Formation and evolution of disk galaxies within cold dark matter halos

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Abstract. We present results of extensive model calculations of disk galaxy evolution within an hierarchical inside-out formation scenario. We first compare properties of the dark halos identified in a cosmological N-body simulation with predictions of a seminumerical method based on an extended collapse model and find a good agreement. We then describe detailed modelling of the formation and evolution of disks within these growing halos and predictions for the main properties, correlations and evolutionary features of normal disk galaxies. The shortcomings of the scenario are discussed.

1. Introduction

The hierarchical cosmic structure formation picture based on the inflationary cold dark matter (CDM) provides a solid framework for models of galaxy formation and evolution. On the other hand, the unprecedented observations of galaxies at different redshifts make it possible to probe and constrain these models. Here we discuss some of the results obtained with a self-consistent scenario of disk galaxy formation and evolution within the context of the hierarchical picture (the extended collapse scenario).

2. Dark matter halos

Using the extended Press-Schechter approximation, we generate the mass aggregation histories (MAHs) of the dark matter (DM) halos. Collapse and virialization of these halos are then calculated assuming spherical symmetry and adiabatic invariance, using a method based on a generalization of the secondary infall model (Avila-Reese, Firmani, & Hernández 1998). These halos will mainly

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correspond to isolated systems. The diversity of MAHs results in diversity of density profiles which, in our model, mainly depend on the MAH. The density profile corresponding to the average MAH is well described by the Navarro et al. (1996) profile. In Avila-Reese et al. (1999) we have compared the outer density profiles, concentrations and structural relations of thousands of halos identified as isolated in a cosmological (ΛCDM) N-body simulation with those obtained with our seminumerical method. We found a good agreement between the model and simulation results.

We have found that \( \sim 13\% \) of the halos in the numerical simulation at \( z = 0 \) are contained within larger halos and \( \sim 17\% \) have significant companions within three virial radii. The remaining 70% of the halos are isolated objects. The slope \( \beta \) of the outer density profile \( (\rho \propto r^{-\beta}) \) and the halo concentration defined as \( c_{1/5} = r_h/r(M_h/5) \), where \( r_h \) and \( M_h \) are the virial radius and mass, depend on the halo environment. For a given \( M_h \), halos in clusters have typically steeper outer profiles and are more concentrated than the isolated halos (for the latter \( \beta \approx 2.9 \) in average and \( \beta \) between 2.5 and 3.8 for 68% of the halos). Contrary to naive expectations, halos in galaxy and group systems as well as the halos with significant companions, systematically have flatter and less concentrated density profiles than isolated halos. A tight correlation between \( M_h \) and the maximum circular velocity \( V_m \) is observed: \( M_h \propto V_m^n \), \( n \approx 3.2 \). This is roughly the slope of the infrared Tully-Fisher relations (TFR). Thus, it seems that there is no room for the mass dependence of the infrared \( M_h/L \) ratio.

3. Galaxy evolutionary models

We model the formation and evolution of baryon disks in centrifugal equilibrium within the growing CDM halos formed as described in §2. We assume that halos acquire angular momentum from large-scale torques with the spin parameter \( \lambda \) distributed log-normally and constant in time. The disks are built inside-out with the gas infall rate (no mergers) proportional to the cosmological mass aggregation rate and assuming detailed angular momentum conservation. The gravitational drag of the disk on the DM halo is calculated. The local SF is assumed to be induced by disk instabilities and regulated by energy balance within the disk turbulent ISM (no SF feedback and self-regulation at the level of the interhalo medium is allowed). We also calculate the secular formation of a bulge. This way, at each epoch and at each radius, the growing disk is characterized by the infall rate of fresh gas, the gas and stellar surface density profiles, the total rotation curve (including the DM component), the local SF rate, and the size of the inner region transformed into bulge component.

4. Highlights of the model results

Results on the structure and dynamics of our model disk galaxies were discussed in Firmani & Avila-Reese (2000); the luminosity properties and topics related to the disk Hubble sequence were treated in Avila-Reese & Firmani (2000), while some evolutionary aspects of the galaxies were presented in Firmani & Avila-Reese (1999). In the following, we highlight some of the results.
Local properties. The (stellar) surface density and brightness profiles are exponential, the sequence of high to low surface brightness (SB) being mainly determined by \( \lambda \). The gas profiles at \( z = 0 \) are also exponential although much lower in density and with a scale radius \( \sim 2 - 4 \) times larger than the stellar profiles. There is a negative radial gradient of the color index: stars in the outer regions of the disk form later than stars in the inner regions. We find that the local SF rate per unit area correlates with the gas surface density as \( \Sigma_{\text{SFR}}(r) \propto \Sigma^0_y(r) \) with \( n \approx 2 \) for most of the models and over a major portion of the disks. The shape of the rotation curves correlates with the SB \( (\lambda) \) and in most cases is approximately flat. The dark halo dominates in the rotation curve decomposition down to very central regions.

