Dark Halos and Galaxy Evolution

Claudio Firmani and Vladimir Avila-Reese

Instituto de Astronomía-UNAM, A.P. 70-264, 04510 México D.F., and Dept. of Astronomy-NMSU, P.O. Box 30001, Las Cruces, NM 88003-8001

Abstract. We study the evolution of disk galaxies within the frame of the cold dark matter (CDM) cosmologies. The hydrodynamics of a centrifugally supported gaseous disk and the growth of a stellar disk is calculated in detail taking into account the energy balance of the ISM and the gravitational instabilities that concern gas and stars. The halo density profile is derived from the primordial cosmological conditions and its gravitational contraction produced by the disk is included. Several features of the spiral galaxies at different redshifts are predicted, and the main factors which influence on these features are found. A strong evidence is provided that the Tully-Fisher (TF) relation is an imprint of the primordial cosmological conditions.

1. Introduction

Individual galaxies provide useful information on the physical properties of dark matter (DM). However, it is necessary first to clarify the link between the luminous matter of the galaxies and their DM halos. In the general problem of how galaxies do form and evolve in a cosmological frame little progress has been done regarding the internal physics of galaxies. We remark three categories of theoretical approaches to the problem of galaxy formation and evolution. 1) The analytical models (Mo, Mao & White 1998; see also Dalcanton, Spergel, & Summer 1997). At a given time an

1 Email: firmani@astroscu.unam.mx
2 Email: avila@astroscu.unam.mx
exponential thin disk with a specific angular momentum is introduced in a DM halo taking into account the gravitational contraction produced by the disk on the halo. The halo properties are taken from the results of N-body simulations. This approach is the most economical and is particularly useful and elegant to study the properties of galaxy populations at different redshifts, as well as some global properties of disk galaxies as the baryon fraction involved in the disk and its angular momentum. However with this approach it was not possible to follow the individual evolution of galaxies. 2) The semi-analytical models (Kauffmann, White & Guiderdoni 1993; Cole et al 1994; Somerville & Primack 1998, and more references therein). In this approach the metabolism of a galaxy is basically identified in the disk-halo feedback. The luminous galaxy is modeled through recipes characterized by free parameters. This method allows to predict several global properties for a given galaxy as well as for a population of galaxies on the basis of their merging histories, but although simplified galaxy structural properties may be introduced, it does not allow to predict the internal properties of galaxies. 3) The numerical simulations (e.g., Yepes 1997, and the references therein). This method is very predictive to identify halo properties and is very promising at future, but at galactic scales technical difficulties related to the resolution and the processes that involve gas and stars make the results of this method currently the less predictive. Because of the reasons listed before we address the problem of galaxy evolution in a cosmological frame, starting with a paradigm which takes into account the internal physics of a galaxy.

2. The method

The kernel of this work is a semi-numerical approach where several internal processes of the disk, not considered in the other methods mentioned before, are taken into account. We start modeling the physics of a galactic disk where the hydrodynamics of the gas and the stars is taken into account with axial symmetry. A secular bulge formation is introduced applying a local gravitational stability criterion to the stellar disk. The star formation (SF) is induced in the disk by gravitational instabilities and it is self-regulated by an energetic balance in the ISM where the main energy source is due to SNs; simple stellar population synthesis models are considered (Firmani & Tutukov 1994; Firmani, Hernández & Gallagher 1996). The galactic evolutionary models are inserted in a cosmological background: the structure and evolution of the DM halos which surround the disks and the mass accretion rates over them are calculated from initial conditions defined by the cosmological model, which is specified by the mass fractions of the DM species (cold \( \Omega_{CDM} \), hot \( \Omega_{\nu} \)), the vacuum energy
Figure 1. The MAHs for a $5 \times 10^{11} M_\odot$ halo at $z=0$ ($\Lambda CDM$) scaled to this mass. The average is given by the thick line.

