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INTERIM REPORT ON THE HST KEY PROJECT TO MEASURE H_0

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ABSTRACT

With an interim calibration based upon half the Key Project's galaxies, the Tully-Fisher relation, the (D_n, σ) relation and type II supernovae yield $H_0 = 73 \pm 10$ km/sec/Mpc.

I. 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. The soundest basis for the extragalactic distance scale is the concurrence of a set of secondary distance indicators with different underlying astrophysics.

II. THE TULLY FISHER CALIBRATION IN 1996

Controversy about the Hubble Constant outside the margins of ±10% 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 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.

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.

(a) Galaxies with Cepheid Distances

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

$$H^{abs}_{-0.5} = -21.3 - 11(\log \Delta V(0) - 2.5) \qquad (1)$$

This is an 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. The scatter around the mean relation is 0.41 mags.

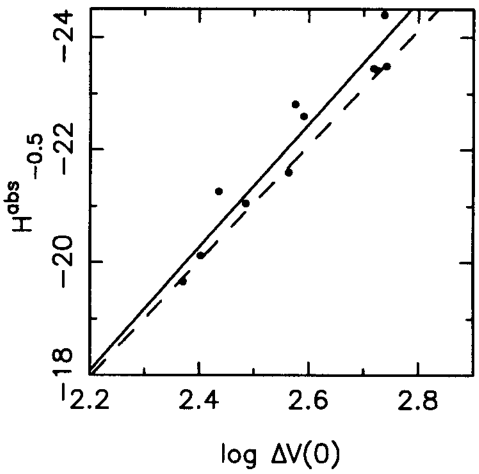

Fig. 1.— M33, M31, N300, N2403, M81, N3621, N3351, N925, N4536, N7331, N3368. The solid line is equation 1; the dashed line is the previous calibration by Freedman 1990.

(b) 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. We begin with H band and show the $H_{-0.5}$ calibration in Figure 2.

Similarly, the inclusion of well known groups of galaxies yields a well-defined I band Tully-Fisher relation (Figure 3). The field and Virgo cluster relations track each other closely. The cluster environment does not seem to delineate a distinct Tully-Fisher relation. Details of these new calibrations are provided by Mould *et al.* (1996).

The interim calibration is

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

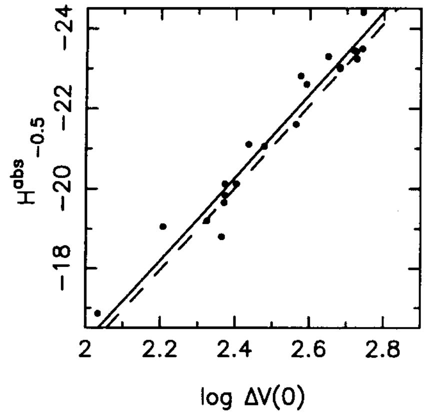

Fig. 2.— M101 group, Leo triplet and N1023 group included

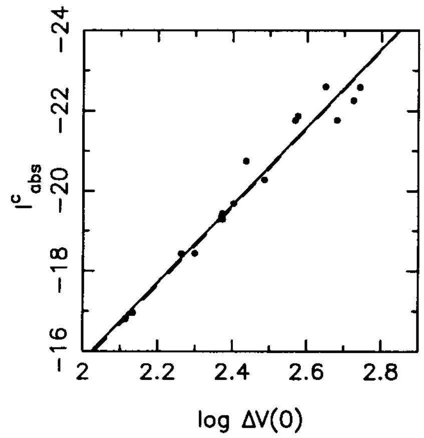

Fig. 3.— M31 M33 N3109 N300 N2366 N2403 N2976 N3031 N4236 N891 N925 N949 N1003 N4536 N3627 N4639. The dashed line is again the Virgo cluster; the solid line is a fit to the data. They are almost indistinguishable.

III. 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 4 shows that this *rms* has a minimum value, which offers 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.

