

For example, two positively charged particles experience a larger repulsive force at a short distance than at a long distance. In scattering experiments, the strength of an interaction depends on the energy of the interacting particle, since larger energy implies both closer and stronger interactions.

Particle physicists now suspect that the strength of all particle interactions (the four forces) merge at high energies, and the details of particle interactions at these energies can be described in terms of a single force (**Figure 11.17**). A unified theory describes what these interactions are like and explains why this description breaks down at low-energy scales. A grand unified theory is a theory that attempts to describe strong and electroweak interaction in terms of just one force. A theory of everything (TOE) takes the unification concept one step further. A TOE combines all four fundamental forces (including gravity) into one theory.

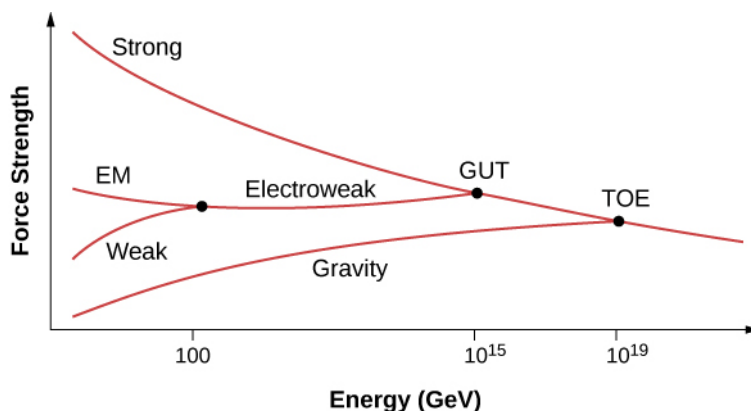


Figure 11.17 Grand unification of forces at high energies.

11.6 | The Big Bang

Learning Objectives

By the end of this section, you will be able to:

- Explain the expansion of the universe in terms of a Hubble graph and cosmological redshift
- Describe the analogy between cosmological expansion and an expanding balloon
- Use Hubble's law to make predictions about the measured speed of distant galaxies

We have been discussing elementary particles, which are some of the smallest things we can study. Now we are going to examine what we know about the universe, which is the biggest thing we can study. The link between these two topics is high energy: The study of particle interactions requires very high energies, and the highest energies we know about existed during the early evolution of the universe. Some physicists think that the unified force theories we described in the preceding section may actually have governed the behavior of the universe in its earliest moments.

Hubble's Law

In 1929, Edwin Hubble published one of the most important discoveries in modern astronomy. Hubble discovered that (1) galaxies appear to move away from Earth and (2) the velocity of recession (v) is proportional to the distance (d) of the galaxy from Earth. Both v and d can be determined using stellar light spectra. A best fit to the sample illustrative data is given in **Figure 11.18**. (Hubble's original plot had a considerable scatter but a general trend was still evident.)

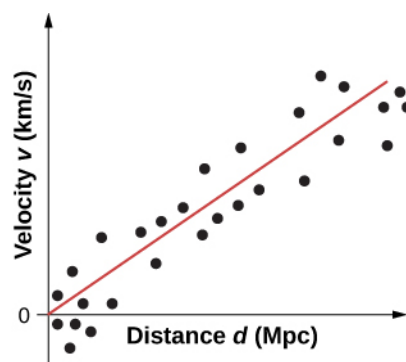


Figure 11.18 This graph of red shift versus distance for galaxies shows a linear relationship, with larger red shifts at greater distances, implying an expanding universe. The slope gives an approximate value for the expansion rate. (credit: John Cub)

The trend in the data suggests the simple proportional relationship:

$$v = H_0 d, \quad (11.12)$$

where $H_0 = 70 \text{ km/s/Mpc}$ is known as **Hubble's constant**. (Note: 1 Mpc is one megaparsec or one million parsecs, where one parsec is 3.26 light-years.) This relationship, called **Hubble's law**, states that distant stars and galaxies recede away from us at a speed of 70 km/s for every one megaparsec of distance from us. Hubble's constant corresponds to the slope of the line in **Figure 11.18**. Hubble's constant is a bit of a misnomer, because it varies with time. The value given here is only its value *today*.



