Hubble Space Telescope Key Project on the Extragalactic Distance Scale

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A "mid-term" summary report is given for the HST Key Project on the Extragalactic Distance Scale. We discuss the aims of the Key Project, progress to date, and present new results on a Cepheid distance to the galaxy NGC 1365 in the Fornax cluster. The implications of these results and a preliminary value of H_0 are given. At this stage in the project, we have Cepheid calibrators for a number of secondary distance indicators, including type Ia supernovae, the Tully-Fisher relation, type II supernovae, the surface-brightness-fluctuation (SBF) method, and the planetary nebula luminosity function (PNLF). The range over which (primary) Cepheid distances can be obtained now matches that for the (secondary) PNLF distances.

Rather than concentrate on one particular method, the goal of the Key Project is to undertake a comparison and calibration of several different methods so that cross-checks on both the absolute zero point as well as relative distances, and therefore ultimately on H_0, can be obtained. The agreement amongst various nearby distance indicators is extremely encouraging. For example, the 1–sigma *rms* difference between the relative distances measured using Cepheids as compared to the SBF, PNLF, and tip of the red giant branch (TRGB) techniques is less than 10% in distance, in all cases.

We present here estimates of H_0 determined in several different ways: The value of H_0 is computed locally (based on Cepheid distances to the Virgo and Fornax clusters), and also based on several nearby groups with Cepheid distances. In addition, the Fornax cluster is used as a stepping stone to a sample of distant clusters for which relative distances have been measured by Jerjen and Tammann using a variety of techniques. A Cepheid distance to the Fornax cluster provides two additional calibrators to the type Ia supernova distance scale, and a value of H_0 based on a total sample of 8 type Ia supernovae is presented. Finally, a comparison of Cepheid and SBF and type II supernovae is given. Our current best estimate of the Hubble constant based on an average for these different techniques is 73 $\pm$ 6 (statistical) $\pm$ 8 (systematic) km/sec/Mpc. Studies are ongoing to reduce the systematic errors; for now we adopt H_0 = 73 $\pm$ 10 km/sec/Mpc, or an overall accuracy of about $\pm$15%.

1. Introduction

It is certainly fitting that the Space Telescope Science Institute host a meeting on the Extragalactic Distance Scale at this time. Large numbers of new distances have been accumulating recently, due both to the availability of the Hubble Space Telescope (HST) in addition to large ground-based programs. Moreover, an accurate extragalactic distance scale and solid measurement of the Hubble constant was one of the top priority science goals of the HST. Although the original plans for a Large Space Telescope were scaled back considerably when the Hubble primary mirror was down-sized during the mid-1970's, one of the primary arguments for an aperture of at least 2.4m was to enable the detection of Cepheid variables in the Virgo cluster (Leckrone, private communication, Smith 1989), a goal that was achieved within months of the corrective optics being installed in HST in December, 1993.

Despite the historic difficulties surrounding the steps to an accurate extragalactic distance scale, tremendous, rapid progress has recently taken place in this field, and it is a very appropriate time to discuss and debate the current issues. Quite possibly, this meeting will be seen as a turning point in the field, putting an end to the persistent factor of two debate, and even perhaps marking the determination of a value of H_0 measured to $\pm$ 15%.

The H_0 Key Project team is a diverse group with a range of expertise in the Cepheid distance scale, secondary distance methods, and crowded-field photometry. The current members of the Key Project include W.L. Freedman, R. Kennicutt, J.R. Mould (co-PI's), S. Faber, L. Ferrarese, H. Ford, J. Graham, J. Gunn, M. Han, J. Hoessel, J. Huchra, S. Hughes, G. Illingworth, B.F. Madore, R. Phelps, A. Saha, S. Sakai, N. Silbermann, and P. Stetson, and graduate students F. Bresolin, P. Harding, D. Kelson, L. Macri, D. Rawson, and A. Turner.

2. Goals of the HST H_0 Key Project

Cepheid distances lie at the heart of the HST Key Project on the Extragalactic Distance Scale (Freedman *et al.* 1994a,b; Kennicutt, Freedman & Mould 1995); and Cepheids are employed in several other HST distance scale programs (*e.g.*, Sandage *et al.* 1996; Saha *et al.* 1994, 1995; and Tanvir *et al.* 1995).

Over the past decade enormous progress has been made in the development and testing of a number of very promising secondary distance indicators. Almost all of the articles in this current volume are a testament to the rapid progress that has been made in this area, primarily using ground-based facilities. Since these distance indicators are covered in detail elsewhere in this volume, we concentrate here on the primary focus of the Key Project, namely the calibration of secondary distance methods.

The Key Project has been designed to use Cepheid variables to determine (Population I) primary distances to a representative sample of galaxies in the field, in small groups, and in major clusters. The galaxies were chosen so that each of the secondary distance indicators with measured high internal precisions can be accurately calibrated in zero point, and then intercompared on an absolute basis. The Cepheid distances can then be used for secondary calibrations and applied to independent galaxy samples at cosmologically significant distances. Cepheid distances to the Virgo and Fornax clusters provide a consistency check of the secondary calibrations. The aim is to derive a value for the expansion rate of the Universe, the Hubble constant, to an accuracy of 10%.

A measurement of the Hubble constant to 10% accuracy poses an immense challenge given the history of systematic errors in the extragalactic distance scale. For this reason, the Key Project has been designed to incorporate many independent cross-checks of both the primary and secondary distance scales. The Key Project is described in more detail in Kennicutt, Freedman & Mould (1995), Freedman *et al.* (1994a), and Mould *et al.* (1995). Briefly, there are three primary goals: (1) To discover Cepheids, and thereby measure accurate distances to spiral galaxies located in the field and in small groups that are suitable for the calibration of several independent secondary methods. (2) To make direct Cepheid measurements of distances to three spiral galaxies in each of the Virgo and Fornax clusters. (3) To provide a check on potential systematic errors both in the Cepheid distance scale and the secondary methods. We briefly review the progress to date of the Key Project in the next section, before moving on to a discussion of our most recent results.