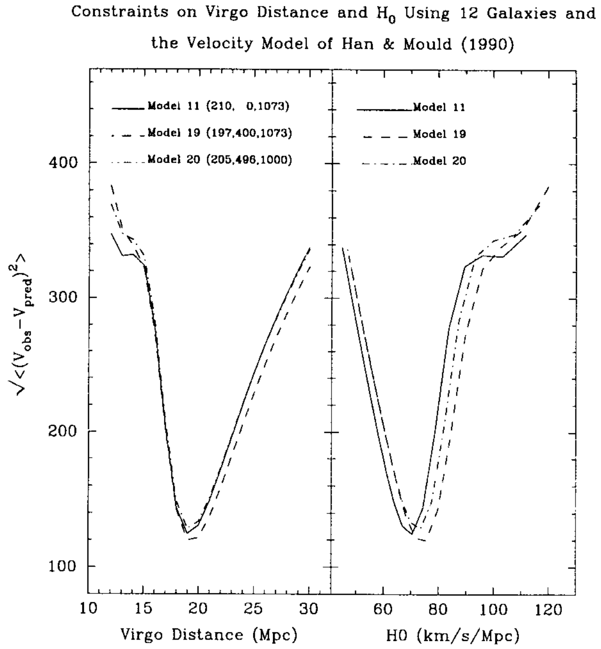

Fig. 4.— Velocity residuals for the Key Project galaxies from the flow model of Han & Mould 1990. The three parameters given in parentheses are Virgocentric infall velocity, Great Attractor infall velocity and Virgo redshift respectively.

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.

IV. CALIBRATION OF THE (D_n, σ) 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.* 1985). 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, σ) and Cepheid distances are:

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

We now select all groups and clusters of galaxies in the database with four or more (D_n, σ) distances. Their redshifts in the cosmic microwave background frame and their distances in Samurai are plotted in Figure 5. The slope of this relation is very well determined

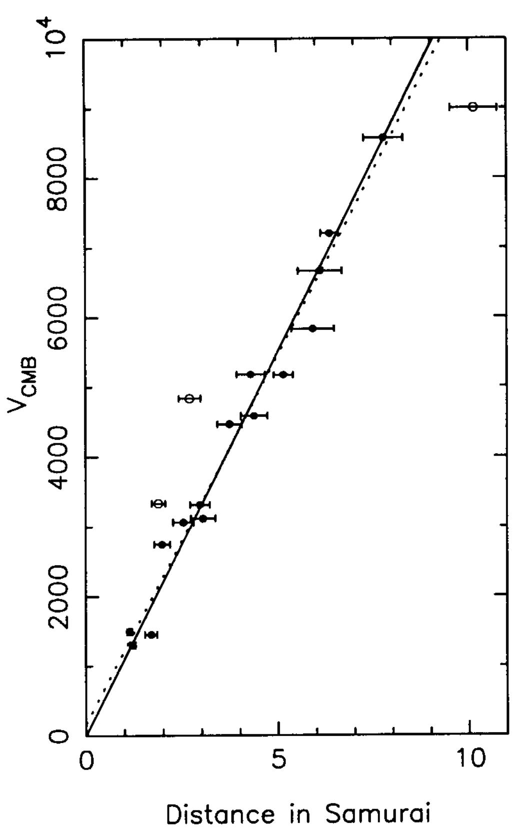

Fig. 5.— Hubble ratios for groups and clusters in the Seven Samurai database. We define the unit of distance (the Samurai) to be the geometric mean of the Leo, Virgo and Fornax clusters. Three clusters with $\chi^2 > 10$ in Table 3 of Faber *et al.* (which is the source of all the data here) are denoted as open symbols and rejected from the fit (solid line through the origin; dotted line with a free intercept).

