13.5: The Basic Big Bang Model

Learning Objectives

- You will know that the Big Bang theory features an expansion of space not an explosion of matter.
- You will know that the expansion of the Universe can be described by general relativity.
- You will know that the expansion leads to a change in the Universe over time, including temperature and density.

The Big Bang

13.5.1: Key Components of the Model

The best and most widely accepted current model for how our Universe changes over time is usually referred to as the standard Big Bang theory, or model. The Big Bang model is based on general relativity and other models from physics and is supported by much observational evidence. According to the Big Bang model, space is expanding and cooling, and every part of the Universe was once extremely hot and dense. The Universe—space, time, and all of the matter and energy in it—came into existence billions of years ago. All of the matter and energy that exists today has existed since the beginning; the Universe has been expanding, cooling, and changing ever since. These ideas lead to the following implications, some more obvious than others:

13.5.1.1: *Implication 1: The Expansion of Space*

On average, galaxies are moving away from each other, in a way that follows the Hubble law, due to the stretching of space. We emphasize that the galaxies are moving away from *each other*, that there is no special central point in the Universe. Finally, unlike objects we are familiar with in everyday life, such as balloons, that expand into space, the Universe itself does not need to be expanding into any other kind of space; instead, the creation of new space is what drives the expansion.

13.5.1.2: *Implication 2: Finite Age*

The Universe has a finite age related to its rate of expansion. None of the objects contained in the Universe can be older than the Universe itself. Current best estimates put the age of the Universe at 13.8 ± 0.1 billion years.

13.5.1.3: *Implication 3: Hot Dense Phase*

If the Universe is expanding, that means that at some time in the past, everything in the Universe was compressed extremely close together, in a state of high density. The high-density state would also have been very hot. The Universe was hot and dense everywhere and every part of it participated in the expansion, including right here. If we go back far enough, we can imagine the density and temperature of the Universe reaching extremely high values. This is different from an explosion, which starts at one point in space and scatters material through other regions.

13.5.1.4: *Implication 4: Big Bang Nucleosynthesis*

A hot, dense plasma as we imagine existed early in the history of the Universe would have undergone nuclear reactions, just as happens inside stars today. This is because, at some point, the conditions in the entire Universe must have been similar to the conditions at the centers of stars. This period would have been fleeting, with earlier temperatures too hot for stable nuclei to exist, and later temperatures too cool for nuclear fusion. However, during this period some of the same reactions that occur in stars today should have taken place throughout the Universe. We should be able to see evidence of this early epoch of Big Bang Nucleosynthesis.

13.5.1.5: *Implication 5: Relic Radiation from the Hot Dense Phase*

The imprint of the hot, dense phase should still be with us in the form of relic radiation. A hot, dense plasma creates a radiation field that is in equilibrium with the matter, so both will have the same characteristically high temperature. As the Universe expands and cools the matter and radiation will eventually come out of equilibrium, but the radiation field will remain. It will cool as the Universe expands, but it should still be in evidence today. We should therefore be able to detect this early relic radiation in every direction we look.

13.5.1.6: *Implication 6: Continual Evolution*

The Universe is continuing to evolve as it expands and cools. The Big Bang model makes predictions about the future evolution of the Universe based upon its current conditions and its contents.

We will explore these implications in the remaining chapters. Each of them lends itself to some remarkably detailed investigations of the cosmos, and each plays an important part in our understanding of the history and evolution of the Universe.

GOING FURTHER 13.5: BIG BANG—WHAT'S IN A NAME?

The Big Bang Model

Watch the two animations, which each show a region of space and the matter in it. In both animations, the grid lines represent space, and the dots represent matter. You can toggle back and forth between the animations with a pull-down menu. The animation begins when you click on the center dot. Reset the animation using the "reset" button. Answer the following questions.

