

2. The Three Pillars of the Big Bang Theory

The evolution of the Universe can be compared to a display of fireworks that has just ended: some few wisps, ashes and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds.

Abbé George-Henri Lemaître

Evidence for the Big Bang

The Big Bang theory has gained general acceptance by its ability to explain in a simple manner three key cosmological observations. These three observations are (1) the expansion of the universe as measured by the redshift of light emitted from galaxies (2) the existence of the cosmic background radiation and (3) the relative amounts of hydrogen, helium and deuterium in the universe. The theory states that the expansion of the universe began at a finite time in the past, in a state of enormous density and pressure. As the universe grew older it cooled and various physical processes came into play which produced the complex world of stars and galaxies we see around us.

The Big Bang theory enables us to understand many different facts about the universe in a cohesive manner. Almost all astronomers believe it to be the best theory of the universe. Let us keep in mind, however, that the finest scholars were completely mistaken about the nature of our universe for most of recorded history. We present-day scientists can only do what any jury does: find the theory that is most consistent with the available facts. We now turn to the details of the three observational pillars of evidence for the Big Bang theory.

The First Pillar: Hubble's Law

In Chap. 1, we learned of the history of astronomy culminating in the debate concerning the nature of the spiral nebulae. The correct answer turned out to be that the spiral nebulae are galaxies much like our own. Vesto Slipher had determined that these galaxies are moving away from us at very high speeds. By measuring their distances, Edwin Hubble demonstrated that the galaxies farthest from us are moving away at the highest speeds—Hubble's law. Let us see what this implies.

Imagine a race among three cars. Car number one travels at a steady speed of 60 miles an hour, car number two travels at a steady speed of 70 miles an hour, and car number three travels at a steady speed of 80 miles an hour. One hour after the start of the race we check on the location of the cars. Car one has gone 60 miles, car two 70 miles, and car three 80 miles. Seen from the starting gate, these cars obey Hubble's law. The car that is farthest from us is the one that is traveling fastest. The first and third car are now separated by a distance of 20 miles after 1 h. In another hour, their separation will have grown to 40 miles. By looking at the cars 1 h after the race started and working back in time, we can conclude that they all left the starting line at the same time. Since galaxies obey Hubble's law, we can draw the same conclusion. In the past, the galaxies were all closer together, and, in the future, they will be farther apart. We thus encounter one fundamental property of the universe: it is evolving. The universe looked different in the past and will look different in the future. The reader may ask why the cars acquire different initial speeds. This is where our simple analogy breaks down. When we look in more detail, we see that, in fact, it is the fabric of space that is expanding rather than objects moving in space.

A simple estimate of the age of the universe can be obtained using Hubble's constant. We can calculate for a given galaxy, knowing its current distance and velocity how long it took to reach its distance from us. This time is equal to (d/v) which turns out to be one divided by Hubble's constant for every galaxy. This rough estimate gives an answer of 14 billion years for the age of the universe, quite close to our correct answer of 13.73 billion years calculated using the proper cosmological models.

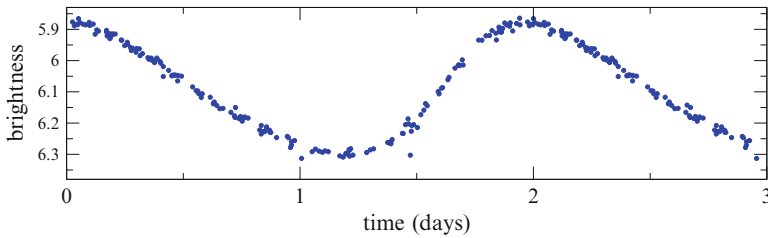


FIG. 2.1 The variation of brightness with time for the Cepheid variable star SU Cas measured by the Hipparcos satellite. The time interval from peak brightness to the next peak is about 2 days. We can use the pulsation time to infer the total luminosity of this star and hence its distance from us. This star is about 1,500 times as luminous as the Sun and 6 times as massive. The distance to the star is about 1,400 light years

Measurements of Redshift and Distance

Hubble's law can be stated in the equation $v = H \times d$. Establishing Hubble's law involves measuring distances (d) and velocities (v) of galaxies. In practice, distance is much harder to measure than velocity. We measure the distances to galaxies in a number of ways, but the principle involved is always the same. We have to be able to identify objects of known luminosity in galaxies. We know how luminous the Sun is. If, for example, we could identify a star like the Sun in another galaxy we could then note how much fainter than the Sun that star appears to us. If the star was a million times fainter than the Sun in the sky, that star would be a 1,000 times farther from us than the Sun is. The problem of measuring distances in astronomy boils down to finding reliable indicators of distance. The indicators used by Hubble were variable stars. Figure 1.4 shows the image that Hubble used to discover a variable star in the Andromeda galaxy. These stars are still used for that purpose today. They vary in brightness because they pulsate (Fig. 2.1). It turns out that pulsation time depends on luminosity. A star with a slow pulsation time is brighter on average than a star with a short pulsation time. A star with a 3-day pulsation period is about one 1,000 times more luminous than the Sun, whereas a star with a 50 day pulsation period is about 10,000 times as luminous as the Sun. By knowing the true luminosity of a star and comparing it with the star's apparent brightness, we can calculate the distance to that star and hence to the galaxy containing that star.

But how do we determine the true luminosities of stars? How was the original period luminosity relation discovered? We can determine the distances to nearby stars using parallax and hence deduce their luminosities. Parallax is the motion in the night sky of nearby stars relative to distant stars over a period of months. Parallax is caused by the Earth's motion around the Sun, it can be used to estimate distances to nearby stars once the Earth-Sun distance is known. We see that variable stars whose distances are known exhibit a period luminosity relation, and we use this relation to deduce the distances to more distant variable stars.

