26. Cosmology: How the Universe Works

There are billions of galaxies, many containing hundreds of billions of active stars. Some of these stars are just being formed from the interstellar dust that collects in large enough pockets so that they are gravitationally stable. Most of the stars we see are in the mature phase of their existence, quietly fusing hydrogen to form helium. Others are in their last days, passing through the various stages of expansion, contraction, explosion, and ultimate death. The explosions return significant amounts of matter to the interstellar medium where it may be used to form new stars that pass through the same cycle.

The story of stars is one part of the broader study of cosmology, the study of the universe itself. How did the universe start? How did it evolve to its present state? How will it change in the future? Will it have an end? Such questions have always intrigued us. Although we still do not know all the answers, evidence is beginning to accumulate and some of the possibilities, at least, can be eliminated.

Some broad outlines become apparent from the dynamics of stars. Each galaxy must have started by the condensation of huge clouds of hydrogen, with particularly dense regions being compressed by gravity until stars were formed. At the present time, the universe is dominated by the fusion of hydrogen to form helium in the cores of mature stars. Its structure seems stable, just as individual stars are stable during their hydrogen-burning maturity. However, these processes are gradually using up the available hydrogen. Someday there will not be enough to sustain hydrogen fusion. What will happen then?

This leaves us with two fascinating questions. Where did the original hydrogen come from? What happens when hydrogen fusion is no longer possible, or what is the ultimate fate of the universe?

Among the many theories, or cosmologies, that have been proposed as answers to such questions, two have been actively studied—the Big Bang Model and the Steady State Model. We shall attempt to describe these models and outline some of the evidence that helps us to decide why one is preferred over the other.

As you will see, our understanding of the universe depends on our ability to measure the distance to other stars and galaxies. The relative speeds of the stars and galaxies are also an important part of the overall picture. For these reasons, we shall pause briefly to discuss the techniques by which these measurements are made. Then we shall return to the question of the structure and evolution of the universe.

Measuring Astronomical Distances

One of the most formidable obstacles in understanding the universe is the problem of distances. Pick out the moon, the sun, or one of the stars in the heavens. How far away is it? A hundred miles? A thousand miles? A billion miles? How could we ever know? Does looking at a star give us any clue?

The Greeks began solving the problem of measuring distances by using geometry. Aristarchus of Samos (ca. 310-230 B.C.) used a heliocentric (sun-centered) model for the solar system and information gathered from the observations of solar and lunar eclipses to estimate the sizes and distances from earth to the sun and moon.

Eratosthenes (284-192 B.C.), the chief librarian at the Library of Alexandria, observed that on midsummer’s day in Syene the sun was directly overhead (a monument located there cast no shadow at midday), while at Alexandria objects at the same time were casting shadows in such a way as to show that the sun was about 7° away from the vertical. Eratosthenes measured the distance from Syene to Alexandria and used the information and geometry to conclude that the earth was spherical and estimated its diameter to be close to the modern value (Fig. 26.1). If the distance from Syene to Alexandria is \(d\), you can estimate the circumference from the direct proportion

\[
\frac{7^\circ}{360^\circ} = \frac{d}{\text{circumference}}.
\]

Hipparchus of Nicea (190-120 B.C.) used geometry to solve for the distance to the moon by using the altitude of a triangle formed by the moon and two observation stations at different latitudes on the surface of the earth. His answer was a bit high, but not terribly different from the present value, and it was an improvement on Aristarchus’ assessment.
Today four principal methods are used to measure the immense distances in space: radar ranging, triangulation, brightness-distance calculations, and cosmological redshift. **Radar ranging** is useful for measuring distances to the comparatively close objects within the solar system—the earth’s moon, the sun, and the planets (Fig. 26.2). A radar beam is directed toward the object of interest. The beam is reflected, a small fraction returning to the earth, and the time required for the round trip is measured. Since radar is electromagnetic radiation (radio waves), its speed is the same as that of light. These two factors, time and speed, allow us to calculate the distance (from distance = speed × time). This method is not useful for measuring distances to stars because they do not reflect enough energy back to the earth and the return signal cannot be detected with present technology. In a variation of the method, a radio signal can be sent to a space probe near a planet or moon and a reply requested.

**Triangulation**, the second distance-measuring technique, is the same method that is often used to measure inaccessible lengths on the earth’s surface. Suppose, for example, we wish to measure the width of a river, the length of line AB in Figure 26.3. We could do so without getting wet by walking a known distance along the river (90 meters in the figure). Then, from our new position, measure the angle between lines AC and BC. Now we could draw a small triangle with the same angles as we have measured. (We assume that the angle between AB and AC is a right angle to make things easy.) Now we know two angles in the big triangle and that means we know all three since they must total 180°. The corresponding lengths of the sides of these two triangles are in the same proportion. In this case, side ab of the small triangle is four-thirds as long as side ac. That means that side AB in the large triangle is also four-thirds as long as side AC. Thus, the river is 120 meters wide.

