Interim report [1] on calibration of the Tully-Fisher relation in the HST Key Project to measure H_0 [2]

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Abstract

With an interim calibration based upon half the Key Project's galaxies the Tully-Fisher relation is beginning to look properly calibrated. Applied to distant clusters the H band and I band TF relations yield $H_0 \approx 73$ km/sec/Mpc with the interim calibration. Allegations of bias in the Tully-Fisher relation are disputed. Confirming evidence is seen in velocity field fits to the Key Project galaxies. Strongly confirming evidence appears in an interim calibration of the (D_n, σ) relation.

1 Introduction

The aim of the Key Project on the Extragalactic Distance Scale is the determination of the Hubble Constant to 10% accuracy. This is a tall order when you consider that no distances outside the local 100 pc are known to better than 5% accuracy. Nevertheless, the Key Project in the first five years of the Hubble Space Telescope program is laying down the database which will remain as the fiducial system for distance determinations in the expanding Universe over the Milky Way's 20 Mpc neighborhood. These Cepheid distance measurements are used in the Key Project to calibrate secondary distance indicators of various kinds. These in turn extend the measurements out to 100 Mpc and beyond.

Controversy about the Hubble Constant outside the margins of $\pm10\%$ will be about how best to deploy secondary distance indicators, about which are the best standard candles. One of the most successful has been the Tully-Fisher relation (Fisher & Tully 1977). The Tully-Fisher relation was perhaps the first of the modern secondary distance indicators, in which the filter used to narrow the luminosity distribution function was quantitative rather than morphological. The Tully-Fisher standard candle is a galaxy of a standard 21 cm velocity width. The role of HST is to determine the luminosity of that standard galaxy. Tully-Fisher distances, however, depend upon the assumption that the structure and dynamics and chemistry of disk galaxies is the same function of luminosity everywhere. In case the word chemistry seems a little broad, we can be more specific and say mass-to-light-ratio.

Although this is a reasonable assumption, it is no more than that. The soundest basis for the extragalactic distance scale is the concurrence of a set of secondary distance indicators with different underlying astrophysics.

2 The calibration data in 1996

The primary data in the H band remains the work of Aaronson *et al.* (1982). Aaronson *et al.* presented H magnitudes evaluated at a fractional isophotal diameter $\log(A/D_1) = -0.5$, where A is the aperture size and D_1 was closely related to the RC2 D_0 diameter. Tormen & Burstein (1995) have recalculated these magnitudes according to the isophotal diameter conventions of the RC3. These are referred to below as H_g magnitudes.

There has been a significant increase since 1982 in the number of galaxies with 21 cm maps and kinematic solutions. There is no evidence for a systematic difference between optical and kinematic inclinations of disk galaxies (Rhee 1996). We have therefore recalculated $\Delta V(0)$ for all Tully-Fisher galaxies without the 3° additive term in the inclination equation (4) of Aaronson, Mould & Huchra (1980).

Some of these data (e.g. N300 and N3351) involve significant ($\sim$1 mag) extrapolation of the original aperture measurements. The references for the new HST Cepheid distances are: Graham *et al.* 1996 (N3351); Silbermann *et al.* 1996 (N925) ; Rawson *et al.* 1996 (N3621); Tanvir *et al.* 1995 (N3368); Saha *et al.* 1996 (N4536).

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3 Galaxies with Cepheid distances

Collecting the currently available H band data we find the following interim calibration relation:

$$H_{-0.5}^{abs} = -21.3 - 11(\log \Delta V(0) - 2.5)$$

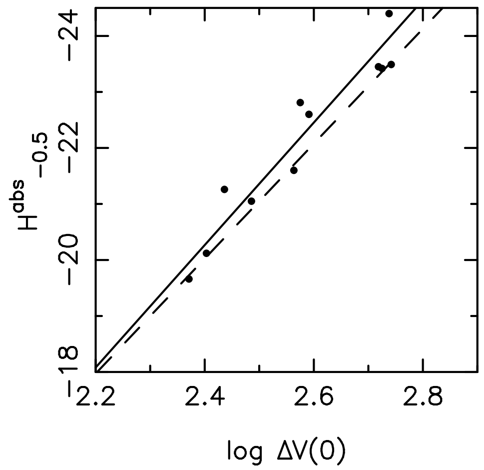

Figure 1: *M33, M31, N300, N2403, M81, N3621, N3351, N925, N4536, N7331, N3368. The solid line is equation 1; the dashed line is the previous calibration by Freedman 1990*

This is a apparently different relationship from the Freedman (1990) calibration we have adopted up to now (Figure 1). The difference is not something to dwell on. The previous calibration was limited by small number statistics, and the interim calibration is still quite poorly determined (*cf.* Figure 4). The corresponding figure using Tormen & Burstein (1995) data instead of Aaronson,Huchra & Mould data is Figure 2. The new data are on a different photometric system and cannot be interchanged. The Freedman calibration should not be used with these new data.

