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The Baryonic Tully–Fisher Relation

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Abstract: We validate the baryonic Tully–Fisher (TF) relation by exploring the Tully–Fisher (TF) and BTF properties of optically and HI-selected disk galaxies. The data includes galaxies from Sakai et al. (2000) calibrator sample, McGaugh et al. (2000: M2000) I-band sample, and 18 newly acquired HI-selected field dwarf galaxies observed with the ANU 2.3-m telescope and the ATNF Parkes telescope (Gurovich 2005a).

As in M2000, we re-cast the TF and BTF relations as relationships between baryon mass and W_{20}. First we report some numerical errors in M2000. Then, we calculate weighted bi-variate linear fits to the data, and finally we compare the fits of the intrinsically fainter dwarfs with the brighter galaxies of Sakai et al. (2000). With regards to the local calibrator disk galaxies of Sakai et al. (2000), our results suggest that the BTF relation is indeed tighter than the TF relation and that the slopes of the BTF relations are statistically flatter than the equivalent TF relations. Further, for the fainter galaxies which include the I-band M2000 and HI-selected galaxies of Gurovich's sample, we calculate a break from a simple power law model because of what appears to be real cosmic scatter. Not withstanding this point, the BTF models are marginally better models than the equivalent TF ones with slightly smaller $\chi^2_{\rm red}$ values.

Keywords: dark matter — galaxies: baryonic Tully–Fisher — gas-rich dwarf galaxies — near-field cosmology

1 Introduction

McGaugh et al. (2000: M2000) provides a valuable sample of I-band data for 63 optically selected dwarf galaxies. Several of these galaxies are isolated field dwarfs and a few are among the slowest rotators of the known population of disk galaxies. Using these galaxies, supplemented by other brighter galaxies, M2000 conjected that a log–log baryonic TF relation (BTF) which includes all the visible baryons (gas plus stars) appears to be more nearly linear than the TF relation, which includes only the stellar component. If true, a BTF relation relates the baryon content to the dark matter halos of galaxies and was probably established at the time of their formation.

Gurovich, Freeman, and McGaugh (in preparation) have shown that arithmetic errors crept into the M2000 I-band data. The I-band magnitudes were systematically over-luminous by $2 \times (V - I)$ (sign error) and the HI masses were overestimated by 0.11 dex (H_0 error). In order to establish the validity of the BTF relation we went back to the original published data and reanalysed it following the methodology of M2000. The empirical BTF relation (Freeman 1999; M2000) for disk galaxies relates the total baryon mass (gas + stars) and W_{20} (the 20th percentile width of the HI profile). For the brighter galaxies W_{20} is a fairly direct measure of the amplitude of the flat part of the rotation curve, but for the less massive and more slowly rotating galaxies this is not so clear.

2 Calculating Stellar and Gas Baryons

We went to the source of the M2000 I-band data for the 64 dwarf galaxies (Pildis et al. 1997; Schombert et al. 1997; Eder & Schombert 2000) and from apparent magnitudes, kindly made available by James Schombert (private communication), we recalculated the stellar and gas baryon masses following the M2000 formulation. For all 64 galaxies we measured the velocity widths W_{20} based on the spectra of Eder & Schombert (2000) and corrected for the inclinations by Pildis et al. (1997).

The M2000 data come from an optically selected sample of dwarf galaxies. In this analysis we have also included 18 HI-selected field dwarf galaxies with inclinations greater than 45° from the HIPASS survey, which are part of a larger study by Gurovich (2005b). In this paper we have also included the brighter local calibrator sample (with Cepheid distances) of Sakai et al. (2000). For the HI-selected galaxies we collected H-band photometry from the Siding Spring 2.3-m telescope and obtained W_{20} and HI masses from narrow-band observations (8 MHz, 1024 channels) with the Parkes telescope. All distances were determined using cosmological

