

Deconstructing Hubble (1929)

A PHYSDepot Scavenger Hunt

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1 Introduction

Edwin Hubble’s 1929 paper, “*A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae*,” is widely regarded as one of the most important astronomical papers of the 20th century. Prior to this publication, the state of the field was in deep transition. Just a few years earlier, the “Great Debate” of 1920 between Harlow Shapley and Heber Curtis had questioned whether the Milky Way was the entire universe or if other “island universes” existed [18]. Hubble settled this in 1925 by identifying Cepheid variable stars in the Andromeda nebula, proving it was far outside our galaxy [7]. Meanwhile, Vesto Slipher had spent the 1910s carefully measuring the spectra of these spiral nebulae, discovering that most were highly redshifted (moving away from us) [17].

Hubble’s 1929 paper merged these two domains: he used absolute-luminosity criteria of stars (like Cepheids) to estimate the distances to these nebulae [6], and compared them to their radial velocities. The result was a roughly linear correlation [6]: the further away a galaxy was, the faster it appeared to be receding. This empirical relationship became known as Hubble’s law, and the slope correction factor K he calculates eventually ends up being known as the Hubble Constant (now Hubble *Parameter*) H_0 .

Upon publication, the paper revolutionized cosmology (although modern evaluations of the Hubble Parameter and the Hubble Tension came later). It provided the observational foundation for the expanding universe, shifting the scientific consensus away from a static universe. Hubble, however, does not make any definitive claim that the universe is expanding in this paper. The reception of this paper was paradigm-shifting, famously prompting Albert Einstein to abandon his “cosmological constant” (which he had introduced to force a static universe in General Relativity; There is a funny story involved here too, and I recommend you look into it if you’re curious). However, the paper is famously deeply flawed by modern standards. For this scavenger hunt, this guide outlines both the “obvious” surface-level problems and the hidden historical quirks and deeper problems that make this paper a fascinating case study in how right answers can sometimes emerge from flawed data.

2 The Paper Itself

1. The Paper’s Summary

In this paper, Hubble uses observations and calibrations of Cepheid variable stars to calculate brightness of extragalactic nebulae (magnitudes) [6]. Using data of 46 extragalactic nebulae that have radial velocities, Hubble filters down to 24 since he needs distance values too, and he only had estimated distances for those 24 [6].

Now, we are moving. The most important factor is that our Sun (and the general Solar System) is moving through the galaxy. As such, the radial velocities of the 24 galaxies Hubble is using will have some correction based on solar motion. He gives this in the equation [6]:

$$rK + X \cos(\alpha) \cos(\delta) + Y \sin(\alpha) \cos(\delta) + Z \sin(\delta) = v. \quad (1)$$

Here v is the velocity. The terms involving X , Y , and Z , as well as α and δ take into account the location of the nebulae (Right Ascension α and Declination δ) plus our motion to account for the solar motion's effect on the radial velocities v of the galaxy we are calculating.

This is the important theoretical step. Technically speaking, the solar motion should account for *all* of the peculiar motion of the velocities, but it doesn't. We seem to notice that nebulae farther away from us seem to have much higher velocities than we'd expect, which gives context to why this radial term rK arises.

In this paper, Hubble calculates the linear correlation term K that represents how much faster a nebula is moving radially compared to its distance. After plotting the data in his Figure 1, he calculates a value $K = 500 \text{ km/s/Mpc}$ [6].

He then states how his linear relationship seems to work well with modern data coming out for NGC 7619, and then he concludes this short paper by not making any explicit claims but briefly discussing the impacts of his result to general cosmology.

2. An Aside on Terminology and Context

There are a few things that are important to note to properly contextualize this paper.

