A test of Tully–Fisher distance estimates using Cepheids and SNIa

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ABSTRACT

We make a direct test of Tully–Fisher distance estimates to 11 spiral galaxies with Hubble Space Telescope (HST) Cepheid distances, and to 12 spiral galaxies with Type Ia supernova (SNIa) distances. The HST Cepheid distances come from the work of Freedman, Sandage et al. and Tanvir et al. The SNIa distances come from Pierce, calibrated using the Cepheid results of Sandage et al. The Tully–Fisher distances mostly come from the work of Pierce. The results show that the Tully–Fisher distance moduli are too short with respect to the Cepheid distances by $0.41 \pm 0.14$ mag, and too short with respect to the SNIa distances by $0.46 \pm 0.19$ mag. Combining the HST Cepheid and SNIa data suggests that, overall, previous Tully–Fisher distances were too short by $0.43 \pm 0.11$ mag, a result which is significant at the 3.8σ level. The Tully–Fisher distance errors appear to increase as galaxy linewidth decreases, which may signify the presence of Malmquist bias. These data therefore indicate that previous Tully–Fisher distances at $v \sim 1000$ km s$^{-1}$ should be revised upwards by $\approx 22 \pm 6$ per cent implying, for example, a Virgo distance of $19.0 \pm 1.8$ Mpc. The value of $H_0$ from Tully–Fisher estimates is correspondingly revised downwards from $H_0 = 84 \pm 10$ to $H_0 = 69 \pm 8$ km s$^{-1}$ Mpc$^{-1}$.

Key words: supernovae: general – Cepheids – galaxies: distances and redshifts.

1 INTRODUCTION

Over the past 20 years, the Tully–Fisher (TF) relation has been one of the main pieces of evidence suggesting that the Hubble constant, $H_o$, was high, in the region of $H_o \approx 85$ km s$^{-1}$ Mpc$^{-1}$ (e.g. Tully & Fisher 1977; Aaronson et al. 1986; Pierce & Tully 1992). The power of the Tully–Fisher route to $H_0$ was that it was possible to calibrate it in the Local Group and its immediate neighbourhood, since six nearby spirals, including M31 and M33, had both Tully–Fisher and ground-based Cepheid distance estimates. This meant that only a single step was needed to proceed from the Local Group to more distant galaxy clusters such as Virgo, Fornax and Centaurus. There had been concerns voiced about both the accuracy and the reliability of the Tully–Fisher relation (e.g. Bottinelli et al. 1986; Sandage 1988; Kraan-Korteweg, Cameron & Tamman 1988). However, with a lack of primary distance indicators, such as Cepheids, in more distant galaxies, these claims were difficult to check.

Here, we use 11 newly available Cepheid distances from the HST Distance Scale Key project (Silbermann et al. 1996; Rawson et al. 1997; Freedman 1997 and references therein) and from other HST (Saha et al. 1994; Tanvir et al. 1995; Saha et al. 1996a,b; Sandage et al. 1996) and ground-based (Pierce, McClure & Racine 1992) observations to test TF distance estimates for more distant galaxies than has previously been possible. We shall supplement the Cepheid–TF data with 12 SNIa–TF galaxies, i.e. galaxies which have both SNIa distances and TF distances. Since the SNIa scale now has five Cepheid-calibrated SNIa luminosities (Sandage et al. 1996 and references therein), this provides a further way to test the calibration of the TF scale. This data set is now large enough to allow us to restrict our attention to only those galaxies with both Cepheid/SNIa and TF distances. In particular, at no point do we make any assumptions about the possible association of the Cepheid/SNIa galaxies with either galaxy groups or clusters (cf. Tanvir et al. 1995; Silbermann et al. 1996; Sandage et al. 1996).

2 OBSERVATIONAL DATA

Table 1 lists the 11 galaxies for which Cepheid distances have recently been obtained and which also have TF distances. In all cases the Cepheid distances are from HST except for NGC4571, for which the Cepheid distance comes from recent ground-based data (Pierce et al. 1992). The source of the Cepheid absolute distance moduli for all 11 galaxies is given, and the listed results are the same as the
Table 1. Tully–Fisher parameters and colours for galaxies with Cepheid distances.

