The Hubble-constant wars, 2013

1. **Freedman et al. 2012** (CHP)
   A mid-infrared calibration of the Hubble constant

2. **Bennett et al. 2013** (WMAP)
   Nine-year WMAP observations: final maps and results

3. **Reid et al. 2013** (MCP)
   A geometric measurement of the Hubble constant from UGC 3789

4. **Planck collaboration 2013**
   Planck 2013 results. XVI. Cosmological parameters
Hubble’s Law

Since the late 1920s we have known the form of the ultimate extragalactic distance-measuring tool:

\[ v_r = H_0 d \]

and have been calibrating it ever since, as the value of \( H_0 \) is fundamental to determinations of the age and fate of the Universe. But it has been a long struggle against systematic error, bias, and complexity in distance-ladder, cosmic-background and geometric measurements.
The Hubble Constant through the ages

Plot from John Huchra’s Hubble Constant Page.
$H_0$ as of Summer 2012

1. The SH0ES team (Riess et al. 2011) rocks the most modern $d$-ladder.

- Only standard candles used are Cepheids (~500) and SNe Ia (240), mostly observed with Hubble WFC3 at 1.6 $\mu$m.
  - 8 SNe Ia have Cepheid distances: $M_V^0 = -19.14 \pm 0.03$.

- Could even do without the LMC Cepheids: enough in MW (10), all of which have trig parallax, and M106 (120), with an orbital parallax and MW-like metallicity.
SN Ia Hubble diagram

Riess et al. 2009, 2011

$0.2m_v^0 \text{ (mag)} = \log(d/\text{Mpc}) + 0.2M_V^0 + 5$
$H_0$ as of Summer 2012 (continued)

2. WMAP derives $H_0$ indirectly from model fits to cosmic-background anisotropies.
   - **WMAP** errorbars overlap SH0ES's by very little: discrepant at 90% confidence?

3. Despite their early adoption of SNe Ia, **Sandage & Tammann et al.** use 8 (!) standard candles, and multiple telescopes/instruments, still including Kodak emulsion.
   - Thus they risk considerable systematic error.
**H₀ 2013: CHP**

1. The Carnegie Hubble Program (CHP) team – descended from the *Hubble Key Project on the Distance Scale* – observed MW and LMC Cepheids with *Spitzer*, IRAC at 3.5 and 4.5 µm.

- Extinction very small.
- Mid-IR luminosity of Cepheids is insensitive to metallicity.
- Ten MW Cepheids have accurate trig parallaxes.

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Freedman et al. 2012

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*HST Key Project*

\[
H = 72 +/− 7 \ [10%]
\]

(Freedman et al. 2001)

*Carnegie Hubble Program*

\[
H = 74.3 +/− 2.1 \ [2.8%]
\]

(Freedman et al. 2012)
Thus they can claim the smallest uncertainties ever for the Leavitt Law’s zero point, and the LMC’s distance.

With these results they reanalyzed the Key Project data, yielding $H_0$ similar to SH0ES.

- HST-KP employed additional Cepheid-calibrated standard candles for $d = 20$-$80$ Mpc, as 1990s SNe Ia and Cepheid distances did not overlap.
The WMAP team did a complete re-reduction and reanalysis of their nine years of data, producing final cosmic-background anisotropy images and an angular power spectrum. The latter is fit with a standard, six-parameter $\Lambda\text{CDM}$ anisotropy model; the fit is great (reduced $\chi^2 = 1.03$), and the first three acoustic peaks are well characterized.