1. **Nebulae:** By "nebulae" throughout this paper (specifically "extragalactic nebulae"), Hubble means galaxies. At this time, the concept of objects outside our galaxy is just starting to be realized (partially by Hubble himself in 1926 with his Tuning Fork galaxy classification paper [8]), and the concepts of these objects being galaxies were just starting to become prominent. As such, even if Hubble was partially responsible for realizing that these are galaxies, the terminology still tended to be nebulae.
2. **Observing:** It is important to note that this is 1929. All observations at this time are in the visual spectrum only. Astronomy was not in the period where we were observing radio waves, infrared observations, X-ray data, UV, and more. It was all visual. For context/reference, we are around the time period where Michelson builds the first functional interferometer to measure the size of the star Betelgeuse [13], which he did in 1921 (eight years prior to this paper). So if you are thinking that "why didn't he just wait for more data?", or something along those lines, there was still a massive gap in what was possible to do at this time. There were no wavelengths observable outside the visible spectrum, there was no such thing as a CCD camera (they were still using things like photographic plates), and there definitely wasn't any sort of space-based telescope. There's much more you could talk about this, but I think this is sufficient to get the point across: there was really only so much data Hubble had at his disposal at the time.

3 The Surface-Level Problems

1. The 9 Groups and the 24 Objects

Hubble doesn't just do his analysis only on the 24 objects that have both radial velocities and distances (which is already a pretty small sample size), but also he splits the data into nine groups based on proximity in distance and direction [6]. This definition of nine groups, however, is unknown. It's possible with a deeper look, you could find out what these nine groups are but it's not clear. Maybe he just looked at the sky and said "these are close enough so let's group them together", and it's likely nebulae near Virgo would likely be grouped in one group? Also he does analysis on the nine groups and compares the parameters to the 24 objects. It's clear how he would calculate a value like K across 24 objects, but how is he calculating it across nine groups? Are they combined later in some way? Is K calculated individually per group then weighted? Well, we don't know.

2. Poor Error Analysis

For most people reading, it is clear the error analysis from this paper is poor. It's not necessarily poor because it's wrong, it's poor because it's unclear. How is he propagating his error? Does he state all his sources of error? Some of these errors seem appreciable, how does that impact his results? His main figure also has no error bars on it, why not?

3. The NGC 7619 Calculation

He calculates the distance with his relation to NGC 7619 and states that he gets close to the distance derived from preliminary observational data of NGC 7619. Why does he choose this one? Why doesn't he look at other systems? Was this the only one that worked? Does this one just happen to be right? It feels strange that he would only do this for one single nebula. What about the distances of the galaxies that we don't know very well that he excluded from his subset?

4. The Hubble Time Paradox

Hubble makes no claims about universal expansion necessarily in this paper, so we can't fault him too much for this. We also can't fault him completely because not all of these concepts were solidified when he was writing this paper. But, in any case, we can take a simplified view of the universe: assume it has been expanding, and at a constant rate. Then, by the Big Bang model of the universe, all the galaxies must've been at one point and expanded at a constant rate to their modern day distances and recession velocities. If this rate is constant (Hubble's K), then the reciprocal of this constant should be able to estimate the age of the Universe, which is now known as the Hubble Time. If this is confusing, think about if you never moved at all, but the ground beneath you propelled you forward through expansion at, say, 1 m/s per year. Then if you know that you are now moving at 5 m/s, then you know you have been expanding for five years. That's the simplified core concept of the Hubble Time. The problem then? Well this what you get if you use Hubble's calculated K value of 500 km/s/Mpc:

$$t_{\text{Univ}} = 1/K = \frac{1}{(500 \text{ km/s/Mpc})(3.2408 \times 10^{-20} \text{ Mpc/km})} \frac{1}{(60 \times 60 \times 24 \times 365.25) \text{ s/yr}} \approx 2 \text{ Gyr.} \quad (2)$$

This means with Hubble's value, we estimate the age of the Universe to be about two billion years... That's kind of bad if you know our Solar System is 4.5 billion years old. Again, you can't fault him too much for this, but the reason I bring this up is because it'll become pertinent later.

5. Where are Slipher's Velocities?

Hubble states that he has the radial velocities of 46 extra-galactic nebulae [6]. But he does not explicitly credit Vesto Slipher in the text for the vast majority of these measurements, despite Slipher spending years doing the grueling telescope work to get these redshifts. Hubble explicitly credits his Mount Wilson colleague Milton Humason for new determinations [6], but glosses over the foundational velocity data he borrowed to make his plot.

