A Test of Tully-Fisher Distance Estimates Using Cepheids and Type Ia Supernovae.

T. Shanks
Dept. of Physics, University of Durham, South Road, Durham DH1 3LE, England

Abstract. We update and extend the results of Shanks (1997) by making a direct test of Tully-Fisher distance estimates to thirteen spiral galaxies with HST Cepheid distances and to ten spiral galaxies with Type Ia supernova (SNIa) distances. The results show that the Tully-Fisher distance moduli are too short with respect to the Cepheid distances by $0.46 \pm 0.11$ mag and too short with respect to the SNIa distances by $0.49 \pm 0.18$ mag. Combining the HST Cepheid and the best SNIa data suggests that, overall, previous Tully-Fisher distances at $v \sim 1000$ km s$^{-1}$ were too short by $0.43 \pm 0.09$ mag, a result which is significant at the 4.6σ level. These data therefore indicate that previous Tully-Fisher distances should be revised upwards by $22 \pm 5\%$ 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 $H_0 = 84 \pm 10$ km s$^{-1}$ Mpc$^{-1}$ to $H_0 = 69 \pm 8$ km s$^{-1}$ Mpc$^{-1}$. There is evidence that the Tully-Fisher relation at large distances is affected by Malmquist bias. In this case, we argue that $H_0 < 50$ km s$^{-1}$ Mpc$^{-1}$ cannot be ruled out by Tully-Fisher considerations.

1. The Importance of Measuring Hubble’s Constant.

Since part of our motivation for investigating $H_0$ arises from its implications for $\Omega_0$, we begin by repeating the reasons for the theoretical preference for a flat or (just) closed Universe. In the absence of a cosmological constant, this means that the Universe has high mass density and the first argument for such an $\Omega = 1$ model was given by Einstein & de Sitter (1932) who argued that given the Universe is spatially flat locally, in the absence of further information we might expect that the Universe is also spatially flat globally. Following Einstein (1918), Wheeler (1964) and Lynden-Bell et al (1995) have further suggested that Mach’s Principle can be more easily accommodated in General Relativity in a (just) closed model rather than in a spatially infinite model because, in the words of Lynden-Bell et al, ‘If we add to Einstein’s theory the requirement that space must be closed...the conundrum of inertia in an almost flat, almost empty space does not occur!’ Another problem with open models was pointed out by Ya.B. Zel’dovich who suggested that if the Universe appeared from a quantum fluctuation then this might be more plausible in a spatially finite Universe rather than a spatially infinite Universe. The more recent arguments of quantum cosmology
also appear to leave the choice of a model where $\Omega_0=1$ exactly or an unphysical model where $\Omega_0=0$ exactly (Turok & Hawking, 1998).

This context of theoretical preference for spatially flat models was reinforced by the success of the inflation model (Guth, 1981, Linde, 1982) in solving the ‘flatness problem’ at the same time as the ‘horizon problem’. The ‘flatness problem’ harks back to the paper of Einstein & de Sitter; to observe an $\Omega_0$ which is lower than unity at the present day, it is required to postulate that $\Omega$ in the early Universe was microscopically different from unity. To avoid the fine-tuning of the density parameter that this requires, inflation suggests that there was a period of exponential expansion at early times which reduced any initial spatial curvature to essentially zero, leaving $\Omega_0=1$ to high accuracy at the present day. This argument partly motivated the introduction of CDM (Peebles, 1982, Blumenthal et al, 1982) because standard baryon nucleosynthesis arguments seem to suggest that the baryon density has to be low.

The possibility that we may live in a low density Universe with a cosmological constant, which again would give us the above theoretical advantages of living in a spatially flat or just closed Universe, has been considered by Peebles (1984) and others. However, as Peebles also notes, this argument appears circular with a high degree of fine tuning required in the early Universe to arrange for inflation to clean out all the vacuum energy into radiation but to leave one part in $10^{120}$ to allow us to observe a cosmological constant at the present day. Also the clear view of particle physicists is that they would prefer the cosmological constant to be either so huge as to be cosmologically impossible or zero (eg Kolb, 1998).