Bennett et al. 2013
## $H_0$ 2013: WMAP9 (continued)

Bennett et al. 2013

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>WMAP$^a$</th>
<th>WMAP+$\epsilon$CMB+BAO+$H_0$ $^a$ $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>6-parameter $\Lambda$CDM fit parameters$^c$</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical baryon density</td>
<td>$\Omega_b h^2$</td>
<td>0.02264 ± 0.00050</td>
<td>0.02223 ± 0.00033</td>
</tr>
<tr>
<td>Physical cold dark matter density</td>
<td>$\Omega_c h^2$</td>
<td>0.1138 ± 0.0045</td>
<td>0.1153 ± 0.0019</td>
</tr>
<tr>
<td>Dark energy density ($w = -1$)</td>
<td>$\Omega_{\Lambda}$</td>
<td>0.721 ± 0.025</td>
<td>0.7135$^{+0.0095}_{-0.0096}$</td>
</tr>
<tr>
<td>Curvature perturbations ($k_0 = 0.002$ Mpc$^{-1}$)$^d$</td>
<td>$10^9 \Delta^2_R$</td>
<td>2.41 ± 0.10</td>
<td>2.46 ± 0.072</td>
</tr>
<tr>
<td>Scalar spectral index</td>
<td>$n_s$</td>
<td>0.972 ± 0.013</td>
<td>0.9608 ± 0.0080</td>
</tr>
<tr>
<td>Reionization optical depth</td>
<td>$\tau$</td>
<td>0.089 ± 0.014</td>
<td>0.081 ± 0.012</td>
</tr>
<tr>
<td>Amplitude of SZ power spectrum template</td>
<td>$A_{SZ}$</td>
<td>&lt; 2.0 (95% CL)</td>
<td>&lt; 1.0 (95% CL)</td>
</tr>
<tr>
<td><strong>6-parameter $\Lambda$CDM fit: derived parameters$^c$</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age of the universe (Gyr)</td>
<td>$t_0$</td>
<td>13.74 ± 0.11</td>
<td>13.772 ± 0.059</td>
</tr>
<tr>
<td>Hubble parameter, $H_0 = 100h$ km/s/Mpc</td>
<td>$H_0$</td>
<td>70.0 ± 2.2</td>
<td>69.32 ± 0.80</td>
</tr>
<tr>
<td>Density fluctuations @ $8h^{-1}$ Mpc</td>
<td>$\sigma_8$</td>
<td>0.821 ± 0.023</td>
<td>0.820$^{+0.013}_{-0.014}$</td>
</tr>
<tr>
<td>Velocity fluctuations @ $8h^{-1}$ Mpc</td>
<td>$\sigma_8 \Omega_{m0.5}$</td>
<td>0.434 ± 0.029</td>
<td>0.439 ± 0.012</td>
</tr>
<tr>
<td>Velocity fluctuations @ $8h^{-1}$ Mpc</td>
<td>$\sigma_8 \Omega_{m0.6}$</td>
<td>0.382 ± 0.029</td>
<td>0.387 ± 0.012</td>
</tr>
<tr>
<td>Baryon density/critical density</td>
<td>$\Omega_b$</td>
<td>0.0463 ± 0.0024</td>
<td>0.04628 ± 0.00093</td>
</tr>
<tr>
<td>Cold dark matter density/critical density</td>
<td>$\Omega_c$</td>
<td>0.233 ± 0.023</td>
<td>0.2402$^{+0.0058}_{-0.0087}$</td>
</tr>
<tr>
<td>Matter density/critical density ($\Omega_c + \Omega_b$)</td>
<td>$\Omega_m$</td>
<td>0.279 ± 0.025</td>
<td>0.2865$^{+0.0006}_{-0.00095}$</td>
</tr>
<tr>
<td>Physical matter density</td>
<td>$\Omega_m h^2$</td>
<td>0.1364 ± 0.0044</td>
<td>0.1376 ± 0.0020</td>
</tr>
<tr>
<td>Current baryon density (cm$^{-3}$)$^f$</td>
<td>$n_b$</td>
<td>$(2.542 ± 0.056) \times 10^{-7}$</td>
<td>$(2.497 ± 0.037) \times 10^{-7}$</td>
</tr>
<tr>
<td>Current photon density (cm$^{-3}$)$^g$</td>
<td>$n_\gamma$</td>
<td>410.72 ± 0.26</td>
<td>410.72 ± 0.26</td>
</tr>
<tr>
<td>Baryon/photon ratio</td>
<td>$\eta$</td>
<td>$(6.19 ± 0.14) \times 10^{-10}$</td>
<td>$(6.079 ± 0.090) \times 10^{-10}$</td>
</tr>
</tbody>
</table>

\[ h = \frac{H_0}{100 \text{ km sec}^{-1} \text{ Mpc}^{-1}} \]
Degeneracy in the fits for the mass and energy densities prevent them from obtaining $H_0$ accurately without additional information.

