Chapter 11: Big Bang Cosmology

The discovery of the redshift-distance relation in 1927, by Georges Lemaître based on Hubble's data, created a great stir among astronomers and physicists. However, only some cosmologists were ready to accept Friedmann's expansion of space as the correct explanation. One concern was that it implied a beginning to the universe, a time when everything was crushed together. For centuries, most cosmologists — including Newton and Einstein — had assumed that the universe was in a steady state. It therefore took several decades for a completely novel model of the universe, and new supporting evidence for that model, to convince cosmologists that the universe indeed started about 14 billion years ago and has been expanding ever since.

The Big Bang Model

In the 1940s, George Gamow proposed that the universe not only had a beginning, but that is was a very exotic one. If the universe is made mainly out of gas — stars, for example, are just big balls of hot, dense gas — then an expanding universe must do what expanding gases do: cool (see Box 11-1). This implies that the universe started out in an extremely hot, dense state and has been cooling as it expands. If this is true, then the scientific version of the first lines of the book of *Genesis* could read: "In the beginning the universe was extremely hot and extremely dense. It was expanding, and has been expanding and cooling ever since."

Despite its logical foundation based on a solid observational result, Gamow's "Big Bang" model was at first considered by most cosmologists to be too radical to be the correct description of the universe. However, since 1964 the evidence in favor of the Big Bang model has become quite strong, as we will discuss later in this chapter. In anticipation of that discussion, we will proceed to describe the evolution of the universe under the assumption that it has expanded from an early extremely hot and dense state similar to that described by Gamov's model.

Box 11-1. Cooling of expanding gases

Our understanding of the history of the universe depends critically on the behavior of expanding gases. The kinetic energy of the expansion needs to come from somewhere, since energy is a conserved quantity in an isolated system. The thermal energy of the gas is available for this purpose. Some of the kinetic energy of the sub-microscopic motions of the gas atoms and molecules is transferred to the kinetic energy of the expansion of the system.

This principle is used in many refrigeration systems. Gas is pumped by an electric motor from a thin pipe into a fat one, with the fat one placed in the location we want to keep cool. (The motor and the thin pipe need to be in a place where the heat they release isn't a problem.) The expanded gas is cold relative to its state when it was in the thin pipe. Another demonstration of this principle is to discharge a carbon dioxide fire extinguisher. What starts out as compressed CO_2 gas at room temperature in the container becomes frigid dry ice when it expands into the air.

Figure 11-1. A carbon-dioxide fire extinguisher at room temperature releases CO_2 gas into a room. As the gas expands, it cools so much that it turns into dry ice, which is frozen CO_2. [Source: http://www.phys.ufl.edu/demo/4_Thermodynamics/C_ChangeofState/AdiabaticExpansion.jpg]

The opposite is also true: compressing a gas heats it up. This is how diesel engines work. Rather than using spark plugs to supply the high temperature needed to ignite the fuel, diesel engines compress the fuel until it ignites. A similar effect occurs when you pump air into a bicycle tire or basketball. The base of the pump becomes hot from the compression of the gas caused by your pumping of the handle.

The relation between the temperature of the gas and its density depends on the composition of the gas. If it is mainly made up of individual particles smaller than molecules, *e.g.*, atoms, then the temperature T is proportional to the density ρ raised to the power of 5/3: $T \propto \rho^{5/3}$. This is true if the mean kinetic energy per particle is less than the rest-mass energy, *i.e.*, if the gas is non-relativistic. In the case of hotter, relativistic gases, the power is 4/3 instead of 5/3.

Progression of the Universe According to the Big Bang Model

During the very early stage of the universe, the temperature was so high that the universe was like a constant high-energy particle physics experiment. It consisted of photons plus other elementary particles, their anti-particle counterparts, and force fields. "Ordinary" matter such as atoms had not yet formed. These photons and particles were colliding with each other at very high speeds, and the collisions caused them to change form, as illustrated in Figure 11-2. For example, when two very high-energy photons (γ rays) collide, they are often converted into a particle–anti-particle pair. The reverse occurs as well, with particles and anti-particles annihilating each other and producing photons. However, the universe eventually cooled so much that the photons no longer possessed enough energy to create even the lowest-mass particles. The anti-particles that had been created all annihilated with their particle counterparts, with only a small fraction of the matter particles surviving. Since then, the number of matter particles has remained essentially constant. After this point, the photons simply passed by each other with no interaction.

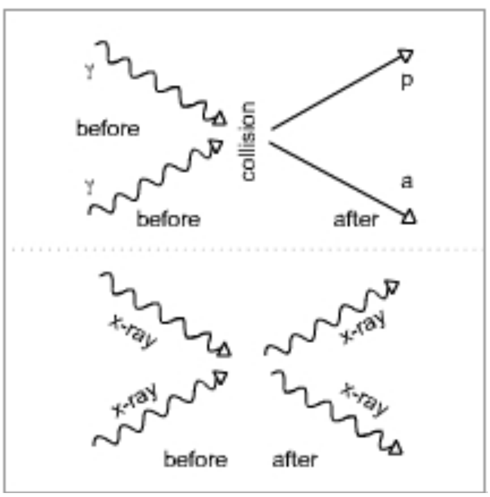

Figure 11-2. Schematic diagram of what happens when two photons pass by each other. *Top:* If the combined energy of the photons is greater than twice the rest mass of a particle, the photons can collide and change into the particle and its anti-particle. *Bottom:* However, if the initial photon energy is too low to do this, the photons will continue past each other with no interaction.

As the universe cooled even further, ultraviolet or X-ray photons striking atoms that had formed could be absorbed by those atoms. The absorbed energy was transferred to the electrons in the atoms, causing them to either escape the atoms (ionization) or jump to higher energy levels (excitation). However, at a still cooler stage, when the photons no longer had enough energy to ionize or excite atoms, they simply passed by the atoms with no interaction.

In summary, the primary physical processes governing matter changed as the universe expanded and cooled. Elementary particles and force fields eventually transformed into atoms. Photons that initially interacted closely with matter and anti-matter particles eventually became free of these interactions. After photons were no longer able to make particles and anti-particles, the anti-particles were eliminated by annihilations with matter particles.

Chronology of the Evolution of the Universe: Overview

We proceed to lay out the history of the universe by describing the main phases in its evolution. All times t listed are rough estimates; the temperature T of the universe is the main factor that determines its state at any given epoch. This is because the temperature is a measure of the average energy per particle.

For the first hundredth of a second after the Big Bang started, the universe was a vast, ultra-dense "sea" of particles and force fields. At first the energies were so high that particles of all the different varieties were continuously changing from one type to another, so that they were essentially indistinguishable from each other. The forces all acted the same as well. But as the temperature cooled during the first second, there was no longer enough energy to make all the particles. This occurred first to the most massive particles and then to the lighter ones. As this happened, the forces became distinct, first gravity, then the strong force, and finally the weak interaction and electromagnetic force.

After the first hundredth of a second, the universe that we know today began to emerge. Quarks connected by gluons made protons and neutrons, then electrons eliminated their positron partners. By a few minutes after the Big Bang started, some of the protons and neutrons had combined to form the very lightest atomic nuclei. 400,000 years later, electrons joined the nuclei to make atoms of hydrogen, helium, and a trace amount of lithium and beryllium. By the time the cosmos was a half billion years old, galaxies with billions of stars had coalesced from gravitational collapse of the denser regions of the universe.