Distance estimation in astronomy is difficult. Absorption of starlight by dust and gas can make stars look dimmer than they really are. Also, nature has contrived to make different kinds of variable stars, and we must not get them confused. Hubble thought that only one kind of variable star existed. This error caused him to underestimate the distances to galaxies by a factor of 10. Today we measure the distances to nearby galaxies to an accuracy of a few percent. For example if we say that a galaxy is 10 million light-years away, a 10 % error means that its distance may lie anywhere between 9 and 11 light years.

What about galaxy velocities? To understand how we measure velocities we must understand something about light and atoms. Atoms are built from particles called electrons, protons, and neutrons. The protons and neutrons are located in the nucleus of the atom, and the electrons orbit this nucleus. Atoms consist mostly of empty space. If you make a fist and imagine your fist is the size of an atomic nucleus, then the atom is as big as the US Capitol and if it happens to be a hydrogen atom then it has a single electron like a moth flitting about in an empty cathedral.

Electrons in atoms of a given element can only have certain specified energies. The electrons can change their energy by emitting and absorbing light or by colliding with other atoms. An atom of a given element, say hydrogen, can emit light only at specific energies or wavelengths. The wavelength of light is a detailed measure of its color. Broadly speaking, red light has a long wavelength and blue light has a short wavelength. Each element (hydrogen, helium, lithium, and so on) has its own set of wavelengths



FIG. 2.2 We measure redshifts using the patterns that are present in the spectra of galaxies. The *upper* spectrum shows schematically where the dark narrow absorption bands might appear in a spectrum of the Sun (in practice we see many more features than are shown). These features would be shifted towards the *red* for a galaxy as shown in the *lower* spectrum. The amount of the shift tells us how fast the galaxy is moving away from us, about 7 % of the speed of light in this case. We can then use Hubble's law to compute the distance to the galaxy in question, which turns out to be about a billion light years, in this example

associated with it, much like a fingerprint. Figure 2.2 illustrates that atoms can absorb light in a very narrow band of wavelengths and leave their mark on the broad colors emitted by stars and galaxies. It is one of the triumphs of twentieth-century physics that we can calculate these wavelengths theoretically. These developments started with the work of Einstein, Bohr and their students. The work culminated in the development of quantum electrodynamics by Feynman, Dyson, Schwinger and Tomonaga.

There is one more detail you need to know. When light is emitted by an atom that is moving away from us, its wavelength is shifted toward the red end of the spectrum. When the atom is moving toward us, the light is shifted toward the blue end of the spectrum. Sound waves behave in a similar manner. We can all hear how the pitch of a car engine increases when the car is moving toward us and decreases when the car is moving away. This effect is known as a Doppler shift. The effect is common to sound and light because both these disturbances propagate as waves. In the case of light, the effect is known as the redshift. Slipher and Hubble observed that the light coming to us from galaxies was shifted toward the red and inferred that these galaxies are moving away from us. You may think we have misidentified the light from the galaxies and that what we think is hydrogen at high redshift is say neon at zero redshift. The answer is that the light we receive from galaxies consists of a pattern of emitted and absorbed light

known as a spectrum. From one galaxy to the next we see the whole pattern shifted towards the red and it is hard to make an error. The concept is illustrated in Fig. 2.2.

Hubble's observations implied that, in the past, galaxies were closer together. In other words, when the universe was younger, it had a higher mean density. The universe began in a state of very high density and has been expanding and decreasing in density ever since. This is the idea at the heart of the Big Bang theory.

How We Use Redshifted Light to Look Back in Time

Imagine the universe is a loaf of bread with raisins embedded in it. If the loaf of bread expands, the raisins move farther apart from each other. We measure how much the loaf (space) has expanded using a quantity called the expansion factor. If the expansion factor doubles over a given time interval, then the distance between any two raisins (galaxies) has also doubled. The concept of expansion factor gives us another way of thinking about the redshift.

Let us imagine that at a certain time light is emitted from a distant galaxy with a wavelength λ_1 . We receive the light in our telescope at a later time when the light has a longer wavelength λ_2 . We calculate the redshift from the ratio of the two wavelengths λ_2 and λ_1 . The ratio of the two wavelengths is just the amount by which the universe has expanded during the time the light traveled from the distant galaxy to Earth. If the universe expanded by a factor 2, the wavelengths will have stretched by a factor 2. We believe the universe to have been expanding since the Big Bang, so the expansion factor has always increased. Our current belief is that the expansion will go on forever. In fact, in a few billion years astronomers in our own milky way galaxy (which will have merged with the neighboring Andromeda galaxy) will not even be able to see any galaxies at all with their telescopes.

There is a simple relation between expansion factor and redshift. The expansion factor is equal to one plus the redshift. If we observe a galaxy at a redshift of 5, we can say that the universe has expanded by a factor 6 in the time since the light from that galaxy started on its way to us. This provides us with another way

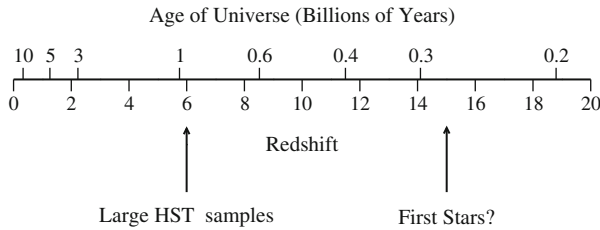


FIG. 2.3 A timeline of the universe comparing the age of the universe with redshift. The redshift measures how much the light emitted by a distant galaxy has been shifted towards the red due to the expansion of the universe. Galaxies which emit light at very early times have very high redshifts. The redshift is an observable quantity. Using known values for the Hubble constant and the density of the universe we can reliably estimate the age of the universe at the time the redshifted light was emitted. The goal of observational cosmology is to explore with observations the area between redshift 6 and redshift 14. We want to know how and when the first stars and galaxies formed in the first billion years after the Big Bang (Credit: Rychard Bouwens)

of thinking of the redshift. Rather than think of galaxies moving away at tremendous speeds, we can think of the wavelength of the emitted light increasing as the light travels on its journey to us. Since we are not at the center of the universe, one might think that certain galaxies should have blueshifts as they move away from the center toward us. In fact, if we consider a string of equally spaced galaxies in a line that appear to obey Hubble's law as seen from one, then an observer on any of these galaxies will think that he is at the center of the universe. This is an application of the cosmological principle, which states that the universe, on average, looks the same to any observer located within it.

