The Tully-Fisher Zero Point Problem

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Abstract. A long standing problem for hierarchical disk galaxy formation models has been the simultaneous matching of the zero point of the Tully-Fisher relation and the galaxy luminosity function (LF). We illustrate this problem for a typical disk galaxy and discuss three solutions: low stellar mass-to-light ratios, low initial dark halo concentrations, and no halo contraction. We speculate that halo contraction may be reversed through a combination of mass ejection through feedback and angular momentum exchange brought about by dynamical friction between baryons and dark matter during the disk formation process.

1. Introduction

The relation between the rotation velocity and luminosity of disk galaxies, commonly known as the Tully-Fisher (TF) relation (Tully & Fisher 1977), is one of the most fundamental properties of disk galaxies. This is because it is a link between luminous mass (i.e. baryons) and dynamical mass (baryons and dark matter) and because it has very little intrinsic scatter $\sigma_{\ln V} \approx 0.1$. Furthermore, unlike the Faber-Jackson relation for early type galaxies, the scatter in the TF relation is independent of surface brightness, size, or offsets from the size-luminosity relation (Courteau & Rix 1999; Courteau et al. 2007).

CDM based disk galaxy formation models are able to reproduce the slope, and in some cases the amount of scatter, in the TF relation. However, a long standing problem has been the matching of the zero point of the TF relation, with the generic problem of galaxies rotating too fast at a given luminosity. This has been seen in analytic models (van den Bosch 2000; Mo & Mao 2000; Dutton et al. 2007), semi-analytic models (e.g. Benson et al. 2003) and cosmological N-body simulations (e.g. Eke, Navarro, & Steinmetz 2001).

2. The TF-LF Challenge

The problem of matching the zero point of the TF relation is made worse when additional constraints, such as disk sizes and number densities, are placed on the models. Semi-analytic models that are able to simultaneously reproduce the TF zero point and LF require that $V_{\text{rot}} = V_{200}$ (e.g. Somerville & Primack 1999) or $V_{\text{rot}} = V_{\text{max}}$ (e.g. Croton et al. 2006). That is, these do not account for halo

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Figure 1. Rotation curves of model galaxies with $V_{2.2} = 200$ km s$^{-1}$. These models are constructed to reproduce the velocity-luminosity-radius scaling relations as well as the relation between concentration and virial mass in ΛCDM. The upper/lower panels show models with/without the effect of halo contraction. The halo contraction model requires a low-mass halo, in conflict with observations, and a high spin parameter, in conflict with theoretical expectations. By contrast the no contraction model satisfies the halo mass constraint and uses a realistic galaxy spin parameter.

contraction, or the self-gravity of the disk. Here $V_{\text{rot}}$ is the observed rotation velocity (corrected for inclination and other observational effects), $V_{200}$ is the halo circular velocity at the virial radius, and $V_{\text{max}}$ is the maximum circular velocity of the dark matter halo in the absence of dynamical evolution. Bullock et al. (2001) showed that $V_{\text{max}} \simeq 1.1 - 1.2V_{200}$ for typical halo concentrations in a ΛCDM cosmology. Support for $V_{\text{rot}} \simeq V_{\text{max}}$ also comes from more direct observational based measurements of halo masses (Eke et al. 2006) and the velocity function of isolated halos (Blanton et al. 2007).

Thus, in the absence of baryonic effects, there appears to be reasonable agreement between theory and observation. Problems occur when the contribution of the baryons to rotation curve and the effect of halo contraction (Blumenthal et al. 1986) are taken into account. These effects increase the observed rotation velocity, and typically result in $V_{\text{rot}} \sim 2V_{200}$ (e.g. Navarro & Steinmetz 2000; Dutton et al. 2007).

