Context. This is the third in a series of papers presenting the first attempt to analyse the growth of the bar instability in a consistent cosmological scenario. In the previous two articles, we explored the role of the cosmology on stellar disks and the impact of the gaseous component on a disk embedded in a cosmological dark matter halo.

Aims. The aim of this paper is to point out the impact of the star formation on the bar instability inside disks having different gas fractions.

Methods. We performed cosmological simulations of the same disk-to-halo mass systems as in the previous works where the star formation was not triggered. We compared the results of the new simulations with the previous ones to investigate the effect of the star formation by analysing the morphology of the stellar components, the bar strength, the behaviour of the pattern speed. We followed the gas and the central mass concentration during the evolution and their impact on the bar strength.

Results. A stellar bar, lasting 10 Gyr, is still living at $z = 0$ in all our cosmological simulations.

The central mass concentration of gas and of the new stars has a mild effect on the ellipticity of the bar but is not able to destroy it, and at $z = 0$ the stellar bar strength is enhanced by the star formation. The bar pattern speed decreases with the disk evolution.

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

1. Introduction

The connection between the bar feature and the star formation process has already been pointed out in the past. [Martinet & Friedli \(1997\)](#) observed that non interacting galaxies displaying the highest star-forming activity have strong and long bars. Conversely, not all strong and long bars are intensively creating stars. [Mazzei & Curir \(2001\)](#) performed SPH simulations to investigate the dependence of the star formation in disks on the geometry and dynamical state of the dark matter (DM) halo. They show that star formation lengthens the lifetime of the bar; however, in their works the evolution of the disk+halo system arises in an isolated framework, outside the cosmological scenario.

The treatment of the star formation in galaxies involves a large number of physical processes that arise with different timescales and spatial lengths. Therefore its inclusion in simulations of galaxy formation is complex ([Mazzei & Curir 2003](#), and reference therein), and many sub-grid parametrisations (i.e. representing all the astrophysical processes that cannot be resolved due to resolution or computing power limitations) of the star formation process exist in the literature. To mimic all these processes with a numerical model of a realistic disk galaxy is just as difficult. Thus the numerical work on this subject focuses either on detailed analysis of the interstellar medium (ISM) and a smaller simulated area ([Wada 2001](#); [Avillez et al. 2000](#)) or on the study of the global instabilities and of the star formation at the cost of simplified ISM models ([Robertson et al. 2004](#); [Semelin & Combes 2002](#); [Combes & Melchior 2002](#)). Models that have tackled both topics have either been in two dimensions ([Wada & Norman 2001](#)) or restricted to a box size a few hundred parsecs across ([Wada 2001](#)). [Rosen & Bregman \(1995\)](#) worked in two dimensions, allowing the ISM to evolve self-consistently

but treated the stars as collisional rather than collisionless fluid. [Tasker & Bryan \(2006\)](#) present the first three-dimensional simulations of a global disk without the need to simplify the structure of the ISM. Their paper is devoted to understanding the fundamental processes of star formation and feedback in a disk galaxy.

We performed cosmological simulations to analyse the effects of the star formation process inside stellar-gaseous disks embedded in a DM cosmological halo evolving in a fully consistent scenario. We employ the sub-grid star formation model by [Springel & Hernquist \(2003\)](#) which is able to produce a self-regulated star formation in galactic disks. We point out that our model is not a general galaxy evolution model, since the gradual formation and growth of the stellar disk has not been taken into account. However our approach, developed in two previous papers ([Curir et al. 2006, 2007](#)), allows us to investigate the effects of different parameters like the disk-to-halo mass ratio and the gas fraction inside the disk, on the growth of the bar instability, its coupling with the star formation rate and its dependence on such parameters in a self-consistent cosmological framework. We compare the results of such a new set of simulations with those of our previous sets with the star formation switched off ([Curir et al. 2006](#), hereafter Paper I; [Curir et al. 2007](#), hereafter Paper II). In Paper I we presented simulations of purely stellar disks with the same disk-to-halo mass ratios, in the same cosmological scenario, and with the same initial conditions as in this new paper. In Paper II we investigated the growth and the evolution of the bar instability in disks with the same disk-to-halo mass ratios as in Paper I, and different gas fractions, but without star formation. Thus, we will compare the results of these new simulations, with those corresponding to the same disk-to-halo mass ratio as in Paper I and to the same gas fraction as in Paper II. The comparison between the parameters

characterising the bar can only be done by evaluating that of the old stars component, since the new stars are not present in Papers I and II. In both these papers, it was shown that in DM-dominated disks a bar feature is triggered and maintained by the cosmology, whereas, in the more massive disks, a gas fraction 0.2 is able to destroy the bar. The focus of the present work is to determine whether the star formation changes this result.