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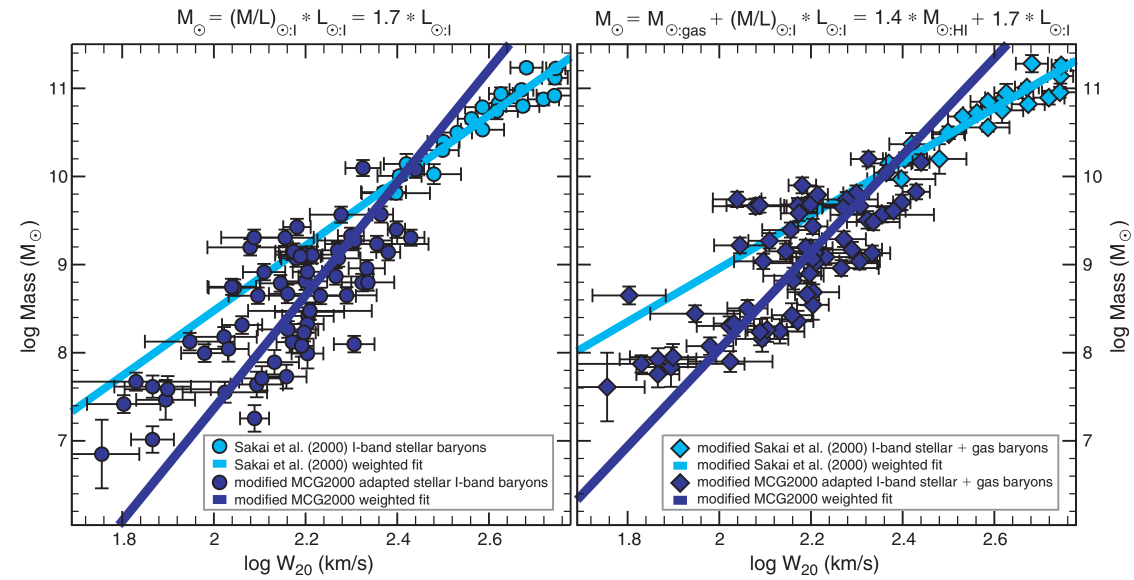

Figure 1 TF (left) and BTF (right) plots for the corrected (M2000) and adapted (Sakai et al. 2000) I-band calibrator, showing the correlation between stellar mass and velocity width W_{20}. Stellar masses are represented by circles. 'Total' masses, which include the stellar plus gas components, are represented by diamonds. The stellar and 'total' mass bi-variate weighted fits are shown. It is clear that the BTF fits are flatter but that the TF and BTF relations break for the fainter M2000 sample. For the TF and BTF Sakai I-band data the $\chi^2_{\rm red}$ values are 0.958 and 1.035 with slopes of 3.7 ± 0.3 and 3.0 ± 0.3 respectively, and for the TF and BTF M2000 I-band data the $\chi^2_{\rm red}$ values are 4.4 and 4.1 with slopes of 6.4 ± 0.3 and 5.5 ± 0.3 respectively.

