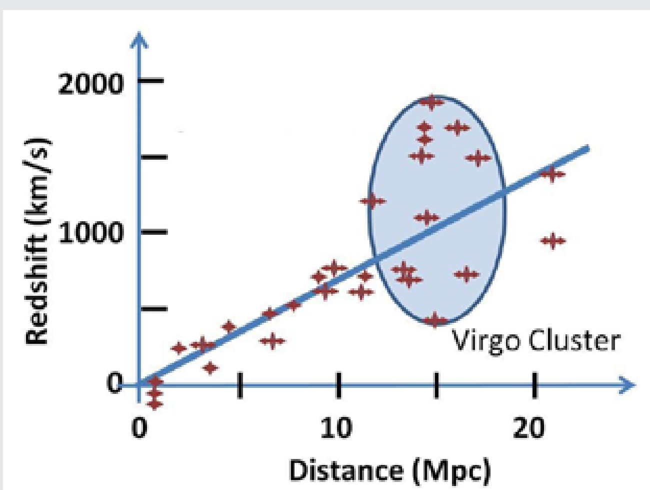
because if it did, the universe would not appear the same in all directions from any noncentral point.

Hubble's Law

American astronomer Edwin Hubble, who spent most of his life studying galaxies, examined the relationship between the velocity of recession and the distance away for many galaxies. In doing so, he discovered a linear relationship between the velocity and distance: *The farther away a galaxy is, the faster it is receding* (Figure 4-20). Hubble's law says that a galaxy's velocity of recession, v, is directly proportional to its distance from us, d. Hubble's law is often expressed as: $v = H_0 d$, where H_0 is known as the **Hubble constant**. It is difficult to determine an accurate value for the Hubble constant due to uncertainties in distance scales outside our own galaxy. There are multiple methods of determining the value of H_0, but most methods agree on a value approximately equal to 70 km/s/Mpc. In recently published research using different methods, researchers obtained values of H_0 equal to 74.03 ± 1.42 km/s/Mpc[109] and 69.8 ± 0.8 km/s/Mpc[110].

FIGURE 4-20[111]

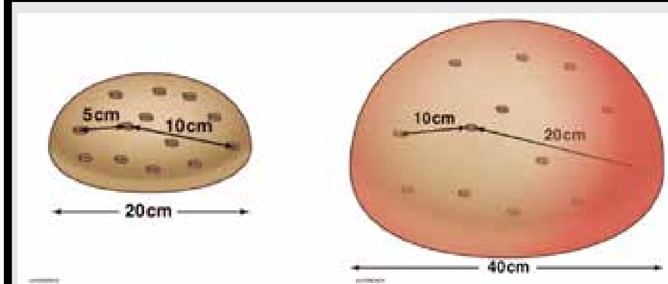


A plot of observed galactic redshift (i.e., rate of recession) versus distance from Earth. The slope of the line of best fit provides an estimate of Hubble's constant.

The Hubble constant is an important and fundamental quantity in cosmology—it gives the rate at which the galaxies are receding, or equivalently, the rate at which the universe is expanding. It also can be used in Hubble's law to determine the distance to galaxies based upon their observed redshifts. For example, if the observed redshift of a galaxy corresponds to a velocity of recession v = 700 km/s, and we approximate H_0 as 70 km/s/Mpc, then the galaxy's distance d from Earth in Mpc must be about 700 divided by 70, or 10 Mpc.

As an analogy for the expanding universe model, consider a loaf of raisin bread expanding as it bakes (Figure 4-21). As the dough expands, the raisins are pushed away from one other at speeds that are proportional to the distance between them. Two raisins that were originally close to each other are pushed apart slowly, but two raisins that were far apart, having more dough between them, are pushed apart faster. There are limitations to this analogy—the universe does not have an edge in the way that the loaf of bread has a crust, for instance—but it is useful for the purposes of illustration.

FIGURE 4-21[112]



Raisins in a baking loaf of bread accelerate away from one another in a similar fashion to galaxies in the expanding universe.

The Big Bang Theory

If we consider the expansion of the universe as a movie, we can imagine running the movie backward to the time at which all the matter and radiation of our present universe were packed together at a singular point. This was the state of the universe at the time of the **Big Bang**—a violent expansion event that marked the beginning of time and space as we know it. The Big Bang theory states that about 13.77 billion years ago our universe expanded rapidly from an infinitely hot, dense state, and it has been evolving ever since. At 10^{-43} seconds after the Big Bang, the temperature was 10^{32} K. The early universe was opaque, made of a nearly featureless hot, charged gas that emitted and trapped high energy photons of light. Expansion cooled the matter and photons of that early inferno. Within a few seconds, protons (hydrogen nuclei), neutrons, and electrons formed. Within minutes, deuterium (heavy