

## High resolution SPH simulations of disk formation in CDM halos; resolution tests

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We perform N-Body/SPH simulations of disk galaxy formation inside equilibrium spherical and triaxial cuspy dark matter halos. We systematically study the disk properties and morphology as we increase the numbers of dark matter and gas particles from  $10^4$  to  $10^6$  and change the force resolution. The force resolution influences the morphological evolution of the disk quite dramatically. Unless the baryon fraction is significantly lower than the universal value, with high force resolution a gaseous bar always forms within a billion years after allowing cooling to begin. The bar interacts with the disk, transferring angular momentum and increasing its scale length. In none of the simulations does the final mass distribution of the baryons obey a single exponential profile. Indeed within a few hundred parsecs to a kiloparsec from the center the density rises much more steeply than in the rest of the disk, and this is true irrespective of the presence of the bar.

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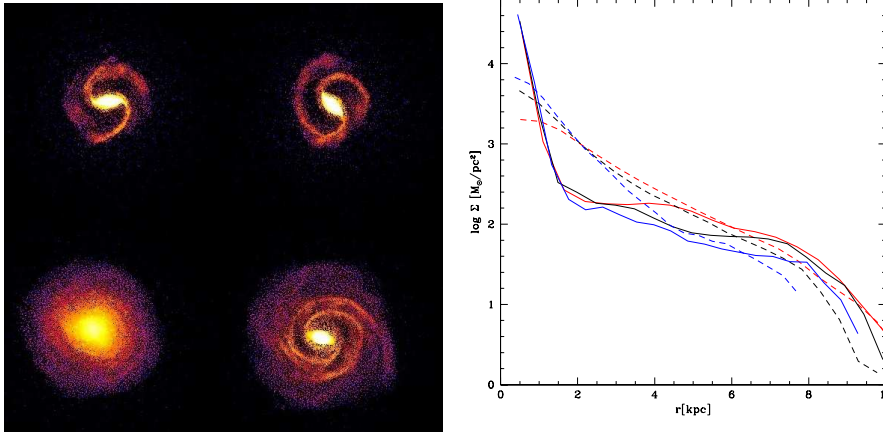
## 1. Introduction and numerical models

Although there is a quite extensive literature on the analysis of numerical effects in cosmological SPH simulations of structure formation (e.g. Steinmetz & White 1997), often the complexity of such simulations makes it nearly impossible to clearly separate what is physical from what is numerical. Attempts have been made to try single out various numerical effects by running simple tests on rotating spheres of gas and dark matter and trying to extrapolate results to the case of the full cosmological simulations (Okamoto et al. 2003). However, these tests adopt quite idealised initial conditions that are barely related to the conditions of cosmic structures in a CDM model. Moreover, even with such idealised experiments, current resolution tests do not probe a large enough range of particle numbers or force resolution to demonstrate convergence. However, we wish to understand if we can trust the current state of the art galaxy formation simulations that end up with about  $10^5$  SPH and dark matter particle in single object at  $z = 0$  (e.g. Governato et al. 2004). We have studied numerical resolution effects that occur during the dissipative cooling of gas within isolated equilibrium dark matter halos. At our best resolution we use a million particles per halo and hundred parsec force softening. The halo models have structural properties and shapes that resemble as closely as possible those arising in CDM simulations. In this high resolution regime artificial heating of gas particles by dark matter particles (Steinmetz & White 1997) should be already under control ( $N > 10^4$  is required to mitigate those effects).

In our models we follow the formation of disks inside haloes on scales comparable to the Milky Way and M33 (respectively  $V_{circ} \sim 140$  and  $\sim 115$  km/s) and with different mass resolutions: LR ( $3 \cdot 10^4$ ), IR ( $9 \cdot 10^4$ ), HR ( $10^6, 5 \cdot 10^5$ ) particles in the dark matter and the gas phases respectively. Our initial conditions comprise in one case of a spherical CDM like halo (Kazantzidis 2004) built with structural parameters expected in the concordance  $\Lambda$ CDM model for the chosen mass scale, and an embedded hot gaseous halo in (approximate) hydrostatic equilibrium. Both components are spinning and have the same specific angular momentum distribution, which we take from results of cosmological simulations (Bullock et al. 2001). The second set of initial conditions we create by merging non-rotating gaseous plus dark matter halos on different orbits (see Moore et al. 2004). These produce equilibrium triaxial or axisymmetric prolate and oblate structures with spin parameters in the same range as found within halos from hierarchical simulations. In these paper we will show the results from runs using the first type of initial conditions. In our highest resolution runs we resolve the gas phase down to  $10^5 M_\odot$  or  $2 \cdot 10^{-5}$  % of  $M_{vir}$ . The dark matter halos have an NFW density distribution and spin parameter  $\lambda = J|E|^{\frac{1}{2}} / (GM^{\frac{5}{2}})$  from 0.045 to 0.1. The gas contributes in mass from 6% to 9% of the total mass of the system. We use the parallel Tree+SPH code GASOLINE (Wadsley et al (2004)) and a standard cooling function for a primordial gas of helium and (atomic) hydrogen.

