The Extragalactic Distance Scale

Gemini Preprint #95

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Carnegie Observatories Astrophysics Series, Vol. 2:
Measuring and Modeling the Universe
ed. W. L. Freedman (Cambridge: Cambridge Univ. Press)

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Abstract

Significant progress has been made during the last 10 years toward resolving the debate over the expansion rate of the Universe. The current value of the Hubble parameter, H_0, is now arguably known with an accuracy of 10%, largely due to the tremendous increase in the number of galaxies in which Cepheid variable stars have been discovered. Increasingly accurate secondary distance indicators, many calibrated using Cepheids, now provide largely concordant measurements of H_0 well out into the Hubble flow, and deviations from the smooth Hubble flow allow us to better measure the dynamical structure of the local Universe. The change in the Hubble parameter with redshift provided the first direct evidence for acceleration and "dark energy" in the Universe. Extragalactic distance measurements are central to determining the size, age, composition, and fate of the Universe. We discuss remaining systematic uncertainties, particularly related to the Cepheid calibration, and identify where improvements are likely to be made in the next few years.

1.1 Introduction

The measurement of distances to the "nebulae" early in the twentieth century revolutionized our understanding of the scale of the Universe and provided the first evidence for universal expansion (an overview of the history of cosmology can be found in Longair (this volume). Distance measurements have played a profound role in unraveling the nature of the Universe and the objects in it ever since. Without knowing how far away objects are, we would not be able to learn very much about their sizes, energy sources, or masses. On a universal scale, extragalactic distance measurements lie at the heart of our understanding of the size, age, composition, evolution, and future of the Universe. The value of the Hubble parameter today, H_0, sets the scale of the Universe in space and time, and measuring H_0 depends heavily on accurate extragalactic distance measurements out to hundreds of Mpc. Accurate distance measurements are also needed to map the deviations from the smooth Hubble expansion, or peculiar velocities, which presumably arise gravitationally due to the distribution of mass in the local Universe.

During the last decade several important steps have been taken toward resolving the factor of $\sim$2 uncertainty in the scale of the Universe that overshadowed observational cosmology for 30 years. Many of the improvements are the direct results of a better calibration and extension of the Cepheid variable star distance scale. While significant systematic uncertainties remain, Hubble constant measurements made using a wide variety of distance measurement techniques are now converging on values between 60 and 85 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$; very few measurements lie outside this range, with the majority falling between 70 and 75 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Several recent advances made the improved Cepheid calibration possible. First, the *Hipparcos* satellite made parallax distance measurements accurate to 10% to Cepheid variable stars in the solar neighborhood. *Hipparcos* parallax measurements helped pin down the zeropoint brightness of the Cepheid variable stars, but not enough Cepheids could be observed to properly determine the slope of the period-luminosity (PL) relation. Second, the *Hubble Space Telescope (HST)* provided the spatial resolution and sensitivity to detect Cepheids in galaxies as far away as 25 Mpc, allowing for the first time a calibration of a number of secondary extragalactic distance indicators using Cepheids. Finally, the OGLE microlensing experiment turned up thousands of Cepheids in the Large Magellanic Cloud (LMC) that were used to accurately determine the PL relation. The improved Cepheid calibration of secondary distance indicators has largely yielded concordance on the scale of the Universe, and the uncertainty in H_0 is now arguably close to 10%.

This summary is not intended to be an inclusive review of all the distance measurement techniques and their relative strengths and weaknesses. Instead, we highlight some recent measurements and identify the most significant remaining systematic uncertainties. Cepheids are emphasized, as they are currently used to calibrate most secondary distance indicators. We close by summarizing how planned future projects will improve our knowledge of the expansion rate and eventual fate of the Universe.

1.2 The Cepheid Calibration

The Hubble Constant Key Project (KP) team set out to determine the Hubble constant to 10% or better by reliably measuring Cepheid distances to galaxies reaching distances of $\sim$25 Mpc (Mould et al. 2000; Freedman et al. 2001). The KP sample galaxies included field and cluster spirals, including several in the nearby Virgo, Fornax, and Leo I clusters. The KP team performed V and I band photometry using two independent reduction packages and analysis techniques to understand and control systematic errors as much as possible. Near-IR measurements with NICMOS were used to check the validity of the reddening law adopted by the KP team (Macri et al. 2001). All the KP results have been presented using a distance modulus to the LMC of 18.50 mag. To keep the KP results on a common footing, the KP measurements were all reported using the PL relation determined by Freedman & Madore (1990), which was derived from a relatively limited set of LMC Cepheids. No adjustment to the PL relation was made to the baseline KP measurements for differences in metallicity between Cepheids (Ferrarese et al. 2000b).

The KP team was not alone in taking advantage of *HST*'s spatial resolution and sensitivity to find Cepheids in relatively distant galaxies. Cepheids have also been measured in supernova (SN) host galaxies by A. Sandage, A. Saha, and collaborators. Their observations targeted galaxies in which Type Ia SNe have occurred for the purpose of calibrating SNe as a standard candle. The Sandage and Saha team made use of similar data reduction techniques as the KP team and the same LMC distance. An additional Cepheid measurement in the Leo I galaxy NGC 3368 was made by Tanvir, Ferguson, & Shanks (1999); NGC 3368 later hosted SN 1998bu.

Data for the entire combined sample of 31 Cepheid galaxies from both teams was presented by Ferrarese et al. (2000b) and Freedman et al. (2001) to facilitate comparison and calibration of secondary distance indicators on a common Cepheid foundation (Ferrarese et al. 2000a,b; Gibson et al. 2000; Kelson et al. 2000; Sakai et al. 2000). Mould et al. (2000) combined these results and found $H_0 = 71 \pm 6$ km s^{-1} Mpc^{-1}. The results of the KP calibration of the SN, Tully-Fisher (TF), fundamental plane (FP), and surface brightness fluctuation (SBF) distance indicators are included in the subsequent sections.