On the basis of the above arguments, the current standard cosmological models are therefore complicated, finely tuned affairs - either open or (just) closed with a small cosmological constant. Invoking CDM in either case introduces further complication. As noted by Peebles (1984), the problem is that the baryon and CDM densities then lie within 1-2 orders of magnitudes of each other which again implies fine-tuning given there is no physical reason for this coincidence. Even those sceptical of fine-tuning arguments might still regard it as circular reasoning to start with inflation to explain a fine-tuning coincidence only to have to introduce CDM and another fine-tuning coincidence at a later stage. Put another way, the introduction of CDM helps solve the overall flatness problem but leaves us looking at the baryon flatness problem which is why is $\Omega_{baryon}$ to within 1-2 orders of magnitude of unity?

Shanks (1985) and Shanks et al (1991) therefore suggested that the simplest model would have $\Omega_{baryon}=1$. In this case there is neither fine-tuning of the overall density parameter, the cosmological constant nor the baryon and CDM matter densities. However, this means that something else has to give and the view that was taken by Shanks (1985) was that it might be Hubble’s Constant that was the problem. After all, distance scale estimates of $H_0$ have been highly uncertain, with Hubble’s final value in 1953 being $H_0 \sim 500\text{km s}^{-1}\text{Mpc}^{-1}$.

Three advantages immediately accrue if the value of Hubble’s Constant turns out to be below today’s usually quoted 50-100 $\text{km s}^{-1}\text{Mpc}^{-1}$ range. First, Shanks (1985) quoted $0.01 < \Omega_{baryon}h^2 < 0.06$ as the allowed range for $H_0$ from nucleosynthesis considerations. Now the upper limit here has oscillated over the years as the observed abundances of Helium-4 and Deuterium have changed...
(Izotov et al, 1997, Burles & Tytler, 1998). However, the above range may still do no disservice to the real observational uncertainties when systematics are taken into account and therefore if $H_0 \sim 25 \text{km s}^{-1}\text{Mpc}^{-1}$ then a model with $\Omega_{\text{baryon}}=1$ would be compatible with the nucleosynthesis constraints. Second, Shanks (1985) noted that there is a significant mass of X-ray gas in the Coma cluster; this culminates in the problem known as the ‘baryon catastrophe’ in the Coma cluster where CDM models with $\Omega_0=1$ cannot explain Coma’s high baryon fraction (White et al, 1993). Shanks (1985) pointed out that the mass of the gas had a much stronger dependence on $H_0$ than the virial mass, leading to the ratio $M_{\text{virial}}/M_{X-\text{ray}} = 15h^{1.5}$. So whereas the X-ray gas is a factor of fifteen away from explaining the virial mass for $H_0=100 \text{km s}^{-1}\text{Mpc}^{-1}$ and a factor of five for $H_0=50 \text{km s}^{-1}\text{Mpc}^{-1}$, if $H_0=25 \text{km s}^{-1}\text{Mpc}^{-1}$ then the X-ray gas is within a factor of two of the virial mass of Coma. Finally, any $\Omega_0=1$ model would prefer a low value of $H_0$, given that the age of the Universe at 6.5-13 Gyr is uncomfortably close to the ages of the oldest stars if $H_0$ lies in its usual 50-100 km s$^{-1}$ Mpc$^{-1}$ range. If a CDM model with $\Omega_0=1$ demands a low $H_0$ anyway on timescale grounds, then the view might be taken that the above arguments could make the introduction of CDM redundant. Therefore if the Hubble Constant was lower than 50 km s$^{-1}$ Mpc$^{-1}$ then there would be considerable advantage for an $\Omega_{\text{baryon}}=1$ model, with no finely tuned $\Omega_{\text{CDM}} : \Omega_{\text{baryon}} : \Omega_{\Lambda}$ ratios to explain, motivating renewed investigations to see whether current cosmological distance scale estimates of $H_0$ are correct.

2. Testing the Tully-Fisher Estimate of $H_0$.

For many years the Tully-Fisher (TF) relation (Tully & Fisher, 1977) has been a principal argument for a high Hubble’s constant. This argument was strong because the TF relation was calibrated using ground-based Cepheid distances to Local Group spirals and so used less distance scale steps than other methods. However, although there have been criticisms of the TF method (Sandage 1994 and refs. therein), a definitive test of the accuracy of the TF distances required Cepheids to be discovered in more distant galaxies.