## 2. Force resolution; disk scalelengths and morphologies

In this section we will discuss the results of the Milky Way-sized models, which have the highest baryon fraction (9%). We ran all simulations with a spline softening of  $h_1 = 0.5$  kpc and  $h_2 = 2$  kpc and focus now on the effects of changing force resolution. The smaller softening leads to the formation of a strong gaseous bar of length comparable to the size of the disk at that time,

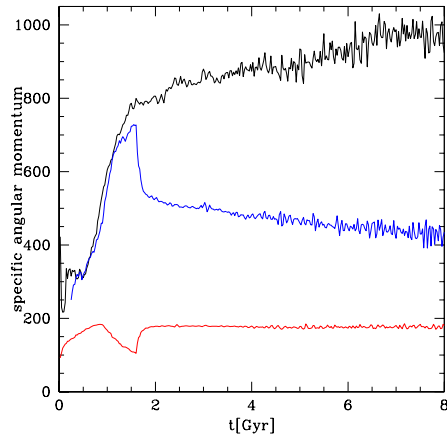


**Figure 1:** Face on views of the gas density within models having softening  $h_2$  (left) and  $h_1$  (right), IR model. The upper and lower pictures show a snapshot after 1 Gyrs and 6 Gyrs respectively within a frame of length 25 kpc on a side. The graph in the right panel shows the logarithmic surface density of the gas disk after 8 Gyr. Run HR, IR and LR are plotted in red, black and blue respectively. Dashed/solid lines: softening 2 kpc/0.5 kpc.

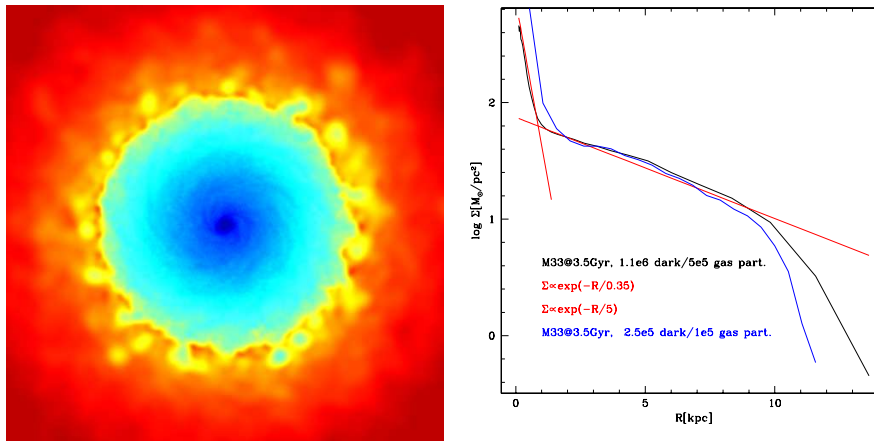
while the disk continues to grow from the inside out with continued gas accretion. Larger values of the softening, typical of that used within most cosmological simulations, suppress the bar. Since  $h_2$  is of order of the disk scale length one expects modes with wavelengths at such scales to be damped (with a spline kernel as the one we adopt softening of gravity disappears only at twice  $h_2$ ). In fact in the IR run with softening  $h_2$  a bar still forms but dissolves in less than 1 Gyr.