The gravitational lensing data of the OGLE experiment increased the number of good Cepheid measurements in the LMC by more than an order of magnitude ($\sim$650 fundamental-mode Cepheids; Udalski et al. 1999a,b). Freedman et al. (2001) applied the new Cepheid PL relation to the combined Cepheid database. The same LMC distance modulus of $\mu_{\rm LMC}$= 18.50 mag used in the earlier KP papers was maintained by Freedman et al. They also argued for a modest metallicity correction of -0.2 ± 0.2 mag dex^{-1} in (O/H) (Kennicutt et al. 1998). It is interesting to note that the new greatly improved PL relation has a somewhat different slope in the *I* band, resulting in a distance-dependent offset. Only the brightest, longest-period Cepheids can be detected in the most distant galaxies, so the revised slope will have the largest effect in the most distant galaxies. Adopting the new PL relation reduces the distance moduli of the most distant galaxies by up to $\sim$0.2 mag. The metallicity correction counteracts the shorter distances to some extent, and the change in the resulting Hubble constant when adopting both the metallicity correction and the new PL relation is small (72 ± 8 km s^{-1} Mpc^{-1}). If the new PL relation is adopted without the metallicity correction, the Hubble constant would increase by a few percent (depending on which Cepheid galaxies are used to calibrate a particular secondary distance indicator). An recent independent survey of LMC Cepheids has confirmed the slope of the OGLE PL relation (Sebo et al. 2002). The new results, derived from Cepheids with periods comparable to those of the more-distant KP galaxies, agrees with the Udalski et al. (1999a,b) OGLE PL zeropoint to 0.04 mag (or 2% in H_0), well within the uncertainties of the two measurements.

In the following sections, all Cepheid-based distance measurements will be compared to the Ferrarese et al. (2000b) scale, using the original KP zeropoint and no metallicity correction, or to the Freedman et al. (2001) compilation, which uses the OGLE (“new”) PL relation and metallicity correction of -0.2 mag dex^{-1}. In all cases, the LMC distance adopted is 18.50 mag. The metallicity-corrected Freedman et al. (2001) and uncorrected Ferrarese et al. (2000b) KP compilations are not strictly comparable; the metallicity difference between Galactic and LMC Cepheids would result in a $\sim$0.08 mag difference in the distance modulus to the LMC.

1.3 Secondary Distance Indicators and the Hubble Constant

Most secondary indicators derive their zeropoint calibration from Cepheids. We focus here on those techniques that have been calibrated using the common foundation of the KP Cepheid measurements. A few new results that are independent of the Cepheid calibration are presented as well (Table 1.1).

1.3.1 Type Ia Supernovae

The brightness of exploding white dwarf SNe can be calibrated using a single parameter (Phillips 1993; Hamuy et al. 1995; Riess, Press, & Kirshner 1996). After correcting their luminosities for decline rates, Type Ia SNe are a very good standard candle with a variance of about 10%. Both the KP and Sandage and Saha teams have calibrated Ia SNe using *HST* Cepheid measurements. While many of the Cepheids observations are identical, the two teams make numerous different choices regarding the detailed analyses. They also make use of different historical SNe to compute the value of H_0. The Sandage and Saha team consistently get larger distances and smaller values of the Hubble constant than the KP team does. The differences are discussed in detail by Parodi et al. (2000) and Gibson et al. (2000). Parodi et al. find $H_0 = 58 \pm 6$ km s^{-1} Mpc^{-1}, while Gibson et al. report $H_0 = 68 \pm 2 \pm 5$ km s^{-1} Mpc^{-1} (the first uncertainty is statistical, the second systematic). Both teams used the same LMC distance and similar reduction software, but included different calibrators and different analysis techniques. Much of the disagreement between the two groups has its origin in the selection and analysis of the individual Cepheid variables and which to exclude. The remaining difference arises from the choice of which historical SN data to trust and which SNe to exclude from the fit to the distant Hubble flow. Hamuy et al. (1996) measured a value of $H_0 = 63 \pm 3 \pm 3$ km s^{-1} Mpc^{-1} using the 30 Ia SNe of the Calan/Tololo survey and four Cepheid calibrators. Ajhar et al. (2001) found that the optical I-band SBF distances to galaxies with Type Ia SNe were entirely consistent when differences between Cepheid calibrators were taken into account. They found that SBFs and SNe give identical values of H_0 [73 km s^{-1} Mpc^{-1} on the original KP system, 75 on the new Freedman et al. (2001) calibration, and 64 on the Sandage and Saha calibration].

SNe at high redshift ($z > 0.5$), and their departure from a linear Hubble velocity, have been used to explore the change in the universal expansion rate with time. The measurements of two collaborations (the High-z Team, led by B. Schmidt, and the Supernova Cosmology Project, led by S. Perlmutter) have provided the best evidence to date that the Universe is expanding at an increasing rate. The implication of the SN data is that ~70% of the energy density in the Universe is in some form of "dark energy" such as vacuum energy, "quintessence," or something even more bizarre (Perlmutter et al. 1997, 1998; Schmidt et al. 1998). The use of SNe to probe the equation of state of the Universe is the topic of other papers in this volume. In general, the distant SNe do not need to be put on an absolute distance scale to study the change in the Hubble parameter with time.

Kim et al. (1997) used the first few SNe discovered by the Supernova Cosmology Project to constrain the Hubble constant. They found that $H_0 < 82$ km s^{-1} Mpc^{-1} in an $\Omega_\Lambda = 0.7, \Omega_m = 0.3$ Universe (as suggested by the distant SN data and cosmic microwave background measurements of the flatness of the Universe).

Tonry et al. (2003, in preparation) have recently compiled a database of all the currently available Type Ia SNe data using a common calibration and consistent analysis techniques. The result is a uniform data set of 209 well-measured SN distances in units of km s^{-1}. An independent distance to any of the galaxies therefore leads immediately to a tie to the Hubble flow out to redshifts greater than one. Six galaxies from the Tonry et al. (2003) database have Cepheid distances determined by the KP team (Freedman et al. 2001). Using the new PL relation and metallicity corrections, the SN data give a Hubble constant of 74 ± 3 km s^{-1} Mpc^{-1}. The exquisite tie to the Hubble flow is shown in Figure 1.1, along with the best fit Hubble constant. The line indicates the evolution of H_0 for an empty ($q_0 = 0$) cosmology, and the deviation from that line at $z \approx 0.5$ to 1 is the best evidence for an accelerating "dark energy" dominated Universe.

