Chapter 12: Cosmic Background Radiation

In Chapter 10 we discussed the evidence for us being in an expanding universe. In particular we saw that distant galaxies are moving away from us with high speeds, and the farther they are away the faster they are moving. In Chapter 11 we considered the details of the data and used this to conclude that it is more likely that we are in a special type of explosion, not an explosion into space, but an expansion of space. In this chapter we will look at a completely different set of evidence that supports this version of the big bang theory – the enormous number of low energy photons that permeate the universe, called the **cosmic background radiation**. While these photons provide, perhaps, the most compelling piece of evidence for the big bang, why they provide evidence is probably the hardest to explain. We start by translating these words and what they have to do with an expanding space-time. We then give a brief history of the universe after the bang so we can see how they fit in as a central part of the story.

12.1 Overview of the cosmic background radiation

Before we can decipher the phrase **cosmic background radiation** we'll define the words in it. The word cosmic means it is important in the cosmos, or that it's everywhere in the universe. The dictionary often defines something that is in the background as being "inconspicuous; out of sight or notice." Finally, radiation is defined as "energy in the form of waves or particles," and photons are just a type of radiation[1]. So, our phrase is just a set of fancy words that means that there are lots of low energy photons, everywhere in the universe which make them hard to notice. Instead of saying cosmic background radiation, some people use the phrase **cosmic microwave background (CMB)** since the photons have the same energy as microwave photons[2].

To understand why the presence of these low energy photons provides evidence for the big bang model and the expansion of space-time, we need to understand a little about the evolution of the universe and what was happening right after the bang itself. Ultimately, any model of the origin and evolution of the universe needs to explain why there are all these photons in the universe, why they are the same in all directions, and why they have the special energies they do. Though the answer is a fairly complicated one, the good news is that once we know the story we can understand how the evidence fits in.

To quickly summarize the answer: our best understanding is that the photons are there now because the universe was once really small, really hot (high temperature) and in thermal equilibrium. This occurred right after the bang. Since we expect lots of photons to be produced during high energy collisions (and there should be lots of them in a small universe with a high temperature), they should still be here today. There is no reason to believe they should have all disappeared since photons don't decay, which explains why they are still around. The reason they have a particular temperature distribution today is because they once were in thermal equilibrium when the universe was smaller. Back then, they would have interacted with each other and mixed with all the other particles of the universe like we described in Chapter 9. They are low energy because since then the space in the universe has expanded which, according to Chapters 5 and 11, stretches their wavelengths and makes their energy go down.

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[1] Radiation therapy can be used to help cure cancer. On the other hand, radiation damage from an atomic bomb has been known to cause birth defects.

[2] Figure 1 in Chapter 5 gives the names of the different energy photons.

Explaining how all this happens is complicated. Let's start out by adding pieces of evidence that are intimately tied into our story. When we look at the universe we observe that:

1. ~75% of the atoms in the universe are hydrogen.
2. ~25% of the atoms in the universe are helium.
3. There is very little of all the other types of atoms.
4. There vast numbers of low-energy photons (microwaves) distributed in all directions that are consistent with a temperature of about 2.7 degrees above absolute zero (Kelvin).

We will tell the story in three pieces: 1) The bang, the particles in the universe and what happens when the particles interact, 2) A hot early universe in thermal equilibrium that has lots of photons but no heavy nuclei, 3) thirteen and a half billion years later we have a cool universe with microwaves.

12.2 The bang, the particles in the universe and what happens when the particles interact

The story goes like this: In the beginning, there was a bang. A really big bang. A tiny fraction of a second after the bang, what we call the **early universe**, the universe is still very small and all energy in the universe was confined inside it. There would have been many different types of particles including electrons and positrons, photons, quarks and anti-quarks, and others that we mentioned in Chapter 3. These particles interacted with each other according to the laws of quantum mechanics and came into thermal equilibrium. Having large numbers of high energy particles with the same energies in a small space is the definition of high temperature. As time went by, the universe expanded. This stretched the wavelengths of the particles which is the same thing as saying the energy of the particles dropped. Since the space is getting bigger and the energy of the particles is going down, this is the same thing as saying that the temperature is dropping.

The story of the evolution of the universe is essentially the story of what happened to all the particles in the universe as the energy of the particles dropped and the universe expanded. The reason this is important is because the *way* that particles interact with each other depends critically on the energy of the particles. At different energies VERY different kinds of things can happen and this drastically alters what's going on in the universe as it gets older.

We start by showing how composite particles such as protons, nuclei and atoms are created. Figure 1 shows both three quarks interacting and combining to form a proton. It also shows a set of pictures showing a proton and an electron combining in an electromagnetic reaction to form a hydrogen atom.

Next we describe other types of interactions with photons, atoms and nuclei. Figure 2 shows four separate interactions with a photon; two where the photon has high energy and two where it has low energy. If the photon has a high enough energy it can bust the atom or the nucleus apart. If it has low energy it will, at most, just bump it. We note that it takes a much higher energy photon to break apart a nucleus than it does to break apart an atom.

Finally, we remind you that there are lots of other types of interactions, like we had in Chapter 9, Figure 7. There we had two high energy photons that collided and turned into an electron and positron. We note that this only occurs for high energy photons. Since mass and energy are equivalent, remember $E=mc^2$, if the photons are not high energy they cannot produce the electrons since the electrons have mass. They will just bump into each other and move off into space. On the flipside, since an electron and positron always have mass, they can always interact to produce a pair of photons. All of this will be important later in the story.

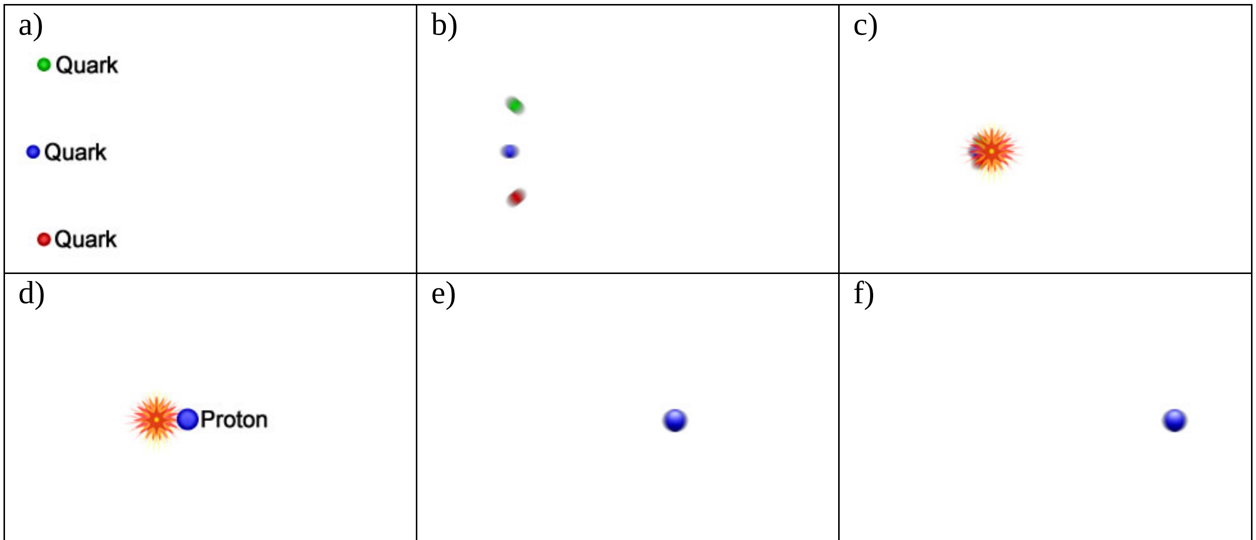


Figure 1: Three quarks combine to form a proton. An electron collides with a proton and forms a hydrogen atom and emits a photon.

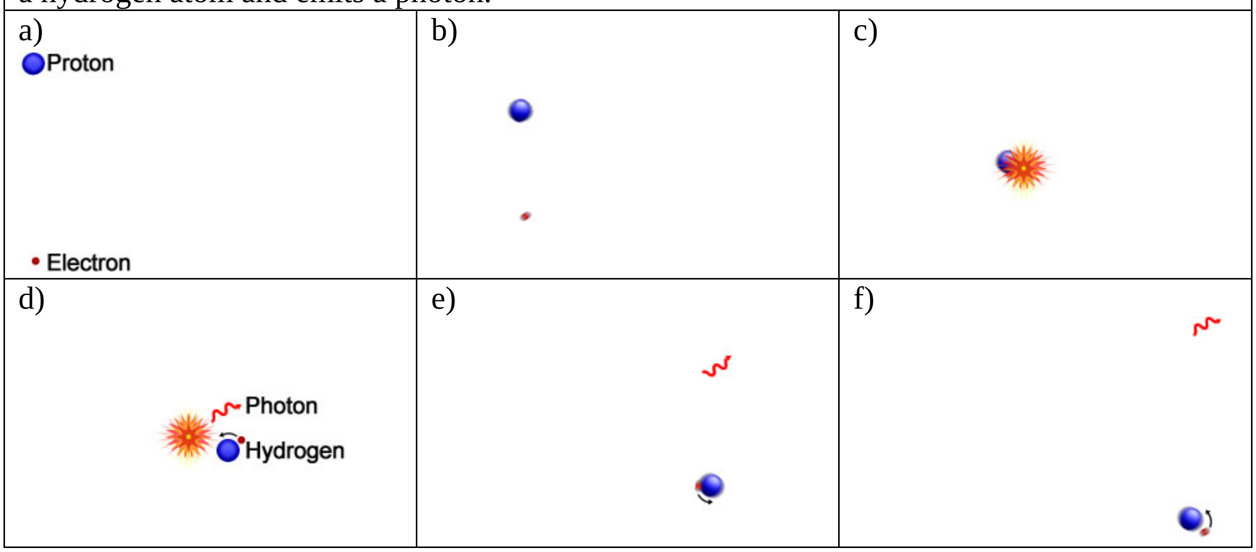
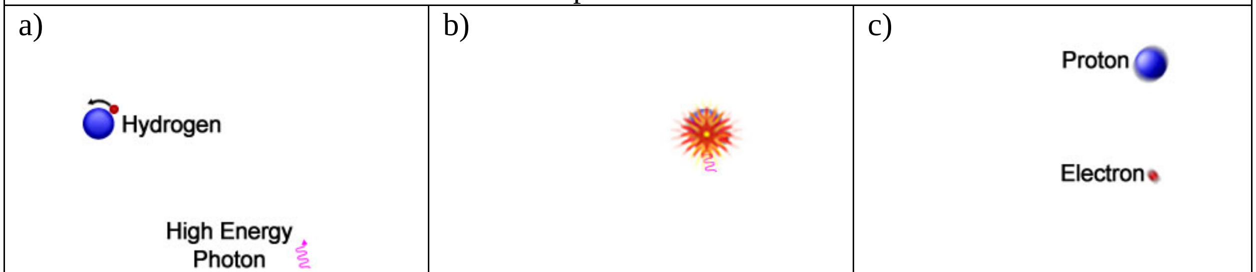
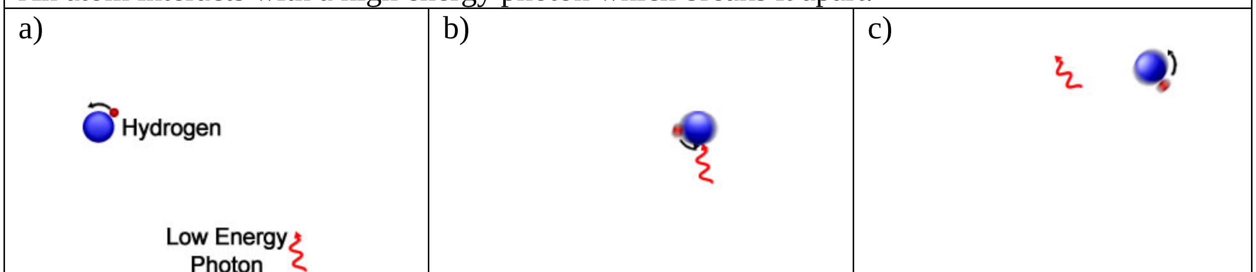


Figure 2: Various interactions between atoms and nuclei with high energy and low energy photons.

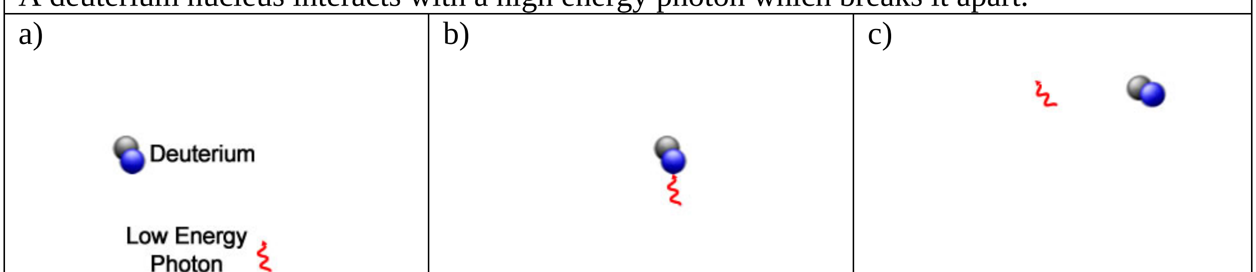


An atom interacts with a high energy photon which breaks it apart.



An atom interacts with a photon which doesn't have enough energy to break it apart. In this case it only bumps the atom.

A deuterium nucleus interacts with a high energy photon which breaks it apart.



A deuterium nucleus interacts with a photon which doesn't have enough energy to break it apart. In this case it only bumps the nucleus.

12.3 A hot early universe in thermal equilibrium has lots of photons but no heavy nuclei

We're now ready to start talking about the evolution of the universe for the first few minutes after the big bang. Remember that our early universe was very hot which just describes the fact that there were lots of high energy particles in a small space. Because of this our universe would quickly come to have lots of high energy photons in thermal equilibrium. This is true for a number of reasons but the biggest one is that even if there weren't a large number of photons directly produced in the bang itself, collisions like the ones described in Chapter 9 between electrons and positrons (or other particles), would have produced them.

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While we could just tell the history of the photons, we want to tell the story of the other particles which eventually turn into stars and galaxies. The stories of these different particles aren't separate, they're intimately related. As we will see, a hot universe with lots of photons explains why we don't have lots of heavy nuclei atoms today.

Figure 1 showed a proton and electron combining in an electromagnetic reaction to form a hydrogen atom. However, since there are lots of high energy photons in the early universe and the universe is very small it doesn't take long before the hydrogen atom encounters a high-energy photon. As shown in Figure 2 the collision splits the atom back into a proton and an electron. Since high-energy photons break up atoms quickly, there are essentially no atoms in the early universe, but there are lots of free electrons and protons. Similarly, Figure 3 shows two protons in the early universe. They will quickly find each other and combine in a nuclear reaction to form a deuterium nucleus (and an electron and a neutron). However, for the same reasons as above, the deuterium nucleus will quickly encounter a high-energy photon which breaks the nucleus up into a proton and a neutron. Thus, even if there were lots of heavy nuclei in the early universe, the high energy photons would quickly break them up. Since high-energy photons break up heavy nuclei before they can find another proton or neutron to form a bigger nucleus, the early universe basically contains only photons, electrons, positrons and neutrons. It's true that we can have other fundamental particles that can be created in high energy collisions, but that happens for a tiny fraction of a second after the bang, we'll come back to it later in Chapters 13 and 20.

