Ay 127, Spring 2013

Extragalactic Distance Scale

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In this lecture:

- Hubble constant: its definition and history
- The extragalactic distance ladder
- The HST Key Project and the more modern work
- Age estimates of the universe
- A comprehensive recent review:

Friedman & Madore 2010, ARAA, 48, 673 (arXiv:1004:1856)

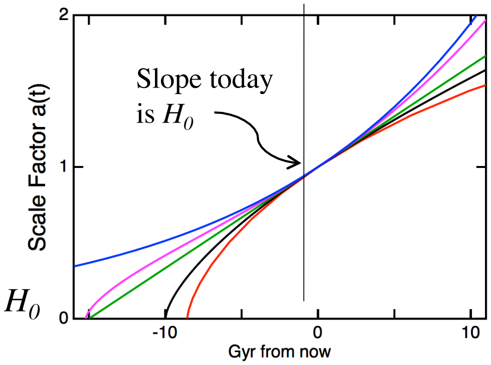
– Check out also:

http://obs.carnegiescience.edu/ociw/symposia/symposium2/

The Hubble Constant

It is the derivative of the expansion law, $R(t)$:

$$\boxed{H \equiv \frac{\dot{R}}{R}}$$



Hubble time: $t_H = 1 / H_0$

Hubble radius: $D_H = c / H_0$

Often written as:

$\boldsymbol{h} = H_0 / (100 \text{ km s}^{-1} \text{ Mpc}^{-1})$, or $\boldsymbol{h_{70}} = H_0 / (70 \text{ km s}^{-1} \text{ Mpc}^{-1})$

$$D_H = c / H_0 = 4.283\ h_{70}^{-1} \text{ Gpc} = 1.322 \times 10^{28}\ h_{70}^{-1} \text{ cm}$$

$$t_H = 1 / H_0 = 13.98\ h_{70}^{-1} \text{ Gyr} = 4.409 \times 10^{17}\ h_{70}^{-1} \text{ s}$$

At low z's, distance $D \approx z\, D_H$

The Scale of the Universe

- The **Hubble length**, $D_H = c/H_0$, and the **Hubble time**, $t_H = 1/H_0$ give the approximate spatial and temporal scales of the universe
- H_0 is independent of the "shape parameters" (expressed as density parameters) Ω_m, Ω_Λ, Ω_k, w, etc., which govern the global geometry and dynamics of the universe
- Distances to galaxies, quasars, etc., scale linearly with H_0, $D \approx cz / H_0$. They are necessary in order to convert observable quantities (e.g., fluxes, angular sizes) into physical ones (luminosities, linear sizes, energies, masses, etc.)

Measuring the Scale of the Universe

- The only clean-cut distance measurements in astronomy are from trigonometric parallaxes. Everything else requires physical modeling and/or a set of calibration steps (the ***"distance ladder"***), and always some statistics:

Use parallaxes to calibrate some set of distance indicators

→ Use them to calibrate another distance indicator further away

→ And then another, reaching even further

→ etc., etc.

→ Until you reach a "pure Hubble flow"

- The age of the universe can be constrained independently from the H_0, by estimating ages of the oldest things one can find around (e.g., globular clusters, heavy elements, white dwarfs)

The Hubble's Constant Has a Long and Disreputable History …

THE VELOCITY-DISTANCE RELATION AMONG EXTRA-GALACTIC NEBULAE[1]

BY EDWIN HUBBLE AND MILTON L. HUMASON (1931, *ApJ* **74**, 43)

The new data extend out to about eighteen times the distance available in the first formulation of the velocity-distance relation, but the form of the relation remains unchanged except for the revision of the unit of distance. The relation is

$$\text{Vel.} = \frac{\text{Dist. (parsecs)}}{1790}, \longrightarrow \boxed{H_0 = 560 \text{ km/s/Mpc}}$$

and the uncertainty is estimated to be of the order of 10 per cent.

Since then, the value of the H_0 has shrunk by an order of magnitude, but the errors were always quoted to be about 10% …

Generally, Hubble was estimating $H_0 \sim 600$ km/s/Mpc. This implies for the age of the universe ~ 1/ H_0 < 2 Gyr - which was a problem!

Distance Ladder

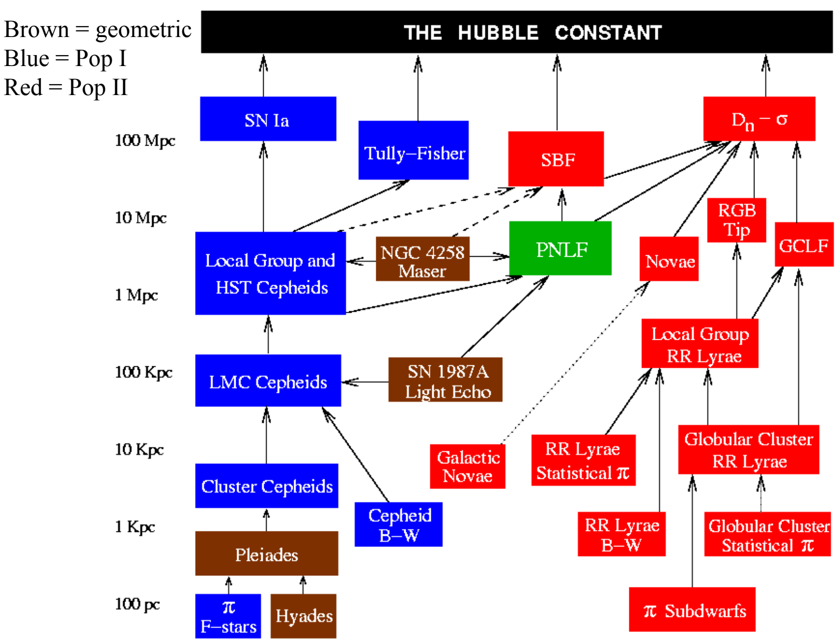
Methods yielding absolute distances:

- Parallax (trigonometric, secular, and statistical)
- The moving cluster method - has some assumptions
- Baade-Wesselink method for pulsating stars
- Expanding photosphere method for Type II SNe
- Sunyaev-Zeldovich effect
- Gravitational lens time delays

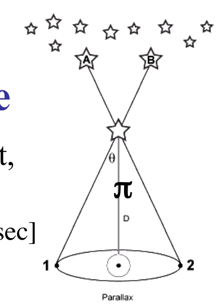
} Model dependent!

Secondary distance indicators: *"standard candles"*, requiring a calibration from an absolute method applied to local objects - ***the distance ladder*:**

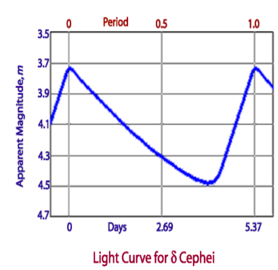
- Pulsating variables: Cepheids, RR Lyrae, Miras
- Main sequence fitting to star clusters
- Brightest red giants
- Planetary nebula luminosity function
- Globular cluster luminosity function
- Surface brightness fluctuations
- Tully-Fisher, D_n-σ, FP scaling relations for galaxies
- Type Ia Supernovae
- … etc.

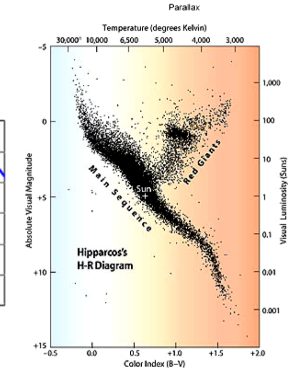


Galactic Distance Scale is the Basis for the Cosmological Distance Scale



- Trig. Parallaxes are ***the only*** model-independent, non-statistical) method - the foundation of the distance scale: **D** [pc] **= 1 / π** [arcsec]
  - The moving cluster method is geometric, but statistical
- Parallaxes calibrate the rest of the Galactic distance scale, which is then transferred to the nearby galaxies, sometimes via star clusters: CMDs, pulsating variables





Cepheids

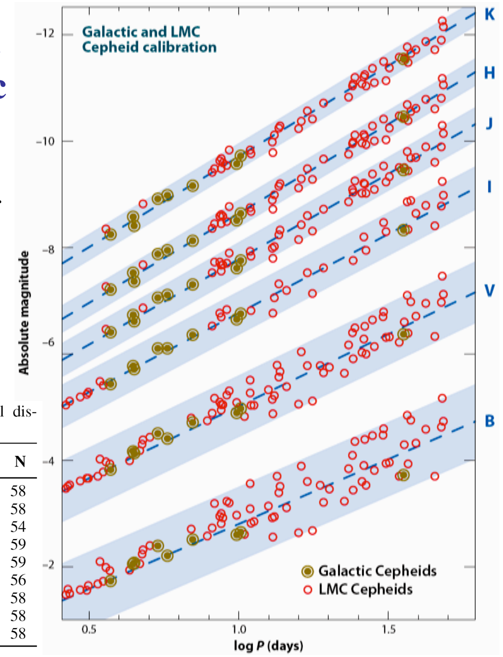
- Luminous ($M \sim -4$ to -7 mag), pulsating variables, evolved high-mass stars on the instability strip in the H-R diagram
- Shown by Henrietta Leavitt in 1912 to obey a period-luminosity relation (P-L) from her sample of Cepheids in the SMC: brighter Cepheids have longer periods than fainter ones
- **Advantages:** Cepheids are bright, so are easily seen in other galaxies, the physics of stellar pulsation is well understood
- **Disadvantages:** They are relatively rare, their period depends (how much is still controversial) on their metallicity or color (P-L-Z or P-L-C) relation; multiple epoch observations are required; found in spirals (Pop I), so extinction corrections are necessary
- P-L relation usually calibrated using the distance to the LMC and now using Hipparcos parallaxes. *This is the biggest uncertainty now remaining in deriving the H_0!*
- With HST we can observe to distances out to ~25 Mpc

Cepheid P-L Rel'n in different photometric bandpasses

Amplitudes are larger in bluer bands, but extinction and metallicity corrections are also larger; redder bands may be better overall

TABLE 3. Galactic Leavitt Laws from fundamental distances. Table adapted from Fouqué *et al.* 2007.