<table>
<thead>
<tr>
<th>Galaxy Name</th>
<th>Cepheid (m-M)</th>
<th>TF (m-M)0</th>
<th>Ceph.-TF (m-M)0</th>
<th>Inc. (deg)</th>
<th>log W2R</th>
<th>By-IT</th>
<th>AIB</th>
<th>AIB</th>
<th>B-I corr</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
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<td>(3)</td>
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<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
<td>(9)</td>
<td>(10)</td>
</tr>
<tr>
<td>New Cepheid-TF Galaxies</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>IC4182</td>
<td>28.36±0.033</td>
<td>26.90±0.4</td>
<td>1.46</td>
<td>30</td>
<td>1.937</td>
<td>0.87</td>
<td>0.04</td>
<td>0.00</td>
<td>0.85</td>
<td>Virgo</td>
</tr>
<tr>
<td>NGC4536</td>
<td>31.10±0.122</td>
<td>30.50±0.3</td>
<td>0.60</td>
<td>70</td>
<td>2.525</td>
<td>1.90</td>
<td>0.30</td>
<td>0.10</td>
<td>1.69</td>
<td>Virgo</td>
</tr>
<tr>
<td>NGC4539</td>
<td>32.00±0.233</td>
<td>31.40±0.3</td>
<td>0.60</td>
<td>55</td>
<td>2.510</td>
<td>1.78</td>
<td>0.17</td>
<td>0.05</td>
<td>1.66</td>
<td>Virgo</td>
</tr>
<tr>
<td>NGC4496A</td>
<td>31.13±0.104</td>
<td>30.40±0.4</td>
<td>0.73</td>
<td>43</td>
<td>2.328</td>
<td>1.92</td>
<td>0.09</td>
<td>0.00</td>
<td>1.47</td>
<td>Virgo</td>
</tr>
<tr>
<td>NGC3929</td>
<td>29.84±0.166</td>
<td>28.80±0.3</td>
<td>1.04</td>
<td>57</td>
<td>2.349</td>
<td>1.58</td>
<td>0.19</td>
<td>0.24</td>
<td>1.34</td>
<td>Virgo</td>
</tr>
<tr>
<td>NGC3351</td>
<td>30.01±0.196</td>
<td>29.56±0.3</td>
<td>0.05</td>
<td>47</td>
<td>2.511</td>
<td>1.12</td>
<td>0.05</td>
<td>0.12</td>
<td>1.45</td>
<td>Leo (M95)</td>
</tr>
<tr>
<td>NGC3621</td>
<td>29.10±0.187</td>
<td>29.26±0.3</td>
<td>-0.16</td>
<td>54</td>
<td>2.471</td>
<td>1.45</td>
<td>0.17</td>
<td>0.42</td>
<td>1.12</td>
<td>Leo (M95)</td>
</tr>
<tr>
<td>NGC3621</td>
<td>30.01±0.218</td>
<td>30.80±0.4</td>
<td>0.24</td>
<td>18</td>
<td>2.700</td>
<td>1.76</td>
<td>0.05</td>
<td>0.00</td>
<td>1.73</td>
<td>Virgo (M100)</td>
</tr>
<tr>
<td>NGC3136</td>
<td>31.32±0.152</td>
<td>31.19±0.3</td>
<td>0.13</td>
<td>44</td>
<td>2.760</td>
<td>2.01</td>
<td>0.09</td>
<td>0.12</td>
<td>1.96</td>
<td>Fornax</td>
</tr>
<tr>
<td>NGC4571</td>
<td>30.87±0.159</td>
<td>30.39±0.4</td>
<td>0.48</td>
<td>35</td>
<td>2.427</td>
<td>1.95</td>
<td>0.04</td>
<td>0.11</td>
<td>1.89</td>
<td>Virgo</td>
</tr>
<tr>
<td>NGC3368</td>
<td>30.32±0.151</td>
<td>30.04±0.3</td>
<td>0.28</td>
<td>46</td>
<td>2.641</td>
<td>2.06</td>
<td>0.10</td>
<td>0.06</td>
<td>2.08</td>
<td>Leo (M95)</td>
</tr>
<tr>
<td>Previous Cepheid-TF Galaxies (Pierce &amp; Tully 1992)</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>M31</td>
<td>24.44±0.125</td>
<td>24.48±0.3</td>
<td>-0.04</td>
<td>78</td>
<td>2.712</td>
<td>2.21</td>
<td>0.61</td>
<td>0.32</td>
<td>1.69</td>
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<tr>
<td>M31</td>
<td>24.63±0.105</td>
<td>24.18±0.3</td>
<td>0.45</td>
<td>54</td>
<td>2.322</td>
<td>1.33</td>
<td>0.16</td>
<td>0.16</td>
<td>1.15</td>
<td></td>
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<tr>
<td>NGC2403</td>
<td>27.31±0.155</td>
<td>27.25±0.3</td>
<td>0.26</td>
<td>61</td>
<td>2.411</td>
<td>1.35</td>
<td>0.20</td>
<td>0.14</td>
<td>1.16</td>
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<tr>
<td>M81</td>
<td>27.80±0.204</td>
<td>27.98±0.3</td>
<td>-0.18</td>
<td>57</td>
<td>2.685</td>
<td>2.02</td>
<td>0.19</td>
<td>0.17</td>
<td>1.82</td>
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<tr>
<td>NGC3109</td>
<td>25.50±0.207</td>
<td>25.67±0.3</td>
<td>-0.17</td>
<td>85</td>
<td>2.032</td>
<td>1.34</td>
<td>0.87</td>
<td>0.13</td>
<td>0.89</td>
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<tr>
<td>NGC3300</td>
<td>26.66±0.152</td>
<td>26.30±0.3</td>
<td>0.36</td>
<td>44</td>
<td>2.284</td>
<td>1.02</td>
<td>0.09</td>
<td>0.05</td>
<td>0.94</td>
<td></td>
</tr>
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</table>

