The Galaxy Disk in Cosmological Context
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Disk Sizes in a ΛCDM Universe

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Abstract. We introduce a model which uses semi-analytic techniques to trace formation and evolution of galaxy disks in their cosmological context. For the first time we model the growth of gas and stellar disks separately. In contrast to previous work we follow in detail the angular momentum accumulation history through the gas cooling, merging and star formation processes. Our model successfully reproduces the stellar mass–radius distribution and gas-to-stellar disk size ratio distribution observed locally. We also investigate the dependence of clustering on galaxy size and find qualitative agreement with observation. There is still some discrepancy at small scale for less massive galaxies, indicating that our treatment of satellite galaxies needs to be improved.

Keywords. Cosmology, Gas Disk, Stellar Disk, Correlation Function

1. Introduction

Understanding the origin of galaxy disks is an important aspect of the study of galaxy formation and evolution. Almost all observed star formation occurs either in galaxy disks or in material which came from galaxy disks (e.g. in starbursts). The size of disks is closely related to their gas surface density which in turn is critical in setting the star formation rate. Galaxy sizes also correlate with many other physical properties, stellar mass, luminosity, circular velocity, etc. These relations, as well as their evolution, pose strong constraints on galaxy formation models.

A long-standing problem for cosmological simulations has been to reproduce galaxies with the proper size distribution. The high efficiency of gas cooling at early times, causes the later assembly of disks to proceed by coalescence of cold gas clumps. As these clumps merge onto the main galaxy, they lose much of their initial angular momentum through dynamical friction. The resulting disks are then substantially smaller than observed and contain relatively little stellar masss. Much effort has been directed to solving this problem, most of it invoking some form of feedback to delay collapse (Sommer-Larsen *et al.* 1999, Thacker and Couchman 2001), or adopting an alternate initial fluctuation spectrum with reduced small-scale power (Sommer-Larsen *et al.* 2001). Some authors (Governato *et al.* 2004) claim the problem can be significantly reduced by improving the numerical resolution, but there is no consensus yet on the true solution.

In this work we implement a new treatment of disk formation within the Munich galaxy formation model used in De Lucia & Blaizot (2007), hereafter DLB07. Our model distinguishes between gas and stellar disks and treats their growth separately. We model the accumulation of mass and angular momentum in a gas disk by conserving the specific angular momentum of the cooling gas and the cold gas component of accreted satellite galaxies. When star formation occurs in the disk, we further assume that the cold gas which is converted into stars has the typical specific angular momentum of the current gas disk. We apply our model to the Millennium Simulation and we compare the stellar mass–size relation of disks and the distribution of the ratio of stellar and gas disk sizes to observation. The dependence of galaxy clustering on galaxy size is also investigated.

2. Galaxy Formation Models

2.1. *Simulation*

The *Millennium Simulation* is one of the largest simulations of cosmic structure evolution so far carried out. It follows $N = 2160^3$ particles within a comoving box of side-length 685 Mpc from redshift $z = 127$ to $z = 0$. Each particle has a mass of $8.6 * 10^8 M_\odot$. The simulation assumes the concordance ΛCDM cosmology with parameters consistent with a combined analysis of the 2dFGRS (Colless *et al.* 2001) and the first-year WMAP data (Spergel *et al.* 2003): $\Omega_\mathrm{m} = 0.25$, $\Omega_\mathrm{b} = 0.045$, $h = 0.73$, $\Omega_\Lambda = 0.75$, $n = 1$, and $\sigma_8 = 0.9$, where the Hubble constant is parameterized as $H_0 = 100h\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$. Galaxy formation models are then implemented on halo merger trees constructed from the stored output of this dark matter simulation. A detailed description can be found in Springel *et al.* (2005).

As the basis for our work, we use the galaxy formation model of DLB07, changing only the treatment of galaxy sizes. We refer the reader to the original papers (Croton *et al.* 2006 and DLB07) for a detailed description of this model.

2.2. *Disk size*

Here we introduce a new disk model by tracking the transfer of angular momentum between the hot gas, the cold gas and the stellar component.