**Figure 26.3.** Triangulation is used to measure the width of a river. How wide is the river?

Distances to nearby stars can be measured in the same way. The two points of observation, corresponding to the points A and C in Figure 26.3, are opposite points on the earth’s trajectory around the sun as in Figure 26.4. Thus, our triangle has one side that is equal to the diameter of the earth’s orbit. Even so, the stars are so far away that the angles are very difficult to measure, and it is impossible to do so without the aid of a telescope. The scale of the earth’s orbit in Figure 26.4 is greatly exaggerated compared to the distance to the star. Measuring the distance to even the nearest stars is like trying to measure a distance of 160 kilometers (100 miles) by taking one step sideways and noting the change in the angle of observation. For these reasons, triangulation is only useful for measuring the distance to stars that are closer than about 500 light-years. (A
The brightness-distance relationship is the simple basis for the third distance-measuring technique. Suppose while driving at night on a lonely stretch of highway we see an approaching motorcycle and want to judge the distance to it. One way is to note the apparent brightness of its headlight. The light seems dim when the motorcycle is far away and bright when it is closer. We might be fooled if the motorcycle has an especially bright or dim headlight, but we can make good estimates based on our previous experience with other headlights we have seen.

A few thousand stars are near enough to the sun so that their distances can be measured by triangulation. Some of these are bright and others are dim. Some of the brighter ones appear dim if they are farther away, but when we know how far away they are, we can correct this misapprehension. Our problem is to estimate the distance to stars that are too far away for triangulation. How can we know which of these are really bright stars that are farther away than we otherwise might estimate?

Two astronomers, H. N. Russell and E. Hertzsprung, solved this puzzle in 1911 and 1913, respectively. They discovered that the brightness of a star and its color are related. In retrospect, we should not be surprised. We already know that hotter objects emit a bluer color than cooler objects. We would also expect hotter objects to be brighter. Several complicated factors determine the brightness of stars, but the important correspondence between color and brightness seems to be valid for the great majority of stars that have been studied. The Hertzsprung-Russell diagram (Color Plate 5) shows the relationship between color and absolute brightness.

The distance to a star can be estimated in the following manner. First, study the spectrum emitted by the star (its color). Then use the Hertzsprung-Russell diagram to determine how bright the star actually is, which is called the absolute brightness. Then measure how bright it seems to be as observed from the earth. This apparent brightness allows us to determine its distance. The farther it is from the sun, the dimmer it will appear. If we know any two of the three—absolute brightness, apparent brightness, and distance—we can compute the third, distance in this case. It is simply a matter of geometry.

Distances to galaxies outside the Milky Way can be measured by the same basic technique. By comparison with known objects, we estimate the absolute brightness of some feature of the galaxy (the brightest stars, a supernova, or perhaps the entire galaxy) and then judge its distance by the apparent brightness it has as we observe it from the earth.

The method of Hertzsprung and Russell can be applied to estimate the distance for some stars, but another method was discovered about the same time that became the foundation for most measurements of distances to our neighboring galaxies. (Galaxies, in fact, were not really “discovered” until the 1920s, although Immanuel Kant (1724-1804) and others had speculated that some small, bright diffuse patches (nebulae) that seemed nestled among the stars of the Milky Way were in reality themselves giant conglomerations of stars which were outside the Milky Way. The giant telescopes of the early 20th century showed this to be true.)

Early in the 20th century, astronomers observed and catalogued a class of stars whose brightness pulsed over a period of time. These are called Cepheid variables. The North Star (Polaris) is a Cepheid variable whose brightness varies by about 9 percent over a period of four days. Other Cepheid variables can be seen in our galaxy and, with modern telescopes, in some of the nearer galaxies (nebulae) that had captured the attention of Kant and others. In 1912 Henrietta Leavitt at Harvard discovered a relationship between the period and the absolute brightness of Cepheid variables. Measurements of the period of a Cepheid variable thus determined its absolute brightness, and with the apparent brightness from observation, the astronomer could find its distance. The astronomer Harlow Shapley used this method to find the shape of our Milky Way galaxy and the position of our solar system in it.

Edwin Hubble found 11 of these Cepheids in a small patch of nebula referred to as NGC 6822. Observations of their periods and brightness (they were in the same object, hence roughly at the same distance) showed that these objects satisfied Leavitt’s relationship between brightness and period. In 1925, Hubble used these 11 stars to estimate the distance to NGC 6822 and showed that it was, in reality, well outside the Milky Way. Similarly, for other galaxies that were relatively nearby, the Cepheid variables could be used to estimate distances. In turn, the absolute brightness of these galaxies could be studied and used to estimate distances to more distant galaxies for which the Cepheids could
not be resolved. However, a new discovery, the “cosmological redshift,” soon provided a new tool for measuring the distances to the more distant galaxies, ultimately the greatest distance of all. Later on in this chapter we shall investigate the method more fully.

In the 1990s yet another “standard candle” was added to the astronomer’s toolkit. This time it came in the form of an exploding star (supernova Type Ia) that is so energetic and bright that one can be seen halfway across the visible universe from earth—and farther with the Hubble Space Telescope. Like the other standard candles, the observed brightness of the explosion can be correlated with the distance of the object. And this one too would bring with it an unexpected and surprising discovery.