As the universe gets older and the average energy of the particles decreases, the way in which the particles interact with each other changes drastically. Instead of being like the interactions in Figure 2 with high energy photons, the interactions are like the ones in Figure 2 with the low energy photons. When the universe is about 3 minutes old the average photon doesn't have enough energy to break apart nuclei any more. So, since deuterium can still be produced but not easily destroyed, it's just a matter of time before we get more deuterium in the universe. Once we have more deuterium in the universe it doesn't take long before a deuterium nucleus encounters a proton and can have an interaction like in Figure 3 of Chapter 8 to form helium, He_3 to be exact. Eventually, with enough He_3 in the universe we can get two He_3 nuclei which will interact and produce He_4 and two more protons, as shown in Figure 4. This is why there is helium in the universe, but much more hydrogen than helium.

We'll talk more about why it's so much harder to build up even heavier nuclei in later chapters. This will explain why there are so little heavy nuclei in the universe. The basic answer for now is that it's hard to form heavy nuclei since you need lots of helium around to do it. Since the universe is expanding quickly and it takes a long time to build up even a small amount of helium in the universe, it just doesn't happen very much.

A few more interesting things before we move on to much later times. We can get some heavy nuclei, but most of the heavy nuclei in the universe will come from stars. This will be described in Chapter 16. It's also interesting to note that the nuclei won't become atoms for several hundred thousand years. As we mentioned before, the reason is that until then the photons are energetic enough to knock electrons out of orbit but not energetic enough to break apart the nucleus. We'll talk more about this in Chapter 14. The bottom line is that a hot early universe in thermal equilibrium explains why there is so much more hydrogen than helium, why there is so little of any other type of atom, and why all these atoms are so uniformly distributed in the universe. What it doesn't explain is how all the atoms condensed into galaxies and black holes. We'll cover that in Chapters 15 through 17. For now, we can talk about what happened to the photons as the universe aged, and why they are a crucial piece of evidence for the big bang description of the origin of our universe.

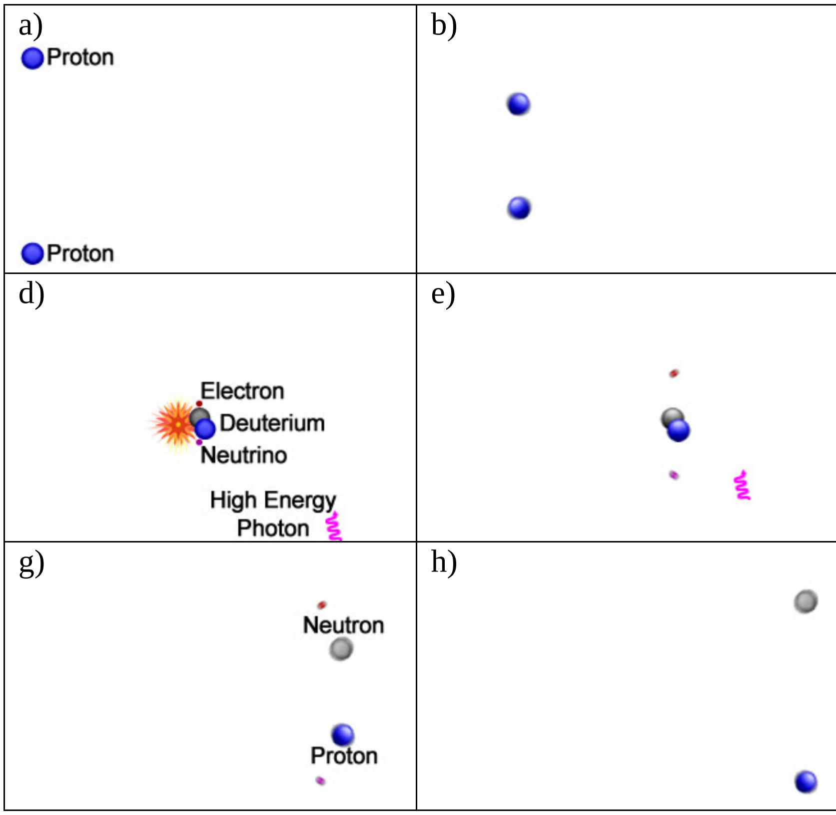

Figure 3: High energy photons break up nuclei before they can find electrons to form atoms or find other nucleons to form heavier nuclei.

