

## A Shared Tully-Fisher Relation for Spirals and S0 Galaxies

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**Abstract.** We measure the positions of the Tully-Fisher relations of 14 lenticular galaxies (S0s) and 14 spirals. We use two measures of rotational velocity. One is derived directly from observed spatially-resolved stellar kinematics and the other from the circular velocities of mass models that include a dark halo and whose parameters are constrained by detailed kinematic modelling. Contrary to the naive expectations of theories of S0 formation, we find no significant difference between the Tully-Fisher relations of the two samples when plotted as functions of both brightness and stellar mass.

### 1. Introduction

The Tully-Fisher (TF) relation is a widely-used and strong correlation between the maximum rotational velocity of spiral galaxies and their total magnitude. It follows naturally from the assumption that spiral galaxies have similar surface brightness profiles and approximately equal dynamical mass-to-light ratios for a given mass.

Many authors have argued that at least some S0 galaxies are the faded direct descendants of spiral galaxies (e.g. Dressler 1980; Dressler et al. 1997). Environmental processes such as strangulation (e.g. Larson et al. 1980) or ram-pressure stripping (e.g. Gunn & Gott 1972) may have stripped these galaxies of their gas and left them unable to form stars. This process should make only a slight change to their dynamical masses, but a significant change to their luminosities. Regardless of the particular mechanism by which S0s form, they are therefore generally expected to have higher mass-to-light ratios than spirals on average. They should therefore have fainter luminosities for a given rotational velocity and lie below the TF relation defined by spiral galaxies.

Here we seek to test this prediction using long-slit stellar kinematics and detailed mass models for a sample of S0 galaxies and a control sample of spiral galaxies. A secondary goal is to investigate whether the size of the offset between the S0 and spiral TF relations (if one exists) changes when we plot a TF-like relation which uses mass rather than luminosity, as expected from the S0 formation mechanisms discussed above.

### 2. Data and Models

We use a sample of 14 early spirals (Sa and Sb) and 14 S0s. All of the galaxies are close to edge-on. Many of them have boxy bulges, which are believed to be

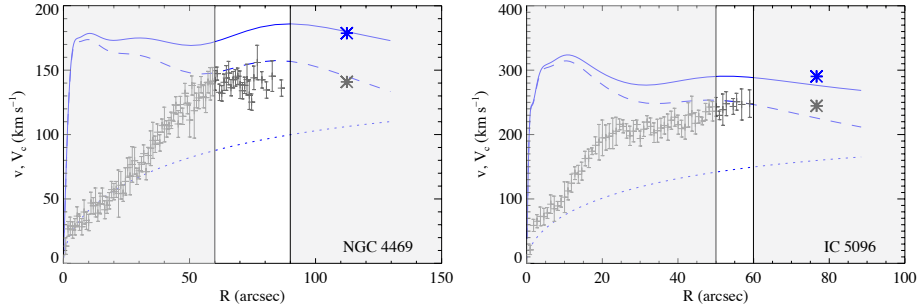


Figure 1. Example rotation curves. The data points show the observed line-of-sight velocities. The lines show the total circular velocities of the axisymmetric mass models (solid), the stellar components (dashed line) and dark halo components (dotted line). The kinematic quantities used in this work,  $v$  and  $V_c$ , are the mean of the data points and model in the unshaded radial region, chosen to be the flat region of the observed rotation curve. They are shown here as large stars.

bars viewed side-on (e.g. Kuijken & Merrifield 1995; Bureau & Freeman 1999). The bar should not, however, affect the present results because we use maximum rotational velocities well outside of the bar regions and the bar fraction in the sample ( $\approx 75$  per cent) is representative of that in the spiral galaxy population ( $\approx 65$  per cent, see, e.g., Sheth et al. 2008 and references therein).

The major-axis long-slit stellar kinematic observations are presented in Chung & Bureau (2004). These data were observed and reduced identically for the spirals and S0s. We measure the maximum observed rotation velocity  $v$  directly from the stellar kinematics by taking the mean of the data points in the flat region of the rotation curve. Two sample rotation curves are shown in Fig. 1.

In Williams et al. (2009) we modelled the mass distribution of each galaxy by assuming they are composed of an axisymmetric stellar component with a constant mass-to-light ratio and an NFW dark halo (Navarro et al. 1997). We determined the two parameters of the mass models (the stellar mass-to-light ratio and total halo mass) by comparing the observed second velocity moment to that predicted by solving the Jeans equations assuming a constant anisotropy (Cappellari 2008).

We compute the circular velocity curves of the galaxies from these models. Circular velocity is of course free from the effects of projection and asymmetric drift, which is particularly important when comparing S0s and spirals, because S0s have greater pressure support. We characterize the circular velocity by a single value  $V_c$  by taking its average at the same radii that were used to measure the maximum observed rotational velocity (see Fig. 1).

We adopt errors in the observed velocity of half the difference between the approaching and receding sides. The uncertainties in the circular velocity curves are due to the errors in the parameters of the mass model, described in Williams et al. (2009).

