A DIRECT CEPHEID MEASUREMENT OF H_0

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We reverse the climb up the distance ladder by computing H_0 directly from galaxies with Cepheid distances from the HST Key Project on the distance scale (H0KP). We adjust for peculiar velocities by using a model derived from galaxies with SBF distances. We find $H_0 = 88 \pm 2$ km sec^{-1} Mpc^{-1} (statistical), considerably larger than the canonical value of 70 km sec^{-1} Mpc^{-1} quoted by the H0KP.

1 Introduction

For the better part of this century, Cepheid variables have justly commanded the bulk of attention during discussions of the cosmological distance scale. The last decade has assigned Cepheids to a secondary role as calibrators for secondary distance indicators, like Type Ia Supernovae, that can push past the limits of the local Hubble Flow. This absolute calibration of secondary distance indicators has been the job of the Hubble Space Telescope (HST) H_0 Key Project Team (H0KP). But, while pushing distance measurements far enough into the Hubble flow to reduce the effect of peculiar velocities, this 'climb up the distance ladder' risks the propagation of systematic errors inherent in the absolute calibration.

2 The SBF Zero Point

For a recent description of the method behind Surface Brightness Fluctutations (SBF[2]), see the contribution by S. Mei to these proceedings.

Over the past 5 years, Tonry et al.[3] have measured distances to galaxies within ~ 3500 km sec^{-1} using the SBF method. They find that the fluctuation magnitudes, $\overline{M}$ are related to color:

$$\overline{M}_I = A + (4.5 \pm 0.25)[(V - I)_0 - 1.15] \tag{1}$$

Table 1: Tonry et al. calibration of the SBF distance scale

Galaxy	$\bar{\mu}_{ceph}$	$(m_I^0)^a$	Zero Point A (mag)
NGC0224	22.67 ± 0.06	24.44 ± 0.10	-1.77 ± 0.12
NGC3031	26.21 ± 0.25	27.80 ± 0.08	-1.59 ± 0.26
NGC3368	28.34 ± 0.21	30.20 ± 0.10	-1.86 ± 0.23
NGC4548	29.68 ± 0.54	31.04 ± 0.08	-1.36 ± 0.55
NGC4725	28.87 ± 0.34	30.57 ± 0.08	-1.70 ± 0.35
NGC7331	28.85 ± 0.16	30.89 ± 0.10	-2.04 ± 0.19

Distances provided by overlapping Cepheid galaxies have been used to calibrate the SBF zero point, A. This gives the SBF relation an absolute distance scale, instead of a relative one. The six galaxies with overlapping SBF and Cepheid data, as well as their individual zero points, are provided in Table 1.

Since SBF measurements yield accurate distance information out to 30 Mpc, they can, when coupled with redshift measurements, be used to measure the local peculiar velocity field, $\mathbf{v}_p(\mathbf{r})$, and H_0 through a maximum likelihood analysis. From the 300 early-type galaxies in the SBF survey, Tonry et al. [1] found $H_0 = 77 \pm 4 \pm 7$ km s^{-1} Mpc^{-1}. Using a smaller (6 galaxy) data set of SBF measurements from the HST, the H0KP[4] team found $H_0 = 69 \pm 4 \pm 6$ km s^{-1} Mpc^{-1}. Differences in the two values are ascribed to differences in data sets, extinction corrections, choice of velocity model, and adopted zero point.

These derived values of H_0 are degenerate with the chosen value of A. Table 1 reveals a spread in A of approximately $.8$ mag, with half of the measured values within $.15$ mag of the Key Project[4] and Tonry et al.[1] adopted values of $A = -1.79 \pm .09$ mag and $A = -1.74$ mag, respectively. Zero point errors are due both to small sample size and to uncertainties in the Cepheid distance scale itself. Also, SBF measurements do not apply well to the spiral galaxies where Cepheids are found.

To avoid complications brought on by the propagation of Cepheid PL errors into the SBF zero point, we adopt a method in which the SBF absolute zero point never enters our procedure; this is accomplished in a two step procedure:
(1) Model $\mathbf{v}_p(\mathbf{r})$ using only relative SBF distances (this requires knowledge of neither H_0 nor A!).
(2) Apply the resulting $\mathbf{v}_p(\mathbf{r})$ to Cepheid galaxies with absolute distances to compute H_0.