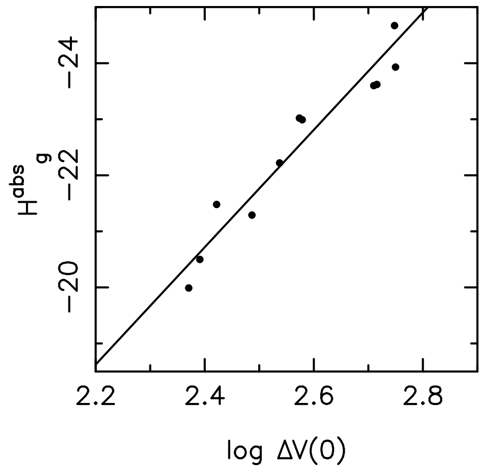

Figure 2: *Solid line – fit to all 11 galaxies; Omission of N300 and N3351 steepens the relation slightly.*

The corresponding interim calibration relation is:

$$H_g^{abs} = -21.7 - 10.5(\log \Delta V(0) - 2.5)$$

The scatter around the mean relation is 0.41 mags.

3.1 I magnitudes

There is a larger body of photometric data in the literature consisting of I magnitudes. The calibrator galaxy data to hand at present is due to Pierce & Tully (1988, 1992) and defines Figure 3.

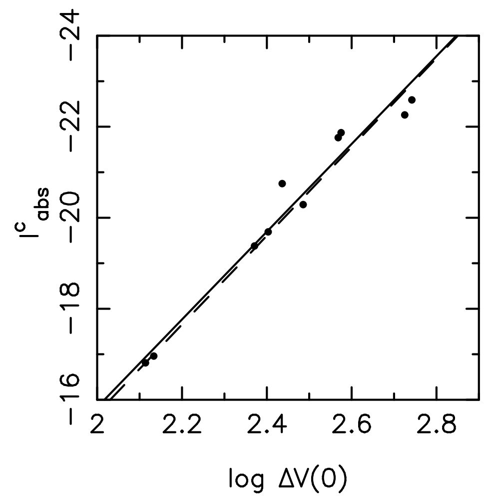

Figure 3: *I band; the dashed line is Virgo from Mould et al. 1991. The following galaxies are shown: M31, M33, N3109, N300, N2366, N2403, N3031, N925, N4536, N4639.*

The interim calibration is

$$I_c^{abs} = -20.7 - 9.75(\log \Delta V(0) - 2.5)$$

4 Galaxies with group and cluster distances

A number of the Key Project Cepheid galaxies provide more than one calibration datapoint to the Tully-Fisher relation. Again we begin with H band and show the $H_{-0.5}$ calibration in Figure 4.

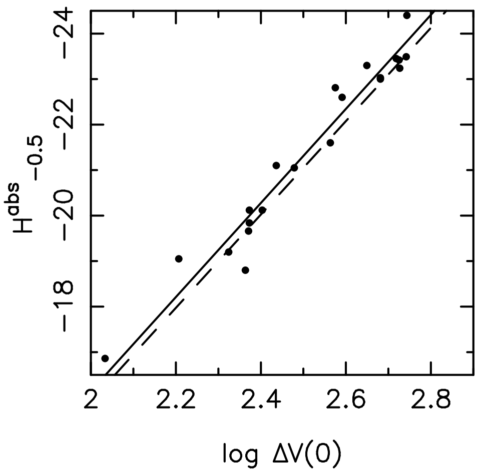

Figure 4: *M101 group, Leo triplet and N1023 group included*

Similarly, the inclusion of well known groups of galaxies yields a well-defined I band Tully-Fisher relation (Figure 5). The field and Virgo cluster relations track each other closely. The cluster environment does not seem to delineate a distinct Tully-Fisher relation.