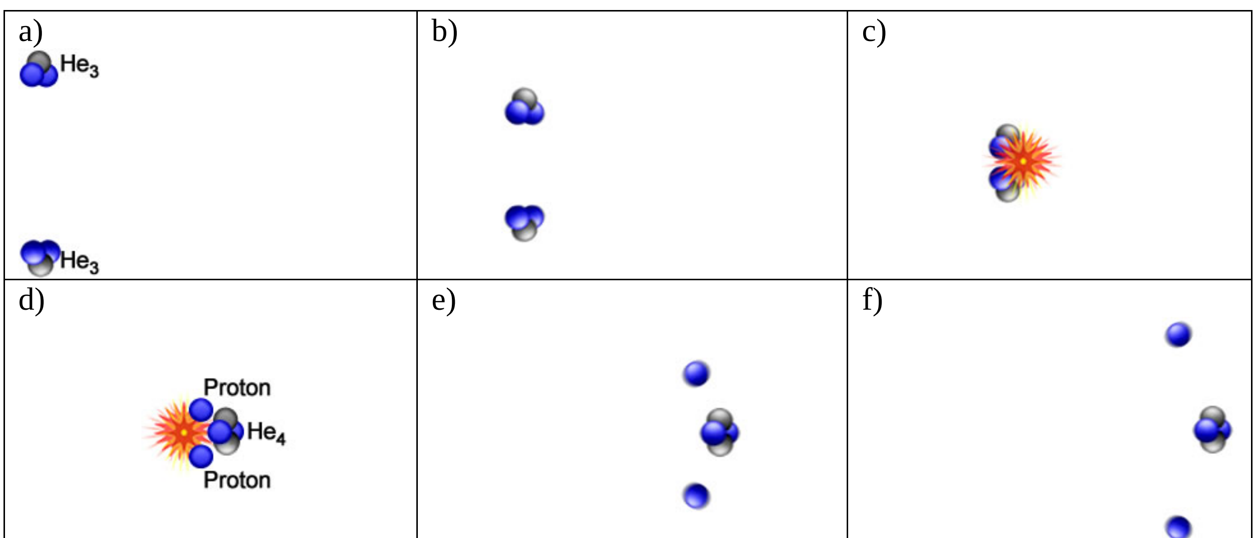

Figure 4: Two helium nuclei, He_3, interact and create a He_4 nucleus and two more protons (hydrogen).

12.4 Thirteen and a half billion years later: photons in a cold universe

We’re finally ready to talk about the last piece of the puzzle: the photons. Thirteen and a half billion years after the bang, essentially all the protons and neutrons are inside nuclei and all the electrons have joined the nuclei and produced atoms. What happened to all the photons as the universe expanded and cooled over time?

As shown in Figure 5, as photons travel through space over billions of years, their wavelengths get longer as the universe expands. This is not only true for photons from galaxies, but for any photon that existed in the early universe that is still around. All the photons in thermal equilibrium with high temperatures in the early universe are now low energy photons with a low temperature today. It was these low energy photons, with microwave energies, that were discovered in 1964 by Arno Penzias and Robert Wilson[3] that convinced most scientists of the validity of the big bang model.

