Bars driven by the Cosmology in stellar-gaseous disks

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Abstract. We present the first attempt to analyse the growth of the bar instability in stellar-gaseous disks evolving in a fully consistent cosmological scenario. We explored the role of the cosmology on pure stellar disks with different mass embedded in a cosmological dark matter halo. We deepened such a study by analysing the impact of different gas fractions and of the star formation onset.

We found that in all these cases, the stellar bar arising inside the less massive disks, i.e., dark matter (DM)-dominated disks, is still living at redshift zero even if the gas fraction exceeds half of the disk mass. Such a bar is a genuine product of the cosmology. However, in the most massive disks there is a threshold value for their gas percentage and lower limit for the central gas concentration able to destroy the bar when the star formation rate is switched off.

On the other hand in the simulations with star formation the central mass concentration of gas and of the new stars has a mild action on the ellipticity of the bar but is not able to destroy it; at $z=0$ the stellar bar strength is enhanced by the star formation. Even if our results qualitatively agree with the classical ones, i.e. with criteria concerning bar instability derived outside the cosmological framework, the same criteria cannot be validated for the DM-dominated disks.

Keywords. physical data and processes: gravitation, hydrodynamics, stellar dynamics; methods: numerical; galaxies: halos, evolution, spiral; cosmology: dark matter

1. Introduction

In a pioneering paper Curir & Mazzei (1999) put the first question mark on the effect of the halo triaxiality on the bar growth and evolution, by carrying on SPH simulations of a disk inside a non-spherical halo, in an isolated context. They embedded a stellar-gaseous disk in dark matter (DM) halos of different masses, shapes and dynamical states. These models allowed to follow for the first time the effect of a live triaxial halo on the disk evolution. Their first result is that a massive halo not yet relaxed has a major role in triggering bar instability.

The gas behaviour in disk galaxies and its connections with the bar feature has been studied in several papers (Friedli & Benz (1993), Berentzen at a. (2001), Bournaud et al. 2005, Michel-Dansac & Wozniak, 2004). 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.

The connection between the bar feature and the star formation process has already been pointed out in the past. Martinet & Friedli (1977) in particular observed that non-interacting galaxies displaying the highest star forming activity have strong and long bars. Mazzei & Curir (2001) investigated further the role of a live non axisymmetric DM
halo, with different geometry and dynamical state, on the star formation and on its role in the bar triggering. They showed that the star formation enhances the bar instability and lengthens the life time of the bar. However in these works the evolution of the disk+halo system arises in a isolated framework.

In a series of papers (Curir et al. (2006), Curir et al. (2007), Curir et al. (2008)) we investigated for the first time the growth of the bar instability in a cosmological context. For this purpose we followed the behaviour of an exponential baryonic disk inserted in a cosmological DM halo evolving in a fully cosmological framework. 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 Governato et al. (2004), Robertson et al. (2004), Sommer-Larsen (2006), where the formation of a spiral galaxy within the hierarchical scenario of structure formation in Λ-dominated cosmologies has been followed self-consistently. However, our approach has the advantage of allowing to vary parameters like the disk-to-halo mass ratio, the gas fraction inside the disk, to switch off and on the star formation with the aim to analyse the growth of the bar instability and its dependence on these parameters in a self-consistent cosmological framework. We embedded a purely stellar and a stellar-gaseous disk inside a cosmological halo selected in a suitable slice of the Universe (see Fig. 1) and follow its evolution inside a cosmological framework: a ΛCDM model with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \sigma_8 = 0.9 \) and \( h = 0.7 \), 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 \( 100h^{-1} \text{ km s}^{-1}\text{Mpc}^{-1} \).
### 2. Overview

#### 2.1. The DM halo

To select the DM halo, we perform a low-resolution simulation of a *concordance* Λ CDM cosmological model, starting from redshift 20.

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 a multi-mass technique. The particles of the DM halo, and those belonging to a sphere with a radius $4h^{-1} \text{Mpc}$, are followed to their Lagrangian position and re-sampled to an equivalent resolution of 1024$^3$ particles. The total number of DM particles in the 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 absence of any embedded 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 84720 halo particles. From the accretion history of our halo, we know that it undergoes no significant merger during the time it hosts our disk, nor immediately before. The prolateness of our halo at $z=2$, where $R_{\text{vir}} = 30 \text{Kpc}$, is 0.9, its spin parameter $\lambda$ has a value 0.04.

#### 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, $r_0 = 4h^{-1} \text{Kpc}$, and $\rho_0$ is the surface central density. The disk is truncated at five scale lengths with a radius: $R_{\text{disk}} = 20h^{-1} \text{Kpc}$. To obtain each disk particle’s position according to the assumed density distribution, we used the rejection method. We examine two values for the mass of the disk: a more massive case, where the disk mass is $1.9 \times 10^9$ solar masses (0.33 in our mass units) and a lighter case where the disk mass is $5.9 \times 10^8$ (0.1 in the same units) The (Plummer equivalent) softening length, the same for DM, gas, and star particles, is $0.5 h^{-1} \text{Kpc}$ in comoving coordinates.