TABLE 1. KEY PROJECT CEPHEID DISTANCES TO DATE

Galaxy	μ_0	d (Mpc)
NGC 3031	27.80±0.20	3.6±0.3
NGC 5457	29.34±0.17	7.4±0.6
NGC 0925	29.84±0.16	9.3±0.7
NGC 3351	30.01±0.19	10.1±0.9
NGC 3621	29.17±0.18	6.8±0.7
NGC 4321	31.04±0.21	16.1±1.5
NGC 1365[1]	31.32±0.19	18.4±1.6

[1] unpublished

3. Summary of Recent Results

All three aspects of the Key Project are now well underway. Midway through our three-year program, we have discovered over 500 new Cepheid variables in 9 galaxies. Most of these galaxies were chosen to provide distances critical to the calibration of secondary distance methods. In the case of the face-on spiral galaxy M101, we have measured samples of Cepheids at two different radial positions in the disk, allowing us to begin undertaking a test of the level of sensitivity of the Cepheid period-luminosity relation to chemical composition.

Prior to the refurbishment of the telescope, observations were made using WF/PC1 in two fields in the nearby galaxy M81, in addition to a field in the outer regions of M101. Since the refurbishment mission in December of 1993, the pace of the program has increased considerably. Data have been acquired for several galaxies: M101 (an inner field), the Virgo cluster galaxy M100; seven inclined spiral galaxies: NGC 925 (a member of the NGC 1023 group), NGC 7331, NGC 3621, NGC 2541, NGC 2090, NGC 3351 (a member of the Leo I Group), and NGC 4414 (a host galaxy for a type Ia supernova). Most recently, data have been acquired for NGC 1365, a barred spiral galaxy located in the southern hemisphere cluster, Fornax.

To date the H_0 key project results have been published for 6 galaxies in the following papers: M81 (Freedman *et al.* 1994b), M100 (Freedman *et al.* 1994a; Ferrarese *et al.* 1996); M101 (Kelson *et al.* 1996), NGC 925 (Silbermann *et al.* 1996), NGC 3621 (Rawson *et al.* 1996), and NGC 3351 (Graham *et al.* 1997). These distances are listed in Table 1, which also includes our new, unpublished distance to NGC 1365. As reported elsewhere in this volume, significant progress has also been made in the HST supernova calibration project; Cepheids have been located and studied in IC 4182 (Saha *et al.* 1994), NGC 5253 (Saha *et al.* 1995) and NGC 4536 (Saha *et al.* 1996). First results have also been published for NGC 4639 and NGC 4496A (Sandage *et al.* 1996). Cepheids have been detected in the Leo I galaxy NGC 3368 (M96) by Tanvir *et al.* (1995).

Currently, the limit for measuring Cepheid distances with HST is about 3,000 km/sec, (Zepf *et al.*, 1997) a distance at which peculiar velocities can still be a substantial component of the overall cosmic expansion velocity. To date, the most distant objects observed with as part of the Key Project have velocities of less than 1,500 km/sec and require substantial amounts of telescope time (over 30 orbits of HST time per galaxy). Hence, the measurement of H_0 to ±10% cannot be achieved with Cepheids alone and the main thrust of the Key Project remains the calibration of secondary distance indicators. How-

TABLE 2. CEPHEID DISTANCES TO VIRGO CLUSTER GALAXIES

Galaxy	Distance Modulus	Distance
NGC 4321	31.04 ± 0.21	16.1 ± 1.5
NGC 4496A	31.13 ± 0.10	16.8 ± 0.8
NGC 4571	30.87 ± 0.15	14.9 ± 1.2
NGC 4536[1]	31.10 ± 0.13	16.6 ± 1.0
NGC 4639	32.00 ± 0.23	25.1 ± 2.5
Mean	31.25 ± 0.45	17.8 ± 4.1

[1] N 4536 corrected for "long" zero point by +0.05 mag

ever, direct Cepheid distances to the Virgo and Fornax clusters at cz$\geq$1,200 km/sec can still provide a consistency check at a level of $\pm$20%.

A preliminary estimate of the Hubble constant was given by Freedman *et al.* (1994a) and by Mould *et al.* (1995), based on the distance to M100 in the Virgo cluster. Initially a search for variables was conducted using only a subset of the Wide-Field camera chips, and twenty high signal-to-noise Cepheids, having periods in the range of 20 to 65 days, were identified (Freedman *et al.* 1994a). A continuing analysis eventually yielded a larger total sample of over 50 Cepheids, and additional calibration data were used to provide a refined zero point yielding a reddening-corrected distance to M100 of 16.1 $\pm$1.3 Mpc (Ferrarese *et al.* 1996).

As discussed in detail in Freedman *et al.* (1994a), one of the dominant uncertainties in the determination of H_0 based on the Virgo cluster is due to the fact that the distribution of spiral galaxies is both extended and complex. Hence, the distance to M100 alone cannot define the mean distance to the Virgo cluster to an accuracy of better than 15–20% (Freedman *et al.* 1994a, Mould *et al.* 1995). Adopting a recession velocity for the Virgo cluster of 1,404 $\pm$80 km/sec (Huchra 1988) and a Virgo distance of 16.1 Mpc (Ferrarese *et al.* 1996) yields a value of H_0 = 87 $\pm$6 (random) $\pm$16 (systematic) km/sec/Mpc. Alternatively, adopting a recession velocity of 1,179 $\pm$17 km/sec (Jerjen and Tammann 1993) results in H_0 = 73 $\pm$14 km/sec/Mpc for the same distance. The dominant sources of uncertainty in this estimate are systematic and are due to (a) the reddening correction, (b) the zero point of the Cepheid PL relation, (c) the position of M100 with respect to the center of the cluster, and (d) the adopted recession velocity of the cluster. Cepheid distances to 5 galaxies in the Virgo galaxy have now been published, and they are listed in Table 2.

