The Hubble Constant

John P. Huchra

The Hubble constant is the constant of proportionality between recession velocity and distance in the expanding universe. It is a fundamental property of cosmology that sets both the scale and the expansion age of the universe. It is determined by measurement of galaxy radial velocities and distances. Although there has been considerable progress in the development of new techniques for the measurements of galaxy distances, both calibration uncertainties and debates over systematic errors remain. Current determinations still range over nearly a factor of 2; the higher values favored by most local measurements are not consistent with many theories of the origin of large-scale structure and stellar evolution.

The birth of modern cosmology took place in the early decades of this century with the combined discoveries of the curvature of space-time by mass-energy and of the general apparent recession of galaxies. These naturally led to the now commonly accepted description of the universe in terms of the Friedmann-Lemaître models (*1*). In these models, the universe today has a finite age and is generally dynamic; that is to say, it must be either expanding or contracting. The observation that galaxies are red-shifted—have spectral features shifted to redder wavelengths in an apparent Doppler recession—strongly supported the expanding universe model. Confidence in the Friedmann-Lemaître models was strengthened further when Edwin Hubble discovered a linear relation between red shift and distance in 1929 (*2*). The constant of proportionality is now known as the Hubble constant and is usually expressed in terms of kilometers per second per megaparsec (*3*). The Hubble parameter is defined as

$$H(t) = \frac{1}{R(t)}\frac{dR(t)}{dt} \qquad (1)$$

where $R(t)$ is the scale factor of the universe. The Hubble constant is the current value of that parameter,

$$H_0 = H(\text{now}) = \frac{\text{Velocity}}{\text{Distance}} \qquad (2)$$

and is estimated by measuring the velocities and distances of extragalactic objects. The Hubble constant actually changes with time as the expansion rate is slowed, for example, by the self-gravity of the matter in the universe. This general, uniform cosmological expansion is called the Hubble flow.

The Hubble constant is perhaps the most important parameter in cosmology because it not only gives the physical scale of the universe, which affects the observed absolute sizes, dynamical masses, and luminosities of extragalactic objects, but it also provides an estimate of the age of the universe. The Hubble constant has the units of inverse time. An estimate of the age of the universe is the Hubble time, $1/H_0$. This is the approximate age of a nearly "empty" universe, one where the expansion has not significantly been slowed by its mass-energy content. In the models currently most favored by cosmological theorists, the gravitational binding energy of the universe exactly balances its kinetic energy. These models are called $\Omega = 1$ models, where Ω is the ratio of the universe's mass-energy density to the critical value required for binding. In these Friedmann-Lemaître models, the expansion rate of the universe approaches 0 as time approaches ∞, and the current age of the universe is $(2/3)H_0^{-1}$. The exact equation in models without a cosmological constant is

$$\text{Age} = \frac{1}{H_0}[(1 - 2q_0)^{-1} - q_0(1 - 2q_0)^{-3/2}\cosh^{-1}(1/q_0 - 1)] \qquad (3)$$

where the deceleration parameter, q_0, is $(1/2)\Omega$, the ratio of the universe's mean mass density to the closure density. An H_0 of 100 km s^{-1} Mpc^{-1} in an empty universe roughly corresponds to an age of 10 billion years, whereas an H_0 of 50 km s^{-1} Mpc^{-1} gives an age near 20 billion years.

Hubble's original crude value for H_0 was >500 km s^{-1} Mpc^{-1}. This led to an uncomfortably short age for the universe of only ~2 billion years, which was smaller than the best geological estimates then for the age of the earth. Since then, considerable effort has been put into improving the calibration of the extragalactic distance scale, especially toward accurately measuring galaxy distances and understanding systematic effects that might bias the determination of the global value of H_0.

The author is a professor, a senior astronomer, and an associate director of the Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138.

Measurement of Galaxy Distances

It is generally possible to measure the apparent recession velocities of all but the nearest (and thus lowest velocity) galaxies with a relative precision better than 1%. The majority of the error in the determination of H_0 comes from errors in the measurement of galaxy distances, provided that the galaxies so surveyed are sufficiently distant that their apparent velocities are primarily due to the cosmological expansion. The large galaxy nearest our own, M31, the Andromeda nebula, is actually moving toward our galaxy because M31 and the Galaxy are gravitationally bound. Similarly, some galaxies in the core of the Virgo Cluster, the nearest rich cluster of galaxies, appear blue-shifted because their orbital motions about the cluster gravitational potential are greater than the cluster's cosmological, or Hubble flow, velocity. Such gravitationally or otherwise induced deviations from the smooth Hubble flow are called peculiar velocities and are discussed in detail below. Currently, peculiar velocities are not thought to exceed a few thousand kilometers per second, so the accurate measurement of distances to galaxies at velocities of a few tens of thousands of kilometers per second should yield a value for H_0 accurate to 10%.