6. Poor Strömberg's PhD and His "Work"

Hubble acknowledges Gustaf Strömberg for checking the general order of these values for different groupings of the data [6]. What this mean exactly? Who knows. Who knows what Strömberg checked, what that ended up being, and more.

Also, Gustaf Strömberg received his PhD in 1916 and had been in the United States since 1922, and yet Hubble still calls him "Mr. Strömberg" [6]. That was fine for Milton Humason, who never attained a PhD, but it was not fair to Strömberg to not be called "Dr." despite having his PhD for a decade and having likely worked with Hubble for a while by this point.

4 The Deeper Problems

1. The Missing Scatter: Lundmark's 1924 Paper

Hubble notes that 46 velocities were available, but he only used 24 for his individual distance estimates [6]. He selected these because they had the "most reliable" distances.

But, about five years earlier in 1924, Swedish astronomer Knut Lundmark published a very similar analysis using 44 galaxies [12]. Because Lundmark included more data points, some with higher uncertainties

in distances, his plot looked more scattered. The linear correlation was less statistically convincing. Hubble’s “clean” linear relation (Figure 1 in his paper) was heavily dependent on his selective exclusion of the noisier data. If you plot all the data available in 1929, his correlation becomes less clear, and without error bars, it becomes less clear which way the slope should point. This is shown in Figure 1.

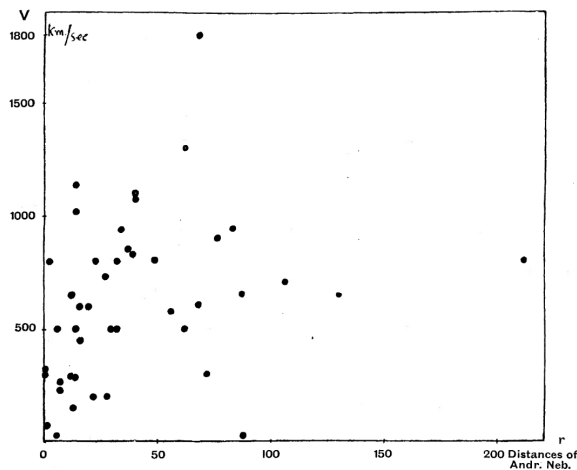


Figure 1: Lundmark’s 1924 plot of the relationship between the relative distances (in units of the distance to the Andromeda galaxy) and the measured radial velocities of 44 spiral nebulae [12]. We can see that Hubble’s clean linear relationship doesn’t seem as apparent here, and this was before his paper!

2. Lemaître Already Did It!

In 1927, two years prior to Hubble’s paper, Georges Lemaître had already done this calculation. He actually did the theory and the math, and utilized 42 nebulae from Hubble and Strömberg themselves to calculate the same correction term K as Hubble does here [11]. He finds a value of $K = 625 \text{ km/s/Mpc}$ [11]. This runs into some of the same issues with Hubble’s earlier, but the point was that Hubble’s calculation was already done two years prior to him doing it! While all speculative, the main suggestion is that since Lemaître did this in France, it is likely that Hubble did not even know this paper existed. If you’d like an interesting read about this tension between Hubble and Lemaître’s calculations and what caused this, I recommend “Georges Lemaître and Stigler’s Law of Eponymy” by David Block [3]. The data Lemaître used, modernized, is shown in Figure 2.

Another cool thing to investigate is the correlation values regarding Hubble and Lemaître’s data, which we should in Figure 3.

3. The Calibration Catastrophe of Cepheids

Hubble’s distances depended upon the application of absolute-luminosity criteria to involved stars including Cepheid variables [6]. Cepheid variable stars are stars that pulsate radially, changing their diameter, temperature, and brightness over some regular period.

The problem: Hubble’s zero-point calibration for the Cepheid period-luminosity relation was fundamentally wrong. He was completely unaware that there are two different types of Cepheid variables: Classical Cepheids (Population I, younger and brighter), and W Virginis stars (Population II, older and dimmer). This was discovered in the 1950s by Walter Baade [1]. Hubble unknowingly used the calibration for the dimmer Population II stars (derived from globular clusters by Harlow Shapley [16]) but was actually observing the brighter Population I stars in the distant spiral arms. This meant his assumed absolute magnitudes were wrong, causing him to underestimate the distances to all galaxies (by roughly a factor of 7)! A modern view of this is shown in Figure 4.