The redshift is an observable quantity, which we can calculate using a galaxy spectrum obtained at a telescope (see Fig. 2.2). Using our models we can compute the age of the universe at the time redshifted light set off on its journey to us. Figure 2.3 illustrates the relation between the redshift and the age of the universe at the time the light was emitted. As the redshifts increase we can look back over aeons of time to a period when the universe was a small fraction of its present age. With our telescopes we can see galaxies out to redshifts of about 8 corresponding to a time when the universe was about 600 million years old, about 5 % of its present age. The Earth is about 4.6 billion years old, and the

oldest rocks on Earth are about 2 billion years old. These rocks, therefore, tell us what conditions were like on our planet when it was slightly over half of its present age. We astronomers, however, can look back in time and see objects as they looked long before the Earth or the Sun had even formed. There is a price we have to pay for this amazing view of the universe. The light of stars like our Sun that peaks in the visible part of the spectrum gets shifted in wavelength into the infrared part of the spectrum for high redshifts. To explore the high redshift universe we need infrared detectors on the largest ground based telescope and also in space.

When we look at the Moon we see it as it was 1 s ago, because that is how long light takes to reach us from the Moon. When we look at the Sun, we see it as it was 8 min ago, because that is how long it takes for light to travel the distance from the Sun to the Earth. The nearest star is 4 light years away. In the movie *Contact*, Jodie Foster used a radio telescope to detect a signal from an alien civilization. The aliens had received our first TV broadcast made in the 1930s and beamed it back to us. Since we received the broadcast 60 years after it was first beamed into space, and assuming the aliens beamed it right back, we could conclude that the aliens were located 30 light years away from us. Imagine a phone conversation where you had to wait 60 years to get a reply! The light travel time to the large spiral galaxy nearest to us, the Andromeda nebula, is 2 million years. You can see this object with your naked eye on a dark night. Keep in mind that the light that hits your eye is 2 million years old. The light from the most distant galaxies that we can see was emitted so long ago that these objects would look quite different if we could see them as they are today.

Astronomy has something in common with geology. Both disciplines deal with an “experiment” that has been run once. Both study the past over immense expanses of time. Geologists do this by studying rocks and fossils, astronomers use telescopes to actually look into the past. Just as geologists see that species in the past were different from the species we see around us today, astronomers see that very distant galaxies look different from nearby galaxies. The distant galaxies are seen as they were when they were young. Indeed, our journey back in time through the universe is like a journey through the strata of the Earth.

The Second Pillar of the Big Bang: The Cosmic Background Radiation

In 1967, the discovery of the cosmic background radiation provided strong support for the Big Bang theory. In fact the radiation's existence had been predicted 20 years earlier. To understand the importance of the background radiation we have to first consider what happens to matter in the early universe.

The density of the universe was higher in the past than it is today since objects were closer together. But just what do we mean by the density of the universe? To estimate the density of the universe, we take a large volume of space—say a cube 100 million light years on a side—and estimate how much mass lies in this volume. The density is obtained by dividing the mass by the volume. If we add up the amount of mass in stars and the gas between the galaxies, we arrive at an average density of 0.1 atoms per cubic meter. When we go back to a redshift of five (the redshift of distant galaxies), the expansion factor has shrunk by a factor six, so the volume of the cube will have shrunk by a factor 6^3 or ~ 200 . The density of the universe would thus be 20 atoms per cubic meter at that time. When we look back at a galaxy of redshift five, we know that the density of the universe at the time that light was emitted was about 200 times the density of the universe today.

Atoms such as hydrogen and helium only account for a few percent of the total observed density of the universe. Most of the mass in the universe is in a form other than atomic matter. Dark matter plays such an important role in cosmology that it will be the subject of Chap. 4. We shall also encounter a mysterious substance called dark energy. Brian Schmidt, Saul Perlmutter and Adam Riess, the leaders of the two teams that proved the existence of dark energy were awarded the 2011 Nobel prize for physics.

The origin of the cosmic background radiation lies in the interaction of light and matter. Metal objects that are heated to a sufficiently high temperature start to glow. Radiation emitted by objects of known temperature is called black body radiation. The color of that radiation is determined by the temperature. For example, the surface of the Sun appears yellow to us because

the Sun's surface has a temperature of about 6,000 K. If the Sun were hotter it would appear bluer, if it were cooler it would appear redder. As the emitting object gets hotter, the radiation it emits shifts to shorter wavelengths. The radiation also has a well defined spectrum (light intensity of its various colors) that has a shape known as the black-body curve. One can show that, in an expanding universe, black body radiation will retain the shape of its spectrum, and appear to us as radiation of a lower temperature. The temperature of the black body radiation falls as the universe expands because the wavelength of the light shifts to longer wavelengths.

Although the cosmic background radiation was detected in 1967, its existence had, in fact, been predicted by George Gamow and collaborators in the 1940s. Gamow assumed that, at some point in its history, the universe was hot enough and dense enough for nuclear fusion reactions to take place, and predicted that the afterglow from this period should be detectable today as cosmic background radiation.

The background radiation left over from the Big Bang lets us see the universe in its early stage of evolution and gives us a window into the origin of structures that will later become the galaxies we see around us. The radiation shows us what the universe must have looked like long ago before galaxies and stars existed, it is in some sense a distant mirror. We will discuss the clues about our past revealed by the radiation in Chap. 7.