Play Activity

Density is how much matter is present in a given volume of space. Use the animation you found to be correct in question #8 along with the aperture tool to figure out how the density of the Universe changes over time. To do this:

- Reset the animation.
- Click aperture control and draw a circle; this represents the volume of space at some early time in the history of the Universe.
- Count the number of dots in the circle.
- Click animation control again. The circle should stay on the screen.
- Run the animation until it stops; this represents some later time in the history of the Universe.
- Again, count the number of dots in the circle.
- If the density is higher, there will be more matter (dots) in a given volume (circle). If the density is lower, there will be less matter (dots) in a given volume (circle).
- (To try again with a different aperture, click outside the circle and the original circle will be erased. You can then draw a new circle.)

We can also relate the change in density of the Universe over time to the change in its temperature over time. Have you ever used "canned air" to clean a computer keyboard or other electronics? The can contains a certain amount of air confined to a small volume. When you press the nozzle and release the gas, it is now spread out over a much larger space. Temperature is a measure of the kinetic energy of the molecules—how fast they are moving and how much they are colliding. When the volume is increased, the molecules will have many fewer collisions because they are spread out. This reduces the temperature and makes the can and the air around the can feel cooler. Although the Universe is not exactly a gas in the same way as what is coming from the canned air, the idea is similar: as the volume of space expands, there are fewer collisions and thus the temperature decreases.

13.5.2: Explaining How the Universe Changes Over Time With General Relativity

General relativity was not developed for cosmological reasons. Rather, Albert Einstein was interested in generalizing special relativity to deal with objects accelerating with respect to each other; recall that that special relativity deals only with objects that have constant relative velocities. He also wanted to explain why our experience of gravity can feel essentially indistinguishable from acceleration. Like all physical theories, however, general relativity applies, or should apply, throughout the Universe. So as soon as it was available it was applied to cosmology in order to understand the properties of the Universe on the largest scales of space and time.

General relativity deals with space as an entity (as opposed to an absence of objects) and it describes how space is warped by mass and energy. The mathematical description is difficult to use for complex distributions of mass and energy, for example, black holes and galaxy clusters. However, it is actually simpler for the Universe as a whole. For that case we can consider mass and energy to be smoothly distributed on scales of billions of light-years.

Fortunately for many models of the Universe, using general relativity is fairly straight-forward. Time is not warped at all and space is only subject to some simple universal stretching—just what we observe in Hubble expansion. For a homogeneous distribution of matter and energy throughout the Universe, we find that we can use a single time that is valid everywhere (often called cosmic time) together with a curved and stretching three-dimensional space. The Friedmann equations are the solution to the Einstein equations for a homogeneous and isotropic Universe. The primary Friedmann equation relates the expansion history of the Universe and the matter and energy density to the curvature of space:

$$H^2 - \frac{8\pi G\rho}{3} = \frac{kc^2}{S^2}$$

(expansion)−(gravity)=(curvature)

This is basically the equation of motion for space, much like Newton's laws give us the equation of motion for an object. The Friedmann equation tells us how the Universe as a whole changes over time. First, we have an expansion term: the Hubble parameter, (H) describes how fast the scale factor of space (S) changes with time ($H = \Delta S/\Delta t$). Next, we have a term for things that affect the dynamics of spacetime: the density of matter and energy (ρ), which affects the stretching of space through gravity. Finally, we have a term that includes the curvature of spacetime (k). This equation embodies the essence of the Einstein Equation: matter and energy affect how spacetime bends.

Again, the interplay between the terms of the Friedmann equation is analogous to the interplay between gravity and the energy of motion that we saw when discussing Newtonian physics. In Newtonian physics, if you throw a ball in the air or launch a rocket, whether or not it will escape into space depends on the relative values of its kinetic energy (like the expansion term in the Friedmann equation) and gravitational potential energy (like the gravity term). The curvature term is like the total energy in a Newtonian system. The rate at which the Universe will expand (or contract) over time will depend on the relative values of the Hubble constant and the density of matter and energy. General relativity tells us that these parameters affect the curvature of space. Over the next several chapters we will see how the evolution of the Universe as a whole plays out according to the Friedmann equation, and how theory compares with observations.

As an example, we will do a short calculation that is analogous to the one we did for escape velocity in Math Exploration 13.2.

