Cosmological Controversy: Resolving the Tension in the Hubble Constant

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"The Hubble constant controversy: status, implications and solutions"
Berlin, November 9, 2018
History of the Hubble Constant

![Graph showing the history of the Hubble constant](image)

Copyright J. Huchra 2005
Final Hubble Space Telescope Key Project Combined Results

HST Key Project:

Discovery of Cepheid variables and a measurement of $H_0$ to an accuracy of 10%.

Freedman et al. 2001
CMB Anisotropies

Planck 2018
The Current Tension in $H_0$

The diagram shows the evolution of $H_0$ (in km s$^{-1}$ Mpc$^{-1}$) from 2002 to 2020, illustrating the tension in different key projects such as SHoES, CMB, and Standard Sirens. The shaded region indicates the range of values over time, with the year of publication marked along the x-axis. The diagram highlights the significant tension observed at around 3.8 σ, indicating a notable discrepancy in the measurements.
# Summary of Recent $H_0$ Values

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Uncertainty (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$ CDM:</td>
<td>$67.8 \pm 0.9$</td>
<td>(1.3%)</td>
<td>[Planck 2015]</td>
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<tr>
<td>+ polarization</td>
<td>$66.93 \pm 0.62$</td>
<td>(0.9%)</td>
<td>[Planck 2016]</td>
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<tr>
<td></td>
<td>$67.4 \pm 0.5$</td>
<td>(0.7%)</td>
<td>[Planck 2018]</td>
</tr>
</tbody>
</table>

| Cepheids                  | $74.3 \pm 2.1$  | (2.8%)          | [WLF+ 2012]        |
| + SN1a:                   | $73.24 \pm 1.74$| (2.4%)          | [Riess+ 2016]      |
|                           | $73.52 \pm 1.62$| (2.2%)          | [Riess+ 2016]      |
Potential New Physics Beyond $\Lambda CDM$, If Real

- Another relativistic species (e.g., an additional neutrino or other ‘dark radiation’)
- A different equation of state for dark energy from $w = -1$
- A decaying relic massive dark matter particle
- Modified gravity (LIGO has already killed many models...)
- Non-zero spatial curvature
The Future of \( H_0 \): Crisis or Concordance?

Oct 4-5, 2018  
Chicago, IL
Vote!

- Option 1: H0<66
- Option 2: H0=66-69
- Option 3: H0=69-71
- Option 4: H0=71-74
- Option 5: H0>74
The Carnegie Chicago Hubble Program (CCHP) : Overview

1. Cepheids
   Magellan, HST, Spitzer, Gaia
2. RR Lyrae
   TMMT, HST, Spitzer, Gaia
3. TRGB
   TMMT, Magellan, Gaia, JWST

$H_0$ to 2% (statistical + systematic)
Carnegie Chicago Hubble Project II : TMMT***

*** Three hundred Millimeter Telescope at Las Campanas
Tip of the Red Giant Branch (TRGB)

Lee, Freedman & Madore (1993); Madore & Freedman (1999)

Advantages : Simplicity of the method

- Found in outer (largely metal-poor) halos of galaxies
  - reddening negligible, especially in IR
  - stellar density significantly lower than disk (minimizing crowding issues)
- Metallicity effects small and directly calibrated, unlike for Cepheids
- No long-term variability follow-up needed
- Can be applied to galaxies of all inclinations and Hubble types
- AGB stars minimal contamination compared to disk

Disadvantages

- $M_I \sim -4$ mag (Cepheids: $-4 < M_I < -1$) **
The Carnegie Chicago Hubble Program (CCHP) : Overview

Tip of the Red Giant Branch

1. Spitzer
2. HST
3. TMMT
4. LCO

TRGB Halos in Nearby Galaxies

Serenelli et al. (2017)

He flash

Bildsten et al. 2012 (MESA)
Cepheids / The Tip of the Red Giant Branch

NGC 4258

(a) Halo TRGB field

TRGB HST ACS field
Mager, Madore & WLF (2008)