We assume that the hot gas cools onto the centre with specific angular momentum which matches the current value for the dark matter halo. The change in angular momentum of the gas disk can then be expressed as

$$\delta J_g = \dot{M}_{cool} \frac{J_{DM}}{M_{DM}} \delta t \tag{2.1}$$

where J_g is the total angular momentum of the gas disk, $\dot{M}_{cool}$ is the cooling rate, δt is the corresponding time interval, and J_{DM} and M_{DM} are the total angular momentum and total mass of the dark matter halo, respectively.

In a minor merger, when the mass ratio of the two merging galaxies is larger than 3, we assume that any cold gas in the satellite galaxy is added to the disk of the central galaxy carrying a specific angular momentum equal to the current value for the dark matter halo. The stars are added to the bulge. The angular momentum change is thus

$$\delta J_g = M_{sat,gas} \frac{J_{DM}}{M_{DM}} \tag{2.2}$$

where $M_{sat,gas}$ is the cold gas mass of the satellite galaxy. The final angular momentum of the gas disk is a vector sum of its original angular momentum, the changes due to gas cooling and accretion from minor mergers, and the angular momentum lost to the stellar disk through star formation (as described below).

For the stellar disk, we assume the star formation rate to be proportional to gas density excess above some threshold. When cold gas is converted into stars we assume it carries the average specific angular momentum.

$$\delta J_* = \dot{M}_* \frac{J_g}{M_g} \delta t = -\delta J_g \tag{2.3}$$

where J_* is the total angular momentum of the stellar disk, M_g is the total mass of the gas disk, $\dot{M}_*$ is the star formation rate and δt is the corresponding time interval. As for the gas disk, the angular momentum of the stellar disk is the vector sum of the original angular momentum and the change due to star formation.

We assume the cold gas and stellar disks to be thin, rotationally supported systems with exponential surface density profiles. For gas disk we have

$$\Sigma(R_g) = \Sigma_{g0} exp(-R_g/R_{gd}) \tag{2.4}$$

and for stellar disk we have

$$\Sigma(R_*) = \Sigma_{*0} exp(-R_*/R_{*d}) \tag{2.5}$$

where R_{gd} and R_{*d} are the scale-lengths and Σ_{g0} and Σ_{*0} are the central surface densities for the gas and stellar disks, respectively. Assuming the circular velocity to be constant, the galaxy to reside in an isothermal dark matter halo, and the gravity of the galaxy to be negligible, the scale-lengths can be calculated as

$$R_{g(*)d} = \frac{J_{g(*)}/M_{g(*)}}{2V_{cir}} \tag{2.6}$$

where $M_{g(*)}$ is the total mass of gas (stellar) disk and V_{cir} is the circular velocity. Here we adopt the maximum velocity of the dark matter halo as V_{cir} (Croton *et al.* 2006).