**Measuring Motion**

The technique used for measuring speeds of stars and galaxies is based on a wave phenomenon called the **Doppler effect**. The motion of a source of waves can affect their wavelength and frequency. The wave crests are closer together in front of the source than they are behind it (Fig. 26.5). (Perhaps you can see why after thinking about it for a moment.) That means that the wave frequency measured in front of the source is higher than the frequency measured behind the moving source. (Remember that frequency and wavelength are inversely related to each other.) Thus, the frequency of any wave is higher if the source is moving toward the receiver and lower if the source is moving away.

You may have noticed the Doppler effect in sound waves. Suppose, for example, that a car is coming toward you with its horn sounding (Fig. 26.6). The horn will have a higher frequency, and therefore a higher pitch, than if the car were not moving. Once the car has passed and is going away from you, the horn has a lower frequency and a lower pitch. The effect is noticeable if the car’s speed is at all appreciable. The amount of frequency change depends on the speed of the wave source and the speed of the wave.

Electromagnetic radiation, including light, also exhibits the Doppler effect. The frequency of observed light depends on the apparent motion of its source. Frequency is higher if the source moves toward the detector and lower if it moves away. (See Color Plate 4, bottom).

The Doppler effect is also used by astronomers to measure the relative speed of distant stars and galaxies. For this purpose, they use the characteristic frequencies associated with electron transitions in atoms. For example, we have noted earlier that hydrogen atoms always emit specific frequencies of light.

Imagine a collection of hydrogen atoms that are moving away from us at high speed, perhaps because they are part of a moving star. These atoms will emit the same frequencies as before, but we shall detect them as emitting lower frequencies and longer wavelengths than those from hydrogen atoms that are not moving (see Color Plate 4). We say that the frequencies have undergone a **cosmological redshift**. The amount of redshift depends on the speed of the emitting atoms. If the atoms were moving toward us rather than away, we would observe a corresponding blueshift toward higher frequencies and shorter wavelengths. By observing Doppler redshifts and blueshifts, astronomers can measure and study the relative motion of stars and galaxies.

**The Expanding Universe**

When the motions of other galaxies are measured by means of the redshifts of their emitted light, it is found that almost all other galaxies seem to be moving away from our own. Some are moving at high speeds (up to 80 percent of the speed of light). Furthermore, when these speed measurements are combined with distance measurements, it is found that the relative speed increases with distance. Those galaxies that are farthest away are moving the fastest.

This relationship between distance and the cosmological redshift is so well established for nearby galaxies that it is used to estimate the distance of the galaxies that are so far away that other distance-measuring tech-
niques do not work. The redshift thus becomes the yardstick for measuring the distance to the most distant objects that can be seen with our most sophisticated telescopes (Fig. 26.7).

The existence of the redshift and its increase with distance indicate that the universe we see is expanding. The galaxies are moving apart, some at high speeds.

The fact that all the galaxies seem to be moving away from us tends to give us an elevated sense of importance. We must be at the center of the universe! However, a little reflection reveals that observers in every galaxy would observe the same thing. To see this, imagine the birds pictured in Figure 26.8. Suppose the wire on which they sit is stretched suddenly so that the birds move farther apart than before. Each bird sees all the others as moving away from itself, with the birds farthest away moving the most.

The galaxies of the universe all seem to be moving away from us, the fastest being farthest away and the slowest being the closest. If they always had moved at their present speeds, they would have taken less than 20 billion years to move to their present locations. This concept of an expanding universe must somehow be explained by any successful cosmology.

**Einstein’s General Relativity**

As discussed in a previous chapter, Einstein gave us a new way of looking at the world in terms of spacetime. For our discussion in this chapter, imagine a grid of lines drawn on a stretched sheet of rubber. The grid allows us to establish coordinates for this two-dimensional “world.” The Special Theory of Relativity introduces an analogous four-dimensional grid, but we shall instead form some mental pictures of the two-dimensional analog represented by the sheet of rubber.

Einstein’s Special Theory of Relativity addressed some unexpected problems associated with measuring distances and time intervals in a world with a speed limit, the speed of light. Einstein went on to enlarge the theory to include the presence of matter, and in doing so created a whole new idea of what gravity is. This latter extension, the **General Theory of Relativity**, has become the framework within which all modern understanding of scientific cosmology is fitted.

For reasons that we won’t elaborate on here, Einstein came to understand that matter and spacetime are intimately connected. The presence of matter gives rise to curvature of spacetime, just as the rubber sheet would be curved if you dropped a heavy ball bearing into its center. In turn, the curvature of spacetime tells matter how to move, just as the path of a second ball bearing would be altered if you rolled it across the rubber sheet which has been warped by the presence of the first bearing (see Fig. 27.4 in Chapter 27). Einstein was
able to develop a set of equations that expressed this interrelationship.

