REVEALING THE ASSEMBLY HISTORY OF DISK GALAXIES:

With the Evolution in The Tully-Fisher Relation to z~1.7

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Using the Tully-Fisher relation to constrain our understanding of disk evolution.
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3.5. Testing Fitting Methods: Fitting, Scatter, and Incompleteness Biases

Methods for fitting linear relations such as Tully-Fisher have sometimes been controversial. Several biases can arise, caused by observational errors, intrinsic scatter, and magnitude limits. Biases can be exacerbated in the high-redshift TF relation by the large intrinsic scatter. Here we describe tests of several fitting methods, to ensure that the parameters listed in Table 1 are reliable.

3.5.1. Scatter-induced Bias in Least-Squares Fitting Algorithms

A common method of fitting a linear relation to data with errors in both coordinates is the fitexy least-squares routine, derived from a $\chi^2$ minimization (Press et al. 1992). The fitexy method does not model relations with intrinsic scatter, so it yields formally rejectable fits with $\chi^2/N < 1$ and can yield biased results when there is scatter. A method that does account for scatter was proposed by Akritas & Bershady (1996), but this method has been criticized by Tremaine et al. (2002) and Novak et al. (2006). These authors in turn generalized the fitexy method by adding the intrinsic scatter as an effective error term in one of the coordinates, so that the best fit has $\chi^2/N = 1$. In the Appendix we show that this intuitive treatment (generalized least-squares, or GLS method) is derivable from a maximum likelihood model, a special case of the maximum likelihood (MLS) method we have used. None of these models explicitly compensate for effects caused by selection limits.

To test biases introduced by scatter and selection limits, we generated simulated data sets with Monte Carlo realizations. We took the true values of $M_B$ in a single redshift range, enforced a TF relation with slope $B_{\text{model}} = 1$, and perturbed the points by Gaussian random variates of the observational errors $\text{error}(M_B)$, $\text{error}(\log V_{\text{rot}})$, and an intrinsic scatter $\sigma_{\log V_{\text{rot}}} = 0.15$ dex.

Measuring and applying the intrinsic scatter in $\log V_{\text{rot}}$ rather than $M_B$ is required because the sample is magnitude selected and sensible because the slope is shallow.

Fig. 7.—TF relation in the TKRS for line-of-sight rotation velocity and rest $B$ magnitude, in four redshift ranges, for the galaxies in the ROTCURVE sample with aligned slits and ellipticity $e > 0.25$. Corrections for inclination and extinction are not applied. Individual galaxies are plotted as small filled circles. Large filled circles and error bars are the mean and rms in magnitude bins. The dashed diagonal line is the fit to the low-redshift range, repeated in all four panels. A shift in the line width $Y$ magnitude relation, at high redshift galaxies are observed brightward or lower velocity compared to the low-redshift fit.

[See the electronic edition of the Journal for a color version of this figure.]

Weiner et al. 2006
LUMINOSITY → STELLAR MASS

Bundy et al. 2005

$z = 0.430$

$\log M_*: 9.1 \pm 0.2$

Bundy et al. 2005
Using the Tully-Fisher relation to constrain our understanding of disk evolution.

**Diagram:**

- **Stellar Mass** vs. **Rotational Velocity**
  - Two graphs showing the stellar mass (M) versus the logarithm of the maximum rotational velocity (log(V_{max})) for different redshift bins:
    - **z < 0.7**
    - **z > 0.7**
  - The graphs include fitted lines and data points from Conselice et al. 2005.
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Kassin et al. 2007
ROTATIONAL VELOCITY

\[ \Delta V \propto \Delta \lambda \]

optical emission extent

position along major axis

\[ V_{\text{max}} \]
ROTATIONAL VELOCITY

optical emission extent

$\Delta V \propto \Delta \lambda$

position along major axis

$V_{\text{max}}$
3.1. Rotation curve model

Optimally fitting rotation curves presents a variety of challenges that become more difficult as redshift increases. Foremost, we seek a functional form which represents the bulk of the observed emission line shapes and has some physical basis. Secondly, we must aim to characterize this functional form with a fiducial velocity that is reliably detected across the sample, preferably without extrapolation to radii where there is no data. Given our extended integrations, we have considered carefully the optimum selection of this characteristic velocity.

The challenges can be appreciated considering Figure 2 where we show various characteristic velocities in the context of the frequently-used arctan model of arctan rotation curve (Courteau 1997) as well as how we extract emission lines for our sample. Several functional forms have been discussed in the literature, such as the “multi-parameter function” in Courteau (1997) and the “universal rotation curve” of Persic et al. (1996). The simplest model flexible enough to fit most rotation curves is the empirically-motivated arctan function (see Fig. 2), which we adopt here, viz:

\[
V = V_0 + \frac{2}{\pi} V_a \arctan\left(\frac{r - r_0}{r_t}\right),
\]

where \(V_0\) is the central or systematic velocity, \(r_0\) is the dynamic centre, \(V_a\) is the asymptotic velocity, and \(r_t\) is the turnover radius, which is a transitional point between the rising and flattening part of the rotation curve (Courteau 1997; Wilkinson 1999). The arctan model does not account for a sharp peak that is found in some local, bulge-dominated rotation curves around the turnover radius, but we typically do not observe this feature in our sample.
ROTATIONAL VELOCITY

optical emission extent

trace to $2.2r_s$ ($r_{2.2}$) on ~ 90% of our disks with extended emission!
THIS STUDY