We use total absolute magnitudes  $M_K$  at  $K$ -band derived from apparent magnitudes (and errors) taken from the 2MASS Extended Source Catalog

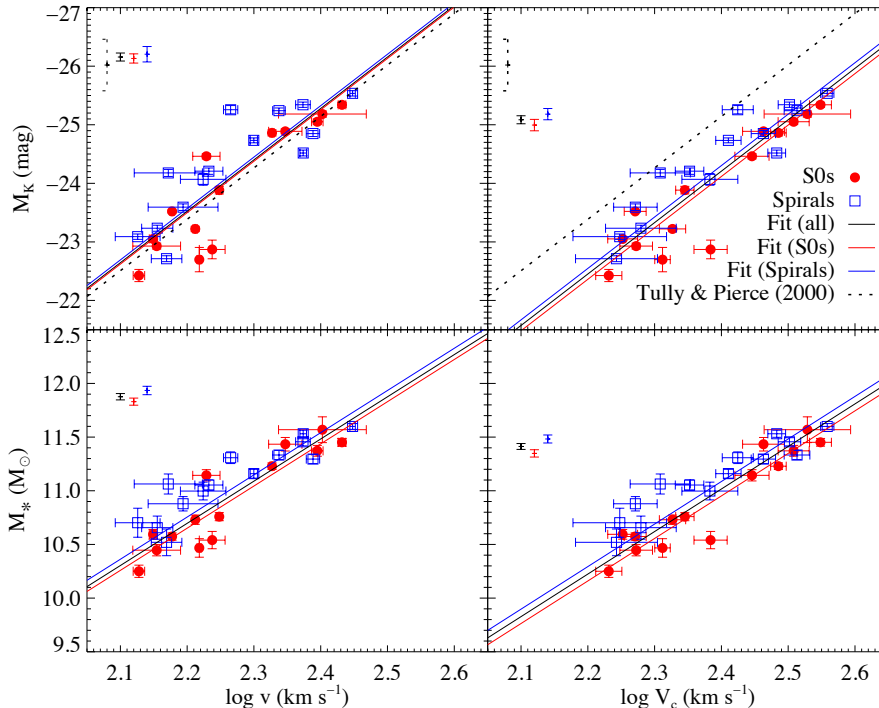


Figure 2. TF-like plots for our samples. Spirals are shown as blue squares and S0s as red triangles. We show power law fits of the form  $M_K = a + b(\log v - 2.5)$  for the two samples as red and blue lines, and a fit to all 28 galaxies as a solid black line. We show  $1\sigma$  confidence intervals on  $a$  for each sample in the top-left of each plot. The TF relation for spirals found by Tully & Pierce (2000) is also shown as a dashed black line in the upper plots.

(Skrutskie et al. 2006) and distances (and errors) from the NASA/IPAC Extragalactic Database.  $K$ -band is chosen to minimize the effects of obscuration by dust, which can be significant in edge-on systems at optical wavelengths. We convert these to stellar masses  $M_*$  using the best-fitting stellar mass-to-light ratios presented in Williams et al. (2009).

We present four TF-like plots derived from the above quantities in Fig. 2. We first plot the maximum observed rotational velocity and model circular velocity against the total magnitude to provide both a purely observed TF relation and one which eliminates asymmetric drift. We also plot both velocities against the stellar mass of the system,  $M_*$ .

It is important to note that at no point in this analysis do we do anything that might systematically affect the S0s in the sample differently to the spirals.

### 3. Discussion

In neither of the TF-like plots showing measures of velocity against measures of magnitude (upper panes of Fig. 2) do we see a significant difference between the

spirals and S0s. This is demonstrated by the error bars in the top-left corner of each plot, which show the  $1\sigma$  confidence interval of  $a$  in fits to each sample, assumed to be of the form  $M_K = a + b(\log v - 2.5)$ . We fixed the gradients of the individual fits in the upper panels at  $-8.78$ , as found by Tully & Pierce (2000).

When we use circular velocity as the measure of rotation, which avoids the effects of asymmetric drift (top-right pane of Fig. 2), there is still no significant difference between the TF relations of the S0s and spirals. Both samples (S0s *and* spirals), however, are significantly offset from the TF relation found by Tully & Pierce (2000), which is derived from unresolved HI kinematics (single-dish spectra).<sup>1</sup> This offset is in the same sense and of approximately the same size ( $\approx +1$  mag or  $+0.1$  dex in velocity) as that found by Bedregal et al. (2006) for their sample of S0s only.

There is a marginal change in the offset between the two samples in the change from magnitude to stellar mass (lower panels), although this could be due to a different slope in the best fits of the two samples. In this work we fixed the gradients of each fit to  $M_*$  to the shared gradient of the two samples (3.92 as a function of  $\log v$  and 3.96 for  $\log V_c$ ).

In conclusion, we find no evidence that S0s lie in a different region of the luminosity/mass–rotational velocity plane than spirals. Present models of S0 formation, which our observations seem to contradict, are nevertheless extremely appealing, so we emphasize that we merely report an observational result and not an astrophysical interpretation. Future work will head in two directions: firstly, we will further attempt to determine the origin of the offset between our TF relations and that of Tully & Pierce (2000) as well as the difference between our findings and those of Bedregal et al. (2006). Secondly, we will characterize the statistical significance of the (lack of) offset and the scatter in TF plots of our samples at both  $K$ -band and  $B$ -band, and seek to interpret the results within the context of models of galaxy evolution.

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<sup>1</sup>We follow Bedregal et al. (2006) in shifting the Tully & Pierce (2000)  $K$ -band TF relation by  $-0.207$  mag to match our adopted  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .