THE FORMATION AND EVOLUTION OF DISK GALAXIES

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Abstract

We review some of our recent progress in modelling the formation of disk galaxies in the framework of hierarchical structure formation. Our model is not only consistent with the local observations, but also provides a good description of disk evolution out to redshift \( z \sim 1 \). We use this model to interpret recent observational results on Lyman-break galaxies (LBGs) at \( z \approx 3 \). Assuming that these galaxies are associated with the most massive halos and adopting an empirical law for their star formation rates, we find that many properties of the LBG population, including their correlations, sizes and kinematics can be accommodated in the model.

1 Overview of disk formation

In standard hierarchical models dissipationless dark matter aggregates into larger and larger clumps as gravitational instability amplifies weak initial density perturbations. Gas associated with such dark halos cools and condenses within them, eventually forming the galaxies we observe today. These two aspects of galaxy formation are currently understood at different levels. The mass function, density profiles and angular- momentum distribution of dark matter halos are well understood from numerical simulations and from analytical treatment; we take these as direct input in our modelling. On the other hand, the gas assembly and the related star formation and feedback processes are not understood in detail. For this uncertain process, we use an updated version of the scheme proposed by Fall & Efstathiou [3]. Briefly, after the initial protogalactic collapse the gas and dark matter are assumed to be uniformly mixed in a virialized object with density profile modelled by the NFW profile [8]. We assume that the gas component gradually settles into an exponential disk and that the gas conserves angular momentum during this process until it finally reaches rotational support.

This model reproduces the properties of local disk galaxies quite well, including the shapes of rotation curves, the size vs. circular velocity relation and, most importantly, the Tully-Fisher relation and its scatter, see [6].
Figure 1: Histograms of the ratio of disk scalelength to (maximum) circular velocity of galaxies. The solid line is for the local sample from [1], [2] and has 306 galaxies. The high-redshift sample is from [10], [11] and includes 16 galaxies.

2 Disk evolution out to redshift \( \sim 1 \)

The disk population is predicted to evolve. For example, the disk scalelength is expected to change according to

\[
R_d \propto \lambda V_c \frac{H_0}{H(z)},
\]

where \( R_d \) is the disk scale length, \( V_c \) is the circular velocity of the dark halo, and \( H(z) \) and \( H_0 \) are the Hubble constants at redshift \( z \) and 0, respectively. Since the Hubble constant increases with redshift, for given circular velocity the disks are predicted to be smaller at higher redshift. To single out the redshift dependence, we use the marginal distribution of \( R_d/V_c \). A comparison of this quantity between the local and high-redshift samples reveals a size evolution of disk galaxies (see Fig. 1). The amount is similar to the model prediction. More comparisons between theory and observations can be found in [5].

As is clear from Fig. 1, the high-\( z \) disk sample is still quite small, and the evolution out to \( z \sim 1 \) is quite modest. It is important to go to higher redshift in order to probe the predicted evolution.

3 Application to Lyman-break galaxies

The Lyman-break technique has been very successful in discovering many galaxies at \( z \sim 3 \). The properties of these galaxies are reviewed in detail by Steidel (these proceedings) and are therefore not repeated here. We assume that LBGs are the central galaxies of the most massive dark halos present at \( z \sim 3 \). The gas in the halo is arrested either by its spin, or by fragmentation as it becomes self-gravitating. We use the empirical results of [4], calibrated by local galaxies, to determine the star formation rates. We identify LBGs as galaxies with the highest SFR and normalize their number density to the observed value.
Figure 2: The left panel shows correlation length as a function of abundance. Both quantities have been scaled to the Einstein-de Sitter (EdS) cosmology by applying appropriate correction factors. Results are shown for four cosmogonies, as indicated in the panel. Observational data for LBGs to three different limiting magnitudes are taken from [9]. The right panel shows the circular velocity distribution for the halos which host LBGs.

The left panel of Fig. 2 shows the correlation length, \( r_0 \), as a function of abundances of LBGs, \( N \), for four different cosmogonies. The models are defined in [7]. Here, we only outline the two models for which some detailed results are summarized in the following. 1) \( \tau \)CDM: \( \Omega_0 = 1.0, \Lambda_0 = 0.0, h = 0.5, \Gamma = 0.2, \sigma_8 = 0.6 \) and 2) \( \Lambda \)CDM: \( \Omega_0 = 0.3, \Lambda_0 = 0.7, h = 0.7, \Gamma = 0.2, \sigma_8 = 1.0 \). The model parameters have their usual meanings (see [7]). As we can see from Fig.2, all four models reproduce the observed correlation strength well. The observed clustering alone does not provide strong constraints on cosmological models. To discriminate between cosmological models, information about the internal structures of LBGs is needed.

Fig. 2 (right panel) shows the distribution of circular velocity for the LBG host halos. In \( \Lambda \)CDM, these circular velocities are quite big, with a median of about 290 km s\(^{-1}\), corresponding to a total halo mass \( M_h \approx 1.0 \times 10^{12} h^{-1} M_\odot \). In this model, LBGs are indeed associated with massive dark halos. In contrast, the halo circular velocities in the \( \tau \)CDM model are much smaller. The median is now about 180 km s\(^{-1}\), corresponding to \( M_h \approx 1.5 \times 10^{11} h^{-1} M_\odot \). In this cosmogony, relatively few massive halos can form before \( z = 3 \), and one has to include lower mass systems in order to match the observed number density of LBGs.

Although our model predicts the circular velocities of LBG host halos to be quite big, the stellar velocity dispersions of the LBGs themselves are roughly a factor of 2 smaller (cf. the left panel of Fig.3). This is a result of a combination of projection effects with the fact that the observed stellar distribution samples only the very central regions of the halo potential well where disk rotation curve is still rising.

The right panel of Fig. 3 shows the predicted distribution of half-light radius, \( R_{\text{eff}} \), for the LBG population. The prediction closely matches the observed sizes for the \( \Lambda \)CDM model while the \( \tau \)CDM model seems to predict sizes that are somewhat too small compared with the observations.
Figure 3: The left panel shows the line-of-sight stellar velocity dispersion distribution of LBGs. Solid and dashed histograms are for $\Lambda$CDM and $\tau$CDM, respectively. The right panel shows the distribution of half-light radii, $R_{\text{eff}}$, for LBGs. The solid histogram gives the model prediction and the dashed histogram shows observational data.

4 Conclusions

In conclusion, the formation and evolution of galactic disks can be well understood in the general framework of structure formation. The model we are studying seems to provide an adequate description of local disk galaxies [6] and of disk evolution out to $z \sim 1$ [5]. The structure and clustering properties of Lyman break galaxies at $z \sim 3$ are also nicely explained on the hypothesis that they are the high-redshift equivalents of local bright disk galaxies [7].

References

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