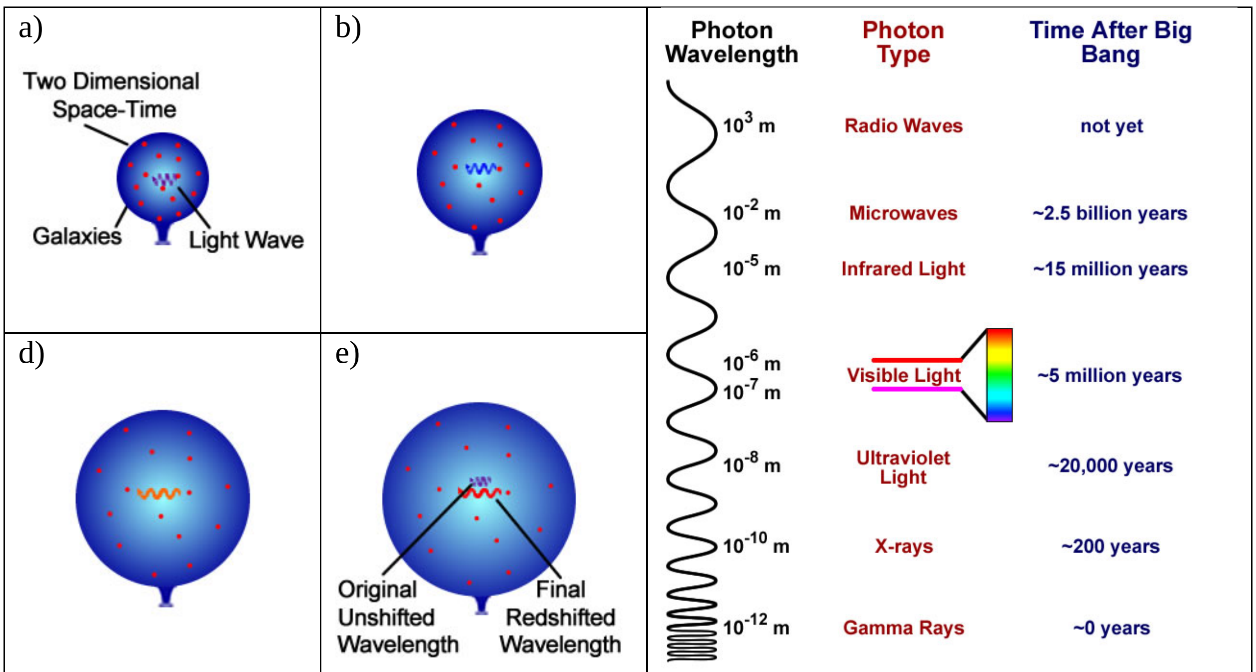

Figure 5 The stretching of a photon wavelength as the universe expands. The photons in the early universe we high energy gamma rays. Now they are low energy microwaves.

There are a number of things that are important about these photons. It isn’t just that there are lots of them. It is incredibly important that they have an energy distribution that is consistent with having a specific temperature AND that the temperature was really low. It is measured today to be 2.728 Kelvin which is -270 degrees Celsius or -454.8 degrees Fahrenheit. This is consistent with what you’d see in an old, cold and expanding universe. Perhaps most importantly, when they measured the temperature they found it was virtually the same in every direction. How uniform is the temperature of the cosmic background radiation? If we look at the

[3] The discovery of the cosmic background radiation is a wonderful story and I encourage you to read about it elsewhere. One of the things that make it so fun is that Penzias and Wilson weren’t looking for these photons; they stumbled on them while they were working other things and had no idea what the “problem” with their experiment was. It wasn’t until talking to some friends who were looking for the photons did they realize what they had discovered.

full sky in a single map and stretch out the sphere onto a flat page, we can draw a temperature map where different colors correspond to different temperatures. This is done in Figure 6, and as you can see the cosmic background radiation is incredibly uniform.