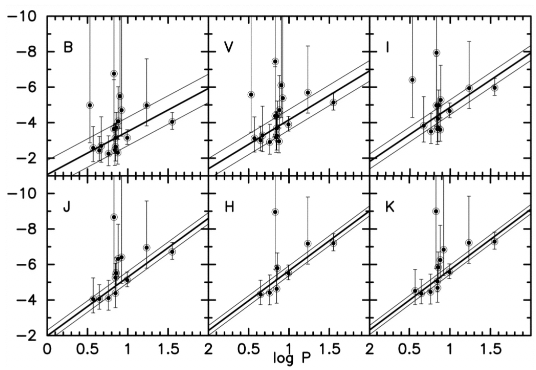
Band	Slope	Intercept	σ	N
B	-2.289 ± 0.091	-0.936 ± 0.027	0.207	58
V	-2.678 ± 0.076	-1.275 ± 0.023	0.173	58
R_c	-2.874 ± 0.084	-1.531 ± 0.025	0.180	54
I_c	-2.980 ± 0.074	-1.726 ± 0.022	0.168	59
J	-3.194 ± 0.068	-2.064 ± 0.020	0.155	59
H	-3.328 ± 0.064	-2.215 ± 0.019	0.146	56
K_s	-3.365 ± 0.063	-2.282 ± 0.019	0.144	58
W_{vi}	-3.477 ± 0.074	-2.414 ± 0.022	0.168	58
W_{bi}	-3.600 ± 0.079	-2.401 ± 0.023	0.178	58



Hipparcos Calibration of the Cepheid Period-Luminosity Relation

P-L relations for Cepheids with measured parallaxes, in different photometric bands

(from Freedman & Madore)



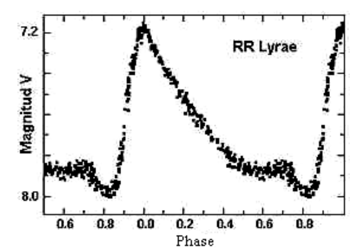
Typical fits give: $\langle M_V \rangle = -2.76 \log P - 1.45$

$\langle M_I \rangle = -2.96 \log P - 1.88$

… with the estimated errors in the range of **~ 5% - 20%**

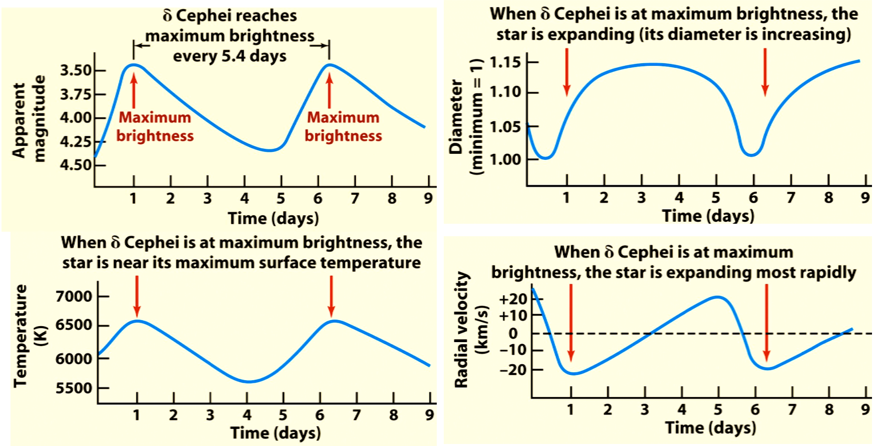
RR Lyrae Stars

- Pulsating variables, evolved old, low mass, low metallicity stars
  - Pop II indicator, found in globular clusters, galactic halos
- Lower luminosity than Cepheids, $M_V \sim 0.75 +/- 0.1$
  - There may be a metallicity dependence
- Have periods of 0.4 – 0.6 days, so don't require as much observing to find or monitor
- **Advantages:** less dust, easy to find
- **Disadvantages:** fainter (2 mag fainter than Cepheids). Used for Local Group galaxies only. The calibration is still uncertain (uses globular cluster distances from their main sequence fitting; or from Magellanic Clouds clusters, assuming that we know their distances)



Physical Parameters of Pulsating Variables

Star's diameter, temperature (and thus luminosity) pulsate, and obviously the velocity of the photosphere must also change



Baade-Wesselink Method

Consider a pulsating star at minimum, with a measured temperature T_1 and observed flux f_1 with radius R_1, then:

$$f_1 = \frac{4\pi R_1^2 \sigma T_1^4}{4\pi D^2}$$

Similarly at maximum, with a measured temperature T_2 and observed flux f_2 with radius R_2:

$$f_2 = \frac{4\pi R_2^2 \sigma T_2^4}{4\pi D^2}$$

Note: T_1 , T_2 , f_1 , f_2 are directly observable! Just need the radius… So, from spectroscopic observations we can get the photospheric velocity $v(t)$, from this we can determine the change in radius, ΔR:

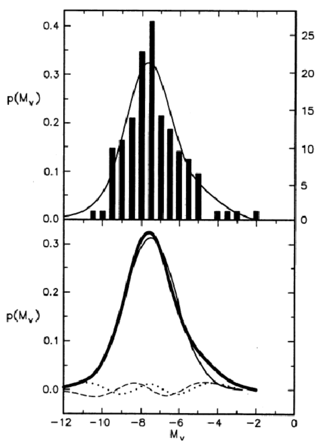
$$R_2 = R_1 + \Delta R = R_1 + \int_{t_1}^{t_2} v(t)\, dt$$

➜ **3 equations, 3 unknowns, solve for R_1, R_2, and D!**

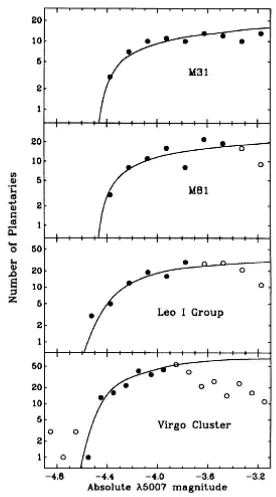
Difficulties lie in modeling the effects of the stellar atmosphere, and deriving the true radial velocity from what we observe.

Some Other Distance Indicators (see Appendix)

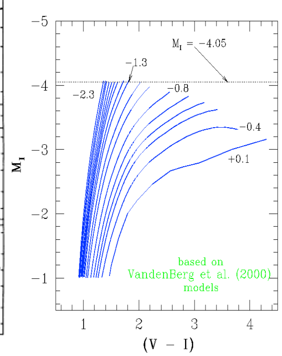
The peak of the globular cluster luminosity function



Planetary nebulae [O III] 5007 line luminosity function

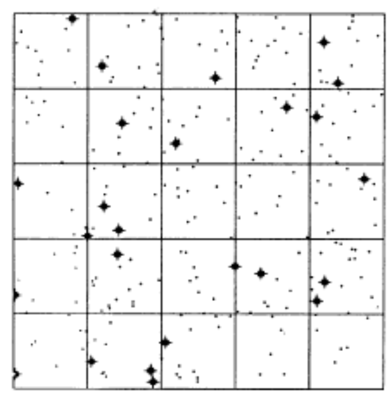


The tip of the red giant branch

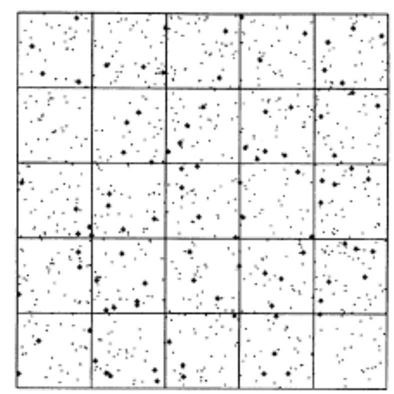


Surface Brightness Fluctuations

Consider stars projected onto a pixel grid of your detector:



Nearby Galaxy



A galaxy twice farther away is "smoother"

Surface Brightness Fluctuations

- Surface brightness fluctuations for old stellar populations (E's, SO's and bulges) are based primarily on their giant stars
- Assume typical average flux per star $<f>$, the average flux per pixel is then $N<f>$, and the variance per pixel is $N<f^2>$. But the number of stars per pixel N scales as D^2 and the flux per star decreases as D^{-2}. Thus the variance scales as D^{-2} and the RMS scales as D^{-1}. Thus a galaxy twice as far away appears twice as smooth. The average flux $<f>$ can be measured as the ratio of the variance and the mean flux per pixel. If we know the average L (or M) we can measure D
- $<M>$ is roughly the absolute magnitude of a giant star and can be calibrated empirically using the bulge of M31, although there is a color-luminosity relation, so $<M_I> = -1.74 + 4.5\,[(V-I)_0 - 1.15]$
- Have to model and remove contamination from foreground stars, background galaxies, and globular clusters
- Can be used out to ~100 Mpc in the IR, using the HST

Pushing Into the Hubble Flow

- Hubble's law: $\boldsymbol{D = H_0\, v}$
- But the total observed velocity v is a combination of the cosmological expansion, and the *peculiar velocity* of any given galaxy, $\boldsymbol{v = v_{cosmo} + v_{pec}}$
- Typically v_{pec} ~ a few hundred km/s, and it is produced by gravitational infall into the local large scale structures (e.g., the local supercluster), with characteristic scales of tens of Mpc
- Thus, one wants to measure H_0 on scales greater than tens of Mpc, and where $\boldsymbol{v_{cosmo} >> v_{pec}}$. This is the Hubble flow regime
- This requires *luminous standard candles* - galaxies or Supernovae

Galaxy Scaling Relations

- Once a set of distances to galaxies of some type is obtained, one finds correlations between distance-dependent quantities (e.g., luminosity, radius) and distance-independent ones (e.g., rotational speeds for disks, or velocity dispersions for ellipticals and bulges, surface brightness, etc.). These are called ***distance indicator relations***
- Examples:
  - Tully-Fisher relation for spirals (luminosity vs. rotation speed)
  - Fundamental Plane relations for ellipticals
- These relations must be calibrated locally using other distance indicators, e.g. Cepheids or surface brightness fluctuations; then they can be extended into the general Hubble flow regime
- Their origins - and thus their universality - are not yet well understood. Caveat emptor!