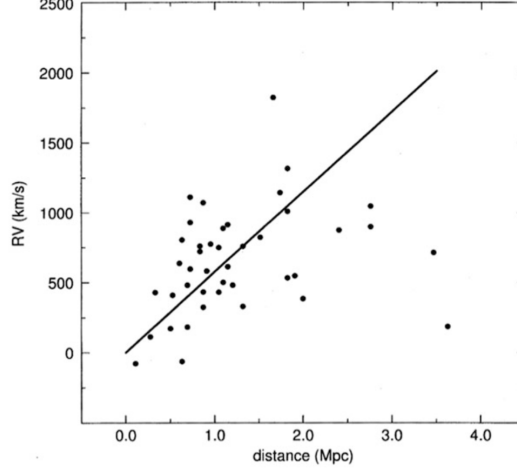


Figure 2: The observational data used by Lemaître and the line fitting of best fit, modernized, used to calculate Lemaître’s constant K two years prior to Hubble’s paper [3].

Correlation

Lemaître : $r = 0.38 \pm 0.15$

Correlation coefficient example: Hubble Constant

Hubble : $r = 0.79 \pm 0.13$

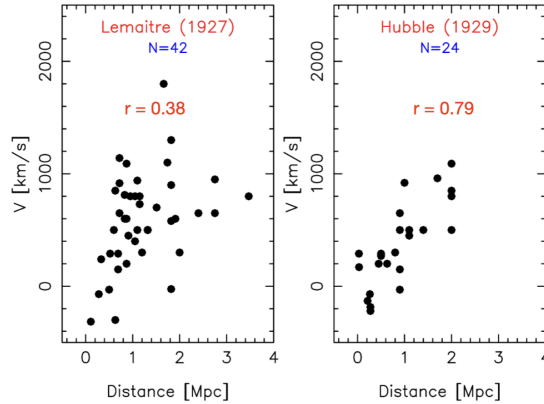


Figure 3: A comparison of Lemaître and Hubble’s data with correlation values r [4]. We can see clearly that Hubble’s selected sample yields a much better correlation of $r = 0.79$ compared to Lemaître’s data of $r = 0.38$, and we can see how Lemaître likely got a higher K value than Hubble. Using Markov Chain Monte Carlo methods (MCMC) on the r values, we can also see how there is little overlap between their correlations, and that Hubble’s correlation is significantly “stronger” than Lemaître’s.

4. Mistaking HII Regions for “Brightest Stars”

For galaxies too far away to resolve Cepheids, Hubble relied on an approximately uniform upper limit to the absolute luminosity of stars on the order of $M(\text{photographic}) = -6.3$ [6]. However, in the more distance galaxies, what Hubble thought were incredibly bright blue stars were actually entire HII regions (giant glowing clouds of ionized gas and star cluster) [10]. By confusing whole clusters with single stars, he vastly underestimated the distance to these further galaxies. Miraculously, this error compounded with his Cepheid error in just the right way to keep his plot relatively straight, albeit with a wildly incorrect slope. We will talk more later about what happens if you fix his distance and luminosity calibrations and recalculate the slope.

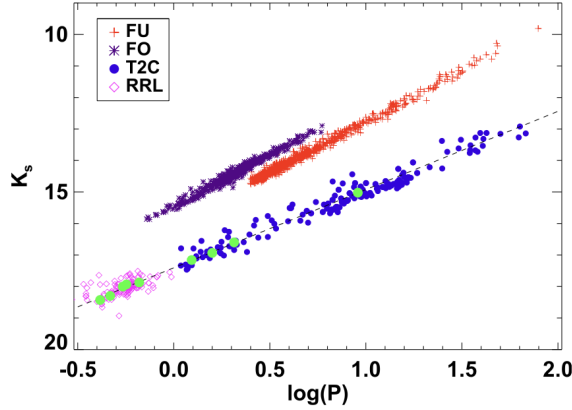


Figure 4: A plot that helps illustrate the two types of Cepheid stars based on their period-luminosity relationship (here the y -axis is the so-called K_s -band magnitude/luminosity and the x -axis is the period) [2]. The purple star FO points represent the classical Population I Cepheids, while the red plus FU points represent the W Virginis Cepheids. If you are mangled between them by using both, it will inherently mess up your period-luminosity relations, that will propagate through everything else you calculate, which is exactly what happened to Hubble for years.