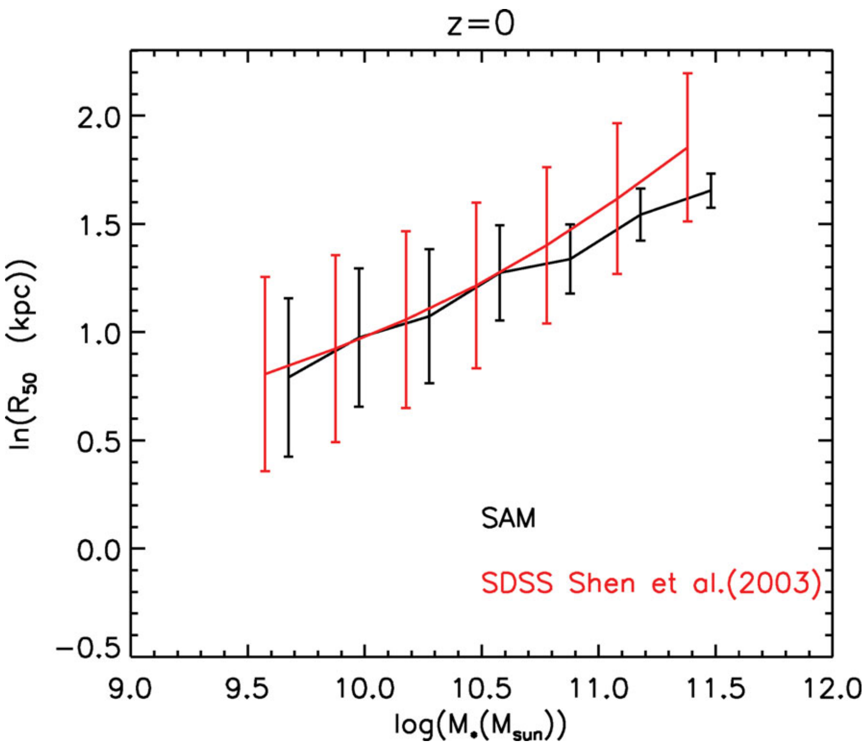

Figure 1. Stellar mass vs. half stellar mass radius relation for spiral galaxies at the local universe. The black curve and black error bars are from our model catalogue and the red curve and red error bars are from SDSS data by Shen *et al.* 2003.

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3. Results

In this section we show our predictions for the relation between stellar mass and size, for the distribution of gas-to-stellar disk size ratios, and for the dependence of galaxy clustering on galaxy size, and we compare them to observation.

3.1. *Galaxy Stellar Mass and Size*

Fig. 1 shows the relation between stellar mass and the half stellar mass radius for spiral galaxies which are selected from our model catalogue using the criteria $1.5 \leqslant \triangle M_I \leqslant 2.6$ ($\triangle M_I = M_{Ibulge} - M_{Itotal}$). Our model reproduces quite well the power-law dependence of galaxy radius on stellar mass. Both the median value and the scatter match well for galaxies less massive than $\sim 10^{10.5} M_{sun}$. For more massive galaxies, the median value is still close to the observed value, but our scatter is much smaller than observed.

3.2. *Gas-to-Stellar Size Ratio*

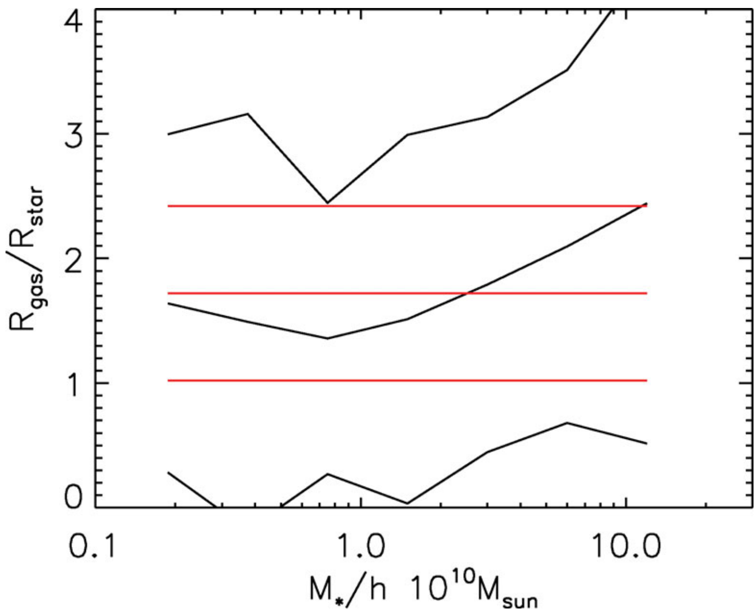

Figure 2. The gas disk to stellar disk size ratio for Sa/Sab galaxies. As in Fig. 1, the black curves represent results from our model. The middle curve is the mean and the outer curves show one standard deviation from the mean. Averaged over all Sa/Sab galaxies, the observational mean value is 1.72 (the middle red line) with scatter 0.70 (the other two red lines).