The distant SN data more tightly constrain the product $H_0 t_0$ than H_0 alone. The long, thin error ellipses of the SN data fall along lines of constant $H_0 t_0$ for SNe at $z \approx 0.5$. The Supernova Cosmology Project found $H_0 t_0 = 0.93 \pm 0.06$ (Perlmutter et al. 1997), and the High-z team measured $H_0 t_0 = 0.95 \pm 0.04$ (Tonry et al. 2003). For an age of the Universe of 13 Gyr, this implies a Hubble constant of ~70 km s^{-1} Mpc^{-1}. In the future, other constraints

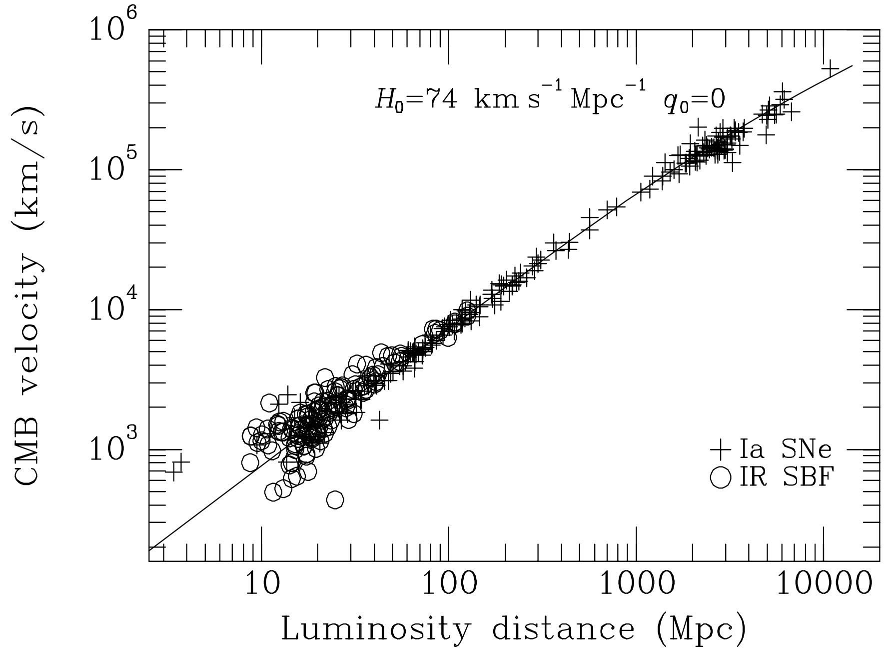

Fig. 1.1. Hubble diagram derived from the combined IR SBF and Type Ia SN data (Jensen et al. 2003; Tonry et al. 2003). The line indicates the expansion velocity for an empty Universe. The fit to the SN data give a Hubble constant of 74 km s^{-1} Mpc^{-1}.

on the age of the Universe, combined with highly accurate values of $H_0 t_0$ from high-redshift SNe at different redshifts, will give us better constraints on the Hubble parameter and how it has changed with time.

1.3.2 Surface Brightness Fluctuations

The amplitude of luminosity fluctuations in dynamically hot systems arises due to statistical fluctuations in the number of stars per resolution element (Tonry & Schneider 1988; Blakeslee, Ajhar, & Tonry 1999). SBFs are distance-dependent: the nearer a galaxy is, the bumpier it appears. The brightness of the fluctuations depends directly on the properties of the brightest stars in a given population, making SBFs a stellar standard candle. Significant SBF surveys have been completed at *I*, where the effects of age and metallicity are degenerate, and in the near-IR, where fluctuations are brightest and extinction is minimized.

The Hubble constant derived from *I*-band SBFs, as calibrated by the KP team (Ferrarese et al. 2000a), is $H_0 = 70 \pm 5 \pm 6$ km s^{-1} Mpc^{-1}(random and systematic uncertainties, respectively), using the four distant *HST* measurements of Lauer et al. (1998). The *I*-band SBF team used the much larger sample of $\sim$300 galaxies and a slightly different calibration to find a somewhat larger Hubble constant of $H_0 = 77 \pm 4 \pm 7$ (Tonry et al. 2000, 2001), using the original KP calibration of Ferrarese et al. (2000b). The *I*-band SBF survey team fitted a detailed model of the velocity field of the local Universe to get their determination of the Hubble constant. Half the difference between the Ferrarese et al. (2000a) and Tonry et al. (2000) results is due to the velocity field corrections, and the other to differences in the choice of Cepheid calibration galaxies. SBFs can be measured in the bulges of a few spiral galaxies with known Cepheid distances, and the preferred SBF calibration of Tonry et al. uses only galaxies with distances known from both Cepheids and SBFs. As with all the secondary indicators calibrated using Cepheids, moving to the new PL relation would result in an increase in the Hubble constant of 3% including the Freedman et al. (2001) metallicity correction, or 8% using the new PL relation alone.

Infrared measurements using NICMOS on the *HST* have extended SBF measurements beyond 100 Mpc, where deviations from the smooth Hubble flow should be small. Jensen et al. (2001) measured a Hubble constant between 72 and 77 km s^{-1} Mpc^{-1} using the original KP Cepheid calibration. When reanalyzed using an updated calibration and the new OGLE PL relation, they find $H_0 = 77$ km s^{-1} Mpc^{-1} using the Freedman et al. (2001) calibration (including the metallicity correction; Jensen et al. 2003).

1.3.3 Fundamental Plane

Elliptical galaxies are very homogeneous in their photometric and dynamical properties. By accurately measuring surface brightness, size, and central velocity dispersion, the position of an elliptical galaxy on the "fundamental plane" (FP) gives an estimate of the distance with an accuracy of ∼20%. The FP is an improved version of the Faber-Jackson and $D_N - \sigma$ relations, which are also used to determine distances to elliptical galaxies. Kelson et al. (2000) combined various FP data for the Fornax, Virgo, and Leo I clusters, for which Cepheid distances had been measured. They applied the Cepheid calibration of the FP relation for the three nearby clusters to 11 more distant clusters. The resulting Hubble constant of $82 \pm 5 \pm 10$ km s^{-1} Mpc^{-1} is somewhat higher than the KP estimates using other secondary distance indicators. Adopting the metallicity correction of Kennicutt et al. (1998) would reduce the value of H_0 by 6%. The relative placement of the spiral Cepheid calibrators and elliptical FP galaxies within the three nearby clusters is one of the primary sources of systematic uncertainty (∼5%).

Hudson et al. (2001) have combined a number of FP data sets, making them much more homogeneous by cross checking the photometry and velocity dispersion measurements. When the Hudson et al. data are analyzed using the Ferrarese et al. (2000b) Cepheid calibration, Blakeslee et al. (2002) find that the Hubble constant is consistent with SBFs and with other secondary distance indicators. They find $H_0 = 68 \pm 3$ km s^{-1} Mpc^{-1}, in excellent agreement with the KP calibrations of the other secondary distance indicators. Using the new PL relation (Freedman et al. 2001), the FP Hubble constant is $73 \pm 4 \pm 11$ km s^{-1} Mpc^{-1}, where SBFs have been used to make a direct connection between the FP galaxies and the Cepheid calibrators.

1.3.4 Tully-Fisher

Like elliptical galaxies, the photometric and kinematic properties of spiral galaxies are closely related. The rotation velocities and brightnesses of spiral galaxies can be measured, making it possible to estimate the distance to a galaxy. Tully-Fisher (TF) distance measurements are among the most widely used, although the accuracy of an individual measurement is generally taken to be about 20%. Sakai et al. (2000) used the compiled TF data for 21 calibrators with Cepheid distances and applied the results to a large data set of 23 clusters within 10,000 km s^{-1} (Giovanelli et al. 1997). Sakai et al. found that the TF Hubble constant is $H_0 = 71 \pm 4 \pm 7$ km s^{-1} Mpc^{-1}, in very good agreement with the other techniques already mentioned.