The plan of the paper is the following. In Sect. 2, we summarise our recipe for the initial *disk+halo* system fully described in Paper I and present our star formation recipe. In Sect. 3, there are our cosmological simulations, and in Sect. 4 we point out our results. The parameters related to the bars formed in the new and the old stars and to the global, old+new, stellar populations are given in this section. Section 5 is devoted to our discussion and conclusions. It contains a table including the parameters characterising the old stellar bar at $z = 0$ in the three papers to allow easier comparison between the results of our papers (Table 2).

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 Λ CDM model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$, $h = 0.7$, where Ω_m is the total matter of the Universe, Ω_Λ the cosmological constant, σ_8 the normalisation of the power spectrum, and h the value of the Hubble constant in units of $100 h^{-1} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

A detailed description of our method of producing the cosmological scenario where the disk is evolved was given in Paper I. Here we present a short overview of our recipe. Paper I 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 performed a low-resolution simulation of a *concordance* Λ CDM cosmological model, starting from redshift 20. With a standard “friends of friends algorithm”, we selected 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 $4 h^{-1} \text{ Mpc}$, are followed to their Lagrangian position and re-sampled to an equivalent resolution of 1024^3 particles. The total number of DM particles in high resolution corresponds to a DM mass resolution of $1.21 \times 10^6 h^{-1} M_\odot$. The high-resolution DM halo is followed to the redshift $z = 0$. We run the DM simulation to extract the halo properties in the 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 $R_{\text{vir}} = 94.7 h^{-1} \text{ kpc}$, which entails 84 720 halo particles. The selected halo is living in an under-dense environment. From its accretion history (see Fig. 1 in Paper I), we conclude that our halo undergoes no significant merger during the time it hosts our disk, or immediately before. The halo density profile is well-fitted by a Navarro, Frenk, and White (NFW) form (Navarro et al. 1996, 1997) at $z \leq 2$. The concentration, C_{vir} , equal to R_{vir}/R_s , takes a high value, 18.1, confirming that this halo does “form” at very high redshift (see, e.g. Wechsler et al. 2002, for a discussion of the link between concentration and the 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; Bett et al. 2007).

Cosmological DM halos are not spherical (Bett et al. 2007, and references therein). From a recent analysis of the halo shapes from the Millennium simulation, Bett et al. (2007) show that halos are triaxial and prolate. Their shape is driven by the hierarchical formation. The prolateness of our halo at $z = 2$, where $R_{\text{vir}} = 30 \text{ kpc}$, is 0.9, much the same as at the disk radius (Paper I, Table 1).

2.2. The baryonic disk

The spatial distribution of particles follows the exponential surface density law: $\rho = \rho_0 \exp(-(r/r_0))$ where r_0 is the disk scale length, $r_0 = 4 h^{-1} \text{ kpc}$, and ρ_0 the surface central density. The disk is truncated at five scale lengths with a radius: $R_{\text{disk}} = 20 h^{-1} \text{ kpc}$. To obtain each disk particle’s position according to the assumed density distribution, we used the rejection method (Press et al. 1986). We used 56 000 star particles and 56 000 gaseous particles to describe our disk. The (Plummer equivalent) softening length, the same for DM, gas, and star particles, is $0.5 h^{-1} \text{ kpc}$ in comoving coordinates.

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 center of mass corresponds to the minimum potential well of the CM halo. The initial redshift corresponds to 10.24 Gyr down to $z = 0$ in our chosen cosmology. During the evolution, new star particles are formed from the gaseous particles. We refer to such new component as “new star component”, whereas we will call “old star component” the non dissipative particles present in the disks at $z = 2$.