We select Sa/Sab galaxies from our model catalogue based on bulge-to-total ratio. More specifically, we select all galaxies satisfying $1 \leqslant \triangle M_I \leqslant 1.4$. The gas-to-stellar disk scale-length ratio is plotted as a function of stellar mass in Fig. 2. There is almost no dependence of the ratio on stellar mass. Averaging over all the galaxies, we get a mean value of 1.67 and a standard deviation of 1.44, quite consistent with observational results (the red lines in Fig. 2) reported in Noordermeer *et al.* (2005), based on the Westerbork HI survey of spiral and irregular galaxies (WHISP).

3.3. *Correlation Functions*

The dependence of clustering on galaxy size is shown in Fig. 3. We divide the galaxies into different mass bins and in each bin we further divide the galaxies into two populations

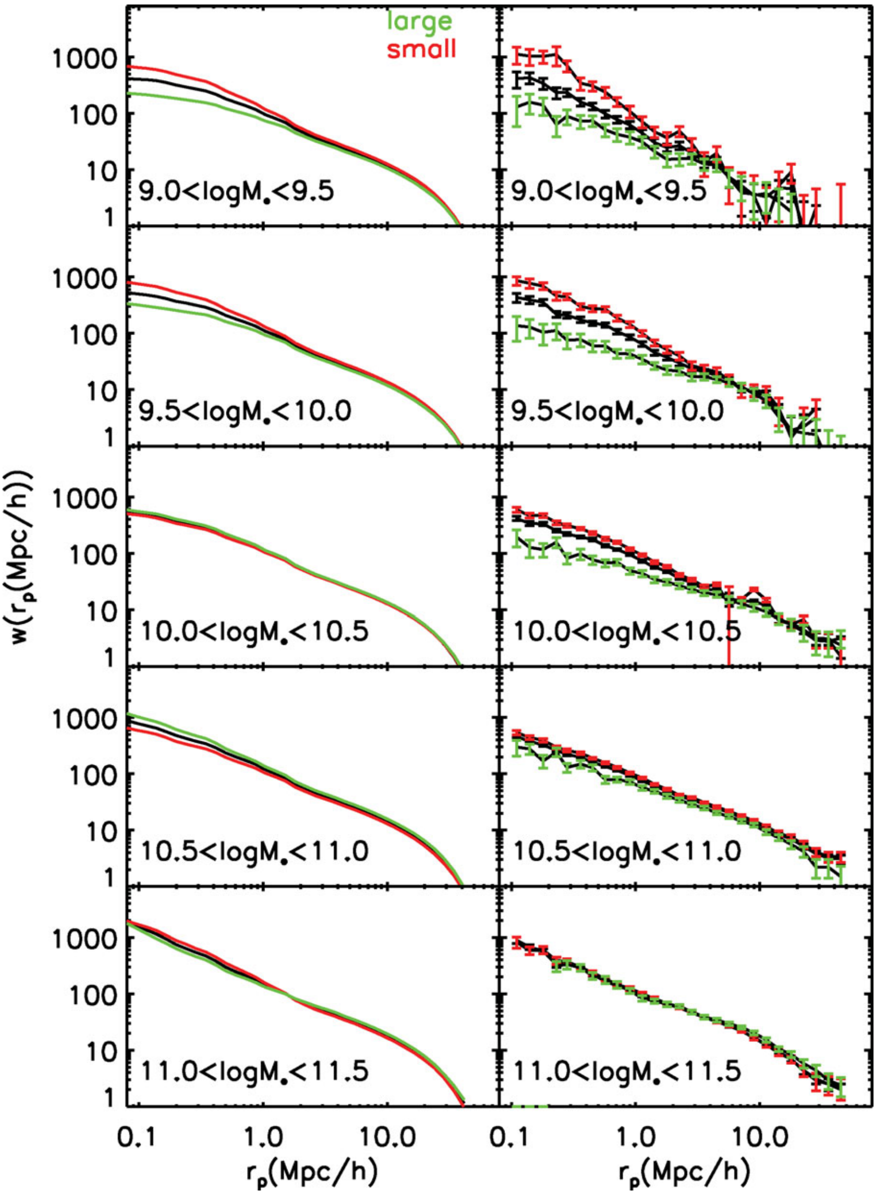

Figure 3. Projected two point correlation function as a function of stellar mass and galaxy size. The left column is for our model and the right column is for SDSS data. The galaxy stellar mass bin is indicated at the bottom left corner of each panel. The projected correlation functions are represented by black curves. In each mass bin the galaxies are further divided into large/low surface density (green) and small/high surface density (red) populations according to their half-mass radius/stellar surface mass density.

