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Cosmological particle-based simulations of galaxy formation; numerical loss of angular momentum and disk heating

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We discuss the role that numerical effects have in cosmological N-Body/SPH simulations of disk galaxy formation. We show that the resolution of current state-of-the-art calculations, about 10^5 SPH and dark matter particles within the virial radius of a Milky Way-sized halo at $z = 0$, is just enough to avoid artificial losses of angular momentum and dramatic numerical disk heating during the phase of disk assembly. Instead both effects will still be an issue at earlier epochs, when the progenitors of the final galaxies are resolved by significantly less than 10^5 particles. This must be at least partially responsible for why simulations show a ubiquitous low angular momentum spheroid that is too massive compared to that of typical disk galaxies.

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1. Introduction

A remarkable problem of current galaxy formation simulations in a LCDM Universe is their inability to produce a disk dominated galaxy. The latest numerical simulations can form disks with reasonable sizes ([1],[2],[3], [4]), but no simulation has managed to form a bulgeless galaxy with a realistic, kinematically cold thin stellar disk. A large fraction of the stellar mass of the simulated galaxies always comes in the form of a low angular momentum, kinematically hot component resembling observed stellar bulges. Traditionally loss of angular momentum of progenitor lumps through dynamical friction has been usually blamed as the cause of excessive angular momentum loss. Feedback from supernovae has been invoked to maintain the gas in a hot, diffuse phase and reduce the effect of dynamical friction. However the physics of feedback is poorly understood and thus its modeling is highly uncertain. But to what extent can we trust the results of the current simulations aside from the feedback issue? It is somehow worrisome that so far essentially only one numerical technique, SPH, has been used to model the hydrodynamics in cosmological simulations of disk galaxy formation. While comparisons with different approaches, for example with adaptive mesh codes, are mandatory, an obvious step to take is trying to understand the role of numerical effects in the current simulations ([5],[6]). A galaxy formation simulation is extremely complex. Just repeating the same simulation with different mass and/or force resolution to seek convergence can be a daunting task if it is not combined with simpler experiments aimed at testing individual aspects of one simulation.

2. Kinematically hot disks and numerical loss of angular momentum

Disk dominated galaxies should form in halos that suffered the last major merger several Gyr before the present epoch. However, simulations done during the past decade ([7]) typically used to study disk formation without first selecting objects with quiet merging histories. In addition to insufficient numerical resolution, this is certainly one reason why disks were found to be an order of magnitude too small compared to the observed ones. Recent simulations do take into account the merging history. For example, [2] selected a galaxy-sized halo with the last major merger occurring at $z = 2.5$ in a large box (using the concordance LCDM model) and carried out a “renormalized” run using increased resolution in a region of about 1 Mpc around such halo; at $z = 0$ there are $\sim 1 \times 10^5$ dark matter particles and $\sim 6 \times 10^5$ between gas and star particles within the virial radius of the selected system (the force resolution was 1 kpc). At $z = 0$ the galaxy has a disk of nearly 16 kpc in size, where the disk edge is defined to be at the radius where stars cease to be predominantly supported by rotaton. Nevertheless, Figure 4 of [2] highlights two problems. One is the presence of a massive spheroid, that produces a central peak in the rotation curve much more pronounced than that of the Milky Way or M31, the other one is the fact that v_{rot}/σ, namely the ratio between rotation and velocity dispersion of the disk stars, is everywhere a factor of 2-3 higher than that of a typical large disk galaxy ($v_{rot}/\sigma > 5$). As a result the galaxy resembles the Sombrero galaxy rather than an Sb galaxy like the Milky Way. While the spheroid is mostly made by old stars that were born in the progenitor lumps or during the last major merger, the disk forms inside out mostly from the smooth accretion of halo gas [8] that cools and gradually settles into centrifugal support. Therefore the formation of the disk component is to a large extent not hierarchical. Certainly there

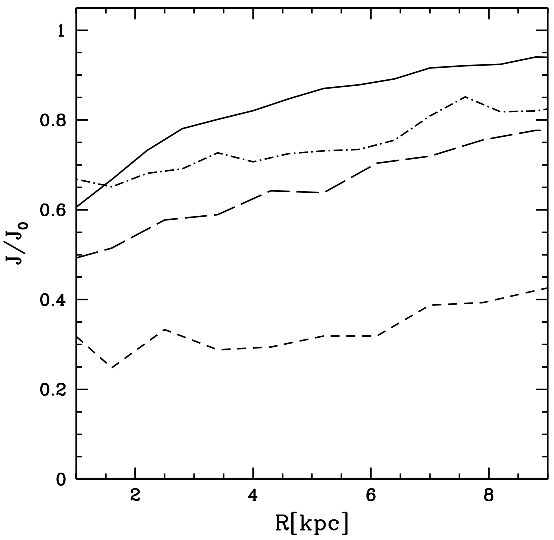

Figure 1: Angular momentum loss in an isolated disk galaxy model with structural parameters as our ΛCDM run at z = 0.6. This model was run for 6 Gyrs (equivalent to the present time). The y axis shows the fractional angular momentum loss for all the baryonic material in the disk as a function of radius. Continuous line:N$_{DM}$ = 100000, Nstar=200000, Ngas=5000 (same as in the cosmo run). Dotted short dashed: N$_{DM}$ and Nstar reduced by a factor of five. Long dashed: Nstars reduced by a factor of 25, the other components unchanged. Short dashed:N$_{DM}$= 4000, namely reduced by another factor of 5), the other components unchanged. At the lowest resolution the disk undergoes the catastrophic angular momentum loss reported in early simulations.

are several satellites orbiting in the main halo; these are partially disrupted by the tides of the primary, yet they never merge with the disk because dynamical friction times are too long, and the amount of stars they lose to the disk is a negligible fraction of its mass. Hence it is sensible to explore numerical effects during the disk assembly phase by setting up controlled experiments with no cosmological initial conditions. One example of this approach can be found in [9] (these proceedings), which presents simulations of disk formation from cooling of gas in an isolated spinning NFW halo. Another example is described in [2], where multi-component equilibrium disk models were used to estimate the angular momentum loss induced by numerical effects. One of such effects is collisions of massive halo particles with much lighter gas and star particles. This is just numerical two-body relaxation in a system with different particle species [10].

