11
The Hot Big Bang

In an expanding universe, matter is diluted as the volume of the universe gets larger. Conversely, if we follow the expansion backwards in time, we find that the universe was denser in its past than it is today. In fact, the density of the universe grows without bound as we wind the clock back to the big bang. Furthermore, the temperature of the universe also soars to extremely high values. How do we know this? And what does this imply about the conditions of the early universe?

11.1 Following the Expansion Backwards in Time

The idea of a *hot* big bang was conceived by the Russian-born physicist George Gamow in the late 1940's (Fig. 11.1). It was based on the simple observation that gases cool down when they expand and conversely heat up when compressed. The temperature of a gas is a measure of the average kinetic energy of its constituent particles. The faster the particles move, the higher the temperature. So let us consider the energetics of particles bouncing off the walls in a box (see Fig. 11.2). When the wall is stationary, any given particle will bounce off at the same speed as it hits the wall. There will be no loss of kinetic energy. However, if the wall is retracting away from the particle, then the particle will rebound at a lower speed. Thus, in an expanding box, every time a particle collides with a retracting wall, it will lose kinetic energy. This loss of energy manifests itself as a decrease in temperature.

D. Perlov and A. Vilenkin, *Cosmology for the Curious,*
DOI 10.1007/978-3-319-57040-2_11

Fig. 11.1 George Gamow's (1904–1968) many significant contributions to physics include being the first to understand radioactivity in terms of quantum mechanics and laying the groundwork for the hot big bang cosmology. He was a great popularizer of science and was known for his risque sense of humor. In 1933 he defected from the Soviet Union, and he moved to the United States in 1934. *Credit* AIP Emilio Segrè Visual Archives, George Gamow Collection

The same cooling effect occurs in an expanding universe, even in the absence of walls. To understand this, let us consider how velocities of gas particles change as they travel through the universe. Suppose a particle flies by galaxy A at velocity v and moves on towards some distant galaxy B. Galaxy B is itself moving away from A at velocity u, determined by Hubble's

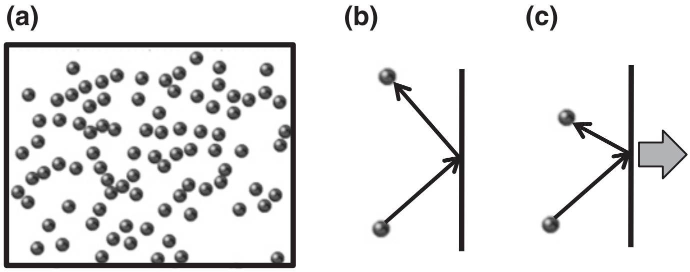

Fig. 11.2 **a** Particles in a box. **b** Particle bouncing off a stationary wall. **c** Particle bouncing off a moving wall. It rebounds with a lower speed than in (**b**)

law. So when the particle catches up with galaxy B, the observers in B will see it moving at a reduced speed, $v - u$. Galaxy C, which is at a greater distance from A, is moving away at a greater speed, so when the particle eventually catches up with C, its observed speed will be further reduced. This applies to all particles and all observers in an expanding universe. As time goes on, observers will see the particles moving slower and slower—which means that any gas filling the universe will be cooling down.

Conversely, if we follow the universe backwards in time, it will get hotter and hotter. As we will see later, the temperature in the early universe is inversely proportional to the scale factor, $T \propto 1/a$. Thus the universe apparently becomes infinitely hot as the scale factor approaches zero at the big bang. What happens to the matter content of the universe under these extreme conditions?

Everything around us consists of molecules that are composed of different types of atoms, held together by chemical bonds. Each atom is made up of electrons swirling around nuclei, which in turn consist of protons and neutrons. None of these components of matter could have existed at the early moments of the nascent universe. They would have been destroyed as energetic particles smashed into one another at super-high temperatures.

The chemical bonds that hold atoms together in molecules break at about 500 K[1]; atoms break up into nuclei and electrons at roughly 3000 K; and nuclei split into protons and neutrons at approximately 10^8 K. At still higher temperatures, above 10^{12} K, neutrons and protons (collectively known as nucleons) break up into their elementary constituents, called *quarks*. All

[1]One degree Kelvin is equal to one degree Celsius. The Kelvin scale however starts at absolute zero (the lowest possible temperature), which is −273.15 °C. For very high temperatures close to the big bang, there is not much difference between the two scales.

complex structures disintegrate as temperature increases. Consequently, the physical state of matter in the early universe was much simpler than it is today. It was just a hot and dense mixture of subatomic particles, which is often called "the primeval fireball".

As we refine our understanding of the fireball, we shall discover that, in addition to the particles that make up atoms, it included other particle species, such as the weakly interacting neutrinos. But most importantly, the fireball was pervaded by intense electromagnetic radiation, as we shall now discuss.