Math Exploration 13.2

The value of the density that causes the Universe to be flat (zero curvature) is called ρ_{crit}, the critical density. It depends on the expansion rate, and that as the expansion rate increases the critical density also increases. The condition is analogous to saying (from a Newtonian perspective) that the escape speed from a planet (analogous to the expansion rate) gets bigger as the mass of the planet (analogous to the density of the Universe) gets bigger. For a Hubble constant around 70 km/s/Mpc, the critical density is around 10^{-29} g/cm^3. If the density is higher than the critical value, then the expansion will not be fast enough; the Universe will eventually stop expanding and then re-collapse. This case is analogous to throwing a ball upward from a planet at less than the escape speed, in which case we know that the ball eventually falls back down. If the density is less than the critical density then the expansion of the Universe is so fast that even after an infinite amount of time the Universe will still be expanding—a case analogous to launching a ball upward with a speed greater than the escape speed. The critical density is therefore the boundary case in which the Universe expands forever but approaches zero expansion rate with time. This is just like launching a projectile at exactly the escape velocity. We will explore these ideas in much greater detail in later chapters.

13.5.3: Summary

In this chapter we have explored the most important discovery we have made about the Universe in the last century, that it is stretching and appears to have started from a hot, high-density state nearly 14 billion years ago. The space we occupy is a thing with properties of its own; it is not just an empty container in which events take place. The Universe is not matter exploding from some special place into some pre-existing structure, and space might be infinite, or might be finite but unbounded. In either case it has no center or edge, and we see only a fraction of all the space there is.

Perhaps the most important thing to realize about the Big Bang theory is that it provides a framework that connects many seemingly unrelated observations and physical principles. In this chapter we have seen our first piece of evidence: the Hubble expansion and some of its implications. In the remaining chapters, we will work through other pieces of evidence and how they help us understand the history and fate of the Universe. We will see how each piece of evidence is related to other pieces of evidence, so the elements of the model fit together and support each other. Given the huge amount and variety of data, it is remarkable that it is possible at all to fit together these various observations in a self-consistent way.

One final thing to keep in mind is that the Big Bang model does not say anything about what caused or created the Universe. It says that at early times the Universe was hot and dense, and that it has expanded and cooled since then, evolving as it does so according to the laws of physics. It does not say anything about how the Universe got to be in its initial state.

Going Further 13.6: the Steady State Theory—a Model Without a Beginning of Timeote

Does a Universe expanding according to Hubble's law require the Universe to extrapolate back to a beginning time? Not necessarily. In the 1950s, Fred Hoyle, Hermann Bondi (1919–2005) and Tommy Gold (1920–2004) developed a Steady State theory in which the Universe was eternal and unchanging. It required the continuous generation of matter everywhere to drive the observed expansion. The continuous emergence of new matter would constantly refresh the Universe, allowing new stars and galaxies to form without end. That is a very different Universe than that predicted by the Big Bang theory. The Big Bang predicts a period of rich star formation at some early time and a slow depletion of material available for new stars as the Universe evolves. In other words, the Universe should change in time.

By the late 1950s, Steady State models were already in serious trouble because observations were showing that the early Universe was very different from the Universe today. Recall that when we look at very distant objects we are seeing them as they were long ago when the light we measure left them, a time when the Universe was much younger than it is now. Observations of the early Universe (distant objects) showed that the density of galaxies was higher than today. What's more, the galaxies were both more active and different in structure than galaxies are now. In addition, the chemical abundance of all the lightest elements in the Universe seemed close to the predictions for the Big Bang theory, an idea we will explore in Chapter 14. In 1965, the Cosmic Microwave Background (CMB) was detected. Big Bang models had predicted just such a glow, coming from the time when the Universe was much denser and hotter than it is today. Steady State models, on the other hand, had no natural explanation for the background radiation, and Steady State accounts of the CMB seemed contrived, created only to fit the observations. From 1965 onward there has been a strong scientific consensus that the expansion we see implies that the Universe started in an ultra-dense, hot state.