Baryonic Tully-Fisher Relations

Stacy S. McGaugh

Department of Astronomy, University of Maryland

Abstract.

I describe the disk mass–rotation velocity relation which underpins the familiar luminosity–linewidth relation. Continuity of this relation favors nearly maximal stellar mass-to-light ratios. This contradicts the low mass-to-light ratios implied by the lack of surface brightness dependence in the same relation.

1. Searching for the Physical Basis of the Tully-Fisher Relation

The Tully-Fisher (TF) relation (Tully & Fisher 1977) is well known. Yet why it works is not clear. A dizzying variety of distinct interpretations have been offered over the years (e.g., Aaronson, Mould, & Huchra 1979; Milgrom 1983; Walker 1999). There is no consensus even when the context is limited to that of NFW halos. Widely divergent pictures have been offered, sometimes in successive papers by the same authors (e.g., Dalcanton, Spergel, & Summers 1995, 1997; van den Bosch & Dalcanton 2000; Mo, Mao & White 1998; Mo & Mao 2000; Steinmetz & Navarro 1999, Navarro & Steinmetz 2000).

It is commonly assumed that mass scales with some power of rotation velocity, and that luminosity traces mass. The first piece of this common wisdom is questionable given the startling lack of dependence of the TF relation on surface brightness (Sprayberry et al. 1995; Zwaan et al. 1995). It matters not at all whether the luminous mass is concentrated or diffuse. This is commonly interpreted to mean that the mass in stars is insignificant. If stellar mass contributes noticeably to the rotation velocity, $V^2 = GM/R$ surely demands some shift (McGaugh & de Blok 1998; Courteau & Rix 1999).

Whether luminosity traces mass is a more tractable issue. I address this here in an empirical way using data which span the largest available dynamic range. This at least makes clear that the fundamental relation which needs explaining is one between rotation velocity and disk mass (McGaugh et al. 2000).

2. The Disk Mass–Rotation Velocity Relation

Implicit in our presumption that light traces mass is the relation

$$L = \Upsilon_* f_* f_d f_b M_{\text{tot}}, \quad (1)$$

where $f_b$ is the baryon fraction of the universe, $f_d$ is the fraction of the baryons associated with a particular galaxy which reside in the disk, $f_*$ is the fraction...
of disk baryons in the form of stars, and $\Upsilon_*$ is the mass-to-light ratio of the stars. Each of the pieces which intervene between $L$ and $M_{\text{tot}}$ must be a nearly universal constant shared by all disks, or a finely tuned function of rotation velocity, in order to maintain the observed TF relation.

We can improve on equation (1) by using the observed gas mass to correct for $f_*$ (Fig. 1). The TF relation works in bright galaxies because they are star dominated: $f_* \geq 0.8$. This breaks down as one examines lower mass galaxies which are progressively more gas dominated (McGaugh & de Blok 1997). Yet if we add in the gas mass, the TF relation is restored (Fig. 1c).

A number of inferences can be drawn from this simple result:

- Disk mass is the fundamental quantity of interest.
- Stars got mass!
- Stars and gas account for nearly all of the disk mass.
- The product $f_df_b$ is constant.

Items (3) and (4) are just sanity requirements. If there were another substantial reservoir of baryons in the disk besides the observed stars and gas, then there should be some signature of its absence like that seen in Fig. 1(a) & (b) where an important component has been ignored. Similarly, the modest scatter in the TF relation only follows if $f_d$ is a constant, which only happens naturally if $f_d \approx 1$ (McGaugh et al. 2000). One could consider $f_d \ll 1$ as long as some mechanism maintained it as a universal constant, or even made it a fine-tuned function of $V_c$. Such a situation is highly contrived (van den Bosch & Dalcanton 2000).

3. Stellar Mass-to-Light Ratios

The baryonic TF relation between disk mass and rotation velocity can be expressed as

$$ M_d = A V_c^b. $$

A fit to the data ($R = 0.92$) in Fig. 1(c) has a slope indistinguishable from $b = 4$ with normalization $A \approx 35 h_{75}^{-2}$. This line is drawn in each panel of Fig. 1.

The greatest source of uncertainty is the mass-to-light ratios of the stars, which must be assumed. The stellar mass-to-light ratios assumed in Fig. 1(c) were normalized to the mean of the dynamically determined $K'$-band maximum disk values for high surface brightness galaxies (Verheijen 1997) with colors from stellar population models of de Jong (1996). These models also give the same $\Upsilon_{K'}^d$, consistent with that of the Milky Way (Gerhard, these proceedings) and the results of Sanders & Verheijen (1998).