11.2 Thermal Radiation

Let us first recall that at the microscopic level electromagnetic waves consist of photons. Important things to remember about photons are that their energy is inversely proportional to their wavelength,

$$E = h\frac{c}{\lambda}, \tag{11.1}$$

and that they can be emitted and absorbed by electrically charged particles. Figure 11.3a illustrates a collision of two particles, which is accompanied by the emission of two photons. In Fig. 11.3b a charged particle absorbs a photon and then emits another one. In the super-dense early universe, these emission and absorption processes occur at a fierce rate, and equilibrium is quickly established where photons are mixed with other particles and are emitted at the same rate as they are absorbed. From the macroscopic point of view, this gas of photons can be pictured as electromagnetic radiation consisting of waves with different wavelengths.

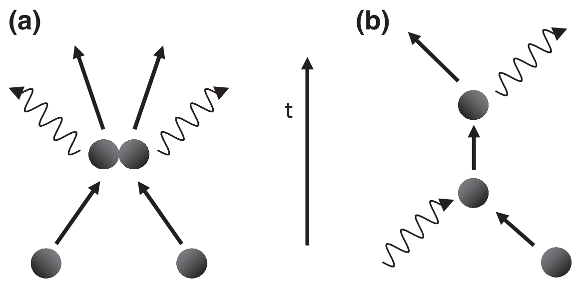

Fig. 11.3 **a** Photons emitted by colliding charged particles. **b** A charged particle absorbs a photon and then later emits another one

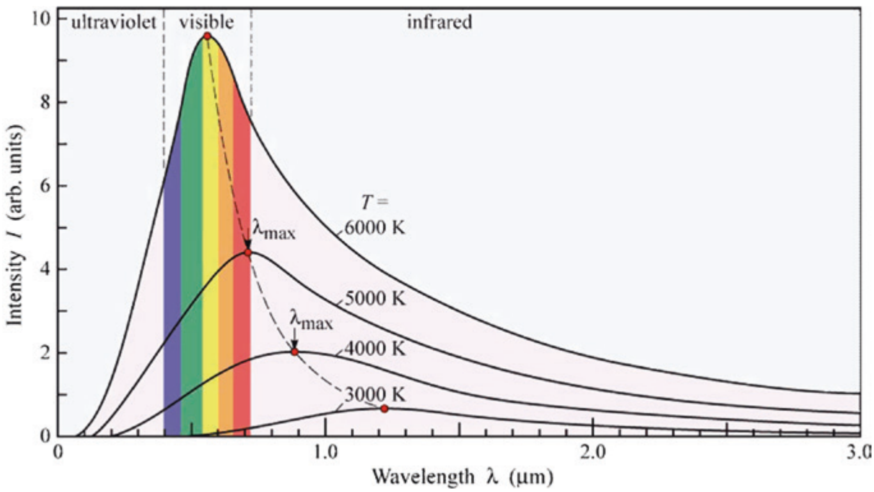

Fig. 11.4 The spectrum of thermal radiation at various temperatures. The *color bands* correspond to the wavelengths of visible light. λ_{max} is the wavelength corresponding to the maximum intensity for a given temperature. *Credit* "Physical Foundations of Solid State Devices", by E. Fred Schubert (EFSchubert@rpi.edu), 275 pages, 2015, available at the Google Play Store for US$ 8.00 (ISBN-13: 978-0-9863826-2-8)

Electromagnetic radiation that is in equilibrium with matter at some temperature is called thermal radiation. The higher the temperature, the higher the intensity (or the energy density) of the radiation. Quantitatively, the total intensity is proportional to the 4th power of the temperature,

$$\rho \propto T^4. \tag{11.2}$$

This intensity is spread over a range of wavelengths, with a distribution (or spectrum) that depends only on the temperature; it is shown in Fig. 11.4 for several different temperatures, and is called a thermal spectrum. The form of this distribution was derived by the German physicist Max Planck at the turn of the 20th century (Fig. 11.5).

The peak intensity occurs at a wavelength inversely proportional to the temperature,

$$\lambda_{peak} \propto 1/T. \tag{11.3}$$

Most of the photons in thermal radiation have wavelengths around λ_{peak}, and it follows from Eq. (11.1) that the typical energy of photons grows in proportion to the temperature,