### 3. Simulations

We performed several cosmological simulations of our disk+halo systems. The first set (Curir et al.(2006)) describes purely stellar disks, the second set (Curir et al.(2007)) stellar-gaseous disks with cooling, and the third set simulates the same stellar-gaseous disks with star formation (Curir et al.(2008)). We exploited the parallel Tree+SPH N-body code GADGET-2 (courtesy of V. Springel). The simulations run on the CLX computers located at the CINECA computing centre (BO, Italy) and on OATo Beowulf-class cluster of 32 Linux-based PC at the Osservatorio Astronomico di Torino.

The main parameters and the final properties of a set of our simulations, the one where the star formation is triggered, are listed in Table 1. The units are $5.9 \times 10^{10} M_\odot$ for the mass, and 20 Kpc for the length.

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

| N | $M_{\text{disk}}$ | gas fraction | $\epsilon$ (o.s.) | $\epsilon$ (n.s.) | $a_{\text{max}}$ (o.s.) | $a_{\text{max}}$ (n.s.) | bulge(o.s.) | bulge(n.s.) | bars in bars |
|---|------------------|--------------|------------------|------------------|------------------------|------------------------|------------|------------|-------------|
| c1 | 0.33 | 0.1 | 0.65 | 0.72 | 8 | 4 | y | n | n |
| c2 | 0.33 | 0.2 | 0.55 | 0.55 | 11 | 5.7 | y | y | n |
| c3 | 0.33 | 0.4 | 0.6 | 0.55 | 8.4 | 6 | y | y | n |
| c4 | 0.1 | 0.1 | 0.1 | 0.1 | 3 | - | n | y | y |
| c5 | 0.1 | 0.2 | 0.45 | 0.03 | 3 | - | n | y | y |
| c6 | 0.1 | 0.6 | 0.5 | 0.02 | 3 | - | n | y | y |
Figure 2. 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).

In the purely stellar disk cases a long living bar (lasting 10 Gyr) appears in all the simulations.

In our massive stellar-gaseous disk when only the cooling is present, 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 these massive disks, where the baryons gravitational field is comparable to that of the DM halo, we find a threshold value for the gas fraction, 0.2, able to destroy the bar, whereas in the DM-dominated disks a stellar bar is still leaving at $z = 0$ even if the gaseous fraction exceeds half of the disk mass. In Fig. 2 we show the behaviour of the ellipticity and of the dynamical parameter $Q_b$ (defined by Combes & Sanders (1981) to measure the bar strength) as a function of the increasing mass fraction in disks of different masses, where only the cooling is activated. The agreement we recover between the trends is remarkable: the dynamical evaluation of the bar strength and the geometrical evaluation of it through ellipticities.

In all our cosmological simulations with star formation, a stellar bar is still living at $z = 0$ in the old star component, even in the disks having the gas fraction higher than the threshold value for the bar dissolution discovered in the simulations with gas and cooling. The new stars component at $z=0$ is arranged in a bulge component which can present a barred shape depending on the initial mass of the disk and on the gaseous fraction (see Fig. 3 and 4). Fig.4 shows that in the DM-dominated disks the new stars structures appear to have the characteristics of pseudobulges as defined by Kormendy, namely of spheroids formed by secular processes and hiding small bars inside.

In this set of simulations, the final bar is increasing its strength with the increasing gas fraction (Fig. 5).

4. Implications

In Curir et al.(2006) we stressed that the purely stellar DM dominated disks show a behaviour that is strongly driven by the cosmology. For these disks, when gas and cooling is present (Curir et al. (2007)) we did not find any value of the gas fraction, in the range 0.1–0.6, able to destroy the bar; moreover even a high value of central gas concentration
Figure 3. Face-on, edge-on, and side-on iso-density contours (from left to right) of simulation c3 at z=0; top panel shows the gaseous component, middle panel the old star component, bottom panel the newly formed stars.

Figure 4. Same as in Fig. 3 but for simulation c6 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. They are features that strongly depend on the dynamical state and on the evolution of the cosmological halo, therefore the classical results emphasising the gas impact obtained outside the cosmological scenario are no longer applicable.

When the star formation is taken into account (Curir et al. (2008)), the new stars in
DM-dominated disks arrange in pseudobulges at $z=0$, but a bar always is maintained in the old stars population. Also in these DM-dominated disks the bars are not due to classical resonances.

5. Conclusions

In self gravitating disks, cooling gas and star formation produce competitive effects in the central regions to maintain and enhance (star formation) or to destroy (gas concentration) the bar feature. In cosmological framework, the results for these disks are qualitatively in agreement with the classical ones. On the other hand for DM-dominated disks the classical criteria to account for bar instability cannot be validated in a cosmological framework. The mass anisotropy, and the dynamical evolution of the DM cosmological halo have indeed a crucial effect in enhancing and fuelling the bar instability also in the cases where isolated halo-disk \textit{ad hoc} models provided stability predictions.

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