Here, we use thirteen newly available Cepheid distances from the HST Distance Scale Key project (Freedman, 1997, Turner et al, 1998, and refs. therein) and from other HST (Tanvir et al, 1995, Sandage et al, 1996 and refs. therein) observations to test TF distance estimates for more distant galaxies than has previously been possible. We shall supplement the Cepheid-TF data with ten SNIa-TF galaxies, i.e., galaxies which have both SNIa distances and TF distances, which provides a further way to test the calibration of the TF scale.

Table 1 of Shanks (1997) lists eight spirals for which Cepheid distances have been obtained and with inclination, $i>40$ deg, which means they have good TF distances. We note that the TF distance modulus for NGC1365 in Table 1 is in error and should read 30.34±0.3. We have also included 5 further galaxies NGC3627, NGC2090, NGC2541, NGC7331, NGC4414 whose Cepheid distances have been published by the Key Project team more recently. (Turner et al, 1998 and refs. therein).

Table 2 of Shanks (1997) shows a further twelve galaxies which have both TF and SNIa distances. Where galaxies have both an SNIa and a Cepheid
distance, the default has been to include them in the Cepheid-TF list of Table 1. NGC3627 and NGC4414 now have Cepheid distances and have therefore been included with the galaxies of Table 1. SN1937D, SN1957A and SN1976B have large dust extinctions. SN1971I and SN1991T are doubtful Type Ia on the basis of their spectra (D. Branch, priv. comm.) which leaves a ‘best’ sample of five SNIa. The SNIa distances have been calibrated using five galaxies with SNIa and Cepheid distances which gives $M_B(\text{max})=-19.38 \pm 0.11$ (Shanks, 1997). Most of the SNIa in Table 2 of Shanks (1997) do not have accurate enough light curves to allow use of the proposed maximum luminosity-decay rate correlation (Hamuy et al, 1996). The Tully-Fisher distances mostly come from Pierce (1994) and otherwise they are calculated following the precepts of Tully & Fouque (1985).

Fig. 1 shows the comparison between Tully-Fisher distances and HST-based Cepheid/SNIa distances (‘best sample’). Also shown are the six galaxies with ground based Cepheid distances which formed the previous Local Calibrators for the TF relation. We see that there is a significant difference between the TF and Cepheid/SNIa distances for galaxies with $(m-M)>29.5$. Taking the thirteen galaxies with HST Cepheid distances and with $i>40\text{deg}$, we find that the TF-Cepheid difference corresponds to $\Delta(m-M)=0.46\pm0.11$ or a $4.2\sigma$ discrepancy. Similarly taking the full sample of ten TF galaxies with SNIa we find $\Delta(m-M)=0.49\pm0.18$ or a $2.7\sigma$ discrepancy. Finally, taking the thirteen HST Cepheid galaxies and the five SNIa galaxies in the ‘best’ sample we obtain an overall discrepancy of $\Delta(m-M)=0.43\pm0.09$ or a $4.6\sigma$ discrepancy. The further inclusion of

Figure 1. The comparison of Tully-Fisher distance moduli with HST Cepheid/SNIa(‘best’ sample) moduli and ground-based Cepheid moduli at lower distances. The solid line shows the 1-1 relation and the dashed line is the least squares fit. The Tully-Fisher distances are $22\pm5\%$ too short compared to the HST Cepheid/SNIa distances.
Figure 2. The correlation of Cepheid/SNIa-TF distance moduli residuals with TF linewidth for distant galaxies with (m-M) > 29.5. The data tentatively indicate at the 2σ level that the lowest linewidth galaxies show the biggest residuals and this is a possible signature that TF distance estimates are affected by Malmquist bias.

The original 6 calibrators reduces the discrepancy to Δ(m-M) = 0.33 ± 0.08 which is still a 4.0σ discrepancy based now on 24 galaxies.

Thus TF distances at v~1000 kms⁻¹ are systematically too short by 22 ± 5%. The TF distance to Virgo of Pierce & Tully (1992) therefore requires a correction from 15.6 Mpc to 19.0 ±1.8 Mpc. Assuming their Virgo infall model, the Pierce & Tully value of H₀ at Virgo is therefore decreased from H₀ = 84 to H₀ = 69±8 kms⁻¹Mpc⁻¹. Thus far there is little controversy in this result, with Giovanelli et al (1997) and Hughes et al (1998) for the HST Key Project Team coming to approximately the same result for H₀. The difference between the old calibrators and the new can be clearly seen in the TF relation shown in Fig. 10 of Hughes et al (1998). This correction to the value for H₀ is in the right direction for Ω_baryon = 1 but it is clearly not yet enough.