$$E \propto T. \tag{11.4}$$

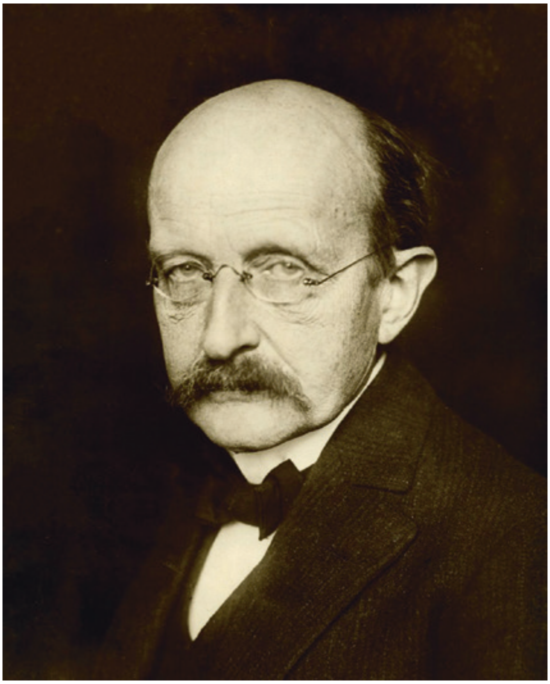

Fig. 11.5 Max Planck derived a formula for the spectrum of thermal radiation in 1901, laying the foundation for quantum mechanics

Any macroscopic object at a non-zero temperature emits radiation with an approximately thermal spectrum. The details of the spectrum depend on the material of the object—specifically on how it absorbs and reflects electromagnetic waves. The spectrum is exactly thermal only for an ideal black body, which absorbs all incident radiation.[2] The thermal spectrum is therefore sometimes called the black body spectrum.

[2]This is not difficult to understand from the following thought experiment. Consider a black body in equilibrium with thermal radiation at some temperature T. The black body absorbs all incident radiation, and in order to maintain equilibrium, it has to emit radiation at the same rate and with the same spectrum.

An ideal black body at zero temperature would look black even if you were to shine light on it. The reason is that it does not reflect any incident light. But at non-zero temperatures "black bodies" are not really black, since they glow with thermal radiation. Stars are good examples of almost ideal black bodies. The surface temperature of the Sun is 6000 K, and the corresponding peak wavelength is right in the middle of the visible spectrum.[3] From Eqs. (11.2) and (11.3) we can tell that a star with a surface twice as hot as the Sun would have a total intensity that is 16 times higher, and a peak wavelength that is half as much. At human body temperature (about 300 K), the peak of thermal radiation is in the infrared range, so humans and animals all glow in the infrared. At the extreme temperatures of the primeval fireball, shortly after the big bang, the photon energies were much higher and their wavelengths much shorter than those of visible light.

11.3 The Hot Big Bang Model

The starting point of the hot big bang model is an expanding fireball of elementary particles and photons. Assuming that the universe was homogeneous and isotropic, the fireball uniformly filled the entire space. One of the main goals of cosmology is to explain how the universe evolved from this simple state to what it is today.

As the universe expands, the fireball dilutes and cools down, and complex structures begin to form. When the universe is roughly a minute old, the temperature T drops to 10^9 K, and protons and neutrons start to combine to form atomic nuclei. This is called *nucleosynthesis*, and will be discussed in Chap. 13. By the time the universe is about 380,000 years old, the temperature cools to $T = 3000\,\mathrm{K}$, and electrons combine with nuclei to form neutral atoms. This process is called "recombination". Eventually stars, galaxies, and galaxy clusters are pulled together by gravity.

Today we find ourselves having front row seats from which to view this history: *as we look further out into the universe, we also look back in time.* If we look at a supernova 10 billion light years away, we see it as it was 7.5 billion years ago (see Sect. 7.7). If we look far enough, we will see the universe as it was when galaxies and the first stars were being formed. What if we look still

[3]Solar radiation has comparable intensity at all wavelengths in the visible spectrum. This should be perceived as white light, and indeed the Sun looks white when viewed from outer space. However, to observers on Earth, the Sun often looks yellow. This is mostly because the blue part of the spectrum is scattered by the Earth's atmosphere.

further, beyond galaxies, as far as our telescopes can reach? We will see the primordial fireball. It is there, in all directions on the sky.

Unfortunately, we cannot see all the way back to the big bang. At very early times the Universe was opaque because photons were frequently scattered by charged electrons and nuclei. However, this changed at recombination, when neutral atoms were formed and the universe became transparent to radiation. Photons interact with atoms much more weakly than they do with charged particles, so they are essentially free to propagate through the universe directly from the fireball, and eventually to our detectors[4]. We say that the photons decouple from matter. Thus when we look back as far as possible, to the epoch of recombination, we should see a panoramic "snapshot" of the universe as it was when its temperature was 3000 K. (This image of the infant universe is sometimes called the "surface of last scattering", because the photons that make up the image arrive at our detectors after traveling on a straight path through space since the last time they were scattered during recombination). The peak wavelength of radiation at this temperature is near the red end of the visible spectrum, so a 3000 K fireball should glow with intense red light. Then why isn't the sky red?