In the following, we define a new, relative SBF zero point, A', and measure all quantities in terms of Hubble flow distance, w, which has units km sec^{-1}.

$$w = H_0 \cdot d = H_0 \cdot 10^{0.2\{\mu - 25\}} = 10^{0.2\{m_I - [A' + (4.5[(V-I)_0 - 1.15])]\}} \quad (2)$$

Note that we preserve the color-dependence of the SBF distance relation.

3 The Peculiar Velocity Model

The strengths of the 300+ galaxies from the SBF survey: sky coverage; internal consistency; intrinsic precision—are well suited to recalibrating the SBF zero point in km sec^{-1} space. We determine the zero point, A', and simultaneously fit for a peculiar velocity model (using a maximum likelihood procedure discussed below) to the SBF survey data.

We use the basic velocity model presented by Tonry et al.[1], but redefine the model to depend on Hubble flow distance, $\mathbf{w}$, and refit for all his parameters accordingly. The model predicts a peculiar velocity, $\mathbf{u}(\mathbf{w})$, and an expected dispersion, $\sigma(\mathbf{w})$, at each point in Hubble flow distance space. Features of the model include a dipole, quadrupole (centered on the Local Group), and Yahil[5] "$\rho^{1/4}$" attractors based on spherical density distributions located at Virgo and the Great Attractor. Dispersions are Gaussians of specified amplitude centered at each of the attractors, as well as on Fornax. An overall thermal dispersion of 187 km sec^{-1} is then added in quadrature to the other dispersions. A more detailed exlpanation of the model is described in Appendix A of Tonry et al.[1]

4 Maximum Likelihood estimate of the Model

4.1 VELMOD fit

VELMOD is a maximum likelihood method designed to handle biases in derivations of peculiar velocity fields. It was described fully by Willick et al.[7] and Willick & Strauss[8]. We present here a brief overview:

Our implementation begins with a Bayesian estimate of the probability of observing an SBF predicted distance modulus, μ_{obs}, given the measured redshift, cz:

$$\begin{aligned} \mathcal{P}(\mu_{obs}|cz) &= \frac{\mathcal{P}(\mu_{obs}, cz)}{\mathcal{P}(cz)} \\ &= \frac{\int_0^\infty \mathcal{P}(\mu_{obs}|\mu(w)) \cdot \mathcal{P}(w)\mathcal{P}(cz|\mathbf{w})dw}{\int_0^\infty \mathcal{P}(cz|\mathbf{w})\mathcal{P}(w)dw} \end{aligned} \tag{3}$$

$\mathcal{P}(cz|\mathbf{w})$ is a Gaussian of dispersion $\sigma(\mathbf{w})$, centered on $\mathbf{w}+\mathbf{u}(\mathbf{w})$; $\mathcal{P}(\mu_{obs}|\mu(w))$ is a Gaussian in μ with σ_{SBF} as the dispersion; and $\mathcal{P}(w) \propto w^2$. We maximize $\prod_i \mathcal{P}_i$ by minimizing $\mathcal{L} = -2 * \ln \prod_i \mathcal{P}_i$.

4.2 Virgo Treatment

Our model works poorly in the immediate vicinity of the Virgo Cluster. We therefore collapse Virgo as follows: If a galaxy is within $12°$ of the Virgo Core ($l = 283.78°, b = 47.49°$), has $cz \leq 3500$ km sec^{-1}, and has Tonry et al.[6] predicted distance modulus μ_T such that $13.3 \leq \mu_T \leq 19.3$, we set the heliocentric redshift to $cz = 1079$ km sec^{-1}. Twenty-six SBF galaxies were collapsed in this treatment of Virgo.

4.3 VELMOD fit results

By carrying out this procedure, we obtain a local peculiar velocity model that is in good agreement with that of Tonry et al.[1]—except ours is in Hubble Flow space: [$\mathbf{u}(\mathbf{w})$, not $\mathbf{u}(\mathbf{r})$].

5 Breaking the Degeneracy between A' and H_0

We now use the peculiar velocity model to compute H_0 directly from 34 galaxies with Cepheid distances.[b] The corrections from the peculiar velocity model adjust the observed redshifts to give velocities that approximate the underlying Hubble flow. There is good, though not perfect, overlap between the location of the Cepheid galaxies and the sampling of our peculiar velocity model as determined by the distribution of the SBF galaxies.