The infrared Tully-Fisher relations (TFR). The slope of the \( M_h - V_m \) relation of the CDM halos remains imprinted in the TFR and agrees with observations. This slope is almost independent of the assumed disk mass fraction \( f_d \) when the disk component in the rotation curve decomposition is gravitationally important \( (f_d > 0.03) \) for the \( \Lambda \)CDM model used here. The zero point of the model TFR is only slightly larger than the observed zero point. The rms scatter in our TFR slightly decreases with mass; from \( V_m = 70 \) to \( 300 \) km/s the scatter is between 0.38 and 0.31 mag. We have found that a major contribution to this scatter is from the scatter in the DM halo structures due to the dispersion of the MAHs; a minor contribution to the scatter is due to the dispersion of \( \lambda \). The TFR for high and low SB models is approximately the same. The slope of the correlation among the residuals of the TF and luminosity-radius relations is small and non-monotonic, although the shape of the rotation curves of our models correlates with the SB. For a given total (star+gas) disk mass, the \( V_m \) decreases with decreasing SB. However, owing to the dependence of the SF efficiency on the disk surface density, the stellar mass \( M_s \) (luminosity) also decreases. This combined influence of the SB \( (\lambda) \) on \( V_m \) and \( M_s \) puts models of different SB on the same \( M_s - V_m \) relation. As a result, high and low SB models follow similar TFRs.

The Hubble sequence. The main properties of the high and low SB disk galaxies and their correlations are determined by the combination of three fundamental physical factors and their dispersions: the halo virial mass, the MAH and the angular momentum given through \( \lambda \). The MAH determines mainly the halo structure, the integral color index, and the gas fraction \( f_g \) while \( \lambda \) determines mainly the disk SB, the bulge-to-disk (b/d) ratio and the shape of the rotation curve. Our models show that the redder and more concentrated (higher SB) is the disk, the smaller is \( f_g \) and the larger is the b/d ratio (disk Hubble sequence). The values of all these magnitudes are in good agreement with observations.

Evolutionary features. In the inside-out hierarchical disk formation scenario galaxies undergo not only luminosity but also structural (size, SB, b/d ratio) evolution. For an Einstein-de Sitter universe we find that the scale radius for normal disk galaxies decreases roughly as \( (1 + z)^{-0.5} \) up to \( z \approx 1.5 \), while the central \( B \)-band SB from \( z = 0 \) to \( z = 1 \) increases by \( \approx 1.2 \) mag.

The SF history in the models is driven both by the MAH and the disk gas surface density. For the average MAH and \( \lambda = 0.05 \), the SF rate reaches a maximum at \( z \approx 1.5 - 2.5 \) which is a factor of 2.5-4.0 higher than the rate at \( z = 0 \). In the same way, \( L_B \) increases towards the past by factors slightly
smaller than the SF rate. The less massive galaxies present a slightly more active luminosity evolution than the massive galaxies. The model galaxies are somewhat bluer in the past; from $z = 0$ to $z = 1$ the $B-V$ decreases on average 0.25-0.30 magnitudes. The total mass-to-$L_B$ ratio also decreases towards higher redshifts: from $z = 0$ to $z = 1$ it decreases on average by a factor $\sim 3.3$, i.e. a galaxy at $z = 1$ is more luminous in the $B$-band and less massive than at $z = 0$. Again, this is a result related to the hierarchical MAHs of the protogalaxies.

Owing to the mass (size) evolution, for a fixed $V_m$, the $H-$band luminosity is a factor $\approx 2.2$ less at $z = 1$ than at $z = 0$; however, owing to the luminosity evolution, $L_B$ is a factor $\approx 2.1$ larger. Therefore, while the zero-point of the $H-$band TFR increases towards the past, in the case of the $B-$band TFR, compensation due to the $L_B$ evolution results in the zero-point remaining approximately constant with time. The slopes in both cases also remain constant.

5. Potential difficulties of the hierarchical scenario

Although several main properties, correlations, and evolutionary features of normal disk galaxies have been successfully predicted by our models, it is important to remark on their problems. We find the following potential conflicts with the observations: 1) the size and SB evolution of the disks is too pronounced, 2) the radial color index gradients are too steep and the $f_g$ is slightly over-abundant, 3) the DM component dominates in the rotation curve decompositions almost down to the center and the halos are too cuspy.

Regarding item 1), if selection effects in the deep field are not so significant as Simard et al. (1999) have claimed, then probably it is not so serious. In fact, some physical ingredients not considered in our models (e.g., merging, angular momentum transfer, and non-stationary SF) all work in the direction to improve models regarding problems 1) and 2). The problem 3) can probably be solved if the inner density profile of the CDM halos can be shallower than predicted (several solutions such as self-interacting CDM, warm DM, non-Gaussian fluctuations, have been proposed). Nevertheless, it is possible that all these problems together with those of the dearth of satellites and the high frequency of disk disruptive mergers, are in general pointing out to serious problems for the Gaussian CDM-based hierarchical picture of structure formation. More observational tests regarding the problems mentioned above and more theoretical effort in modeling galaxy formation and evolution are urgently required.

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