The reason is cosmological redshift. As photons propagate to us from the fireball, their wavelength is stretched by the expansion of the universe and is shifted far out of the visible range. At the same time, the density of photons is diluted by the expansion, so the radiation arrives at us highly red-shifted and with a strongly diminished intensity. If indeed the early universe was homogeneous and isotropic, the intensity of this relic radiation should be nearly the same in all directions on the sky.

11.4 Discovering the Primeval Fireball

Relic radiation from the primeval fireball was first predicted in the 1940's by George Gamow's two young colleagues, Ralph Alpher and Robert Herman. They estimated the present temperature of the radiation to be about 5 K. Detecting radiation of such a low temperature was a challenging task, and most observers at the time felt that it could not be done. So the prediction passed almost unnoticed (Fig. 11.6).

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[4]This process is similar to how photons make their way from inside the Sun to the Earth. Photons that are inside the Sun (or any other star) are constantly scattered in random directions, and it can take millions of years for them to make their way to the surface of the Sun. Once they get there, they are no longer jostled about, and stream freely towards us, arriving within a mere 8 min.

Fig. 11.6 Ralph Alpher (*right*) and Robert Herman (*left*) predicted that relic radiation from a hot early epoch should pervade our universe. The word "Ylem" on the label of the bottle is the term invented by Gamow (depicted here as a genie coming out of a bottle) and his friends for the primeval fireball

More than a decade later, Robert Dicke at Princeton reinvented the idea of a hot primeval fireball and realized that it leads to the prediction of a pervasive cosmic radiation. Dicke assembled a group of three young physicists, assigning one of them, Jim Peebles, to work out the details of the theory and the other two, Peter Roll and David Wilkinson, to build a detector that would put the theory to test. Peebles was not aware of the work of Gamow's group, so he had to start from scratch. He completed the calculation in early 1965, predicting radiation with a thermal black body spectrum at a temperature of about 10 K. At that time the detector setup was also nearly complete, so the Princeton group was poised to either discover the primeval fireball or to prove that it never existed.

In the meantime, at Bell Telephone Laboratories in New Jersey, less than 50 km away from Princeton, Arno Penzias and Robert Wilson were testing a sensitive radio antenna that they hoped to use in a study of radio emission from the Milky Way. They first needed to account for possible sources of noise, such as radio emission from the Earth's atmosphere, and electronic noise in their antenna. But after half a year of work there still remained a persistent radio noise of unexplained origin. Penzias and Wilson measured

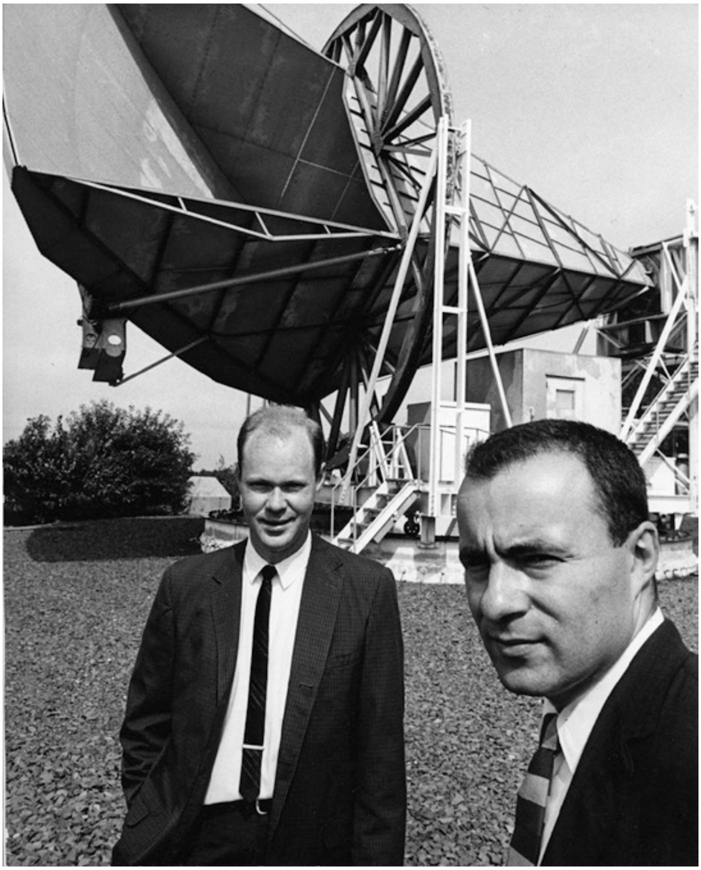

Fig. 11.7 Wilson (*left*) and Penzias (*right*) in front of their radio antenna. *Credit* AIP Emilio Segre Visual Archives, Physics Today Collection

the characteristic temperature of the noise to be about 3 K, corresponding to microwaves with a wavelength of 2 mm. The noise did not depend on the time of day or the direction in the sky, ruling out the atmosphere as a source. They also ruled out electronic noise and, believe it or not, pigeon droppings on the antenna! (Fig. 11.7).