One way to avoid the error due to the uncertainty in the Virgo cluster velocity is to tie into more remote clusters (using relative distance indicators) and step out to a distance where peculiar velocities are a smaller fractional contribution to the overall expansion velocity. For example, an estimate of H_0 can then also be made using the measured relative distance between the Virgo cluster and the more distant Coma cluster (Freedman *et al.* 1994a). Adopting a distance of 16.1 Mpc for the Virgo cluster, a relative Virgo-Coma distance of 77 Mpc, and a recession velocity for Coma of 7,200 km/sec, yields a value of H_0 = 77 $\pm$6 (random) $\pm$15 (systematic) km/sec/Mpc. These results indicate that the value of the Hubble constant is $\sim$80 km/sec/Mpc out to a distance of 100 Mpc, with an estimated uncertainty of $\pm$20%.

Coma is but one example of a cluster for which relative distances have been measured using a variety of secondary methods. As described above, in addition to M100 in Virgo, we have now measured Cepheid distances to a total of 8 galaxies, and as we report here for the first time, most recently including NGC 1365 in the Fornax cluster. A preliminary value of the Hubble constant based on a calibration of the Tully-Fisher relation for a sample of distant clusters is given by Mould *et al.* (this volume) and also by Madore *et al.* (1996). Based on our new Cepheid distance to the Fornax cluster, a value of H_0 is determined by tying into the distant cluster frame defined by Jerjen and Tammann (1993). Furthermore, as described below, a Cepheid distance to the Fornax cluster provides two additional calibrators for the type Ia supernova distance scale.

4. New Results on the Distance to the Fornax Cluster

At present we are analyzing a sample of 53 newly discovered Cepheids in the galaxy NGC 1365 in Fornax. The Fornax cluster is a particularly important cluster for a number of reasons. First, because it is a very compact cluster (see Figure 2), it provides a calibration of several secondary methods. Of particular importance is that it contains two well-observed recent type Ia supernovae, allowing a direct comparison between the type Ia distance scale and other well-studied secondary indicators with small measured dispersions such as the Tully-Fisher relation, surface brightness fluctuations, and planetary nebula luminosity function.

A detailed presentation of the preliminary results for NGC 1365 is given in Madore *et al.* (1996), and here we summarize the highlights. There are several independent pieces of evidence that NGC 1365 is a *bona-fide* member of the Fornax cluster. First, NGC 1365 is an optical member of the cluster as it lies directly along our line of sight to Fornax, projected only ~70 arcmin from the geometric center of the (~200 arcmin diameter) cluster itself. Second, NGC 1365 is also coincident with the Fornax cluster in velocity space; its velocity off-set from the mean is only half of the overall cluster velocity dispersion. Hence, both positional and velocity constraints place NGC 1365 physically in the Fornax cluster. Finally, NGC 1365 sits only 0.02 mag from the central ridge line of the *apparent* Tully-Fisher relation as defined by other cluster members defined by recent studies of the Fornax cluster (*e.g.,* Bureau, Mould & Staveley-Smith 1996, Schroder 1996). (We note here in passing that NGC 1365 is amongst the most luminous galaxies in the local Universe on the basis of the Tully-Fisher relation. It is brighter than M31 or M81, and comparable to NGC 4501 in the Virgo cluster or NGC 3992 in the Ursa Major cluster.)

Details of the observations for NGC 1365 will be given by Madore *et al.* (1996) and Silbermann *et al.* (1997). The V and I period-luminosity relations for a preliminary set of 53 Cepheids are shown in the upper and lower panels of Figure 1, respectively. The solid line is a minimum χ^2 fit to the fiducial PL relation for LMC Cepheids (Madore & Freedman 1991) corrected for $< E(B-V) >= 0.10$ mag, scaled to an LMC true distance modulus of $\mu_0 = 18.50$ mag, and shifted into registration with the Fornax data. Correcting for a derived total line-of-sight reddening of $E(V-I) = 0.10$ mag (derived from the NGC 1365 Cepheids themselves) gives a true distance modulus of $\mu_0 = 31.32$ ± 0.12 mag. This corresponds to a distance to NGC 1365 of 18.4 ± 1.0 Mpc. The quoted error quantifies only the statistical uncertainty generated by photometric errors in the data combined with the intrinsic magnitude and color width of the Cepheid instability strip.

