The Hubble Tension

How are we trying to solve one of the biggest crises in Astronomy?

Dr. Adam Batten

Swinburne University of Technology Public Astronomy Lecture 30-03-2023



SWINBURNE UNIVERSITY OF TECHNOLOGY

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Acknowledgement of Country

We respectfully acknowledge the Wurundjeri People of the Kulin Nation, who are the Traditional Owners of the land on which Swinburne's Australian campuses are located in Melbourne's east and outer-east, and pay our respect to their Elders past, present and emerging.

We are honoured to recognise our connection to Wurundjeri Country, history, culture, and spirituality through these locations, and strive to ensure that we operate in a manner that respects and honours the Elders and Ancestors of these lands.

We also respectfully acknowledge Swinburne's Aboriginal and Torres Strait Islander staff, students, alumni, partners and visitors.

We also acknowledge and respect the Traditional Owners of lands across Australia, their Elders, Ancestors, cultures, and heritage, and recognise the continuing sovereignties of all Aboriginal and Torres Strait Islander Nations.



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The Hubble Constant

The Hubble Constant





The Hubble Constant



Cosmic Distance Ladder

Hubble Constant



Cosmic Distance Ladder



Cosmic Microwave Background



67.7

Cosmic Microwave Background

Planck Collaboration (2020)

Reiss et al. (2022)





Image Credit: NASA/ESA



Image Credit: NASA/ESA







How do you measure a galaxy's velocity?



Fire Truck Moving



Fire Truck Moving

The Sun's Spectrum



Image Credit: N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF



Object at Rest – Not Moving



At Rest - Not Moving



Object moving towards us – "Blueshifted"



At Rest - Not Moving



Object moving away from us – "Redshifted"



At Rest - Not Moving



Object moving away from us – "Redshifted"



How far away is this galaxy?







Distance Measurement Tool #1: Parallax



Distance Measurement Tool #1: Parallax









Distance Measurement Tool #1: Parallax

 $\star\star$









Distance Measurement Tool #2:



Distance Measurement Tool #2: Supernovae

NGC1365
Distance Measurement Tool #2: Type Ia Supernovae



Distance Measurement Tool #2: Type Ia Supernovae



Distance Measurement Tool #3: Cepheid Variable Stars











Parallax + Accurate!

- Can only be used on stars inside our galaxy.



Parallax + Accurate! Supernovae + Can be used for large distances!

- Can only be used on stars inside our galaxy. - Needs to have calibrations from known distances.



Parallax + Accurate! Supernovae + Can be used for large distances!

Cepheids + Can be found in our galaxy and nearby galaxies!

- Can only be used on stars inside our galaxy. - Needs to have calibrations from known distances. - Needs to have calibrations from known distances.













Image Credit: Durham Department of Physics





67.7

Cosmic Microwave Background

Planck Collaboration (2020)

Reiss et al. (2022)

Cosmic Microwave Background (CMB)

(B) 67.7 Cosmic Microwave Background

Image Credit: ESA and Planck Collaboration

67.7 Cosmic Microwave Background



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Cosmic Microwave Background (CMB)

(B) 67.7 Cosmic Microwave Background

Image Credit: ESA and Planck Collaboration

67.7 Cosmic Microwave Background

How does the cosmic microwave background tell you H₀?



67.7 Cosmic Microwave Background

Warning: Equation Incoming!

$$H_{0} = \sqrt{\frac{8\pi G\rho}{3(\Omega_{\Lambda,0} + \Omega_{M,0}a^{-3} + \Omega_{\gamma,0}a^{-4})}}$$

Microwave Background

Warning: Equation Incoming!



Microwave Background



67.7

Microwave Background

Cosmic Microwave Background



CMB

Determine properties of the Universe

HO

67.7 Cosmic Microwave Background



67.7

Cosmic Microwave Background

Planck Collaboration (2020)

Reiss et al. (2022)



Distance to the

Parallax

Stars

Supernovae

 H_0

Sun

- **Direct measurement** • of H_0 .
- Based on our ability to • calibrate each rung of **Cepheid Variable** the distance ladder.
 - Many rungs in the • distance ladder, and small errors can lead to large errors in H_0 .





CMB

Determine properties of the • Universe

 H_0

- **Indirect Measurement** • of H_0 .
 - **Based on observations** and our current model of the Universe.
- This is a model, and • models can be wrong or overly simplistic.

Why is this a "crisis"?

If the cosmic distance ladder measurement is incorrect:

1. We don't know how to measure distances in the local Universe.

If the CMB measurement is incorrect:

67.7 Cosmic Microwave Background

If the cosmic distance ladder measurement is incorrect:

- 1. We don't know how to measure distances in the local Universe.
- 2. We also don't know where we are going wrong with out measurements to fix it.

If the CMB measurement is incorrect:

67.7 Cosmic Microwave Background

If the cosmic distance ladder measurement is incorrect:

- 1. We don't know how to measure distances in the local Universe.
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If the CMB measurement is incorrect: 67.7 Cosmic Microwave Background

1. Our understanding of cosmology is wrong.

If the cosmic distance ladder measurement is incorrect:

- 1. We don't know how to measure distances in the local Universe.
- 2. We also don't know where we are going wrong with out measurements to fix it.