Notes

2. In column (3) the TF distance for NGC3621 is based on an I_r derived from de Vaucouleurs & Longo (1988) using (V - I)_Johnson = 1.3(V - I)_KC to convert I_r into I_KC and an aperture correction of 0.35 mag, giving I_r = 8.83 mag.

3. Column (4) contains the Cepheid–TF distance modulus residual; column (5) contains the galaxy inclination; column (6) contains the corrected 21-cm linewidth; column (7) contains the galaxy colour; columns (8) and (9) contain the B-band absorption corrections for galaxy inclination and Galactic latitude; column (10) contains the absorption-corrected galaxy colour assuming A_V = 0.44A_B; column (11) contains details of galaxy cluster or group membership and galaxy Messier numbers.

values reviewed by Freedman (1997) in the 10 overlapping cases quoted. The source of the TF parameters and the B - I colours are also given. In nine cases, the TF distance moduli come from the work of Pierce (1994) or Pierce & Tully (1988) or, in the cases of NGC3351 and NGC3368, from a Pierce & Tully private communication, quoted by Ciardullo, Jacoby & Ford (1989). In the case of NGC3165, the TF distance modulus, I_r magnitude and the linewidth come from Bureau, Mould & Staveley-Smith (1996), who use the precepts of Tully & Fouqué (1985), consistent with the procedures of Pierce (1994). In the case of NGC3621, we have taken the linewidth from the Third Reference Catalogue (de Vaucouleurs et al. 1991) and obtained the total Kron–Cousins magnitude, I_r, by converting the I_Johnson aperture magnitude from de Vaucouleurs & Longo (1988). The TF distance is then found, also by following the procedures of Pierce (1994).

The B_r - I_r colours come in seven cases from the work of Pierce (1994) and Pierce & Tully (1988). In the cases of NGC3351 and NGC3368, where the Pierce & Tully CCD data is not yet published, we have taken the linewidths from the Third Reference Catalogue, and inferred the corrected I_r magnitudes from the Pierce & Tully distance moduli quoted by Ciardullo et al. (1989). For the two galaxies and for NGC3621 and NGC1365, we then took B_r and the axial ratio R_e from the Third Reference Catalogue and produced corrected B_r - I_r colours and linewidths in a manner consistent with the procedures of Pierce (1994). Thus the results for the TF parameters and galaxy colours in Table 1 either come directly from the work of Pierce (1994) or Pierce & Tully (1988) or have been determined using methods similar to theirs.