The Tully-Fisher Relation

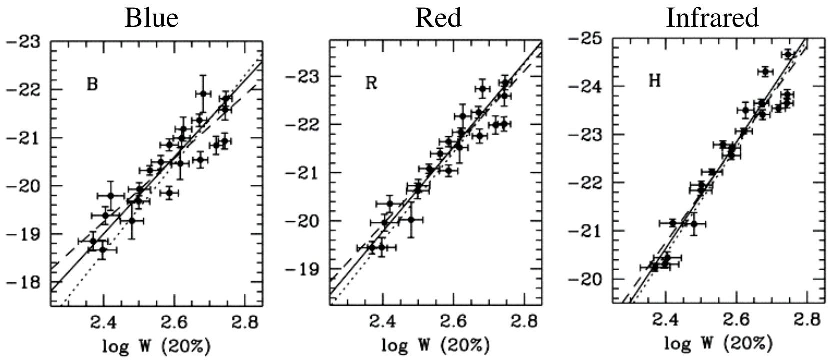
- A well-defined luminosity vs. rotational speed (often measured as a H I 21 cm line width) relation for spirals:

$$L \sim v_{rot}^{\gamma}\,,\ \gamma \approx 4, \text{ varies with wavelength}$$

Or: $M = b\,log\,(W) + c$, where:

  - M is the absolute magnitude
  - W is the Doppler broadened line width, typically measured using the HI 21cm line, corrected for inclination $W_{true} = W_{obs} / sin(i)$
  - Both the slope b and the zero-point c can be measured from a set of nearby spiral galaxies with well-known distances
  - The slope b can be also measured from any set of galaxies with roughly the same distance - e.g., galaxies in a cluster - even if that distance is not known
- Scatter is ~ 10-20% at best, which limits the accuracy
- Problems include dust extinction, so working in the redded bands is better

Tully-Fisher Relation at Various Wavelengths



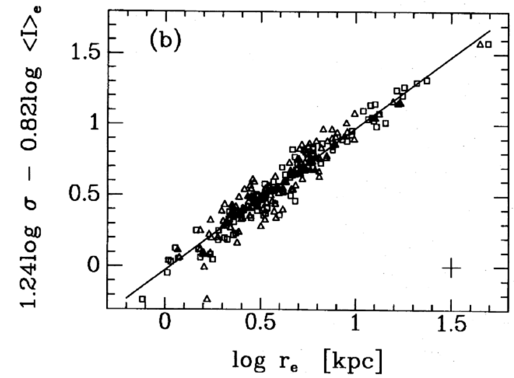
Slope= 3.2
Scatter=0.25 mag

Slope= 3.5
Scatter=0.25 mag

Slope= 4.4
Scatter=0.19 mag

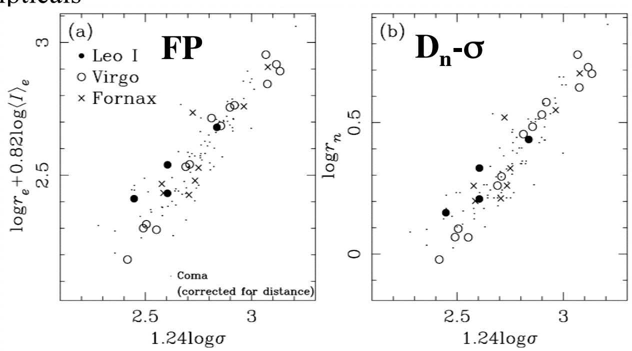
Fundamental Plane Relations

- A set of bivariate scaling relations for elliptical galaxies, including relations between distance dependent quantities such as radius or luminosity, and a combination of two distance-independent ones, such as velocity dispersion or surface brightness
- Scatter ~ 10%, but it could be lower?
- Usually calibrated using surface brightness fluctuations distances



The D_n-σ Relation

- A projection of the Fundamental Plane, where a combination of radius and surface brightness is combined into a *modified isophotal diameter* called D_n which is the angular diameter that encloses a mean surface brightness in the *B* band of $\langle\mu_B\rangle = 20.75$ mag/arcsec^2
- D_n is a *standard yardstick*, and can be used to measure relative distances to ellipticals
- Also calibrated using SBF

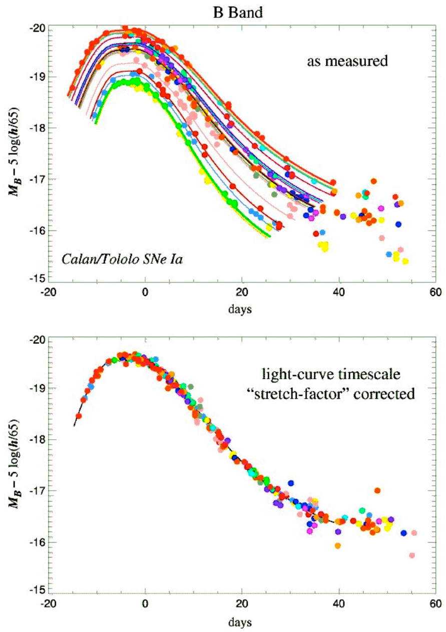


Supernovae as Standard Candles

- Bright and thus visible far away
- Two different types of supernovae are used as standard candles:
  - **Type Ia** from a binary WD accreting material and detonating
    - These are pretty good standard candles, peak $M_V \sim -19.3$
    - There is a diversity of light curves, but they can be standardized to a peak magnitude scatter of ~ 10%
  - **Type II** = hydrogen in spectrum, from collapse of massive stars (also Type Ib)
    - These aren't good standard candles, but we can measure their distances using the "Expanding Photosphere Method" (EPM), essentially the Baade-Wesselink method of measuring the expansion of the outer envelope
    - Not as bright as Type Ia's

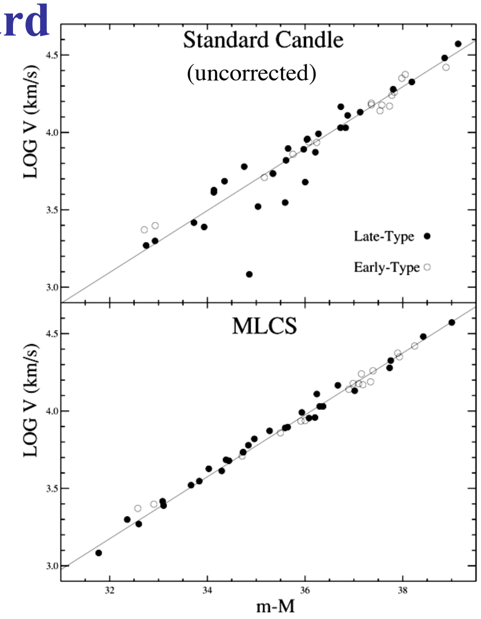
SNe Ia as Standard Candles

- The peak brightness of a SN Ia correlates with the shape of its light curve (steeper → fainter)
- Correcting for this effect standardizes the peak luminosity to ~10% or better
- However, the absolute zero-point of the SN Ia distance scale has to be calibrated externally, e.g., with Cepheids



SNe Ia as Standard Candles

- A comparable or better correction also uses the color information (the Multicolor Light Curve method)
- This makes SNe Ia a superb cosmological tool (note: you only need relative distances to test cosmological models; absolute distances are only needed for the H_0)



The Expanding Photosphere Method (EPM)

- One of few methods for a direct determination of distances; unfortunately, it is somewhat model-dependent
- Uses Type II SNe - could cross-check with Cepheids
- Based on the Stefan-Boltzmann law, $L \sim 4\pi R^2 T^4$

  If you can measure T (distance-independent), understand the deviations from the perfect blackbody, and could determine R, then from the observed flux F and the inferred luminosity L you can get the distance D

EPM assumes that SNII radiate as dilute blackbodies

Apparent Diameter

$$\theta_{ph} = \frac{R_{ph}}{D} = \sqrt{\frac{F_\lambda}{\zeta^2 \pi B_\lambda(T)}},$$

Fudge factor to account for the deviations from blackbody, from spectra models

Determine the radius by monitoring the expansion velocity

$$R_{ph} = v_{ph}(t - t_0) + R_0,$$

And solve for the distance!

