13.4: The Age of the Universe

Learning Objectives

- You will be able to perform calculations and understand conceptually the relationship between the expansion rate and age of the Universe.
- You will be able to distinguish the concepts of Universe and observable Universe.

Age of the Universe

13.4.1: Olbers' Paradox - The Dark Night Sky Tells Us That Time Had a Beginning

It is possible to make a simple observation that shows that the Universe cannot be both infinitely old and completely uniform. This is the observable fact that the night sky is dark!

If the entire Universe was similar to the region around us, whether we define that region as a few hundred light-years of stars or a few hundred million light-years of galaxies, and if it was also essentially unchanging over time—with the same assortment of stars or galaxies forever—we would be cooked in a fraction of a second. In such a Universe, if you looked in any direction, your line of sight would eventually intersect a distant star. An average star has a surface temperature of several thousand kelvin, so the whole sky would glow with that mean temperature—just like the surface of a star. In fact, the Universe would be hotter than the hottest oven. Heinrich Olbers (1758–1840) pointed this out in 1823, though others had noted it before, with Thomas Digges (c.1546–1595) being the first. Nonetheless, this is referred to as Olbers' paradox, though it is only a paradox if one believes the Universe to be infinite in time and spatial extent.

One early attempt to remedy the paradox and permit an infinitely old and uniform cosmos was to propose that gas and dust between the stars were absorbing much of their radiation and therefore lowering the mean radiant temperature of the sky. However, that does not work. The gas and dust would soon be heated to the same high temperature as the stellar surfaces, and oven-like conditions would prevail. So either the Universe is not uniform out to infinite distances, or it cannot be infinitely old. It is easy to imagine—though difficult to account for—a Universe consisting of a finite set of stars like the Milky Way, surrounded by emptiness. Then, only when we looked exactly in the direction of one of its hundred billion stars would we measure a radiative temperature of thousands of degrees. Because stars subtend such tiny angles, the average temperature of the sky could be very low. We do not live in such a Universe. We see galaxies spread quite uniformly around us out as far as we can see.

A different solution to the paradox is immediately implied by the Hubble expansion—the Universe has a finite age. Even if it is infinite in extent, light has only had time to reach us from the closest galaxies and the average sky temperature must remain extremely low as a consequence. In addition, the stretching of space has increased the wavelength and therefore lowered the energy (and corresponding effective temperature) of the radiation coming from the most distant reaches of space.

13.4.2: Hubble Time

Imagine the Hubble expansion scenario playing like a movie in reverse. Instead of galaxies moving away from each other as time goes forward, galaxies would rush toward each other as time goes backward. Galaxies would be closer and closer together in the past, until at some time in the distant past the matter that makes up the galaxies would have been very close together. We can extrapolate back to this time, the beginning of the Universe. If we know the expansion rate for the Universe and assume that it has been constant, we can calculate how much time the Universe has been stretching.

The Hubble constant is an example of a stretching rate. The Hubble constant is generally expressed in units of km/s/Mpc due to how it is measured. However, both km and Mpc are units of distance and cancel out, so the Hubble constant, or any stretching rate, actually has units of 1/time. Again, assuming that the expansion rate has been constant, we therefore have an expression for the age of the Universe t.

$$t = \frac{1}{H_0}$$

In this expression for the age, t is called the Hubble time. It is computed by taking the reciprocal of the Hubble constant, H_0. This expression tells us that if H_0 is bigger, then t will be smaller and vice versa. A faster expansion rate will lead to a younger age for the Universe. A slower expansion rate will lead to an older age of the Universe. To go back to our stretchy band analogy, if the expansion rate is faster, it will take less time for the galaxies to reach their current distances from each other. If the expansion rate is slower, it will take them a greater amount of time.

This mathematical formula can also be expressed graphically, as in Figure 13.9.

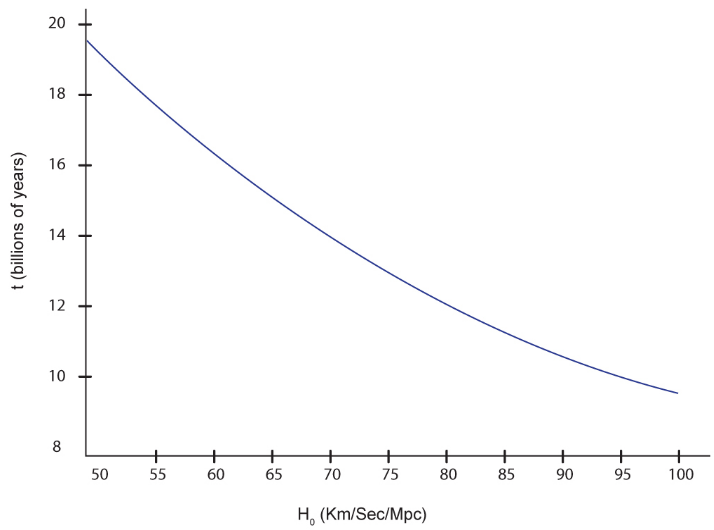

Figure 13.9: The current age of the Universe (t) is plotted vs. the current expansion rate (H_0). This is the graphical form of the equation $t = 1/H_0$. Credit: NASA/SSU/ Aurore Simonnet