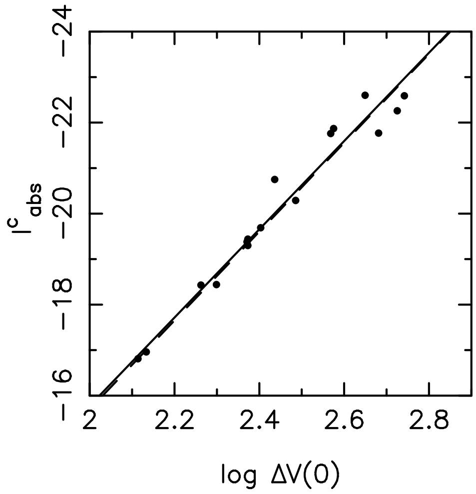

Figure 5: *M31 M33 N3109 N300 N2366 N2403 N2976 N3031 N4236 N891 N925 N949 N1003 N4536 N3627 N4639. The dashed line is again the Virgo cluster; the solid line is a fit to the data.*

5 Biases resulting from selection effects

In a series of papers Sandage & Tammann have examined the effects of flux limits on the measurement of extragalactic distances. Sandage (1994a) notes that neglect of selection effects will lead to a Hubble constant which increases outward (with increasing distance from the observer). Sandage (1994b) shows how to correct samples of field galaxies whose Tully-Fisher distances are more likely to be underestimated than overestimated. A worked example is provided by Sandage, Tammann, & Federspiel (1994) in the case of Mathewson, Ford & Buchorn's (1992) sample, a primary database in the study of peculiar velocities. Federspiel, Sandage, & Tammann [FST] (1995) consider the effect of flux limits on the measurement of cluster distances. The effect is the same as it is on the Cepheid period luminosity relation, namely to bias (luminosity / velocity-width) or (luminosity / period) slopes to too shallow values. However, Figure 6 shows that the correction derived by FST is not appropriate.

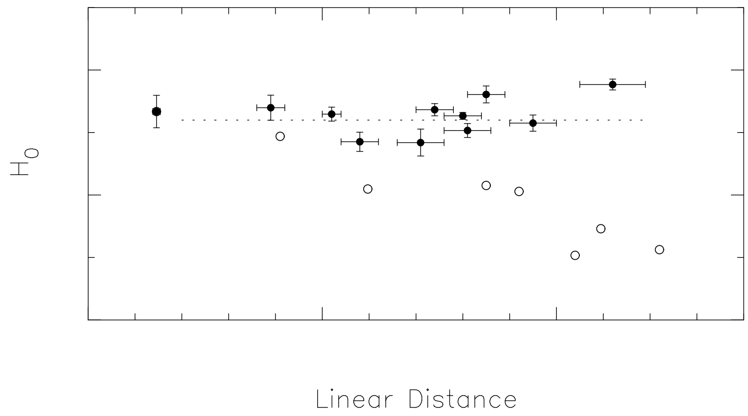

Figure 6: *The velocity distance ratios of the 11 clusters of galaxies studied by Aaronson et al. (1986). Ratios corrected by FST are denoted by open symbols. This CPIB correction is misconceived and should not be applied.*

This is because FST have addressed the wrong problem. The Aaroson *et al.* Tully-Fisher data are effectively 21 cm flux limited, not infrared flux limited. Every galaxy which can be detected at 21 cm can be detected at optical and infrared wavelengths. While it is true that these data are not the result of a 21 cm survey as such, optical searches of these clusters from the Palomar Observatory Sky Survey were carried out in support of this work to deeper limits than the Zwicky catalog.

If H_0 = 50 km/sec/Mpc the Tully-Fisher diagram for the Pisces cluster compared with that of the calibrators in Figure 4 is shown in Figure 7. Assuming the data are correct, there are two possibilities. Either a selection effect is causing us to miss galaxies like the solid symbols in Pisces or H_0 significantly exceeds 50 km/sec/Mpc. Omission of the correction of the Pisces redshift for 490 km/sec motion of the observer (which may or may not be shared by Pisces) makes the discrepancy in Figure 7 0.2 mag worse. Compare Figure 7 with Figure 1 of Sandage (1994b). In both cases Sandage would have us believe the first of these possibilities, the selection effect.