$$t = D\left(\frac{\theta_{ph}}{v_{ph}}\right) + t_0$$

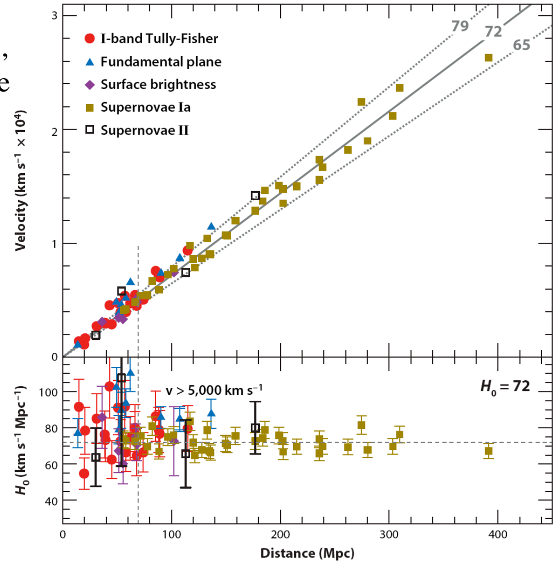
The HST H_0 Key Project

- Started in 1990, final results in 2001! Leaders include W. Freedman, R. Kennicutt, J. Mould, J. Huchra, and many others (reference: Freedman *et al*. 2001, ApJ, 553, 47)
- Observe Cepheids in ~18 spirals to test the universality of the Cepheid P-L relation and greatly improve calibration of other distance indicators
- Their Cepheid P-L relation zero point is tied directly to the distance to the LMC (largest source of error for the H_0!)
- Combining different estimators, they find:

  H_0 = 72 ± 3 (random) ± 7 (systematic) km/s/Mpc
- Since then, the Cepheid calibration has improved, and other methods yield results in an excellent agreement

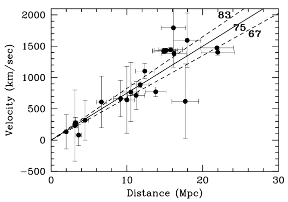
The HST H_0 Key Project Results

Overall Hubble diagram, from all types of distance indicators ➞

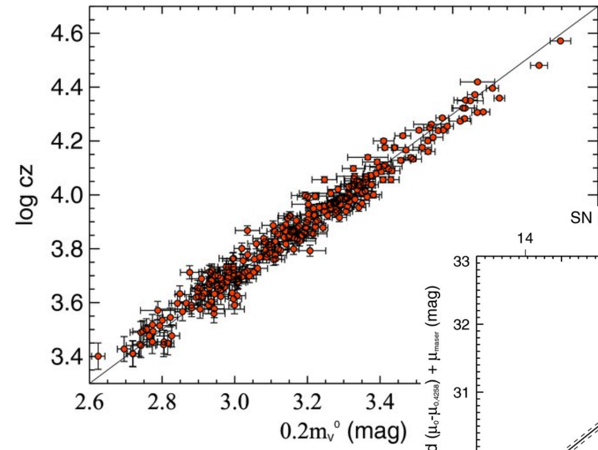


$H_o = 72 \pm (3)_r \pm [7]_s$

From Cepheid distances alone ➘

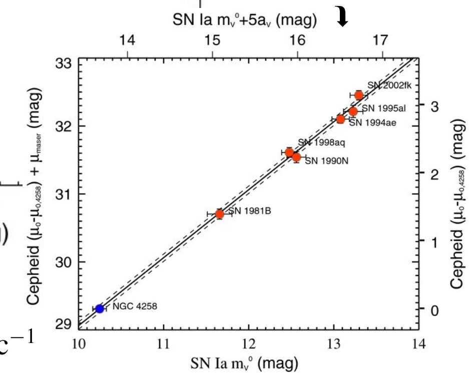


The Low-Redshift SN Ia Hubble Diagram



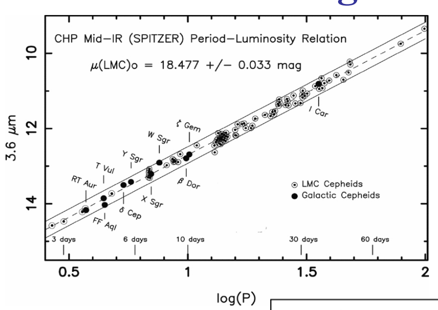
Riess et al. 2009 (also Riess et al. 2011 – slight changes)

Cepheid calibration ➘



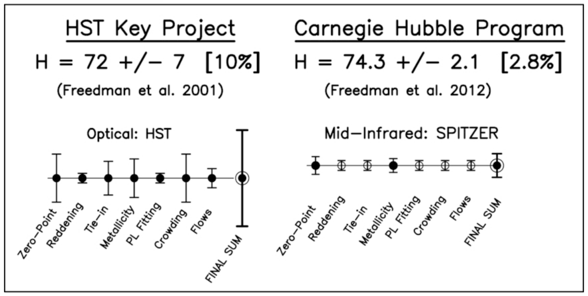
$H_0 = 74.2 \pm 3.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$

The Carnegie Hubble Program



Friedman et al. 2012

Using Mid-IR Cepheid calibration from *Spitzer*

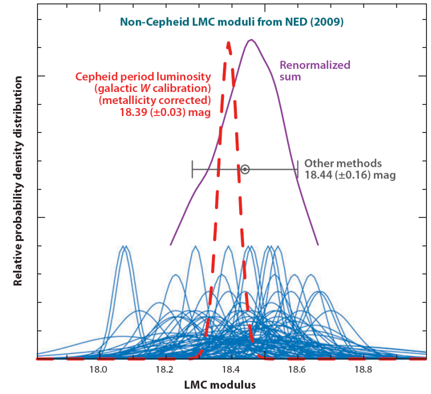


How Well Do the Different Distance Indicators Agree?

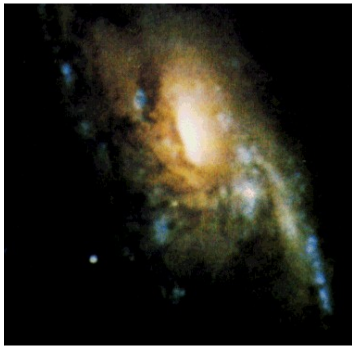
Consider the distance measurements to the Large Magellanic Cloud (LMC), one of the first stepping stones in the distance scale.

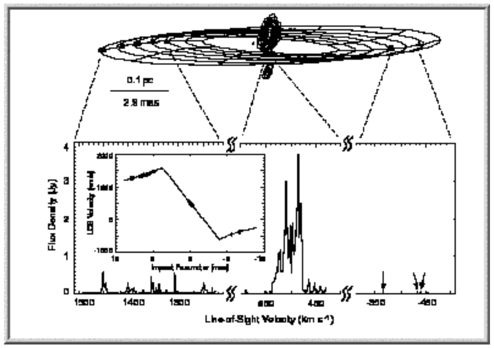
Different techniques give distance moduli $(m\text{-}M) = 5 \log [D/\text{pc}] - 5$, in the range ~18.07 to 18.70 mag, (distance range ~ 41 to 55 kpc) with typical errors of ~ 5 –10% (see the Appendix)

Cepheids give:
$(m\text{-}M) = 18.39 \pm 0.03$ mag



Another Test: Nuclear Masers in NGC 4258

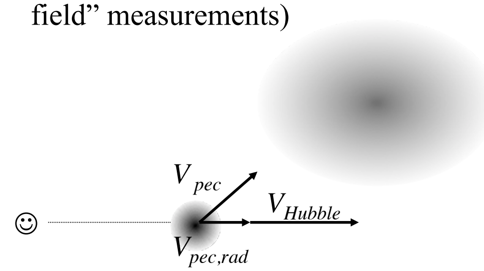




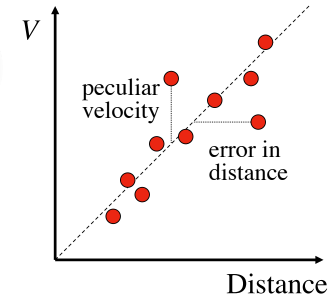
Herrnstein *et al.* (1999) have analyzed the proper motions and radial velocities of NGC 4258's nuclear masers. The orbits are Keplerian and yield a distance of 7.2 ± 0.3 Mpc, or $(m\text{-}M)_0$ = 29.29 ± 0.09. This is inconsistent with the Cepheid distance modulus of 29.44 ± 0.12 at the ~1.2σ level.

Another Problem: Peculiar Velocities

- Large-scale density field inevitably generates a peculiar velocity field, due to the acceleration over the Hubble time
- Note that we can in practice only observe the radial component
- Peculiar velocities act as a noise (on the $V = cz$ axis, orthogonal to errors in distances) in the Hubble diagram - and could thus bias the measurements of the H_0 (which is why we want "far field" measurements)



$$V_{total} = V_{Hubble} + V_{pec,rad}$$



Bypassing the Distance Ladder

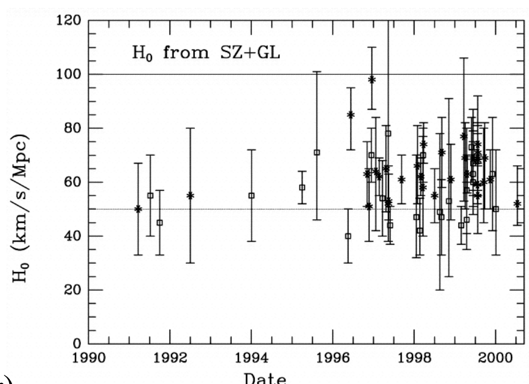
There are a two methods which can be used to large distances, which don't depend on local calibrations:

1. **Gravitational lens time delays**
2. **Synyaev-Zeldovich (SZ) effect for clusters of galaxies**

Both are very ***model-dependent!***

Both tend to produce values of H_0 somewhat lower than the HST Key Project

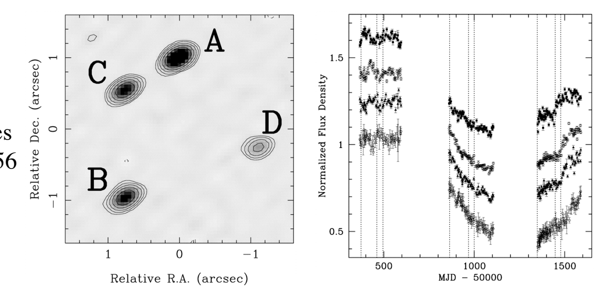
… And finally, the **CMB fluctuations** (more about that later)



Gravitational Lens Time Delays

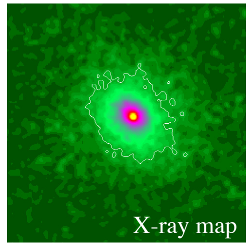
- Assuming the mass model for the lensing galaxy of a gravitationally lensed quasar is well-known (!?!), the different light paths taken by various images of the quasar will lead to time delays in the arrival time of the light to us. This be can be traced by the quasar variability
- If the lensing galaxy is in a cluster, we also need to know the mass distribution of the cluster and any other mass distribution along the line of sight. The modeling is complex!