All the while, the universe was expanding, mostly at a pace similar to what we now witness in the form of the redshift-distance relation called the Hubble Law. But cosmologists think that, for a very brief instant, the universe inflated by roughly 10^{50} times following a colossal conversion of potential to kinetic energy in the vacuum of space.

Before about 0.000001 s after the expansion started, when the temperature was higher than about 10^{13} K, the conditions were more extreme than can be explored even with the most powerful particle accelerators on Earth. At still earlier stages, any statements that we make are more speculative, although based on "reasonable" models of the behavior of particles and fields at very high energies.

Chronology of the Evolution of the Universe: The Major Stages

Planck Epoch, $t \approx 10^{-43}$ s, $T \approx 10^{32}$ K: Before this time, gravity is thought to have been unified with the other forces so that there was only one force field in the universe. Because there is not yet a complete theory that combines quantum theory with gravity, we cannot yet describe this even earlier period. When the temperature lowered to approximately 10^{32} K, <u>gravity became distinct from the other forces</u>.

Epoch of Inflation, $t \approx 10^{-36}$ s, $T \approx 10^{28}$ K: Between the Planck epoch and this point, the strong nuclear force, the weak interaction, and the electromagnetic force — but no longer gravity — were unified. During this period both high- and low-mass particles, along with their anti-particle counterparts, were continually created as well as annihilated. As the temperature of the universe dropped below 10^{28} K, the strong nuclear force split from the weak interaction and electromagnetic force. At about this time, the universe is thought to have entered a temporary unstable state called a "false vacuum." This means that there was a substantial amount of potential energy in space, similar to what happens to water when it is cooled below 0 °C faster than it can freeze. In the case of water, it soon freezes very suddenly, releasing energy in the form of heat as the molecules settle into the lower energy state of ice crystals. According to a popular hypothesis (discussed more in a later section), the potential energy of space was suddenly converted into kinetic energy, causing an extremely rapid, temporary period of expansion of the universe that was much faster than the rate at which it was already expanding. This is referred to as <u>**Inflation**</u>.

After Inflation, which we discuss further later in this chapter, the universe resumed its previous rate of expansion. The next important stage of the universe occurred after it cooled much further, although this still took only another instant. From this point on, we have more confidence in the description since it is based on physics that we can observe in laboratories on the Earth.

"Primordial Soup" of Particles, $t \approx 10^{-11}$ s, $T \approx 10^{15}$ K: At this time, the temperature had dropped to the point that the electromagnetic and weak forces became distinct, so that all four of the fundamental forces have acted separately from this point on. The universe was composed of high-energy photons (γ rays), as well as various particles and their anti-particle counterparts interacting with each other through the forces. The particles and their anti-particles were continually colliding to create photons plus various types of particle–anti-particle pairs, and the photons in turn were continually colliding to make pairs. The universe at this stage was therefore composed of interacting particles and anti-particles, plus the four force fields.

Formation of Protons and Neutrons, $t \approx 10^{-5}$ s, $T \approx 10^{12}$ K: About 10 μs after the universe's expansion began, the energy of collisions with photons and other particles was too weak to break apart protons and neutrons when they were created by up and down quarks combining under the influence of the strong force via the action of gluons (see Chapter 8).

Annihilation of the protons and neutrons that already existed annihilated with their antimatter counterparts. If matter and anti-matter had been perfectly symmetric – that is, if particles and anti-particles had existed in equal numbers – then only the low-mass particles like electrons and positrons (anti-electrons) would have remained. However, for reasons that are not 100% clear, there is a slight asymmetry in the interactions of particles that caused normal matter to outnumber antimatter by one part in a billion. Therefore, after all the anti-quarks annihilated with quarks, there were still some quarks left over to make protons and neutrons. However, because of this epoch of anti-quark annihilation, there are about 1 billion times more photons in the universe today than there are protons and neutrons.

Annihilation of Anti-matter, $t \approx 2$ s, $T \approx 3\text{x}10^9$ K: Processes such as γ-ray photon collisions with other γ rays create as many anti-matter particles as they do matter particles. However, a slight asymmetry in processes such as the decays of unstable particles led to a slight excess of matter over anti-matter: for every billion anti-particles (e.g., anti-protons) there were a billion plus one "ordinary" particles of the same type (e.g., protons). Shortly after 1 s had elapsed since the expansion began, the energies of the photons had become low enough that they were X-rays rather than γ rays. As a consequence, they were no longer capable of making electron-positron pairs (see Fig. 11-2, bottom). The remaining positrons annihilated with electrons until essentially none were left and only about one-billionth of the original electrons remained. The anti-protons and anti-neutrons had already annihilated with their matter counterparts by this time. Since the photons outnumbered the ordinary matter particles by about one billion times, there was much more energy in X-rays than in the mass-energy of the matter at this stage.

Era of Nucleosynthesis, $t \approx 1$-4 min, $T \approx 1\text{x}10^9$ K: Once the temperature of the universe fell to about a billion degrees Kelvin, the collisions between protons and neutrons or other protons were at velocities low enough to allow the strong force to bond the nucleons together. The nucleons then formed nuclei slightly more complex than simple hydrogen. Subsequent collisions were not energetic enough to separate these nuclei. This is called the Era of Nucleosynthesis. A substantial number of helium nuclei were made this way — about 10% the number of hydrogen nuclei, so that the mass in helium was about 30% that of hydrogen. Small amounts of deuterium ($^2_1$H), lithium (Li, atomic no. 3), and beryllium (Be, atomic no. 4) were synthesized as well. Essentially none of the nuclei of heavier elements existed until they were made inside stars at a much later stage. The amount of deuterium that survived this period was controlled by the density of the universe at this epoch: denser conditions would have favored collisions that destroy deuterium nuclei, resulting in a lower abundance. Because of this, the observed deuterium abundance in the cosmos is a sensitive indicator of the density at this stage.

Epoch of Formation of Atoms ("Recombination"), the Transparent Universe, $t \approx 400{,}000$ yr, $T \approx 3{,}000$ K: After the temperature dropped below about 3,000 K, the photons and electrons no longer had enough energy to ionize or excite hydrogen and helium atoms as they passed by (see Fig. 11-3). Once a bare nucleus captured an electron to form an ion or atom, there was no source of energy for the electron to absorb and jump to a higher energy level or exit the atom entirely. After this point, the photons ceased to interact significantly with matter. The universe had become transparent after forming neutral atoms.

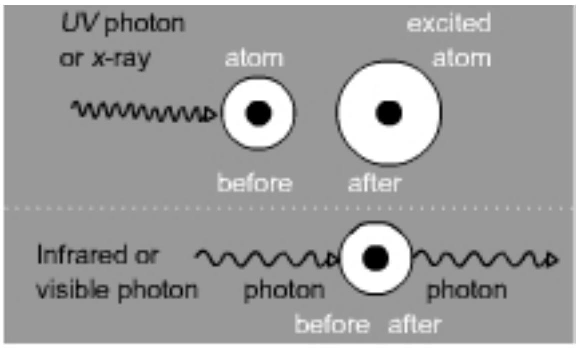

Figure 11-3. *Upper panel:* collision of an ultraviolet or X-ray photon with an atom. The photon is absorbed, while the electron either jumps to a higher energy state (excitation), as shown here, or leaves the atom altogether (ionization). *Bottom panel:* After about 400,000 yr since the start of the Big Bang, photons no longer had enough energy to interact with atoms, so they just passed on by without any change.