[b] Space constraints prevent a detailed analysis of the derivation of galactic distances based on the thousands of periods and luminosities now available from the Lanoix compilation and the HST KP website. The distances used, however, are our own and differ by no more than 2% from published HST KP distances to the same galaxies.

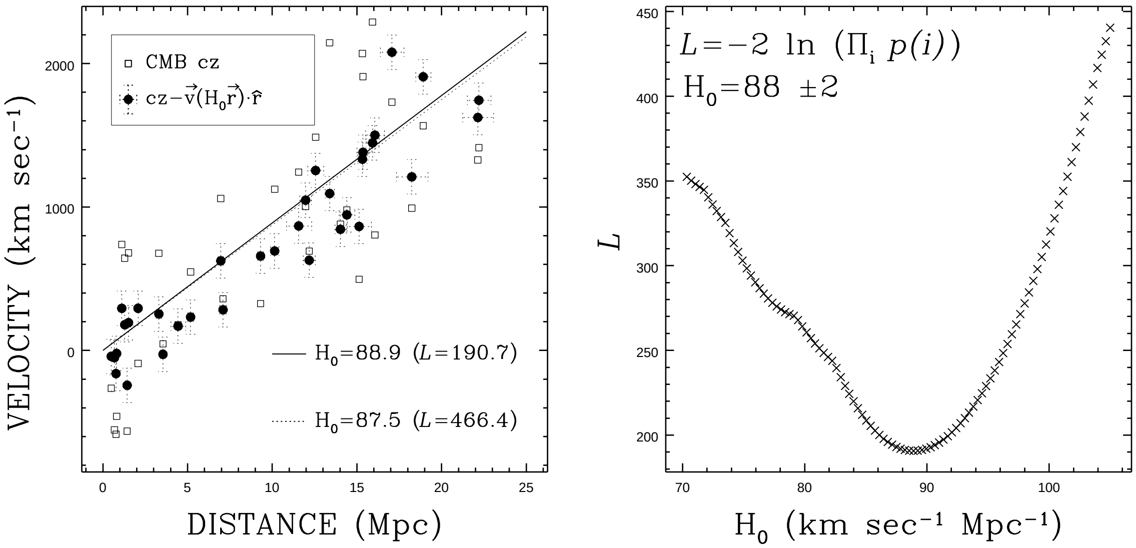

Figure 1: The panel on the left shows the best-fit Hubble diagram. The squared points are (CMB frame) redshifts with cepheid distances, while the dark circles are the redshifts corrected for peculiar velocities. The dark line is the best-fit model, while the dashed line is the result of a similar analysis with zero peculiar velocities. For the purposes of comparison, σ has been hardwired to 120 km sec^{-1}. The panel on the right shows the likelihood curve for the best fit model.

The fit uses the same likelihood maximization algorithm described previously. In this final analysis, however, the velocity model parameters are fixed. The remaining parameter, H_0, enters in only one place: the velocity model predictions for the Cepheid galaxies, $\mathbf{u}(\mathbf{w})$, take as input $\mathbf{w} = H_0 \cdot \mathbf{r}_{ceph}$.

6 Results

We find that $H_0 = 88 \pm 2$ km sec^{-1} Mpc $^{-1}$ when we apply our velocity model to the Cepheid galaxies, independent of whether we perform the entire algorithm in the CMB or Local Group frame. A zero peculiar velocity model (open squares in the left panel of figure 1) yields $H_0 = 87.5$ (CMB frame) and $H_0 = 76.3$ km sec^{-1} Mpc^{-1} (Local Group[c]). We note an abrupt improvement in the zero peculiar velocity model fit in the Local Group frame.

The minimization parameter is plotted for the CMB fit in the right panel of figure 1. The minimum value of this best fit model, $L = 190.6$, is significantly lower than the value for the zero-pecuilar velocity fit in the CMB frame, $L = 466$, and for the zero-peculiar velocity fit in the Local Group frame, $L = 251$. The near-local minima in the likelihood curve are the results of the clumping of cepheid observations with similar redshifts.

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[c]Transformations taken from Courteau & van den Bergh[9]

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