What the equations say is that matter curves spacetime, then spacetime acts back on the matter to tell it how to move. Gravity is then a geometrical phenomenon. Matter in motion under the sole influence of what we understand as gravity is following the contours of spacetime. What we interpret as motion due to gravitational force is really motion without “force,” but motion that follows the contours of spacetime. Notice that Einstein’s interpretation of gravity is philosophically quite different than Newton’s.

When Einstein’s General Relativity passed certain crucial experimental tests (it accounted accurately for the bending of the path of light as it passed the edge of the sun in moving from a distant star to earth, and for a hitherto unexplained feature of the motion of the planet Mercury, etc.), it became the preferred gravitational theory.

When Einstein’s equations are applied to the universe, the matter is assumed to be spread out and smoothly continuous. A natural first reaction to this is similar to describing a cow as being spherical and uniformly filled with milk! However, it really depends on the scale of distance you use. Water can be observed as smooth and continuous, unless you shrink yourself down and wander among the molecules. When you get down to the scales of individual galaxies, the universe starts to look lumpy. For the most part, Einstein’s equations are used to describe the dynamic behavior of the large-scale universe and the accompanying spacetime.

The Big Bang Universe

One possible explanation for the expanding universe is an expansion of spacetime itself. The universe begins with matter concentrated at almost unimaginable density and temperature, followed by expansion. But it is an expansion of spacetime itself; it is not to be thought of as an explosion from a point inside a preexisting infinite space. As the matter cools and expands, nucleons, atoms, stars, and galaxies begin to condense as separate structures (Fig. 26.9).

If the Big Bang took place, then the motions and relative positions of the galaxies should allow us to estimate how long ago it occurred. Telescopes are “time machines.” They allow us to look into the past. When we “see” a galaxy that is 100 million light years away, we are seeing it not as it is today, but as it was 100 million years ago when the light first began its journey to earth. From the speeds and relative positions inferred from the cosmological redshifts, we can estimate that the Big Bang occurred about 13.7 billion years ago.

An important observation supports the Big Bang hypothesis. The model suggests that initially there must have been an incredibly dense and hot “soup” of matter, which would have released enormous amounts of electromagnetic radiation. Calculations were performed using the General Theory of Relativity to predict how such radiation would appear today. The results showed that the universe should be filled with significant amounts of microwave radiation traveling in all directions. Such radiation was actually observed and measured in 1965. This residual radiation from the primordial fireball seems to be a striking confirmation of the Big Bang Model of the universe.

The Big Bang Model is also consistent with one other important piece of evidence. We do not know much about the nature of matter in the state that preceded and immediately followed the Big Bang. However, several models have been proposed that lead to some calculations regarding the kind of matter that would be formed in such an event. The models agree in predicting that the emerging nuclear matter should be about 75 percent hydrogen and 25 percent helium by mass, with traces of heavier nuclear fragments. Present observations verify that this three-to-one ratio is about the same as the hydrogen/helium ratio that occurs in matter that has not been involved in stellar nuclear fusion.

These results make the Big Bang the best existing scientific model for the origin of the universe. Yet, it still leaves some interesting questions unanswered. First, there is nothing in the model to suggest what precedes or causes the Big Bang. Did it suddenly come into existence at that particular moment, or was there something before? Does “before” even exist?

Also, what is to happen in the future? Will the

Figure 26.9. The Big Bang Model of the universe. The first frame is schematic only. The Big Bang expansion is an expansion of spacetime itself. There is no “outside” perspective of the expanding universe.
expansion continue forever? If so, the future course of events seems clear. Stars will be born, proceed through their normal cycle of evolution, and die. The nuclear fires will all go out eventually, after which the universe will become a cold, vast collection of black cinders, neutron stars, and black holes, which become farther and farther apart with the passage of time. Or, will the expansion come to an end, only to have the matter collapse back to a Big Crunch that returns the matter of the stars to quark soup?

There are other puzzles, too. The large-scale universe appears to be surprisingly homogeneous. The speed limit of light prohibits some parts of our visible universe at opposite extremes ever to have been in communication over the finite period of its existence. Yet these extremes are similar in density and other characteristics. How do they know what common characteristics to assume? Moreover, we cannot find evidence for a balance of matter and antimatter in the cosmos. Somehow, the universe seems biased in favor of what we have come to call matter. For all of these puzzles there are hypotheses and models, but it will take much more time and effort to subject them to scrutiny and testing. There is probably much that is yet to be understood.

A Plausible Scenario for the Big Bang

Nevertheless, we can sketch a fairly detailed and plausible scenario for the evolution of the universe. We cannot be dogmatic about it, but neither is it done without justification. Much of the detail is consistent with actual observations or can be subjected to experimental test. The basic themes of the story are the changes that occur as the expanding universe cools. As this happens certain thresholds are passed that initiate or terminate processes and freeze the evidence of the passing for subsequent humans to observe and consider as they try to recreate the history of their universe. In what follows we shall omit most of the justifying argument and simply provide the basic concepts. (The concept here follows that of James S. Trefil in his book *The Moment of Creation* and of Nobel Laureate Steven Weinberg in his book *The First Three Minutes.*)

Stage 1

Time = 0 to $10^{-43}$ seconds

We imagine a beginning of matter and of spacetime itself at time $t = 0$. Temperatures and densities are unimaginably high. A description of matter at this stage would require a quantum theory of spacetime that does not presently exist. We have neither theory nor experimental evidence that can be brought to bear on the description. Spacetime does not exist before this point and there is no meaning to the question of what went before so far as science is concerned. The expansion that begins as an expansion of spacetime itself, as if a rubber sheet on which a grid of coordinates has been drawn, is beginning to stretch.