Because only about one-billionth of the matter particles survived the epochs of annihilation, the photons now outnumber the matter particles by a billion to one. Since the universe was opaque before this time, the spectrum of the light should follow that of a blackbody. **The Big Bang model therefore predicts that the universe should be full of photons with the spectrum of a blackbody.**

Formation of Galaxies and Stars, $t \approx 10^9$ yr: By half a billion years after the beginning, galaxies were forming from the gravitational collapse of regions with higher density than their surroundings. The mass of such regions needed to be high enough that the gravitational force could overcome the spreading out of material by the overall expansion of the universe.

This highlights an important point: the Hubble Law only affects motions of unrelated galaxies relative to each other. ("Unrelated" means not in the same cluster or group.) Gravity holds together planets, stars, planetary systems, galaxies, and even clusters of galaxies, so that they do not expand as space spreads out.

Evidence Supporting the Big Bang Model

The Big Bang Model is extraordinarily exotic, much more so than any of the ancient cosmological myths and theories. Some of the ancient ideas are vaguely similar, though. For example, Anaximander of ancient Greece proposed that the universe evolved from an initial state of chaos to the present order. However, none envisioned the ultra-hot "primordial soup" of photons, particles, and anti-particles, continually colliding at temperatures of trillions of degrees, changing form and acting under the influence of force fields. Since it stretches human imagination so much, it is proper to demand that the Big Bang model be supported by compelling evidence.

1. *The Big Bang Model explains the Hubble Law as a consequence of the expansion of the universe.* Recall that Friedmann's model of expanding space preceded Hubble's discovery of the redshift-distance relation. The Big Bang model is basically a detailed description of the consequences of the expansion of the universe that Friedmann proposed and Hubble confirmed.

2. *The Big Bang model predicted the existence of a background of microwave photons with the spectrum of a cold blackbody. This has been verified by observations.* Gamow predicted that the universe should be full of photons that were released when the universe became transparent about 400,000 years after the

expansion began. Furthermore, since the universe was opaque before this time, the spectrum of this cosmic background radiation should be that of a blackbody. Gamow calculated that the temperature of this blackbody should be quite low, from a few K to perhaps 20 K, but the rate of expansion was not known well enough in the 1940s to calculate the temperature accurately. Still, this range of temperatures predicted that the intensity of the radiation should be greatest at wavelengths of millimeters to centimeters — the "microwave" part of the radio portion of the electromagnetic spectrum.

Detection of a nearly uniform background of radio waves from all directions is, in fact, rather difficult, since there is almost no contrast from one direction to another and it requires blocking out non-cosmic sources of microwaves. In 1964, Arno Penzias and Robert Wilson of Bell Laboratories built a type of radio telescope that could do this. Their goal was to measure any cosmic sources of static that might interfere with microwave communications from future satellites in space. After painstakingly removing or

Figure 11-4. Arno Penzias (left) and Robert Wilson standing in front of the radio receiver that first detected the Cosmic Microwave Background (CMB) radiation. The odd shape of the antenna is designed to shield the instrument from stray microwaves emitted by sources on the ground. In 1978, Penzias and Wilson won the Nobel Prize in Physics for their discovery. [Source: www.emu.dk]

taking into account sources of radiation in their instrument — including cleaning out pigeon droppings from inside the antenna! — Penzias and Wilson still detected microwaves that seemed to come from every direction. Communication with cosmologists led them to understand that they had detected the Cosmic Microwave Background (CMB) radiation, the signature of the Big Bang predicted by Gamow.

Verification that the spectrum has a blackbody shape took quite some time, since the Earth's atmosphere is not very transparent at the CMB's wavelengths. The matter was settled in 1992 when the Cosmic Background Explorer (COBE) satellite measured the spectrum accurately: it has a nearly perfect blackbody shape (see Fig. 11-5)! The temperature of the blackbody is 2.73 K, which we can consider to be the present temperature of the universe.

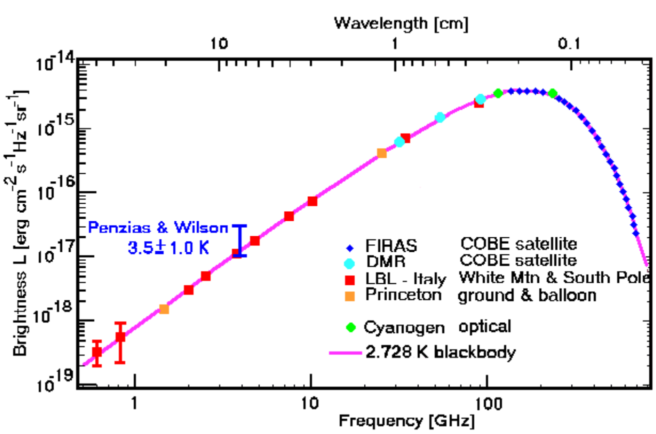

Figure 11-5. Spectrum of the Cosmic Microwave Background (CMB) radiation. The light purple curve indicates the spectrum of a blackbody with a temperature of 2.73 K. Astronomers interpret this as the current temperature of the universe. [Source: ircamera.as.arizona.edu]

Since the spectrum of the CMB has a well-defined peak at a wavelength of about 2 mm, any motion relative to this radiation can be measured with the Doppler effect. That is, we can determine the combined velocity of the Earth's orbit around the Sun, the Sun's orbit around the Galactic Center, the Milky Way's motion in the Local Group of galaxies, and the Local Group's motion through the cosmos by measuring the exact wavelength of the peak in different directions. This will be at shorter wavelengths in the direction toward which we are moving relative to the CMB, and at longer wavelengths in the opposite direction. The measurement by COBE indicates that the Milky Way is moving in the direction of the constellation Leo at about 400 km/s.

3. *The abundance of helium in the oldest stars matches the value from the Big Bang model.* Another prediction of the Big Bang Model is that about 30% of the mass of the ordinary matter in the universe should be composed of helium. The helium nuclei were created during the era of nucleosynthesis a few minutes after the expansion started. This prediction agrees with measurements of the helium abundance in various types of old stars. Furthermore, the theory of stellar evolution, which agrees well with observations of stars, cannot explain the creation of such a large amount of helium through nuclear fusion reactions in the cores of stars. The Big Bang Model also predicts roughly the amount of deuterium ($^2_1$H) that is observed, although the deuterium abundance is more difficult to measure than that of helium. Furthermore, the amount of deuterium expected depends on the density of the universe when the temperature was optimal for nucleosynthesis (see the description above of the era of nucleosynthesis).

4. *The Big Bang model explains why the night sky is dark* (the dark night sky paradox). Recall that this is a problem for a universe that has an infinite size and has existed forever. In this case, starlight should have filled the universe and the night sky should be bright in every direction. The Big Bang Model avoids this since the stars have not existed forever: the first stars and galaxies formed somewhat more than 13 billion years ago — about half a billion years after the Big Bang started. Because of this, beyond about 13.2 billion lt-yr from the Earth there simply were no stars at the time the light would have had to be emitted in order to reach us today. In other words, there has not yet been enough time for starlight to fill the universe. In most directions in which we can look, no stars ever existed; our eyes only see darkness in these directions.

