Measuring the Hubble Constant: It takes a Village

Massive Stars the Supernovae,
Bariloche, 2018
A Brief History of $H_0$

\[ \frac{v}{c} = \frac{\delta l}{\delta t_1} = 1 = \frac{R_2}{R_1} - 1 \]

measures the effect of the Doppler effect due to the variation of the ray of the universe. It is equal to the ratio of an infinite ratio of the rays of the universe to the light ray at the instant it is emitted and at the instant it is received. $v$ is the velocity of the observer who would produce the same effect. When the source is sufficiently close, we can write approximately:

\[ \frac{v}{c} = \frac{R_2 - R_3}{R_1} = \frac{dR}{R} = \frac{R'}{R} \frac{dt}{R} = \frac{R'}{R} r \]

where $r$ is the distance of the source. We have then:

\[ \frac{R'}{R} = \frac{r}{ct} \]

\[ [\ldots] \]

Using the 42 nebulae listed in the lists of Hubble and Strömgren (1), and taking into account the proper velocity of the sun (300 km. in the direction $\alpha = 315^\circ$, $\delta = 62^\circ$), we find an average distance of 0.95 million parsecs and a radial velocity of 600 km/sec, or 625 km/sec at $10^6$ parsecs (2).

We adopt:

\[ \frac{R'}{R} = \frac{v}{ct} = \frac{625 \times 10^6}{10^6 \times 3.08 \times 10^{18} \times 3 \times 10^{13}} = 0.68 \times 10^{-27} \text{ cm}^{-1} \]  

Lemaitre, G. (1927)

Annales de la Société Scientifique de Bruxelles, A47, p. 49-59
A Brief History of $H_0$

The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space. In the de Sitter cosmology, displacements of the spectra arise from two sources, an apparent slowing down of atomic vibrations and a general tendency of material particles to scatter. The latter involves an acceleration and hence introduces the element of time. The relative importance of these two effects should determine the form of the relation between distances and observed velocities; and in this connection it may be emphasized that the linear relation found in the present discussion is a first approximation representing a restricted range in distance.

deSitter’s solution (like Einstein’s) was a static, empty space-time with positive curvature. The Hubble law in such a universe would look linear at small distances, but was in fact quadratic.

Hubble, E. (1929), PNAS
A Brief History of $H_0$

$H_0$ since 1920

$H_0$ (km/s/Mpc)

Date

D. Fabricant/Harvard
A Brief History of $H_0$
A Brief History of $H_0$

![Graph showing the evolution of $H_0$ since 1920 with error bars.]
H(L)ST Key Project

Freedman et al. 2003
H(L)ST Key Project

Freedman et al. 2003
H(L)ST Key Project

![Graph showing velocity vs. distance with data points and error bars. The graph is based on Freedman et al. (2003).](image)

Freedman et al. 2003
Cepheids are Difficult at Large Distances
Not just dimmer, but fields are more crowded.

Riess et al. (2016)
SNe Ia to the Rescue!

Phillips et al. (1999)
Pros: Bright, and Unlike Cepheids, SNe Ia Fade
Con: Another Rung in Distance Ladder

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**Leavitt Law**

**Phillips Relation**

**Geometric Distances**

Type Ia Supernovae → redshift(z)

\[ D_L(z,H_0) \]

Cepheids → Type Ia Supernovae

\[ \mu_L(z,H_0) = 73.0, q_0, j_0 \]

\[ \Delta \text{mag} \]

Riess et al. (2016)

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Results shown are an approximate fit as discussed in the text.
**Con:** Another Rung in Distance Ladder

![Image of distance ladder](image)

**Fig. 10.**— Complete distance ladder. The simultaneous agreement of pairs of geometric and Cepheid-based distances (lower left), Cepheid and Type Ia Supernovae-based distances (middle panel) and Type Ia and redshift-based distances provides the measurement of the Hubble constant. For each step, geometric or calibrated distances on the X-axis serve to calibrate a relative distance indicator on the Y-axis through the determination of $M$ or $H_0$. Results shown are an approximation to the global fit as discussed in the text.

