Disk Galaxies as Cosmological Benchmarks: 
Cold Dark Matter versus Modified Newtonian Dynamics

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Abstract. We discuss a comparison of models for the formation of disk galaxies both in a Universe dominated by cold dark matter (CDM) and one in which the force law is given by modified Newtonian dynamics (MOND). Our main aim is to address the claim made by McGaugh & de Blok that CDM suffers from severe fine-tuning problems, which are circumvented under MOND. As we show, CDM indeed requires some amount of tuning of the feedback efficiencies to obtain a Tully-Fisher relation (TFR) as steep as observed. However, that same model is in excellent agreement with a wide variety of additional observations. Therefore, the modest amount of feedback needed should not be regarded a fine-tuning problem. Instead, its requirement should be considered a generic prediction for CDM, which might be tested with future observations and with detailed modeling of feedback processes. We also show that galaxy formation in a MOND universe can not simultaneously reproduce the TFR and the lack of high surface brightness dwarf galaxies. We thus conclude that CDM is a more viable theory for the formation of disk galaxies than MOND.

1. Introduction

Because of their fairly simple geometrical and dynamical structure disk galaxies are the ideal benchmarks to test our theories of galaxy formation, gravity, and cosmology. One notable characteristic of disk galaxies is the flatness of their rotation curves, which implies either that (i) disks are embedded in a massive dark matter halo, or (ii) our theory of gravity is incorrect. One theory build around the latter option is Modified Newtonian Dynamics (MOND), originally proposed by Milgrom (1983a). In MOND a characteristic acceleration a_0 is assumed, such that for accelerations a ≪ a_0 the true acceleration a = \sqrt{a_0a_N}, with a_N the standard Newtonian acceleration. This implies flat rotation curves, with an asymptotic value \( V_\infty = (GMa_0)^{1/4} \), without the need for dark matter.

Here we examine how MOND fairs in comparison to CDM when it comes to explaining global properties of disk galaxies in the context of a model for disk galaxy formation. A more detailed treatment of the models and results presented here can be found in van den Bosch (1998; 2000) and van den Bosch & Dalcanton (2000). Here we merely summarize some of our results.
2. The Tully-Fisher relation

The zero-point, scatter, and slope of the TFR of disk galaxies \((L \propto V_{\text{rot}}^\alpha)\) all strongly depend on the photometric band in which the TFR is defined. In the near-infrared, where one is least sensitive to dust-extinction and to uncertainties regarding the ages and metallicities of stellar populations, one finds \(\alpha \simeq 4\) (i.e., Verheijen 1997).

In the CDM scenario, one predicts a TFR of the form:

\[ L \propto \frac{\epsilon_{\text{gf}}}{\Upsilon_d} V_{\text{vir}}^3 \]  

(see van den Bosch 2000 and references therein) with \(V_{\text{vir}}\), the circular velocity at the virial radius, \(\Upsilon_d\) the mass-to-light ratio of the disk, and \(\epsilon_{\text{gf}}\) a parameter that describes what fraction of the baryons inside the virial radius resides in the disk (as either stars or cold gas). Thus, \(\epsilon_{\text{gf}}\) is related to the efficiencies of feedback and cooling.

In the case of MOND, direct application of the modified acceleration results in a TFR of the form

\[ L \propto \frac{1}{\Upsilon_d} V_{\infty}^4 \]  

(see Milgrom 1983b). Thus, CDM and MOND make distinct predictions regarding the slope \(\alpha\) of the TFR. Furthermore, the prediction for MOND is in better agreement with the near-infrared TFR. For CDM to yield a TFR as steep as observed the process of galaxy formation has to be such that \(\epsilon_{\text{gf}}/\Upsilon_d \propto V_{\text{vir}}\). Advocates of MOND have used this to argue against CDM, as they have claimed that this requires extremely difficult fine-tuning (i.e., McGaugh & de Blok 1998a,b).

In the upper panels of Figure 1 we plot the \(K\)-band TFR for the data as well as for three of our models: the ΛCDM model, and two MOND models (a and b). As can be seen, the ΛCDM TFR is as steep as the data (\(\alpha = 4.2\)), which we accomplished by adjusting the feedback efficiency. Thus, indeed some amount of tuning is required in a CDM Universe. The MOND a model, which has zero feedback, also reveals a TFR in excellent agreement with the data. The MOND b model, however, in which feedback is included, yields a TFR that is too steep and with too much scatter at the low-mass end. The reason for the inclusion of the feedback in this latter model becomes apparent below.