1.3.5 Type II Supernovae

The expanding-photospheres method of determining distances to Type II SNe can be calibrated using a zeropoint based on Cepheid distances (although the expanding-photospheres method is a primary distance indicator that does not require a Cepheid calibration, as described in § 1.6). The KP team (Freedman et al. 2001) applied the new Cepheid calibration to the SN measurements of Schmidt et al. (1994) and found $H_0 = 72 \pm 9 \pm 7$ km s^{-1} Mpc^{-1}, in close agreement with the value of $H_0 = 73 \pm 6 \pm 7$ reported by Schmidt et al. A second way of using Type II SNe as a distance estimator has been developed by Hamuy (2001). The expansion velocity for a particular type of "plateau" SN is correlated with its luminosity. The average of four SNe give a Hubble constant of 75 ± 7 km s^{-1} Mpc^{-1} using a Cepheid calibration comparable to the Freedman et al. zeropoint (M. Hamuy, private communication). The best-measured and only modern SN of the four (SN 1999em) gives $H_0 = 66 \pm 12$ km s^{-1} Mpc^{-1}.

1.3.6 Other Distance Indicators Calibrated Using Cepheids

The KP team also presented Cepheid calibrations of several other distance indicators, including the globular cluster luminosity function (GCLF), the planetary nebula luminosity function (PNLF), and the tip of the red giant branch (TRGB). Ferrarese et al. (2000a,b) compiled results for these techniques and compared them to SBFs.

The GCLF technique has been recently shown to be as good a distance indicator as other secondary techniques when appropriate corrections are made for completeness, background sources, and luminosity function width (Kundu & Whitmore 2001; Okon & Harris 2002). To measure reliable distances, globular clusters fainter than the GCLF peak must be detected. Some earlier measurements did not go deep enough to reach the peak luminosity, and the results were less reliable and possibly biased toward smaller distances. By measuring GCLF distances relative to the Virgo cluster, and adopting a distance to Virgo of 16 Mpc as the calibration (which is independent of, but consistent with, the Cepheid calibration), the resulting Hubble constant is near 70 km s^{-1} Mpc^{-1} (Okon & Harris 2002). The Cepheid distance to Virgo from Ferrarese et al. (2000a) is 16.1 Mpc; thus, the agreement between the KP calibration of the GCLF technique and the newer measurements is very good.

Ciardullo et al. (2002) recently made a detailed comparison of the PNLF technique to the Cepheid distance scale. The current PNLF technique makes a correction for metallicity of the host galaxy. Using a distance of 710 kpc to M31 to determine the zeropoint for the PNLF method, they found that the Cepheid and PNLF distances are consistent within the statistical uncertainties of the two methods. The agreement between Cepheids and PNLF in the particular case of NGC 4258 also leads to a $\sim$1-σ disagreement with the geometrical maser distance.

In Table 1.1 we summarize a few recent measurements of H_0 and the Cepheid calibration used (when appropriate). Most of the measurements are calibrated directly using the original KP zeropoint or the new OGLE PL relation ("New PL"). Many also include metallicity corrections (indicated by "+Z"). References and additional calibration details are included. Willick & Batra (2001) provide an independent calibration of the Cepheid distance scale using the new OGLE PL relation.

Table 1.1. *A Few Recently Published Hubble Constant Measurements*

Technique	H_0 (km s^{-1} Mpc^{-1})	Cepheid calibration	Reference
Key Project summary	72 ± 8	New PL+Z	Freedman et al. 2001
Cepheids+IRAS flows	85 ± 5	New PL	Willick & Batra 2001
Type Ia Supernovae	59 ± 6	Sandage team	Parodi et al. 2001
	59 ± 6	Sandage team	Saha et al. 2001
	$71 \pm 2 \pm 6$	New PL+Z	Freedman et al. 2001
	74 ± 3	New PL+Z	Tonry et al. 2003, in prep.
	$73 \pm 2 \pm 7$	New PL+Z	Gibson & Stetson 2001
I-band SBFs	$77 \pm 4 \pm 7$	Orig. KP	Tonry et al. 2000
	$70 \pm 5 \pm 6$	New PL+Z	Freedman et al. 2001
	75	New PL+Z	Ajhar et al. 2001
H-band SBFs	$72 \pm 2 \pm 6$	Orig. KP+*I*-SBF	Jensen et al. 2001
	$77 \pm 3 \pm 6$	New PL+Z	Jensen et al. 2003, in prep.
K-band SBFs	71 ± 8	Orig. KP+*I*-SBF	Liu & Graham 2001
Tully-Fisher	$71 \pm 3 \pm 7$	New PL+Z	Freedman et al. 2001
Fundamental Plane	$82 \pm 6 \pm 9$	New PL+Z	Freedman et al. 2001
	$73 \pm 4 \pm 11$	New PL+Z	Blakeslee et al. 2002
Type II Supernovae	$72 \pm 9 \pm 7$	New PL+Z	Freedman et al. 2001
	75 ± 7	New PL+Z	M. Hamuy, private comm.
Globular Custer LF	~ 70	similar to Orig. KP	Okon & Harris 2002
Sunyaev-Zel'dovich	$60 \pm 3 \pm 30\%$	...	Carlstrom et al. 2002
Gravitational lenses	61 to 65	...	Fassnacht et al. 2002
	$59 \pm 12 \pm 3$	...	Treu & Koopmans 2002
Type Ia SNe (theory)	67 ± 9	...	Höflich & Khokhlov, 1996
Type II SNe (theory)	67 ± 9	...	Hamuy 2001

1.4 Systematic Uncertainties in the Cepheid Calibration

The KP and SN calibration teams have provided a large and uniform data set of consistently calibrated Cepheid distances. There are, however, several systematic uncertainties that prevent achieving an accuracy much better than 10% in distance. The primary systematic uncertainties are common to all the Cepheid measurements, and are all similar in magnitude (Freedman et al. 2001). A concerted effort to improve the accuracy in several areas is therefore needed to significantly reduce the uncertainty in H_0 using Cepheid-calibrated secondary distance indicators.