Dicke and his group at Princeton were ready to start their measurements when they learned about Penzias and Wilson's predicament. They knew immediately that the mysterious noise whose origin puzzled Penzias and Wilson was precisely the signal of relic radiation that they were hoping to detect. The two teams published back-to-back papers in the same journal. Penzias and Wilson described their experiment, and the Princeton group interpreted it as a measurement of the cosmic radiation left over from the big bang.[5] Today this radiation is called the cosmic microwave background (or CMB).

And what about Gamow's group? By the time of the CMB discovery none of them was actively working in cosmology. In the mid-1950s Gamow became interested in biology, where he contributed important insights into the genetic code, while Alpher and Herman moved on to careers in industry. Penzias and Wilson were awarded the Nobel Prize in 1978. No prize has ever been awarded for the prediction of the CMB.

Penzias and Wilson measured the intensity of the CMB at only one wavelength. To determine if this radiation was indeed part of a thermal spectrum, cosmologists still had to measure the radiation intensity over an extended range of wavelengths. This problem was tackled in a number of experiments in subsequent years, culminating in 1990 with the launch of NASAs Cosmic Background Explorer (COBE) satellite. COBE measured the spectrum of the CMB with unprecedented precision and found a perfect thermal spectrum (as predicted by the theory) with $T = 2.725\,\mathrm{K}$ (Fig. 11.8). Furthermore, the radiation intensity measured by COBE was nearly the same in all directions, with variations of less than $1/1000$. Thus the early universe was indeed very isotropic and homogeneous.

11.5 Images of the Baby Universe

What do we actually see in the CMB? This depends on how accurately we measure the radiation temperature. If the accuracy is less than one part in 1000, then all we can see is a uniform radiation background, as in Fig. 11.9a. Here, the sky is represented with the so-called Mollweide projection, which is often used to represent the surface of the globe on a flat map.

[5]The observed value of the CMB temperature (3 K) is close to the theoretical prediction (5–10 K). The discrepancy between the two was mostly due to the uncertainty in the average matter density that was used in the calculations.

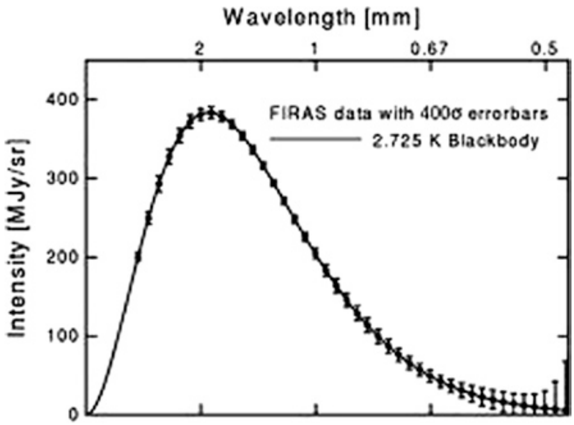

Fig. 11.8 COBE's measurement of the cosmic background radiation spectrum. The theoretical blackbody spectrum (*solid curve*) is superposed on the data points. The *error bars* have been magnified 400 times, so that they are visible

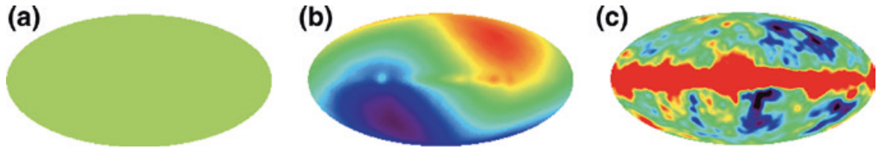

Fig. 11.9 COBE temperature pattern, at various levels of sensitivity. **a** Smooth background indicating the universe is homogeneous and isotropic. **b** Dipole pattern due to our motion relative to the CMB. In the direction we are heading, the CMB photons are slightly blueshifted (so their temperature is higher; hence this part of the sky is marked *red* in the figure, and in the opposite direction they are *redshifted* [so the corresponding part of the sky is *blue* (This choice of *color coding* can be confusing. Here the convention of everyday life, where *red* means "hot" and *blue* means "cold", like on faucets, is followed. Unfortunately this convention is opposite to the fact that *blueshifted light* is hotter and bluer)]. **c** The *red band* comes form microwave emission in our galaxy. The other patches indicate tiny temperature fluctuations of the CMB, due to the presence of small density fluctuations at the time the CMB photons were emitted