3. Other observational constraints

The panels in the second row of Figure 1 plot the gas mass fractions \((M_{\text{HI}}/L_B)\) as function of the absolute magnitude. The data reveals a systematic decrease of \(M_{\text{HI}}/L_B\) with increasing magnitude, which is remarkably well reproduced by the models and owes in large part to the stability related threshold densities for star formation used in our models.

Panels in the third row plot the central surface brightness of the disk as function of \(V_{\text{flat}}\) (the amplitude of the flat part of the rotation curve). The data indicates an absence of high surface brightness (HSB) galaxies at the low mass end (indicated by the thin solid line). This is nicely reproduced by the
Figure 1. A comparison of three models (one ΛCDM model and two MOND models) with various data on disk galaxies (for the sources of the data see van den Bosch & Dalcanton 2000). Upper panels plot $K$-band TFRs. The thick solid lines indicate the best-fit linear relation to the data, and has a slope of $\alpha = 4.2$. Panels in the second row plot the gas mass fraction $M_{\text{HI}}/L_B$ as function of absolute $B$-band magnitude. The thin lines have no physical meaning but are plotted to facilitate a comparison between models and data. Panels in the third row plot central surface brightness versus the amplitude of the flat part of the rotation curve. Finally, the panels in the lower row plot the enclosed mass-to-light ratio $\Upsilon(R)$ versus the local acceleration $V_{\text{rot}}^2(R)/R$. 
ACDM model, and owes to the particular feedback model used. In the MOND model, however, no such deficit of low-mass HSB disks is present, in clear contradiction with the data. In model $b$ we included feedback, for which we tuned the parameters to reproduce the data. Note, however, that this model yields a TFR that is too steep.

Finally, in the lower panels of Figure 1 we plot the enclosed mass-to-light ratio

$$\Upsilon(R) = \frac{RV_{\text{rot}}^2(R)}{GM_{\text{disk}}(R)},$$

as function of the local acceleration $V_{\text{rot}}^2(R)/R$. Here $M_{\text{disk}}$ is the ‘visible’ mass of the disk (stars and cold gas), and $R$ is the galactocentric radius. Each data point represents one resolved measurement in the rotation curve (RC) of a disk galaxy. As first pointed out by McGaugh (1998), the observed RCs of galaxies reveal a characteristic acceleration. This is evident from the fact that the data in the lower-left panel reveals very little scatter. The presence of such a characteristic acceleration is exactly the ‘ansatz’ of MOND, and, not surprisingly, the MOND models $a$ and $b$ nicely reproduce the data. However, the ACDM model is also in good agreement with the data. Therefore, the appearance of a characteristic acceleration is not a unique prediction of MOND.

4. Conclusions

The ACDM model requires tuning of the feedback parameters to yield a TFR as steep as observed. However, once this is achieved the model reproduces the gas mass fractions, the absence of low mass HSB galaxies, and reveals a characteristic acceleration as observed. All the particular problems for CDM pointed out by McGaugh & de Blok (1998a) are in fact solved by this one simple tuning. The MOND models, however, are unable to simultaneously reproduce the TFR and the absence of low-mass HSB disks. Although we do not consider this a strong proof against MOND (as our particular assumptions underlying the model for galaxy formation might not be valid under MOND), we do want to emphasize that our results largely remove the claimed advantages of MOND over CDM.

References

McGaugh, S. S. 1998, preprint [astro-ph/9812327]
McGaugh, S. S., & de Blok, W. J. G. 1998a, ApJ, 499, 41
McGaugh, S. S., & de Blok, W. J. G. 1998b, ApJ, 499, 66
Milgrom, M. 1983a, ApJ, 270, 365
Milgrom, M. 1983b, ApJ, 270, 371
van den Bosch, F. C. 1998, ApJ, 507, 601
van den Bosch, F. C. 2000, ApJ, 530, 177
van den Bosch, F. C., & Dalcanton, J. J. 2000, ApJ, 534, 146
Verheijen, M. A. W. 1997, PhD Thesis, University of Groningen