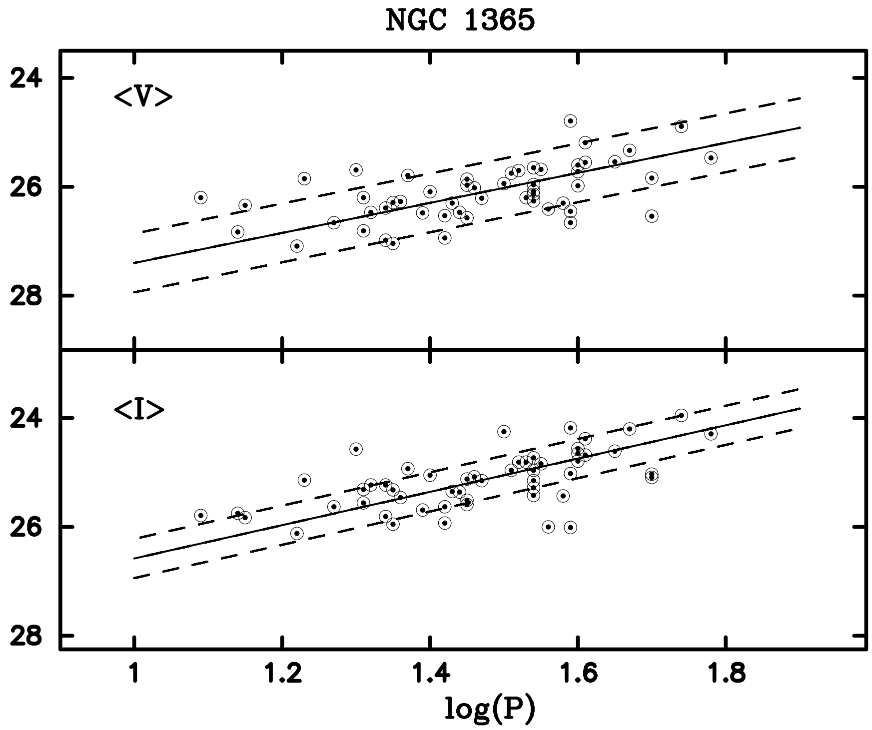

FIGURE 1. Preliminary V and I Period-Luminosity relations for 53 Cepheids in the Fornax galaxy NGC 1365. The fits are to the fiducial LMC relations given by Madore and Freedman (1991) shifted to the apparent distance modulus of NGC 1365.

4.1. *Estimates of H_0 Based on the Distance to the Fornax Cluster*

We briefly present three different estimates of H_0 based on the distance to the Fornax cluster; the reader is referred to Madore *et al.* (1996) for more details. The first estimate is based solely on the velocity and the Cepheid distance to the Fornax cluster. The second estimate is based on the nearby volume of space, up to and including both the Virgo and Fornax clusters. The third estimate comes from using the Cepheid distance to Fornax to lock into secondary distance indicators, thereby allowing us to step out to cosmologically significant velocities (10,000 km/sec and beyond) corresponding to distances on the order of 100 Mpc. The first two estimates are subject to larger uncertainties due to the local flow field.

4.1.1. *The Hubble Constant at Fornax*

As described above, one of the largest uncertainties in the estimation of H_0 based on the distance to M100 in the Virgo cluster (Freedman *et al.* (1994a), is the issue of the line-of-sight positional uncertainty of M100 relative to the elliptical-rich core of the cluster. The second major uncertainty is due to the uncertain Virgocentric flow velocity correction for the Local Group. Fortunately, the situation for the Fornax cluster is far less uncertain.

In Figure 2, we show a comparison of the two clusters of galaxies drawn to scale, as seen projected on the sky. Both clusters are located at very similar distances from us. However, as can be clearly seen in this figure, NGC 1365 is projected significantly closer to the core of the Fornax cluster than is M100 with respect to the ellipticals in

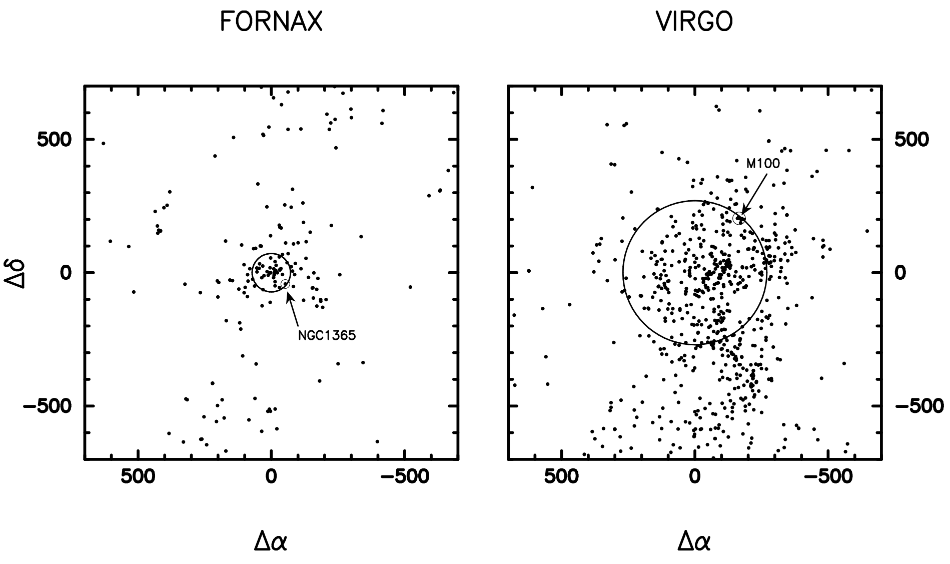

FIGURE 2. The distribution of galaxies as projected on the sky for the Virgo cluster (right panel) and the Fornax cluster (left panel). The positions of M100 and NGC 1365 are marked by arrows.

Virgo. Furthermore, since the Fornax cluster is simply more centrally concentrated than Virgo, the back-to-front uncertainty associated with its three-dimensional spatial extent is dramatically reduced for any randomly selected member. Both the compactness of the Fornax cluster and the actual proximity of NGC 1365 to the core of that cluster result in a statistical uncertainty of only 2-3% taking the Cepheid distance to NGC 1365 and identifying it with the distance to the core of the Fornax cluster group (Madore *et al.*, 1996).