Evidence against the Steady-State Models

The Big Bang model has therefore been the prevailing theory of the cosmos since the mid-1960s. The other main competing hypothesis was the steady-state cosmology of Bondi, Gold, and Hoyle. In this model the universe has existed forever in its current state; it has always been expanding, although not from an initially hot, dense state. This requires some modifications to the laws of physics, but these are perhaps no less strange than the description of the early universe under the Big Bang model. The main evidence against the steady-state model is that it predicts that the universe at great distances — and therefore at earlier times as we view them — should be the same as it is today. Galaxies should appear the same and the densities of certain types of galaxies — *e.g.*, ones that are bright at radio frequencies — should be similar to those in the local universe. Observations indicate, however, that this is not the case. Instead, the universe is evolving such that galaxies today are quite different from galaxies as they were billions of years ago.

Our Cosmic Horizon

We can only observe a section of the universe. Our cosmic horizon is set by the most distant object whose light has had time to reach us. Since the universe is 13.7 billion years old, this must correspond to 13.7 billion light years. However, the most distant luminous objects that we have seen are about 13.2 billion lt-yr away, so the light we now observe left them about half a billion years after the universe started to expand. Astronomers estimate that there are about 2 trillion galaxies within our cosmic horizon.

Inflation stretched out space enormously, and the current expansion continues to do so. Because of this, the part of the universe that we can see now is just a tiny fraction of the whole, and we will never receive light from most of the universe.

Problems Solved by Inflation

The basic Big Bang model, with the rate of expansion changing slowly with cosmic time, leaves unexplained some features of our universe. One is that space-time can be quite curved theoretically, but is observed to be nearly flat or perhaps even exactly flat. Recall from Chapter 9 that this means that the shortest distance between two points in the general universe (i.e., not close to a massive object) — a geodesic — is very close to being a straight line. Another issue is the uniformity of fundamental physical constants such as Newton's gravitational constant. This includes the constants that determine the wavelengths of spectral lines, which we observe to be the same out to very great distances in all directions. Our model should explain how the different regions of the universe could communicate with each other to average out differences in these constants that may have existed at the start. Finally, one would expect a mixture of fundamental particles to be completely homogeneous so that the density is the same everywhere. Yet we now observe a clumpy universe, with galaxies and clusters of galaxies.

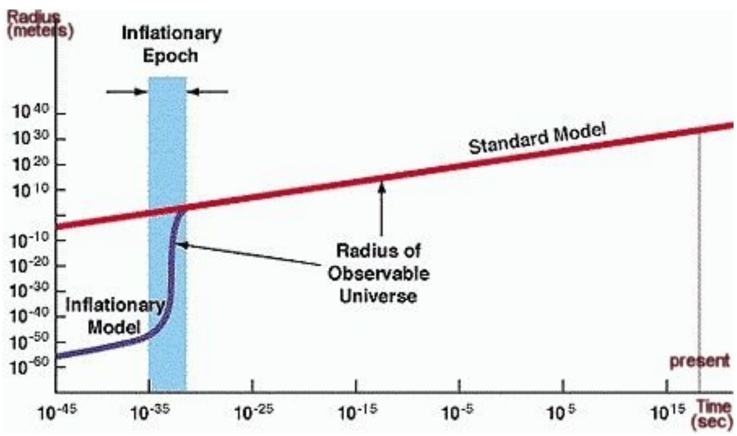

Figure 11-6. Size as a function of cosmic time of a section of the universe. The size increased greatly during the period of Inflation. "Standard Model" refers to the basic Big Bang model without Inflation, while "Radius of Observable Universe" refers to the section of the universe that we can see at the present epoch. [Source: www.Universe-Review.ca]

The proposed solution to these problems is the epoch of Inflation mentioned in the chronology above. The universe is imagined to have had a very brief interval of time when the expansion suddenly sped up so that the universe stretched by an enormous amount — roughly 10^{50} times. This stretching flattened space-time. As an analogy, consider a basketball. The curvature of its surface is obvious. Now look at the ground outside. Although you see hills and depressions, the curvature of the spherical Earth is not at all obvious. This is because the Earth is large compared with how far we can see easily when standing on the ground. So, the curvature of larger objects is less than that of smaller ones (see Fig. 11-7). Cosmologists think that Inflation increased the size of the universe so much that any initial curvature was stretched out beyond recognition. As a consequence, the current universe is extremely flat.

The rapid expansion during the ultra-brief epoch of Inflation made the basic properties of the universe nearly uniform across vast regions. Consider a section of the universe that was small enough so that the influence of the force fields was the same throughout the section before Inflation. Since information about force fields is transmitted at the speed of light, this requires simply that the size of the section was smaller than the speed of light times 10^{-35} s, or $3\text{x}10^{-27}$ m. This is smaller than our currently observable section of the universe was at 10^{-35} s according to the basic Big Bang model. But it is larger than the same section was at that time according to the model that includes Inflation (Fig. 11-6). Such a region would therefore have uniform physical properties. Inflation then expanded this region by 10^{50} times; since then, the universe has expanded further, although more slowly, so that the region is now huge. The Inflation model therefore provides an explanation of why the universe appears to be roughly the same everywhere we look in the vast section of the universe that we can observe.

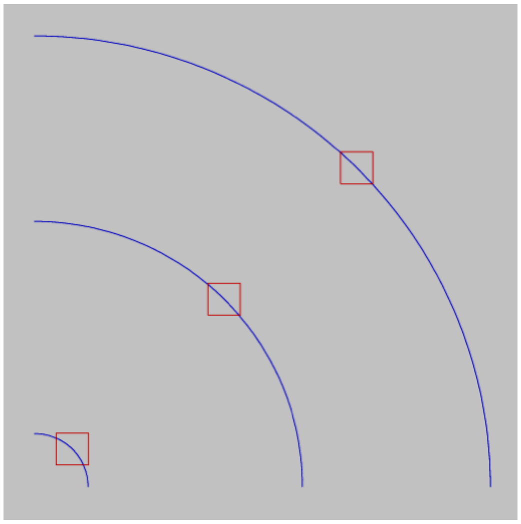

Figure 11-7. The curvature of a sphere or circle is only apparent when the radius is not many of orders of magnitude larger than we can see. Note how the section of the circle inside the square becomes straighter as the radius of the circle increases. According to current cosmological theory, Inflation did the same to the universe, making space-time very flat.

How could such drastic expansion of the universe occur? An analogy is the state of water after its temperature has dropped rapidly to below 0 ˚C but before it turns to ice. Since ice is a lower energy state of water than liquid is at such temperatures, there is a potential energy that is converted to another form of energy (heat in the case of ice) as the water freezes. Ice can start forming at any time, at which point the water undergoes a phase change from liquid to solid. This has two effects: the release of energy (for ice, the energy is called the "latent heat of fusion") and cracking because the ice expands while the density and temperature — and therefore its strength — are not perfectly uniform. According to the Inflation picture, the universe underwent such a phase change shortly after the strong force became distinct from the electromagnetic and weak forces. The energy that was suddenly released caused an extremely rapid, temporary phase of expansion much faster than the rate at which the universe was already expanding. In the case of universe, the analogy to the cracking of ice as water freezes is the creation of regions of different density — higher-density "lumps" and lower-density "bubbles." The difference between the lumps and the average density was only about 1 part in 100,000. Nevertheless, as is discussed in more detail in Chapter 12, cosmologists think that this was sufficient for the lumps and bubbles eventually to form regions rich in galaxies as well as other regions that are nearly devoid of galaxies.