1.4.1 The Distance to the Large Magellanic Cloud

The distance to the LMC is a fundamental rung in the distance ladder. The LMC is large enough and distant enough to contain a wide assortment of stellar types at nearly the same distance, yet close enough for individual stars to be easily resolved. The LMC contains stars and globular clusters spanning a wide range in age. It also hosted the Type II SN 1987A, the best-studied SN ever. The LMC is crucial for the Cepheid calibration because there are not enough Galactic Cepheids with independently determined distances to pin down the zeropoint, the PL relation, and metallicity dependence simultaneously. Only in the LMC do we have a sample of thousands of Cepheids at a common distance.

The fact that the distance to the LMC is not yet well determined is a significant and persistent problem (Walker 1999; Paczyński 2001; Benedict et al. 2002a). There are, unfortunately, still "long" and "short" LMC distance scales. While everyone would probably agree that a distance modulus of $\mu_{\rm LMC} = 18.35$ mag is consistent with the "short scale," and

18.6 mag corresponds to the "long" scale, the distinction between the two is somewhat artificial. It is interesting to note that, while some techniques favor longer or shorter distance scales on average, the measurements cover the range with no appreciable bimodality. Furthermore, one author may state a distance or range of distances as being consistent with the long scale, while another, quoting a distance in the same range, will state that it supports the short scale. We regard the distinction as arbitrary; in reality, there is a continuous range of measurements that span values significantly larger than the statistical uncertainties of the individual measurements.

There have been several compilations of LMC distances recently (e.g., Walker 1999; Mould et al. 2000; Benedict et al. 2002a), and we do not review them here. While it is very helpful to broadly survey all the recently published measurements, it is important to remember that a large number of publications of a particular value does not necessarily indicate correctness. Nor do more recent measurement necessarily deserve more trust than older ones. There is some hope of resolving the debate if we look to some recent measurements that make use of new or improved geometrical techniques (a few are listed in Table 1.2). Hopefully, modest improvements in the near future will resolve the issue of the LMC distance, at least at the 10% level.

The study of the SN 1987A has resulted in several recent geometrical distance determinations (or upper limits), ranging from $\mu_{\rm LMC} < 18.37$ to 18.67 mag (Gould & Uza 1997; Panagia 1999; Carretta et al. 2000; Benedict et al. 2002b). The "light echo" measurements are particularly important because of their insensitivity to adopted extinction values. A recent spectral fitting of the expanding atmosphere of SN 1987A by Mitchell et al. (2002) gives a distance of 18.5 ± 0.2 mag. The SN 1987A measurements are consistent with both $\mu_{\rm LMC} = 18.35$ and 18.50 mag.

One of the most promising techniques today makes use of detached eclipsing binaries (DEBs), for which the orbital parameters can be determined and the geometrical distance derived. The three DEBs that have been observed in the LMC have distances in the range of 18.30 to 18.50 mag. Two measurements are consistent with the short distance scale (18.38 mag by Ribas et al. 2002; 18.30 mag by Guinan et al. 1998) and the other two are larger (18.50 mag by Fitzpatrick et al. 2002; 18.46 mag by Groenewegen & Salaris 2001). We can only conclude that DEBs are consistent with a distance modulus to the LMC of both 18.35 and 18.50 mag. Measurements of many more DEBs in the LMC and other nearby galaxies will be invaluable in helping to resolve the controversy surrounding the distance to the LMC.

Cepheid distance measurements to the LMC generally favor the long scale, although values as low as 18.29 mag (and as high as 18.72 mag) have been reported (Benedict et al. 2002a). A good summary of the Cepheid measurements was presented by Benedict et al. (2002a,b), who find a mean distance modulus of 18.53 mag (average of many measurements and techniques). This is consistent with their own measurement of 18.50 ± 0.13 mag based on new *HST* parallax measurements of δ Cephei. Recently, Keller & Wood (2002) measured $\mu_{\rm LMC} = 18.55 \pm 0.02$ mag, and Di Benedetto (2002) reported a distance modulus of 18.59 ± 0.04 mag. Although Cepheids alone cannot yet rule out the short-scale zeropoint of 18.35 mag, the most recent measurements are weighted toward values nearer to 18.5 mag. Whether or not Cepheid luminosities depend significantly on metallicity is an open question (see the discussion in Freedman et al. 2001). The effect of applying the metallicity correction of -0.2 ± 0.2 mag dex^{-1} (O/H) metallicity would be to decrease the distance to the LMC by 0.08 mag relative to the higher-metallicity Galactic Cepheids. Further work with larger samples of Galactic Cepheids with higher metallicities than are found in the LMC is needed to resolve this issue. One promising line of research suggests that first-overtone Cepheids should be less sensitive to metallicity than the fundamental-mode pulsators. Bono et al. (2002) report overtone Cepheid distances near 18.5 mag, in good agreement with the longer-period fundamental-mode Cepheids.

NGC 4258 is the only other external galaxy besides the LMC with a reliable geometrical distance measurement. The orbital properties of masers around the central black hole in NGC 4258 can be determined to give an absolute geometrical distance of 7.2 ± 0.5 Mpc (Herrnstein et al. 1999). Cepheids have been discovered in NGC 4258, and they provide an independent distance measurement that is approximately 1 Mpc larger (Maoz et al. 1999; Newman et al. 2001); the KP Cepheid calibration (Freedman et al. 2001) is discrepant at the 1-σ level if the distance to the LMC is 18.50 mag. The two measurements would agree if $\mu_{\rm LMC}$= 18.31 mag. If the maser and Cepheid distances are both reliable, they could be used to rule out a distance of 18.50 to the LMC. One alternative possibility is that the Cepheid distance is a bit off; given the relatively small number of Cepheids detected (18), this may not be unreasonable. A second possibility is that the Cepheid metallicity correction should have the opposite sign as that used by the KP, as suggested by the theoretical work of Caputo, Marconi, & Musella (2002). The recent results of Ciardullo et al. (2002) using the PNLF distance to this galaxy suggests that the distance to the LMC should be reduced; both Cepheids and PNLF would be consistent with the maser distance if $\mu_{\rm LMC}$ were 18.3 mag.

While the original controversy between long and short distance scales arose primarily due to differences between RR Lyrae variables and Cepheids, the two methods are starting to converge. Statistical parallax measurements favor values between 18.2 and 18.3 mag, while Baade-Wesselink measurements prefer larger distances. The average value of many RR Lyrae measurements is 18.45 mag, and new data based on *HST* parallax distances to Galactic RR Lyrae stars give $\mu_{\rm LMC}$ values between 18.38 and 18.53 mag (Benedict et al. 2002a,b). The RR Lyrae distances now agree with Cepheid distances at the 1-σ level.