Hubble, his successor Sandage, and their co-workers developed a detailed scheme for obtaining distance measurements of distant galaxies called the cosmological distance ladder (*4*). There are several steps to the process, which generally involve the calibration of absolute luminosities for "standard candles" or absolute diameters for "standard yardsticks." These are single objects (usually stars) or collections of objects (star clusters, parts or whole galaxies) that can be identified at moderate to large distances and that have an absolute brightness or size that is invariable or dependent only on other observable parameters, such as color or pulsation period, but not directly dependent on distance. The first rung of the distance ladder is occupied by Cepheid variables, pulsating supergiant stars for which luminosity is a function of pulsation period and a weaker function of surface temperature (as measured by color).

These stars are sufficiently bright to be visible with large ground-based telescopes to approximately 50% of the distance to the Virgo Cluster of galaxies. The absolute calibration for the luminosity of Cepheids comes from the measurement of distances to star clusters in the Galaxy and is currently accurate to about the 10% level, with only small corrections necessary for chemical composition (*5*). Significant improvements to the zero point as well as the elimination of systematic effects due to chemical composition and absorption by dust have come through the use of measurements at longer wavelengths. The RR Lyrae variable stars, typically 100 times as faint as the Cepheid variables, have also been used to confirm the Cepheid distances to the nearest galaxies, especially the Magellanic Clouds and now M31.

The second rung of the distance ladder is composed of measurements of several types of objects that have included the brightest stars in galaxies; the luminosity functions (numbers of objects per luminosity interval) of globular star clusters (GCLF); the sizes, luminosities, or internal velocity dispersions of giant HII regions; novae (luminosity at maximum light versus rate of decay of the brightness); and a number of relations between integrated properties of galaxies and their luminosities. The crudest of these last is the luminosity class or luminosity index (*6*), which, because of its large uncertainties, is not currently in significant usage. The two most prominent are the Tully-Fisher relation and its variants at different wavelengths (*7*), which are correlations between the rotation rate of a spiral galaxy and its luminosity and size, and the correlation between the central velocity dispersion and luminosity or size for elliptical galaxies (*8*), now often called the $D_n - \sigma$ relation. The infrared Tully-Fisher (IRTF) relation has been applied to particularly large data sets for nearby galaxies and more distant galaxy clusters. It is possible to derive calibrations for a few of these techniques, such as novae luminosities from expansion parallaxes for galactic novae and the GCLF in the Galaxy, but the calibrations in external galaxies are preferred. A number of these techniques have lost and gained prominence in the last two decades; for example, the brightest stars are currently thought to be difficult to use even in nearby galaxies, whereas the use of the GCLF is gaining adherents (*9*).

In addition to the secondary distance indicators, there are also several tertiary indicators that require calibration in systems beyond the reach of Cepheid and other primary measurements. These include the luminosities of type Ia supernovae (SN Ia) and the brightest galaxies in clusters. The $D_n - \sigma$ relation for elliptical galaxies is sometimes considered to be in this category, as Cepheids are not generally found in early-type galaxies. Of the tertiary indicators, SN Ia are perhaps the most useful (*10*) and may soon become secondary indicators when Cepheid calibrations become available for the two nearest galaxies that have had SN Ia, IC4182 and NGC5253. It is also possible that, with the development and empirical testing of detailed models for the detonation of SN Ia that predict absolute luminosity, they will be considered "global" distance estimators. Global distance estimators include expansion parallaxes for supernovae of type II (SN II), application of the Sunyaev-Zeldovich effect to distant rich clusters of galaxies, and the measurement of the time delay between the different images of gravitationally lensed objects. These are discussed in more detail below.

Several reviews and conferences describing the state of the distance-scale debate in the early 1980s (*11*) as well as a popular account of the activities of Sandage, one of the leading researchers in the field (*12*), have been published.

Systematic Effects

Perhaps the most important work on the distance scale in the last decade has been that on understanding and measuring two important systematic biases. The first of these is the Malmquist effect, which causes one, for example, to generally overestimate the brightness of distant objects in flux-limited samples of finite dispersion and thus to overestimate the value of the Hubble constant. The amplitude of this effect depends critically on the dispersion, σ, of the parameter used as a distance indicator (scatter caused both by any intrinsic variation about the mean as well as by measurement errors); the correction to the derived absolute magnitude is approximately $\Delta M = 1.4\sigma^2$ (*13*). Perfect measurements of a perfect standard candle require no correction; however, if one uses a technique such as the blue Tully-Fisher relation from a sample of galaxies with a dispersion of a factor of 2 in luminosity about the mean relation with 21-cm line width, correction factors near 2 may be required (*14*). Much of the debate over different estimates of H_0 during the last decade made by different applications of the same technique has centered on the amplitude and direction of the Malmquist bias (*14, 15*). The severity of this effect has prompted renewed efforts both to understand and minimize the scatter for several distance estimators and to develop new techniques for distance estimation with very small dispersions (see below). It should be noted that distance estimators with large dispersions are not only biased but are also difficult to calibrate accurately, because the number, N, of calibrating galaxies for most relations is very small, and the error in zero point only decreases as $\sqrt{N}$.

