

Investigating the Hubble Tension: Observations, Analysis, and Significance

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Abstract. The Hubble constant quantifies the current expansion rate of the universe. Two main methods are used to measure its value: the distance ladder involving standard candles, especially Cepheid variables and Type Ia supernovae, and the analysis of Cosmic Microwave Background anisotropies within the Λ CDM model. The discrepancy between the Hubble constant values obtained from the two is the Hubble tension. This paper reviews the theoretical and observational foundations of both measurement techniques and presents an analysis of Pantheon+ data to estimate H_0 , with two estimates derived, one considering uncertainties through error bars and one without. The results indicate that the discrepancies between the two methods are difficult to explain with random errors and may involve systematic errors or new physics, such as early dark energy, additional relativistic components, or modified theories of gravity. The findings contribute to ongoing discussions on the Hubble tension, highlighting the need for continued precision in observations and the exploration of potential new physics beyond the Λ CDM model.

Keywords: Hubble Tension, Distance Ladder, Standard Candles, Cosmic Microwave Background.

1. Introduction

The Hubble constant H_0 describes the rate of expansion of the universe and is a central parameter in modern cosmological research. Its precise determination has become one of the core problems. The so-called Hubble tension refers to the phenomenon of significant differences in values measured by different observation methods. For example, measurements based on standard candlelight (such as Type Ia supernovae and Cepheid variables) yield the H_0 of $\sim 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, while cosmic microwave background (CMB) data based on Planck satellite observations yield the H_0 of $\sim 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [1]. The difference between the two suggests that there may be systematic errors that have not yet been identified, or that new physics needs to be introduced beyond existing cosmological models.

Based on this, the paper aims to review the methodologies underlying both distance ladder and CMB-based measurements, emphasising their theoretical foundations, calibration processes, and possible sources of uncertainty.

2. Theoretical Basis

2.1. Hubble's Law

One of the foundational formulae in cosmology is Hubble's Law, which describes the linear relationship between the distance to a galaxy and its recessional velocity due to the expansion of the universe.

$$v = H_0 \cdot d \quad (1)$$

Where v is a galaxy's recessional speed, in km s^{-1} , d is galaxy's distance from Earth, in Mpc, and H_0 is the Hubble constant, representing the current rate of cosmic expansion, in $\text{km s}^{-1} \text{ Mpc}^{-1}$.

This law implies that the universe is expanding uniformly on large scales, meaning that the further away a galaxy is, the faster it appears to be receding. Using this, the age t of the universe can be estimated from the Hubble constant.

$$t \approx \frac{1}{H_0} \quad (2)$$

However, this is only an approximation because the expansion rate is not constant throughout the course of the universe [2].

2.2. Redshift

Redshift z is determined by identifying spectral features such as emission lines and comparing the observed wavelengths of those features with the wavelength obtained from laboratory data.

$$1 + z = \frac{\lambda_{observed}}{\lambda_{emitted}} \quad (3)$$

Where λ is the wavelength. For low redshifts ($z \ll 1$) typical in nearby galaxies used for local determinations, redshift can be converted to an approximate recessional velocity using

$$v \approx cz \quad (4)$$

Where c is the speed of light [3].

2.3. Distance Ladder

The usage of standard candles is fundamental in determining cosmic distances and, therefore H_0 . A standard candle is an astronomical object whose luminosity can be determined by a physical property, allowing its distance to be calculated by comparing its luminosity with its observed apparent brightness. Since direct distance measurements, such as the parallax method, are limited to nearby stars, a distance ladder is built to calibrate more distant bodies. The two important factors of building this ladder are Cepheid variable stars and Type Ia supernovae [4].

For most standard candles, their distances away can be calculated with their apparent magnitude, which is measured, and their absolute magnitude, which is known, using the distance modulus relation.

$$m - M = 5 \log_{10}(d) + 25 \quad (5)$$

Where d is distance in Mpc, m is apparent magnitude, and M is absolute magnitude.

Cepheid variables are pulsating stars whose brightness varies periodically due to cyclic changes in their outer layers. The pulsation period P of a Cepheid is correlated with its luminosity, sometimes called the period-luminosity ($P-L$) relation. By measuring P and the apparent magnitude m , the absolute magnitude M can be determined, and hence the distance via the distance modulus relation. Cepheids are luminous enough to be observed in nearby galaxies (up to tens of Mpc away), making them an ideal calibrator for more distant standard candles. Modern calibrations of Cepheids rely on geometric distance anchors such as parallax measurements from Gaia in galaxies like NGC 4258 [5, 6].