In his classic of popular science writing entitled *The First Three Minutes*, Steven Weinberg noted that the existence of this radiation could have been confirmed experimentally at the time the prediction was made. The Big Bang theory at the time was sufficiently removed from mainstream science that people did not think it worth their while to carry out experiments to confirm or deny it. The absorption of light by cyanogen molecules implied a temperature of 2.3 K for the coldest clouds of molecular gas in our galaxy. The Kelvin temperatures are quoted relative to absolute zero ($^{\circ}\text{K} = ^{\circ}\text{C} + 273$). This 2.3 K temperature measurement dated from the 1940s and was quoted in a famous textbook in the 1950s, which stated that the temperature arrived at had a "very restricted meaning." In fact, it was an unwitting measurement of the temperature of the cosmic radiation left over from the Big Bang.

The Third Pillar of the Big Bang: The Abundances of Deuterium and Helium

If in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? Everything is made of atoms.

Richard Feynman

We know that close to 90 % of all atoms in the universe are hydrogen atoms. The other 10 % are almost all helium atoms. The Big Bang theory explains why this is the case. In fact the Big Bang theory provides an accurate explanation for the relative amounts or abundances of the lighter atoms (hydrogen, deuterium, helium and lithium) that we see in the universe. How are the helium and deuterium observed? Helium was first discovered in the Sun in 1868 and later observed on Earth. Helium abundances can be determined in the spectra of hot stars, in the upper solar atmosphere, and in the solar wind. One can also indirectly infer the helium abundance by comparing theoretical model predictions for the temperatures and luminosities of stars. Deuterium abundances are even more difficult to measure. Interstellar molecules composed of hydrogen, or deuterium, carbon and nitrogen are used to estimate deuterium abundances.

As Feynman points out, “The most remarkable discovery in all astronomy is that the stars are made of atoms of the same kind as those on Earth”. In 1835 the French philosopher Auguste Comte stated that “we shall never be able by any means to study the chemical composition of the stars”. However, in the early 1920s, methods became available for calculating the abundances of elements in a gas by observing its spectrum. In 1925, using these methods, Cecilia Payne analyzed the spectrum of the Sun and reached the conclusion that hydrogen and helium make up 98 % of the mass of the Sun. This result surprised people who expected the composition of the Sun to be similar to that of the Earth which is made mostly of iron. The stars were thought to have the same mix of elements as the Sun, so this discovery suggested that the stars were also made mostly of hydrogen and helium. The precise conclusion is that for every 10,000 atoms of hydrogen

in the universe there are 975 atoms of helium, 6 atoms of oxygen and 1 of carbon. All the other elements are present in smaller quantities than 1 atom per 10,000 hydrogen atoms. A more detailed look suggested that the abundances of the elements reflected the properties of atomic nuclei. Maybe nuclear physics processes were responsible for producing the abundances of the elements.

Already in 1903 Rutherford and Soddy had hinted that nuclear processes were responsible for generating energy in the Sun;

The maintenance of solar energy, for example, no longer presents any fundamental difficulty if the internal energy of the component elements is considered to be available, that is, if processes of subatomic change are going on.

When this question was examined by von Weizacker he found that many different sets of conditions were required to produce the mix of elements that we see in nature.

The Sun produces energy by turning hydrogen into helium. So, why can't nuclear fusion in stars be used to account for all the helium in the universe? There is not enough time. The stars can only account for about 2 % of the helium production in the universe. To create elements from hydrogen requires extremely high temperatures. If the stars cannot do the job, where can we find another furnace hot enough to form helium?

George Gamow was the first to explore the idea that nuclear processes could have taken place in the first few minutes of the Big Bang when it was hot enough for nuclear fusion to occur. The physicists Alpher and Herman worked out the details and found that nuclear processes which we will discuss below produced just the right abundance of helium to match that seen in stars. These processes also account for lithium and deuterium abundances. The inescapable conclusion is that only the very lightest atoms were created during the hot Big Bang. The heavier elements it turns out are made inside stars and during supernova explosions.

To understand more of the workings of nuclear alchemy we need to explore the properties of atoms. Atoms are made from particles called electrons, neutrons, and protons. The neutrons and protons form the nucleus, and the electrons orbit the nucleus. In this sense, the atom resembles the solar system. In the solar system, most of the mass resides in the Sun; in atoms most of the mass resides in the nucleus. There are certain allowed orbits

or energy levels for electrons in atoms. These can be precisely calculated using the formalism of quantum theory, which was developed in the 1920s. The electron can jump from one level to another by emitting or absorbing light of known energy and wavelength (i.e. color). This is a crucial property of atoms, which astronomers make use of to measure redshifts as we have seen. Without sending a probe to the Sun, we can tell which elements are present in the Sun. The absorption lines in the Sun's spectrum occur because atoms near the Sun's surface absorb some of the light generated in the Sun's interior. The absorption occurs because electrons in these atoms jump up from one energy level to another and absorb light in the process.

You are no doubt familiar with the concept of chemical elements, such as carbon, nitrogen, and so on. What differentiates one element from another is the number of protons in the atomic nucleus. Hydrogen, the simplest atom, consists of one electron orbiting one proton. The helium atom consists of two protons and two neutrons in the nucleus with two electrons in orbit. The number of protons in the nucleus determines how many electrons are present in each atom. This is because atoms have no net charge; the negative charge of the electrons is needed to balance the positive charge of the protons. It is the properties of the electron orbits that determine the chemical properties of the elements. The periodic table of the elements is an ordering of elements according to the number of protons in their nucleus which in turn determines their chemical properties.