Two-body heating can artificially randomize and increase the kinetic energy of a (kinematically) cold rotating stellar disk [11]. It can also increase the thermal energy of the gas and affect the amount of cold gas, and thus stars, that ends up in the disk component. [12] showed that the second effect is under control when the number of halo particles is above $\sim$ 1000, hence it is negliglible in current simulations (except maybe in the earliest structures that form at high redshift). To test the first effect we built a multi-component galaxy model (with stellar disk, bulge and gaseous disk embedded in a NFW adiabatically contracted dark halo) having structural parameters that match

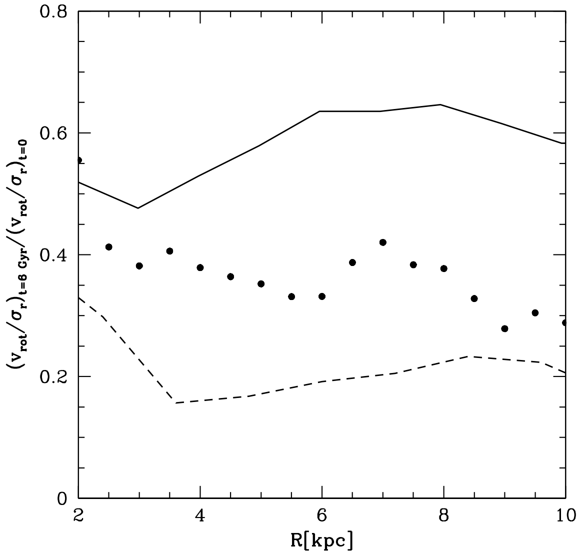

Figure 2: Radial profile of v_{rot}/σ after $\sim$ 6 Gyr of evolution for the hi-res (solid line) and the low-res (dashed line) isolated galaxy test (see text), normalized to the profile of v_{rot}/σ at $t = 0$. The filled dots show the same profile for the galaxy in the LCDM simulation at $z = 0$ normalized to that at $z = 0.6$.

very closely those of the galaxy in the LCDM simulation at $z = 0.6$ (at this time most of the disk mass is already in place). We evolved the model for about 6 Gyr, roughly the time span between $z = 0.6$ and $z = 0$ in a LCDM model. The number of particles of both gas, dark matter and star particles was varied by more than an order of magnitude. The relative angular momentum loss in the disk for the different runs is shown in Figure 1. The plot suggests that angular momentum loss mainly correlates with the number of dark matter particles employed, as expected if two-body heating between dark matter and star particles (most of the disk mass is stellar) is the main responsible. Residual losses due to artificial viscosity and other effects [6] may contribute to the slightly different outcomes seen in tests done at fixed number of dark matter particles. The bottom line is that at least 10^5 dark matter particles should be used to keep artificial losses close or below the 20% level (note that we do not actually demonstrate convergence here); an equivalent, more useful statement is that the mass ratio between dark matter and disk particles should be lower than 20:1. The LCDM simulation in [2] satisfies this requirement at $z \sim 0.6$.

However there is another side of artificial two-body heating, namely the increase in random kinetic energy; this will combine with the loss of angular momentum to lower the stellar v_{rot}/σ. In Figure 2 we compare the variation of v_{rot}/σ for the two test runs which differ the most in terms of resolution, and we also compare that with the variation v_{rot}/σ for the galaxy in the LCDM simulation. We can draw two conclusions from Figure 2; the first is that, not surprisigly, resolution effects on v_{rot}/σ are even more dramatic than on angular momentum alone, the second is that the decrease of v_{rot}/σ in the LCDM galaxy is larger than that occurring in the test done using comparable resolution. The latter discrepancy is more evident in the outer part of the disk; the biggest responsible for this is probably a large satellite, with mass roughly 1:10 of the disk mass, that violently plunges through the disk at $z \sim 0.1$. We note that, taken at face value, the curve for the high resolution test might be telling us that even with 10^5 particles there is still room for a $30-40\%$ numerical effect on v_{rot}/σ (since we have not demonstrated complete convergence yet); if that is the case it would make up for most of the variation of v_{rot}/σ seen in the LCDM galaxy. This is however the worst case scenario since bar formation and buckling of the bar is observed in the hi-res test, which certainly contributes to vertical heating.

3. Final remarks

The requirement on halo mass resolution to minimize two-body effects is not met in the early progenitors of our LCDM galaxy. The same is true for other requirements on the resolution of the SPH component ([9]). This certainly plays a role in the fact that central “old” stellar bulge tends to be too massive. While it is reasonable that mergers at high redshift certainly produce a kinematically hot stellar component, we argue that in the simulations the bulge is too massive because the angular momentum has been degraded by two-body heating accumulated over time across the merging tree ([13]). Seeking exact convergence for the angular momentum in a CDM model cannot be achieved by simply increasing the mass resolution because that would just shift the numerical loss towards earlier times in smaller scale progenitors of a given system that were not previously resolved – there will be always a step in the merger tree that will be modeled with too few particles. One could imagine that if enough resolution is achieved in the most massive progenitors the problem could be substantially solved. Alternatively, simulations with truncated power spectra are potentially a powerful tool to perform well-posed resolution studies since a limiting scale for structure formation is naturally introduced.

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