Assuming conservation of angular momentum and an exponential surface density profile for the cold disk material Mo, Mao & White (1998, MMW) calculated the disk scalelength to be  $R_d = \frac{1}{\sqrt{2}} \left( \frac{j_d}{m_d} \right) \lambda r_{200} f_c^{-0.5} f_R(\lambda, c, m_d, j_d)$ . The expected scale length for the Milky Way simulations should be  $R_d = 2.2$  kpc for  $\lambda = 0.045$  and by replacing  $r_{200}$  with the cooling radius (which is 110 kpc in HR model) in the simulations. For the HR models we find scalelengths of  $\sim 2$  or  $\sim 3$  kpc depending on whether the bar is absent or present (smaller scale lengths are found in LR and IR models), see Figure 1. The gaseous bar affects heavily the evolution of the baryonic surface density, and thus the disk scale length, by transporting angular momentum from the inner part to the outer part of the galaxy. This can be seen in Figure 2, where the evolution of the specific angular momentum of some disk gas particles which initially formed a ring around the bar, is plotted. Such transport of angular momentum of course has a duration comparable to the lifetime of the bar, which varies considerably depending on the softening as we noted, and is also affected by the adopted mass resolution (number of particles). The transition from a barred galaxy to a nonbarred one in the IR model is apparent in Figure 1 and 2.

An analytic estimate of the stability against bar formation is given by the  $\epsilon_d$  parameter (Efsthathiou, Lake & Negroponte 1983, Mayer & Wadsley 2004):  $\epsilon_d = V_{peak} / \sqrt{(GM_{disk}/R_d)}$ , where  $V_{peak}$  is the peak rotational velocity usually reached around  $2R_d$  and  $M_{disk}$  is the total mass of the disk. We measured  $\epsilon_d$  for one of our barred simulations at 0.75 Gyr - shortly before it went bar unstable - and got  $\epsilon_d = 0.60$ , which is clearly smaller than 0.94,, the value found to be required for



**Figure 2:** Influence of the bar to the evolution of angular momentum of gas disk particles. We followed a ring of particles which never reach the inner two kpc, hence they always stay outside the bar: IR model, in black: softening 0.5 kpc, in blue: softening 2 kpc, in red: angular momentum of the particles which were initially in the bar, softening 2 kpc. How much the angular momentum of such particles grows appears to be correlated with the formation of the bar: the bar dissolves for the big softening shortly before 2 Gyr.



**Figure 3:** The left panel shows a colour density map of the high resolution M33 gasdisk after 3.5 Gyr. The transient spiral patterns closely resemble Sc-Sd galaxies. The right panel shows the surface density profile with fitting curves of this model.

stability of gas dominated disks against bar formation (see Mayer & Wadsley 2004).

### 3. Initial baryon fraction and spin parameter

The baryon fraction plays an important role. Decreasing the initial baryon fraction to 6% and using  $\lambda = 0.1$  lowers the final amount of cold gas by 47% and completely changes the morphological evolution of the disk. Even with high force resolution (softening  $h = 250\text{pc}$ ) the disk remains stable and no bar develops, although we found a small nucleus in the centre and some very weak spiral arms.

This high resolution galaxy model provides an ideal testbed for the analytic model of Van den Bosch (2001) for disk structure. Assuming cuspy CDM halos and initial gaseous angular momentum profiles similar to the dark matter, he finds that it is impossible to form a pure exponential disk, in all cases a central luminosity spike results from central low angular momentum material. Indeed we are also unable to find a pure exponential disk and we find a steeper profile in the center in our simulations (Figure 3). However our M33 model only has a small nuclear gas spike and it is possible that with even higher resolution this material collapses to form a dense nuclear star cluster as observed within galaxies such as M33. It remains to be seen whether the mass distribution is comparable to that in the models by Van den Bosch (2001), which also included star formation but do not fully include disk self-gravity.

We resolve for the first time the mass better than  $10^5 M_\odot$ . At such resolution there is clumping of infalling gas visible at the edge of the disk; this is the first time that such clumpy gas accretion is witnessed in numerical simulations.

#### 4. Summary

We simulated the formation of a gaseous disk embedded in a dark matter halo at very high resolution. Bar formation is a very common process - particularly with high baryon fractions, low spin parameters, and needs high force resolution. Independent of the adopted temperature floor all the “Milky Way” disks become bar unstable as soon as we reached a force resolution of 0.5 kpc or  $\sim 0.25\%$  of  $r_{vir}$ . This picture changes in the M33 model with lower mass and baryon fraction: An exponential outer disk plus a small dense exponential nucleus are formed in this case.

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