Going Further 13.4: Another Way to Think About the Hubble Constant

Another way to look the Hubble law and the Hubble constant is from the perspective of elementary physics. We can find the distance traveled by an object moving at constant speed if we multiply the speed by the time traveled. Mathematically this idea is expressed as distance (d) equals speed (v) times time (t), or

$$d = vt$$

Hubble’s Law has exactly this same form:

$$v = H_0 d$$

This might not look like the same form at first, but lets rearrange terms a little bit. Dividing both sides by the Hubble constant we get:

$$d = vH_0 = v\left(\frac{1}{H_0}\right)$$

Now the first and the last equations look exactly the same. We just have to realize that the Hubble constant is the reciprocal of a time:

$$t = \frac{1}{H_0}$$

But what time is this? It is the time needed for any given galaxy to travel to its current distance, and of course, this time is the same for all galaxies. The faster galaxies travel farther during this time; the slower ones travel not as far. This is a consequence of what we reasoned before, but some students prefer to think about it in this manner.

The Expansion and Age of the Universe

In this activity, you will use the graph in Figure 13.9 to explore the relationship between the expansion rate today (H_0) and the current age of the Universe (t).

Converting the Expansion Rate Into Units of Inverse-Seconds

Because of the way it is measured, the Hubble constant has strange units: km/s/Mpc. However, km and Mpc are both units of distance, so we can cancel them and express the Hubble constant in inverse-seconds (1/s). You will practice doing so in this activity.

You will need the conversion between Mpc and km: 1 Mpc = 3.09×10^{19} km.

Worked Example

1. Convert H_0 = 70 km/s/Mpc to inverse-seconds (1/s) by canceling out the distance units.

To make the conversion, it is best to start with the units of H_0 written out carefully rather than in shorthand notation. So, 70 km/s/Mpc can also be written like this.

$$\frac{70\ \mathrm{km/s}}{\mathrm{Mpc}}$$

This form makes it easier to see how to convert the units.

$$\left(\frac{70\ \mathrm{km/s}}{\mathrm{Mpc}}\right) \times \left(\frac{1\ \mathrm{Mpc}}{3.09 \times 10^{19}\ \mathrm{km}}\right) = 2.27 \times 10^{-18}\ \mathrm{sec}^{-1}$$

Notice the km and Mpc on the top and bottom canceled out, leaving the answer in 1/s.

Questions

The Relationship Between H_0 and T

As described in the text above, assuming the Universe has been expanding at a constant rate since its beginning, then its age is $t = 1/H_0$, where t is in units of seconds (s) and H_0 is units of 1/s. We will use this relationship to compute the age of the Universe for several possible values of H_0.

Worked Example

1. If H_0 = 70 km/s/Mpc, what is the age of the Universe in seconds?

- Given: Using the results of the previous activity, the Hubble constant in units of inverse-seconds is H_0 = 2.27E-18 1/s
- Find: t, the age of the Universe

- Concept: $t = 1/H_0$
- Solution: t = 1/(2.27E-18 1/s) = 4.41E17 s

2. Convert the age of the Universe to years. 1 year = 3.15 × 10^7 s.

t = 4.41E17 s x (1 yr / 3.15E7 s) = 1.4E10 yr

3. Convert the age of the Universe to billions of years. 1 billion = 1 × 10^9.

t = 1.4E10 yr x (1 billion / 1E9) = 14 billion yr

So, if the Hubble constant is 70 km/s/Mpc, then the Universe is 14 billion years old.

Questions

13.4.3: The Hubble Constant Over Time

The Hubble time, as we have just derived it, gives us a rough idea of the age of the Universe. Of course, we have no reason to expect that the stretching rate has been constant across the history of the Universe. So Hubble "constant" is another of those cases where a term in astronomy can be somewhat misleading. The Universe's stretching rate will be close to a constant value throughout space at any short instant in time, including today, so in that sense the "Hubble constant" is a constant. However, it is also likely to have varied over long time scales. To distinguish these two possibilities, astronomers often reserve the term Hubble constant, denoted H_0, only for its value today. They then use the term Hubble parameter, denoted H (without the subscript), when referring to the expansion rate at other times. But you should still be prepared to see the term Hubble constant in both contexts, because not everyone always uses the term Hubble parameter.