($\Omega_\Lambda$), and the baryon matter ($\Omega_b$), and by the value of the Hubble constant ($h = H_0/100 \text{Kms}^{-1} \text{Mpc}^{-1}$). We have taken as the representative models the $SCDM$ ($\Omega_{CDM} = 0.96$, $h = 0.5$), the $\Lambda CDM$ ($\Omega_{CDM} = 0.327$, $\Omega_\Lambda = 0.65$, $h = 0.65$), the $OCDM$ ($\Omega_{CDM} = 0.327$, $h = 0.65$), and the $H+CDM$ ($\Omega_{CDM} = 0.94$, $\Omega_\nu = 0.2$, $\Omega_b = 0.06$, $h = 0.5$). The value of $\Omega_b$ was taken equal to $0.01h^2$ where it is not specified. The primordial density fluctuation field is characterized by a gaussian statistical distribution with a power spectrum taken from Sugiyama (1996) and normalized to the COBE data. With a method based on the conditional probability (Bower 1991, Lacey & Cole 1993) we follow the merging and mass aggregation history (MAH) of a given halo in a linear regime. We are interested in haloes that have not suffered during their entire evolution a major merger. Thus, we exclude from our statistics the evolutionary tracks of those haloes that in some time have collided with another halo with a mass greater than half of its mass at that time (this reduce our sample of halo evolutionary tracks roughly by less than 20%). Assuming spherical symmetry and using a statistical approach to follow the shell-by-shell non-linear evolution of density fluctuations, we calculate the halo density profile evolution (Avila-Reese, Firmani & Hernández 1998). The non radial component of the kinetic energy is calibrated on the base of N-body simulations. The angular momentum is calculated assuming a specific value of the spin parameter $\lambda$, in agreement with the Zeldovich approximation. We have assumed an average value of $\lambda = 0.05$ with a lognormal distribution where the $1 - \sigma$ distribution
Figure 2. Rotation curve decompositions. The DM halo contribution \textit{with} and \textit{without} the gravitational contraction due to the disk is shown. Panel (b) is for a DM halo with a near constant density core.

is given at $\lambda = 0.03$ and $\lambda = 0.08$. Once a mass shell is incorporated into the halo, its baryon fraction falls onto the disk assuming that the disk-halo feedback is negligible (we consider that the SN energy feedback is localized into the disk in agreement with the observational evidence). The gas shell is distributed across the disk assuming rigid rotation of the shell and detailed angular momentum conservation during the gas collapse. The disk mass growth produces a halo gravitational contraction that is calculated using an adiabatic invariant technique.

3. Results

The MAHs for one halo of $5 \times 10^{11} M_{\odot}$ at $z = 0$ (\Lambda CDM) are presented in fig. 1. We see here a wide range of MAHs which after virialization produce a wide range of density profiles. The average MAH is shown by the central thick line. This MAH produces the density profile obtained in N-body simulations by Navarro, Frenk and White (1997). However, our method gives in a natural way the statistical deviations from the average MAH, which lead to a rich variety of halo profiles (Avila-Reese et al 1998). The rotation curves obtained for the average MAHs, $\lambda = 0.05$, and for the masses $5 \times 10^{10}$, $5 \times 10^{11}$ and $5 \times 10^{12} M_{\odot}$ are approximately flat. This explains the cosmological nature of the conspiracy between baryon and dark matter in the flat profile of the rotation curves. The decomposition of the rotation curve for the model with $5 \times 10^{11} M_{\odot}$ (\Lambda CDM) is shown in fig. 2a, where the halo gravitational contraction due to the disk is shown comparing the halo rotation curve component \textit{with} and \textit{without} this contraction. We note
Figure 3. The predicted TF relation for several cosmologies compared with the observational data in the infrared. For the references see Avila-Reese et al 1998

here a serious problem already pointed out in Flores & Primack (1994), Moore (1994), and Burkert (1995): the gravitational contribution of the halo is dominant until the center. Even if the uncertainty on the observational attempts to decompose the rotation curve is large, we agree with Burkert’s opinion that some physical process is misunderstood here. Recent numerical results obtained by Kravtsov et al. (1998) might be showing that the problem is not too serious, and, comparing with our results, suggest that the merging process and the slope of the power spectrum at the scale in consideration are the responsible of giving rise to shallow cores in the DM halos. If we assume that the central density halo profile before the gravitational contraction due to the disk agrees with the profiles observed in dwarf and low surface brightness galaxies, then the final rotation curve decomposition it looks like as it is shown in fig. 2b.