At a somewhat higher accuracy, a "yin-yang" pattern emerges, as shown in Fig. 11.9b. Red coloring corresponds to higher and blue to lower than average temperature. This so-called dipole pattern is due to the motion of our Milky Way galaxy relative to the CMB. The highest temperature is observed in the direction of our motion, and the lowest temperature in the opposite direction. This is just the Doppler effect: as we move towards the incoming radiation, its wavelength shrinks and the temperature increases. The velocity of our motion through the CMB is about 600 km/s; it can be attributed to

Fig. 11.10 The COBE team leaders John Mather (*left*) and George Smoot (*right*) won the 2006 Nobel Prize in Physics for this work. *Credit* (for John Mather photo) NASA, courtesy AIP Emilio Segre Visual Archives, W. F. Meggers Gallery of Nobel Laureates. This image also available from NASA.*Credit* (for George Smoot photo) Photograph by Jerry Bauer, courtesy AIP Emilio Segre Visual Archives, W. F. Meggers Gallery of Nobel Laureates

the gravitational attraction of a large concentration of mass in the direction of the Virgo supercluster (Fig. 11.10).

The dipole component can easily be subtracted from the CMB temperature map. This reveals a pattern of higher and lower temperature regions shown in Fig. 11.9c. The red “equatorial” band comes from the microwave emission of our galaxy. In the rest of the map, the typical temperature variation between red and blue regions is only about one part in 100,000. These tiny variations reflect fluctuations in density. Higher density regions will later evolve into galaxies and galaxy clusters, as we will discuss in Chap. 12.

The temperature map in Fig. 11.9c was produced by the COBE satellite in 1992, after two years of taking data. It showed for the first time that the early universe did have small density fluctuations. However the resolution of COBE was rather limited, and much more work remained to be done to mine the vast amount of cosmological information contained in the CMB. Thus, NASA's Wilkinson Microwave Anisotropy Probe (WMAP) satellite[6] was launched in

[6]The satellite was named after David Wilkinson who played a major role in CMB research. (Remember, Wilkinson was one of the young fellows that Robert Dicke recruited to build a CMB detector in the1960s).

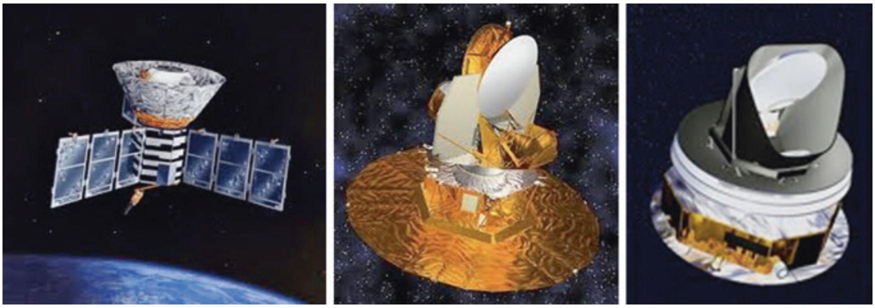

Fig. 11.11 The COBE (launched 1989), WMAP (launched 2001), and Planck (launched 2009) satellites. *Credit* GSFC/NASA, NASA / WMAP Science Team, and ESA

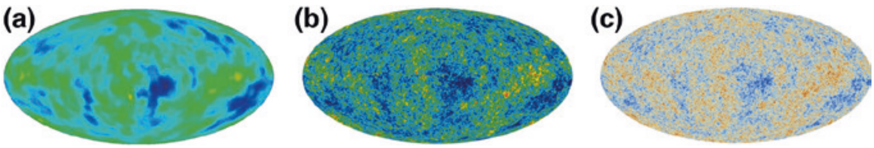

Fig. 11.12 CMB temperature maps of increasing resolution produced by **a** COBE, **b** WMAP, and **c** Planck satellites. *Credit* **a COBE b** NASA / WMAP Science Team**c** Copyright ESA and the Planck Collaboration

2001 to succeed COBE. While COBE's resolution was 7° (note the angular size of the full moon is 0.5°), WMAP had a resolution that is 33 times higher, and was 45 times more sensitive. WMAP operated successfully for 9 years, returning precision data that led to accurate determinations of the age, composition, and geometry of the universe. WMAP was succeeded by the Planck satellite, which had triple the resolution and was 10 times more sensitive. As the resolution improved, the image of the baby universe has become more and more focused (see Figs. 11.11 and 11.12). This image contains important information about physical phenomena that took place way before the epoch of recombination. We will have more to say about this later.

11.6 CMB Today and at Earlier Epochs

CMB photons are all around us, in huge numbers. Their number density (that is, the number of photons per cubic meter) is[7] $n_\gamma \approx 4 \times 10^8\ \mathrm{m}^{-3}$. This is comparable to the density of photons coming to us from a full moon.