2.3. Star formation recipe

We use the sub-grid star formation prescription by Springel & Hernquist (2003). In it, when a gas particle overcomes a given density threshold its gas content, is considered to reside in a multi-phase state, that corresponds to the equilibrium solution of an analytical model describing the physics of the multi-phase interstellar medium. Such a solution gives an effective temperature for the gas particle, obtained as a weighted average of the (fixed) temperature of the cold phase and of the hot phase. The temperature of the hot phase is set by supernova feedback and by the efficiency of cloud evaporation. The resulting inter stellar medium (ISM) has an effective equation of state $P_{\text{eff}}(\rho)$, which is stiffer than isothermal and prevents Toomre instabilities even when a large amount of gas is present. When this prescription is used, the star formation rate agrees with the Schmidt law in disk galaxies, as obtained e.g. by Kennicutt (1998). A detailed description of the numerical prescription and several tests can be found in Springel & Hernquist (2003). The effective temperature drives hydrodynamical interactions of the gas particles. Moreover, the model consistently gives a star formation rate, which is used to spawn a star particle from the gas one on the basis of a stochastic prescription; the initial mass function adopted is the Salpeter’s one. The star-forming from the gas has the same position and velocity as the gaseous particle.

3. Simulations

We performed six cosmological simulations of a disk+halo system. We exploited the parallel Tree+SPH N -body code GADGET-2 (Springel 2005) (courtesy of V. Springel). The simulations run on the CLX computers located at the CINECA

Table 1. Simulations: final values. o.s. = old stars , n.s. = new stars.

N	M_{disk}	Gas fraction	ϵ (o.s.)	ϵ (n.s.)	Q_b (o.s.)	Q_b (o.s.+n.s.)	a_{max} (o.s.)	a_{max} (n.s.)	Bulge (o.s.)	Bulge (n.s.)	Bars in bars
c1	0.33	0.1	0.65	0.72	0.45	0.5	8	4	y	n	n
c2	0.33	0.2	0.55	0.55	0.51	0.66	11	5.7	y	y	n
c3	0.33	0.4	0.6	0.55	0.58	0.69	8.4	6	y	y	n
c4	0.1	0.1	0.39	0.01	0.5	0.41	3	-	n	y	y
c5	0.1	0.2	0.45	0.03	0.46	0.42	3	-	n	y	y
c6	0.1	0.6	0.5	0.02	0.51	0.47	3	-	n	y	y

computing centre (BO, Italy) and on the OATo Beowulf-class cluster of 32 Linux-based PC at the Osservatorio Astronomico di Torino. The main parameters and the final properties of our set of simulations are listed in Table 1. As a geometrical measure of the bar strength, we define the value of the ellipticity, $\epsilon = 1 - b/a$ (Table 1); 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: $Q_r = \frac{F_T^{\text{max}}(R)}{\langle F_R(R) \rangle}$ where $F_T^{\text{max}}(R) = [\partial\Phi(R, \theta)/\partial\theta]_{\text{max}}$ is the maximum amplitude of tangential force and $\langle F_R(R) \rangle = R(\partial\Phi_0/\partial r)$ is the mean axisymmetric radial force derived from the $m = 0$ component of the gravitational potential at the same radius, R . The maximum value of $Q_r(R)$ provides a measure of the bar strength Q_b for the whole galaxy. Stronger bars correspond to higher Q_b values. To compare the results with Papers I and II, the values of Q_b are evaluated in the bars formed in the old star component, since in our previous works we did not include the star formation process.

We also give here in Table 1 the value of the parameters related to the bars formed in the new stars component and to the bar strength of the global old+new star populations. In Table 1 we present the simulation number (I column), the mass of the disk in code units (i.e. $5.9 \times 10^{10} M_\odot$) (Col. II), and the fraction of gas, i.e. gas-to-disk mass ratio (Col. III). Moreover, as final values (i.e. at $z = 0$) we present the maximum ellipticity for the old star system (Col. IV) and for the new star (Col. V), the bar strength according to Combes & Sanders (1981) for the old stars (Col. VI), and for the old+new stars system (Col. VII), the major axis (physical kpc) corresponding to the maximum ellipticity for the old stars (Col. VIII) and for the new stars (Col. IX), the morphology of the inner region of the disk for the old stars (Col. X) and for the new ones (Col. XI), peculiar features inside the disk (Col. XII)

4. Results

In all our cosmological simulations, a stellar bar is still living at $z = 0$ in the old star component. The new star component at $z = 0$ is arranged in a bulge component that can or cannot present a barred shape depending on the initial mass of the disk and on the gaseous fraction. In Figs. 1–8 we present the isodensity contours of the old stars, gas and new stars for simulations in Table 1. All these figures have constructed with the same box-size, number of levels, and density contrast (see caption of Fig. 1) as in Papers I and II.

