

Hubble's Law and the expanding universe

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In one of the most famous classic papers in the annals of science, Edwin Hubble's 1929 PNAS article on the observed relation between distance and recession velocity of galaxies—the Hubble Law—unveiled the expanding universe and forever changed our understanding of the cosmos. It inaugurated the field of observational cosmology that has uncovered an amazingly vast universe that has been expanding and evolving for 14 billion years and contains dark matter, dark energy, and billions of galaxies.

It is difficult to imagine that only 90 years ago, we did not know about the existence of most of the universe around us. From today's perspective, the reality of a very large, old, expanding universe, filled with billions of galaxies that are receding from each other as the cosmic space expands from an initial "Big Bang" billions of years ago seems so obvious that we expect it must have been known for centuries. Not so. It was Edwin Hubble's seminal 1929 PNAS paper, "A relation between distance and radial velocity among extra-galactic nebulae" (1), that led to a turning point in our understanding of the universe. In his short paper, Hubble

presented the observational evidence for one of science's greatest discoveries—the expanding universe. Hubble showed that galaxies are receding away from us with a velocity that is proportional to their distance from us: more distant galaxies recede faster than nearby galaxies. Hubble's classic graph of the observed velocity vs. distance for nearby galaxies is presented in Fig. 1; this graph has become a scientific landmark that is regularly reproduced in astronomy textbooks. The graph reveals a linear relation between galaxy velocity (v) and its distance (d)

$$v = H_0 \cdot d,$$

This relation is the well-known Hubble Law (and its graphic representation is the Hubble Diagram). It indicates a constant expansion of the cosmos, where, like in an expanding raisin cake that swells in size, galaxies, like the raisins, recede from each other at a constant speed per unit distance, thus, more distant objects move faster than nearby ones. The slope of the relation, H_0 , is the Hubble Constant; it represents the constant rate of cosmic expansion caused by the stretching of space-time itself. Although

the expansion rate is constant in all directions at any given time, this rate changes with time throughout the life of the universe. When expressed as a function of cosmic time, $H(t)$, it is known as the Hubble Parameter. The expansion rate at the present time, H_0 , is about 70 km/s/Mpc (where 1 Mpc = 10^6 parsec = 3.26×10^6 light-y). The inverse of the Hubble Constant is the Hubble Time, $t_H = d/v = 1/H_0$; it reflects the time since a linear cosmic expansion has begun (extrapolating a linear Hubble Law back to time $t = 0$); it is thus related to the age of the Universe from the Big Bang to today. For the above value of H_0 , $t_H = 1/H_0 \sim 14$ billion years.

Hubble's remarkable observational relation was obtained using 24 nearby galaxies for which both measured velocities and distances were available. Most of the velocities were from the pioneering spectroscopic Doppler-shift observations by the famous astronomer Vesto Melvin Slipher (although no reference is given in Hubble's paper). The distances to these galaxies (an inaccurate determination in those days) had been measured by Hubble—with much greater accuracy than previously possible—from the apparent brightness of their stars and, for the four most distant galaxies in the sample, each located in the Virgo cluster (with recession velocity of $\sim 1,000$ km/s), from their galactic brightness. This method uses the stars (or galaxies) as "standard candles"; it compares their known intrinsic luminosity (known from similar well-calibrated nearby objects) with their observed apparent brightness to yield the distance to each object. The farther away the object, the dimmer it appears. Hubble distance determinations were sufficiently good to sort out the nearer galaxies from the farther ones well enough to be able to detect this astonishing linear relation. In addition to plotting all of the individual 24 galaxies in the graph, Hubble also "binned" them into nine groups

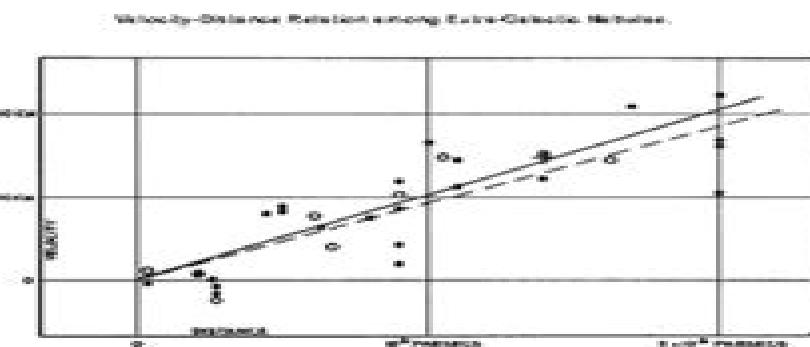


Fig. 1. The velocity-distance relation among extra-galactic nebulae (1). "Stellar velocities, corrected for solar motion, are plotted against distances estimated from measured stars and more from nebulae" (ref. 1) reflect in a cluster. The black dots and full line represents the relation for older galaxies using the nebulae individually; the circles and broken line represents the relation on reflecting the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 23 nebulae whose distances could not be estimated individually" (1). (Error: Velocity units should be in kilometers per second.)

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This article is part of the special series of PNAS 100th Anniversary Volume to celebrate the 100th anniversary of PNAS. Please see the accompanying "100 years between discovery and recognition: One centenary volume: A review between discovery and award: Reciting extra-galactic nebulae" on pages 2005 to 2015; "100 years: 15," and see also "Message" on page 2104.

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