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Cosmos Unveiled: The Hubble Constant

Measuring the Universe's Expansion

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Conclusion

This free sample contains the Introduction and Chapter 1. The complete book contains the full contents above.

Introduction

Hubble's law, officially the Hubble-Lemai tre law, is the observation in physical cosmology that galaxies are moving away from Earth at speeds proportional to their distance. Thus, the farther a galaxy is from the Earth, the faster it moves away. A galaxy's recessional velocity is typically determined by measuring its redshift, a shift in the frequency of light emitted by the galaxy.

The discovery of Hubble's law is attributed to work The Friedmann equations showed the universe might be expanding, and presented the expansion speed if that were the case. Before Hubble, astronomer Carl Wilhelm Wirtz had, in 1922 and 1924, deduced with his own data that galaxies that appeared smaller and dimmer had larger redshifts and thus that more distant galaxies recede faster from the observer.

In 1927, Georges Lemai tre concluded that the universe might be expanding by noting the proportionality of the recessional velocity of distant bodies to their respective distances. He estimated a value for this ratio, which - after Hubble confirmed cosmic expansion and determined a more precise value for it two years later - became known as the Hubble constant.

Hubble inferred the recession velocity of the objects from their redshifts, many of which were earlier measured and related to velocity by Vesto Slipher in 1917.

Combining Slipher's velocities with Henrietta Swan Leavitt's intergalactic distance calculations and methodology allowed Hubble to better calculate an expansion rate for the universe.

The discovery of Hubble's law is attributed to work published by Edwin Hubble in 1929, but the notion of the universe expanding at a calculable rate was first derived from general relativity equations in 1922 by Alexander Friedmann. Friedmann's mathematics had already shown expansion was possible and computed how fast it should run.

The "redshift velocity" vrs is not so simply related to real velocity at larger velocities, however, and this terminology leads to confusion if interpreted as a real velocity. Next, the connection between redshift or redshift velocity and recessional velocity is discussed.

If light is emitted from a galaxy at time te and received by us at t0, the light has been stretched by cosmic expansion, and its redshift is defined as:

Suppose a galaxy is at distance D, and this distance changes with time at a rate dtD.

We call this rate of recession the "recession velocity" vr:

Though the Hubble constant H0 is constant at any given moment in time, the Hubble parameter H, of which the Hubble constant is the current value, varies with time, so the term constant is sometimes thought of as somewhat of a misnomer. The units of the Hubble constant are km/s/Mpc, which gives the speed of a galaxy 1 megaparsec (3.09 x 1019 km) away as 70 km/s.

The reciprocal of H0 is the Hubble time (14.4 billion years).

The Hubble constant can also be stated as a relative rate of expansion. In this form H0 = 7%/Gyr, meaning that, at the current rate of expansion, it takes one billion years for an unbound structure to grow by 7%. A decade before Hubble made his observations, a number of physicists and mathematicians had established a consistent theory of an expanding universe by using Einstein field equations of general relativity.

Applying the most general principles to the nature of the universe yielded a dynamic solution that conflicted with the then-prevalent notion of a static universe. In 1912, Vesto M. Slipher measured the first Doppler shift of a "spiral nebula" (the obsolete term for spiral galaxies) and soon discovered that almost all such objects were receding from Earth.

He did not grasp the cosmological implications of this fact, and indeed at the time it was highly controversial whether or not these nebulae were "island universes" outside the Milky Way galaxy. In 1922, Alexander Friedmann derived his Friedmann equations from Einstein field equations, showing that the universe might expand at a rate calculable by the equations.

The parameter used by Friedmann is known today as the scale factor and can be considered as a scale invariant form of the proportionality constant of Hubble's law.

Georges Lemai tre independently found a similar solution in his 1927 paper discussed in the following section. The Friedmann equations are derived by inserting the metric for a homogeneous and isotropic universe into Einstein's field equations for a fluid with a given density and pressure. This idea of an expanding spacetime would eventually lead to the Big Bang and Steady State theories of cosmology.

In 1927, two years before Hubble published his own article, the Belgian priest and astronomer Georges Lemai tre was the first to publish research deriving what is now known as Hubble's law. According to the Canadian astronomer Sidney van den Bergh, "the 1927 discovery of the expansion of the universe by Lemai tre was published in French in a low-impact journal.

In the 1931 high-impact English translation of Lemai tre's 1927 paper, a critical equation was changed by omitting reference to what is now known as the Hubble constant." It is now known that the alterations in the translated paper were carried out by Lemai tre himself. Before the advent of modern cosmology, there was considerable talk about the size and shape of the universe.

In 1920, the Shapley-Curtis debate took place between Harlow Shapley and Heber D. Curtis over this issue.

Shapley argued for a small universe the size of the Milky Way galaxy, and Curtis argued that the universe was much larger. The issue was resolved in the following decade with Hubble's improved observations. Edwin Hubble did most of his professional astronomical observing work at Mount Wilson Observatory, home to the world's most powerful telescope at the time.

His observations of Cepheid variable stars in "spiral nebulae" enabled him to calculate the distances to these objects.