Requiring continuity in the present relation provides an interesting constraint: stars must have significant mass to avoid the discontinuity apparent in Fig. 1(b) & (d). Such mass-to-light ratios are plausible in terms of both dynamics and stellar populations. However, this contradicts the much lower mass-to-light ratios needed for rotation curve fits with NFW halos and the observed lack of shift with surface brightness in the TF relation itself.
Figure 1. TF relations constructed from the $H$-band data of Bothun et al. (1985) and the $I$-band data of Pildis, Schombert, & Eder (1997). The data of Bothun et al. (1985) cover the range $V_c > 100 \, \text{km} \, \text{s}^{-1}$ traditionally covered by TF studies. The range $V_c < 100 \, \text{km} \, \text{s}^{-1}$ is now probed by data from Eder & Schombert (2000). This greatly increases the dynamic range over which the TF relation can be examined, revealing a number of interesting points. 

a) The ordinary TF relation, plotting stellar mass in place of luminosity using $M_\ast = \Upsilon_\ast L$ with $\Upsilon_\ast^H = 1.0$ and $\Upsilon_\ast^I = 1.7 \, M_\odot / L_\odot$. While the usual relation is apparent for massive galaxies, it breaks down at the low mass end. 

b) The gas-only TF relation which follows from the observed HI ($M_g = 1.4 M_{HI}$), ignoring the stars. Clearly there is no “HI TF relation” for massive galaxies, though there does seem to be one for low mass objects.

c) The Baryonic TF relation which follows by summing stellar and gas mass: $M_d = M_\ast + M_g$. This nicely recovers a continuous relation over the entire observed range, suggesting that the disk mass is the fundamental quantity of interest in the TF relation. 

d) The same as (c) but assuming lower mass-to-light ratios for the stars: $\Upsilon_\ast^H = 0.4$ and $\Upsilon_\ast^I = 0.7$. This causes a noticeable discontinuity in slope, implying that the higher mass-to-light ratios adopted in (c) are more appropriate.
4. Conclusions

The Tully-Fisher relation appears to be a manifestation of a more fundamental relation between disk mass and rotation velocity (see also de Jong & Bell, these proceedings). This relation is now observed to span over 4 decades in mass, twice what can be found in most TF studies. That the TF relation continues to hold over such a large range, despite the reversal of dominance of gas at the low masses to stars at the high masses, is a tribute to its fundamental importance for understanding disk galaxies. Just why there should be a relation of the form $M_d \propto V_c^4$ remains open to debate.

Acknowledgments. I am grateful to my collaborators, Jim Schombert, Greg Bothun, and Erwin de Blok for all their many contributions. I also thank Ken Freeman, Stephanie Coté, Eric Bell, and Roelof de Jong for stimulating conversations on this topic.

References

Aaronson, M., Mould, J., & Huchra, J. 1979, ApJ, 229, 1
Bothun, G.D., Aaronson, M., Schommer, B., Mould, J., Huchra, J.; Sullivan, W.T., III 1985, ApJS, 57, 423
Courteau, S., & Rix, H.-W. 1999, ApJ, 513, 561
Dalcanton, J. J., Spergel, D. N., & Summers, F. J. 1995, astro-ph/9503093
Dalcanton, J. J., Spergel, D. N., & Summers, F. J. 1997, ApJ, 482, 659
de Jong, R.S. 1996, A&A, 313, 377
Eder, J.A., & Schombert, J.M., 2000, astro-ph/0006290
McGaugh, S.S., & de Blok, W.J.G. 1997, ApJ, 481, 689
McGaugh, S.S., & de Blok, W.J.G. 1998, ApJ, 499, 41
McGaugh, S.S., Schombert, J.M., Bothun, G.D., & de Blok, W.J.G., 2000, ApJ, 533, L99
Milgrom, M. 1983, ApJ, 270, 371
Mo, H.J., & Mao, S. 2000, astro-ph/0002451
Mo, H.J., Mao, S., & White, S.D.M. 1998, MNRAS, 295, 319
Navarro, J.F., & Steinmetz, M. 2000, ApJ, 538, 477
Pildis, R.A., Schombert, J.M., & Eder, J.A. 1997, ApJ, 481, 157
Sanders, R.H., & Verheijen, M.A.W. 1998, ApJ, 503, 97
Steinmetz, M., & Navarro, J.F., 1999, ApJ, 513, 555
Sprayberry, D., Bernstein, G. M., Impey, C. D., & Bothun, G. D. 1995, ApJ, 438, 72
Tully, R. B., & Fisher, J. R. 1977, A&A, 54, 661
van den Bosch, F.C. & Dalcanton, J.J. 2000, ApJ, 534, 146
Verheijen, M.A.W. 1997, Ph.D. thesis, University of Groningen
Walker, M. 1999, MNRAS, 308, 551
Zwaan, M.A., et al. 1995, MNRAS, 273, L35