4.1. Morphologies

We discuss first the bar features as far as the old star component is concerned. Figures 1 and 2 show the evolution of this component from $z = 2$ to $z = 0$ for simulations c1 and c4. The bar feature is well-defined since $z = 1.75$ in both the cases. In the more massive case, the evolving bar becomes stronger and

Fig. 1. Face-on isodensity contours of simulation c1 from $z = 2$ to $z = 0$. Spatial resolution is always $0.5 h^{-1} \text{ physical kpc}$ and the box size is 40 times the spatial resolution. Contours are computed at 11 fixed levels ranging from 2×10^{-4} to 0.015 in terms of the density fraction of stars (gas) within the spatial resolution to the total star (gas) density in the map.

dominates the disk, whereas the bar remains a central structure inside the disk in the less massive cases, generating a bar-in-bar feature. The strongest bar arises from simulation c1 (Fig. 3). In this case, the ellipticity, evaluated through the isodensity plots, is higher (0.65) than the one measured in the purely stellar disk of the same mass (0.52, Paper I), but slightly lower than measured in the case of a disk with the same mass and the same gas fraction (0.68, Paper II). The enhancement of the stellar bar strength in comparison to the gas-free case is due to the coupling of the gaseous component to the stellar one: the gaseous bar is indeed superimposed on the stellar one, as pointed out in Paper II. However, this effect is slightly reduced by the star formation activity.

Fig. 2. Face-on isodensity contours of simulation c4 from $z = 2$ to $z = 0$. Isodensity levels and spatial resolution are the same as in Fig. 1.

Fig. 3. 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 gaseous component, *middle panel* the old star component, *bottom panel* the newly formed stars. Isodensity levels and spatial resolution for gas and stars are as in Fig. 1.

In simulation c2, the stars produce a barred feature, lasting until $z = 0$ (Fig. 4). This is an important difference with the case having the same gas fraction in Paper II, where the bar decreased its strength and disappeared at $z \approx 0.15$. The same behaviour arises in the c3 case, (Fig. 5), which corresponds to a larger initial gas fraction: the bar is living until the final redshift, whereas the bar disappeared at $z \approx 0.6$ without the star formation.

Fig. 4. Same as in Fig. 3 but for simulation c2.

Fig. 5. Same as in Fig. 3 but for simulation c3.

Fig. 6. Same as in Fig. 3 but for simulation c4.

The gas forms a bar since the beginning of the disk evolution and the new stars originating from the gaseous component assume an elongated structure that fuels the old star bar feature: the new stars are dynamically cold and they strongly feel the resonances in the equatorial plane, where they are born. In the simulations with higher gas fractions, they are swept out in the central regions by vertical resonances, which results in the formation of a central young bulge (Friedli & Benz 1995). According to the claim of Berentzen et al. (1998), the growth of a gas mass concentration in the disk dissolves the regular orbits in the stellar bar. In Paper II, we deduced a threshold value for the gas concentration inside a radius of 2 kpc, 9%, able to destroy the bar in the more massive disks. If the star formation is included, it transforms the dissipative component into a non dissipative one,

Fig. 7. As in Fig. 3 for simulation c5.

Fig. 8. As in Fig. 3 for simulation c6.

Fig. 9. 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), 5 kpc (black full line) for simulation c2. In the upper panel we present the time behaviour of the gas as fraction of the disk mass, and in the lower panel we see the same for the sum of the gas and the newly formed stars.

lowering the central concentration of the gas. Figures 9 and 10 show the evolution of the gas mass in the inner regions, i.e., of the gas concentration (upper panel) and that of the mass of gas plus new stars (lower panel) in the same regions, in simulations c2 and c3, respectively. In both these cases, the gas mass inside 2 kpc never rises over the threshold value pointed out in

Fig. 10. Same as in Fig. 9 but for simulation c3.

Fig. 11. Evolution in redshift of the ellipticity for simulations c2 (blue full line) and c3 (red dashed line).

Paper II. However, the gas+new star concentration in simulation c3 exceeds this threshold value at $z = 0.6$, without any consequence for the observed bar (Fig. 11). This is because the effect of bar dissolution due to the central mass concentration cannot be achieved when including the mass of new stars that are crossing the central region through elongated orbits and are not really as concentrated as the gas. In the simulation c3, the gas shows more developed arms at $z = 1$ than in case c1 (Fig. 12). But this feature, which is considered as a possible mechanism for the bar destruction, has no impact on the bar in these new simulations (Bournaud et al. 2005).

