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Galaxy Simulations after the Angular Momentum Catastrophe

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Abstract. Current simulations have enough resolution to study in detail the evolution of galactic angular momentum by looking separately at the various stellar dynamical components. The comparison of this kind of simulation results with observations is non trivial given all the caveats for estimating angular momentum in the latter. Therefore, mock observations of high resolution zoom-in simulations are a necessary step for a more meaningful comparison with observations.

Keywords. galaxies: structure, galaxies: kinematics and dynamics, methods: numerical

The current state of zoom-in cosmological simulations

Analytical models of galaxy formation have a long history of reproducing observed galaxy properties (e.g. Dalcanton, Spergel & Summers 1997). Simulations, on the other side, have only recently reached enough realism. For almost two decades simulations produced galaxies with too small sizes (Navarro & Benz 1991), a problem known as "the angular momentum catastrophe". Solutions to the problem of catastrophic gas cooling and angular momentum loss in simulations have been proposed in the early 2000s, the most effective ones including: accurate force symmetrization in Smoothed Hydrodynamical simulations (e.g. Serna et al. 2003) increasing the resolution (e.g. Governato et al. 2004), and modeling in greater detail the impact of star formation on the gas (e.g. Okamoto et al. 2005, Stinson et al. 2006).

Nowadays, various groups using different kind of numerical codes that implement these solutions are able to simulate realistic galaxies in a cosmological context (e.g. Brook et al. (2011), Stinson et al. 2013, Roškar et al. 2014, Marinacci et al. 2014, Wang et al. 2015, Grand et al. 2017, Hopkins et al. 2018, Buck et al. 2018). In particular, Brook et al. 2011 were the first to show that supernova feedback is effective in removing low angular momentum (AM) gas from the inner galaxy, and that some of this gas is subsequently re-accreted at larger radii, thus driving the formation of extended disks.

High resolution zoom-in cosmological simulations are extremely demanding in terms of computational time, and for this reason most efforts are being spent on simulating one type of galaxy. The NIHAO project (Numerical Investigation of a Hundred Astrophysical Objects) of Wang et al. (2015) has adopted a different approach by providing cosmological zoom-in simulations of galaxies spanning nearly four orders of magnitude in mass, from dwarfs to MWs, with $\sim 10^6$ (dark matter) particles per halo at all masses. The NIHAO

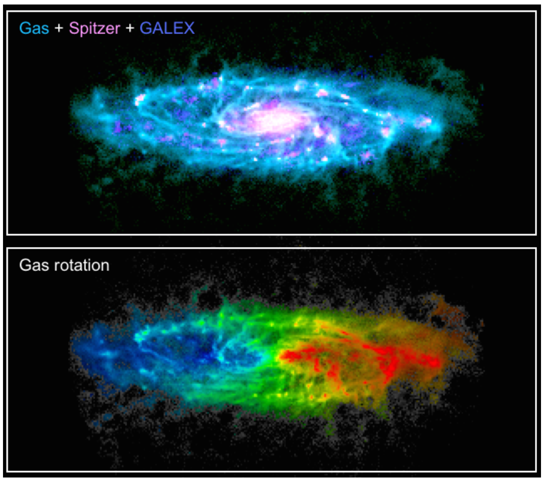

Figure 1. Composite image of the high resolution NIHAO galaxy g8.26e11.

project has been run with the N-body SPH code Gasoline2.1, last described by Wadsley et al. (2017). Star formation follows a Kennicutt-Schmidt relation. The implementation of metal line cooling is described in Shen et al. (2010). The star formation feedback includes two different effects: blastwave from SNe II (Stinson et al. 2006) and gas pre-heating by the massive stellar progenitors of SNe II ("early stellar feedback"; Stinson et al. 2013). These two types of feedback are crucial for the simulated galaxies to respect the multi-epoch abundance matching (e.g. Moster et al. 2013).

One NIHAO galaxy very similar to the Milky Way in terms of total stellar mass and disk structure, g8.26e11, is part of a project to re-simulate at higher resolution ($\sim 10^7$ particles/halo) some of the most massive galaxies in the original sample (Buck et al. 2018). This galaxy is shown in Fig. 1 as a composite image of HI gas, Spitzer MIPS 70μm and GALEX FUV on the top panel, while the bottom panel shows the HI column density map color coded by the HI velocity. The Spitzer and GALEX images have been obtained with the radiative transfer code GRASIL-3D (Domínguez-Tenreiro et al. 2014).

Stellar angular momentum in observations and simulations

The level of detail in recent simulations opened the possibility to study the evolution of galactic AM. It is important though to keep in mind that while galactic AM in simulations can be directly computed, observationally it can only be inferred from (biased) tracers of the true rotational velocities and mass distributions. Also, given that stellar orbits keep at least partial memory of the way in which galaxies assemble, it is particularly interesting to study separately the different dynamical components of simulated galaxies and compare the results with observations. For this purpose, we used a sub-sample of 25 NIHAO galaxies to first look for ways of identifying the dynamical stellar structures like (thin/thick) disks, bulges, spheroids, halos and inner disks in simulations (Obreja et al. 2018b). Our method of choice is Gaussian Mixture Models (GMM) on a 3D parameter space of normalized angular momentum projections and binding energy (Obreja et al. 2018a), extending previuos work by Doménech-Moral et al. (2012).

The stellar particles of the least massive galaxies in this 25 NIHAO galaxy sample can be meaningfully separated using GMM into a disk and a spheroid, while the more massive objects host up to five different components. In particular, the MW analogue g8.26e11 has a thin and a thick disk, a classical and a pseudo- bulge, and a stellar halo (Obreja et al. 2018a). Fig. 2 shows the stellar surface mass density profiles (left), and the various velocity measures (right) of g8.26e11 dynamical components. This galaxy is a good example of how biased the assumptions made in observations can sometimes be.