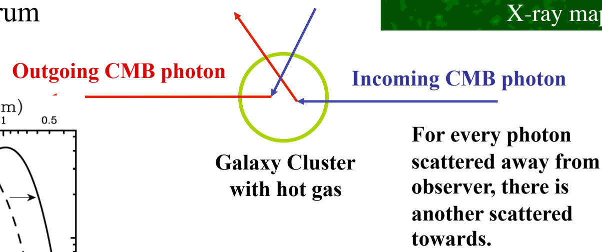
Images and lightcurves for the lens B1608+656 (from Fassnacht *et al.* 2000)

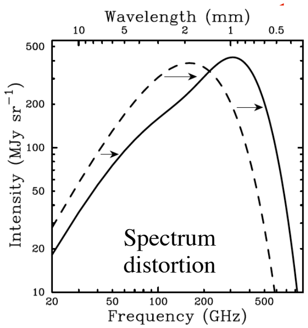


Synyaev-Zeldovich Effect

- Clusters of galaxies are filled with hot X-ray gas
- The electrons in the intracluster gas will scatter the background photons from the CMBR to higher energies (frequencies) and distort the blackbody spectrum



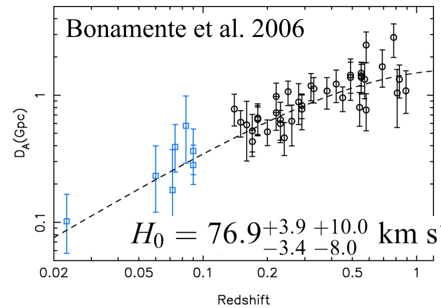




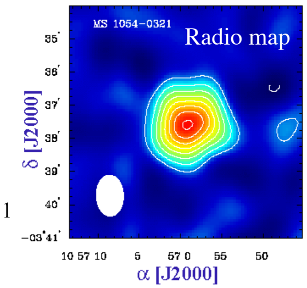
This is detectable as a slight temperature dip or bump (depending on the frequency) in the radio map of the cluster, against the uniform CMBR background

H_0 From the Synyaev-Zeldovich Effect

- From the amplitude of the CMB dip and X-ray data estimate the electron density and temperature of the X-ray gas along the line of sight and thus estimate the path length along the line of sight
- Assume on average depth ~ width, from the projected angular diameter we can determine the distance to the cluster
- Potential uncertainties include cluster substructure or shape. Also, X-ray temperature measurements are difficult

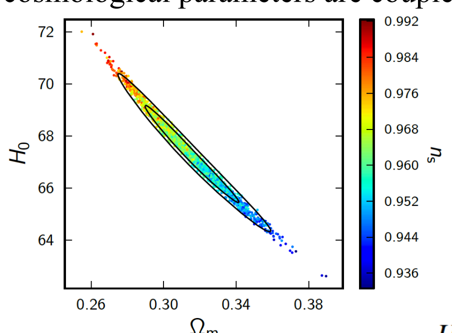


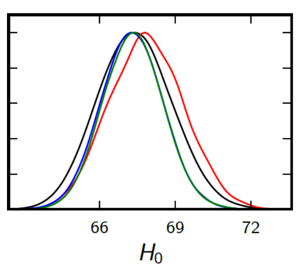
$$H_0 = 76.9^{+3.9}_{-3.4}{}^{+10.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$$



H_0 From the CMB

- Bayesian solutions from model fits to CMB fluctuations – cosmological parameters are coupled





- Planck (2013) results:

$$H_0 = (67.3 \pm 1.2) \text{ km s}^{-1} \text{ Mpc}^{-1}$$

	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037

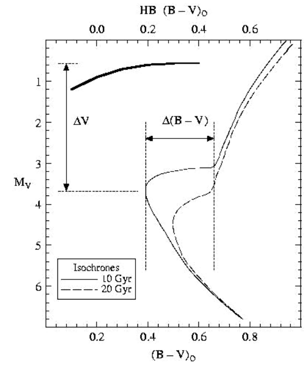
Measuring the Age of the Universe

- Related to the Hubble time $t_H = 1/H_0$, but the exact value depends on the cosmological parameters
- Could place a ***lower limit*** from the ages of astrophysical objects (pref. the oldest you can find), e.g.,
  - **Globular clusters** in our Galaxy; known to be very old. Need stellar evolution isochrones to fit to color-magnitude diagrams
  - **White dwarfs**, from their observed luminosity function, cooling theory, and assumed star formation rate
  - **Heavy elements**, produced in the first Supernovae; somewhat model-dependent
  - Age-dating **stellar populations** in distant galaxies; this is very tricky and requires modeling of stellar population evolution, with many uncertain parameters

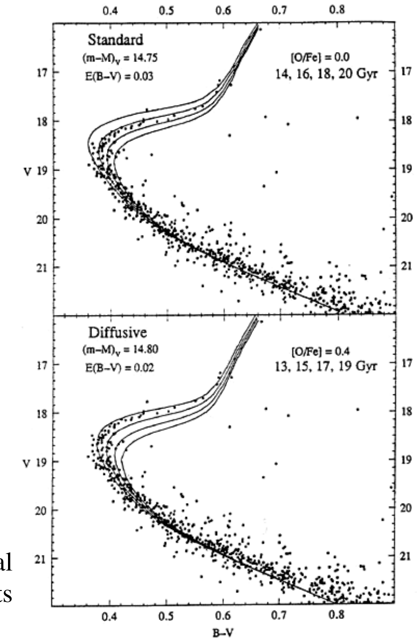
Ages of Globular Clusters

- We measure the age of a globular cluster by measuring the magnitude of the main sequence turnoff or the difference between that magnitude and the level of the horizontal branch, and comparing this to stellar evolutionary models of which estimate the surface temperature and luminosity of a stars as a function of time
- There are a fair number of uncertainties in these estimates, including errors in measuring the distances to the GCs and uncertainties in the isochrones used to derive ages (i.e., stellar evolution models)
- Inputs to stellar evolution models include: oxygen abundance [O/Fe], treatment of convection, He abundance, reaction rates of $^{14}N + p \rightarrow {}^{15}O + \gamma$, He diffusion, conversions from theoretical temperatures and luminosities to observed colors and magnitudes, and opacities; and especially ***distances***

Globular Cluster Ages

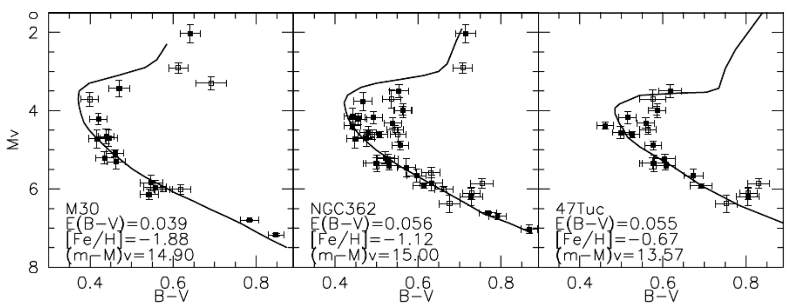


Schematic CMD and isochrones



Examples of actual model isochrones fits

Globular Cluster Ages From Hipparcos Calibrations of Their Main Sequences



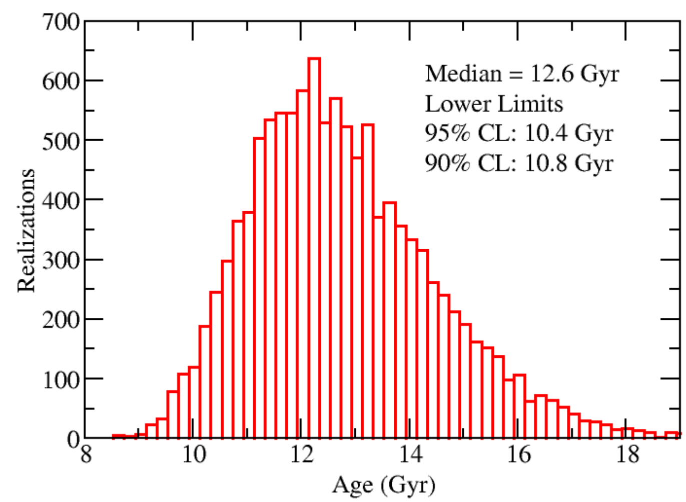
Examples of g.c. main sequence isochrone fits, for clusters of a different metallicity (Graton et al.)