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**Type Ia Supernovae → redshift(z)**

**Geometry → Cepheids**

**Leavitt Law**

**Phillips Relation**

**Geometric Distances**

**Riess et al. (2016)**
The Carnegie Supernova Project I (CSP-I)
Major goals of CSP:

- Well-defined photometric system
- Leverage the NIR to characterize/reduce dust systematics
- NIR Hubble-Lemaître diagram
- Measure Hubble constant

Three corrections

- Faster-Fainter
- Redder-Fainter
- Host Mass/Metallicity/SFR

Folatelli et al. (2010)
A New Shape Parameter

The graph shows the magnitude relative to B maximum over days since B maximum for two datasets: SN2005ke and SN2006mr.
A New Shape Parameter

$$\Delta m_{15}(B)$$
A New Shape Parameter

Max Stritzinger
question
To: Christopher Burns

Hi Chris,

I'm making up plots, and in the case of the sub-luminous events we know snpy gives template fits. My question is, after doing spline fits, is there a way to dump the spline fits to a file so I can plot them with the observed data?

Max
A New Shape Parameter

Burns et al. (2018)
Extinction

Using Fitzpatrick (1999) reddening law
• A new light-curve shape \((s_{BV})\) that is more robust for NIR and fast-decliners.

• Extinction from observed colors using extinction law (Fitzpatrick '99)

• \(R_V\) is not a constant: drawn from a distribution.
CSP-I Hubble Diagram

\[ H_0 = 73.2 \pm 2.3 \text{ km/s/Mpc} \]

\[ H_0 = 72.7 \pm 2.1 \text{ km/s/Mpc} \]
Host Mass Effect

Residuals (SN-Hubble) vs. log(Host Stellar Mass / $M_\odot$)

- B panel
- H panel

Tripp

E(B-V)
More Drama
CMB Can also Measure $H_0$

$$D_A(z = 1100, H_0, \Omega_m, \Omega_\Lambda)$$

E-mode polarization (cold spots)  E-mode polarization (hot spots)
Resolving the Tension

• Problem with the Planck data? Not likely.
• Problem with the SN Ia data? Not likely.
• Living in a local bubble?
• Problem with LCDM?
• Problem with the Cepheid calibration?
• New Physics?
Living in a Bubble?

Wu & Huterer, 2017
Living in a Bubble?

Wu & Huterer, 2017

NOPE

Wu & Huterer, 2017
Could LCDM be the Problem?

Use $D_A(z)$ directly measured by SNe Ia to turn $\theta_s \rightarrow r_s$.

Bernal, Verde, and Riess 2016
Could LCDM be the Problem?

Use \( D_A(z) \) directly measured by SNe Ia to turn \( \theta_s \rightarrow r_s \).

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Use \( D_A(z) \) directly measured by SNe Ia to turn \( \theta_s \rightarrow r_s \).
Cepheid Calibration?

MAYBE
Carnegie Hubble Project

The Tip of the Red Giant Branch

Mager, Madore & WLF (2008)

Measure 1st derivative of luminosity function

Mager, Madore & Freedman (2008)

Re-calibrate the SN Ia distance ladder using TRGB, independent of Cepheids.

Mager, Madore & Freedman (2008)
CSP-II

Near-Infrared Hubble Diagram for SNe Ia to $z \approx 0.11$

First imaging observations in the optical and the NIR for the Cosmology subsample are displayed. As may be seen, optical imaging was obtained for half of the subsample at 4 days earlier, and 2 days or earlier in the NIR.

Figure 2. (Top) Histogram of heliocentric redshifts of the 125 SNe Ia comprising the Cosmology subsample, and (bottom) the 90 SNe Ia in the Physics subsample. In the top panel, the median redshift of the CSP-I sample is indicated by an arrow. The middle panel displays a histogram of the redshifts of the LSQ subsample.

2.2. Physics Subsample

To realize the full potential of SNe Ia as distance indicators at NIR wavelengths, we must determine accurate K-corrections, which account for the effect of cosmological expansion upon the measured magnitudes (Oke & Sandage 1968). Poorly understood K-corrections directly impact the peak magnitudes of the SNe and inflate both statistical and systematic errors. Prior to the CSP-II, NIR spectra had been published for only 33 SNe Ia, with the total number of useful spectra amounting to 75. Boldt et al. (2014) used this sample to study the errors inherent in NIR K-corrections. Their main