The derived infall correction to Fornax is quite *insensitive* to the assumed infall velocity to Virgo: for an infall velocity of the Local Group towards Virgo of +200 ±100 km/sec the flow correction for Fornax is only −40 ±20 km/sec. The cosmological expansion rate of Fornax (determined from the barycentre of the Local Group) is then calculated to be 1,330 km/sec. Using our Cepheid distance of 18.4 Mpc for Fornax gives $H_0 = 72 \pm 3 \ \pm 18$ km/sec/Mpc. The first uncertainty includes random errors in the distance from the PL fit to the Cepheid data, as well as random velocity errors in the adopted Virgocentric flow, combined with the distance uncertainties to Virgo propagated through the flow model. The second uncertainty represents the systematic errors associated with the adopted mean velocity of Fornax, and the adopted zero point of the PL relation (combining in quadrature the LMC distance uncertainty and a measure of the metallicity uncertainty).

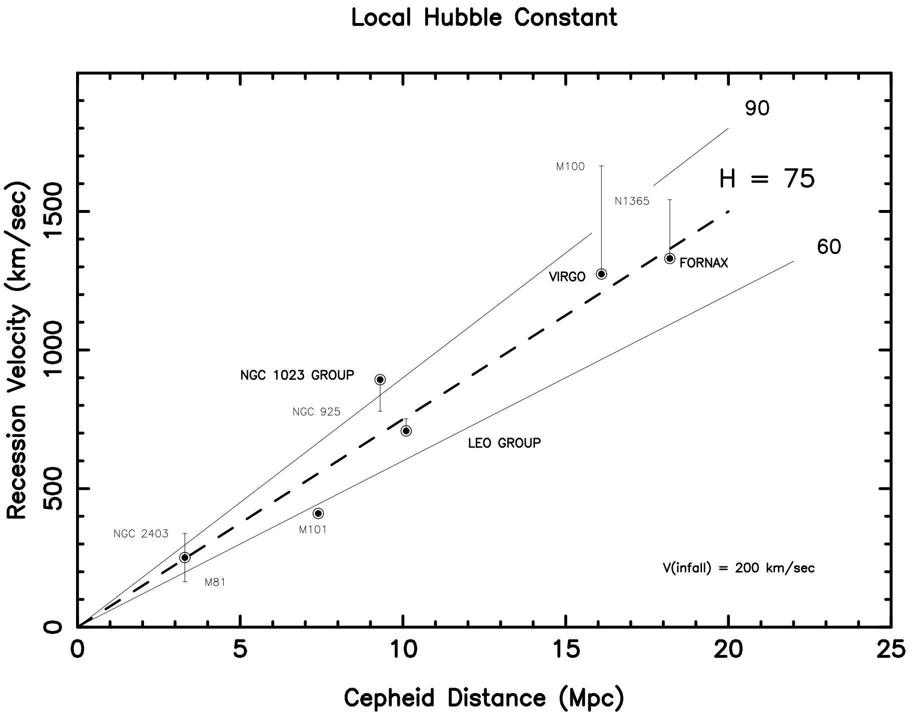

FIGURE 3. The Hubble velocity-distance relation for nearby galaxies having Cepheid distances. Circled dots denote the velocities and distances of the parent groups or clusters. The velocities for the individual galaxies are also indicated at the ends of the bars. The broken line represents a fit to the data giving $H_0 = 75 \pm 15$ (solid lines) km/sec/Mpc.

4.1.2. *The Near-by Flow Field*

In Figure 3, we present a Hubble diagram (in the sense originally plotted by Hubble (1929)) of distance versus velocity. The galaxies/groups in this plot all have distances determined directly from Cepheids. The expansion velocities are individually corrected for Virgocentric flow (using a Local Group infall velocity of 200 km/sec.) At 3 Mpc the M81-NGC 2403 Group (for which both galaxies of this pair have Cepheid distance determinations) gives $H_0 = 75$ km/sec/Mpc. Working further out to M101, the NGC 1023 Group and the Leo Group, the calculated values of H_0 vary from 65 to 95 km/sec/Mpc. An average of the six independent determinations including Virgo and Fornax, gives $H_0 = 75 \pm 8$ km/sec.

Although at these nearby distances, one expects a large scatter due to peculiar velocities, an interesting feature about this figure is how remarkably low in dispersion this Hubble relation is. More distances are required to ascertain whether this low scatter is simply a consequence of small-number statistics, or whether it is signaling a true, quiet, local flow (beyond the influence of the Virgo cluster).

The two determinations of H_0 in this and the preceding section, make no explicit allowance for the possibility that the inflow-corrected velocities of both the Fornax and Virgo clusters could be perturbed significantly by other mass concentrations or large-scale flows; *i.e.,* that the local (25,000 Mpc^3) volume of space delineated by them may not be at rest with respect to the distant galaxy frame. However, it is interesting to note that these local estimates do agree very well with the determinations of H_0 at larger distances, where peculiar velocities are a fractionally-smaller uncertainty (see below).

4.1.3. *H_0 via Secondary Indicators*

Although these preliminary estimates of H_0 from Cepheids in the Virgo (M100) and Fornax (NGC 1365) clusters are illuminating, the primary route to H_0 in the Key Project is through the calibration of secondary indicators, which can extend the distance scale well outside the local supercluster. To avoid these local uncertainties we step out from Fornax to the distant flow field based on: (1) Using the distance to Fornax to tie into averages over previously published differential moduli for independently selected distant-field clusters, (2) Recalibrating the type Ia supernova luminosities at maximum light, and applying that calibration to events as distant as 30,000 km/sec. and, (3) Using these data are used to calibrate the Tully-Fisher relation (see the article by Mould *et al.,*this volume).