2.1. Illustration of the Problem

As an illustration of the problem we consider the idealized case of an exponential disk embedded in an NFW halo. We pick $V_{2.2} = 200$ km s$^{-1}$, then from the TF relation (Courteau et al. 2007; Pizagno et al. 2007) we know the typical I-band luminosity, which is converted into a stellar mass using typical galaxy colors and
the relations in Bell et al. (2003). From the size-luminosity relation (Pizagno et al. 2005; Courteau et al. 2007) we know the average scale length of the galaxy. From cosmological simulations we know the average concentration parameter of dark matter halos of a given mass (Bullock et al. 2001; Macciò et al. 2007). Here we assume the WMAP 3rd year cosmology ($\sigma_8 = 0.78, \Omega_0 = 0.268, \Lambda = 0.732, \Omega_b = 0.045, h = 0.70$). This model is fully specified, and we can solve for the virial mass (including the self gravity of the baryons and halo contraction). The resulting rotation curve is shown in Fig. 1. This galaxy has $V_{2.2}/V_{200} \sim 1.8$, where $V_{2.2}$ is the total rotation velocity at $2.2R_d$.

2.2. Possible solutions to the TF zero-point problem

We now discuss the three possible solutions to this problem.

Lowering the stellar mass to light ratio: This reduces the contribution of the disk to $V_{2.2}$, which thus induces less halo contraction. For our fiducial galaxy, an $M_*/L$ reduction of 0.2 dex is required. There is no observationally supported IMF that would achieve this, and most dynamical estimates of galaxy masses suggest baryons (disks and bulges) contribute substantially (i.e. at least half the mass) to $V_{2.2}$ (Courteau & Rix 1999; Weiner et al. 2001; Bershady et al. in these proceedings).

Lowering the initial halo concentration: This preserves the inner structure of the halo while increasing its virial radius and thus reducing $V_{2.2}/V_{200}$. However, for $V_{2.2}/V_{200} = 1.1$ an initial concentration of $\sim 3$ is required. Such low halo concentrations require cosmological parameters inconsistent with the WMAP 3rd year constraints (Spergel et al. 2007).

Turning off or reversing halo contraction: Our model matches the $V_{2.2}/V_{200}$ constraint if we turn off halo contraction. A net halo expansion would be required if we were to adopt a smaller disk scale length.

3. Halo contraction

For isolated halos with smooth cooling the halo contracts. This is well tested and well understood (e.g. Sellwood & McGaugh 2005; Choi et al. 2006). However, in the hierarchical structure formation paradigm disk galaxies are not expected to form from smooth cooling in isolated non-evolving halos.

Since cosmological simulations are still unable to make realistic disk galaxies that follow the scaling relations between rotation velocity, luminosity and size (see Courteau et al. in these proceedings), something must be missing. Numerical resolution is certainly still an issue, but more importantly, key physics relating to gas cooling, star formation, and feedback is not yet understood.

3.1. Is the reversal of halo contraction physically possible?

Two mechanisms that are expected to occur during galaxy formation have the ability to reverse the effects of halo contraction.

- **Feedback**: If disks form adiabatically and a large fraction of the disk mass is removed rapidly then net halo expansion can result (e.g. Gnedin & Zhao 2002). If this process is repeated several times a substantial reduction in halo density can be achieved (Read & Gilmore 2005). Feedback also offers
Dutton et al.

a mechanism to explain why galaxy formation is so inefficient, since cooling is very efficient in galaxy mass halos (e.g. van den Bosch 2002).

- **Angular momentum exchange:** Dynamical friction between baryons and dark matter can cause the halo to expand. This process can occur both in a formed disk through bars (Weinberg & Katz 2002; Sellwood 2006), or during the formation process via large baryonic clumps (El Zant et al. 2001; Mo & Mao 2004; Tonini et al. 2006).

A potential problem for the angular momentum exchange solution occurs if the baryons lose too much angular momentum, then the resulting disks will be too small. Furthermore, as baryons lose angular momentum and move to smaller radii they will drag in the dark matter halo, which may cancel out the halo expansion achieved through the angular momentum exchange. Feedback can help solve these problems by ejecting (low angular momentum) material from the centers of galaxies and causing the halo to expand.

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