It is a triumph of physics to have explained the properties of the periodic table in terms of the structure of atoms. This structure is determined by some simple fundamental equations. The power of physics lies in the ability to unify seemingly unrelated phenomena using simple underlying principles. A number of key discoveries about atoms and their constituent particles were made at the Cavendish Laboratory in Cambridge, England. The discovery of the electron, the neutron, and the atomic nucleus were all made at the Cavendish Laboratory. Ernest Rutherford, who discovered the atomic nucleus, was once asked how it was that he always seemed to be riding the crest of the wave in nuclear research. His answer was characteristic "I created the wave." Immodesty aside, this is an attribute of great men, they create the environment in which their and other talents can flourish. Niels Bohr did this to

great effect in Copenhagen in the 1920s and 1930s. Many great physicists of that period passed through Bohr's institute.

The Particle Zoo

To understand more of the early universe we need to briefly discuss the elementary particles. These particles are classified according to which forces of nature they respond to. We have so far encountered two properties of particles; charge and mass. Another property is spin. Spin can be measured and has whole number values (for example 1, 2) or fractional values (such as $\frac{1}{2}$ and $\frac{3}{2}$). Particles such as electrons have a spin of one half and are called fermions. Particles with integer spins are called bosons. Bosons and fermions behave in different ways when they are pushed close together.

Since like charges repel, and the atomic nucleus contains only positively charged particles and neutral particles, what holds the nucleus together? A force of attraction called the strong force overcomes the electric repulsion on small scales. We have a picture of the atom with an outer shell of electrons and a compact nucleus. The atomic nuclei can also react with each other. They can stick together in a process known as nuclear fusion. For elements lighter than iron, the fusion process releases energy, although it takes very high temperatures to get it going. It is this energy release that powers the Sun and most stars. The reason fusion reactions take place only at very high temperatures is that nuclei are positively charged and therefore repel each other. They have to approach each other at high speeds to overcome the repulsion and get close enough for the short range strong interaction that causes fusion to be felt. One might think of rolling a bowling ball up the side of a hill with a crater at the top. If the ball has enough speed it can make it to the top and settle in the crater. If the speed is too slow the ball will roll back down the hill. Temperature is a measure of the speed of particles hence the need for high temperatures for fusion to take place.

Another force, the weak force, plays a role in fission. We have now encountered the four fundamental forces of nature, the strong force, the weak force, electromagnetism, and gravity. Electromagnetism describes the phenomena arising from electric and magnetic forces which were united in one framework by

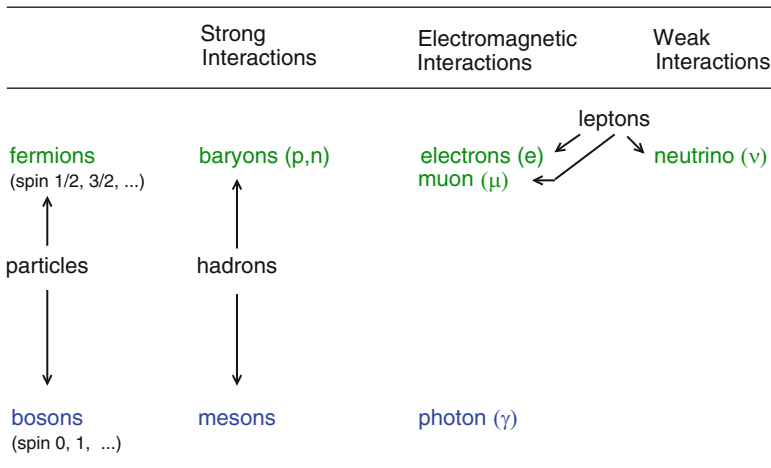


FIG. 2.4 The particle terminology. For each particle its strongest interaction is shown. In general it has all the interactions to the right of its entry, so that baryons, for example, have electromagnetic and weak interactions in addition to their strong interaction. Fermions are shown in *green* and bosons are shown in *blue*

James Clerk Maxwell. He showed that electromagnetic fields could propagate through space in the form of radiation that we see as light.

The fermion family of particles can be further subdivided into hadrons and leptons. The hadrons are strongly interacting fermions, whereas the leptons are weakly interacting fermions. Examples of leptons are electrons and neutrinos; examples of hadrons are protons and neutrons (protons and neutrons have spins of one half). It turns out that hadrons have structure. We believe them to be made of even more fundamental particles called quarks. Hadrons which consist of three quarks, are called baryons. Hadrons which consist of a quark antiquark pair, are called mesons. Antiquarks are an example of antimatter. Each particles has its own antimatter counterpart, a particle with opposite charge but identical mass. The electron's counterpart is called a positron. The existence of the positron was predicted by Paul Dirac (1902–1984) who devised a theory combining quantum physics and relativity.

The particle terminology we have introduced is shown schematically in Fig. 2.4. Baryons will be the subject of further discussion and are the most common form of hadron. To keep things

simple, we may think of neutrons and protons when we use the word baryon. Other baryons exist, but they are very-short lived particles and do not play a role in our story.

Is there such a thing as an elementary particle? The atoms were shown to have structure, then the nucleus was shown to have structure, and most recently, the constituents of the nucleus have been shown to have structure. We can ask ourselves whether a fundamental level of matter exists. Do the quarks themselves have structure? We cannot answer this question at the present time. We also cannot explain the masses of the particles. Experiments underway at the Large Hadron Collider in Geneva, Switzerland aim to test theories of the origin of particle masses.

The First Three Minutes

Calculations of the fusion rates in the early universe predict that after nucleosynthesis is complete, the atomic matter in the universe should consist of 75 % hydrogen by mass, with 25 % helium, and only traces of other elements. This remarkable prediction is in agreement with the observed chemical composition of the atmospheres of the oldest known stars. Let us take a closer look at the process of helium formation.

Initially the universe was so hot that neither neutral atoms nor even atomic nuclei could exist. At that point the universe consisted of a mix of radiation and particles as shown in Fig. 2.5. When the universe was about 2 min old, the temperature had ‘cooled’ to one billion Kelvin, much hotter than the center of the Sun. The density of the universe at this time is about half that of the air you breathe.