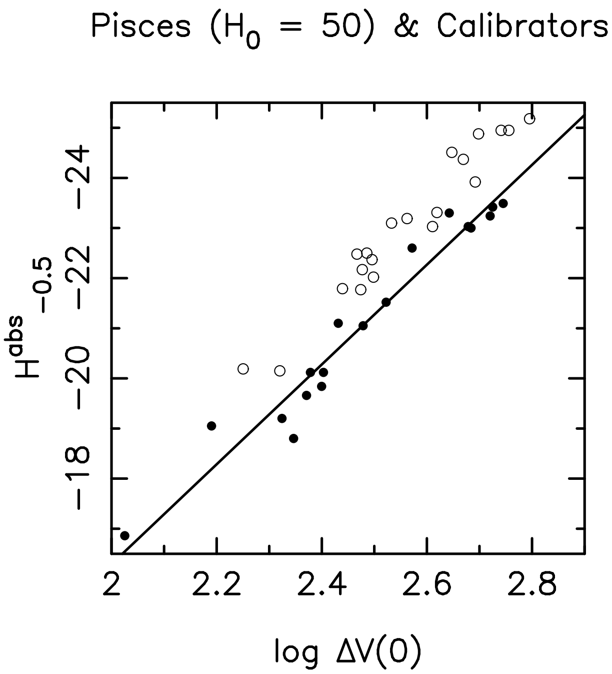

Figure 7: *Solid symbols: galaxies from Figure 4; open symbols Pisces cluster galaxies for* H_0 = *50 km/sec/Mpc*

Now selection bias does affect Tully-Fisher data. Elliptical and S0 galaxies tend to be missing from HI selected samples. The resultant bias was considered by Mould *et al.* (1991). One of the more robust arguments in the "bias series" of papers is that conclusions about the physical world should not depend on the depth of the sample. In Figure 8 we divide the sample for cluster AWM 3 (Mould *et al.* 1993) into HI flux greater and less than its median value. We do not see an effect like Figure 7.

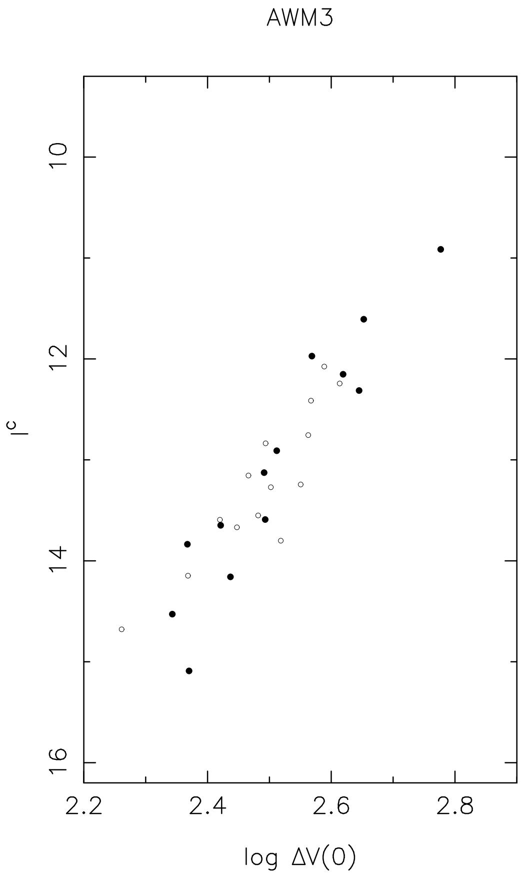

Figure 8: *Solid symbols: HI flux > 3 Jy-km/sec; open symbols: HI flux < 3 Jy-km/sec*

The third possibility is environmental effects. We have already remarked on the near identity of field and Virgo cluster Tully-Fisher calibrations. Giovanelli (this volume) has also searched for environmental effects without detecting their presence. Schroder (in a poster) has drawn attention to B–I color differences at constant line-width in different clusters. Stellar population differences of this sort are minimized in the infrared Tully-Fisher relation.

6 Flow Models

With the absolute distances for a field sample of galaxies in hand, the flow model of Han and Mould (1990) is able to put strong constraints on the distance of Virgo and hence the Hubble constant in km/s/Mpc instead of km/sec/Virgo.

We did the following tests using Model 11,19 & 20 in Table 4 of Han & Mould. For each model, the Virgo distance was allowed to change from 12 Mpc to 30 Mpc, and the rms of the residual velocity was calculated (observed – predicted velocity). Figure 9 shows this rms against Virgo distance shows a minimum, which is a best estimate of the Virgo distance from the input data (and the model). The Hubble velocity of the Virgo is a model output, so the H_0 value naturally emerges for each model.