Red clump stars have been used as a distance indicator in support of the short-distance scale (Benedict et al. 2002a). Red clump measurements span the range in distance modulus, from 18.07 to 18.59 mag (Stanek, Zaritsky, & Harris 1998; Romaniello et al. 2000). Recent near-IR measurements that minimize uncertainties in extinction result in a distance modulus of 18.49 ± 0.03 mag (Alves et al. 2002). Pietrzynski & Gieren (2002) find 18.50 ± 0.05 mag, with a statistical uncertainty of only 0.008 mag. Red clump distance measurements do not yet exclude either the long or the short distance scales.

Many other distance measurement techniques have been applied to the LMC, and we refer the reader to the compilation in Benedict et al. (2002a). Most of the measurements of $\mu_{\rm LMC}$ published this year are consistent with a distance modulus between 18.45 and 18.55 mag, with the notable exception of the Cepheid distance to NGC 4258, which implies $\mu_{\rm LMC}$= 18.31 mag (although uncertainties in the metallicity correction to Cepheid distances lessen the significance of the discrepancy, as explained by Caputo et al. 2002). Since the NGC 4258 Cepheid distance is only discrepant at the 1-σ level, we believe that a change from the LMC distance of 18.50 mag is not justified at the present time.

Resolving the debate between the long and short distances to the LMC will not necessarily reduce the uncertainty in the Hubble constant. The differences between techniques have usually exceeded the quoted uncertainties, both systematic and statistical. The systematic uncertainty in $\mu_{\rm LMC}$ adopted by the KP team was 0.13 mag. Even if we choose the best re-

Table 1.2. *A Summary of Recently Published LMC Distances*

Technique	$\mu_{\rm LMC}$ (mag)	Reference
Cepheids/masers (NGC 4258)	18.31 ± 0.11	Newman et al. 2002
Cepheids (δ Cep)	18.50 ± 0.13	Benedict et al. 2002b
Cepheids (mean of many techniques)	18.53	Benedict et al. 2002a,b
Eclipsing binaries	18.38 ± 0.08	Ribas et al. 2002
	18.50 ± 0.05	Fitzpatrick et al. 2002
	18.46 ± 0.07	Groenewegen & Salaris 2001
	18.30 ± 0.07	Guinan et al. 1998
SN 1987A	18.5 ± 0.2	Mitchell et al. 2002
RR Lyr	18.38 to 18.53	Benedict et al. 2002a
RR Lyr (mean of many techniques)	18.45 ± 0.08	Benedict et al. 2002a,b
Red clump	18.49 ± 0.03	Alves et al. 2002
Red clump	$18.50 \pm 0.008 \pm 0.05$	Pietrzynski & Gieren 2002

sults from the different techniques that fall closest to the adopted modulus of 18.50 mag, the scatter will likely still be >0.13 mag. Furthermore, it is likely that any individual measurement, taken on its own as the most reliable available, will have a total uncertainty no better than 0.1 mag. Reducing the uncertainty in the LMC distance modulus will require more than the elimination of systematic errors that are not completely accounted for in the current set of uncertainty estimates. It is, however, a crucial step in our progress toward improving the precision of the distance ladder techniques.

1.4.2 Metallicity Corrections to Cepheid Luminosities

The possibility that the luminosity of a Cepheid variable star depends on its metallicity is one of the most significant remaining uncertainties. Most of the distant galaxies with known Cepheid distances have metallicities similar to those of the Galactic Cepheids, and significantly higher metallicity than the LMC Cepheids. The magnitude of the metallicity correction is not very important, provided that it is applied consistently. At the present time it is not clear if a metallicity correction is justified or not (Udalski et al. 2001; Caputo et al. 2002; Jensen et al. 2003).

Most of the Cepheid distance measurements published, including the KP papers prior to Freedman et al. (2001), have no metallicity correction applied. For the final KP results, Freedman et al. adopted a metallicity correction of -0.2 mag dex^{-1} in (O/H) (Kennicutt et al. 1998). Since both the old and new Cepheid calibrations use the same LMC distance $\mu_{\rm LMC} = 18.50$ mag, it should be noted that a direct comparison between the old calibration (Ferrarese et al. 2000b) and the Freedman et al. (2001) calibration, which includes the metallicity correction, requires an offset of $\sim$0.08 mag due to the difference between Galactic and LMC Cepheid metallicities. In other words, the difference between the Mould et al. (2000) and Freedman et al. (2001) values of H_0 would be 4% larger than reported if Galactic and LMC Cepheids were metallicity-corrected the same as Cepheids in the more distant galaxies.

The Freedman et al. (2001) distances derived using the new PL calibration can be used without the metallicity correction, with a corresponding increase in H_0. Because of the distance-dependent nature of the change to the new PL relation, the Hubble constant that results from using no metallicity correction depends on which Cepheid calibrators are used to tie to distant secondary techniques. For the case of I-band SBFs, the new PL relation without metallicity corrections results in an increase in the Hubble constant of 8% over the original KP calibration, and 5% over the new PL relation with metallicity corrections included.

1.4.3 Systematic Photometric Uncertainties

One significant source of systematic error in the data taken with WFPC2 has been the uncertainty in the photometric zeropoint, which the KP team estimate at 0.09 mag. Extinction corrections also contribute to the photometric uncertainties in Cepheid measurements. More details can be found in the KP papers (see Freedman et al. 2001).

Blending of Cepheids with other stars is another potential source of systematic uncertainty. If blending is significant, the Cepheid distances to the most distant galaxies surveyed may be underestimated by 10 to 20% (Mochejska et al. 2000). Gibson, Maloney, & Sakai (2000) found no evidence of a trend in residuals with distance and no difference between the WF and PC camera measurements, which have different spatial sampling and therefore different sensitivities to blending. Ferrarese et al. (2000c) also found no significant offset in the Cepheid photometry due to crowding. They based their uncertainty estimate of 0.02 mag on tests in which they added artificial stars to their images and processed them in the same way as the real stars. The strict criteria for selecting and measuring Cepheids used by the KP team can explain the small effect of blending on the photometry of the artificial stars added.

Although improved spatial resolution helps minimize the effects of blending, it is not complete protection. Physical companions to Cepheids cannot be resolved. Furthermore, the effect of blending on Cepheid distances is not limited to a single companion. The surface brightness fluctuations in the underlying population are a background with structure on the scale of the point-spread function that can make the Cepheid look brighter or fainter. In the most distant galaxies, there will be a slight detection bias in favor of Cepheids superimposed on bright fluctuations. The fluctuations are very red, so not only will the brightness of the Cepheid be overestimated, but the color observed will be too red. The corresponding extinction correction will be larger than it should be, enhancing the overestimate of the Cepheid luminosity and underestimate of the distance.