Surprisingly, these objects were discovered to be at distances which placed them well outside the Milky Way. They continued to be called nebulae, and it was only gradually that the term galaxies replaced it. The velocities and distances that appear in Hubble's law are not directly measured. The velocities are inferred from the redshift z = Delta lambda /lambda of radiation and distance is inferred from brightness.

Hubble sought to correlate brightness with parameter z.

Combining his measurements of galaxy distances with Vesto Slipher and Milton Humason's measurements of the redshifts associated with the galaxies, Hubble discovered a rough proportionality between redshift of an object and its distance.

Though there was considerable scatter (now known to be caused by peculiar velocities - the 'Hubble flow' is used to refer to the region of space far enough out that the recession velocity is larger than local peculiar velocities), Hubble was able to plot a trend line from the 46 galaxies he studied and obtain a value for the Hubble constant of 500 (km/s)/Mpc (much higher than the currently accepted value due to errors in his distance calibrations; see cosmic distance ladder for details).

From this perspective, Hubble's law is a fundamental relation between (i) the recessional velocity associated with the expansion of the universe and (ii) the distance to an object; the connection between redshift and distance is a crutch used to connect Hubble's law with observations.

This law can be related to redshift z approximately by making a Taylor series expansion:

If the distance is not too large, all other complications of the model become small corrections, and the time interval is simply the distance divided by the speed of light:

According to this approach, the relation cz = vr is an approximation valid at low redshifts, to be replaced by a relation at large redshifts that is model-dependent. Strictly speaking, neither v nor D in the formula are directly observable, because they are properties now of a galaxy, whereas our observations refer to the galaxy in the past, at the time that the light we currently see left it.

Another common source of confusion is that the accelerating universe does not imply that the Hubble parameter is actually increasing with time; since

From this it is seen that the Hubble parameter is decreasing with time, unless q < -1; the latter can only occur if the universe contains phantom energy, regarded as theoretically somewhat improbable.

However, in the standard Lambda cold dark matter model (Lambda-CDM or Lambda CDM model), q will tend to -1 from above in the distant future as the cosmological constant becomes increasingly dominant over matter; this implies that H will approach from above to a constant value of about 57 (km/s)/Mpc, and the scale factor of the universe will then grow exponentially in time.

The mathematical derivation of an idealized Hubble's law for a uniformly expanding universe is a fairly elementary theorem of geometry in 3-dimensional Cartesian/Newtonian coordinate space, which, considered as a metric space, is entirely homogeneous and isotropic (properties do not vary with location or direction).

An opening note concerns the number's origin, which the reader should meet as a personality. The constant was named for the astronomer who published the expansion's evidence, and the naming is the field's habit of compressing a history into a symbol; but the reader should know the fuller genealogy, that the relation was derived and published by others, that the redshift data came from the observers of the galaxies, and that the constant's true author, in the sense that matters, is the whole early-century community that measured redshifts, photographed galaxies, and argued about distances at the moment the universe was found to have a history. The number on the page is a team portrait in one symbol, and the chapters that follow are its biography.

Chapter 01: The Discovery of The Hubble Constant

The number this book is built around was born from a discrepancy nobody had asked for. In the years before 1929, Vesto Slipher at Lowell Observatory had already measured the light of several dozen spiral nebulae and found their spectra shifted overwhelmingly toward the red - as if nearly all of them were receding from us. The velocities were enormous by any stellar standard, but without reliable distances, the pattern could not be turned into a law.

Distance was Edwin Hubble's contribution. Working at Mount Wilson with Milton Humason, who had started at the observatory as a mule driver and janitor and ended up taking some of its most important spectra, Hubble paired

Slipher's velocities with distances derived from Cepheid variable stars and other markers. The 1929 paper plotted a couple dozen galaxies and found the straight line: the farther a galaxy, the faster it recedes. The slope of that line - velocity divided by distance - is the Hubble constant, though the phrase came later and the symbol H with a subscript zero later still.

The first published value was around 500 in the conventional units of kilometers per second per megaparsec, roughly eight times what we accept today. The error is forgivable: the Cepheid calibration of the era rested on a handful of stars in the Small Magellanic Cloud, misidentified in ways no one could yet detect, and the distances were underestimated almost uniformly. What mattered was the relation, not the slope.

The following two decades became a long argument about that slope. Hubble and Humason pushed their sample deeper and published declining values; Walter Baade's 1952 resolution of Cepheids into two populations doubled the cosmic distance scale overnight; and Allan Sandage, inheriting Hubble's program and his telescope time, spent thirty years driving the constant downward, to values that in hindsight were too small. For most of the twentieth century the honest summary of the field was a factor-of-two uncertainty, and the number acquired a reputation, in a long-running astronomy joke, as the one quantity whose reciprocal was known.

The discovery phase closed not with a single measurement but with a standardization of method. By the 1990s the argument had hardened into a well-posed problem: calibrate a ladder of distance indicators far enough that the recession law's slope could be read off cleanly, then argue about error bars. Everything in the later chapters of this book - the tension between competing answers, the pride of precision instruments and the discomfort of

disagreement - descends from that simple line of galaxies on a 1929 plot.

End of free sample. The full book is available at putrabooks.github.io

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.