Acceleration of the Expansion and Dark Energy

Although we do not understand why the universe is expanding, we do know from General Relativity that gravity should counter that expansion. This is because mass bends space-time, while space-time forms the lattice through which masses move. Hence, mass and space-time are tied to each other. For this reason, it is natural to expect that the expansion should have decelerated as the universe aged. It is actually possible to determine directly whether this is the case.

When we observe distant galaxies, we are looking back in time, since the light that we detect left that galaxy long before it reached us after traveling across space. If the expansion has been slowing down, then the value of the slope of the velocity *vs*. distance graph should be higher at very large distances corresponding to times closer to the beginning of the Big Bang. That is, if the rate of expansion were higher in the past, the graph would curve up rather than remain a straight line. In this case, Hubble's "constant" would not really be constant.

Actually, when we observe extremely distant galaxies it is no longer convenient — or even correct — to use velocity on the Hubble Law graph (Fig. 10-2). Rather, astronomers usually plot on the horizontal axis the redshift z, which is defined in equation (10-3). One plus the redshift ($1+z$) (see eq. 10-2) corresponds to how many times the universe has expanded since the light we now observe left the galaxy that emitted it. For example, for a galaxy at a redshift $z=3$ (so $1+z = 4$), the universe has expanded by 4 times during the time it took for the light to travel from the galaxy to us. On the vertical axis astronomers often plot the brightness of the object, which is the quantity that they measure when they determine the distance through use of equation (6-2).

Figure 11-8 shows the graph of the brightness of a number of Type Ia supernovae (a type of exploding star) vs. redshift z. Although the data points are somewhat scattered in the crucial upper right-hand corner, the observations agree better with the case in which <u>the expansion of the universe is</u> <u>accelerating</u>.

What could cause the expansion of the universe to accelerate? There must be some property of the universe or some force that is stronger than the combined gravity of all the matter in the universe. Recall from Chapter 10 that Einstein included such a property, which he called the <u>Cosmological constant</u>, in General Relativity. This would need to have strange properties to remain constant while the volume of the universe increases. An alternative, nicknamed "ether," is some hypothetical property of space that would provide the tendency to expand, perhaps similar to the potential energy that fed the period of Inflation. In either case, the mystery is deep, and cosmologists refer to the accelerating factor as "<u>dark energy</u>". They usually use the symbol Λ for the dark energy, although originally Λ referred only to the specific form of the Cosmological constant that Einstein proposed.

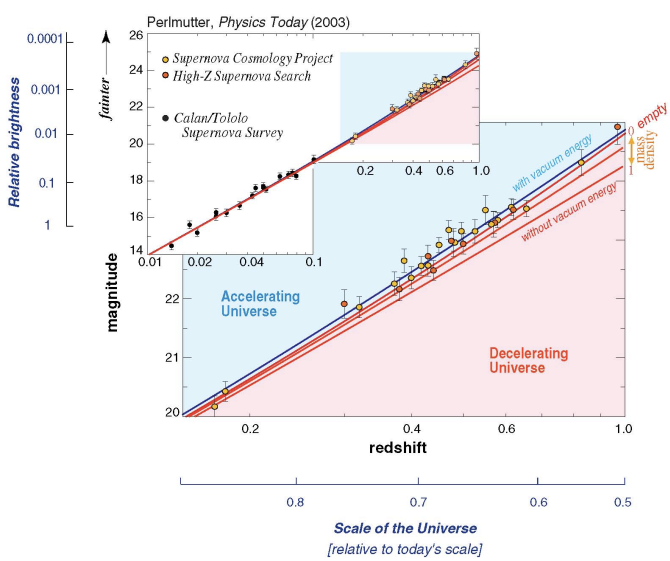

Figure 11-8. Graph of brightness (on a logarithmic scale called "magnitude") *vs*. redshift of Type Ia supernovae in distant galaxies. As explained in Chapter 6, these exploding stars serve as "standard candles" for measuring distances. If the expansion of the universe were neither speeding up nor slowing down, the line dividing the pink and blue sections would fit the data. Instead, most of the data points lie a bit above the line, in the blue section corresponding to an accelerating expansion. There are two nested plots: the upper left one shows data for redshifts from 0 to 1, while the larger plot in the lower right is a blow-up of the colored section in the upper right of the smaller plot. [From S. Perlmutter et al., http://www-supernova.lbl.gov/public/figures/bigcomposite.jpg]

Cosmologists express densities of matter and the dark energy in terms of a **<u>critical density</u>** whose value is about 9×10^{-27} kg/m^3. This is equivalent to about 5 hydrogen atoms per cubic meter, almost an empty vacuum. The actual density divided by the critical density is given the symbol $\mathbf{\Omega_0}$. As with Hubble's constant, the subscript "0" refers to the current value. The critical density is the density needed to give space-time a flat geometry. If there were no accelerating dark energy, the critical density would be the density of matter at which gravity would be strong enough to stop the expansion eventually — just barely at an infinite time in the future.

The normal matter in the universe — stars, etc. — has a density of only about $0.05\Omega_0$. In addition to familiar forms of matter, astronomers have detected non-luminous dark matter from the gravitational influence that it has on galaxies. Dark matter is probably composed of some as yet undiscovered particles that interact very weakly with the particles of normal matter. The density of the dark matter is much greater than that of the normal matter, roughly $0.25\Omega_0$. The density of the dark energy (energy per unit volume divided by the square of the speed of light) is greatest, $0.7\Omega_0$. These values correspond to the model that best fits the various observations, such as those displayed in Figure 11-8.

Another, more complex observation supports the values of Ω_0 listed above. The Wilkinson Microwave Anisotropy Probe (WMAP) and Planck satellites measured slight deviations in the temperature of the CMB radiation across the sky. These deviations, shown in Figure 11-9, are measured in micro-Kelvins. Because the universe did not have exactly the same temperature and density everywhere 400,000 yr after the Big Bang started, the pressure varied from place to place. These pressure differences created acoustic waves — sound waves with very long wavelengths – that propagated through space. To use a metaphor, Inflation "rang the universe's bell" by introducing the variations in density and pressure. As occurs in a ringing bell or plucked guitar string, the highest amplitude of the oscillation was at the fundamental wavelength, with lower amplitude peaks occurring at the harmonic wavelengths (see Ch. 5). The temperature variations in the CMB as a function of position on the sky should therefore display a wave pattern, with more intense variations occurring at fixed angular distances from each other. These angular distances correspond to the fundamental and harmonic wavelengths, which are set by Hubble's constant and the densities of the matter and dark energy. Figure 11-10 shows how the amplitude of the temperature variations depends on angular distance as measured by WMAP. The oscillations are obvious and the wavelengths agree very closely with those predicted if Ω_0 of the matter is about 0.3 and Ω_0 of the dark energy is about 0.7.