4.1.4. *Beyond Fornax: Distant Clusters*

Jerjen & Tammann (1993) have compiled a set of relative distance moduli based on their evaluation and averaging of a number of independent secondary distance indicators, including brightest cluster galaxies, Tully-Fisher relation and supernovae. They conclude that this sample is "minimally biased". We have adopted without modification their differential distance scale and tied into the Cepheid distance to the Fornax cluster, which was part of their sample. The results are shown in Figure 4 which extends the velocity-distance relation out to more than 150 Mpc. No error bars are given in the published compilation but it is clear from the plot itself that the observed scatter can be fully accounted for by 10% errors in distance and/or velocity. This sample is sufficiently distant to average over the potentially biasing effects of large-scale flows, and yields a value of $H_0 = 72 \pm 4$ km/sec (random), with a systematic error of 10% being associated with the distance (but not the velocity) of the Fornax cluster. Again, the coincidence of H_0 measured at Fornax with that for the far field, seems to indicate that Fornax itself does not have a large component of motion with respect to the microwave background.

4.1.5. *Calibration of Type Ia Supernovae*

The Fornax cluster elliptical galaxies NGC 1316 and NGC 1380 are host to the well-observed type Ia supernovae 1980N and 1992A, respectively. (The supernova 1981D was also observed in NGC 1316, but the data are photographic, and hence are not of as high quality as the other two, and will not be considered here.) The new Cepheid distance to NGC 1365, and associated estimate of the distance to the Fornax cluster discussed above thus allow two additional very high-quality objects to be added to the calibration of type Ia supernovae. Details of this calibration are given in Freedman *et al.* (1997, in preparation) where corrections for interstellar extinction and decline-rate correlations are presented. Application to the distant Type Ia supernovae of Hamuy (1995) gives H_0 = 64–68 km/sec/Mpc. The range of values reflects different choices of weighting to both the calibrator galaxies, in addition to the distant supernova sample.

In Figure 5, we show the absolute-magnitude decline-rate relation for type Ia supernovae having direct Cepheid distances (top panel); for comparison the lower panel shows the same relation for the distant supernova sample of Hamuy *et al.* (1995) and Phillips

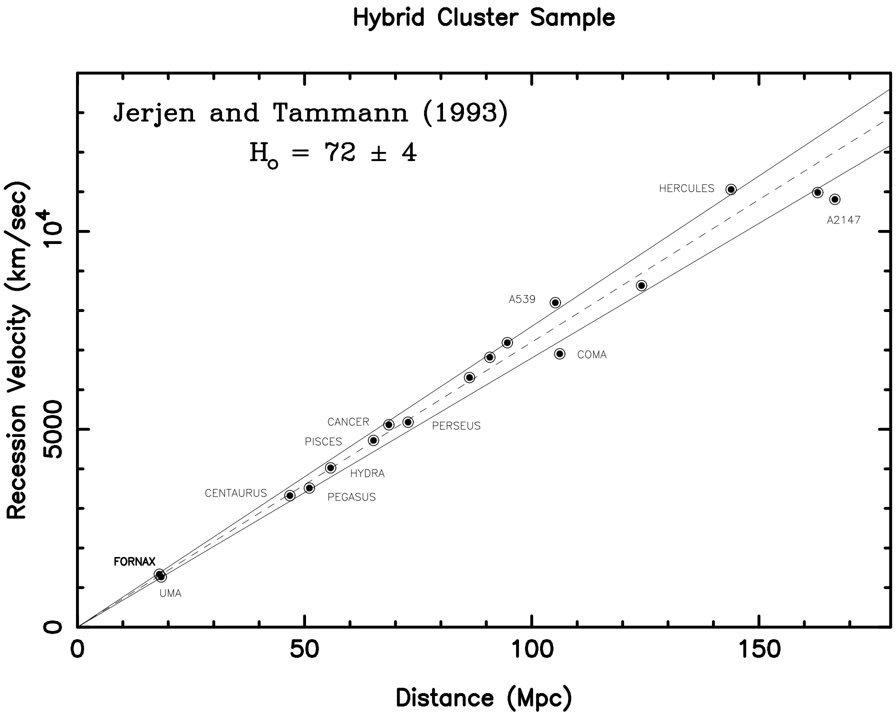

FIGURE 4. Recession velocity versus distance for a sample of 17 distant clusters from Jerjen & Tammann (1993). Absolute distances are calculated by tying the relative cluster distances to the Cepheid distance of the Fornax cluster.

(1993). It should be recalled that in the cases of 1980N and 1992A, the supernovae occurred in elliptical galaxies in the Fornax cluster (that is, not in NGC 1365 for which the Cepheid distance has been measured). The same is true of SN 1989B (Sandage *et al.* 1996), although in this case the association of the host galaxy NGC 3627 with the Leo triplet is not very well established.

The Cepheid-calibrating galaxies provide confirming evidence for an absolute-magnitude decline-rate relation for type Ia supernovae as suggested by Phillips (1993), Hamuy *et al.* (1995), Reiss, Press, and Kirshner (1996), and are contrary to the earlier arguments on this issue by Sandage *et al.* (1996). The larger value of H_0 reported here compared to that of Sandage *et al.* (1996) (57 km/sec/Mpc) is due to three factors: (1) low weight is given here to historical supernovae observed photographically, (2) we have included a decline-rate absolute-magnitude relation, and (3) the addition of the new Fornax calibrators. All three factors contribute in roughly comparable proportions.