Type Ia supernovae, also known as SNe Ia, are thermonuclear explosions of white dwarf stars in binary systems. They have a nearly uniform peak luminosity since they all reach the Chandrasekhar mass (maximum mass of a white dwarf). SNe Ia serve as powerful standard candles that can be observed out to redshifts $z > 1$, mapping the expansion of the universe on large scales. To use SNe Ia for, H_0 , their luminosity is calibrated using Cepheids in nearby host galaxies [7, 8].

The construction of a distance ladder typically consists of three consecutive steps. First, geometric methods such as parallax are used to determine the distances between neighbouring stars and galaxies to provide local anchor points for subsequent measurements. Then, based on the anchors at these known distances, the period-photometric relationship of Cepheids is established, making Cepheids a reliable tool for longer-distance measurements. Finally, in supernova host galaxies containing calibrated Cepheids, the distance of these Cepheids is used to fix the absolute magnitude of Ia-type supernovae, so that Ia-type supernovae can be used to determine the distance of galaxies well beyond the observation limit of Cepheids. Through this step-by-step measurement method, the distance ladder provides a key source of distance data for drawing the Hubble diagram (the relationship between recession velocity and distance) and accurately determining the Hubble constant H_0 [9].

2.4. The Cosmic Microwave Background

The cosmic microwave background (CMB) provides a powerful method of finding H_0 , independent of standard candles. The CMB is the leftover radiation from when the universe became transparent about 380,000 years after the Big Bang. Its small temperature anisotropies encode information about the universe's contents and expansion history.

Before recombination, photons and baryons were tightly held in a hot plasma, which carries acoustic oscillations. When the universe cooled down enough for recombination to start, the phase of the oscillations at that moment was stopped and recorded as temperature fluctuations in the CMB. The angular size of these acoustic peaks recorded as temperature fluctuations depends on the expansion rate between recombination and today. The angular power spectrum of the CMB describes the variance of temperature fluctuations as a function of angular scale. By fitting the observed spectrum with a cosmological model, parameters including the present-day H_0 can be found.

It is important to note that the accuracy of CMB measurements depends on the assumed cosmological model, which is often the Λ CDM model [10, 11].

3. Recent Work

3.1. Measurements from Standard Candles

Recent analyses using standard candles, which combine Gaia-calibrated Cepheids and standardized SNe Ia, have obtained H_0 values of around $73 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The SH0ES (Supernovae H for the Equation of State) team has played a leading role in this work. By combining Gaia-calibrated parallaxes of Cepheid variables with high-precision observations of SNe Ia, they derived $H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This calibration depends heavily on accurate distance measurements to nearby Cepheids using Gaia DR3 parallaxes, and measurements of SNe Ia in host galaxies containing Cepheids [12]. The Pantheon+ compilation, an expanded and homogenized dataset of over 1,500 SNe Ia across a wide redshift range, supports this finding with $H_0 = 73.3 \pm 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ using the same Cepheid-based calibration method [13].

More recently, the James Webb Space Telescope (JWST) provided near-infrared imaging of Cepheids in SN Ia host galaxies with high resolution. These observations confirmed previous Hubble Space Telescope measurements, reinforcing the reliability of Cepheid-based distances and yielding $H_0 = 73.0 \pm 1.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [14].

Independent cross-checks using the Tip of the Red Giant Branch (TRGB) method, which calibrates luminosity based on the helium flash in low-mass stars, produced slightly lower values of $H_0 \approx 69\text{--}71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, but these values are still consistent with the Cepheid-based distance ladder as they lie within statistical uncertainties [15].

3.2. Measurements from the CMB

The Planck 2018 data analysis, which fit the full temperature and polarization angular power spectrum under the Λ CDM model, gave $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This analysis uses the method discussed previously, which involves deriving H_0 through precise measurements of the acoustic peaks in the CMB power spectrum [11].

The Atacama Cosmology Telescope (ACT) 2021 data, which focuses on small-scale anisotropies of the CMB, yielded a consistent value of $H_0 = 67.9 \pm 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Similarly, the South Pole Telescope's third-generation survey (SPT-3G) and joint analyses involving ACT, SPT, and Planck datasets also converge on values near $67\text{--}68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [16, 17]. Compared with H_0 measured by the standard candlelight method, this value is lower, which proves that there are significant differences between different measurement methods, which may indicate unknown systematic errors or new physical effects [12].