- Assuming the Universe to be flat ($\Omega_M + \Omega_\Lambda = 1$), $H_0 = 70 \pm 2$ km sec$^{-1}$ Mpc$^{-1}$, for which the errorbars reach SH0ES’s and CHP’s.
- Or: adding the SH0ES measurement as a Gaussian prior, and adding information from baryon acoustic oscillation observations (see Hinshaw et al. 2013), $H_0$ decreases slightly from the “flat” value. (??)
\( H_0 \) 2013: WMAP9 (continued)

- In all, the results are quite similar to those the WMAP team released two years ago with the first seven years of data.
  - Same \( H_0 \) mean value, slightly smaller uncertainties.
  - WMAP9 and SN Ia/Leavitt-law \( H_0 \) about 2\( \sigma \) apart, though: discrepant at 95% confidence?

- Diagram showing various measurements of \( H_0 \) from different studies:
  - Riess et al. 2011 (SH0ES), MW + M106
  - Freedman et al. 2012 (CHP), mid-IR MW+LMC
  - Riess et al. 2011 (SH0ES), MW+M106+LMC
  - Komatsu et al. 2011 (WMAP7)
  - Bennett et al. 2013 (WMAP9)
  - Reid et al. 2013 (MCP)
  - Planck collaboration 2013
  - Sandage et al. 2010
  - AST 142 adopted value, 2013

- Chart showing values of \( H_0 \) in km/sec/Mpc.
The Megamaser Cosmology Project (MCP) is exploiting the great radio-frequency sensitivity and resolution of VLBA and 100-m single dishes (GBT, Effelsberg) to make geometric, orbital parallax measurements of the distances to 22 GHz water masers in circumnuclear disks of active galaxies.

- Principle: With VLBI imaging and orbital radial-velocity ($V_r$) monitoring of maser spots close to the systemic velocity, one can determine their centripetal accelerations.
- Thus one gets their linear orbital radius, $r = V_r^2 / a$.
- From the spatial distribution of the other maser spots comes the angular dimensions of the disk and the orbit of the systemic-velocity maser spots, $\Delta \theta$.
- Whence $d = r / \Delta \theta$, to several-percent accuracy.
Megamasers geometry

Circumnuclear disk, viewed nearly edge-on.

Jet

Systemic-velocity masers

Measure $a$ from drift over time of peak velocity of each systemic maser spot.

Herrnstein et al. 1999
Caveats (potential systematic errors in $a, \Delta \theta$ or $v$):

- Maser spots in disks are not discrete, coherent objects like stars – they represent paths with high maser gain. Beware of detecting *pattern* velocities rather than orbital velocities.
- Masers closely spaced in spectrum; blending makes it hard to be confident of the identity of features over time.
- There are few megamaser galaxies, and only three have yielded orbital parallaxes so far – all of which also present problems with the $v$ in $v = H_0 d$.
  - M106 (NGC 4258): too close to us (not in Hubble flow).
  - NGC 6264, UGC 3789: members of groups, and have unknown velocity besides that from Hubble flow.
- So uncertainties are large and mean values keep changing.
But the opportunity to use a geometric, standard-candle-free distance in the Hubble constant should not be passed up. The latest MCP analysis of UGC 3789 gives geometric distance $d = 49.6 \pm 5.1$ Mpc (luminosity distance $50.8 \pm 5.2$ Mpc) and corrected recession velocity $v = 3466 \pm 175$ km sec$^{-1}$, for $H_0 = 69 \pm 7$ km sec$^{-1}$ Mpc$^{-1}$.

Resulting uncertainties embrace all contending $H_0$ values.