5. Comparison of Cepheid, SBF, PNLF, and TRGB Distances

A detailed discussion of the SBF and PNLF methods is given by Tonry and Jacoby in this volume. Here we consider only a comparison of the Cepheid distances with those obtained using both the SBF and PNLF methods. This comparison yields agreement to

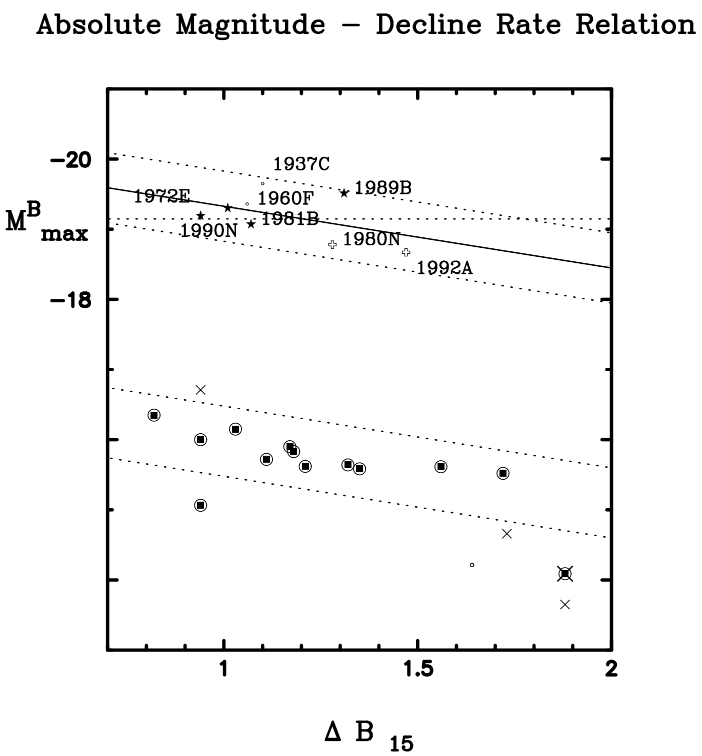

FIGURE 5. Decline rate as a function of absolute B magnitude. The points in the top half of the plot are for type Ia supernovae located in galaxies for which Cepheid distances have been measured. An arbitrary magnitude scale is indicated for the distant supernovae in the bottom part of the panel. The X's in the bottom panel denote supernovae with peculiar spectra (SN 1986G, 1991T, and 1991bg) and SN 1992J, a supernova with a red (B-V>0.5 mag) color. The small circle is for 1971I. The slope of the solid line is determined from the Hamuy *et al.* (1995) sample.

better than ± 10% (1–sigma) in distance. In Figure 6, the Cepheid distances are plotted versus SBF distances (Tonry, private communication), out to and including the distance to the Fornax cluster. Although both the SBF and PNLF distances are calibrated using the Cepheid distance to M31, the *relative* agreement of these methods is extremely encouraging.

In another article in this volume by Madore, Freedman & Sakai, the Cepheid distance scale is compared to the RR-Lyrae calibrated tip of the red giant branch (TRGB) method. Again, the results of this comparison are noteworthy, with the agreement at a level of ±5% in distance.

6. Comparison of Cepheid and Type II Supernova Distances

The expanding photosphere method (EPM) for type II supernovae is described in an article in this volume by Kirshner. In Table 3, we list the current galaxies having both Cepheid and EPM distances. The EPM distances are from Schmidt, Kirshner, &

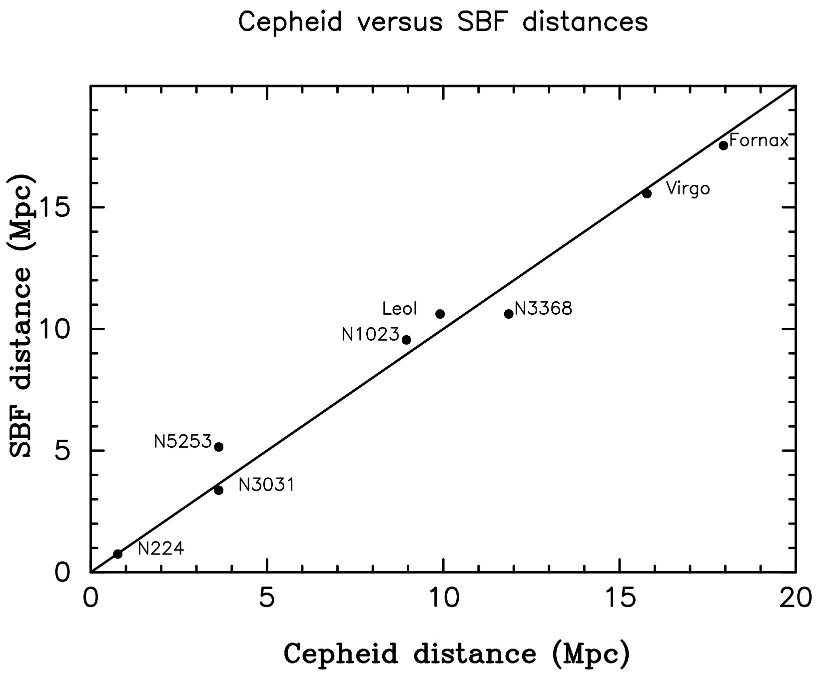

FIGURE 6. A comparison of distances obtained using Cepheids and the surface-brightness-fluctuation method. The latter data are from Tonry (1996, private communication).

Eastman (1992) and updated by Kirshner (private communication). The agreement is excellent: the mean ratio of distances amounting to 0.96.

The results of this and earlier comparisons are striking. The underlying physics of expanding supernova atmospheres, He-flash red giant stars, Cepheids, and planetary nebulae are completely independent. Yet, the relative distances for these methods are in remarkable agreement. These results offer encouragement that the systematic errors that have traditionally affected the extragalactic distance scale are being very significantly reduced. Moreover, the current uncertainties will continue to be reduced as ongoing large ground-based programs, as well as the HST Key Project reach completion.