A different discussion is devoted to the DM-dominated disks, which, as already stressed in Papers I and II, show bars that are not a classical product of the self-gravity or of angular momentum exchanges, but they are features that strongly depend on the dynamical state and evolution of the cosmological halo. We did not observe their destruction even by higher gas concentration. Old stars in simulation c4 show a stronger stellar bar than in the pure stellar disk of the same mass (ellipticity 0.39 instead of 0.3, see Table 2) but weaker than arising from the simulation with the same disk mass and gas fraction, but without star formation (Paper II). Bar-in-bar features are present during the whole evolution (simulation c4) until $z = 0$ (Fig. 6). Simulations c5 and c6, which correspond to increasing gas fractions, show similar features during the system evolution. In this set of DM-dominated disk simulations, the final bar increases in its strength with the increasing gas fraction (Fig. 13, Table 1). This trend is different

Fig. 12. Gas morphologies at $z = 1$ for simulations c1 (*upper panel*) and c3 (*lower panel*).

Fig. 13. 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).

from the one we observed in Paper II, where the increasing gas fraction produces an increase to a maximum and then a decrease in the bar strength.

In DM-dominated disks, the bars in the old star component are the imprint of the halo cosmological properties, as discussed in the previous papers. Figure 14 shows the isodensity contours of the halo in the plane of disk in the same frame, with the same isodensity levels and box sizes as those of the old stars in Figs. 1 and 2. The semimajor axis of the triaxial DM halo, for $z < 1.8$, is both in phase with the central bar of the disk and they have the same pattern speed.

In the more massive disks (Fig. 15), the central DM region becomes rounder, due to the impact of the disk itself, and the coupling with the stellar bar disappears. Therefore, in the case of the lighter disks, the cosmological halo properties drive the

Fig. 14. Isodensity contours of the DM in the xy plane, from redshift $z = 2$ to $z = 0$ for the simulation c4. Density levels and spatial resolutions are the same as in Fig. 1. The synchronicity of the semimajor axis of the halo with the one of the inner old stellar bar can be noticed by direct comparison of each panel (after $z = 1.8$) with the corresponding one in Fig. 2.

formation of the bar, whereas the bar is a classical product of the disk instability, in the more massive disks. In the DM-dominated disks the new stellar component produces a small spheroidal bulge that has a disk shape in the simulation c6. The gas component is confined in the central regions from the beginning of the evolution, and therefore the new stellar component arranges itself in a small spheroidal bulge. Therefore, in a DM-dominated disk, the new stars at $z = 0$ have no bar features, a difference from more massive disks. We recall that the bars in DM-dominated disks are not caused by classical resonances, so the new stars do not feel these resonances, whereas this is what happens in the case of the more massive disks. The decoupling between new and old stars is depicted also in Fig. 17, where the distribution of radial velocity dispersions in a massive disk at $z = 1$ is compared with the one in a DM-dominated disk at the same redshift; in such a case, the decoupling between new and old stars is depicted. The radial velocity dispersion of this new star component is lower than that of the old stars. At the end of the evolution, we therefore see a small bulge of new stars hiding a small nuclear bar of old stars. Such a nuclear bar remains, as observed in Papers I and II and stressed by Fig. 14, as a genuine

Fig. 15. Isodensity contours of the DM, as in the previous figure, for the simulation c1.

product of the cosmology, since the light disks are classically below the instability threshold.

4.2. Bar pattern speed

The bar pattern speed Ω_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 as in Paper II. The values of Ω_p as a function of the redshift for the more massive disks and the lighter disks are shown in Figs. 18 and 19 respectively.

For the more massive disks, we observe a decrease in Ω_p in all the simulations. This is a different behaviour from the one observed in Paper II, where we noticed an increase in the pattern speed coupled with the increasing gas fraction, since the gas presence both shortens the bar and decreases its ellipticity.

This mechanism no longer works when the star formation is activated, since the ongoing star formation reduces the gas concentration in the central regions and the new stars arrange into an elongated structure that also enforces the length of the original bar (Fig. 20, see also the previous section).

For the DM-dominated disks, the evaluation of Ω_p in this paper, as in the previous ones, is done by referring to the angular

Fig. 16. Same as in Fig. 12 but for simulations c4 and c6.

velocity of the long-lived central bar. Its behaviour is the same as observed in Paper II; namely, it shows a fast decrease before redshift $z \approx 1$ (see also Debattista & Sellwood 1998, 2000), and then quasi stationary behaviour until redshift 0.