The very simple mechanism we assume to distribute the gas on the disk, leads to a surface brightness distribution reasonably close to an exponential profile. Observations show systematic blue radial color gradients in spiral galaxies. Our models show a similar trend, although some excessive gradient appears compared to the observations. This problem may arise from the simple population synthesis technique that works in our code or because a more complex process drives the gas infall onto the disk. The final global properties of our models follow the same trends of observed galaxies across the Hubble sequence: the redder and higher the surface brightness are, the smaller is the gas fraction, and the larger is the bulge-to-disk ratio. The three key factors that determine the final properties of our models are the mass, the MAH and $\lambda$.

A main result of our work is the prediction of the TF relation starting
The maximum rotation velocity vs. $(1+z)$ for different cosmologies. Figure 4. The maximum rotation velocity vs. $(1+z)$ for different cosmologies.

from the primordial conditions of the universe. The density fluctuation power spectrum establishes the degree of the halo concentration for each scale, and this leads to a relation between the rotation velocity and the mass. Fig. 3 shows the TF relation predicted by the different cosmologies, and the observational data obtained by different authors in the infrared. The $SCDM$ model predicts rotation velocities that exceed by a factor 1.4 the observations. This is due to the high power level of the density fluctuations on galactic scale predicted by the $SCDM$ cosmology. A similar result has been obtained on larger scales by galaxy counts. The $ΛCDM$, $OCDM$ and $H^+CDM$ cosmologies predict TF relations very close in slope and zero point with the observations. We have explored the robustness of this result with respect to the baryon fraction and the infall dissipative processes that retain the gas in the halo. In both cases we find a surprising final robustness of our results, mainly due to the gravitational contraction “conspiracy” of the DM halo. Concerning the scatter around the TF relation, we have combined the fluctuations due to the statistical nature of the MAHs and $λ$ (considering the range of flat rotation curves), and we have obtained for $ΛCDM$, $OCDM$ and $H+CDM$ an average scatter of roughly 0.4 mag that agrees reasonably well with observations. For the $SCDM$ we predict an average scatter of 0.6 mag which definitively exceeds the observed value. We conclude that the TF relation represents an imprint of the primordial cosmological conditions on the galactic scales (see also Navarro et al. 1997).

The semi-numerical approach allows us to follow the evolution of an individual galaxy, then we are able to predict how a galaxy appears at different redshifts. Fig. 4 shows the behavior of $V_{max}$ vs. $z$. Here we see the difficulty of $H+CDM$ to produce galaxies with high rotation velocity in the redshift range proper of the damped $Lyα$ absorbers (e.g., Klypin et al. 1995). In fig. 5 we show the evolution of the TF zero point in the H and B
bands, together with a B band upper limit derived by Vogt et al (1997) (the slope is almost constant). While in the H-band the zero-point decreases with $z$, in the B-band the zero-point remains almost constant because of the increase of the B-band luminosity toward the past (Firmani & Avila-Reese 1998). Finally fig. 6 displays the disk scale radius vs. $(1+z)$. An inside-out evolution is evident. It is important to remark that our evolutionary tracks concern basically isolated galaxies, where the environment may supply any amount of gas to a galaxy according to its gravitational field. Our results are not representative of the average conditions of the universe neither of more complex situations as the case of galaxies in clusters. More work is planned in the future on this direction.

4. Conclusions

1) The semi-numerical models presented in this work support the viability of an inside-out disk galaxy formation scenario, where the rate of gas accretion on the disk is dictated mainly by the cosmological (hierarchical) mass aggregation rate. 2) The TF relation is predicted as a product of the cosmological initial conditions. The gravitational pull of the luminous matter on the dark halo makes this relation robust with respect to intermediate processes (cooling, feedback). 3) Concerning the predictive abilities of different cosmologies with respect to galaxy formation and evolution: i) $\Lambda CDM$ and $O CDM$ cosmologies are able to predict many of the galaxy features up to intermediate redshift. ii) $SCDM$ is ruled out because is unable to predict the TF relation. iii) $H+CDM$ is marginal because predicts a too late galaxy formation.
Figure 6. The scale radius vs. (1+z) and a lower limit stablished by the observations.

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