The same group has published two slightly different estimates of the mean age of the oldest clusters:

$$\mathrm{Age} = 11.8^{+2.1}_{-2.5}\mathrm{Gyr}$$

$$\mathrm{Age} = 12.3^{+2.1}_{-2.5}\ \mathrm{Gyr}$$

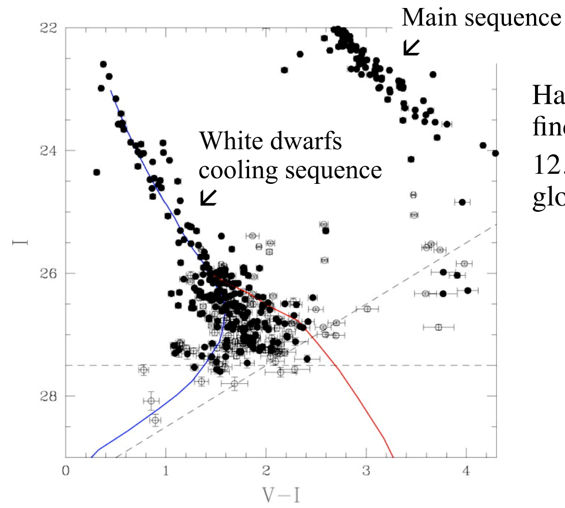
Range of possible GC ages (Chaboyer & Krauss 2003)



White Dwarf Cooling Curves

- White dwarfs are the end stage of stellar evolution for stars with initial masses < 8 $M_{\odot}$
- They are supported by electron degeneracy pressure (not fusion) and are slowly cooling and fading as they radiate
- We can use the luminosity of the faintest WDs in a cluster to estimate the cluster age by comparing the observed luminosities to theoretical cooling curves
- Theoretical curves are subject to uncertainties related to the core composition of white dwarfs, detailed radiative transfer calculations which are difficult at cool temperatures
- White dwarfs are faint so this is hard to do. Need deep HST observations
- Only been done for one globular cluster, consistent with the ages of GCs found from the main sequence turnoff luminosities, would be nice if there were more

An Example: White Dwarf Sequence of M4



Hansen *et al*. (2002) find an age of 12.7 ± 0.7 Gyr for the globular cluster M4

Blue = hydrogen atmosphere models
Red = helium atmosphere models
for a 0.6 $M_{\odot}$ WD

Nucleocosmochronology

- Can use the radioactive decay of elements to age date the oldest stars in the galaxy
- Has been done with ^{232}Th (half-life = 14 Gyr) and ^{238}U (half-life = 4.5 Gyr) and other elements
- Measuring the ratio of various elements provides an estimate of the age of the universe given theoretical predictions of the initial abundance ratio
- This is difficult because Th and U have weak spectral lines so this can only be done with stars with enhanced Th and U (requires large surveys for metal-poor stars) and unknown theoretical predictions for the production of r-process (rapid neutron capture) elements

Nucleocosmochronology:

An Example Isotope Ratios and Ages for a Single Star

Chronometric Age Estimates for BD +17°3248

Chronometer Pair	Predicted	Observed	Age (Gyr)	Solar[a]	Lower Limit (Gyr)
Th/Eu	0.507	0.309	10.0	0.4615	8.2
Th/Ir	0.0909	0.03113	21.7	0.0646	14.8
Th/Pt	0.0234	0.0141	10.3	0.0323	16.8
Th/U	1.805	7.413	≥13.4	2.32	11.0
U/Ir	0.05036	0.0045	≥15.5	0.0369	13.5
U/Pt	0.013	0.0019	≥12.4	0.01846	14.6

[a] From Burris et al. 2001.

(from Cowan *et al.* 2002)

Mean = 13.8 +/- 4, but note the spread!

Summary: The Key Points

- Measurements of the H_0 are now good to 5 – 10%, and may be improved in the future; various methods are in a good agreement
- The concept of the distance ladder; many uncertainties and calibration problems, model-dependence, etc.
- Cepheids as the key local distance indicator
- SNe as a bridge to the far-field measurements
- Far-field measurements (SZ effect, lensing, CMB)
- Ages of the oldest stars (globular clusters), white dwarfs, and heavy elements are consistent with the age inferred from the H_0 and other cosmological param's

Appendix: Supplementary Slides

Discovery of the Expanding Universe

Vesto Melvin Slipher (1917)

Knut Lundmark (1924)

And also Carl Wirtz (1923)

TABLE I.

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

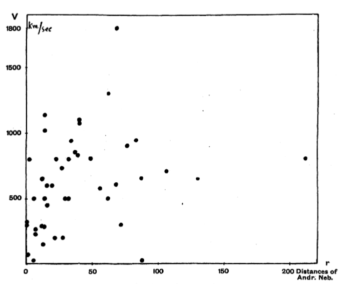
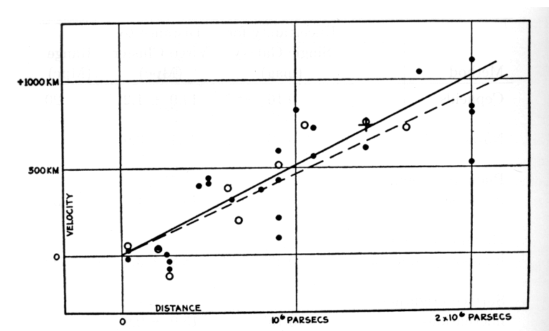


FIG. 5.—Relation between the relative distances (the unit is the distance of the Andromeda nebula) and the measured radial velocities of spiral nebulæ.

Discovery of the Expanding Universe

Edwin Hubble (1929)



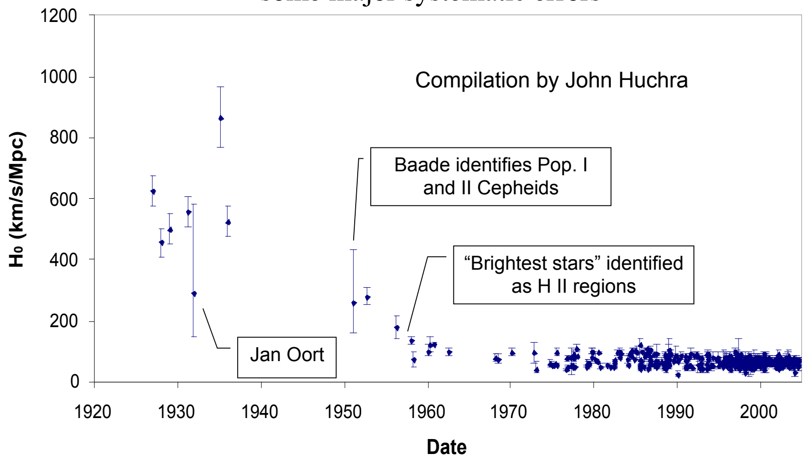
The Hubble diagram (1936)

The expansion of the universe was then called "the De Sitter effect"

Einstein failed to predict this amazing fact, and even tweaked the cosmological constant to make the universe static (as believed then)

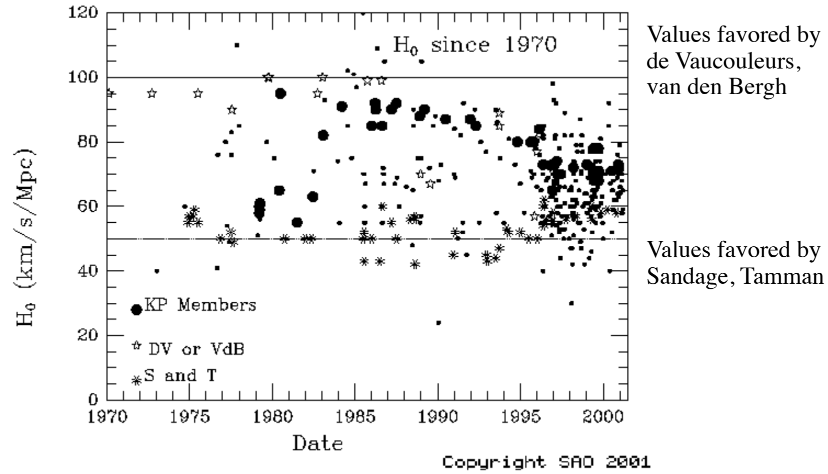
The History of H_0

Major revisions downwards happened as a result of recognizing some major systematic errors



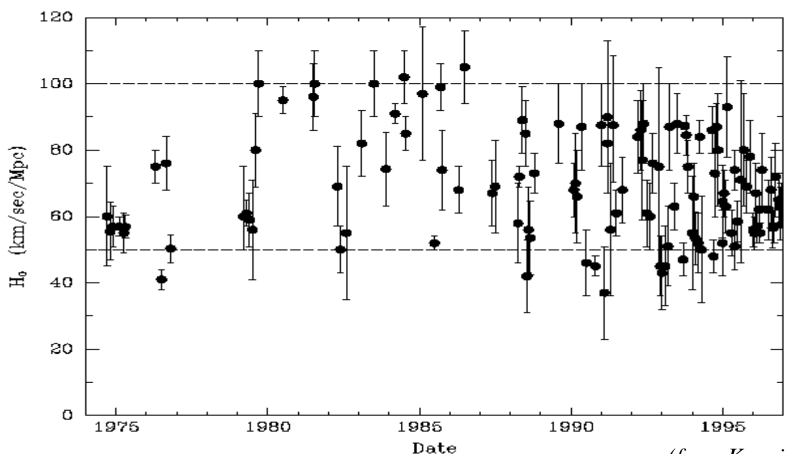
The History of H_0, Continued …

But even in the modern era, measured values differed covering a factor-of-2 spread!