In later chapters we will look in detail at why we think the Hubble parameter might not actually be constant over the age of the Universe. For the time being you should simply keep in mind that the rate of expansion could change, and this will affect our estimate of the age of the Universe.

13.4.4: Independent Age Estimates

The Universe must naturally be older than all of its constituents. This constraint can serve as a consistency check for our physical theories: when objects in the Universe have estimated ages greater than our best estimate for the age of the Universe, something must be reconciled. Either our estimate of the cosmological age is in error or the estimate of the age of the objects in question is wrong.

When Hubble made his first determination of the Hubble constant in 1929, he made a number of understandable errors. These made the Hubble constant several times too large and the Hubble time correspondingly too small—only 2 billion years. That was in serious conflict with the ages of the oldest known stars calculated from our knowledge of nuclear physics, not to mention the age of Earth itself. Even in the late 20th century there were problems. Estimates of the Hubble time could still be as short as 10 billion years. At the same time, the oldest structures in our Galaxy, globular clusters, were calculated to be as much as 15 billion years old. There were large uncertainties in both values, around 2 billion years in the case of the age of the Universe, and 3 billion years for the ages of globular clusters. Still, the inconsistency between these ages pushed scientists to improve their theories of stellar evolution and to improve their cosmological measurements. As a result, today most estimates fit without conflict and with much greater precision, partly as a consequence of the discovery of new physics.

One exception is the value of the Hubble constant that we measure from expansion compared to its value as measured by the Cosmic Microwave Background. We will return to this conflict in the chapter on the background radiation.

13.4.5: The Observable Universe

Another important consequence of the finite age of the Universe is that we can only ever see part of it—that part from which light has had time to reach us. We do not know how big the entire Universe is, and it might be infinite. In either case, it is likely that the Universe is much bigger than the part from which we can receive information.

The size of the observable Universe is easily calculated. We have seen that the age of the Universe is 13.8 billion years. If the Universe was static, we would only be able to see objects 13.8 billion light-years away. Light from anything farther away would not have had time to reach us. Even though space has been stretching during all those years, we can still think in terms of the lookback times to the objects we observe. Consider the following thought experiment.

Think of your observable Universe as a sphere. This sphere is centered on you—as it would be around any other observer anywhere today. The sphere extends out to anything with a lookback time of 13.8 billion years; that is the size of the sphere because that is how long light has been traveling in the Universe. Anything farther away is not visible. For example, if there is a galaxy with a lookback time of 15 billion years away from you, you cannot see it right now because light has not had enough time since the beginning of the Universe to traverse the distance separating you from that galaxy. We say that it would be beyond your observable Universe, or cosmic horizon. To see such a galaxy, you would have to wait another 1.2 (15.0 – 13.8) billion years.

Observers somewhere in the Andromeda galaxy right now would see a similar spherical volume, but it would be centered on themselves instead of on us. So they would see a little sliver more of the Universe on the side of their sphere away from us, and a little sliver less on the side toward us. Observers way out toward the edge of our observable Universe would see our galactic neighborhood as being way out toward the edge of their observable Universe. In the opposite direction they would see a huge swath that we cannot see at all—and visa versa. Of course they would see us as we were many billion years ago, not as we are now, just as we see them as they were many billion years ago, not as they are now.

The Observable Universe

In this activity, we will explore the concept of observable Universe.

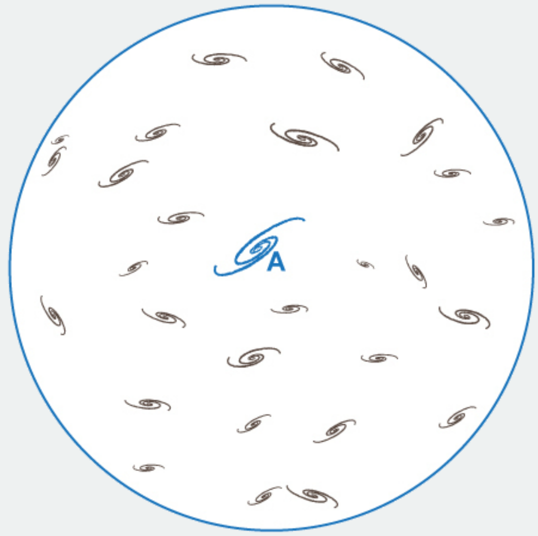

Figure A.13.2: The blue line represents the observable Universe for galaxy A. Credit: NASA/SSU/Aurore Simonnet