The second systematic effect is the existence of bulk peculiar motions or large-scale flows in the vicinity of the Local Group. The observed velocity, v_O, of any galaxy consists of two components, the object's true Hubble velocity, v_H, and a peculiar velocity, v_P, that might result from local gravitational distortions of the universe's expansion:

$$v_O = v_H + v_P \qquad (4)$$

Although distortions of the Hubble flow in dense systems such as groups and clusters of galaxies have been known for 50 years, the suggestion that the perturbations are sufficiently large to affect the determination of H_0 (*16*) did not gain credence until the solid detection of the microwave background dipole anisotropy (*17*) and the detection and measurement of the infall of the Local Group into the Virgo Cluster (*18*) at a rate somewhere between 0.2 and 0.4 of the cluster's apparent velocity. Such an infall velocity directly affects the value of H_0 derived with any indicator and will increase the correct value of H_0 by 20 to 40% if not corrected for. Further work on more distant samples of galaxies and clusters of galaxies has uncovered evidence for even larger perturbations of the Hubble flow on larger scales (*19*). These discoveries point to the need for detailed mapping of the velocity field, the determination of the scale on which peculiar velocities no longer contribute significantly to the error in the determination of H_0, and the accurate measurement of distances on that scale.

Biases in distance estimates can also be caused by the presence of large-scale structures. Sampling biases such as the Malmquist bias can produce both underestimates and overestimates of the Hubble constant (*14, 15*) and can significantly affect the determination of non-Hubble velocities (*20*). With knowledge of the sample properties and the spatial and velocity distributions of the galaxies used, unbiased estimates can be derived (*15, 18*).

Recent Developments

Since the last major reviews of the cosmological distance scale, there have been several developments worth noting. The most basic of these is the successful test of the linearity of the velocity-distance relation (*21*). This result not only refutes several arguments about the basic cosmological model (*22*) but also places limits on the existence of extremely large scale flows. The second fundamental development has been the use of array detectors [charge-coupled devices (CCDs)] and infrared photometry to significantly improve the detection and measurement of Cepheid variables in nearby galaxies (*5, 23*). There are now Cepheid distances to over a dozen galaxies, of which six are large spirals suitable for calibrating several secondary distance indicators (Table 1). In particular, two groups have used these distances to derive new calibrations as well as estimates of the intrinsic dispersion of multicolor Tully-Fisher relations (*24, 25*). The zero points of the calibration of absolute magnitude versus line width in the B, R, I, and H bands are essentially the same as most previously published results; the scatter in the R, I, and H relations is extremely small, less than 0.3 magnitude, and perhaps as low as 0.15 magnitude at H, such that the uncertainty in the zero point of the H-band relation is less than 0.08 magnitude, or 4% in the distance scale so derived. Although there appears to be environmental dependence in the B-band, if these results are universal, the Malmquist bias is not significant. The application of these calibrations to existing high-quality data sets (spirals of regular morphology, high signal-to-noise 21-cm line profiles, and well-determined and large inclinations, $i \geq 45°$) for the Virgo Cluster and the Ursa Major cloud, including infall velocity corrections, yields values for H_0 between 80 and 90 km s^{-1} Mpc^{-1}.

In the last 4 years, two new and independent distance estimators have been discovered. The first of these is the surface brightness fluctuation technique (SBF) (*26*). This technique is based on measurements of the surface brightness fluctuations in elliptical galaxies and spiral bulges. The amplitude of the fluctuations depends on the number of giant stars per unit solid angle—nearby galaxies will have fewer stars per unit area (per pixel on a CCD array) so that the variance in the number of photons per pixel will be larger than that for more distant galaxies. This technique has been used to derive $H_0 = 82 \pm 7$ km s^{-1} Mpc^{-1} from measurement of the distance to the Virgo Cluster (*27*). It shows promise of being able to derive 5% distances to early-type systems as far as 4,000 km s^{-1} from the ground and to 10,000 km s^{-1} with a corrected Hubble Space Telescope (HST).

The second new estimator is the use of the luminosity function of planetary nebulae (PNLF) (*28*). Planetary nebulae can be identified relatively easily with narrow-band interference filters and CCD arrays. Tests of this technique have shown it to be relatively insensitive to Hubble type, and its application to the measurement of the Virgo Cluster distance yields values of H_0 in the ranges 81 ± 6 to 94 ± 6, depending on assumptions about the infall velocity into Virgo (*29*). The measured distances to the Virgo Cluster and to several intermediate galaxies and galaxy groups show excellent agreement among the IRTF, the SBF, and the PNLF techniques and moderately good agreement with relative $D_n - \sigma$ distances.