according to their sizes. On scales larger than a few Mpc, there is no dependence of clustering on size for any stellar mass. On smaller scales and for low-mass galaxies, the clustering of small galaxies is much stronger than of large ones. The size dependence becomes weaker with increasing stellar mass. For galaxies more massive than $\sim 10^{10} M_{sun}$, there is almost no dependence on galaxy size.

These differences reflect size differences between central and satellite galaxies of similar mass. For low-mass galaxies, centrals tend to be larger than satellites of similar mass. This difference is much less for more massive systems and probably reflects the facts that low-mass galaxies tend to survive much longer as satellites than massive systems. The latter merge much more quickly because of shorter dynamical friction times. The size dependence of our model galaxy is qualitatively consistent with the SDSS results taken from Li *et al.* (2006). Quantitatively, however, the dependence is stronger in the observational data and extends to more massive galaxies. A possible way to remove this discrepancy would be to include the tidal stripping of satellite galaxies in our model. This would reduce the sizes of long-lived satellites further.

4. Conclusion

We have modeled the growth of gas and stellar disks in galaxies separately using a semi-analytic approach which tracks the accumulation of their angular momentum. The differing angular momentum accumulation histories of galaxies and of dark matter halos make it possible for a galaxy to have higher or lower specific angular momentum than, and to be misaligned with, its surrounding halo. The gas and stellar disks can also be misaligned, allowing the modelling of galaxy warps.

We show that our model can reproduce many observed size-related relations including the stellar mass vs. size relation and the gas-to-stellar disk size ratio distribution. Both the mean values and the scatter are well reproduced, especially for galaxies less massive than $10^{10.5} M_{sun}$. For the dependence of clustering on galaxy size, we qualitatively reproduce observed trends, but some discrepancy remains on the small scale for less massive galaxies. Further improvement of our treatment of satellite galaxies, including tidal stripping, may help to clarify the reasons behind this.

References

Colless, M., Dalton, G., Maddox, S., & etc. 2001, *MNRAS*, 328, 1039

Croton, D. J., Springel, V., White, S. D. M., De Lucia, G., Frenk, C. S, Gao, L., Jenkins, A., Kauffmann, G., Navarro, J. F., & Yoshida, N. 2006, *MNRAS*, 365, 11

De Lucia, G. & Blaizot, J. 2007, *MNRAS*, 375, 2

Governato, F., Mayer, L., Wadsley, J., Gardner, J. P., Willman, B., Hayashi, E., Quinn, T., Stadel, J., & Lake, G *ApJ*, 607, 688

Li, C., Kauffmann, G., Jing, Y. P., White, S. D. M., Börner, G., & Cheng, F. Z. 2006, *MNRAS*, 368, 21

Noordermeer, E., van der Hulst, J. M., Sancisi, R., Swaters, R. A., & van Albada T. S. 2005, *A&A*, 442, 137

Shen, S., Mo, H. J., White, S. D. M., Blanton, M. R., Kauffmann, G., Voges, W., Brinkmann, J., & Csabai, I. 2003, *MNRAS*, 343, 978

Sommer-Larsen, J., Gelato, S., & Vedel, H. 1999, *ApJ*, 519, 501

Sommer-Larsen, J. & Dolgov, A. 2001, *ApJ*, 551, 608

Spergel, D. N., Verde, L., Peiris, H. V., & etc. 2003, *ApJS*, 148, 175

Springel, V., White, S. D. M., Jenkins, A., Frenk, C. S., & etc. 2005, *Nature*, 435, 629

Thacker, R. J. & Couchman, H. M. P. 2001, *ApJ*, 555, 17