When the universe had cooled down to one billion degrees, it was cool enough for deuterium to hold together. This is because at temperatures higher than this a proton colliding with a deuterium nucleus has enough energy to break it apart. This illustrates the general point that at lower temperatures, matter exists in bound structures, while at higher temperatures, matter exists in the form of individual particles flying around (see Fig. 2.6).

The presence of deuterium enables helium to form at a rapid pace. The deuterium nucleus consists of one proton and one neutron. It is an isotope, having the same chemical properties as

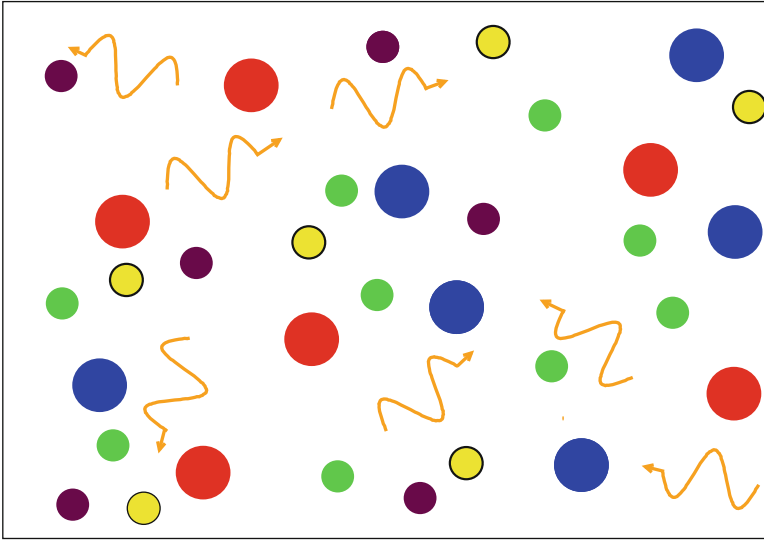


FIG. 2.5 Less than 1 s after the Big Bang, densities are high and interactions happen quickly. Protons (*red*) can convert to neutrons (*blue*) in reactions involving positrons (*yellow*) electrons (*brown*) and neutrinos (*green*). Light particles (photons) are shown as *orange* wiggly lines. The reactions take place via the weak interaction, one of the fundamental forces of nature

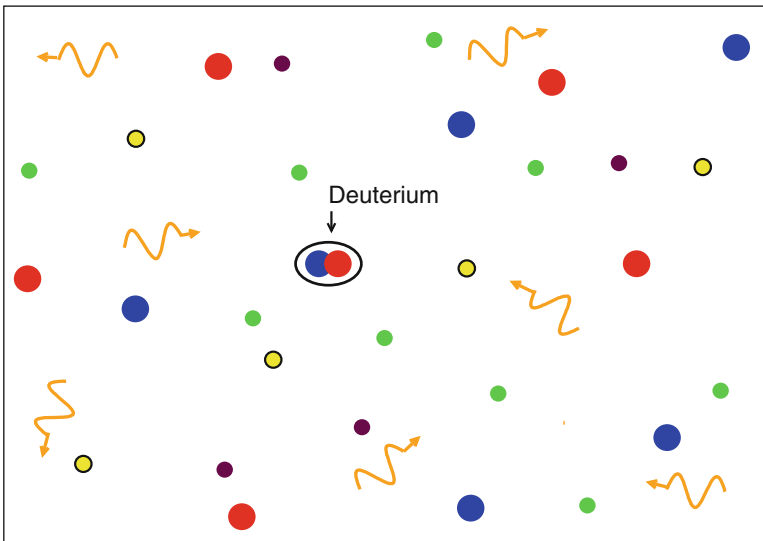


FIG. 2.6 As the universe cools interactions freeze out. Residual neutrons (*blue*) combine with protons (*red*) to form Deuterium, Helium, and Lithium in the first few minutes after the Big Bang

hydrogen, but with a nucleus that contains an extra neutron. We can write the formation of deuterium as an equation:



That is to say, a neutron (n) plus a proton (p) combine to form deuterium (D) and release energy in the form of light (γ). The last symbol on the line, γ , represents a photon or light particle. The reaction can go either way resulting in the formation or destruction of deuterium.

Once deuterium has formed, two particles of deuterium can combine to form a helium nucleus. There is a small window of opportunity for helium to form in the early universe. It must be cool enough that deuterium nuclei can survive, but hot enough that the deuterium nuclei can collide and form helium. It is remarkable that in the 14 billion years of the history of the universe there were a few minutes during which conditions were just right for nuclear fusion to take place. Fusion reactions don't take place at room temperature because of the force of repulsion between positively charged atomic nuclei. As we described in our hill with a crater metaphor, the repulsive force must be overcome for the particles to get close enough together to feel the strong nuclear force, which is a short range force. It is only at high temperatures that nuclei collide with sufficient speed to get close enough to interact via the strong force.

Deuterium and the Formation of Helium

The formation of deuterium is critical to the formation of helium because a helium nucleus can form by the collision of just two deuterium particles. To form a helium nucleus spontaneously from protons and neutrons would involve four particles colliding at the same time. Accidents involving two cars occur much more frequently than accidents involving four cars. So it is with particle collisions.

Almost all the deuterium formed in the Big Bang is used to make helium nuclei. To calculate how much helium formed in the big bang we need to know how much deuterium was present in the early universe. This, in turn is determined by the number of neutrons relative to protons at the time of nucleosynthesis.