Prompted by detailed observations at multiple wavelengths of the type II supernova 1987A, researchers have developed improved models for the expanding atmospheres of these objects and have measured expansion parallaxes to SN II in the Virgo Cluster and beyond to derive $H_0 = 60 \pm 10$ km s^{-1} Mpc^{-1} (*30*). This is somewhat higher than earlier determinations (*31*). The current situation for the application of SN Ia, despite the promise of these objects as global calibrators, remains somewhat confused. There are four different possible calibrations for the maximum luminosity of these objects, based on (i) SN Ia in our galaxy, (ii) theoretical models of their light curves based on ^{56}Ni and ^{56}Co decay, (iii) the brightest star distance to IC4182, the nearest galaxy with a well-observed SN Ia, and (iv) the Virgo distance (*31, 32*). Values of H_0 derived from SN Ia range from 40 to 100 km s^{-1} Mpc^{-1}, and a new calibration of the distance to IC4182 suggests that the value of H_0 based on calibration (iii) should be 86 ± 12 km s^{-1} Mpc^{-1} (*33*). In addition to supernovae, an intensive search for novae in Virgo Cluster galaxies has been made at the Canada-France-Hawaii telescope (CFHT). The analysis and a reanalysis of these data gave values for H_0 of 69 ± 14 and 58 ± 12, respectively (*34, 35*). The CFHT is on Mauna Kea, an astronomical site with exceptionally small atmospheric turbulence or seeing, and is equipped to take advantage of these conditions to produce sub-arcsecond images. Observational programs to image galaxies out to the distance of the Virgo Cluster to search for Cepheid variables and identify the brightest stars should have a significant effect on the local calibration of the distance scale.

Since the discovery of large-scale flows (*18, 19*) a decade ago, there have been substantial studies of the local velocity field, including measurements of galaxy distances and peculiar velocities (*36–38*) and the local density field (*39*), as well as attempts to produce detailed models and comparisons of the measured and expected flow fields (*40*). These studies remain crude compared to what is required for an accurate local determination of H_0. Galaxy distances are known to fewer than 2000 galaxies, and accurate distances, with errors smaller than 10%, are known to fewer than 100. Density-field maps are primarily based on samples of galaxies discovered by the Infrared Astronomical Satellite (IRAS), which can more easily probe low galactic latitudes, but these maps undersample the density field both locally and at distances greater than ~5000 km s^{-1} owing to the relatively low space densities of strong infrared emitters among all galaxies (*39*).

Table 1. Cepheid distances to nearby galaxies [from (*5*), (*24*), and (*25*)]. The Wolf-Lundmark-Melotte galaxy is denoted by WLM; $m - M$, distance modulus in magnitudes.

Galaxy	Type	$m - M$ (mag)	Distance (Mpc)
LMC	SmIII	18.5	0.050
SMC	ImIV-V	18.75	0.056
NGC6822	ImIV-V	23.59	0.52
IC1613	ImV	24.42	0.77
M31	SbI-II	24.44	0.77
M33	ScII-III	24.63	0.84
WLM	ImIV-V	24.89	0.95
Sextans A	ImIV-V	25.75	1.41
Sextans B	ImIV-V	25.80	1.44
NGC3109	SmIV	25.50	1.26
NGC300	ScII	26.50	2.00
NGC2403	ScdIII	27.51	3.18
M81	SbI-II	27.59	3.30
M101	ScI	29.38	7.52

Global Measurements

Most of the previously mentioned determinations of H_0 are "local" because they only measure distances to objects at relatively small red shifts. This means that almost by definition they can be affected by local velocity anomalies, such as our infall into the Virgo Cluster or into larger superclusters such as the Great Attractor, or, more generally, can be biased by any density inhomogeneity, positive or negative, on those scales. For this reason, there is also considerable interest in "global" determinations of H_0. Supernovae of type Ia, discussed above, have the potential to be observed at maximum luminosity to very great distances (red shifts > 0.5), but so far the necessary searches with very large telescopes have not been initiated. Two other global techniques for the determination of H_0 have recently been applied with some success. The first of these is the measurement of the Sunyaev-Zeldovich effect. This is a decrease of the cosmic microwave background temperature in the direction of a rich cluster of galaxies caused by the inverse Compton scattering of the background photons off the hot intracluster gas. The angular diameter distance D_A of the cluster can be estimated from measurements of its x-ray flux F_X, the radio brightness temperature decrease ΔT, the cluster gas electron temperature T_e, and its angular size θ:

$$D_A \propto \Delta T^2 F_X{}^{-1} T_e{}^{-3/2} \theta^{-1} \quad (5)$$

Although the Sunyaev-Zeldovich effect has been known for many years, the first moderately successful application of it to the measurement of H_0 for the rich cluster Abell 665 was completed last year and produced a fairly low value of 40 to 50 ± 12 km s^{-1} Mpc^{-1} (*41*). This technique, although independent of all of the local calibration, depends on a number of assumptions regarding the cluster gas geometry, temperature, and density distribution as well as on background source contamination and the cosmological model.