Only two galaxies with HST Cepheid distances have been excluded from our analyses. We have been unable to obtain a TF distance for NGC5253 because of the lack of a published I-band magnitude. Also, M101 has been excluded because it is too face-on to allow us to apply the TF relation.

Table 1 also contains the previous ground-based Cepheid distances and TF data for the six galaxies on which the Pierce & Tully (1992) TF calibration was used; M31, M33, NGC2403, M81, NGC300 and NGC3109. We have taken the latest estimates of the Cepheid distances to these galaxies from the references given in Table 1 rather than using the older results quoted by Pierce & Tully (1992). Although Cepheid distances to individual galaxies have


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Table 2. Tully–Fisher parameters and colours for SNIa galaxies.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>SNIa (m-M)</th>
<th>SNIA (m-M)</th>
<th>AB (SNIA)</th>
<th>TF (m-M)</th>
<th>SNIA-TF (m-M)</th>
<th>Inc. (deg)</th>
<th>log W_R</th>
<th>(B-I) corr</th>
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</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
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<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
<td>(9)</td>
</tr>
<tr>
<td>NGC1003</td>
<td>1937D</td>
<td>29.0±0.4</td>
<td>2.2</td>
<td>29.7±0.3</td>
<td>0.18</td>
<td>77</td>
<td>2.297</td>
<td>1.29</td>
</tr>
<tr>
<td>NGC2592</td>
<td>1956A</td>
<td>31.6±0.4</td>
<td>0.3</td>
<td>31.4±0.3</td>
<td>0.28</td>
<td>66</td>
<td>2.684</td>
<td>1.90</td>
</tr>
<tr>
<td>NGC2841</td>
<td>1957A</td>
<td>31.9±0.4</td>
<td>1.8</td>
<td>31.3±0.3</td>
<td>0.68</td>
<td>70</td>
<td>2.785</td>
<td>2.95</td>
</tr>
<tr>
<td>NGC3389</td>
<td>1967C</td>
<td>32.3±0.3</td>
<td>0.4</td>
<td>31.3±0.3</td>
<td>1.08</td>
<td>62</td>
<td>2.445</td>
<td>2.13</td>
</tr>
<tr>
<td>NGC3555</td>
<td>1971L</td>
<td>30.9±0.3</td>
<td>0.5</td>
<td>29.3±0.3</td>
<td>1.68</td>
<td>61</td>
<td>2.623</td>
<td>1.74</td>
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<tr>
<td>NGC3389</td>
<td>1971L</td>
<td>32.1±0.3</td>
<td>0.0</td>
<td>32.0±0.3</td>
<td>0.18</td>
<td>48</td>
<td>2.659</td>
<td>1.31</td>
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<tr>
<td>NGC4414</td>
<td>1974G</td>
<td>31.3±0.4</td>
<td>0.5</td>
<td>31.3±0.3</td>
<td>0.08</td>
<td>50</td>
<td>2.696</td>
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</tr>
<tr>
<td>NGC4602</td>
<td>1976B</td>
<td>30.4±0.6</td>
<td>4.3</td>
<td>30.8±0.3</td>
<td>-0.32</td>
<td>74</td>
<td>2.422</td>
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<tr>
<td>NGC4419</td>
<td>1984A</td>
<td>30.9±0.4</td>
<td>0.8</td>
<td>30.3±0.4</td>
<td>0.59</td>
<td>75</td>
<td>2.462</td>
<td>2.47</td>
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<tr>
<td>NGC3627</td>
<td>1989B</td>
<td>30.0±0.2</td>
<td>1.8</td>
<td>29.4±0.3</td>
<td>0.69</td>
<td>59</td>
<td>2.603</td>
<td>1.77</td>
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<tr>
<td>NGC4579</td>
<td>1989M</td>
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<td>1.0</td>
<td>31.1±0.3</td>
<td>-0.02</td>
<td>42</td>
<td>2.705</td>
<td>1.97</td>
</tr>
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<td>NGC4579</td>
<td>1989M</td>
<td>30.6±0.1</td>
<td>0.3</td>
<td>30.6±0.3</td>
<td>0.08</td>
<td>78</td>
<td>2.548</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Notes
1. In column (3), the supernova distance uses the $B_{max}$ listed by Pierce (1994), calibrated using the average of 5 SNIa with Cepheid distances from Saha et al. (1994, 1995, 1996a, b) and Sandage et al. (1996), as described in the text.
2. The SNIa $B$-band absorption in column (4), the Tully–Fisher distance modulus in column (5), the galaxy inclination in column (7), the corrected TF linewidth in column (8) and the corrected $B-I$ colour in column (9) are taken from Pierce (1994).