Neutrons are neutral particles that have a mass slightly larger than that of the proton. A free neutron can decay into a proton and an electron through the following reaction:

$$n \rightarrow p + e + \bar{\nu}$$

The symbol $\bar{\nu}$ stands for an antineutrino. The typical time for this reaction to take place is about 15 min. This is the time it takes for a free neutron in space to turn into a proton. Note that a neutron inside a nucleus is stable, it will not turn into a proton. It may seem strange to see this number that we use in everyday life being relevant to the early universe. Initially there are roughly equal numbers of protons and neutrons in the universe. The neutrons can turn into protons but there is a resupply of neutrons from protons colliding with neutrinos. As the temperature drops there are fewer neutrons relative to protons. By the time the universe is a few seconds old, proton-neutron interchanging reactions have been brought to an end because the density is low enough that neutrinos cease to interact with anything. After 2 min the universe is cool enough for the remaining neutrons to combine with protons to form deuterium. At this time there are 2 neutrons for every 14 protons in the universe. These neutrons are absorbed into deuterium, so there are 2 deuterium nuclei for every 12 protons in the universe. Almost all these deuterium nuclei then combine to form helium nuclei. The end result is that there is 1 helium nucleus for every 12 protons in the universe which amounts to one quarter of the mass of nucleons in the universe.

A helium nucleus consists of two protons and two neutrons. Essentially, all the neutrons in the universe available at the time of nucleosynthesis end up inside helium nuclei. The amount of helium in the universe is thus determined by the neutron-to-proton ratio at the time when deuterium forms. For example if the neutron-to-proton ratio had been zero,—that is, no neutrons—no helium would form at all. If the neutron to proton ratio had been one, then the universe would consist entirely of helium. The helium abundance is a strong prediction of the Big Bang theory. There is not much room for maneuver. If the universe started in a hot, dense phase, then one quarter of the mass of baryons must consist of helium nuclei. The fact that helium was produced in the Big Bang would also explain why the helium abundance does not vary much from one location to another in the universe.

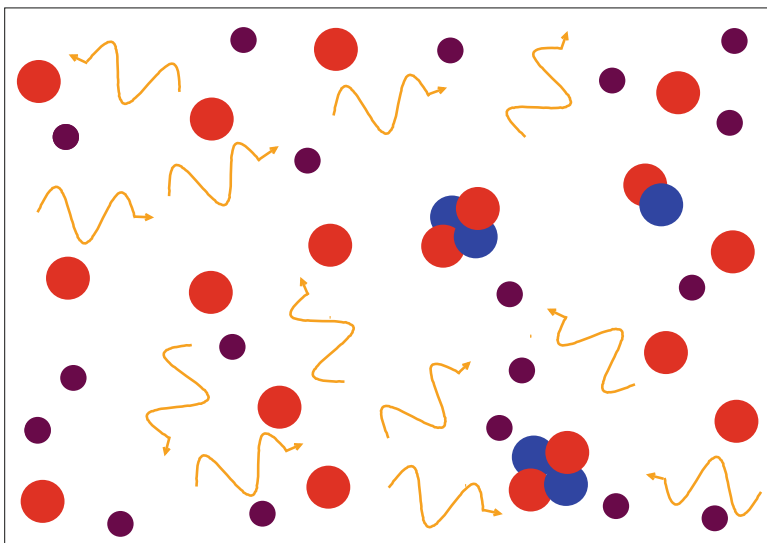


FIG. 2.7 In the first 400,000 years after the Big Bang, temperatures are so high that electrons (*brown circles*) cannot join protons (*red circles*) or helium and deuterium nuclei to form atoms. This is because the photons (*orange wavy lines*) are energetic enough to knock electrons away from atoms. During this period photons cannot travel far before interacting

After nucleosynthesis, the universe consisted of a mix of photons, electrons, protons, and helium and deuterium nuclei (Fig. 2.7). It was still much too hot at this time for atoms to form.

There is just a little deuterium left over from the Big Bang because the production of helium does not completely use up all of the deuterium nuclei. We can use the abundance of deuterium seen today to estimate the density of baryons in the universe. For a higher baryon density there should be very little deuterium left, but for a lower baryon density, more deuterium should survive. The abundance of deuterium in the universe today implies a present baryon density of the universe of 0.2 atoms per cubic meter, about double the density of matter seen in stars and gas. Studies of the cosmic background radiation lead us to the conclusion that the total density of matter in the universe is 1.3 atoms per cubic meter. Putting together the two we are forced to conclude that most of the matter in the universe does not consist of ordinary atoms. The question of the nature of this non-baryonic dark matter in the universe is one of the major issues of cosmology.

The Nature of the Big Bang

Most cosmologists explain their observations within the framework of the Big Bang theory. Some theoreticians like to think about what happened at the earliest times, minute fractions of a second after the Big Bang, and even discuss how the Big Bang might have occurred. The theory of inflation purports to account for the starting conditions of the Big Bang. In particular it explains why the universe is expanding, why it is homogeneous, and, why on large scales the universe has a flat geometry. Variants of the theory also suggest that different parts of the universe each have their own elementary particles and constants of nature. These areas form a sort of foam with a bubble structure. This idea, known as the multiverse, purports to explain why the constants of nature seem finely tuned so that we can exist in the universe. For example if the strong interaction was slightly stronger, then two protons would be able to bind together and form helium without two neutrons. This would have happened in the early universe with the result that no hydrogen would remain to provide fuel for stars, and water could not exist. These coincidences have led the distinguished physicist Freeman Dyson to state that:

As we look out into the universe and identify the many accidents of physics and astronomy that have worked together to our benefit, it almost seems as if the universe must have known that we were coming.

In the multiverse picture, the constants of nature take a wide range of values. Intelligent observers exist only in those rare bubbles in which by pure chance the constants happen to be just right for life to evolve. These ideas are very speculative and make few predictions that we can test. Recently though, it has been suggested that these processes might leave their mark on the cosmic background radiation in a way that we could detect. An interesting prediction of the multiverse idea was that galaxies would form in regions where the dark energy density is comparable to the dark matter density, this is indeed the case in our observable universe and could be viewed as a prediction of the model since it predates the discovery of dark energy.