However, it is interesting to consider the possible reasons for the change in the zeropoint of the TF relation. Hughes et al consider that the only problem may have been the poor statistical precision of the previous calibration which was only based on six galaxies. However, it has been claimed previously that the TF relation may be affected by Malmquist bias (Sandage 1994 and references therein) and it has to be said that Fig. 1 does give the impression of there being a scale-error in the TF relation rather than simply a zeropoint error. The least squares fitted line in Fig. 1 gives a 2.1σ rejection of a null hypothesis of a slope of unity; this is evidence that the TF error is distance dependent. Sandage (1994) has further predicted that a signature of Malmquist bias in the TF relation would be if the value of H₀ was a function of the line-width of the galaxy. In
Fig. 2, which shows the correlation between Cepheid/SNIa-TF residuals and TF linewidths for galaxies with (m-M) > 29.5, we find that there is some evidence for this effect with low linewidth galaxies showing the biggest (∼0.7 mag) residuals. Again the effect is at the 2σ level and is to be confirmed in larger samples. Of course, if the Cepheid/SNIa-TF error is caused by Malmquist bias then the 22±5% effect noted here may be a lower limit to the actual error in the TF scale at larger distances. Since the TF relation has been used as far as the Coma cluster and beyond, the further validation of the TF distance scale may await the detection of Cepheids in spirals at the distance of the Coma cluster; such observations would be possible from a Next Generation Space Telescope with diffraction limited performance in the visible wavebands.

3. Conclusions & Discussion.

Our conclusions are as follows:

- Cepheid and SNIa observations suggest that Tully-Fisher distances at $v \sim 1000\text{ km s}^{-1}$ are too short by 22±5%.
- The Pierce & Tully (1992) Tully-Fisher distance to Virgo therefore increases from 15.6 Mpc to 19.0±1.8 Mpc.
- The corresponding Pierce & Tully estimate of $H_0$ at Virgo therefore decreases from $H_0 = 84$ to $H_0 = 69\pm8\text{ km s}^{-1}\text{ Mpc}^{-1}$, assuming their Virgo infall model.
- Tully-Fisher distances may be affected by Malmquist bias which implies that the TF-Cepheid/SNIa discrepancy could worsen at larger distances.

We finally consider whether the real value of $H_0$ could still be significantly lower than that quoted above. If we take the view that the TF relation at large distances may be affected by Malmquist bias then we may only trust TF estimates of $H_0$ at $v \sim 1000\text{ km s}^{-1}$. Then we take our revised TF distance of 19.0±1.8 Mpc and apply the 17% Cepheid zeropoint correction of Feast & Catchpole (1997) based on Hipparcos parallaxes of Cepheids and the likely effects of metallicity. This then results in a Virgo distance of 22.2±2.5 Mpc. Assuming neither our infall velocity into Virgo nor the peculiar motion of Virgo we naïvely take the heliocentric velocity of Virgo of 1016±42 km s$^{-1}$ of Pierce & Tully (1992) which results in an estimate of $H_0 = 46\pm5\text{ km s}^{-1}\text{ Mpc}^{-1}$. Now clearly the error here does not take into account the large systematic error caused by our ignorance of the peculiar velocities. And certainly if we repeat the above experiment with the revised TF estimates of the distance to Fornax we then obtain $H_0 = 65\pm7\text{ km s}^{-1}\text{ Mpc}^{-1}$; with Ursa Major we obtain $H_0 = 43\pm5\text{ km s}^{-1}\text{ Mpc}^{-1}$. Clearly the effects of peculiar velocity are important and are causing significant errors in our $H_0$ estimate. However, our only aim here is to point out that the range of $H_0$ estimates from the Hipparcos/HST Cepheid recalibrated TF scale at $v \sim 1000\text{ km s}^{-1}$ certainly brackets values as low as $H_0 \sim 40\text{ km s}^{-1}\text{ Mpc}^{-1}$. Thus we take the view that the Tully-Fisher estimate of $H_0$ may not yet have converged to its final value and that the Tully-Fisher relation may still allow our simple cosmological model with $\Omega_{\text{baryon}} = 1$. 
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