Because of the method used, these results are model-dependent. Nevertheless, their internal consistency and statistical precision make them compelling benchmarks for comparison [18].

3.3. Comparison

To illustrate the significance of the difference in Hubble constant measurements, the age of the universe in billions of years can be calculated using the above measurements, and the results are shown in Table 1.

Table 1. Age of the Universe Values based on H_0 [11-17]

Type	Source	H_0 / km s ⁻¹ Mpc ⁻¹	Age of the Universe / Gyr
Standard Candles	SH0ES	73.04 ± 1.04	13.39 ± 0.19
	Pantheon+	73.3 ± 1.0	13.35 ± 0.18
	JWST	73.0 ± 1.0	13.40 ± 0.18
	TRGB	69 to 71	13.78 to 14.18
CMB	Planck	67.4 ± 0.5	14.52 ± 0.11
	ACT	67.9 ± 1.5	14.41 ± 0.32
	SPT-3G	67 to 68	14.39 to 14.61

As shown in Table 1, while the age predictions from the same method mostly lie within each other's uncertainty, the values obtained from different methods often exceed uncertainty boundaries, suggesting that this difference is not due to statistical random errors.

To further complement the comparison of H_0 measurements, a numerical estimation of H_0 is implemented using the available Pantheon+ dataset of SNe Ia [8]. Based on this data, this article generates two Hubble diagrams (Figs. 1 and 2) in Python. Fig. 1 is a Hubble diagram without considering distance uncertainty, and Fig. 2 is a diagram that includes error bars representing distance uncertainty to demonstrate the impact of uncertainty on the measurement results. Both have recessional velocity v against distance d and are limited to low-redshift supernovae ($z < 0.3$) so that $v \approx cz$ is valid.

The Pantheon+ dataset provides SNe redshifts and apparent magnitudes. Therefore, the redshifts were converted into recessional velocities in km s⁻¹ using $v \approx cz$, and the apparent magnitudes were converted into distances in Mpc using $m - M = 5 \log_{10}(d) + 25$.

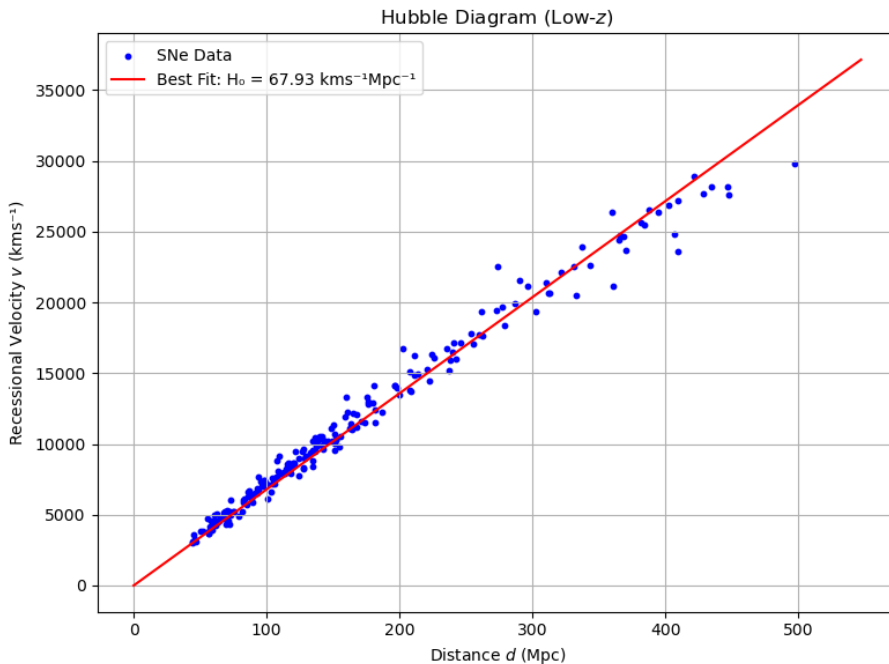


Fig. 1 Hubble Diagram for Low-z SNe Ia from Patheon+ Dataset, no Error Bars (Photo credit: Original).