Watch this **video** (<https://openstaxcollege.org/l/21hubble>) to learn more about the history of Hubble's constant.

Hubble's law describes an average behavior of all but the closest galaxies. For example, a galaxy 100 Mpc away (as determined by its size and brightness) typically moves away from us at a speed of

$$v = \left(\left(70 \frac{\text{km}}{\text{s}} \right) / \text{Mpc} \right) (100 \text{ Mpc}) = 7000 \text{ km/s}.$$

This speed may vary due to interactions with neighboring galaxies. Conversely, if a galaxy is found to be moving away from us at speed of 10,000 km/s based on its red shift, it is at a distance

$$d = v/H_0 = (10,000 \text{ km/s}) / \left(\left(70 \frac{\text{km}}{\text{s}} \right) / \text{Mpc} \right) = 143 \text{ Mpc}.$$

This last calculation is approximate because it assumes the expansion rate was the same 5 billion years ago as it is now.

Big Bang Model

Scientists who study the origin, evolution, and ultimate fate of the universe (**cosmology**) believe that the universe began in an explosion, called the **Big Bang**, approximately 13.7 billion years ago. This explosion was not an explosion of particles through space, like fireworks, but a rapid expansion of space itself. The distances and velocities of the outward-going stars and galaxies permit us to estimate when all matter in the universe was once together—at the beginning of time.

Scientists often explain the Big Bang expansion using an inflated-balloon model (**Figure 11.19**). Dots marked on the surface of the balloon represent galaxies, and the balloon skin represents four-dimensional space-time (**Relativity**). As the balloon is inflated, every dot “sees” the other dots moving away. This model yields two insights. First, the expansion is observed by all observers in the universe, no matter where they are located. The “center of expansion” does not exist, so Earth does not reside at the “privileged” center of the expansion (see **Exercise 11.24**).

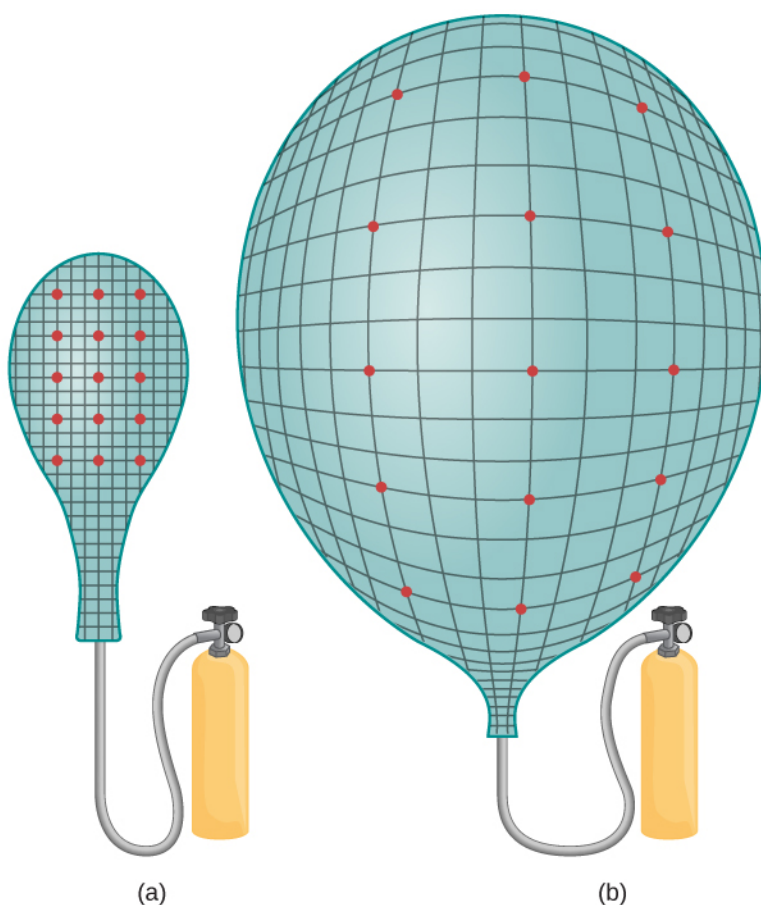


Figure 11.19 An analogy to the expanding universe: The dots move away from each other as the balloon expands; compare (a) to (b) after expansion.