Another global measurement of H_0 results from the determination of the time-delay and path-length differences between multiple images of gravitationally lensed objects. For a given mass distribution, the time delay expected is roughly inversely proportional to H_0. As for the Sunyaev-Zeldovich effect, this property of lenses has been known for a long time but has again only recently been effectively applied to the data for the lensed quasar and lens 0957+561. A simple lens model that accounts for its imaging properties yields an estimate

$$H_0 = (90 \pm 10)\left(\frac{\sigma_v}{390 \text{ km s}^{-1}}\right)^2 \left(\frac{\Delta t}{1 \text{ year}}\right)^{-1} \quad (6)$$

where σ_v is the velocity dispersion of the central lensing galaxy and Δt is the measured time delay between the A and B images (*42*). The time delay had been estimated as near 400 days. An observation of the galaxy's velocity dispersion was combined with the smaller value of the time delay to estimate a value of H_0 of 50 $\pm$ 17 km s^{-1} Mpc^{-1} (*43*). This estimate may be high because the time delay is now thought to be closer to 500 days (*44*), but it may be low if cluster contribution to the surface mass density has been underestimated.

Current Limits and Future Prospects

Table 2 is a compilation of recent (since 1986) determinations of H_0. This listing is not meant to be complete, as it is approximately limited to one reference per research group per technique, but is meant rather to present the flavor of the current debate and the directions in which research is proceeding. In addition to the measurements discussed above, Table 2 lists several recent and often conflicting derivations based on the application of the optical and IRTF relations (*36, 45–50*), the $D_n - \sigma$ relation (*51, 52*), luminosity classes (*53–55*), novae and supernovae (*56*), and the velocity dispersions of giant HII regions (*57*). The last six entries present efforts by several researchers to synthesize "best" values for H_0, either at conferences or in review papers (*58–63*). Many of the authors whose results and summaries are shown here quote internal errors only. When a full accounting of external errors is given, almost all of the results overlap within 2 standard deviations (*61*).

Since the reviews of a decade ago, both the bounds and range of quoted values of H_0 are decreasing; no recent determinations exceed 100 km s^{-1} Mpc^{-1}. Values are still clustered about two numbers, but those numbers are now 50 and 85. A preponderance of the newest local estimates favors the higher value of 85 km s^{-1} Mpc^{-1}; the agreement between widely different techniques with different systematic biases is extremely encouraging. On the opposite side, SN Ia need a firmer calibration, but the agreement between the two global measurements is also encouraging. The disagreement between the global and most of the local measurements is disturbing and may be pointing to a problem with our assumption that the local universe is representative of the universe as a whole.

What does this mean for cosmology? If the value of H_0 is indeed >75 km s^{-1} Mpc^{-1}, as the best recent local measurements indicate, the age of the universe is less than 15 billion years. If the ages of globular cluster stars are indeed near 15 billion years, then the cosmic mean mass density is likely to be small, $\Omega \approx$ 0.1 to 0.3. It is possible to construct a cosmological model with a small Ω and a moderately large H_0 that meets almost all observational constraints. This, however, is in serious conflict with the precepts of the inflationary model, which essentially requires $\Omega = 1$ (*64*). Such a matter-dominated, low-density model is also one in which galaxy formation is difficult (*65*).

If H_0 is 85 km s^{-1} Mpc^{-1} and the oldest globular clusters are 18 billion years old, a serious problem exists. One possible explanation that has been attracting attention lately is the possibility that the cosmological constant Λ, proposed and then rejected by Einstein (*66*), is nonzero. A positive Λ could make up the difference between the actually observed Ω_{matter}, which is 0.2 to 0.3 (*67*), and the $\Omega_{\text{total}} = \Omega_{\text{matter}} + \Lambda/3H_0^2 = 1$, as predicted by inflation (*68, 69*). In models with a positive cosmological constant, the age of the universe will be longer than H_0^{-1} (*66, 68*). Observational tests of this hypothesis have yielded mixed results (*70, 71*), but a high value of H_0 and a large globular cluster age will require a cosmological constant even if the inflationary hypothesis is incorrect. On the other hand, it is also possible that the local measurements of H_0 are severely affected by large-scale flows or that we live in a particularly underdense region of the universe. The latter is somewhat unlikely given the linearity of the velocity-distance relation (*21*). Neither hypothesis can be ruled out at present.

Directions for future research are both clear and difficult. Improved calibrations for the low-dispersion distance indicators, IRTF, SBF, PNLF, and possibly SN Ia (*71*) and the GCLF, must be obtained with accurate Cepheid distances from a repaired HST. These techniques must be used to map the "local" velocity field ($v \leq 15{,}000$ km s^{-1}). This will have the by-product of producing a more global determination of Ω if the density field is also well mapped. The use of global techniques must be developed, including the identification of additional suitable candidate gravitational lenses from quasar surveys and Sunyaev-Zeldovich clusters from Roentgen Satellite (ROSAT) and Advanced X-ray Astrophysics Facility (AXAF) studies. The Hubble constant debate is far from over, but new developments in distance indicators and our knowledge of the distribution of matter in space are making the path to its resolution more clear.

Table 2. Some recent measurements of H_0 (in kilometers per second per megaparsec). In several of the below cases, the published values have been restated in terms of a mean value and a range.