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**H_0 2013: MCP (continued)**

- Riess et al. 2011 (SH0ES), MW + M106
- Freedman et al. 2012 (CHP), mid-IR MW+LMC
- Riess et al. 2011 (SH0ES), MW+M106+LMC
- Komatsu et al. 2011 (WMAP7)
- Bennett et al. 2013 (WMAP9)
- Reid et al. 2013 (MCP)
- Planck collaboration 2013
- Sandage et al. 2010
- AST 142 adopted value, 2013

![Graph showing H_0 values](graph.png)
\textbf{H}_0 \textbf{2013: Planck}

\textbullet\ Planck has angular resolution \((3\times)\) and sensitivity \((10\times)\) advantages over WMAP, though it lasted only 30 months with its full capabilities.

\begin{itemize}
  \item 7 acoustic peaks detected. (!)
  \item Again a six-parameter \(\Lambda\)CDM model was fit to the power spectrum of CMB anisotropies, and \(H_0\) derived from these somewhat-degenerate parameters.
\end{itemize}

\textit{Planck collaboration 2013}
$H_0$ 2013: Planck (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Omega_b h^2$</th>
<th>$\Omega_c h^2$</th>
<th>$100\theta_{MC}$</th>
<th>$\tau$</th>
<th>$n_s$</th>
<th>$\ln(10^{10} A_s)$</th>
<th>$\Omega_\Lambda$</th>
<th>$\Omega_m$</th>
<th>$\sigma_8$</th>
<th>$z_{re}$</th>
<th>$H_0$</th>
<th>$10^9 A_s$</th>
<th>$\Omega_m h^2$</th>
<th>$\Omega_m h^3$</th>
<th>$Y_p$</th>
<th>Age/Gyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best fit</td>
<td>0.022068</td>
<td>0.12029</td>
<td>1.04122</td>
<td>0.0925</td>
<td>0.9624</td>
<td>3.098</td>
<td>0.6825</td>
<td>0.3175</td>
<td>0.8344</td>
<td>11.35</td>
<td>67.11</td>
<td>2.215</td>
<td>0.14300</td>
<td>0.09597</td>
<td>0.247710</td>
<td>13.819</td>
</tr>
<tr>
<td>68% limits</td>
<td>0.02207 ± 0.00033</td>
<td>0.1196 ± 0.0031</td>
<td>1.04132 ± 0.00068</td>
<td>0.097 ± 0.038</td>
<td>0.9616 ± 0.0094</td>
<td>3.103 ± 0.072</td>
<td>0.686 ± 0.020</td>
<td>0.314 ± 0.020</td>
<td>0.834 ± 0.027</td>
<td>11.4 ± 4.0</td>
<td>67.4 ± 1.4</td>
<td>2.23 ± 0.16</td>
<td>0.1423 ± 0.0029</td>
<td>0.09590 ± 0.00059</td>
<td>0.24771 ± 0.00014</td>
<td>13.813 ± 0.058</td>
</tr>
</tbody>
</table>
Some of the fit and derived cosmological parameters differ significantly from those in WMAP9.

Planck did not assume flatness to break degeneracies in obtaining $H_0 = 67.3 \pm 1.2 \text{ km sec}^{-1} \text{ Mpc}^{-1}$; even lower than WMAP.
**H₀ 2013: Planck (continued)**

- So the cosmic-background anisotropy/ΛCDM measures of H₀ differ from distance-ladder measures by 2-2.5σ (95-98.6% confidence). Why?
  - Forcing H₀ to lie within the SH0ES errorbars drives matter down, dark energy up, χ² way up.
  - *Planck* looked at a series of 7-parameter models: highly recommended reading but no help for the discrepancy.
**$H_0$ 2013: summary**

- So there’s no easy CMB fix.
- And we’re running out of places systematic errors of this magnitude can hide in the Leavitt Law and the SNe Ia. (Noise is already small.)
- *Planck*: is the discrepancy “**a pointer to new physics**?”

Meanwhile I’ll side with the distance ladder methods, and teach my class that

$$H_0 = 74.2 \pm 1.5 \text{ km sec}^{-1} \text{ Mpc}^{-1}.$$