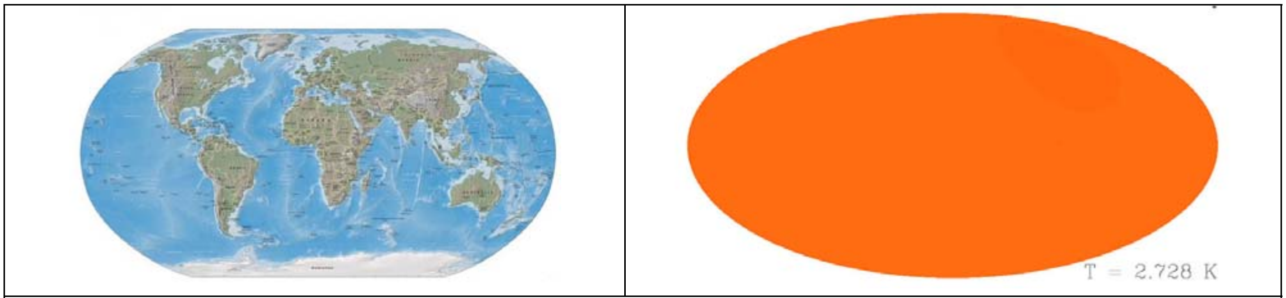

Figure 6: Looking at all directions is difficult to draw on two-dimensional paper. On the left is a two dimensional representation of the Earth mapped out. Similarly, but looking out, is the temperature map of the cosmic background radiation. Different temperatures are shown with different shadings. As you can see the incredibly uniform shading shows that the temperature is the same every direction.

In summary, we have laid out a story of the origin of our universe with a big bang that has a space-time described by general relativity and which evolved into the universe we have today. This story is supported by an enormous amount of evidence, including the receding of distant galaxies and the incredible numbers of photons that are consistent with having been in thermal equilibrium. We observe a universe that is consistent with having a size that is around thirteen and a half billion years old and a temperature that reflects this age. The expansion of space-time helps explain why the galaxies are all moving away from us the same way in all directions, why the further-away ones are moving away quicker, and why the background radiation looks the same in all directions. While there may be some better explanation out there that we don't know about, this one does a remarkable job of explaining an amazing amount of data. These separate pieces of evidence otherwise would appear to be a remarkable coincidence.

Next, in Unit 4, we will learn more about the evolution of the universe. In particular, we will study what happened right after the big bang and follow the history of time in more detail through the first three minutes all the way through galaxy and black hole formation until the modern day.

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Chapter 12 Problems:

1) What is the temperature of the cosmic background radiation?

A) 2.7 degrees Kelvin
B) 2.7 degrees Fahrenheit
C) 100.0 degrees above absolute zero
D) 98.9 degrees Fahrenheit
E) 1000 degrees Kelvin

2) Which of the following statements describe evidence that lead us to believe that the universe passed through a state of thermal equilibrium?

A) The uniform nature of the cosmic background radiation
B) That the temperature is of the cosmic background radiation is basically the same in all directions
C) Both A and B are true
D) The primary piece of evidence has nothing to do with the background radiation

3) The measurement that the universe looks the same in all directions is thought to be a consequence of what property of the early universe?

A) The fact that there were a large number of photons present in the early universe
B) The presence of more matter than antimatter in the early universe
C) The fact that it passed through a state of thermal equilibrium
D) The expansion of the early universe was slower than it is now
E) None of these properties describes this consequence

4) Since the universe appears to be a giant vat of gas (of various types of particles) that has the same temperature in all directions, this means it is likely to have been in thermal equilibrium at one point.

- True/False

5) If the universe was in thermal equilibrium then we are restricted in our knowledge about what happened before everything came into thermal equilibrium

- True/False

6) There were lots of atoms in the early universe?

- True/False

7) There were lots of protons in the early universe?

- True/False

8) Most of the heavy elements in our universe were produced by:

A) Collisions between electrons
B) Collisions between photons
C) Collisions between electrons and protons
D) Stars

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9) The photons in the cosmic background radiation today are mostly

A) Gamma rays
B) Electrons
C) X-rays
D) Microwaves
E) Radio waves

10) Most of the atoms in the universe are hydrogen. The rest are mostly:

A) Helium
B) Carbon
C) Oxygen
D) Nitrogen

11) Photons always break up which of the following:

A) Atoms
B) Nuclei
C) Both, regardless of their energy
D) Neither, regardless of their energy
E) It depends on the energy of the photon

12) Photons in cosmic background radiation are low energy today because

A) They've been interacting with atoms for billions of years
B) Photons just lose energy over time
C) The universe is expanding which stretches their wavelength
D) It takes a lot of energy to make that many photons