3. COMPARISON OF CEPHEID/SNIa AND TULLY–FISHER DISTANCES

Fig. 1(a) shows the plot of Cepheid-versus-TF distance for the 11 galaxies in Table 1 which have recent Cepheid distances, mostly from HST. For the moment we exclude the six galaxies used previously by Pierce & Tully (1992) to calibrate the TF relation, since we first want to make an independent test of the previous result. It can immediately be seen that almost all the TF distances are too short with respect to the Cepheid distances. An unweighted mean of the differences shown in Column (4) of Table 1 gives the size of the offset as

$$(m-M)_{Cepheid} - (m-B)_{TF} = 0.50 ± 0.14 \text{ mag}.$$
mean of the differences shown in Column (6) of Table 2 gives the size of the offset as

\[(m - M)_{\text{SNla}} - (m - M)_{\text{TF}} = 0.43 \pm 0.16 \text{ mag.}\]

This result is therefore significant at the 2.7\(\sigma\) level. Removing the four galaxies containing the heavily absorbed

SN1937D, 1957A, 1976B and 1989B produces the offset

\[(m - M)_{\text{SNla}} - (m - M)_{\text{TF}} = 0.49 \pm 0.21 \text{ mag,}\]

corresponding to a larger offset but at a slightly reduced significance of 2.3\(\sigma\). We shall adopt the average value

\[(m - M)_{\text{SNla}} - (m - M)_{\text{TF}} = 0.46 \pm 0.19 \text{ mag}\]  \hspace{1cm} (2)

as best characterizing the offset in this case. Clearly both the \textit{HST} Cepheid and the SNIa supernovae are consistently and independently suggesting that the previous TF distance moduli are too low. Weighting the results in equations (1) and (2) in inverse proportion to the square of the errors gives the result for the TF offset from the \textit{HST} Cepheid and the SNIa samples as

\[(m - M)_0 - (m - M)_{\text{TF}} = 0.43 \pm 0.11 \text{ mag,}\]  \hspace{1cm} (3)

where the offset is now significant at the 3.8\(\sigma\) level and is based on 20 galaxies.

Fig. 2 shows the combined Cepheid–TF distance comparison, which now also includes the six previous primary calibrators of Pierce & Tully (1992). As might be expected, the six previous calibrating galaxies on their own give the much smaller offset

\[(m - M)_{\text{Cepheid}} - (m - M)_{\text{TF}} = 0.11 \pm 0.11 \text{ mag.}\]

Including these six galaxies, the combined \textit{HST}/ground-based Cepheid sample (14 galaxies) gives the overall Cepheid–TF distance modulus offset

\[(m - M)_{\text{Cepheid}} - (m - M)_{\text{TF}} = 0.28 \pm 0.10 \text{ mag.}\]  \hspace{1cm} (4)
With the inclusion of the six galaxies, the combined Cepheid/SNIa distance offset given in equation (3) becomes

\[(m-M)_0 - (m-M)_{TF} = 0.35 \pm 0.09 \text{ mag}, \]  

which is significant at the 3.9σ level. This comparison is now based on 26 galaxies.

Since the previous six Cepheid calibrators give a smaller offset than the more distant \(HST\) Cepheid galaxies, there is some suggestion that there may be a scale error with distance in Tully–Fisher distance estimates. The dashed line in Fig. 2 represents a least-squares linear fit to all 26 galaxies with Cepheid and SNIa distances. A Student's \(t\)-test suggests that a slope of unity is rejected at moderate significance (90 per cent confidence), supporting the possibility that there may be a non-linearity in the TF distance estimates.

Finally, we use the above Cepheid–TF data to derive the error on TF distances. The scatter around the mean of the TF–Cepheid comparison corresponds to \(\pm 0.40\) mag from equation (1) and \(\pm 0.37\) mag from equation (4). The mean error on each Cepheid distance is \(\pm 0.17\) mag in the first case and \(\pm 0.16\) mag in the second. By subtracting these errors in quadrature from the total error estimates, the error in the TF distances is therefore inferred to be in the range \(\pm 0.33\)–\(0.36\) mag. However, as discussed in the next section, if Malmquist bias is the explanation for the TF scale error, then this rms error estimate may also be biased and may actually form a lower limit to the true error in the TF relation.

