Hubble's Law and the Hubble Tension: A Brief Overview

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In 1929, Edwin Hubble released a paper that may have been the most disruptive of its time; rivaling even Einstein's 1916 paper outlining general relativity paper. The paper, titled "A relation between distance and radial velocity among extra-galactic nebulae," presented evidence that the Universe was expanding. In this data, Hubble laid the groundwork for acceptance of Georges Lemaître's Big Bang Theory and development of present-day λCDM cosmology, the latter of which uses Hubble's findings as one of its four main observational pillars (Bahcall 2015).

In Hubble's original paper, he utilizes a data set of 24 "extra-galactic nebulae" (which we now know to be other galaxies) for which reasonable distance estimates could be obtained with the information available to him at Mt. Wilson Observatory, and for which radial velocity measurements existed in the literature. Distance estimates where obtained through a few different means. In general, they all use a "standard candle" method for obtaining distances. This method tells us that if we know the actual brightness of a given star in a galaxy, we can measure the apparent magnitude and use the difference in brightness to calculate the distance via the distance modulus equation.

$$m - M = 5log_{10}(\frac{d}{10})$$

Where m is the observed (apparent) magnitude, M is the absolute magnitude, and d is the distance to the star in parsecs. The primary standard candles used where Cepheid Variable stars, which have absolute magnitudes that can be determined via Leavitt's Law, and "novae," which are now referred to as type-1a supernovae and all effectively have the same absolute magnitude.

The radial velocities, which Hubble pulled from existing literature, were obtained using spectrometry and redshift. The cosmological redshift of an object expanding away from us can be measured as a change in the locations of known emission lines on it's observed spectrum. This redshift can then be converted into an effective radial velocity using the Doppler shift equation.

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda_{known}}$$

Where v is the radial velocity, c is the speed of light, $\Delta\lambda$ is the change in line location, and λ_{known} is the known location of the line with zero redshift.

The primary and most significant result of Hubble's paper is the Hubble Diagram, a plot showing clearly the correlation between distance from Earth and radial velocity of the 24 galaxies studied.

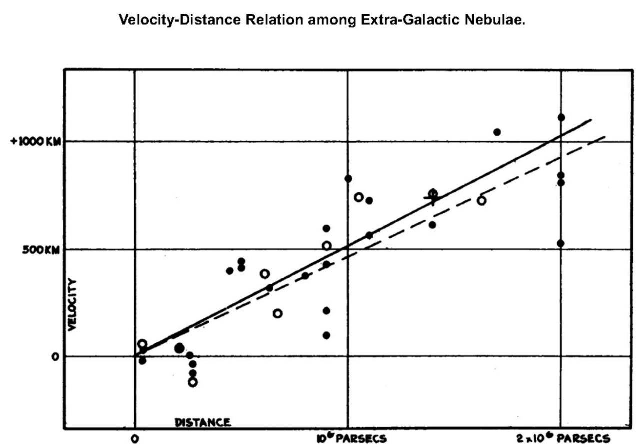

Figure 1: The original Hubble Diagram from Hubble 1929.

Hubble understood the incredible significance of these results. So much so that he refrained from explicitly referencing the expanding universe in his initial paper, saying, "it is thought premature to discuss in detail the obvious consequences of the present results (Hubble 1929)."

In the decades since Hubble's first publication, new methods for determining H_0 have been created. Additionally, Hubble's original methods have been built on and improved. As is common in the history of astronomy, better observational technology and a better distance ladder have greatly reduced the errors in all these measurements. While reduced error is generally a good thing in science, it has posed a new and serious issue in the determination of H_0 , the Hubble Tension. The three primary methods for obtaining a Hubble Constant, outlined below, have begun to yield different values with no statistical overlap.

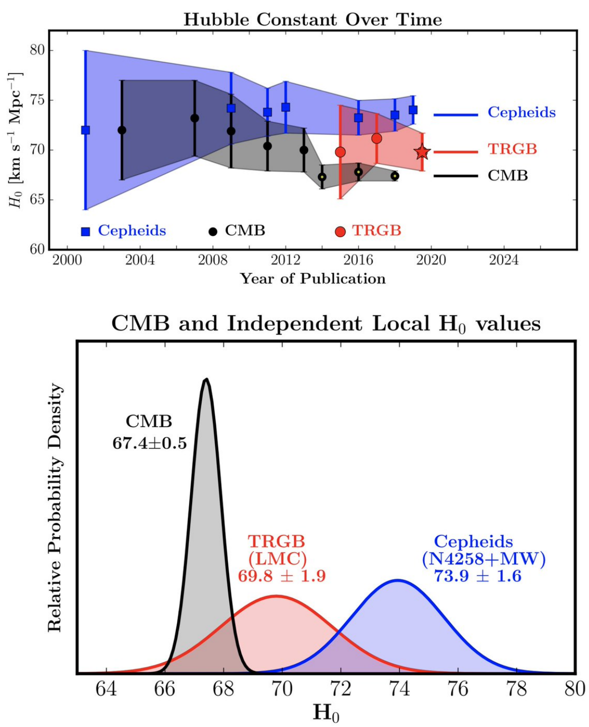

Figure 2: Two useful visual representations of the Hubble Tension, taken from Freedman et al. 2019