Disk Cepheid fields

Cepheid HST ACS + WFPC2 fields
Macri + Riess et al. (2006)
The Tip of the Red Giant Branch

Mager, Madore & WLF (2008)
The Tip of the Red Giant Branch

(a) NGC 4258

Measure 1st derivative of luminosity function

Mager, Madore & WLF (2008)
The Tip of the Red Giant Branch

IC 1613

Hatt et al (2017)
Calibration of the Tip of the Red Giant Branch: II. LMC

Geometry of the LMC seen in the LMC red giant branch stars

Hoyt, WLF et al. (2019)
Based on JHK LMC data from Macri et al (3.5 million sources; 860,000 RGB stars)

Comparison: 2MASS catalog
2 million sources
Calibration of the Tip of the Red Giant Branch: II. LMC

Hoyt, Freedman, Madore et al. (2018)

\[ \mu = 18.477 \]
\[ \sigma = 0.030 \]
TRGB Distances to SN Ia Galaxy Hosts
HST ACS/WFC Observations
Comparison of TRGB & Cepheid Distances *Preliminary*

![Graph comparing TRGB and Cepheid distances](image)

- **N = 28**
- **σ = 0.09**
- **LMC**
- **N1365**
- **M101**
- **N4258**
- **M31**

WLF et al. (2018)
The Carnegie Supernova Project (CSP)

Las Campanas Observatory
Carnegie Supernova Project (CSP)

Swope 1-meter

M. Phillips, PI

- $u'BVg'r'i'YJHK$ photometry 123 SNe Ia
- 2.5-meter, 6.5-meter optical spectroscopy

du Pont 2.5-meter

Magellan 6.5-meter

W. Freedman, PI

0.2 < $z$ < 0.8 55 SNe Ia

CSP II:

- $BVg'r'i'YJHK$ photometry 116 SNe Ia
- Magellan FIRE 6.5-meter spectroscopy

Multi-wavelength Light curves

0.03 < $z$ < 0.1
Supernovae ("Standardizable" Candles)

![Graph showing luminosity vs. time from peak for supernovae with luminous and less luminous SNs fading at different rates.](image)

Supernova Cosmology Project
CCHP TRGB Calibration of $H_0$

(Preliminary)

Burns et al. 2018
WLF et al. 2018
CSP and SHoES comparison

(Preliminary)

SHoES and CSP samples

$N \text{(SHoES)} = 218$

$N \text{(CSP)} = 119$
Gaia – Data Release 2

- April 25, 2018
- 22 months of data
- Gaia data alone
- 1.3 billion stars
- Parallax uncertainty:
  - ~ 0.04 mas G < 15 mag
  - ~ 0.1 mas @ 17 mag
  - ~ 0.7 mas @ 20 mag

Note:
“There is a significant parallax zero-point offset of about -30 μas.”

DR3: delayed until mid- to late 2020.
TRGB Increasing Precision and Accuracy for Future

Gaia parallaxes

$H_0$ to 1%

Hubble Space Telescope (HST)

James Webb Space Telescope (JWST)
Launch date: March 30, 2021
Concluding Remarks

There is no single, obvious systematic effect that has emerged at the 0.2 mag level, which would be required to reconcile the value of $H_0$ if the true, local $H_0$ were equal to that inferred from Planck + ΛCDM.

[For reference, recall that the evidence for acceleration from SNeIa is comparable in size.]
The Future

1. Future results from Gaia will provide a calibration with <<1% uncertainty (for Cepheids, TRGB, RR Lyrae stars)

2. JWST and 1% statistical precision for calibration of total sample of 25 SNe Ia using TRGB method

3. LIGO sirens

The potential for a robust measurement of the local $H_o$ value to both a precision and accuracy at the percent level is real, and with multiple routes (to ascertain systematic uncertainties), could be achieved within a decade.