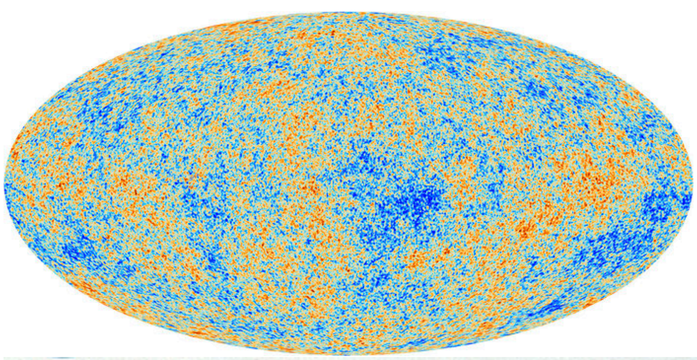

Figure 11-9. Planck satellite measurements of deviations of the blackbody temperature of the CMB radiation. Here the entire sky is mapped into an ellipse. The red areas are hotter by about 200 micro-Kelvins than the average CMB radiation, while the dark blue areas are about 200 micro-Kelvins cooler than the average. [Source: European Space Agency]

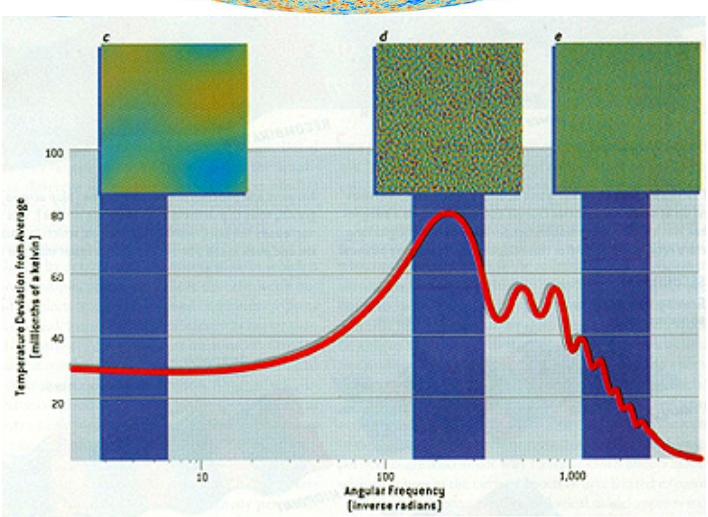

Figure 11-10. The oscillations of the temperature variations of the CMB radiation as measured by WMAP. The intensity of the variations is plotted against the angular frequency, which is one divided by the angle on the sky separating the peaks. The three boxes on the top show how the variations would look in Fig. 11-9 if there were only one small range of angular frequencies, corresponding to the blue shaded area under each box. [From *Scientific American*, Feb. 2004]

These different densities all add up to the critical value, $\Omega_0 = 1$ to within the uncertainty of the measurement. This is significant because it corresponds to a net mass-energy of zero! That is, the amount of positive energy in the form of mass and dark energy equals the amount of negative binding energy of gravity. As was discussed in Chapter 10 (Box 10-2), this zero net mass-energy has led to speculation that the universe could have arisen from a sort of grand quantum fluctuation in a "multi-verse" that continually creates a multitude of universes in addition to our own.

The rate of expansion of the universe should have decreased because of gravity for some time before the matter spread out so much that dark energy began to dominate, causing the expansion to accelerate. Indeed, the most recent versions of the Hubble diagram compiled from supernova observations (see Fig. 11-11) shows that this occurred several billion years ago.

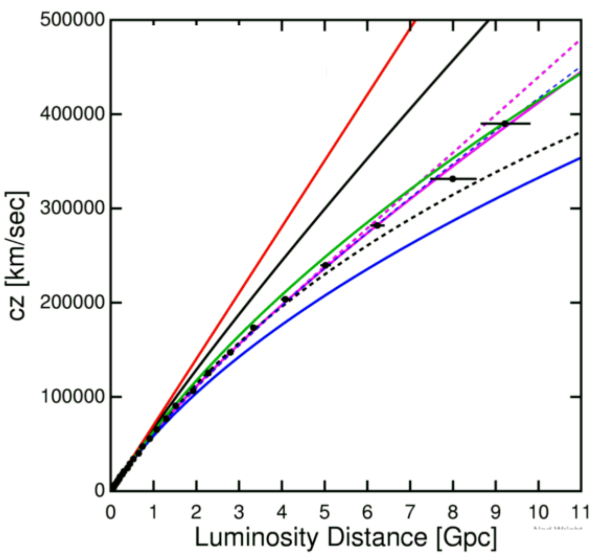

Figure 11-11. The redshift vs. distance relationship from the Type Ia supernova data. ("Luminosity distance" refers to the distance obtained from eq. 6-2 using brightness and luminosity and "Gpc" is a billion parsecs.) The solid curves correspond to a high-density universe ($\Omega_0 = 2$) in red, a critical-density universe with Ω_0(matter)= 1 in black, an essentially empty Universe ($\Omega_0 = 0$) in green, a steady-state model in blue, and a model with Ω_0(matter) = 0.27 and $\Omega_0(\Lambda)$ = 0.73 in purple (dotted: finite sized universe; solid: infinitely large universe with flat space-time). The data indicate that the expansion is currently accelerating but was decelerating at earlier times corresponding to higher redshifts. [From E. Wright, www.astro.ucla.edu/~wright/ sne_cosmology.html]

The Age of the Universe

In Chapter 10, we calculated an approximate age of the universe from the value of Hubble's constant. This estimate adopted a constant rate of expansion, which does not appear to be the case. When we take into account the initial deceleration and the more recent acceleration of the expansion, though, we get essentially the same answer: the universe is 13.7 billion years old, with an uncertainty of ±0.2 billion years.

The Future of the Universe

The observed acceleration of the expansion indicates that the universe will expand forever. As it does, it will become ever colder and less dense on average, and eventually the last stars will form, shine, run out of fuel, and die, leaving the universe a collection of cold cinders. Some theories of particle physics predict that protons and neutrons will eventually decay, in which case the universe will return to a particle state.

If there were no dark energy and the density of matter exceeded the critical density, gravity would decelerate the expansion until it stopped and then reversed to a collapse, changing the Big Bang to a big crunch. Perhaps the universe would then once again attain the conditions that caused the expansion. This would result in another Big Bang, starting one of endless numbers of bang-crunch cycles. However, the observational data do not support this type of cyclic model of the universe.

Of course, since we do not understand dark energy, we should not assume that we know enough to predict with confidence the bleak future of a slow, cold death for the universe. Astronomers and physicists consider the study of dark energy to be one of the greatest challenges of contemporary science. You will undoubtedly learn about further developments in the popular media in the future.

A Universe without a Boundary and without a Center in Space

Many people ask what is outside the universe and where its center is located. The answer to the first question is that there is no boundary, at least not in space. But Einstein taught us that space and time combine to form a four-dimensional structure called space-time. It is difficult to think in four dimensions, so a classic analogy used by cosmologists to explain the geometry of the universe is that of a balloon. The two-dimensional surface of the balloon represents the three-dimensional "surface" of the space part of space-time. Imagine yourself to be a bug crawling on the surface of the balloon, unable either to jump off it or to dig a hole into it. As the balloon is blown up, all the points on the surface appear to separate from each other: the space on the surface expands, just as the three dimensions of space expand in our universe.