Stage 2

Time = $10^{-35}$ seconds

Temperature = $10^{26}$ °Celsius

Form of Matter: free quarks, gluons, electrons, positrons, neutrinos, photons. These are all structureless, elementary particles. Dark matter (nature unknown).

There is much matter and antimatter at this stage with a very slight preponderance of matter that will persist to become the matter of galaxies, stars, and people of later ages. However, most of the matter and antimatter will mutually annihilate to form photons at a later and cooler stage.

In order to explain the puzzle of the unusual uniformity of the distribution of matter in the universe at very large distances of separation, it is postulated that within the first $10^{-32}$ seconds, spacetime must have expanded at a rate even faster than the speed of light before slowing to a more sedate rate. This so-called cosmological inflation would have had to be driven by a potent energy source of unknown nature and now vanished.

The dark matter above is also of an unknown kind. In a much later stage of the evolution of the universe (in 1970), Vera Rubin and W. K. Ford will discover that the motion of interstellar matter about the centers of spinning galaxies cannot be accounted for by the pull of the mass of the visible matter in the galaxies. It is as if visible matter in galaxies is only a small part of a larger halo of invisible matter. Various arguments will rule out most conventional kinds of matter, leaving only the tentative conclusion that the dark matter is cold and exerts gravitational force, but is otherwise unlike any known conventional matter. Estimates in the early 21st century will place the amount of dark matter at 23% of the mass-energy content of the universe.

Stage 3

Time = 0.0001 to 0.001 second

Temperature = $3 \times 10^{11}$ °Celsius cooling to $10^{11}°C$

Density = $10^8$ times the density of water

Form of Matter: protons, neutrons, electrons, positrons, neutrinos, photons, dark matter

The temperature has cooled sufficiently so that the
quarks “stick” together to form nucleons, the first compound structures of the universe. Free quarks no longer exist. There is about one proton for every billion photons and about one neutron for every proton. There are no nuclei, no atoms, no galaxies, and no stars. Electrons and positrons are continually formed and annihilated. Interaction between the various particles is intense. The matter is opaque to photons and neutrinos.

Note: The description up to this stage is consistent with current physical theory, but it is applied to phenomena without experimental confirmation. The conditions in the early universe are beyond the range of current experimental ability to duplicate or approximate.

The existence of dark matter has been inferred but it has not yet been directly observed. Searches for dark matter are currently underway.

From this point on, present technology exists to test details of the theories. In some cases the experiments have already been done; in others they can be done in principle. At this stage we are no longer guided only by theory.

Stage 4

Time = 0.1 second to 3 minutes
Temperature = $3 \times 10^8$ °Celsius cooling to $10^8$ °C
Form of Matter: protons, neutrons, electrons, positrons, neutrinos, photons, dark matter

As the expansion continues, the temperature falls.

The slight mass difference between protons and neutrons results in slightly different interactions at these lower temperatures, and the neutron-to-proton ratio gradually falls from 50%/50% to a ratio of 14%/86%. At the beginning of this stage the matter is opaque to both photons and neutrinos, but with the falling temperature the neutrinos soon cease to interact and decouple from the remaining matter. From then on they play a role only through their gravitational interaction.

At the beginning of the stage, electrons and positrons are easily produced in pairs and just as easily annihilated. Toward the end the temperature is too low for pair creation, and the numbers of electrons and positrons begin to decrease through annihilation in favor of more photons.

Also toward the end of this stage, some simple nuclei ($^3$H, $^3$He, $^4$He) begin to form. At first they are quickly destroyed by collisions, but as the temperature falls a few form and remain. However, the rather loosely bound nucleus, $^3$H, does not survive the collisions even at the lowest temperatures of this stage.

Stage 5

Time = 3 minutes to 35 minutes
Temperature = $9 \times 10^8$ °Celsius cooling to $3 \times 10^8$ °C
Form of Matter: same as Stage 4 with $^3$H added

Heavier elements are formed by fusion through a series of steps. The nucleus $^3$H is one of the steps, and so long as it is not formed the synthesis of heavier elements is blocked. In this stage $^4$He forms and remains stable, allowing the formation of some simple nuclei. The remaining neutrons are used up in this process and the ratio of neutrons/protons is frozen at 13%/87%. The helium-to-hydrogen ratio is frozen at about 22%-28%/72%-78%. These ratios will be measured billions of years later and will be used as evidence for the Big Bang scenario.