Optical Tully-Fisher (*45*)	85 ± 10
Optical Tully-Fisher (*46*)	57 ± 1*
Optical Tully-Fisher (*47*)	68 ± 8*
Optical Tully-Fisher (*48*)	92 ± 20
Optical Tully-Fisher (*49*)	56 ± 13*
IR Tully-Fisher (*50*)	88 ± 35
IR Tully-Fisher (*36*)	90 ± 15
L-σ (*51*)	85 ± 5*
L-σ (*52*)	67 ± 10
Planetary nebulae (*29*)	87 ± 12
Fluctuations (*27*)	82 ± 7*
Supernovae II (*30*)	60 ± 10
Supernovae Ia+II (*31*)	57 ± 10*
Supernovae Ia (*32*)	87 ± 12
Supernovae Ia (*33*)	86 ± 12
Novae + SN Ia (*56*)	70 ± 15
Novae (*34*)	69 ± 14
Novae (*35*)	58 ± 12
Giant HII regions (*57*)	89 ± 10
Luminosity classes (*53*)	105 ± 11
"Sosies" (*54*)	99 ± 15
Sc I galaxies (*55*)	42 ± 11
Sunyaev-Zeldovich (*41*)	45 ± 12*
Gravitational lens time delay (*43*)	50 ± 17
Summary (*58*)	90 ± 20
Summary (*59*)	45 ± 3*
Summary (*60*)	66 ± 10
Summary (*61*)	70 ± 20
Summary (*62*)	73 ± 10
Summary (*63*)	92 ± 30

*Quoted with internal error estimates only.

REFERENCES AND NOTES

1. For example, S. Weinberg, *Gravitation and Cosmology* (Wiley, New York, 1972); P. J. E. Peebles, *Physical Cosmology* (Princeton Univ. Press, Princeton, NJ, 1971).
2. For a good description of his early work, see E. Hubble, *The Realm of the Nebulae* (Yale Univ. Press, New Haven, CT, 1936).
3. One megaparsec is 3.26 million light-years. Galaxy recession or radial velocities are usually in the range of hundreds to tens of thousands of kilometers per second. When reluctant to quote a Hubble constant, astronomers often quote galaxy distances either directly in recession velocity, v_r, or in red shift, v_r/c.
4. M. Rowan-Robinson, *The Cosmological Distance Ladder* (Freeman, San Francisco, 1985).
5. B. Madore and W. Freedman, *Publ. Astron. Soc. Pac.* **103**, 933 (1991).
6. S. van den Bergh, *Astrophys. J.* **131**, 215 (1960); G. de Vaucouleurs, *ibid.* **233**, 433 (1979).
7. R. B. Tully and R. Fisher, *Astron. Astrophys.* **54**, 661 (1977); M. Aaronson, J. Huchra, J. Mould, *Astrophys. J.* **229**, 1 (1979).
8. S. Faber and R. Jackson, *Astrophys. J.* **204**, 668 (1976); S. Djorgovski and M. Davis, *ibid.* **315**, 59 (1987); A. Dressler *et al.*, *ibid.* **313**, 42 (1987).
9. R. Humphries and M. Aaronson, *Astrophys. J. Lett.* **318**, L69 (1987); W. Harris, in *The Extragalactic Distance Scale*, S. van den Bergh and