What corresponds to time in this analogy? Time is represented by the radius of the balloon! As the radius (time) increases (passes), the space on the surface (three-dimensional space) expands. Note that there is no boundary to space on the surface of the balloon, just as there is no boundary on the surface of the Earth. Instead, the boundary is in the radial direction (down and up), which corresponds to the past and future in our analogy. This means that the outer boundary of the universe is the immediate future! What is the center? It is simply the beginning, *i.e.*, zero time. Again, there is no center in space, just as there is no center to the surface of the Earth.

It is very difficult to determine whether the universe is finite or infinite in size. This is primarily because Inflation straightened out the shape of space-time, so the observational difference between an original closed geometry — analogous to a sphere — or an open geometry that stretches out forever, is very small. Nevertheless, data such as the points in Figure 11-11 can eventually determine whether or not the universe is infinitely large.

Summary

Our observations of the universe have led to some rather startling conclusions. The universe is expanding, which implies that it had a beginning. From the rate of expansion — Hubble's constant — and observations of how much the expansion rate has changed over cosmic time, we can determine its age to be 13.7 billion years. The material of the universe is mostly made out of gas and particles, and expanding gases cool. So the universe must have started out in an extremely hot, dense state. At such high temperatures, the universe contained only photons, particles, and anti-particles interacting via force fields. The cooling from the expansion caused the initially unified forces to start acting in different ways. Since about 0.01 s after the expansion started, the four fundamental forces — gravity, the strong nuclear force, the weak interaction, and electromagnetism — have been distinct. Meanwhile, the anti-particles annihilated with the particles, leaving behind an excess of particles that is only one part in a billion of the number of particle-antiparticle pairs that had been present earlier. In terms of number, there are now about a billion times more photons than matter particles. Within a few minutes, some of the nucleons had stuck together to produce helium nuclei plus a lower abundance of other light nuclei, so that the "normal" matter in the universe was mostly composed of hydrogen — whose nucleus usually contains only a single proton — and helium. After about 400,000 years, complete atoms formed from electrons and nuclei. At this point the universe became transparent. Since this time, the universe has been awash in a "sea" of Cosmic Microwave Background (CMB) photons that are now mostly at millimeter and centimeter wavelengths. Starting about half a billion years after the expansion began, galaxies formed from the gravitational contraction of "lumps" of higher than average density that emerged from earlier times. We can explain some important properties of the universe by a very early, brief phase of extremely rapid expansion called Inflation. This event resulted from an enormous conversion of potential to kinetic energy throughout the universe. The universe stretched by about 10^{50} times during the Inflation episode. This flattened the initial curvature of space-time so that the geometry of the universe is now very flat, meaning that the shortest distance between two points is a straight line. Before Inflation occurred, the section of the universe that we can observe was small enough to blend together so that it has uniform physical properties. Inflation also produced density contrasts that later became regions of high concentrations of galaxies as well as voids where few galaxies exist.

Solid evidence has convinced most scientists that the Big Bang model is a valid description of the development of the universe. An expanding universe explains the Hubble Law, the increase in redshift of galaxies with distance. The discovery of the CMB radiation in 1964, and the later measurement of its spectrum showing that it has a blackbody shape, propelled the model into the forefront of cosmology. Further support came from the realization that the amount of helium predicted by Big Bang nucleosynthesis matched that observed in the oldest stars. Finally, the finite age of the universe explains why the night sky is dark: there has not yet been enough time for starlight to fill space.

Recent observations indicate that the expansion of the universe is accelerating. The acceleration is caused by "dark energy," which can be either Einstein's Cosmological constant or another property of space that promotes expansion. In either case, its origin is currently the greatest mystery in cosmology. According to recent observations, 73% of the mass-energy of the universe is in the form of the dark energy. Another 23% of the mass-energy comes from "dark matter" particles that have yet to be detected on the Earth. Only 4% is contained in the normal matter that composes stars, planets, and everything with which humans come in contact.

Our knowledge allows us to predict the general future of the universe. Current observations indicate that it will expand and cool forever, eventually becoming an extremely cold, lifeless expanse. It will take trillions of years for this to happen, so this bleak future is no cause for despair!

Glossary

<u>The universe</u>: An abstract concept meaning the natural world in which we exist. Originally, it meant everything that exists, but it is possible that there are other universes and collections of universes.

<u>Big Bang model</u>: Theoretical description of the development of the universe from an extremely hot, dense state to its current cold, low-density state.

<u>Steady-state model</u>: Theory — unsupported by the data — in which the universe (on average) does not change with time.

<u>Cyclic model of the universe</u>: Theory — unsupported by the data — in which the universe undergoes multiple episodes of expansion that start with a state of extremely high temperature and density.

<u>Dark night sky paradox (often referred to as "Olber's paradox")</u>: Problem with models in which the universe is infinite in space and has always existed: the night sky would be bright from distant starlight.

<u>Cosmological Principle (sometimes called the "Copernican" Cosmological Principle)</u>: Assumption that the universe has the same appearance, on average, as observed from any place inside it.

Cosmological constant (symbol: Λ): A term in Einstein's equations describing the space-time of the universe. It corresponds to a "dark energy" that promotes expansion.

Parsec (abbreviation: pc; 1 kpc = 1000 pc; 1 Mpc = 1 million pc; 1 Gpc = 1 billion pc): Distance unit used for stars and galaxies. 1 parsec is the distance of a star with a parallax (see Ch. 6) of 1 arcsecond. [1 parsec = 3.26 light-years = 3.1×10^{16} m, 1 kpc = 3.1×10^{19} m, 1 Mpc = 3.1×10^{22} m, 1 Gpc = 3.1×10^{25} m]

Light-year (abbreviation: lt-yr): The distance traveled by light in one year. There are 3.26 lt-yr in 1 pc.

Blackbody: An opaque object. Its luminosity depends strongly on its temperature and size, and its spectrum (intensity vs. wavelength) has a characteristic shape.

Hubble Law: The relation (Fig. 10-2 and eqs. 10-1 and 10-4) between velocity or redshift and distance of galaxies beyond the Local Group. Can be used to determine distances to remote objects. Led to the conclusion that the space of the universe is expanding.

Hubble's constant (symbol: H_0): Slope of the Hubble Law. Its value at the current epoch of the universe is about 70 km/s/Mpc.

Epoch: Time after the expansion of the universe began when the universe was at a particular stage in its development.

Planck epoch: Very early stage of the universe when all the forces of nature were unified, *i.e.*, acted the same. This period ended when the universe was only about 10^{-43} s old with a temperature of about 10^{32} K.

Inflation: Hypothesized period of the very early universe when space expanded by about 10^{50} times during a very brief period following a sudden drop in the potential energy of space.

"Primordial soup": Nickname often given to the early universe, which was a mixture of many different kinds of particles, with "lumps" of slightly higher-than-average densities.

Nucleosynthesis: Nuclear fusion of protons and neutrons to form nuclei of atoms other than simple hydrogen, which is only a single proton.

Cosmic Microwave Background (abbreviation: CMB) radiation: Radio and infrared photons that arrive from every direction in the sky with a very nearly uniform brightness and the spectrum of a blackbody. Thought to be the light released when the universe first became transparent, it has since increased in wavelength because of the expansion of space.

Dark matter: Material (probably particles that we have not yet discovered in laboratories on the Earth) that does not emit light but whose gravitational influence is apparent in galaxies and clusters of galaxies.