Except for a few electrons that remain to balance the charge of the protons, the electrons and positrons have disappeared. Nuclear processes have stopped. Atoms have not yet formed. The photons are cooling due to the expansion.

Stage 6

Time = 380,000 years
Temperature = 30,000 °Celsius
Form of Matter: atoms, photons, neutrinos, dark matter

Stable atoms of hydrogen and helium begin to form. The photons no longer interact appreciably with the matter and the pressure, which has prevented galaxy formation, subsides. The photons, in particular, will be observed billions of years later (1965) by Arno Penzias and Robert Wilson, who will be given the Nobel Prize for discovering the microwave radiation with just those properties that makes them an important evidence for the Big Bang. By the time of observation, the temperature of the photons will have fallen to 3°Celsius above absolute zero (Fig. 26.10).

From this point forward, matter will remain pretty much the same, but cooling to the eventual overall temperature of 3°Celsius above absolute zero. At a time of about 300 million years, the first stars begin to appear. The newly blazing stars re-ionize the existing hydrogen and helium atoms and the night sky begins to show points of light. Galaxies soon thereafter begin to form and evolve.

But at a time of about 9 billion years, something unexpected happens. The density of the conventional and dark matter has been steadily decreasing as the volume of the universe increases. They have, until this time, had a slowing effect on the expansion rate of the universe. As the universe expands, one expects the mutual pull of gravity to slow the expansion, just as the
pull of the earth’s gravity would slow the escape of a ball thrown into the air. Indeed, astronomers in the 21st century will use the brightness-distance relation for Type Ia supernovae to establish the expected slowing. But, in 1998, Saul Perlmutter and Brian Schmidt will be surprised, almost shocked, to observe Type Ia supernovae that are fainter in brightness than expected, indicating that they are located at larger distances than expected. Skeptical at first, astrophysicists challenge the data but eventually are drawn to the improbable conclusion that the expansion of the universe began to speed up again about 5 billion years ago for the first time since the early inflation. As a cause of the acceleration people will begin a search for some kind of dark energy that permeates the universe. They estimate that it makes up to 73% of the mass-energy of the universe. Together with the dark matter, the two total about 96% of the mass-energy of the universe…and both of a mysterious and unknown nature!

The Steady State Universe

One additional cosmological model has received attention, although it has fallen into disrepute with the accumulating evidence. It is called the Steady State Model of the universe.

The basic idea of the model is that the part of the universe we can observe does not change with time. It is true that the galaxies are moving apart, but the model hypothesizes that matter is spontaneously created to fill in the resulting voids. This newly created matter coalesces into galaxies and then into stars, so that the density of matter in any large volume of space remains essentially unchanged.

The required rate of creation would be modest, about one hydrogen atom per 1000 years in a volume equal to that of a small house. Thus, the required non-conservation of mass does not seem large.

However, the Steady State Model has no explanation for the observed microwave radiation that fills the universe. The Big Bang Model explains this as the remnant of the radiation from the primordial fireball. The Steady State Model also has no way to explain the observed hydrogen/helium ratio. It is also inconsistent with the observed change in expansion rate.

Thus, the Steady State Model does not appear to be a correct model of the universe. It is not likely to receive additional consideration unless new findings rule out the other model.

Summary

After many decades of observation, all available evidence shows that our universe is expanding. The galaxies seem to be moving away from some powerful cataclysmic event, a Big Bang, that occurred about 13.7 billion years ago. While the Big Bang is pretty solidly established, there remain many details of the evolution of the universe yet to be understood.

Historical Perspectives

Is the universe infinite in space and time?

The Aristotelian model of the rotating spheres, which became the cosmology of Christianity up to the time of Copernicus and Galileo, was a bounded universe in space and, in the Christian version, of relatively recent origin. But the Greek philosophers had never been of one mind, even though Plato and Aristotle carried the day. The Stoic philosophers followed Zeno (ca. 4th-3rd century B.C.) and they rejected the bounded Aristotelian machine for a universe of starry matter with finite extent, imbedded in a starless void of infinite extent. Space, beyond that occupied by the matter, was empty and without boundary. On the other hand, the Epicureans followed Epicurus of Samos (342?-270 B.C.), and they held that the universe was of infinite extent and filled with worlds throughout.

However, there is a problem with the Epicurean view if one imagines that both time and space are infinite. This problem was recognized by Thomas Digges in 1576, by Johannes Kepler in 1610, and by Wilhelm Olbers in 1823. Today we refer to it as Olber’s paradox. If the universe were filled with stars that fill space in all directions without end, and if we were to look in any direction, our line of sight would intersect a star.
The Gravitational Interaction:
The name given to Albert Einstein's General Relativity:
The model de Sitter would find a third nonstatic solution in 1931.)

Newton also recognized that the problem was not completely solved by adopting the Epicurean view. The equilibrium that he had created was unstable. Each object was in a precarious balance, and any perturbation would trigger the collapse he wished to avoid. The situation was akin to balancing an infinite number of needles on their ends. We could do it in principle, but with the slightest movement then over they would go. Newton thought that God had avoided this problem by spacing matter at great distances. To avoid the collapse Newton could have envisioned the stars to be in rapid and chaotic motion, much like molecules in a gas. However, in Newton's time when the motion of the earth itself was accounted for, the stars appeared to be fixed in space. Thus, Newton arrived at an infinite universe, uniformly filled with matter. The universe was unchanging, the stars were at rest, and the universe was in precarious balance.