5. The Local Group and Peculiar Velocities

Hubble includes very nearby galaxies in his fit, like M31 and M32 [6]. At such close distances, gravitational bound motions (peculiar velocities) dominate over the cosmological expansion [19]. For example, Andromeda is actually moving *towards* the Milky Way. Hubble was trying to extract a cosmological expansion law from local galaxies where the expansion is barely measurable against local gravitational noise. He notes that NGC 404 has a peculiar motion large in comparison to the distance effect [6], but failed to realize how heavily peculiar motions contaminated his entire low-distance sample.

5 The Real Great Coincidence and Future Focus

1. Sandage and Co. Find The “Truth”

So, we discussed how Baade helped discover the two types of Cepheids [1]. Humason (alongside Allan Sandage) helped resolve the distance issue in HII regions in 1956 [10]. After adjusting Hubble’s errors for both of these, Sandage himself recalculated the K value for the slope of the velocity-distance plot, yielding the first reasonable accurate measurement of the Hubble constant at 75 km/s/Mpc [15], which is close to modern estimates.

I find this to be the real “Great Coincidence” of astronomy (typically astronomers consider the concept of a total solar eclipse the great coincidence; We get total solar eclipses because the Sun and Moon happen to be the exact same angular size in the sky, and happen to eclipse in such a fashion to cause solar eclipses). This is a huge coincidence because adjusting Hubble’s calibrations yields a modern value of the Hubble constant. On top of that, remember the earlier discussion we had with the Hubble Time? Well with Sandage’s value, you get a Hubble time of about 14 billion years [15]. This value happens to be in agreement with modern values, like the Planck 2018 age of 13.8 billion years [14].

2. The Evolution of the Hubble Parameter and the Hubble Tension

You might have noticed I used “truth” (in quotes) in the last subsection. That’s because we don’t actually really know the true Hubble constant/Hubble parameter value, at least to good constraints. While the work of many astronomers have constrained the value to a sensible range, there’s still a disagreement on what the

actual value is. First, let's look at the evolution of the Hubble constant H_0 over time, shown in Figure 5. We show a closer inspection of the modern value in Figure 6.

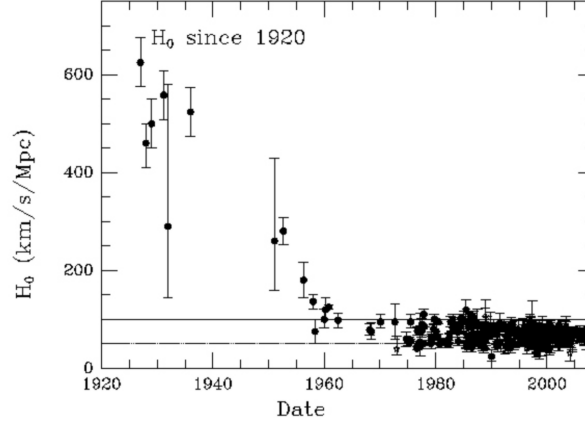


Figure 5: A figure of the evolution of H_0 over time as we started to better constrain the values with more modern measurements [9]. The first point on the far left is Lemaître's initial calculation of 625 km/s/Mpc. Around 1929 we can see Hubble's point (the third point) of 500 km/s/Mpc. Sandage's value of 75 km/s/Mpc is located in the exact center of the solid and dashed horizontal lines in 1958. Those lines represent the two "camps" who started disagreeing on the true value of H_0 of 50 km/s/Mpc and 100 km/s/Mpc. More importantly, we can see where all the modern values lie, especially within those two horizontal lines.