C. Pritchet, Eds. (Astronomical Society of the Pacific, Provo, UT, 1988), p. 231.
10. A. Sandage and G. Tammann, *Astrophys. J.* **256**, 339 (1982).
11. P. Hodge, *Annu. Rev. Astron. Astrophys.* **19**, 357 (1981); M. Rowan-Robinson, *Space Sci. Rev.* **48**, 1 (1988). See also the conference proceedings *Galaxy Distances and Deviations From Universal Expansion*, B. Madore and R. B. Tully, Eds. (Reidel, Dordrecht, Netherlands, 1986), and *The Extragalactic Distance Scale*, 100th Astronomical Society of the Pacific Anniversary Symposium, S. van den Bergh and C. Pritchet, Eds. (Astronomical Society of the Pacific, Provo, UT, 1988).
12. D. Overbye, *Lonely Hearts of the Cosmos* (Harper Collins, New York, 1991).
13. K. Malmquist, *Medd. Lund. Astron. Obs. Ser. 2* (no. 22) (1920); P. Teerikorpi, *Astron. Astrophys.* **45**, 117 (1975); E. Giraud, *Astrophys. J.* **301**, 7 (1986); L. Bottinelli, L. Gouguenheim, G. Paturel, P. Teerikorpi, *Astron. Astrophys.* **156**, 167 (1986).
14. A. Sandage, *Astrophys. J.* **331**, 605 (1988).
15. R. B. Tully, *Nature* **334**, 209 (1988).
16. G. de Vaucouleurs, *Astron. J.* **63**, 253 (1958).
17. For example, E. Cheng, P. Saulson, D. Wilkinson, B. Corey, *Astrophys. J. Lett.* **232**, L139 (1979).
18. P. Schechter, *Astron. J.* **85**, 801 (1980); J. Tonry and M. Davis, *Astrophys. J.* **246**, 680 (1981); M. Aaronson *et al.*, *ibid.* **258**, 64 (1982).
19. M. Aaronson *et al.*, *Astrophys. J.* **302**, 536 (1986); A. Dressler *et al.*, *Astrophys. J. Lett.* **313**, L37 (1987); D. Lynden-Bell *et al.*, *Astrophys. J.* **326**, 19 (1988). The last two papers describe the discovery of a large mass concentration at perhaps four times the Virgo Cluster distance, now called the "Great Attractor."
20. G. Bothun, M. West, J. Mould, R. Schommer, *Astrophys. J.* **353**, 344 (1990).
21. A. Sandage and J. M. Perlemuter, *ibid.* **370**, 455 (1991).
22. I. E. Segal, *Proc. Natl. Acad. Sci. U.S.A.* **72**, 2473 (1975); *ibid.* **77**, 10 (1980).
23. K. Cook, M. Aaronson, G. Illingworth, *Astrophys. J. Lett.* **301**, L45 (1986), Cepheids in M101; W. Freedman and B. Madore, *ibid.* **332**, L63 (1988), Cepheids in M81 and NGC 2403.
24. W. Freedman, *ibid.* **355**, L35 (1990).
25. M. Pierce and R. B. Tully, *Astrophys. J.* **387**, 47 (1992); M. Capaccioli, G. Piotto, F. Bresolin, *Astron. J.* **103**, 1151 (1992).
26. J. Tonry and D. Schneider, *Astron. J.* **96**, 807 (1988).
27. J. Tonry, E. Ajhar, G. Luppino, *Astrophys. J. Lett.* **346**, L57 (1989); J. Tonry, *ibid.* **373**, L1 (1991).
28. G. Jacoby, *Astrophys. J.* **339**, 39 (1989).
29. R. Ciardullo *et al.*, *ibid.* **383**, 487 (1991); G. Jacoby *et al.*, *ibid.* **356**, 332 (1990).
30. B. Schmidt, R. Kirshner, R. Eastman, *ibid.*, in press.
31. D. Branch, in *The Extragalactic Distance Scale*, S. van den Bergh and C. Pritchet, Eds. (Astronomical Society of the Pacific, Provo, UT, 1988), p. 146.
32. M. Fukugita and C. Hogan, *Astrophys. J. Lett.* **368**, L11 (1991).
33. M. Pierce, M. Ressler, M. Shure, *Astrophys. J.*, in press.
34. C. Pritchet and S. van den Bergh, *ibid.* **318**, 507 (1987).
35. A. Sandage and G. Tammann, *ibid.* **328**, 1 (1988).
36. M. Aaronson *et al.*, *ibid.* **338**, 654 (1989); J. Mould *et al.*, *ibid.* **383**, 467 (1991); J. Willick, *ibid.* **351**, L5 (1990).
37. S. Faber and D. Burstein, in *Large Scale Motions in the Universe*, G. V. Coyne and V. Rubin, Eds. (Vatican Press, Rome, 1988), p. 116.
38. D. Mathewson, V. Ford, M. Buchhorn, *Astrophys. J.*, in press.
39. M. Rowan-Robinson *et al.*, *Mon. Not. R. Astron. Soc.* **247**, 1 (1990); M. Strauss, M. Davis, A. Yahil, J. Huchra, *Astrophys. J.*, in press.
40. E. Bertschinger, A. Dekel, S. Faber, A. Dressler, D. Burstein, *Astrophys. J.* **364**, 349 (1990).
41. M. Birkinshaw, J. Hughes, K. Arnaud, *ibid.* **379**, 466 (1991).
42. E. Falco *et al.*, *ibid.* **372**, 364 (1991).
43. G. Rhee, *Nature* **350**, 211 (1991).
44. W. H. Press, G. Rybicki, J. N. Hewitt, *Astrophys. J.* **385**, 404 (1992).
45. M. Pierce and R. B. Tully, *ibid.* **330**, 579 (1988).
46. R. Kraan-Korteweg, L. Cameron, G. Tammann, *ibid.* **331**, 620 (1988).
47. P. Fouque, L. Bottinelli, L. Gouguenheim, G. Paturel, *ibid.* **349**, 1 (1990).
48. M. Fukugita, S. Okamura, K. Tarusawa, H. Rood, B. Williams, *ibid.* **376**, 8 (1991).
49. A. Sandage, *ibid.* **331**, 605 (1988).
50. J. Huchra, in *The Extragalactic Distance Scale*, S. van den Bergh and C. Pritchet, Eds. (Astronomical Society of the Pacific, Provo, UT, 1988), p. 257.
51. M. Pierce, *Astrophys. J.* **344**, L57 (1989).
52. A. Dressler, *ibid.* **317**, 1 (1987).
53. R. Buta and H. Corwin, Jr., *Astron. J.* **62**, 283 (1986).
54. G. de Vaucouleurs and H. Corwin, Jr., *Astrophys. J.* **308**, 487 (1986).
55. A. Sandage, *ibid.* **331**, 583 (1988).
56. M. Capaccioli *et al.*, *ibid.* **350**, 110 (1990).
57. J. Melnick, R. Terlevich, M. Moles, *Mon. Not. R. Astron. Soc.* **235**, 297 (1988).
58. M. Aaronson and J. Mould, *Astrophys. J.* **303**, 1 (1986).
59. A. Sandage and G. Tammann, *ibid.* **365**, 1 (1990).
60. M. Rowan-Robinson, *Space Sci. Rev.* **48**, 1 (1988).
61. S. van den Bergh, in *The Extragalactic Distance Scale*, S. van den Bergh and C. Pritchet, Eds. (Astronomical Society of the Pacific, Provo, UT, 1988), p. 375.
62. N. Visvanathan, *Aust. J. Phys.* **43**, 189 (1990).
63. J. Huchra, in *13th Texas Symposium on Relativistic Astrophysics*, M. Ulmer, Ed. (World Scientific, Singapore, 1987), p. 1.
64. A. Guth, *Phys. Rev. D* **23**, 347 (1981).
65. G. R. Blumenthal, S. M. Faber, J. R. Primack, M. J. Rees, *Nature* **311**, 517 (1984).
66. S. Weinberg, *Rev. Mod. Phys.* **61**, 1 (1989). The cosmological constant, Λ, is a pressure term introduced by Einstein into his theory of general relativity, before he knew of the universal expansion, to allow for a static solution for the universe.
67. J. Huchra, in *Dark Matter*, the proceedings of the first Institute for Fundamental Theory conference, in press; S. Faber and J. Gallagher, *Annu. Rev. Astron. Astrophys.* **17**, 135 (1979).
68. P. J. E. Peebles, *Astrophys. J.* **284**, 439 (1984); G. Efstathiou, W. J. Sutherland, S. J. Maddox, *Nature* **348**, 705 (1990).
69. E. Turner, *Astrophys. J. Lett.* **365**, L43 (1990).
70. M. Fukugita *et al.*, *ibid.* **361**, L1 (1990).
71. See, for example, D. Miller and D. Branch [*Astron. J.* **100**, 530 (1990); *ibid.* **103**, 379 (1992)], who show that the dispersion for SN Ia may be as low as 0.3 magnitude.
72. This work is dedicated to the memory of Marc Aaronson, with whom I spent many nights observing galaxies and pondering the cosmic distance scale. I also thank the Hubble Space Telescope Key Project team: J. Mould, R. Kennicutt, J. Graham, W. Freedman, B. Madore, H. Ford, J. Hoessel, P. Stetson, G. Illingworth, S. Faber, and J. Gunn, as well as B. Schmidt, R. Kirshner, and R. Schommer for thoughtful discussions. Supported in part by the National Aeronautics and Space Administration and the Smithsonian Institution.