We note the following:

1. M100 is not used, because it is too close to the Virgo center; the velocity model is not reliable in the immediate region of the infall center.

2. The "local anomaly" is included in all the models (Han & Mould; Faber & Burstein 1988)

3. The experiment was repeated without N4536, as N4536 appears to have the largest residual. The differences are less marked than those arising from different model parameters.

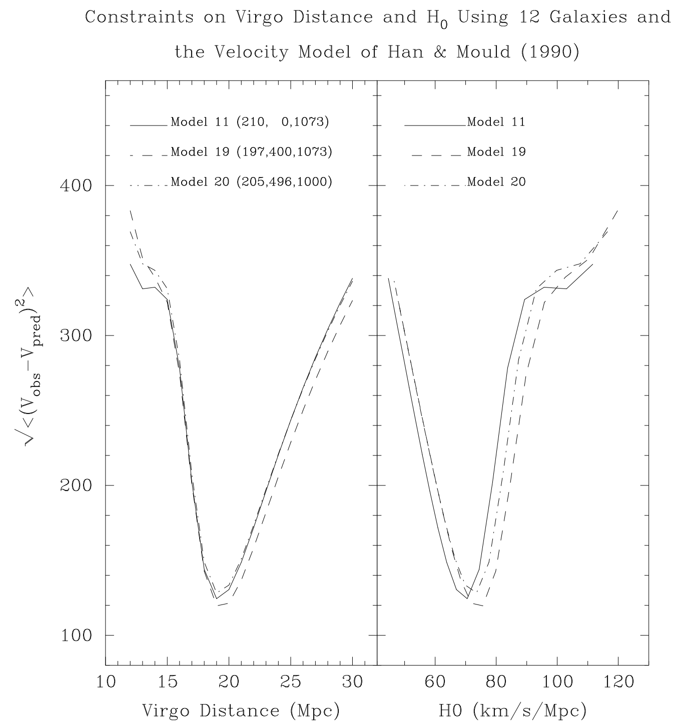

Figure 9: *Velocity residuals for the Key Project galaxies from the flow model of Han & Mould 1990. The three parameters given in parentheses are Virgocentric infall velocity, Great Attractor infall velocity and Virgo redshift respectively.*

4. The three models illustrated here are respectively, (11) pure Virgocentric flow, (19) infall to two centers (Virgo and the Great Attractor), and (20) the same as 19 with a lower Virgo cluster redshift. The latter two models have the added strength that they reproduce the cosmic microwave dipole anisotropy quite well.

7 Calibration of the $(D_n,\ \sigma)$ relation

Perhaps the best example of a set of relative distances awaiting absolute calibration is that established by the Seven Samurai (Burstein *et al.* 1987). Careful attention has been paid to the homogeneity of the photometry and velocity dispersion information for this database (Faber *et al.* 1979). To provide an interim calibration of these data we define the unit of distance (the Samurai) to be the geometric mean of the Leo, Virgo and Fornax clusters. The corresponding $(D_n,\ \sigma)$ and Cepheid distances are:

$$R = 1175 \pm 51 \quad km/sec \qquad\qquad D = 15 \pm 1 Mpc$$

We now select all groups and clusters of galaxies in the database with four or more $(D_n,\ \sigma)$ distances. Their redshifts in the cosmic microwave background frame and their distances in Samurai are plotted in Figure 10. The slope of this relation is very well determined at 1100 $\pm$ 22 km/sec/Samurai. The corresponding determination of the Hubble Constant is H_0 = 73 $\pm$ 6 km/sec/Mpc. Velocity field and $(D_n,\ \sigma)$ systematics should be added into the error budget. The possibility that NGC3351, NGC4321, and NGC1365 are in the foreground of the elliptical galaxies in their respective clusters should also be added to the error budget.