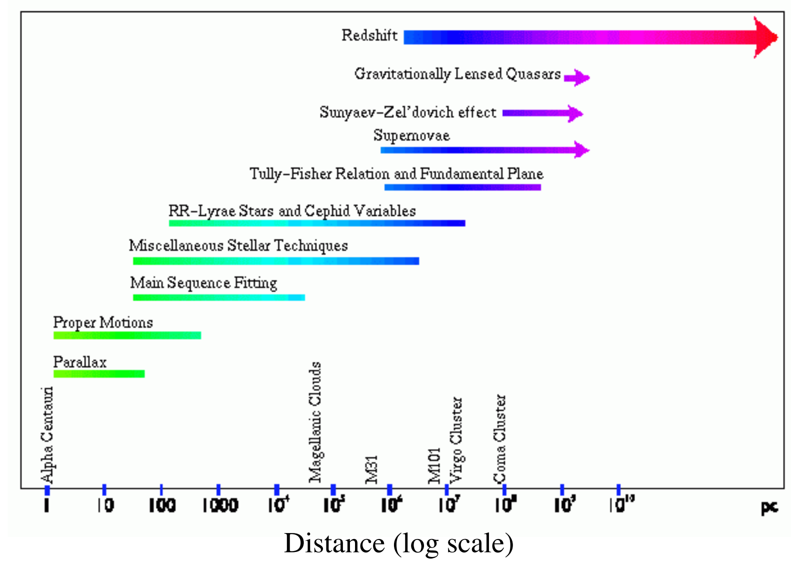
The History of H_0, Continued …

Note that the spread greatly exceeded the quoted errors from every group!



(from Kennicutt)

Distance Ladder

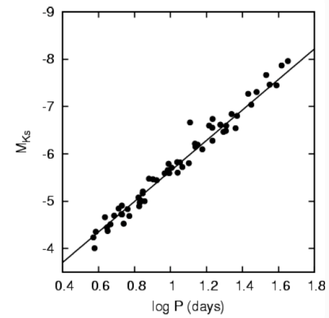


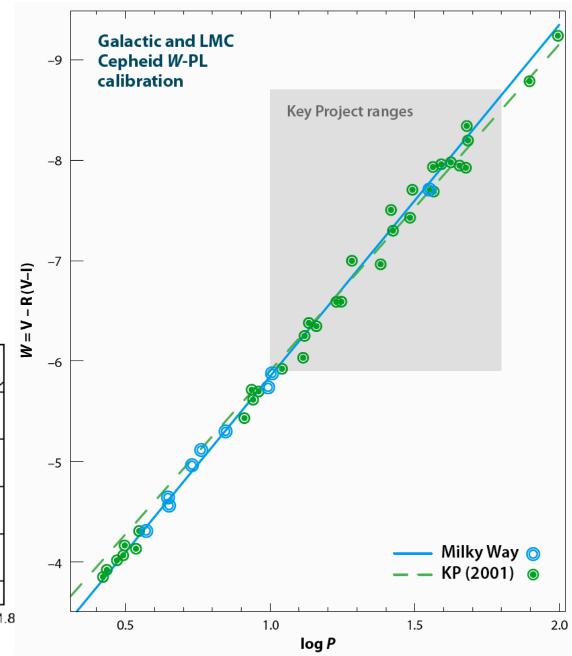
Calibration of the Cepheids

Table 1 Galactic cepheids with geometric parallaxes

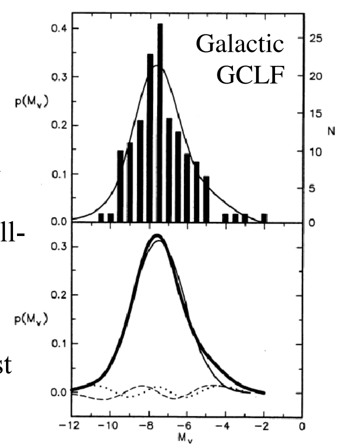
Cepheid	P(days)	log P	μ (mag)	σ (%)	Distance (pc)
RT Aur	3.728	0.572	8.15	7.9	427
T Vul	4.435	0.647	8.73	12.1	557
FF Aql	4.471	0.650	7.79	6.4	361
δ Cep	5.366	0.730	7.19	4.0	274
Y Sgr	5.773	0.761	8.51	13.6	504
X Sgr	7.013	0.846	7.64	6.0	337
W Sgr	7.595	0.881	8.31	8.8	459
β Dor	9.842	0.993	7.50	5.1	316
ζ Gem	10.151	1.007	7.81	6.5	365
ℓ Car	35.551	1.551	8.56	9.9	515

Cepheid Calibration

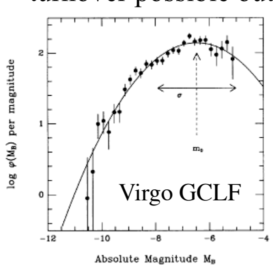




Globular Cluster Luminosity Function



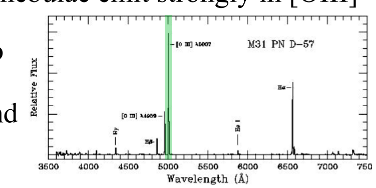
- GC's have a characteristic luminosity function, roughly log-normal, with a well defined peak ($M_B = -6.6 \pm 0.3$)
- GCLF is empirical, physical basis not well-understood
- **Advantages:** GCs are luminous, easy to find in elliptical galaxies, measuring the turnover possible out to 200 Mpc. No dust



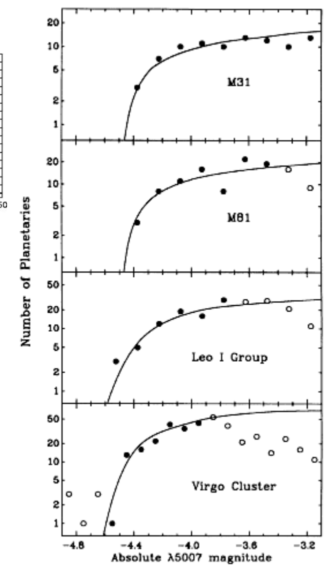
- **Disadvantages:** can't be used for late-type galaxies (Sc's and later). Need deep photometry to detect GCLF turnover. There is a slight metallicity dependence. Not as precise as other methods

Planetary Nebula Luminosity Function

- Planetary nebulae emit strongly in [OIII] λ5007 so are easy to find using narrowband filters

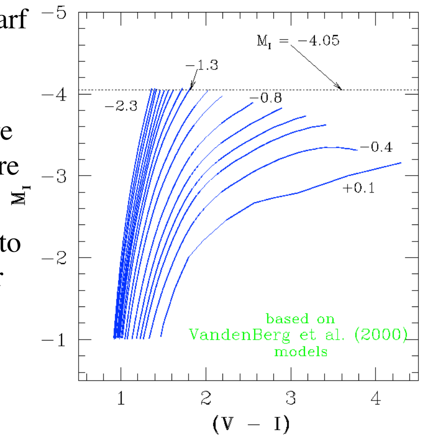


- Planetary Nebula Luminosity function (PNLF) has a characteristic sharp cutoff at the bright end which can be used as a standard candle, M_* (5007) = –4.48 ± 0.04, with a small metallicity correction
- Physical basis fairly well-understood from stellar evolution
- PNe are found in all Hubble Types (but requires a small metallicity correction)
- Only useful out to ~ 20 Mpc (Virgo)

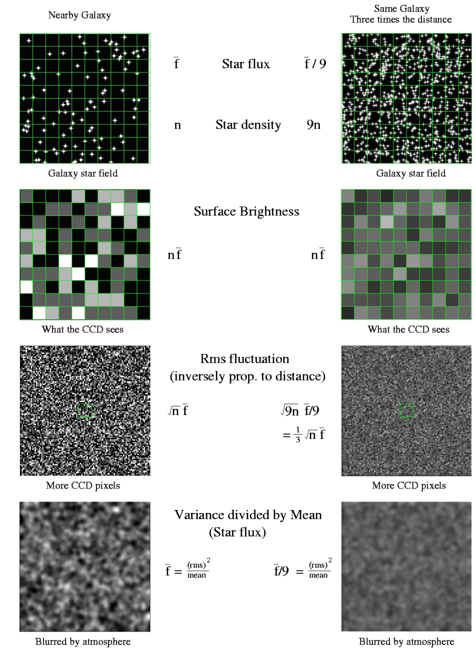


Tip of the Red Giant Branch

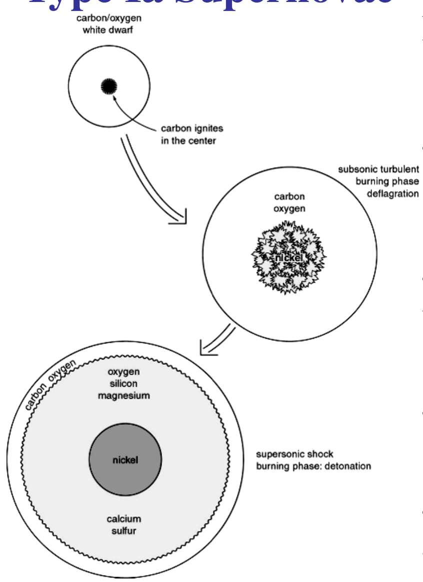
- Brightest stars in old stellar populations are red giants
- In I-band, $M_I = -4.1 \pm 0.1 \approx$ constant for the tip of the red giant branch (TRGB) if stars are old and metal-poor ([Fe/H] < –0.7)
- These conditions are met for dwarf galaxies and galactic halos
- **Advantages:** Relatively bright, reasonably precise, RGB stars are plentiful. Extinction problems are reduced
- **Disadvantages:** Only good out to ~20 Mpc (Virgo), only works for old, metal poor populations
- Calibration from subdwarf parallaxes from Hipparcos and distances to galactic GCs