The view of an essentially static, unchanging universe persisted through the 18th and 19th centuries. When Einstein developed his ideas of gravity, relativity, and spacetime in 1915, the static universe idea was so strong that he also looked for a static and stable solution to his equations. But he ran into exactly the same problem that had confronted Newton—the balancing of the needles on end. To find a static solution, he assumed that gravity becomes a repulsive force at large enough distances. There was absolutely no physical basis for doing so, other than to find a static solution, but he built the possibility into his equations. Later, when it became clear that the universe was not static, he would say that assuming gravity to become repulsive at large distance was the greatest mistake of his life and he would remove the possibility from his equations.

It is more than a little ironic, therefore, that when the acceleration of the expansion of spacetime was discovered in 1998 by Perlmutter and Schmidt that people returned to Einstein's equations and found that this "greatest mistake" was exactly what was needed to explain the accelerating expansion. The missing piece would be returned to his equations where it would now describe the presence in the universe of "dark energy."

It thus fell to a Russian, Alexander Friedmann, to find in the year 1922 two solutions to Einstein's own equations that were not static at all, but represented either an expanding or a collapsing universe. (Einstein and William de Sitter would find a third nonstatic solution in 1931.)

While Einstein and Friedmann were worrying about Einstein's equations, things were beginning to happen elsewhere that would have great bearing on the problem. During the early years of this century people began the task of building the great 100-inch telescope at Mount Wilson (1918) and later the 200-inch telescope at Palomar (1948). One of the workers who freighted materials to the Mount Wilson site was Milton Humason, a tobacco-chewing laborer with an eighth-grade education. After the telescope was completed, he stayed on as a handyman and eventually became a respected astronomer. After World War I, Humason was joined by the brilliant and polished Rhodes Scholar Edwin Hubble. Together they began studying the spectra of the galaxies and discovered the redshift, that was soon interpreted as a Doppler shift of rapidly receding galaxies (ca. 1926).

When the experimental evidence for the redshift was joined with Friedmann's solutions of the Einstein equations, the Big Bang was born. In Friedmann's first model the universe expands, stops, and then recollapses. In this model the universe is finite, but without boundary (like the two-dimensional surface of a globe). In his second model, the galaxies move apart slowly but never stop. The Einstein-de Sitter solution is critically balanced on the edge between these two possibilities. In the latter two, space is infinite. In all three, time has a boundary—the Big Bang. The Big Bang is a singularity in spacetime, a place where the curvature of spacetime is infinite and the concepts of space and time cease to have meaning.

STUDY GUIDE
Chapter 26: Cosmology: How the Universe Works

A. FUNDAMENTAL PRINCIPLES
2. General Relativity: The name given to Albert Einstein's extension of the Special Theory of Relativity to include gravity. In the theory, the gravitational force is seen to be a geometrical consequence of the curvature of spacetime by the presence of mass-energy.

B. MODELS, IDEAS, QUESTIONS, OR APPLICATIONS
1. The Big Bang Model of the Universe: The model of the universe that accounts for the observed recession of the galaxies from one another as an
expansion of spacetime from an earlier epoch of extremely high density and high temperature.

2. **The Steady State Model of the Universe**: The model of the universe, now discredited, in which the universe expands in an infinite and unchanging process. The density of the universe is maintained by an ongoing creation of small amounts of hydrogen that are injected into space.

3. How is the distance to moons, planets, stars and galaxies determined?

4. How is the relative motion of stars and galaxies determined?

5. Why do many believe in an expanding universe?

6. What is the difference between Einstein’s interpretation of gravity and Newton’s interpretation of gravity?

C. **GLOSSARY**

1. **Absolute Brightness**: The actual brightness of a star as one would judge if all stars were observed from the same distance (32.6 light-years).

2. **Apparent Brightness**: The brightness of a star as it appears as a consequence of its actual distance from earth.

3. **Brightness-Distance Measurement**: Name given to a method for measuring distances to stars in our galaxy and some stars in nearby galaxies by comparing the star’s absolute brightness (inferred form some observable characteristic of the star such as its color or pulsation period) to its apparent brightness.

4. **Cepheid Variable**: A class of pulsating stars for which the rate of variation of the brightness is correlated to the average absolute brightness of the star. Knowledge of the absolute brightness of the stars allows one to determine the distances to them.

5. **Cosmological Inflation**: A super-rapid expansion of spacetime in the first \(10^{-32}\) seconds after the Big Bang. It is postulated in order to account for the remarkable uniformity of the universe.

6. **Cosmological Redshift**: The name given to the observation that the spectra of sources of light in virtually all distant galaxies is shifted toward longer wavelengths than the wavelengths in spectra of stationary sources. The Cosmological Redshift is usually interpreted as a Doppler shift in the observed light.