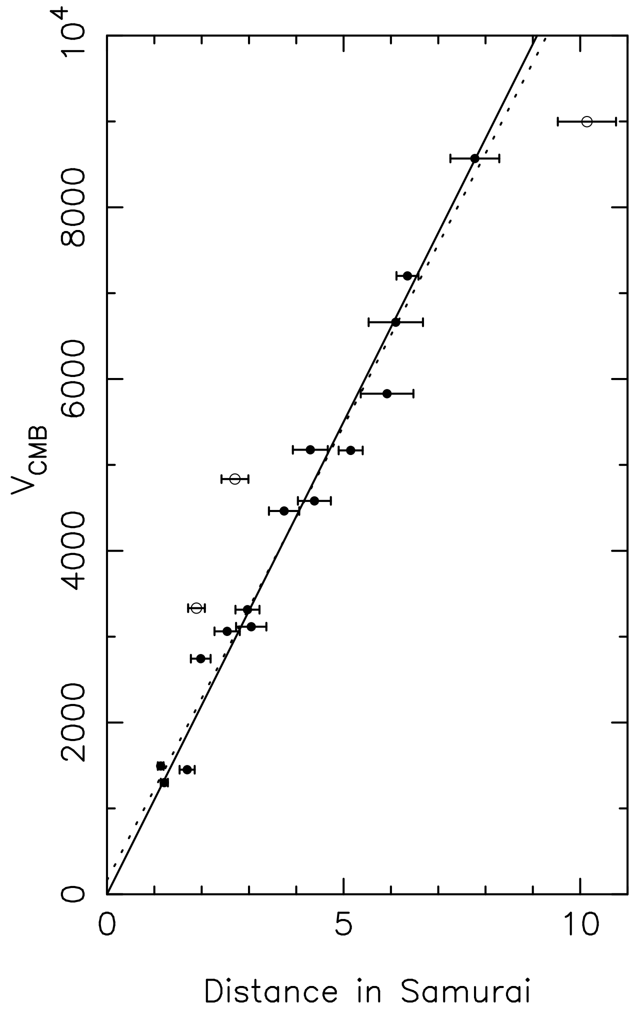

Figure 10: *Hubble ratios for groups and clusters in the Seven Samurai database. We define the unit of distance (the Samurai) to be the geometric mean of the Leo, Virgo and Fornax clusters. Three clusters with $\chi^2 > 10$ in Table 3 of Faber et al. (which is the source of all the data here) are denoted as open symbols and rejected from the fit (solid line through the origin; dotted line with a free intercept).*

8 H_0 from the Tully-Fisher relation

Let us return now to the Tully-Fisher relation. Fitting the I magnitude calibration to 5 clusters of galaxies, we obtain the results shown in Figure 11. The I band photometry has the advantage of a basis in total rather than isophotal galaxy magnitudes. Fitting the $H_{-0.5}$ magnitude calibration to 7 clusters of galaxies from Aaronson *et al.* (1986, 1989), we obtain the lower part of Figure 11.