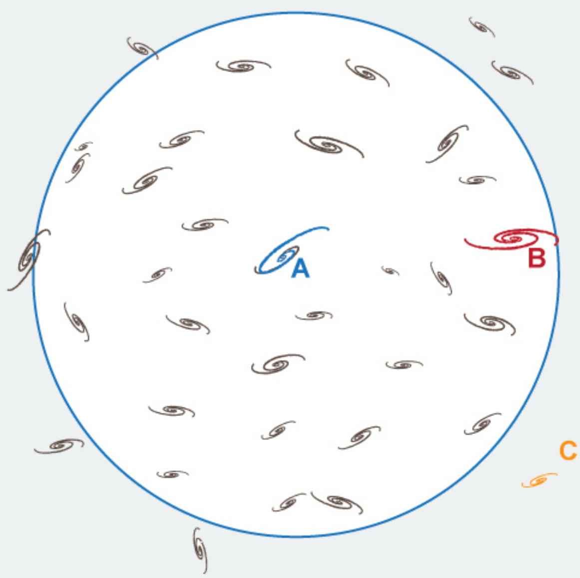

Figure A.13.3: The blue line represents the observable Universe for galaxyA. Credit: NASA/SSU/Aurore Simonnet

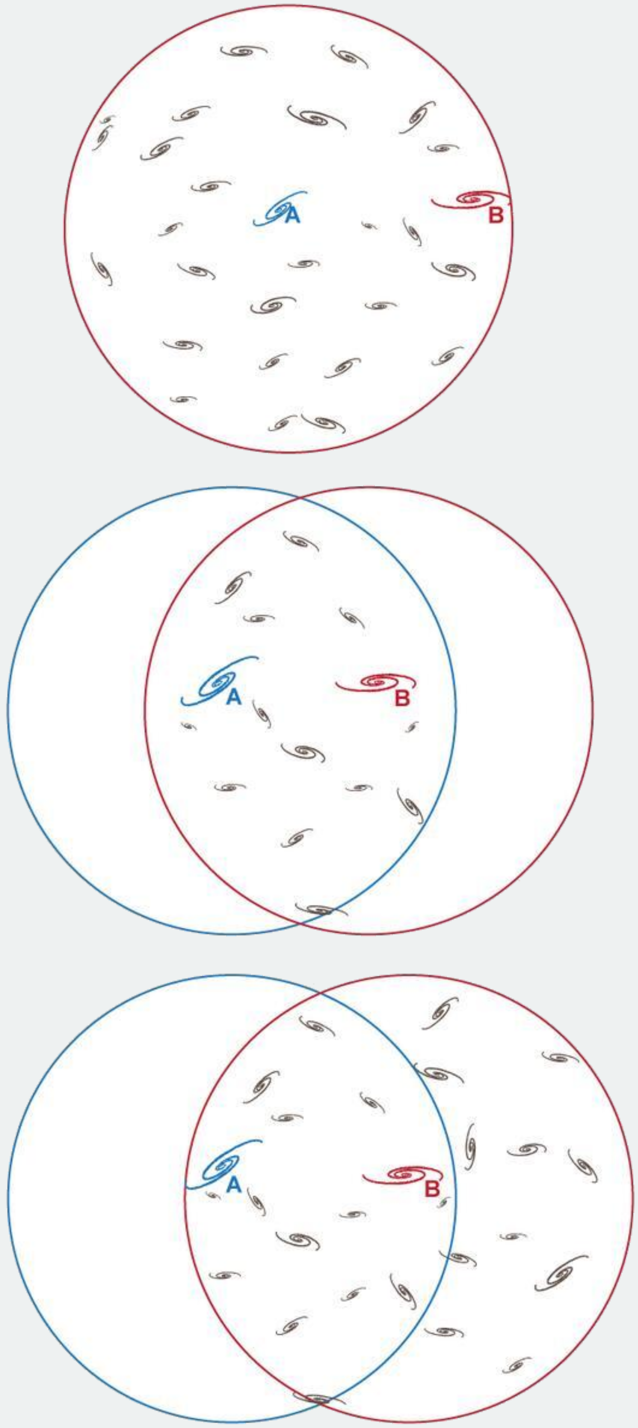

Figure A.13.4: The red circles represent three possibilities for the observable Universe and its contents for galaxy B. Credit: NASA/SSU/Aurore Simonnet

In the last activity, you should have found that the **observable Universe** for an observer is centered on that observer, and is a subset of the whole Universe. The finite age of the Universe and the finite speed of light combine to limit what we can observe of the Universe in several ways. There is a boundary to our observable Universe called the cosmic horizon. We cannot observe anything beyond that boundary because light from there has not had enough time to reach us—even 13.8 billion years has not been enough time. The size of the observable Universe gets bigger as the distance that light has traveled since the start of the Universe gets bigger. In other words, there may be objects beyond our current cosmic horizon that we cannot see right now, but as the Universe gets older, we will be able see more of them.