5. Discussion and conclusions

We have presented six cosmological simulations with the same disk-to-halo mass ratios as in Papers I and II. In order to study the impact on the bar of the new stars forming by the gaseous component, we included and varied its percentages inside disks of different disk-to-halo mass ratios, as in Paper II where the star formation was switched off. In Table 2 we show the final data for ellipticities and semimajor axes summarising the results of our three papers.

The old star component shows a long-lasting bar, 10 Gyr old, in all the simulations of this work. Moreover, in all but simulation c6, the bar is stronger than is developed in the pure stellar case with the same disk-to-halo mass ratio but weaker than what is formed in the case of the same gas fraction without star formation.

We find that the star formation, by reducing the central gaseous mass concentration, allows the bar to also survive until the end of the evolution in the more massive disks, at variance with the results in Paper II (where the gas was not allowed to form stars): in such a case a gas fraction 0.2 was able to destroy the bar. Even if some details of the disk morphologies obviously depend on the star formation prescription, the bars arising here in the c2 and c3 simulations are caused by the reduced central gas concentration and thus to the weakening of its effect on the bar itself. We verified this point by rerunning simulation c2 and changing the star formation prescription. Instead of the GADGET-2 effective model, we used a simple algorithm in which, when a gas particle reaches a given density threshold with a temperature lower than a minimum temperature

Table 2. Cosmological disks simulations: global results.

Disk mass	Gas fraction	No star formation ellipticity	$a_{\max}$	Star formation ellipticity	$a_{\max}$
0.33	0.	0.52	5	—	—
0.33	0.1	0.68	8.4	0.65	8
0.33	0.2	0.1	no bar	0.55	11
0.33	0.4	0.07	no bar	0.6	8.4
0.1	0.	0.3	6.5	—	—
0.1	0.1	0.58	5.8	0.39	3
0.1	0.2	0.6	5.4	0.45	3
0.1	0.6	0.42	5.8	0.5	3

Fig. 17. Radial velocity dispersion at $z = 1$ of old stars (red open circles) and new stars (green crosses) for simulations c2 (*upper panel*) and c5 (*lower panel*). **Fig. 18.** Evolution of the bar pattern speed with the redshift for simulation c1 (black dashed line), c2 (red full line), and c3 (magenta dotted line). **Fig. 19.** Evolution of the bar pattern speed with the redshift for simulation c4 (black dashed line), c5 (red full line) and c6 (magenta dotted line). **Fig. 20.** Behaviour of the semimajor axis for the simulations c2 (blue full line) and c3 (red dashed line).

threshold, it is converted into a star particle, as in [Katz et al. \(1996\)](#). Figure 21 shows the morphology of the old stellar component for such a different star formation recipe: the survival of the bar is due to the star formation, independent of its details.

In all the simulations of more massive disks, the new stellar component shows a barred shape coupled with that of old stars, but with semimajor axis and ellipticity values lower than those. In all the simulations of DM-dominated disks, a bar feature is maintained in the old stellar component at the disk centre, and the new stars form a spheroidal bulge that hides the bar of the old stars. This effect could be of interest for observations of the Milky Way where, in addition to the main bar, a small nuclear bar consisting of old stars seems to be included in the bulge (see e.g. [Alard 2001](#)). The final strength of these old star bars increases by increasing the gas fraction, and their pattern speed quickly decreases before $z = 1$.

Fig. 21. Isodensity contours of the old stars at $z = 0$, for the simulation c2, rerun with the Katz'96 star formation recipe

The classical results obtained outside the cosmological scenario are no longer applicable. This conclusion underlines the results of Curir & Mazzei (1999) and Paper I, where it was shown that in the DM-dominated disks the bar feature is triggered and maintained by the cosmological properties of the halo (namely its triaxiality and its dynamical state).

From the models presented here we suggest that a very low pattern speed (few $\text{km s}^{-1} \text{ kpc}^{-1}$) could be the signature of a dominating halo and not the classical product of the disk instability. The whole set of cosmological simulations we presented here suggests that the star formation works toward maintaining the bar feature in self gravitating disks, against the effect of increasing gas fractions, whereas in DM-dominated disks, it reduces the bar strength slightly. Moreover, inside such disks, the new stars are arranged in non barred systems that are decoupled from the bar of the old star component.

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