Constraints on Galaxy Formation from the Tully-Fisher Relation

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Abstract. New models for the formation of disk galaxies are presented. I discuss the constraints on galaxy formation that follow from fitting the model to the near-infrared Tully-Fisher (TF) relation, with an emphasis on reproducing the small amount of scatter observed. Once the parameters that describe the supernova feedback are tuned to fit the slope of the observed TF relation, the model reproduces the correct amount of TF scatter, and yields gas mass fractions, mass-to-light ratios, and characteristic accelerations that are all in excellent agreement with observations.

1. Introduction

Understanding the formation of galaxies is intimately related to understanding the origin of the fundamental scaling relations. In particular, any successful theory for the formation of disk galaxies should be able to explain the slope, zero-point and small amount of scatter of the Tully-Fisher relation (TFR). The empirical TFR which most directly reflects the mass in stars and the total dynamical mass of the halo is the $K$-band TFR of Verheijen (1997), which uses the flat part of the rotation curve as velocity measure, and we use this relation to constrain our models.

2. Modeling the Formation of Disk Galaxies

We assume disks to form by the settling of baryonic matter in virialized dark halos described by the NFW density profile (Navarro, Frenk & White 1997). It is assumed that baryons conserve their angular momentum, thus settling into a disk (cf. Mo, Mao & White 1998). Adiabatic contraction of the dark halo is taken into account, as well as a recipe for bulge formation based on a self-regulating mechanism that ensures disks to be stable (van den Bosch 1998). Once the density distribution of the baryonic material is known, we compute the fraction of baryons converted into stars. Only gas with densities above the critical density given by Toomre’s stability criterion is considered eligible for star formation (cf. Kennicutt 1989). A simple recipe for supernovae feedback is included, which describes what fraction of the baryonic mass is prevented from becoming part of the disk/bulge system. The slope and scatter of the TFR depend strongly on the luminosity and velocity measures used. Therefore, it is essential that one extracts the same measures from the models as the ones in the TFR used to constrain those models. We improve upon previous studies by
Figure 1. TFRs for three models (open circles) compared to the empirical K-band TFR of Verheijen (1997, solid line). See the text for details.

carefully doing so. Details of the models can be found in van den Bosch (1999) and van den Bosch & Dalcanton (1999).

3. Results

Within the framework of dark matter, simple dynamics predict a TFR of the form $L \propto V_{\text{rot}}^\gamma$, with $\gamma = 3$. The empirical K-band TFR, however, has $\gamma \approx 4.2$. If we ignore feedback and the star formation threshold density, such that all the available baryons are transformed into a stable disk/bulge system, our models indeed yield a TFR with $\gamma = 3$, but with a large amount of scatter (Figure 1, model L0). This scatter owes to the spread in the angular momenta, J, of proto-galaxies: halos with lower J yield more compact disks and, because of the adiabatic contraction, more concentrated halos. Consequently, less rapidly spinning proto-galaxies result in disks with higher rotation velocities.

Taking the stability related star formation threshold densities into account increases $\gamma$ from 3.0 to 3.6 (Figure 1, model L1). In addition, the scatter is strongly reduced. This owes to the fact that more compact disks have higher disk mass fractions that are eligible for star formation, resulting in brighter disks. The spread in J therefore induces a spread along the TFR, rather than perpendicular to it.

Additional physics are required to further steepen the TFR to its observed slope of $\gamma = 4.2$. In van den Bosch (1999) we argue that feedback is the only feasible mechanism to achieve this. We have tuned the model parameters that control the feedback from supernovae to tilt the TFR to its observed slope. The resulting model (L5) predicts an amount of scatter that is in excellent agreement with observations (see panel on the right in Figure 1).

In order to assess the robustness of the resulting model, we now compare model L5 to other independent observations. In Figure 2 we plot the gas mass fractions, $M_{\text{HI}}/L_B$, as function of both absolute magnitude and central surface brightness. The models are in excellent agreement with the data. This success owes mainly to the star formation recipe used, which yields lower gas mass
fractions in more compact disks, as observed. The panels on the right in Figure 2 plot the characteristic mass-to-light ratio \( \Upsilon_0 \) (see van den Bosch & Dalcanton 1999 for details) as function of the central surface brightness. Once again, the model is in good agreement with the data, nicely reproducing the observed \( \Upsilon_0 - \Sigma_0 \) “conspiracy” (cf. McGaugh & de Blok 1998).

McGaugh (1998) has shown that mass discrepancies in disk galaxies set in at a characteristic acceleration of \( \sim 10^{-10} \text{ m s}^{-2} \). In Figure 3 we plot the enclosed mass-to-light ratio of 40 randomly chosen galaxies from model L5 (each sampled at 15 different radii) as function of radius, orbital frequency, and local acceleration. As observed, the model galaxies reveal a narrow correlation between mass-to-light ratio and acceleration. This is a remarkable success for the dark matter model; there is no obvious reason why disks in dark halos would reveal a characteristic acceleration, unlike in the case of modified Newtonian dynamics, where it is integral to the theory.

4. Conclusions

We have shown that simple models for the formation of disk galaxies in a dark matter scenario can explain a wide variety of observations. After tuning the feedback parameters to fit the slope of the empirical \( K \)-band TFR, the model
Figure 3. The enclosed mass-to-light ratio $M_{\text{tot}}/M_{\text{lum}}$ as function of radius $R$ (left), orbital frequency $\omega$ (middle) and local acceleration $\alpha$ (right) for galaxies of model L5. The scatter in $M_{\text{tot}}/M_{\text{lum}}$ is minimized when plotted versus $\alpha$, indicative of a characteristic acceleration, and in good agreement with observations (see McGaugh 1998).

Predicts gas mass fractions, characteristic accelerations, an $\Upsilon_0 - \Sigma_0$ “conspiracy”, and global mass-to-light ratios that are all in excellent agreement with observations, without additional tweaking of the parameters. This strongly contrasts with the picture drawn by McGaugh (1999). Although the results presented here may appear a baby step (cf. McGaugh 1999) to some advocates of modified Newtonian dynamics, they can be considered a giant leap for those who believe in dark matter.

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