If the CMB measurement is incorrect: 67.7 Cosmic Microwave Background

1. Our understanding of cosmology is wrong.

2. We don't understand what the cosmic microwave background is telling us.

How do we solve this crisis?



CMB with Planck

CMB without Planck Dutcher et al. (2021), SPT: 68.8 ± 1.5 Aiola et al. (2020), ACT: 67.9 ± 1.5 Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1 Zhang, Huang (2019), WMAP9+BAO: 68.36⁺0.83 Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2

No CMB, with BBN

P₁(k) + CMB lensing

Riess et al. (2020), R20: 73.2 ± 1.3 Breuval et al. (2020): 72.8 ± 2.7 Riess et al. (2019), R19: 74.0 ± 1.4 Camarena, Marra (2019): 75.4 ± 1.7 Burns et al. (2018): 73.2 ± 2.3

Follin, Knox (2017): 73.3 ± 1.7

Pesce et al. (2020): 73.9 ± 3.0

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Denzel et al. (2021): 71.8+3.9

Baxter et al. (2020): 73.5 ± 5.3 Qi et al. (2020): 73.6 ± 18 Liao et al. (2020): 72.8 ± 19 Liao et al. (2020): 72.8 ± 19 Liao et al. (2021): 72.2 ± 21 Shajib et al. (2019), STRIDES: 74.2 ± 3 Wong et al. (2019), HOLICOW 2018: 72.5 ± 3 Birrer et al. (2016), HOLICOW 2018: 72.5 ± 3 Borvin et al. (2016), HOLICOW 2018: 77.9 ± 3 Borvin et al. (2016), HOLICOW 2018: 77.9 ± 3 Borvin et al. (2016), HOLICOW 2018: 77.9 ± 3 Borvin et al. (2016), HOLICOW 2018: 77.9 ± 3 Borvin et al. (2016), HOLICOW 2018: 77.9 ± 3 Borvin et al. (2016), HOLICOW 2018: 77.9 ± 3 Borvin et al. (2016), HOLICOW 2018: 71.9 ± 3 Borvin et al. (2016), HOLICOW 2018: 77.9 ± 3 Borvin et al

> Optimistic average Di Valentino (2021): 72.94 ± 0.75

Di Valentino (2021): 72.7 ± 1.1

GW related

TRGB – SNIa

Masers

SNII

Cepheids – SNIa

Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.53

Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54 Ade et al. (2016), Planck 2015, H₀ = 67.27 ± 0.66

Pogosian et al. (2020), eBOSS+Planck $\Omega_m H^2$: 69.6 ± 1.8 Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60

D Amico et al. (2020), BOSS DR12+BBN: 68.5 ± 2.2 Colas et al. (2020), BOSS DR12+BBN: 68.7 ± 1.5 Philcox et al. (2020), *P*₁+BAO+BBN: 66.5 ± 1.1 Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1 Alam et al. (2020), BOSS+BBN: 67.9 ± 0.97

Philcox et al. (2020), P_l(k)+CMB lensing: 70.6+3.7

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Fernández Arenas et al. (2018): 71.0 ± 3.5

Lensing related, mass model - dependent

Birrer et al. (2020), TDCOSMO+SLACS: 67.4⁺¹/₂, TDCOSMO: 74.5⁺²/₂ Yang, Birrer, Hu (2020): H₀ = 73.65⁺²/₂ Millon et al. (2020), TDCOSMO: 74.2 ± 1.6

Ultra – conservative, no Cepheids, no lensing

Gayathri et al. (2020), GW190521+GW170817: 73.4^{+6,9} Mukherjee et al. (2020), GW170817+ZTF: 67.6⁺² Mukherjee et al. (2019), GW170817+VLBI: 68.3⁺⁴ Abbott et al. (2017), GW170817: 70.0⁺⁵ Abbott et al. (2017), GW170817: 70.0⁺⁵

How do we solve this crisis?

Image Credit: Valentino et al. (2021)



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GW related

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How do we solve this crisis?

I am using this one

"Tip of the **Red Giant Branch Stars**"

Image Credit: Valentino et al. (2021)

How far away is this galaxy?




Bluer Stars

How far away is this galaxy?

Redder Stars

Image Credit: ESA/Hubble & NASA





Main Sequence Star

Image Credit: Freedman (2021)



Tip of the Red Giant Branch Star

Image Credit: Freedman (2021)



Red supergiant Star Antares

Image Credit: Freedman (2021) & NASA/ESO



NGC4639

We can find tip of the Red Giant Branch stars in the outskirts of nearby galaxies.









Cosmic Distance Ladder (TRGB)





Summary



Twitter: @adamjbatten

Slides: https://adambatten.com/talks/

- The Universe is expanding!
- The two main methods for measuring the rate of expansion of the Universe (H_0) are in tension.
- The cosmic distance ladder: **73.3 km/s/Mpc**.
 - Distance to the Sun -> Parallax
 - Parallax -> Cepheid Variables
 - Cepheid Variables -> Supernovae
 - Supernovae -> H₀
- Cosmic microwave background: 67.7 km/s/Mpc.
 - Determines the amount of matter, dark matter, dark energy and radiation in the Universe.
 - Uses these quantities to calculate H_0 .
 - I am using stars at the tip of the red giant branch to recalibrate supernovae for the cosmic distance ladder.



The Bullet Cluster









Dark Matter + Dark Energy

Modified Newtonian Dynamics