4 DISCUSSION

The above results clearly indicate that previous TF distance moduli were systematically too short by between 0.3–0.5 mag. There is also evidence that the galaxies at larger distances show larger discrepancies between TF and Cepheid distances, implying that there may be a non-linear scale error in the TF distance-scale. We therefore believe that the best estimate of the average offset for distant TF galaxies, such as those used in \(H_0\) estimation, is given by equation (3), which requires an increase in TF distance estimates of \(0.43 \pm 0.11\) mag or \(22 \pm 6\) per cent, for galaxy distance moduli in the range \(29.5 < (m-M)_0 < 32\) mag. Thus we immediately conclude that the Virgo and Ursa Major TF distances of \(15.6 \pm 1.5\) and \(15.5 \pm 1.2\) Mpc quoted by Pierce & Tully (1988) have to be increased to \(19.0 \pm 1.8\) and \(18.9 \pm 1.5\) Mpc, respectively. The value of \(H_0 = 84 \pm 10\) km s\(^{-1}\) Mpc\(^{-1}\) from Pierce (1991) from consideration of the Tully–Fisher distance to the above clusters therefore reduces to \(H_0 = 69 \pm 8\) km s\(^{-1}\) Mpc\(^{-1}\).

We now discuss possible reasons for the systematic error in the previous Tully–Fisher distances. The first possibility we consider is that the field environment of the six local calibrators causes systematic differences with TF galaxies at the larger distances found in galaxy cluster environments. However, Table 1 shows that several cluster galaxies such as NGC1365 (Fornax) and NGC4321 (Virgo) have smaller residuals in the Cepheid–TF comparison than do many other galaxies. We conclude that at present there is no immediate, positive evidence for any simple environmental effect.

Next, we consider whether the Tully–Fisher distance residuals may correlate with galaxy colour. Pierce & Tully (1992) reported that five of the six local calibrators lay at the extreme blue edge of the distance-independent colour-linewidth plane formed by the Virgo and Ursa Major TF galaxies. They argued that this might just be indicative of extra star formation affecting the B-band in the local calibrators, and so \(f\)-band Tully–Fisher distances might not be affected. However, another possibility is that galaxy colour might be a second parameter for the TF relation and the new availability of highly accurate Cepheid distances to TF galaxies offers a further opportunity to investigate this issue. In Fig. 3, we therefore compare the position of the Cepheid galaxies in the corrected \(B - f\) colour–linewidth plane with the position of the primary and secondary local TF calibrators, and other TF galaxies (see also Pierce & Tully 1992, fig. 2b). A line has been drawn to mark the upper envelope of the local TF calibrators at the blue edge of this relation. Below the line, close to the local calibrators, lie four Cepheid–TF galaxies (crosses), NGC1365, 3351, 3621 and 4321; from Table 1 (column 4) and from Fig. 1(a), it can be seen that these are the galaxies for which the Cepheid–TF residuals are smallest. However, Table 2 (column 6) and Fig. 1(b) also show that this correlation of residuals with colour is not repeated in the colour–linewidth plane for the SNIa galaxies since NGC2841, 3389, 5055 and 6384 (open circles).
circles) lie close to the calibrators at the blue edge of the distribution, but the first three show large Cepheid–TF residuals. Thus the question of whether galaxy colour represents a second parameter for the TF relation remains open at this point.

Another possibility is that the linewidths or magnitudes of the six local calibrators have systematic errors. However, the 21-cm measurements of the linewidths are generally supported by optical rotation curve measurements. Also, Pierce & Tully (1992) took great care to re-measure the magnitudes of galaxies such as M31 so as to mimic as far as possible the way in which more distant galaxy magnitudes are measured.