The most recently published[1] value for H_0 using the same standard candle/distance ladder method originally used by Hubble can be found in Riess et al. 2019. This paper focuses on reducing error in previous estimates with new observations of some 70 Cepheid Variable stars in the Large Magellanic Cloud. The LMC is a dwarf galaxy and relatively very close to our Solar System, so close that its distance can be determined geometrically

[1]An even more recently obtained, but not yet published, value will be discussed later.

via parallax observations. With a separate independent method of obtaining distance, Riess et al. 2019 works to fine-tune the period-luminosity relationship of Cepheids as described by Leavitt's law. Reducing the error on the absolute magintudes of standard candles serves to further reduce the error on the H_0 estimate. Redoing the H_0 estimate with this improved data, Riess et al. 2019 finds a final value of $H_0 = 74.03 \pm 1.42 \frac{km}{s(Mpc)}$, an error of $\sim 1\%$.

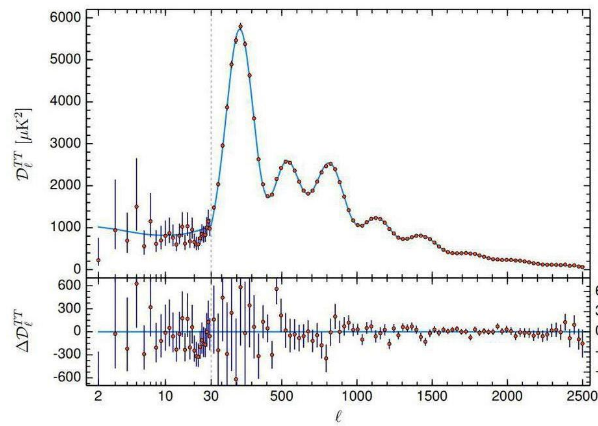

Figure 3: An angular power spectrum of the CMB, taken from Planck Collaboration et al. 2020.

A newer method of determining H_0 uses the Cosmic Microwave Background (CMB). The CMB was discovered accidentally in 1963, and is the barrier past which we cannot observe light. The CMB was emitted at the last moment before the Universe turned from opaque to transparent after the big bang–the "surface of last scattering." While the CMB is largely homogeneous in temperature, there exist local anisotropies. Fig. 3 shows a temperature power spectrum representing the fluctuations. Using the state-of-the-art Planck Satellite, the authors of Planck Collaboration et al. 2020 are able to take high-quality measurements of the anisotropy, and model it according to λCDM cosmology. There are several parameters involved in fitting this model, including H_0 and the relative amounts of normal matter, radiation and dark matter in the Universe. By finding the model that best fits the data, the Planck group is able to obtain $H_0 = 67.4 \pm 0.5 \frac{km}{s(Mpc)}$.

In an attempt to further probe the Hubble Tension, the authors of Freedman et al. 2019

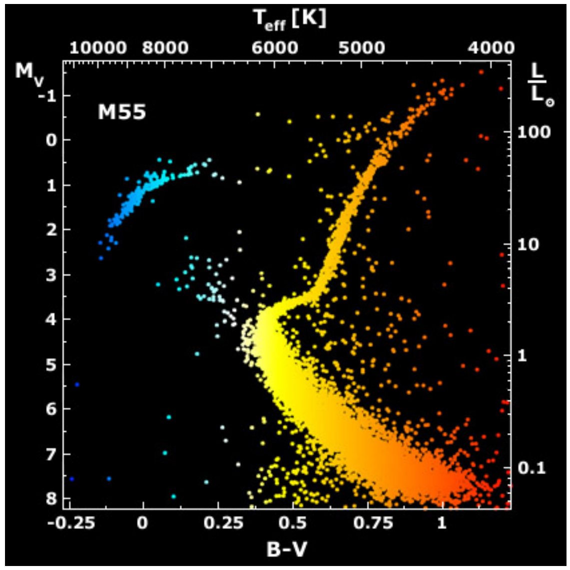

Figure 4: An example HR diagram of Globular Cluster M55, the tip of the red giant branch can be seen in the upper right. (*APOD: M55 Color Magnitude Diagram* 2001)

presented a new method for obtaining H_0 . This method is very similar to but independent from the Cepheid method outlined above. Instead of relying on Cepheid variable stars to build a distance ladder, the group uses Red Giant stars at a point in their evolution where they are about to start fusing helium instead of hydrogen. These stars are said to exist at the "tip of the red giant branch" because of their apparent position on a Hertzsprung Russell diagram (see Fig. 4). Using this version of the distance ladder, Freedman et al. 2019 finds $H_0 = 69.8 \pm 0.8(\pm 1.1\% stat) \pm 1.7(\pm 2.4\% sys)\frac{km}{s(Mpc)}$. This value sits right in between the values obtained via Cepheid Variable stars and the CMB, only further confusing the issue of the Hubble Tension.

As of May 24, 2021, a new paper has recently been submitted to the arXiv claiming to solve (at least in part) the Hubble Tension. This paper, Mortsell et al. 2021, builds upon the results of Riess et al. 2019. The group applies a more dynamic approach to dealing with reddening when measuring the magnitude of the calibrating Cepheid variable stars. In doing so, they are able to recalibrate the distance ladder used, and obtain a value of $H_0 = 66.9 \pm 2.5\frac{km}{s(Mpc)}$, well within agreement of the current CMB-obtained value.

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