Second, as mentioned already, the Big Bang expansion is due to the expansion of space, not the increased separation of galaxies in ordinary (static) three-dimensional space. This cosmological expansion affects all things: dust, stars, planets, and even light. Thus, the wavelength of light (λ) emitted by distant galaxies is “stretched” out. This makes the light appear “redder” (lower energy) to the observer—a phenomenon called cosmological **redshift**. Cosmological redshift is measurable only for galaxies farther away than 50 million light-years.

Example 11.8

Calculating Speeds and Galactic Distances

A galaxy is observed to have a redshift:

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = 4.5.$$

This value indicates a galaxy moving close to the speed of light. Using the relativistic redshift formula (given in **Relativity**), determine (a) How fast is the galaxy receding with respect to Earth? (b) How far away is the galaxy?

Strategy

We need to use the relativistic Doppler formula to determine speed from redshift and then use Hubble’s law to find the distance from the speed.

Solution

- According to the relativistic redshift formula:

$$z = \sqrt{\frac{1 + \beta}{1 - \beta}} - 1,$$

where $\beta = v/c$. Substituting the value for z and solving for β , we get $\beta = 0.93$. This value implies that the speed of the galaxy is 2.8×10^8 m/s.

- b. Using Hubble's law, we can find the distance to the galaxy if we know its recession velocity:

$$d = \frac{v}{H_0} = \frac{2.8 \times 10^8 \text{ m/s}}{73.8 \times 10^3 \text{ m/s per Mpc}} = 3.8 \times 10^3 \text{ Mpc}.$$

Significance

Distant galaxies appear to move very rapidly away from Earth. The redshift of starlight from these galaxies can be used to determine the precise speed of recession, over 90% of the speed of light in this case. This motion is not due to the motion of galaxy through space but by the expansion of space itself.



11.8 Check Your Understanding The light of a galaxy that moves away from us is “redshifted.” What occurs to the light of a galaxy that moves toward us?



View this **video** (<https://openstaxcollege.org//21expansion>) to learn more about the cosmological expansion.

Structure and Dynamics of the Universe

At large scales, the universe is believed to be both isotropic and homogeneous. The universe is believed to be isotropic because it appears to be the same in all directions, and homogeneous because it appears to be the same in all places. A universe that is isotropic and homogeneous is said to be smooth. The assumption of a smooth universe is supported by the Automated Plate Measurement Galaxy Survey conducted in the 1980s and 1990s (**Figure 11.20**). However, even before these data were collected, the assumption of a smooth universe was used by theorists to simplify models of the expansion of the universe. This assumption of a smooth universe is sometimes called the cosmological principle.