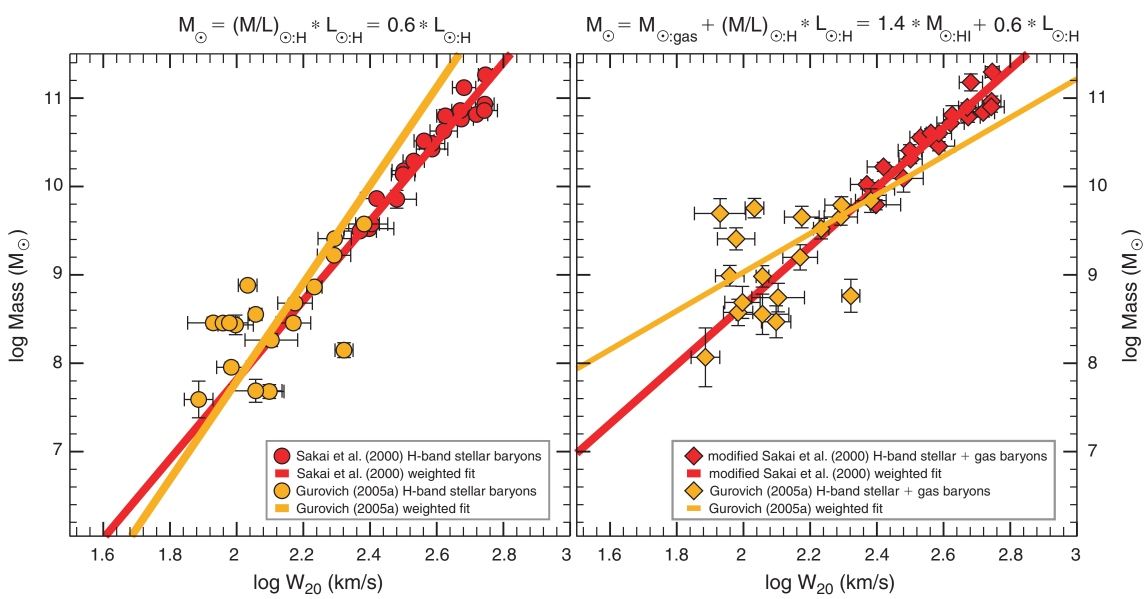

Figure 2 TF (left) and BTF (right) plots for the H-band data of the HI-selected galaxies from Gurovich (2005a) sample and of the adapted Sakai et al. (2000) H-band calibrator data. Stellar masses are represented by circles. 'Total' masses, which include the stellar plus gas components, are represented by diamonds. The stellar and 'total' mass bi-variate weighted fits are shown. It is clear that the slopes of the BTF fits are flatter, but that the TF and BTF relations break for the fainter HI-selected sample. For the HI-selected sample the TF and BTF $\chi^2_{\rm red}$ values are 9.7 and 6.9 with slopes 5.5 ± 0.9 and 2.2 ± 0.4, respectively, and for the Sakai H-band data the TF and BTF $\chi^2_{\rm red}$ values are 0.868 and 1.109 with slopes of 4.4 ± 0.3 and 3.3 ± 0.3 respectively.

redshifts, from the HI systemic velocities, calculated for $H_0 = 75\,{\rm km\,s^{-1}\,Mpc^{-1}}$, except where reliable secondary distances were available. The HI data for the Sakai et al. (2000) galaxies were calculated from Martin (1998) and Pilyugin et al. (2004) but rescaled to the Sakai et al. (2000) distances. Total magnitudes are extrapolated to infinity. We performed a TF and BTF analysis on all four data sets by following M2000 and adopted $M/L_I = 1.7$, $M/L_H = 0.6$ and estimated the gas mass $M_g = 1.4 M_{\rm HI}$ from cosmological abundances.

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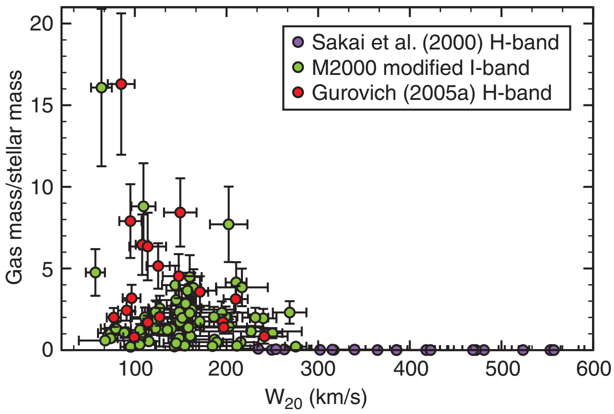

Figure 3 Gas fraction for the optically selected samples of M2000 and Sakai et al. (2000) and HI-selected sample of galaxies in this paper.

2.1 Weighted Bi-Variate Fits

We used `fitexy` (Press et al. 1992) to find weighted bi-variate least-squares linear TF and BTF fits. This algorithm fits the line that minimises the scatter in both the $\log(W_{20})$ and the $\log M$ variables, weighting the residuals by the uncertainties in each quantity.