7. Summary

At the time of writing, data have been acquired for 12 out of the 18 galaxies ultimately comprising the target sample for the HST Key Project on the Extragalactic Distance Scale. We have presented here a status report of our results to date which yield a value of $H_0 = 73 \pm 6$ (statistical) $\pm$ 8 (systematic) km/sec/Mpc. The systematic error takes into account a number of factors including: the present uncertainty in the zero point of the Cepheid period-luminosity relation of $\pm 5\%$ (or equivalently the uncertainty in the distance to the LMC), the potential uncertainty due to metallicity, also in the

TABLE 3. COMPARISON OF CEPHEIDS AND TYPE II SUPERNOVAE

Host Galaxy	Cepheid Distance	EPM Distance	Cepheid/EPM Distance Ratio	Supernova Name
LMC	0.50 ± 0.02	0.49 ± 0.03	1.02 ± 0.08	SN 1987A
M81	3.6 ± 0.3	4.2 ± 0.6	0.86 ± 0.18	SN 1993J
M101	7.5 ± 0.7	7.4 ± 1.2	0.97 ± 0.20	SN 1970G
M100	16.1 ± 1.8	15.0 ± 4.0	1.07 ± 0.26	SN 1974C
NGC 1058	9.3[1] ± 0.7	10.6[2] ± 1.5	0.88 ± 0.23	SN 1969L

[1] Group membership NGC 1023; Cepheid distance to NGC 925
[2] Revised distance (Kirshner, private communication)

TABLE 4. SUMMARY OF KEY PROJECT RESULTS ON H_0

Method	H_0			
Virgo	80 ± 17			
Coma via Virgo	77 ± 16			
Fornax	72 ± 18			
Local	75 ± 8			
JT clusters	72 ± 8			
SNIa	67 ± 8			
TF	73 ± 7			
SNII	73 ± 7			
$D_N - \sigma$	73 ± 6			
Mean	73 ± 4			
Systematic Errors	**$\pm$ 4** (LMC)	**$\pm$ 4** ([Fe/H])	**$\pm$ 5** (global)	**$\pm$ 2** (photometric)

TABLE 5. Current values of H_0 for various methods. For each method, the formal statistical uncertainties are given. The systematic errors (common to all of these Cepheid-based calibrations) are listed at the end of the table. The dominant uncertainties are in the distance to the LMC and the potential effect of metallicity on the Cepheid PL relations, plus an allowance is made for the possibility that locally the measured value of H_0 may differ from the global value. Also allowance is made for a systematic scale error in the photometry which might be affecting all software packages now commonly in use. Our best current weighted mean value is $H_0 = 73 \pm 6$ (statistical) $\pm$ 8 (systematic).

Cepheid period-luminosity relation at a level of $\pm 5\%$, an uncertainty which allows for the possibility that the locally measured H_0 out to say, 10,000 km/sec may not be the global value of H_0 of $\pm 7\%$, plus an allowance for a scale error in the photometry that could affect all of the results of $\pm 3\%$. **Our current adopted value for H_0 is 73 $\pm$ 10 km/sec/Mpc.** At the present time, the total uncertainties amount to about $\pm 15\%$. This result is based on a variety of methods, including a Cepheid calibration of the Tully-Fisher relation, type Ia supernovae, a calibration of distant clusters tied to Fornax, and direct Cepheid distances out to $\sim$ 20 Mpc. We summarize in Table 4 the values of H_0 based on these various methods.

Currently, we estimate the total 1-σ *rms* uncertainty in the value of H_0 to be approximately $\pm 15\%$. The formal internal uncertainties in the individual secondary methods are small (<10%). The dominant overall error is systematic. All of these uncertainties will be reduced in the near term as more Cepheid calibrators become available as a result the Key Project, the supernova, and Leo I programs, and in later cycles as infrared observations of Cepheids become available once NICMOS has been installed on HST.

The results that we have seen presented at the meeting this week are extremely encouraging. A large number of independent secondary methods appear to be converging on a value of H_0 in the range of 60 to 80 km/sec/Mpc. The factor-of-two discrepancy in H_0 appears to be behind us. However, these results again underscore the importance of reducing remaining errors in the Cepheid distances (*e.g.,* reddening and metallicity), since at present, the majority of distance estimators are tied to the Cepheid distance scale. A 1-σ error of $\pm 10\%$ on H_0 (the aim of the Key Project) currently amounts to approximately $\pm$ 7 km/sec/Mpc, and translates into a 95% confidence interval of roughly 55 to 85 km/sec/Mpc.

While this is an enormous improvement over the factor-of-two disagreement of the previous decades, it is not sufficiently precise, for example, to discriminate between current models of large scale structure formation, or to resolve definitively the fundamental age problem, or the possibility of a non-zero value of Λ. Before compelling constraints can be made on cosmological models, it is imperative to rule out remaining sources of systematic error in order to severely limit the alternative interpretations that can be made of the data. The spectacular success of HST, and the fact that a value of H_0 accurate to 10% (1-σ) now appears quite feasible, also brings into sharper focus smaller (10-15%) effects which used to be buried in the noise in the era of factor-of-two discrepancies. Fortunately, a significant improvement will be possible with the new infrared capability afforded by NICMOS. NICMOS observations planned for Cycle 7 will reduce the remaining uncertainties due to both reddening and metallicity by a factor of 3.

We heartily thank the other members of the HST H_0 Key Project team, whose dedicated efforts have made this Key Project a reality. Sincere thanks also to Bob Williams for his support of this program, Doug van Orsow for his heroic efforts to schedule our observations, Mario Livio for organizing this conference, and to all of the others at STScI whose contributions enable observations to be made with HST. We also thank John Tonry for providing us with unpublished data, and Bob Kirshner for updated distances. The work presented in this paper is based on observations with the NASA/ESA HubbleSpace Telescope, obtained by the Space Telescope Science Institute, which is operated by AURA, Inc. under NASA contract No. 5-26555. Support for this work was provided by NASA through grant GO-2227-87A from STScI.

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