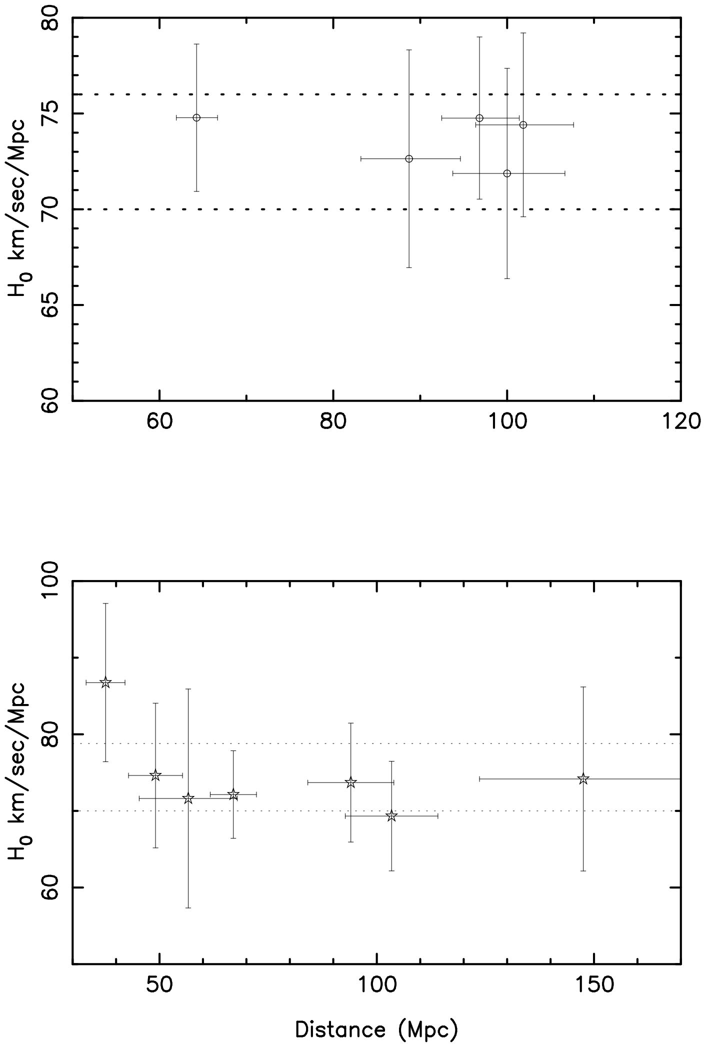

Figure 11: *Tully-Fisher distances with the interim calibration for the five clusters of Mould et al. 1993 without evidence of substructure. The dotted lines are 2σ limits on H_0 (internal error). The lower part of the figure show similar clusters studied by Aaronson et al. with 10 or more members. The lowest redshift cluster is Antlia which probably has a positive peculiar velocity in the CMB frame.*

One might conclude from Figure 11 that the interim value of H_0(Tully-Fisher) is 73 ± 4 km/sec/Mpc. But in addition to possible I band versus H band differences, the dominant systematic errors are a 6% error in distance from the still sparse calibration and a 5% uncertainty in the distance of the LMC.

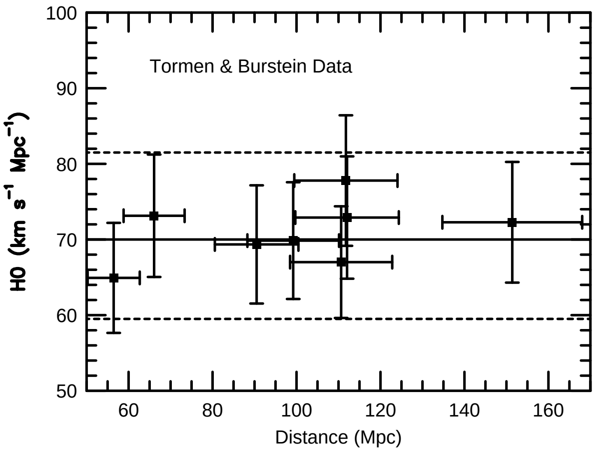

Figure 12: *Eight of the clusters of Aaronson et al. with distances from photometry reduced by Tormen & Burstein.*

Agreement between I band and H band cluster distances is in fact disturbed by adoption of the Tormen & Burstein corrected H photometry, which yields a distance for Coma 5% larger than that obtained with the original Aaronson photometry, even after correction by $1.9z$ for $(1 + z)^4$ 25th isophote dimming.

We tend to prefer the original photometry for the following reasons.

1. The TB isophotal diameters D_g are corrected to face on using precepts which assume optically thick disks in spiral galaxies (Valentijn 1990). There is significant counter-evidence (Byun, Freeman & Kylafis 1994).

2. Aaronson *et al.* isophotal diameters D_1 are more often than not based on direct CCD surface photometry. Although the surface photometry of Cornell *et al.* (1987) is included in the RC3 transformation database, the catalog values for our cluster galaxies are transformed UGC and ESO eye estimates.

Fortunately, the I band magnitudes are total rather than isophotal magnitudes and independent of these concerns. They are dependent on more significant internal extinction corrections, but there is less scope for systematic distance error in these than in the inhomogeneous isophotal diameter database of the RC3. For Coma Bernstein *et al.* (1994) have succeeded in measuring total H magnitudes. However, there is nothing equivalent available to calibrate a total H Tully-Fisher relation.

9 Conclusions

Significant progress has been made in the last few years in reducing the uncertainty in the value of the Hubble Constant, the key timescale parameter in cosmological models. Cepheid distance determinations with HST are in the process of recalibrating distance indicators based on galaxy dynamics (*e.g.* Tully and Fisher 1977) and supernova standard candles (*e.g.* Kowal 1968). We have progressed beyond the famous factor of two controversy (*e.g.* Sandage & Tammann 1990; de Vaucouleurs 1985) and results are converging to values between $\sim$80 km/sec/Mpc for surface brightness fluctuations (Tonry, this volume) and $\sim$60 km/sec/Mpc for SNeIa (Riess *et al.* 1995; Sandage *et al.* 1996). A Hubble Constant good to 10% (1σ uncertainty) is the goal of the H_0 key project for HST. The surviving differences in the results just cited suggests that there are systematic errors still to be found in secondary distance indicators. These must be tracked down by comparison with the other top ranked distance indicators, the planetary nebula luminosity function (PNLF) and surface brightness fluctuations.

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