2.2 Errors Used for Weighting the Bi-Variate Fits

All estimates of baryon masses and W_{20} have errors arising from uncertainties in the assumed distances, W_{20} measurements, integrated HI fluxes (mom0), inclinations, and total extrapolated magnitude measurements.

For the Gurovich sample and the corrected M2000 I-band data, we adopt random peculiar velocities of $180\,\mathrm{km\,s^{-1}}$ (2.4 Mpc in distance) from Tonry et al. (2000), integrated mom0 errors of 20%, and total extrapolated magnitude errors of $\sim$0.1 mag. We believe that our distance errors are probably overestimates (Karachentsev et al. 2003). The W_{20} errors are in the range $5\,\mathrm{km\,s^{-1}} \lesssim \delta W_{20} \lesssim 25\,\mathrm{km\,s^{-1}}$ and $8\,\mathrm{km\,s^{-1}} \lesssim \delta W_{20} \lesssim 50\,\mathrm{km\,s^{-1}}$ for the two samples, respectively. The errors for the Sakai et al. (2000) galaxies were taken from that paper and the integrated HI flux errors from the standard deviation of the mean values found in the literature re-scaled to the Sakai et al. (2000) distances. These errors were propagated following Bevington (1969) and subsequently used in the weighted bi-variate fits.

3 Results of the Fits and Conclusions

The fits are plotted in Figures 1 and 2. The slope and χ^2_{red} values can be found in the captions. These results indicate that for the brighter spiral galaxies (Sakai et al. 2000) the BTF fits are tighter than the TF fits and have shallower slopes than the equivalent TF fits. The TF and BTF fits for the fainter galaxies of M2000 and Gurovich (2005b) break from this simple power law model, as is evident from the large χ^2_{red} values — $\chi^2_{\mathrm{red,TF}} = 4.4$ and $\chi^2_{\mathrm{red,BTF}} = 4.1$ for the I-band and $\chi^2_{\mathrm{red,TF}} = 9.7$ and $\chi^2_{\mathrm{red,BTF}} = 6.9$ for the H-band data, respectively. We would like to highlight the fact that careful consideration went into the error analysis, and that this result reveals an inadequate model and is not due to an underestimation of the errors.

4 Discussion

Figure 3 shows the gas mass fraction (G/S) for the galaxies in this paper. As is expected, the fainter galaxies are relatively gas-richer than the brighter spirals of Sakai et al. (2000). It is interesting that the brighter spirals which have smaller G/S are better modelled by a BTF than a TF model. This is consistent with the conjecture that there is a strict proportionality between the HI and dark baryons (M2000; Pfenniger & Revaz 2004). It is equally interesting that the fainter disk galaxies that have larger G/S ratios are not well modelled by a simple BTF power law fit. It could be that this non-linearity arises partly from the assumptions of the constant $M/L_I = 1.7$, $M/L_H = 0.6$, and $M_{\mathrm{g}} = 1.4 M_{\mathrm{HI}}$. In fact Pfenniger & Revaz (2004) conclude that $M_{\mathrm{g}} = 3 M_{\mathrm{HI}}$ is a more realistic proportionality. It is perhaps worth discussing the fainter galaxies in the right panels of Figures 1 and 2 that appear to be exceptionally baryon-rich for their observed W_{20}.

Are these galaxies unusual in having a large baryon mass or a small value of W_{20}? One possible interpretation is that the gas in these galaxies is not quite at the flat part of the rotation curve and hence their W_{20} values are lower limits of the true rotation amplitude. However, we note that these galaxies do appear to better follow the (stellar) TF relation. Another possibility is that the gas fell into these galaxies after the stellar disk had settled, so that the extra baryons are not part of the original galaxy. An even more speculative possibility is that a subsample of these systems have dark halos which are significantly less dense than would be expected from the Kormendy & Freeman (2004) scaling laws for dark halos, and hence have atypically low values of W_{20}.

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