[7] The Greek letter gamma, γ, is often used to denote photons.

If our eyes were sensitive to microwaves, we might be able to see in the cosmic light!

We can compare n_γ to the average number density of nucleons: $n_n \approx 0.24\,\mathrm{m}^{-3}$. The nucleon to photon ratio is

$$\frac{n_n}{n_\gamma} \approx 6 \times 10^{-10} \tag{11.5}$$

which means that there are more than a billion photons present for every nucleon in the universe.

Even though microwave photons are much more numerous than nucleons, the energy (and equivalent mass) of each photon is very small compared to that of a nucleon. As a result, the mass density of the CMB is much smaller than the density of matter today

$$\frac{\rho_{\gamma 0}}{\rho_{m0}} \approx 1.7 \times 10^{-4}. \tag{11.6}$$

We now consider how the cosmic radiation evolves with time. As the universe expands, the wavelength of CMB photons grows in proportion to the scale factor, $\lambda \propto a$, and their energy decreases as $E \propto 1/a$. Since the wavelengths of all photons are stretched by the same factor $a(t)$, the thermal form of the radiation spectrum is preserved. The radiation temperature T is proportional to the average energy of photons; hence

$$T \propto 1/a. \tag{11.7}$$

It follows from Eq. (11.7) that

$$\frac{T}{T_0} = \frac{1}{a}. \tag{11.8}$$

Here, $T_0 \approx 3\,\mathrm{K}$ is the present CMB temperature and we use the convention that the scale factor is $a_0 = 1$ at the present time. This useful formula allows us to determine how much the universe has expanded since the time when it had temperature T. For example, the temperature at recombination is $T_{rec} \approx 3000\,\mathrm{K}$, and we find from Eq. (11.8) that the scale factor at that time was $a_{rec} \approx 10^{-3}$. This means that the universe has expanded by a factor of 1000 since the time of recombination. The corresponding redshift is $z_{rec} \approx 1000$.

The cosmic time t_{rec} at recombination can be found by solving the Friedmann equation for the scale factor $a(t)$. This gives $t_{rec} = 380{,}000$ years.

The CMB thus provides an image of the universe at 380,000 years after its birth—a very early time, compared to the present cosmic age of about 14 billion years.

In the course of cosmic expansion, the number density of photons is diluted as

$$n_\gamma \propto \frac{1}{V} \propto a^{-3}, \tag{11.9}$$

where $V \propto a^3$ is the volume of an expanding region. At the same time, the energy of each constituent photon decreases as $E \propto a^{-1}$, due to redshift. The overall effect is that the radiation energy density is proportional to

$$\rho_\gamma \propto a^{-4}. \tag{11.10}$$

11.7 The Three Cosmic Eras

The energy density of the universe is now dominated by dark energy (69%), it has a substantial matter component (dark 26% and atomic 5%), and trace amounts of radiation. However, the three energy components evolve in different ways: the matter and radiation densities decrease respectively as $\rho_m \propto a^{-3}$ and $\rho_\gamma \propto a^{-4}$, while the vacuum energy density remains constant. As a result, the composition of the universe at earlier times was rather different from what it is now (see Fig. 11.13).

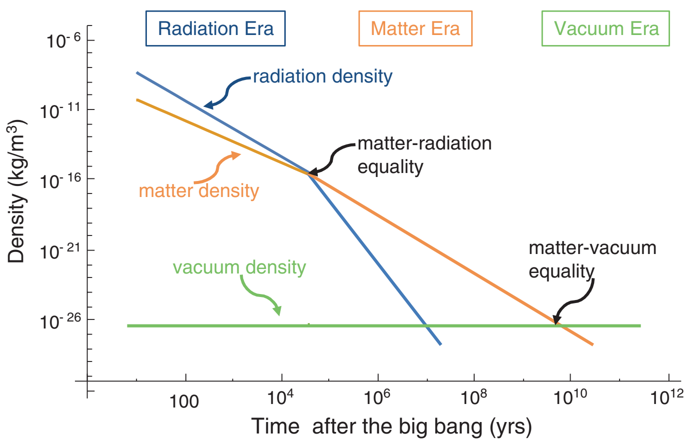

Fig. 11.13 The evolution of energy density for each cosmic component

Even though ρ_γ is much smaller than ρ_m today, as we follow cosmic evolution back in time, the radiation density grows faster than that of matter, and at $t_{eq} \approx 60{,}000$ years the two densities become equal (see the Appendix). At earlier times the radiation density was larger than both the matter and dark energy density. Thus this era is called the radiation era. At later times, the matter density dominates over radiation and dark energy. This matter era lasts for several billion years. Finally, roughly 5 billion years ago, the matter density dropped below that of the vacuum energy density, and the universe entered its current vacuum dominated era.