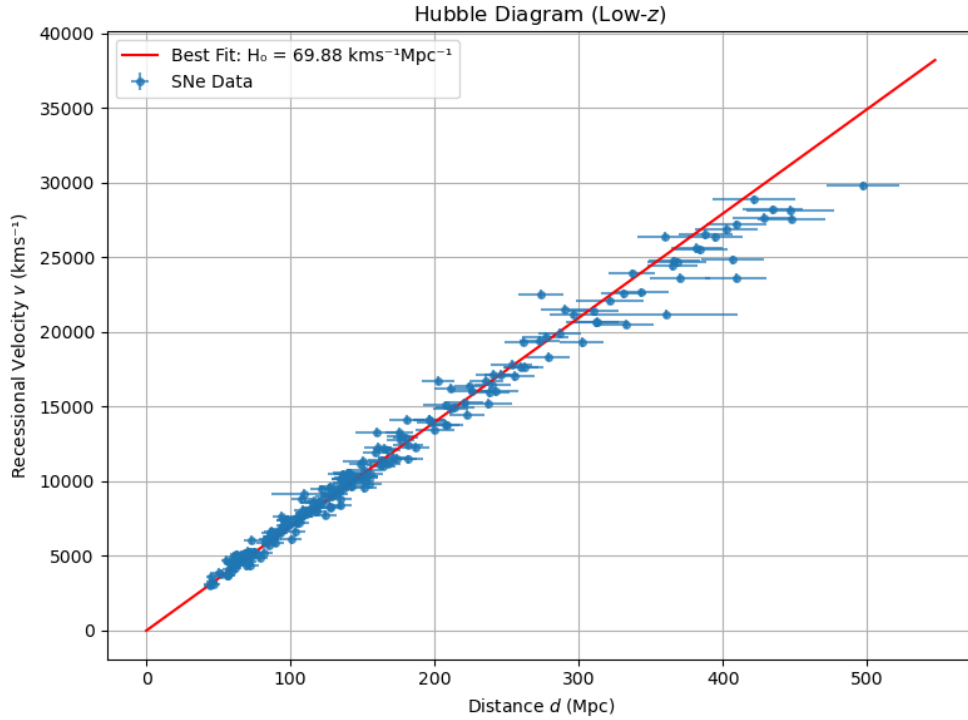


Fig. 2 Hubble Diagram for Low- z SNe Ia from Pantheon+ Dataset, with Error Bars (Photo credit: Original).

Fig. 1 does not consider any uncertainties. This gave a value of $H_0 = 67.93 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from its line of best fit, which is somewhat close to the published value from Pantheon+ mentioned above ($H_0 = 73.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Fig. 2 includes error bars that represent uncertainties from the distance values and gives a value of $H_0 = 69.88 \text{ km s}^{-1} \text{ Mpc}^{-1}$, reflecting that considering uncertainties improves the accuracy of the result.

3.4. Nature and Significance of the Hubble Tension

The discrepancy between the standard candle and the CMB measurements is the Hubble tension, which now exceeds the 5σ threshold, further suggesting that it is unlikely to be due to random error, as exceeding 5σ entails that there is only a 1 in ~ 3.5 million chance that this difference is due to random error. This tension challenges the completeness of the Λ CDM model and has prompted a wide range of possible explanations [12, 19].

Systematic errors have been extensively investigated on both sides. For the distance ladder, this includes uncertainties in parallax measurements, photometric calibration, and supernova standardization. For CMB-based measurements, potential issues investigated include foreground contamination, beam modelling, and assumptions built into the Λ CDM framework [8, 11, 12].

As of today, systematic errors are not completely ruled out, but if they are, the Hubble tension could indicate new physics. Many proposals have been made, including early dark energy episodes, additional relativistic species, and decaying dark matter. Some researchers have also explored modified gravity interactions between dark matter and dark energy [20, 21].

Resolving the Hubble tension is a major goal for next-generation observational programs. JWST continues to provide improved calibrations for Cepheids. The upcoming Nancy Grace Roman Space Telescope will yield high-resolution infrared data for thousands of SNe Ia. Meanwhile, experiments like CMB-S4 and the Simons Observatory aim to refine CMB measurements with increased precision [12, 22].

Combining many independent approaches, such as baryon acoustic oscillations (BAO) and gravitational wave standard sirens, will provide additional cross-checks, since a convergent value of H_0 from these methods will help confirm whether the tension signals new physics or a deeper understanding of existing data [19].

4. Importance

Understanding and determining H_0 is a highly valued goal in modern cosmology as it quantifies the current rate of expansion of the universe, a value that fundamentally shapes our understanding of the nature of the universe.