• 306 disks, including irregular and disturbed

• $0.2 \leq z \leq 1.7$
  ➜ DEIMOS: $0.2 \leq z \leq 1$ (N = 236)
  ➜ LRIS: $1 \leq z \leq 1.7$ (N = 70)

• $M_* \sim 10^{8.5-11.5}$ $M_\odot$

• HST ACS, WFC3 and ground-based $K_s$

• 6-8 hours of exposure time

• 63 passive, 73 compact emission, 171 extended emission
MODELING ROTATION CURVES FROM DEIMOS (0.2 ≲ z ≲ 1)

- z~0.54
- z~0.97
- z~0.94
- z~0.47
- z~0.94
DISK SIZE AND PROJECTION

- **disk scale length**: $r_{2.2}$

  Fit exponential disk (and BULGE when necessary)

- **inclination**

  $$V_{corr} = \frac{V_{obs}}{(\sin i)} \quad i = \cos^{-1} \sqrt{\frac{(b/a)^2 - q_0^2}{1 - q_0^2}}$$

- **position angle offset between slit and major axis**

  $$V_{corr} = \frac{V_{obs}}{\cos(\Delta PA)}$$

Only 10 galaxies in our final sample have velocity correction.

**GALFIT**

Peng et al. 2010
STELLAR MASS TULLY-FISHER RELATION
WELL-ESTABLISHED AT $z \sim 1$

$\Delta M^* \sim 0.04 \pm 0.07$ dex from $\langle z \rangle \sim 1$ to $\langle z \rangle \sim 0.3$

$\sigma_{\text{int}} \sim 0.05$ dex in $V/\text{km s}^{-1}$
$\sim 0.2$ dex in $M/M_\odot$

B-Mag Tully-Fisher Relation

- Slope: $-7.55 \pm 0.58$
- Absolute B-Magnitude slope: $-7.55 \pm 0.58$
- $\sigma_{\text{int}} \sim 0.05-0.09 \, \text{dex V/km s}^{-1}$
- $\Delta M_B \sim 0.85 \pm 0.28 \, \text{dex}$ from $\langle z \rangle \sim 1$ to $\langle z \rangle \sim 0.3$

Less fundamental at $z \sim 1$
PUSHING TO HIGHER REDSHIFT

DEIMOS - $z \sim 0.9$

to LRIS

DEIMOS - $z \sim 1.0$

to LRIS
PUSHING TO HIGHER REDSHIFT

DEIMOS LRIS log($V'_{2.2}/$km s$^{-1}$) vs. DEIMOS log($V_{2.2}/$km s$^{-1}$)
<table>
<thead>
<tr>
<th>HST ACS</th>
<th>LRIS</th>
<th>MODEL</th>
<th>RESIDUAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$z \sim 1.3$</td>
<td>$r_s \sim 4.7$ kpc</td>
<td>$V_{2,2} \sim 164$ km s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$z \sim 1.0$</td>
<td>$r_s \sim 3.9$ kpc</td>
<td>$V_{2,2} \sim 215$ km s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$z \sim 1.5$</td>
<td>$r_s \sim 5.6$ kpc</td>
<td>$V_{2,2} \sim 160$ km s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$z \sim 1.6$</td>
<td>$r_s \sim 4.6$ kpc</td>
<td>$V_{2,2} \sim 140$ km s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$z \sim 1.6$</td>
<td>$r_s \sim 2.9$ kpc</td>
<td>$V_{2,2} \sim 161$ km s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$z \sim 1.2$</td>
<td>$r_s \sim 3.3$ kpc</td>
<td>$V_{2,2} \sim 137$ km s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$z \sim 1.3$</td>
<td>$r_s \sim 3.7$ kpc</td>
<td>$V_{2,2} \sim 99$ km s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$z \sim 1.5$</td>
<td>$r_s \sim 3.9$ kpc</td>
<td>$V_{2,2} \sim 86$ km s$^{-1}$</td>
</tr>
</tbody>
</table>
PUSHING TO HIGHER REDSHIFT

Stellar Mass, $\log \left( \frac{M_*(r_{2.2})}{M_{\odot}} \right)$

Velocity, $\log \left( \frac{V_{2.2}}{\text{km s}^{-1}} \right)$

Miller et al. 2012
PUSHING TO HIGHER REDSHIFT ($1 \lesssim z \lesssim 1.7$)

This study, $N=42$

Miller+11, $z:0.2-1.0$

$V_{2.2}$ in km s$^{-1}$
Miller et al. 2012
EVOLUTION WITHIN THE TULLY-FISHER RELATION?

Miller et al. 2012 (in prep)

Disks with a bulge
Disks without a bulge

Bulgeless disks offset in stellar mass or velocity?
MORPHOLOGICAL BAND-PASS SHIFTING

$z > 1$

WFC3 H

ACS i
1) 171 rotation curve measurements from $0.2 \leq z \leq 1.7$ with HST imaging

2) Stellar Mass Tully-Fisher relation tightly in place by $z \sim 1$

3) Little evolution in relation since $z \sim 1.7$ ($\sim 10$ Gyr lookback time)
   - zero-point shift $\Delta M_* \sim 0.02 \pm 0.02$ dex
   - up to 60% increase in scatter at $1 \leq z \leq 1.7$

4) Baryons constitute 50-100% of dynamical mass within $r_{2.2}$

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