Last, we consider whether Malmquist bias may explain the scale error in the TF distances. As has been emphasized by Sandage (1994 and references therein), the effect of Malmquist bias on a distance indicator is to cause it to underestimate distances systematically as true galaxy distance increases, which appears to reflect the behaviour seen in Fig. 2. As Sandage (1994, fig. 8) notes, the signature of Malmquist bias in the TF distance scale would be that, at large redshifts, low linewidth galaxies would produce higher values of $H_0$ than high linewidth galaxies, because low linewidth galaxies are fainter and more subject to selection bias. We therefore looked for this signature in the present data set by taking the galaxies in Fig. 2 with $(m-M)_o > 29.5$ mag and dividing them into the three TF linewidth bins. The bins at log $W_k = 2.8 \pm 0.1, 2.6 \pm 0.1$ and $2.4 \pm 0.1$ give the respective average offsets, $(m-M)_o-(m-M)_o = 0.06 \pm 0.33$ (2 galaxies), $0.44 \pm 0.19$ (8 galaxies) and $0.86 \pm 0.21$ mag (4 galaxies). For comparison, the offset for the four galaxies with $(m-M)_o < 29.5$ mag and log $W_k = 2.4 \pm 0.1$ is $(m-M)_o-(m-M)_o = 0.23 \pm 0.17$ mag. Thus the error in the TF distances for the more distant galaxies is largest for the lowest linewidth galaxies, which is the signature of Malmquist bias. These offsets are generally at least as large as predicted by Sandage (1994) who assumed an rms scatter of $\pm 0.7$ mag for the TF relation in his Malmquist bias calculation. Although the effect is therefore surprisingly strong, we conclude that Malmquist bias is the most likely explanation for the TF scale error.

We finally note that our estimate of $H_0 = 69 \pm 8$ km s$^{-1}$ Mpc$^{-1}$ from the Tully–Fisher spiral distance scale at the Virgo/Ursa Major distance is in agreement with the value of $H_0 = 69 \pm 5$ km s$^{-1}$ Mpc$^{-1}$ derived by Giovanelli et al. (1997), who used eight of the galaxies in Table 1 together with the six primary primary calibrators to produce a new calibration of the TF relation. It is also in excellent agreement with the value of $H_0 = 69 \pm 8$ km s$^{-1}$ Mpc$^{-1}$ derived from the early-type galaxy distance-scale calibrated via the HST Cepheid distance to the Leo group (Tanvir et al. 1995). Thus the HST has now given evidence for a $\approx 20$–25 per cent upward revision of the traditional 'short' distance-scale using both early- and late-type galaxies. However, we warn against over-confidence that the final value of $H_0$ has therefore been reached. First, the TF result for $H_0$ in this paper is derived by recalibrating the Virgo and Ursa Major distances and therefore depends on uncertain estimates of the peculiar component of the recession velocities of these clusters. Really, distances to galaxies at higher redshifts are required to circumvent this problem but if the TF relation is increasingly Malmquist-biased then this TF route to $H_0$ becomes more problematic. Even the early-type route of Tanvir et al. (1995) via Leo, Virgo and Coma depends to some level on the TF relation because TF distance estimates contribute to the estimated Virgo–Coma distance. A further problem with this early-type route is that it depends heavily on SBF estimates of the Leo–Virgo distance, which may be less accurate than previously believed (Morris & Shanks 1997). Also, it should be noted that there may still be problems with the calibration of the Cepheid P–L relation which depends on distances determined via main-sequence fitting to Galactic star clusters at several kpc in the Galactic plane. These distances may therefore be suspect both because of the wide main-sequence found for local stars by Hipparcos parallax measurements (M. J. Penston & F. van Leeuwen, private communication) and because of the large $(A_V \approx 2$ mag) foreground absorption typically found in front of these clusters. Indeed, Feast & Catchpole (1997), using Hipparcos parallaxes of nearby short-period Cepheids, have already found problems at the 17 per cent level in the calibration of the P–L relation. Together with the continuing cosmological time-scale problem, which even the revised Tully–Fisher estimate of $H_0 = 69 \pm 8$ km s$^{-1}$ Mpc$^{-1}$ implies for the theoretically preferred $\Omega_m = 1$ model, there is clearly strong motivation for future work at every rung of the distance-scale ladder.

Acknowledgments

I acknowledge useful discussions with D. Branch, P. W. Morris and N. R. Tanvir. I also acknowledge useful comments from an anonymous referee on an earlier version of this paper.

References


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