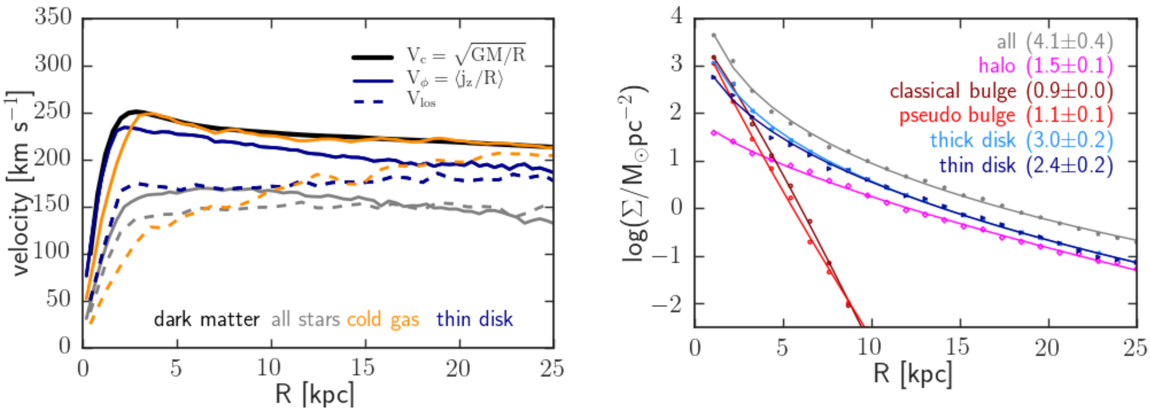

Figure 2. Edge-on line-of-sight velocities V_{los} (colored dashed) vs rotational velocities V_ϕ (colored solid) vs total circular velocity V_c (black thick solid), and edge-on stellar surface mass density profiles (with Sérsic indices in parenthesis) for the various dynamical components of g8.26e11.

One particularly important assumption in observations is that all the stars on circular orbits (the dynamical disks) are well described by a purely exponential surface mass density profile, extending all the way to the centre of the galaxy (the exponential disk). However, the thin stellar disk of g8.26e11 is better described by a Sérsic profile with $n = 2.4 \pm 0.2$. While this occurrence might seem unexpected, recent dynamical modeling of a large sample of galaxies shows that in some cases the stellar material on circular orbits can have $n > 1$ (Zhu et al. 2018). Regarding the velocity factor when computing the stellar AM, the left panel of Fig. 2 shows that the true rotational velocity V_ϕ of the (thin) stellar disk (solid navy) of g8.26e11 coincides with the edge-on line-of-sight (los) velocity V_{los} (dashed navy) only at very large radii, the former being larger than the latter by up to ~50 km/s at small radii. Large differences can be seen also between the cold (or HI) gas velocities V_ϕ and V_{los}. Moreover the stellar disk rotation is not the same as the HI rotation. Thus, the left panel of Fig. 2 shows the case of a galaxy for which it seems highly unlikely that an accurate AM value can be computed without a proper dynamical modeling of the complete stellar surface brightness and velocity maps.

While keeping in mind all the caveats previously discussed, it is still interesting to compare the simulations and observations in terms of AM. Therefore, Fig. 3 shows the (thin) disks of the 25 NIHAO galaxies in the M_*-J_* plane (Fall 1983). The NIHAO disks follow a very tight power law with an exponent close to the value of 5/3 predicted

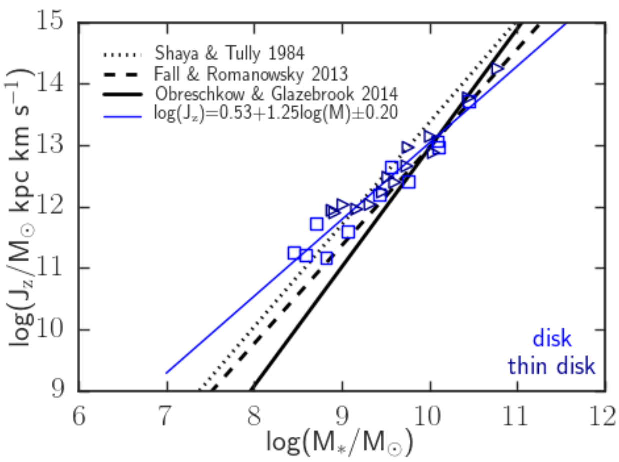

Figure 3. M_*-J_* relation for disks.

analytically by Shaya & Tully (1984). A very similar relation is followed by the disks disentangled from observations by Romanowsky & Fall (2012) and Fall & Romanowsky (2013), who assume exponential mass profiles and use ionized gas to trace the rotational velocity of the stellar disk components. On the other hand, the observational study of Obreschkow & Glazebrook (2014) who use the complete HI velocity field to trace the rotation of the stellar disks results in a larger exponent for the power law. These two observational studies use not only different velocity tracers, but also different methods to estimate the total disk AM, and therefore it is not totally unexpected they result in different M_*-J_* power laws. Given the assumptions behind the observational values and the analytical predictions, it is actually a wonder that all four data sets overlap to such a large degree.

Summary

Simulations are now reaching the resolution to study galaxy stellar structures such as (thin/thick) disks, bulges and stellar halos. Thus, in the context of galactic AM, zoom-in cosmological simulations can provide invaluable information for interpreting observations.

We use a sub-sample of NIHAO to show that: projection corrected LOS velocities are only approximating the rotation, HI is not a good tracer for stellar rotation, and not all dynamical disks are well represented by exponentials. In this light, simulation efforts have to be dedicated to produce mock observations, while accurate galactic AM measurements in observations require dynamical modeling of IFU data extended to large radii.

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