4.1. Scientific and Technological Impact

The push to measure H_0 with increasing precision has driven major advances in observational astronomy and data analysis techniques. Tools such as the Hubble Space Telescope, the Gaia mission, the Planck satellite, and advanced ground-based observatories have all been adapted to gather data. These technologies also have direct applications in other fields, improved imaging and data processing developed for analysing CMB data have led to better remote sensing and medical imaging technologies. For example, Wiener filtering has been used to suppress noise and reconstruct remote sensing images. Research has shown that Wiener filtering performs well in CMB data analysis, effectively reducing noise and improving image quality. In remote sensing, techniques such as maximum entropy reconstruction and Wiener filtering—first refined in cosmic microwave background analysis—have enhanced satellite-based Earth observation, enabling higher-resolution monitoring of climate-related features, such as sea surface temperatures and vegetation indices. In medical imaging, algorithms originally used in astrophysical image reconstruction have improved Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI). Specifically, the use of reconstruction techniques from astronomical image processing has resulted in clearer, more accurate images in low-dose CT scans, reducing radiation exposure for patients while keeping the quality of scans [23-25, 31].

Furthermore, debates on the Hubble tension have encouraged theoretical innovation, such as models involving early dark energy and modifications to general relativity. These debates also link directly to broader discussions about the completeness of the Λ CDM model [20].

4.2. Societal and Cultural Impact

Understanding the expansion of the universe is linked to many philosophical questions, such as the origin of humanity and the ultimate fate of the universe. These questions concern the origin, meaning, and destiny of humanity. For many people, exploring the vastness of the cosmos represents a source of humility and curiosity, encouraging reflection on humanity's place in the universe. This inspires public interest in space exploration and cosmological discovery, bringing together a community that values critical thinking and long-term perspectives. Questions about the beginning and end of the universe resonate across many cultures, which brings diverse perspectives on the relationship between science and philosophy. The social impact is seen in the growth of science communication, public lectures, documentaries, and educational outreach programs, making complex ideas accessible to the public [8].

Furthermore, investment in astronomical infrastructure and international collaborations, such as NASA and observatories around the world, fosters global cooperation and drives technological development. The economic returns of such large-scale science initiatives also result in more applications and high-skill employment [26].

4.3. Future Implications

As precision improves, the Hubble tension may either be resolved within the existing Λ CDM model or signal the need for fundamental changes, such as invoking early dark energy or modifications to gravity at cosmological scales. The ability to find out the reason behind the Hubble tension depends heavily on the next generation of observational instruments [12].

The JWST, with its unprecedented sensitivity in infrared radiation, enables precise photometry of Cepheid variables and supernovae in distant galaxies, allowing for better calibration in the distance ladder. It also helps to probe earlier epochs of galaxy formation, which can potentially find systematic

effects that influence local measurements of H_0 . The Vera C. Rubin Observatory will carry out the Legacy Survey of Space and Time (LSST), a large imaging survey that will detect millions of SNe Ia and help reduce statistical uncertainties in distance measurements [12, 27].

For the CMB, future experiments such as the Simons Observatory, CMB-S4, and the LiteBIRD mission will improve measurements of temperature values of the CMB with higher sensitivity and resolution. Complementary data from large-scale structure surveys will also help cross-check expansion history and CMB values through baryon acoustic oscillations (BAO), gravitational lensing, and galaxy clustering [28, 29, 30].

Beyond cosmology, these technologies often have ripple effects across science and society. Innovations in other fields, including cryogenics, radiation-hardened detectors, low-noise electronics, and precision mechanics, benefit medical imaging (PET and MRI). Data analysis methods developed especially for astronomical datasets have influenced tools used in climate modelling, epidemiology, and finance [24, 26, 31].

5. Conclusion

The persistent discrepancy between these methods suggests that there may be unknown physics beyond the current standard cosmological model. This has emphasized how well-established scientific quantities can be the subject of active debate and research that pushes the boundaries of our cosmological knowledge.

In general, the effort to measure H_0 and resolve the Hubble tension extends beyond technical expertise in cosmology. It represents an important area of scientific debate that pushes the boundaries of human understanding of the universe. Accurately determining H_0 is not only about refining measurements and improving instruments; it also challenges our fundamental models of cosmology. This pursuit reflects humanity's curiosity to understand the fate of the universe. Each new insight into the Hubble tension has the potential to reshape how humans view the cosmos.

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