7. **Cosmology**: The study of the origin and evolution of the universe.

8. **Curved Spacetime**: Within Einstein’s General Theory of Relativity, the presence of mass-energy gives curvature to four-dimensional spacetime in an analogous fashion to what a heavy ball bearing would do to a two-dimensional space if placed onto a stretched rubber membrane.

9. **Dark Energy**: A still not understood form of energy thought to permeate the universe and to be responsible for the observed accelerating expansion of spacetime over the past 5 billion years. It is currently thought to account for 73% of the mass-energy in the universe.

10. **Dark Matter**: A still not understood form of gravitating mass in galaxies whose presence is evident in the observed motion of visible interstellar matter as it revolves about the center of a galaxy. It is currently thought to account for 23% of the mass-energy of the universe.

11. **Doppler Effect**: The shift in frequency of a wave as a consequence of the relative motion between the source and the observer.

12. **Expanding Universe**: The interpretation that if the Cosmological Redshift is a Doppler shift, then the galaxies of the universe are moving apart from one another, i.e., the universe is expanding.

13. **Galaxy**: Name given to a gravitational structure of individual stars, usually numbering in the billions, and separated from other similar structures by distances of the order of a million light-years.

14. **Hertzsprung-Russell Diagram**: A graph of a correlation between the color (temperature) of a star and its absolute brightness. Knowledge of the absolute brightness of stars (as obtained from the diagram by observation of their color) allows one to calculate the distance to them.

15. **Olber’s Paradox**: An expected, but unobserved consequence of a universe that is infinite in both space and time. If the universe were infinite in space and time and filled with stars, the starlight from the stars would be expected to make the night-time sky as bright as noonday.

16. **Radar Ranging**: Name given to a method for measuring distances to nearby members of the solar system by bouncing a radio or laser signal from the object and measuring the time of flight of the signal.

17. **Spacetime**: The combination of the three dimensions of space and the dimension of time into a four-dimensional “world”. In Einstein’s General Theory of Relativity, gravitation is understood as a consequence of the curvature of spacetime caused by the presence of mass-energy.

18. **Triangulation**: Name given to a geometrical method for measuring distances to nearby stars within our own galaxy.

D. **FOCUS QUESTIONS**

1. Describe three procedures for measuring distances to planets, stars and galaxies. For each procedure, indicate the range of distances that can be studied.

2. Consider the Big Bang Model of cosmology: a. Describe three important observations that can be explained by the model.
b. Outline the model. Include a description of changes in composition and structure, density, temperature, and size of the universe with increasing time.
c. What does the model predict about the future of the universe?

E. EXERCISES

26.1. Describe the Doppler effect.

26.2. The horn of a moving car is sounding. Use the Doppler effect to describe and explain the changes in the tone heard by a pedestrian as the car passes by.

26.3. Light from hydrogen atoms in a particular star seems to be bluer than from hydrogen atoms in the earth’s atmosphere. What can you conclude? Explain your answer.

26.4. Why would it be important to know the diameter of the earth’s orbit before measuring the distance to the stars?

26.5. Explain how you might measure the height of a nearby mountain without climbing it.

26.6. How can electromagnetic radiation be used to measure the size of the solar system?

26.7. What is meant by the “cosmological redshift”?

26.8. Describe the evidence that indicates that the universe is expanding.

26.9. If the Big Bang Model were valid, why might we expect the rate of expansion to become slower as the matter separated? What does dark energy do?

26.10. What does the cosmological redshift suggest about the universe? Explain your answer.

26.11. Summarize the “Big Bang” model of the universe.

26.12. Summarize the evidence which supports the Big Bang Model of the universe

26.13. Why does it seem unlikely that the Steady State Model is valid?

26.14. At approximately what time after the Big Bang
   (a) do nucleons form?
   (b) is the neutron/proton ratio frozen at its current value?
   (c) does the microwave radiation separate?
   (d) do atoms form?

26.15. Which of the fundamental interactions in nature reveals the existence of dark matter?

26.16. Describe the Steady State Model of the universe.

26.17. Why does Olber’s Paradox suggest that the universe is either not infinite in time, or not infinite in space, or both?

26.18. What is wrong with a universe that is static, but not infinite?

26.19. What is wrong with a universe that is static, but infinite?

26.20. Give an example of an unbounded, finite (closed) space. Give an example of an unbounded, infinite (open) space. What essential feature of the universe is thought to determine whether it is open or closed?

26.21. The universe is thought to be expanding. What is the best evidence for this?
   (a) cosmological redshift
   (b) background radiation
   (c) gravitational slowing of expansion
   (d) electrical repulsion
   (e) He/H abundances

26.22. List three observed, physical puzzles associated with the cosmologies we have described that remain unanswered by what we have described.

26.23. Which one of the following is “acceptable” in both the Big Bang and Steady State Models?
   (a) background radiation
   (b) He/H abundances
   (c) universe is expanding
   (d) expansion rate is slowing
   (e) matter is created spontaneously