It has also been argued that the universe could have spontaneously been created out of nothing. In quantum theory any

process which is not forbidden by the laws of nature has a finite probability of taking place. In this view there is no cause needed for the creation of the universe.

The Timeline of the Universe

The Big Bang theory states that the expansion of the universe began at a finite time in the past, in a state of enormous density and pressure. As the universe grew older it cooled and various physical processes came into play which produced the complex world of stars and galaxies we see around us. The history of the universe can be outlined as follows:

The earliest period that has any significance in cosmology is known as the Planck time. This amazingly small time interval is 10^{-43} of a second. After this time, general relativity can be used to describe the interaction of matter and radiation with space. Before the Planck time, we have no theory to describe the universe. We require an idea that incorporates the concepts of quantum physics and general relativity into one unified theory. Stephen Hawking and his colleagues work on such problems, but no definitive answer has been arrived at yet.

- 0 to 10^{-43} s: This takes us from the moment of the big bang up to the Planck time. We have no physical theory to describe the behavior of matter under the conditions that prevailed this early in the history of the universe.
- 10^{-43} to 10^{-35} s: During this time a slight excess of matter over anti-matter was produced. After the matter and antimatter annihilated, a small amount of matter was left over. Today there is only one baryon per billion photons in the universe.
- 10^{-35} to 10^{-6} s: The fundamental forces separate into four recognizable forces that we see today. At the end of this era, quarks combine to form hadrons (e.g. neutrons and protons) and mesons.
- 10^{-6} to 10^{-4} s: This is known as the hadron era. During this time, the baryons and antibaryons annihilated, resulting in a slight excess of baryons being left over to form the stars and galaxies that we see around us.

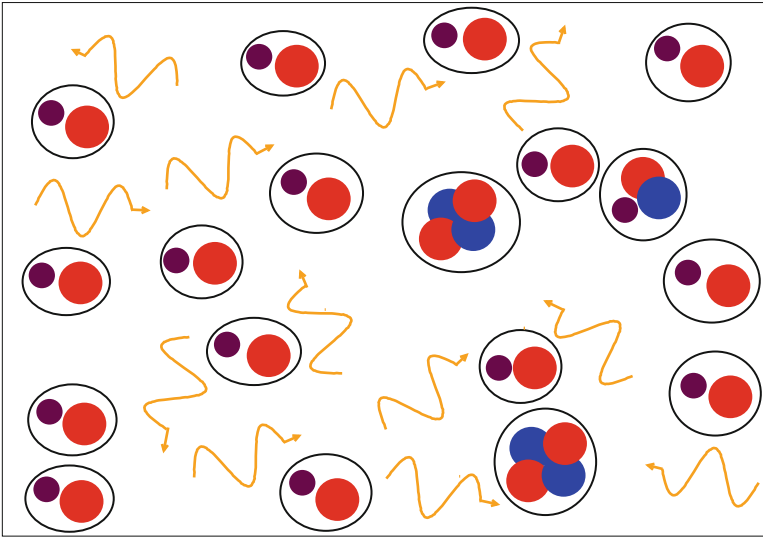


FIG. 2.8 Four hundred thousand years after the Big Bang, the universe has cooled sufficiently that atoms can form for the first time and light can travel freely through the universe. We detect this light today as the cosmic background radiation. The atoms present at this time are almost all hydrogen and helium

- 10^{-4} to 10s: This is the lepton era. Leptons are particles that feel the weak interaction, such as the electron. At 0.1 s the neutron to proton ratio starts to tilt in favor of protons. At 1 s, neutrinos stop interacting with matter and each other. At 10s the neutron to proton ratio became fixed, which in turn determined the deuterium and hence the helium abundance in the universe.
- Three to twenty minutes: Nuclear fusion occurs, producing helium and a little deuterium and lithium. The explanation of the helium abundance is one of the triumphs of the Big Bang theory. The big bang also explains the abundance of very small amounts of deuterium and lithium.
- 10 to 10^{11} seconds (3,000 years): This is the radiation era. Radiation dominates the energy density of the universe during this period.
- 10^{13} s (400,000 years): The universe becomes cool enough for neutral atoms to survive and thus become transparent. Radiation can travel freely through the universe with very little chance of being scattered or absorbed (see Fig. 2.8).

- 10^{13} s to present: During this time, regions of the universe that are slightly denser than their surroundings begin to collapse and eventually form stars, galaxies and clusters of galaxies. With the formation of the first stars nuclear fusion reactions occur again inside these stars for the first time since the first few minutes of the universe.

The Evolution of the Universe

As the universe ages it evolves. From being hot enough to act as a furnace for nuclear reactions, the universe has cooled to a few degrees above absolute zero. From the inferno of the first 3 min the universe cooled to a temperature that allowed the first clouds of primordial gas to collapse, at which point the first stars formed. The focus of the largest ground based 8–10 m mirror telescopes and space telescopes is to get a direct window into the first billion years of the universe and observe the growth and evolution of the cosmic structures mapped out by stars and galaxies. Astronomers are currently discovering objects that are recognizable as galaxies at a redshift of about eight. The light from these objects was emitted when the universe was less than 5 % of its present age (see Fig. 2.3).

By looking over great distances we look back to ever earlier times. To understand our findings we make the assumption that, averaged over sufficiently large scales, the universe is essentially the same everywhere. We thus assume that the galaxies we see in the distant past resemble what galaxies in our local ‘neck of the woods’ would have looked like at comparably early times. The practical challenges are; the most distant galaxies are extremely faint, their light gets shifted to progressively longer wavelengths and, dust and gas can obscure the light from young stars.

We shall describe this fascinating world of galaxies, the realm of the nebulae as Hubble called it, in Chap. 3.

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Cosmic Dawn

The Search for the First Stars and Galaxies

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