LIGO: The Laser Interferometer Gravitational-Wave Observatory

Alex Abramovici, William E. Althouse, Ronald W. P. Drever, Yekta Gürsel, Seiji Kawamura, Frederick J. Raab, David Shoemaker, Lisa Sievers, Robert E. Spero, Kip S. Thorne, Rochus E. Vogt, Rainer Weiss, Stanley E. Whitcomb, Michael E. Zucker

The goal of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Project is to detect and study astrophysical gravitational waves and use data from them for research in physics and astronomy. LIGO will support studies concerning the nature and nonlinear dynamics of gravity, the structures of black holes, and the equation of state of nuclear matter. It will also measure the masses, birth rates, collisions, and distributions of black holes and neutron stars in the universe and probe the cores of supernovae and the very early universe. The technology for LIGO has been developed during the past 20 years. Construction will begin in 1992, and under the present schedule, LIGO's gravitational-wave searches will begin in 1998.

Einstein's general relativity theory describes gravity as due to a curvature of space-time (*1*). When the curvature is weak, it produces the familiar Newtonian gravity that governs the solar system. When the curvature is strong, however, it should behave in a radically different, highly nonlinear way. According to general relativity, the nonlinearity creates black holes (curvature produces curvature without the aid of any matter), governs their structure, and holds them together against disruption (*2*). Inside a black hole, the curvature should nonlinearly amplify itself to produce a space-time singularity (*2*), and near some singularities the nonlinearity should force the curvature to evolve chaotically (*3*). When an object's curvature varies rapidly (for example, because of pulsations, colli-

The authors are the members of the LIGO Science Steering Group. A. Abramovici, W. E. Althouse (Chief Engineer), R. W. P. Drever, S. Kawamura, F. J. Raab, L. Sievers, R. E. Spero, K. S. Thorne, R. E. Vogt (Director), S. E. Whitcomb (Deputy Director), and M. E. Zucker are with the California Institute of Technology, Pasadena, CA 91125. Y. Gürsel is at the Jet Propulsion Laboratory, Pasadena, CA 91109. D. Shoemaker and R. Weiss are at the Massachusetts Institute of Technology, Cambridge, MA 02129.