Surface Brightness Fluctuations



Type Ia Supernovae

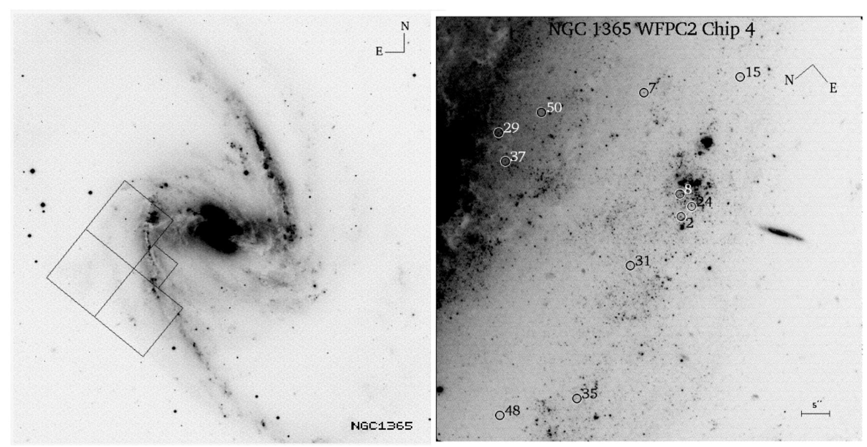


Identification of Type Ia supernovae with exploding white dwarfs is still somewhat circumstantial, but strong:

- No H lines, and Si lines in absorption
  At most ~ 0.1 $M_\odot$ of H in vicinity
  Nuclear burning all the way to Si must occur
- Observed in elliptical galaxies as well as spirals
  Old stellar population - not young massive stars
- Remarkably homogenous properties
  Same type of an object exploding in each case
- Lightcurve fit by radioactive decay of about a Solar mass of ^{56}Ni

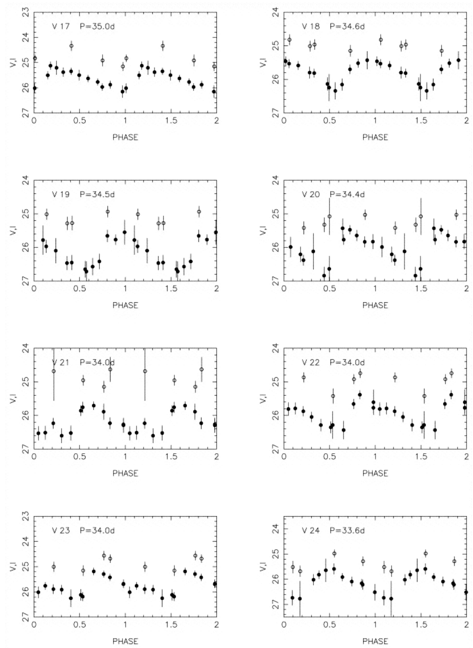
The HST H_0 Key Project

Sample images for discovery of Cepheids

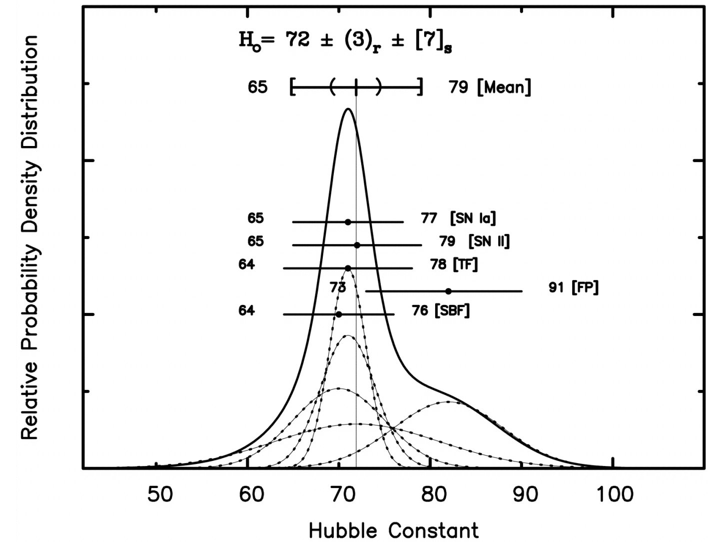


The HST H_0 Key Project

Sample Cepheid light curves for NGC 1365



The HST H_0 Key Project Results



The H_0 Key Project: Uncertainties

UNCERTAINTIES IN H_0 FOR SECONDARY METHODS

Method	H_0	Error (random, systematic) (%)
36 Type Ia SN, $4000 < cz < 30{,}000$ km s^{-1}	71	± 2 ± 6
21 TF clusters, $1000 < cz < 9000$ km s^{-1}	71	± 3 ± 7
11 FP clusters, $1000 < cz < 11{,}000$ km s^{-1}	82	± 6 ± 9
SBF for 6 clusters, $3800 < cz < 5800$ km s^{-1}	70	± 5 ± 6
4 Type II SN, $1900 < cz < 14{,}200$ km s^{-1}	72	± 9 ± 7

OVERALL SYSTEMATIC ERRORS AFFECTING ALL METHODS

Source of Uncertainty	Description	Error (%)
LMC zero point	Error on mean from Cepheids, TRGB, SN 1987A, red clump, eclipsing binaries	±5
WFPC2 zero point	Tie-in to Galactic star clusters	±3.5
Reddening	Limits from NICMOS photometry	±1
Metallicity	Optical, NICMOS, theoretical constraints	±4
Bias in Cepheid PL	Short-end period cutoff	±1
Crowding	Artificial star experiments	+5, −0
Bulk flows on scales >10,000 km s^{-1}......	Limits from SN Ia, CMB	±5

NOTE.—Adopted final value of H_0: $H_0 = 72 \pm 3$ (random) $\pm$ 7 (systematic) km s^{-1} Mpc^{-1}.

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 ± 2 ± 6	New PL+Z	Freedman et al. 2001
	74 ± 3	New PL+Z	Tonry et al. 2003, in prep.
	73 ± 2 ± 7	New PL+Z	Gibson & Stetson 2001
I-band SBFs	77 ± 4 ± 7	Orig. KP	Tonry et al. 2000
	70 ± 5 ± 6	New PL+Z	Freedman et al. 2001
	75	New PL+Z	Ajhar et al. 2001
H-band SBFs	72 ± 2 ± 6	Orig. KP+*I*-SBF	Jensen et al. 2001
	77 ± 3 ± 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 ± 3 ± 7	New PL+Z	Freedman et al. 2001
Fundamental Plane	82 ± 6 ± 9	New PL+Z	Freedman et al. 2001
	73 ± 4 ± 11	New PL+Z	Blakeslee et al. 2002
Type II Supernovae	72 ± 9 ± 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 ± 3 ± 30%	...	Carlstrom et al. 2002
Gravitational lenses	61 to 65	...	Fassnacht et al. 2002
	59 ± 12 ± 3	...	Treu & Koopmans 2002
Type Ia SNe (theory)	67 ± 9	...	Höflich & Khokhlov, 1996
Type II SNe (theory)	67 ± 9	...	Hamuy 2001

How far is the LMC?

Indicator	$(m-M)_{0,LMC}$	Authors
Subwarf fitting	18.54 ± 0.12	Carretta et al. 1998
Cepheids	18.70 ± 0.10	Feast & Catchpole 1997
	18.50 ± 0.07	Madore & Freedman 1998
Miras	18.54 ± 0.18	van Leeuwen et al. 1997
SN1987a ring	18.37 ± 0.04	Gould & Uza 1998 (circular)
	18.44	Gould & Uza 1998 (elliptical)
	18.59 ± 0.03	Panagia et al. 1997
	18.67 ± 0.08	Lundqvist & Sonneborn 1997
Eclipsing binaries	18.6 ± 0.2	Guinan et al. 1995
HB clump	18.07 ± 0.12	Udalski 1998
	18.31 ± 0.12	revised by Girardi et al. 1998
	18.43 ± 0.12	E(B−V)=0.10
HB trig. parallax	18.37 ± 0.10	Gratton 1998
	18.42 ± 0.12	eliminating HD17072
Stat. parallax	18.29 ± 0.12	Layden et al. 1996
	18.26 ± 0.15	Fernley et al. 1998a
Baade-Wesselink	18.26 ± 0.04	Clementini et al. 1995
	18.34 ± 0.04	Clementini et al. 1995 (p=1.38)
	18.53 ± 0.05	McNamara 1997
GC Dynamical models	18.44 ± 0.11	Rees 1996, revised by Chaboyer

Possible Improvements on H_0

Table 2 Systematics error budget on H_0: past, present, and future

Known	Key Project	Revisions	Anticipated	Basis
Systematics	(2001)	(2007/2009)	*Spitzer*/JWST	
(1) Cepheid Zero Point	± 0.12 mag	± 0.06 mag	± 0.03 mag	Galactic Parallaxes
(2) Metallicity	$\pm$ 0.10 mag	± 0.05 mag	± 0.02 mag	IR + Models
(3) Reddening	± 0.05 mag	± 0.03 mag	± 0.01 mag	IR 20–30 × Reduced
(4) Transformations	± 0.05 mag	± 0.03 mag	± 0.02 mag	Flight Magnitudes
Final Uncertainty	± 0.20 mag	± 0.09 mag	± 0.04 mag	Added in Quadrature
Percentage Error on H_0	$\pm 10\%$	$\pm 5\%$	$\pm 2\%$	Distances