1.5 Peculiar Velocities

Any measurement of the Hubble constant relies on both distance *and* velocity measurements. Within 50 Mpc, the clumpy distribution of mass leads to peculiar velocities that can be larger than the Hubble expansion velocity. It is therefore critical that recession velocities within 50 Mpc be corrected depending on where the galaxy lies relative to the Virgo cluster, Great Attractor, and so forth. Differences in how these corrections are applied has led to significant differences in measured values of H_0. Half the difference between the KP SBF Hubble constant and that of Tonry et al. (2000) is due to differences in the velocity model. Furthermore, there is some evidence suggesting that the local Hubble expansion rate is slightly larger than the global value, which would be the natural result of the local Universe being slightly less dense than the global average (Zehavi et al. 1998; Jensen et al. 2001). While the evidence is far from conclusive (Giovanelli, Dayle, & Haynes 1999; Lahav 2000), it reinforces the importance of measuring the expansion rate of the Universe as far out as possible. There is obviously great advantage in measuring H_0 at distances large enough to be free of peculiar velocities. Beyond 100 Mpc, even the largest peculiar velocities ($\sim$1500 km s^{-1}) are only a fraction of the Hubble velocity ($\sim$7000 km s^{-1}). The Ia SNe, SBF, Tully-Fisher, and FP Hubble constant measurements made beyond 100 Mpc presented in the previous sections all show the excellent consistency expected from a solid tie to the distant Hubble flow.

1.6 Bypassing the Distance Ladder

Two techniques, gravitational lens time delays and the Sunyaev-Zel'dovich (SZ) effect, promise to provide measurements of H_0 at significant redshifts independent of the calibration of the local distance scale. Both of these techniques are discussed in detail elsewhere in this volume (Kochanek & Schechter and Reese, this volume).

Time delay measurements in multiple-image gravitational lens systems can provide a geometrical distance and Hubble constant provided the mass distribution is known in the radial region between the images of the gravitationally lensed quasar (Kochanek 2002, 2003). Recent time-delay measurements give $H_0 \approx 60$ km s^{-1} Mpc^{-1}, and are somewhat lower than H_0 found using Cepheid-calibrated secondary distance indicators. Treu & Koopmans (2002) reported $H_0 = 59^{+12}_{-7} \pm 3$ km s^{-1} Mpc^{-1} for an $\Omega_\Lambda = 0.7, \Omega_m = 0.3$ Universe. Fassnacht et al. (2002) found values between 61 and 65 for the same cosmological model. Cardone et al. (2002) found $H_0 = 58^{+17}_{-15}$ km s^{-1} Mpc^{-1}, in good agreement with the others. Kochanek (2002) showed that values of H_0 between 51 and 73 km s^{-1} Mpc^{-1} are possible; the lower limit corresponds to cold dark matter M/L concentrations, while the upper limit is set by the constant-M/L limit. Now that more accurate time delays have been measured for $\sim$5 systems using radio, optical, and X-ray observations, the distribution of mass in the lensing galaxy is the largest remaining uncertainty in gravitational lens measurements of the Hubble constant.

The SZ effect at submillimeter wavelengths, when combined with X-ray measurements of the hot gas in galaxy clusters, can be exploited to determine the angular diameter distance to the cluster (Carlstrom, Holder, & Reese 2002; Reese et al. 2002). To date, there are 38 SZ distance measurements extending to redshifts of $z = 0.8$. A fit to the 38 measurements yields $H_0 = 60 \pm 3$ km s^{-1} Mpc^{-1}, with an additional systematic uncertainty of order 30% (Carlstrom et al. 2002). The primary systematic uncertainties arise from cluster structure (clumpiness and departures from isothermality) or from point-source contamination. The SZ Hubble constant is also a function of the mass and dark energy density of the Universe; the value presented here assumes $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ (Reese et al. 2002). Future SZ surveys are expected to discover hundreds of new clusters, which should greatly improve our understanding of the density and expansion rate of the Universe to $z \approx 2$ (Carlstrom et al. 2002).

Using models to predict the absolute luminosity of a standard candle is another way to sidestep the issues with empirical distance scale calibrations. Both Type Ia and II SNe, along with SBFs, can be primary distance indicators. We usually choose to calibrate SNe and SBFs empirically using Cepheids because of the acknowledged uncertainties in the many model parameters. The models are good enough, however, to provide some constraints on the distance scale and the quality of the Cepheid calibration.

Recent models of Type Ia SNe are now detailed enough to predict the absolute luminosity of the burst and therefore allow distances to be derived directly. The results reported by Höflich & Khokhlov (1996), for example, show that Ia SN models are consistent with a Hubble constant of 67 ± 9 km s^{-1} Mpc^{-1}. While there are clearly many details in the explosion models that must be carefully checked against observations, it is reassuring that the predictions are in the right ball park. Type II SNe have also been used as primary standard candles using a theoretically calibrated expanding-photosphere technique (Schmidt et al. 1994; Hamuy 2001). Schmidt et al. found $H_0 = 73 \pm 6 \pm 7$ km s^{-1} Mpc^{-1}, independent of the Cepheid calibration. Hamuy's (2001) updated measurement using the same technique yielded 67 ± 7 km s^{-1} Mpc^{-1}.

SBFs are proportional to the second moment of the stellar luminosity function. Standard stellar population models can be integrated to predict SBF magnitudes for populations with particular ages and metallicities, and then compared to observations (Blakeslee, Vazdekis, & Ajhar 2001; Liu, Charlot, & Graham 2000; Liu, Graham, & Charlot 2002). In the *I* band, SBF comparisons with stellar population models would agree with observations better if the original KP Cepheid zeropoint were fainter by 0.2 ± 0.1 mag (Blakeslee 2002), which would make H_0 10% larger. Jensen et al. (2003) found that *H*-band SBFs were entirely self-consistent with both the Vazdekis (1999, 2001) and Bruzual & Charlot (1993) models when the calibration of Freedman et al. (2001) was used without metallicity corrections. The Hubble constant implied by the IR population models is 8% higher than that determined using the original KP Cepheid calibration of Ferrarese et al. (2000a) and 5% higher than that of Freedman et al. (2001) with the metallicity correction.

1.7 Probability Distributions and Systematic Uncertainties

As distance measurement techniques mature, two things generally happen: first, the number of measurements increases, reducing the statistical uncertainty, and second, the larger data sets make it possible to correct for secondary effects that modify the brightness of the standard candle. The result is a reduction in the statistical uncertainty to the point that systematic effects start to dominate. This is certainly true for Cepheids and the secondary distance indicators calibrated using them. As shown in previous sections, systematic uncertainties in the Cepheid distances dominate statistical uncertainties and the systematic differences between different secondary techniques. Addressing systematic uncertainties is a difficult job that cannot proceed until a sufficiently large number of measurements has been made to understand the intrinsic dispersion in the properties of a standard candle.