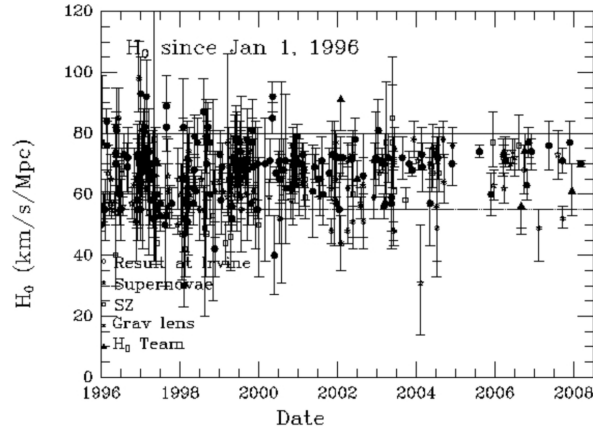


Figure 6: A closeup view of the Hubble constant H_0 over time compared to Figure 5. We will ignore the all the methods for measuring these values for now, but we can see that modern measurements have constrained this value much better, with H_0 falling near ~ 70 km/s/Mpc.

So, you might be asking, then what is this Hubble Tension? At surface level, it might seem that these values have some spread with big error bars, but that shouldn't be a problem as measurements get more precise, right? Well, not exactly. There are many ways to measure the Hubble constant, but let's look at a view of three ways to measure it: Cepheids (like how Hubble did it), the Tip of the Red Giant Branch (TRGB), and through cosmological Cosmic Microwave Background (CMB) measurements. I won't go into how each of these actually calculate H_0 , but just know these are three different, independent ways of measuring H_0 among many others. A graph of these ways of measuring H_0 over time is shown in Figure 7. We can see that different ways of measuring H_0 , even as they get more precise and error bars decrease continue to disagree on H_0 , meaning this is an interesting and active area of modern research too!

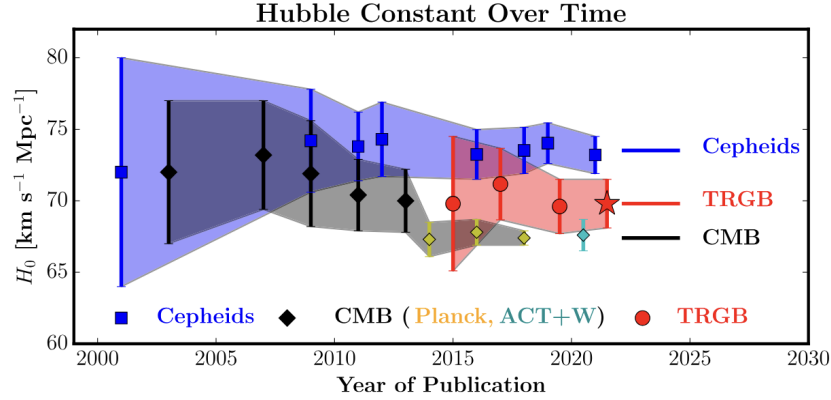


Figure 7: A graph of the Hubble constant over time based on three independent ways to measure it: Cepheids, CMB, and TRGB measurements [5]. We can clearly see the Hubble tension here, because even with error bars, the values don't agree. This is the crux of the Hubble tension issue: as measurements get more precise and error bars get smaller, different methods of calculating H_0 continue to disagree at a higher level. This graph is slightly out of date, and current measurements of the TRGB *agree* with Cepheids, but both still disagree with CMB measurements. The modern tension is stated to be 5σ , meaning that there's a 5σ disagreement between the methods.

6 Conclusion

I think it's best to keep the conclusions short so you all can form your own conclusions. But, I think Hubble's 1929 paper is a masterclass in how a scientist can be fundamentally wrong about their calibrations, selective with their data, mistake gas clouds for stars, completely miss the theoretical underpinning (Lemaître's 1927 expanding universe model derived from General Relativity), and *still* make one of the greatest discoveries in human history. I also hope you take away how you should and should not be writing your research papers, should you ever write one in the future.

7 References

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