During the radiation and matter era, the scale factor grows as $a(t) \propto \sqrt{t}$ and $a(t) \propto t^{2/3}$, respectively (as we show in the Appendix). In both of these eras the horizon distance grows linearly with time, $d_{hor} \sim t$, which is faster than $a(t)$. Thus more and more of the universe becomes visible with time. The situation, however, is different in the vacuum era where the scale factor grows faster than the horizon. In this case, more and more of the observable universe exits our horizon, and less and less of the universe becomes visible with time (we will return to this in Chap. 16).

Summary

When we follow the expansion of the universe backwards in time, the density and temperature increase without bound. All structure disintegrates at high temperatures; thus the early universe starts out as a fireball of the most basic particles, including electrons, protons, neutrons, and photons. The fireball uniformly fills the whole universe. As the universe expands, it cools down, and composite objects begin to form. Within the first three minutes after the big bang, the temperature dropped sufficiently for protons and neutrons to bind together into atomic nuclei. Then at about 380,000 years, electrons and nuclei combined to form neutral atoms, and the universe became transparent to light. We can now detect the radiation emitted from the fireball at that epoch; it comes to us from all directions in the sky. This is what we call the cosmic microwave background radiation.

In broad-brush terms, the history of the universe can be divided into three cosmic eras: the radiation era, the matter era, and the current dark energy era. During each era the energy density is dominated by radiation, matter and dark energy, respectively.

Questions

1. As we follow the universe backwards in time, what happens to its temperature T and density ρ as we approach the big bang?

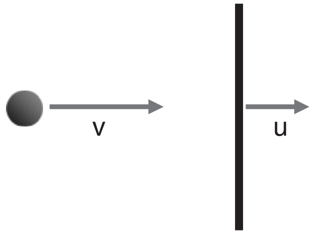

Fig. 11.14 Particle and retracting wall

2. What happens to the temperature of gases as they expand? And as they are compressed?
3. Consider a particle moving at speed v towards a wall which is retracting at speed $u < v$ in the same direction, as shown in Fig. 11.14. What will be the particle's speed after it bounces off the wall? (Hint: consider how this process looks to an observer moving with the wall, who sees the particle bounce back at the same speed as it arrives.)
4. Today the universe is filled with complex structures like atoms and molecules. What happens to these structures as we go far back to the hot early universe?
5. Is it possible to break nuclei into separate protons and neutrons? Would this happen at a higher or lower temperature than the ionization of hydrogen? (An atom of hydrogen is "ionized" when its electron is separated from the nucleus.)
6. If photon A has twice the wavelength of photon B, by how much is its energy greater or less than that of photon B?
7. Briefly explain the relation between the rate of photon emission and absorption for a system that is in thermal equilibrium.
8. The Sun is a thermal emitter with a surface temperature of 6000 K. If the temperature of the Sun's surface were to double, what would happen to the intensity of the sun's radiation?
9. The peak intensity of radiation of the Sun is right in the middle of the visible part of the spectrum. Do you think this is just a coincidence?
10. Did the initial fireball explode into empty space? Please explain.
11. What is recombination? What is the "surface of last scattering"?
12. As we observe distant objects in the universe, do we see them as they are today, or as they were at some time in the past? Why? Does this help or hinder us in our quest to understand the evolution of the universe?

13. Why can we not look all the way back to the big bang?
14. The microwave background radiation was emitted when the temperature of the universe was 3000 K. Objects in thermal equilibrium at this temperature glow red, so why are we surrounded by a sea of microwave photons, instead of red photons?
15. What happens to the wavelength of photons as they propagate in an expanding universe?
16. Is there any way to account for the CMB radiation in the steady state theory?
17. Does the CMB spectrum shape (the solid curve in Fig. 11.8) vary from one direction in the sky to another? Does it change as the universe evolves? Why?
18. Explain in what sense the CMB provides an image of the universe at 380,000 years after the big bang.
19. What do the differences in color on the CMB maps in Fig. 11.12 represent?
20. If someone claimed to discover a galaxy at a redshift of 2000, would you believe it? Why/Why not?
21. Why is the CMB slightly hotter in one half of the sky than in the other?
22. Consider a galaxy at a redshift of $z = 1$. What was the average matter density at the time light left the galaxy compared to today? What was the average energy density of radiation then compared to today? What was the temperature of the CMB then?
23. By how much has the universe grown in size since the time when matter and radiation densities were equal to each other? (Hint: you may use the present value of the ratio $\frac{\rho_\gamma}{\rho_m}$ in Eq. (11.6) and figure out how this ratio depends on the scale factor a.) What was the temperature of the universe at the time of equal matter and radiation densities?
24. If there are any observers around in half a trillion years from now, will they be able to see other galaxies? Will they see CMB radiation? If so, how would that radiation be different from what we observe today?