Some of the techniques discussed have not yet been applied to enough systems to conclusively say that small number statistics are not an issue, even though the formal statistical uncertainty of an individual measurement might be small. Gravitational lens time delays have only been measured in five systems, for example. SZ measurements are only now reaching large enough samples to start addressing the systematic uncertainties. Fortunately, the sample sizes will increase significantly as surveys to find and measure more lensed quasars and SZ clusters proceed. Supernovae of all types are rare enough that finding enough nearby SNe for calibration purposes has required using limited and often old, unreliable data.

The probability distributions of systematic uncertainties is not always known, and is frequently not Gaussian. For example, the range of H_0 values permitted by the gravitational lens measurements is set by systematic uncertainties in the lens mass distribution. The extremes are rather rigidly limited by constraints on the possible fraction and distribution of dark matter in galaxies. The probability distribution is therefore rather close to a top hat, with "sigma limits" that are not at all Gaussian (e.g., $2\text{-}\sigma < 2 \times \sigma$). It is clearly not appropriate to add errors of this nature in quadrature.

Many researchers have maintained separate accounting of systematic and random uncertainties when possible (cf., Ferrarese et al. 2000a). Even this approach requires the addition of different systematic uncertainties in quadrature, assuming that individual systematic uncertainties are independent and Gaussian in nature. In many cases this is probably justified; in others, simply reporting a range of possible values is more appropriate. The problem with reporting such ranges as a systematic uncertainty is that they are often viewed as being overly pessimistic by the casual reader who regards them as "1-σ" uncertainties. Given the difficulty in comparing very different systematic uncertainties, it is probably premature to judge the SZ and gravitational lens results as being inconsistent with the Cepheid-based distance indicators at the present time when the number of measurements is still rather few and the systematics have not been explored in great detail.

1.8 Future Prospects

The secondary distance indicators, mostly calibrated using Cepheids, are all in good agreement when calibrated uniformly. These imply a Hubble constant between 70 and 75 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Many other techniques that do not rely on the calibration of the traditional distance ladder generally agree with this result at the 1-σ level; further concordance between independent techniques will require a careful analysis of systematic uncertainties and new survey data that will become available in the next few years. Improvements in the Cepheid calibration will require a better zeropoint and larger samples covering a range of period and metallicity. Near-IR photometry will help reduce uncertainties due to extinction. High-resolution imaging will help reduce blending and allow measurements of Cepheids in more distant galaxies. Improved photometry and excellent resolution will make the ACS and WFPC3 on *HST* powerful Cepheid-measuring instruments.

SIM and *GAIA* are two astrometry satellite missions planned by NASA and ESA that will help reduce systematic uncertainties in the extragalactic distance scale by providing accurate (1%) parallax distances for a significant number of Galactic Cepheids. *SIM* and *GAIA* will allow us to calibrate the Cepheid zeropoint, PL relation, and metallicity corrections without having to rely on the LMC sample or the distance to the LMC. We are optimistic that the debate over the "long" and "short" distance scales for the LMC will soon be behind us. While this will be a significant milestone, it will not help much to reduce the statistical uncertainty in the measured value of the Hubble constant. It will, however, remove one persistent source of systematic error. To achieve a Hubble constant good to 5% using a distance estimator tied to the LMC will require much more accurate geometrical measurements, and a reduction of the other systematic uncertainties as well.

With *SIM* and *GAIA*, the calibration of several variable star distance scales in addition to the Cepheids will be solidified. These include RR Lyrae variables, delta Scuti stars, and shorter-period overtone pulsators. The increased sensitivity and spatial resolution of the next generation of large ground and space telescopes will allow us to detect these fainter variables in the distant galaxies in which only Cepheids are currently detectable. Other variable stars will allow us to resolve questions about bias that arise when only the very brightest members of the Cepheid population are detected and used to determine the distance.

The number of ways to bypass the Cepheid rung of the distance ladder will increase dramatically when *SIM* and *GAIA* allow us to calibrate a number of secondary distance indicators directly from statistical parallax distance measurements to M31, M32, and M33. Techniques like SBF, Tully-Fisher, FP, GCLF, PNLF, and so forth, have already been used to determine accurate relative distances between the Local Group members M31, M32, and M33 and more distant galaxies. By determining their distances directly from statistical parallax measurements, the systematic uncertainties in the Cepheid calibration and LMC distance will be avoided altogether.

Improvements in techniques that bypass the local distance ladder and secondary distance indicators are imminent. Larger samples of well-measured gravitational lens time delays and SZ clusters will help reduce statistical uncertainties and provide insight into the systematics. Better mass models for gravitational lenses will not only lead to better determinations of H_0, but also be valuable in constraining the quantity and distribution of dark matter in galaxies. The increasing number of SZ measurements will lead to a better understanding of galaxy cluster structure and evolution.

The number of direct geometrical distance measurements to nearby galaxies will also increase. The masers detected in NGC 4258 must also exist in other galaxies. A larger sample of detached eclipsing binaries, both in the LMC and in other galaxies, will help overcome the systematic uncertainties and provide more consistent distances. These techniques, like SNe in nearby galaxies, are limited by small-number statistics. An individual measurement may seem reliable, but until more are found, our confidence in them will be limited.

Several new synoptic and survey facilities are currently being planned that will discover many thousands of SNe. The *SNAP* satellite will discover thousands of SNe over its lifetime. It will be able to measure optical and near-IR brightnesses and collect spectra for SN classification. The Large Synoptic Survey Telescope (LSST) and PanSTARRs survey telescopes, currently in the planning stages, will discover hundreds of thousands of Ia SNe every year. The synoptic telescopes will also reveal a multitude of faint variable stars in the Galaxy. With this wealth of data, systematic uncertainties can be addressed and the expansion rate of the Universe determined as a function of redshift to $z > 1$. We will only be limited by our ability to follow up the SN discoveries to determine reliable distances.

Perhaps the best determination of H_0 in the future will come from the combination of multiple joint constraints, just as the conclusions regarding the $\Omega_\Lambda = 0.7, \Omega_m = 0.3$ Universe came from merging the Type Ia SN results with the measurements of $\Omega_{tot} = 1.0$ from the cosmic microwave background experiments. For example, both $H_0 t_0$ and $\Omega_b h^2$ are now known to 5%. Other examples of joint constraints that include H_0 are described elsewhere in this volume.

Acknowledgements. J. Jensen acknowledges the support of the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., on behalf of the international Gemini partnership of Argentina, Australia, Brazil, Canada, Chile, the United Kingdom, and the United States of America.

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