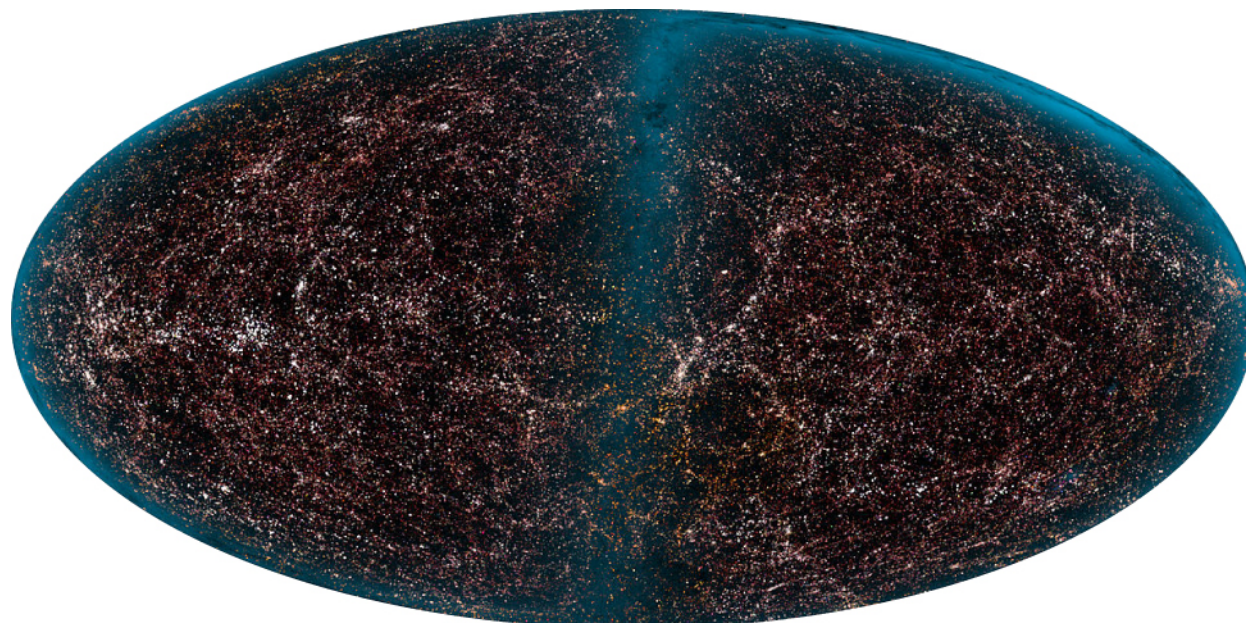


Figure 11.20 The Automated Plate Measurement (APM) Galaxy Survey. Over 2 million galaxies are depicted in a region 100 degrees across centered toward the Milky Way's south pole. (credit: 2MASS/T. H. Jarrett, J. Carpenter, & R. Hurt)

The fate of this expanding and smooth universe is an open question. According to the general theory of relativity, an important way to characterize the state of the universe is through the space-time metric:

$$ds^2 = c^2 dt^2 - a(t)^2 d\Sigma^2, \quad (11.13)$$

where c is the speed of light, a is a scale factor (a function of time), and $d\Sigma$ is the length element of the space. In spherical coordinates (r, θ, ϕ) , this length element can be written

$$d\Sigma^2 = \frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2), \quad (11.14)$$

where k is a constant with units of inverse area that describes the curvature of space. This constant distinguishes between open, closed, and flat universes:

- $k = 0$ (flat universe)
- $k > 0$ (closed universe, such as a sphere)
- $k < 0$ (open universe, such as a hyperbola)

In terms of the scale factor a , this metric also distinguishes between static, expanding, and shrinking universes:

- $a = 1$ (static universe)
- $da/dt > 0$ (expanding universe)
- $da/dt < 0$ (shrinking universe)

The scale factor a and the curvature k are determined from Einstein's general theory of relativity. If we treat the universe as a gas of galaxies of density ρ and pressure p , and assume $k = 0$ (a flat universe), then the scale factor a is given by

$$\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}(\rho + 3p)a, \quad (11.15)$$

where G is the universal gravitational constant. (For ordinary matter, we expect the quantity $\rho + 3p$ to be greater than zero.) If the scale factor is positive ($a > 0$), the value of the scale factor “decelerates” ($d^2a/dt^2 < 0$), and the expansion of the universe slows down over time. If the numerator is less than zero (somehow, the pressure of the universe is negative), the value of the scale factor “accelerates,” and the expansion of the universe speeds up over time. According to recent cosmological data, the universe appears to be expanding. Many scientists explain the current state of the universe in terms of a very rapid expansion in the early universe. This expansion is called inflation.

11.7 | Evolution of the Early Universe

Learning Objectives

By the end of this section, you will be able to:

- Describe the evolution of the early universe in terms of the four fundamental forces
- Use the concept of gravitational lensing to explain astronomical phenomena
- Provide evidence of the Big Bang in terms of cosmic background radiation
- Distinguish between dark matter and dark energy

In the previous section, we discussed the structure and dynamics of universe. In particular, the universe appears to be expanding and even accelerating. But what was the universe like at the beginning of time? In this section, we discuss what evidence scientists have been able to gather about the early universe and its evolution to present time.