Dark energy: Nickname given to some agent (*e.g.*, the Cosmological constant) that counteracts gravity to promote expansion of the universe.

Critical density: The mass-energy per unit volume that would be required for the universe to decelerate gradually toward a steady state because of gravity, if there were no accelerating agent.

Omega (symbol: Ω_0): The actual current density of the universe divided by the critical density.

Redshift (symbol: z, no units): A measurement of the increase in wavelength caused by the expansion of the universe. Similar to the Doppler shift. See eqs. 10-2 and 10-3. One plus the redshift ($1+z$) equals by how many times the universe has spread out since the light we now receive left the object being observed.

Type Ia supernova: A class of exploding stars with the important characteristic that the luminosity at maximum brightness is the same from one to the other, except for minor differences that can be determined from the spectrum. Very useful as a standard candle to measure distances to galaxies since Type Ia supernovae are extremely luminous.

Multiverse: Hypothetical realm of existence containing many universes.

Questions for Discussion

A. What do you expect to see when observing a galaxy that is at a distance, for example, of 3 billion pc (10 billion lt-yr)? Should it have the same general appearance and properties that we observe for the Milky Way, given that the universe is 13.7 billion yr old?

B. How convincing is the evidence in support of the Big Bang model?

C. If the CMB radiation had not been found to have a blackbody spectrum, how would our interpretation of its origin and the Big Bang model have changed?

D. We often use the word "evolution" in reference to the development of the universe. In what ways is this usage of the word similar to and different from the evolution of life?

E. How can a universe have no boundary in space? What does it expand into?

Examples of How to Solve Problems Related to the Big Bang Model

1. If the correct value of Hubble's constant were H_0 = 100 km/s/Mpc, what would be the approximate age of the universe?

Answer: As discussed at the beginning of the chapter, the age of the universe is

$$
\begin{aligned}
t \approx 1/H_0 &= 1/(100\text{ km/s/Mpc}) = [1\text{ Mpc}/100\text{ km}]\text{ s} \\
&\approx [(1\times10^{6}\text{ pc/Mpc})(3.1\times10^{16}\text{ m/pc})] / [(100\text{ km})(1000\text{ m/km})]\text{ s} \\
&\approx (3.1\times10^{17}\text{ s}) / (3.16\times10^{7}\text{ s/yr}) \approx \underline{10\text{ billion yr}}
\end{aligned}
$$

As we will find in Chapter 13, this is less than the ages of the oldest stars. So, there would be a conflict with other observations if Hubble's constant were measured to be this high.

2. A galaxy is discovered that has a redshift $z = 5$. At what wavelength do we observe a photon from a star that was emitted at a rest wavelength of 500 nm in the rest frame of the distant galaxy?

Answer: We use eq. (10-2) to relate redshift to wavelength:

$\lambda_{obs}/\lambda_0 = (1+z)$, so $\lambda_{obs} = (1+z)\lambda_0 = (1+5)(500\text{ nm}) = \underline{3000\text{ nm}}$.

We observe this as an infrared photon. Telescopes that operate at visible wavelengths are not very useful when studying the most distant galaxies.

Homework Problems

This table of distance d as a function of redshift z might be helpful in answering one or more of the questions:
$z = 0.5$ $d = 5.1$ billion lt-yr
$z = 1$ $d = 7.8$ billion lt-yr
$z = 2$ $d = 10.5$ billion lt-yr
$z = 5$ $d = 12.5$ billion lt-yr
$z = 20$ $d = 13.5$ billion lt-yr
$z = 230$ $d = 13.696$ billion lt-yr
These calculations correspond to a current age of the universe of 13.700 billion years.

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1. If the value of Hubble's constant were revised to $H_0 = 50$ km/s/Mpc, as once thought, what would be the new estimate of the approximate age of the universe?

2. The most distant galaxy discovered thus far has a redshift $z \approx 8$. At what wavelength do we observe a photon from a star that was emitted at a rest wavelength of 600 nm in the rest frame of the distant galaxy?

3. The James Webb Space Telescope (JWST) will be able to measure spectra of galaxies and quasars at wavelengths as long as 28 microns (2.8×10^{-5} m).
a. What is the highest redshift of a galaxy or quasar for which the Lyman-α spectral line of hydrogen, whose rest wavelength is 121.6 nm (1.216×10^{-7} m), will be within the wavelength range of JWST?
b. There are reasons why JWST will not see any galaxies or quasars at such a redshift. After thinking about this, state and explain briefly one of these reasons. [Hint: one possible answer is related to how time and distance depend on redshift.]

Homework Questions Requiring Logic
Explain how you arrive at your response to each question.

4. a. If the universe were 10 times less hot at all times than our current estimates given in the "Chronology of the Development of the Universe" section, how would the events in the chronology have been altered? That is, which would have been altered and in what sense? [For this question and question (b) below, assume that the density at any given time was the same as for our actual universe.]
b. If the universe were 10 times hotter at all times than our current estimates given in the "Chronology of the Development of the Universe" section, how would the sequence of events have been altered? That is, which would have been altered and in what sense?

5. If electrons had a mass 10 times lower than their actual value, how would this have affected the time when they annihilated with positrons?

6. If Inflation had never occurred, how might the universe we observe be different?

7. If Penzias and Wilson had found that the CMB radiation were much brighter in one general direction and much fainter in the opposite direction, what explanation could there have been? (Even if there would have been multiple explanations, you only need to devise one.)

8. Propose a type of observation that could potentially determine whether space-time is curved other than comparing models with the redshift-distance relation.

Homework Questions Requiring Extra Thought

9. The density of the universe was higher by a factor $(1+z)^3$ at the time the light left the objects we now observe at redshift z. The current temperature of the universe is 2.73 K. For an object we now observe at a redshift $z = 5$, what was the temperature of the universe when the light left the object? Do this calculation for the case when the universe is dominated by
a. gas that is non-relativistic, meaning that the mean kinetic energy per particle is less than the rest-mass energy.
b. gas that is relativistic.
[Hint: see the end of Box 11-1 for the relevant proportionalities, then form an algebraic ratio.]

10. How solid is the evidence for acceleration of the universe? Some astronomers have suggested that the luminosity of type Ia supernovae might change as the universe develops, perhaps because the number of atoms of heavy elements keeps increasing with time. By approximately how much would the luminosity of a high-redshift type Ia supernova (see Fig. 11-8) need to increase or decrease (specify which) in order to cause the redshift-distance data to match the model curve corresponding to constant expansion (drawn in black in the figure)?

Astronomical Puzzle (Class Exercise)

11. The data showing that the expansion of the universe is accelerating took cosmologists by surprise. Most of them had assumed that Einstein's Cosmological constant was zero. One possibility is that the redshift vs. distance relation derived from type Ia supernovae is incorrect. Propose two hypotheses that would change the data in Figure 11-8 so that they agree with the model curve corresponding to constant expansion (marked "without vacuum energy" in the figure). Then figure out some observational tests for each hypothesis.

Suggestion: Inspect Figure 11-8 and consider what assumptions are involved in converting an observation of brightness of a Type Ia supernova into a distance. Note that the vertical axis, marked "magnitude" has a scale such that each increase by 1 magnitude corresponds to multiplying the brightness by 0.40, and 0.5 magnitudes to multiplying the brightness by 0.63. (That is, greater magnitude corresponds to lower brightness.)