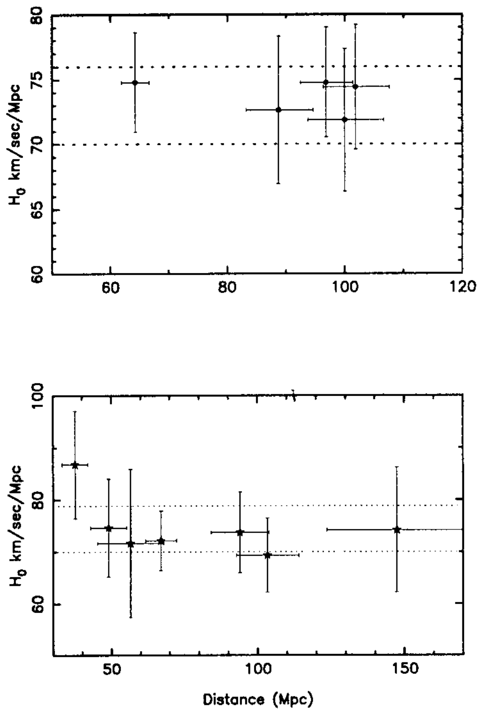

Fig. 6.— Tully-Fisher distances with the interim calibration for the five clusters of Mould *et al.* 1993 without evidence of substructure. The dotted lines are 2σ limits on H_0 (internal error). The lower part of the figure show similar clusters studied by Aaronson *et al.* with 10 or more members. The lowest redshift cluster is Antlia which probably has a positive peculiar velocity in the CMB frame.

at 1100 ± 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.

V. 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 6. 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 6.

One might conclude from Figure 6 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.

VI. TYPE II SUPERNOVAE

Although not blackbodies, as Baade & Wesselink assumed, Type II supernovae have photospheres, whose emissivity can be calculated. Distances are derived from a comparison of photospheric angular diameter and the time integrated expansion velocity. Sophisticated radiative transfer ca lculations can make EPM an *ab initio* measurement of distance. A more empirical approach is to test the models with SNIIe like SN1987A and others in galaxies with Cepheid distances.

There is no evidence that any empirical recalibration of the expanding photospheres method (EPM) is required at present by the Cepheid data. EPM provides independent and consistent constraints on the Hubble constant, currently yielding $H_0 = 73 \pm 11$ km/s/Mpc (see Figure 7 from Schmidt *et al.* 1994).

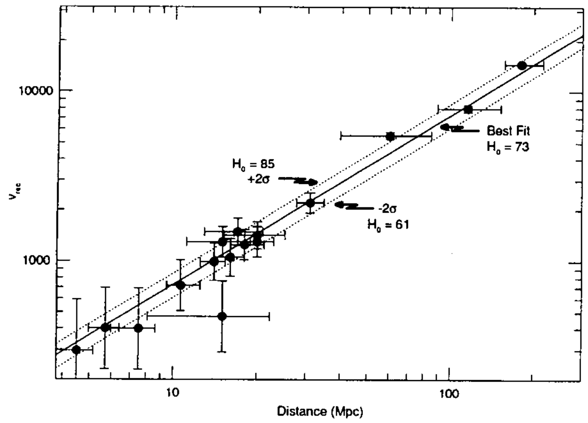

Fig. 7.— The Hubble flow from EPM distances (Schmidt *et al.* 1994).

VII. TYPE Ia SUPERNOVAE

Freedman *et al.* (1996) discuss the recalibration of the Type Ia supernova standard candle, when the decline rate parameter is taken into account in the context of high quality photometric data. Freedman finds $H_0 = 68 \pm 8$ km/sec/Mpc from a fit to the data shown in Figure 8.

VIII. 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.* Fisher and Tully 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 ~80 km/sec/Mpc for surface brightness fluctuations and ~60 km/sec/Mpc for SNeIa (Riess *et al.* 1995; Saha *et al.* 1996). A Hubble Constant good to 10% (1σ uncertainty) is the goal of the H_0 key project for HST (Kennicutt, Freedman & Mould 1995). 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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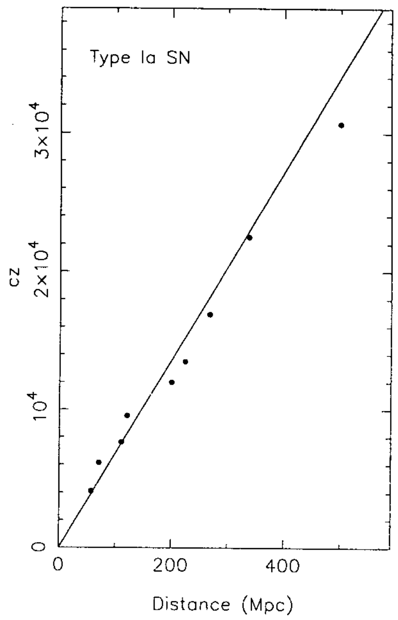

Fig. 8.— The Hubble flow from SN Ia distances (Freedman *et al.* 1996).

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