# 10. Big Bang Nucleosynthesis and the Cosmic Microwave Background

**Reading:** Assuming that you have already read Chapter 5 and Sections 8.1-8.3 (go back to them if you haven't), go on to read section 8.4. You can skip 8.5, which is a level of detail we won't have time to get to.

Then read Chapter 10. If you want to understand more about nuclear reactions, which is useful background, then read Chapter 9, especially 9.6; however, Chapter 9 is optional.

## The Big Bang Theory

Recall the definition of the BBT I gave back in Section 5:

The universe has expanded from a very hot, very dense state that existed at a finite time in the past (approximately 14 billion years ago).

We are now in a position to be somewhat more specific in our definition, namely that the BBT assumes:

(a) that the universe on large scales (roughly speaking, tens of millions of light years or more) can be approximated as homogeneous

(b) that the expansion of the universe is governed by GR, given the matter and radiation (e.g., photons) present in the universe

(c) that atoms and nuclei and radiation obeyed the same fundamental physical laws in the past that they do today.

Together, assumptions (a) and (b) mean that the expansion factor $a(t)$ follows the Friedmann equation given back in Section 8, according to which

$$\ddot{a}(t) = -\frac{4\pi G}{3} \times a(t) \times \left(\bar{\rho} + \frac{3p}{c^2}\right).$$

Here $\ddot{a}(t)$ is a mathematical way of denoting "the acceleration of $a$ at time $t$."

You should have an intuitive feel for what this means — if the acceleration is negative, then the expansion is slowing down — but don't worry about the mathematical details.

When we say "the big bang" we mean the time $t = 0$ when $a(t) = 0$.

We don't really have empirical evidence about what was happening at $t = 0$.

Remarkably, however, we have strong empirical evidence for the accuracy of the BBT back to at least $t = 1$ second, and good reasons to think it remains accurate back to at least $t = 10^{-12}$ seconds (the first trillionth of a second).

## The chemical composition of stars

Spectral absorption lines tell us that there are many different chemical elements present in the atmosphere of the sun.

In her 1925 PhD thesis at Radcliffe College (now part of Harvard), Cecilia Payne showed that although many elements can be detected in the sun, hydrogen and helium are by far the dominant elements in terms of mass.

This conclusion, that the composition of the sun was radically different from that of the earth, was widely disbelieved at the time, but it soon proved to be correct.

Today we know from interpreting spectra that in most of the sun, hydrogen atoms account for 70% of the mass, helium for 28% of the mass, and all other elemental species for 2% of the mass.

(The exception is in the central core of the sun, where nuclear fusion has been converting hydrogen into helium.)

The same is true of other stars like the sun.

In the *oldest* stars we can find, the mass is about 75% hydrogen and 25% helium, with just a tiny fraction of heavier elements.

By the late 1950s, it was recognized that the nuclei of most elements heavier than helium were made by nuclear fusion in the cores of stars, eventually expelled into space by stellar explosions.

(Every atom in your body that is not hydrogen or helium was once part of a star.)

But by the early 1960s, astronomers were finding that even stars with no heavy elements still had a lot of helium. Where did it come from?

**Big Bang Nucleosynthesis**

According to the BBT, when the universe was 1 second old, the temperature was about 10 billion degrees. (You can show this using the Friedmann equation and the properties of radiation.)

At this temperature, atomic nuclei would collide so fast that they would break apart, so there were only protons and neutrons. (Also electrons and photons and neutrinos and dark matter.)

There was about one neutron for every seven protons.

This ratio arises because neutrons are slightly more massive than protons, with the result that it is easier for neutrons to decay into protons and electrons than it is for protons and electrons to combine into neutrons.

When the universe was about two minutes old, its temperature had fallen to about one billion degrees.

At this temperature, protons and neutrons can fuse into deuterium nuclei ("heavy hydrogen").

Once the deuterium nuclei are created, they can quickly be fused into helium nuclei (two protons + 2 neutrons).

However, helium nuclei don't fuse because the isotope they would create (Beryllium-8, with four protons and four neutrons) is unstable and breaks apart immediately.

Bottom line: by the time the universe is 3 minutes old, nuclear fusion has pushed nearly all of the neutrons into helium nuclei.

The "extra" protons (6/7 of the original protons) are left behind as hydrogen nuclei.

When you work out the numbers, you find that approximately 75% of the mass is hydrogen and 25% is helium. (More precisely, it's 76% hydrogen and 24% helium.)

**History and confirmation**

The history of big bang nucleosynthesis is complicated. In brief:

In the 1940s and 1950s, the physicist George Gamow realized that nuclear fusion should occur in the hot early universe.

However, he did not recognize the bottleneck at Beryllium-8, so he thought that all elements might be made in the early universe.

Other physicists (not necessarily aware of what Gamow had done) picked up this idea in the early 1960s, correctly computing the 25% helium fraction.

This was the same time that observers were realizing that the oldest stars still had 25% helium abundance.

Conclusion: Big bang nucleosynthesis is the explanation of the "primordial" 25% helium abundance. Heavier elements (and additional helium) were made later by nucleosynthesis in stars.

Smoking gun evidence that this is the correct explanation:

• Discovery of the cosmic microwave background, in 1965 (see below)

• Roughly one in a hundred thousand deuterium nuclei "escapes" and doesn't get turned into helium. This is the fraction of deuterium that is observed in clouds of ancient gas.

The second confirmation has come out gradually over a couple of decades, with steadily improving measurements and predictions.

**The Background Radiation**

Gamow also realized that the hot matter in the early universe would produce photons — a background of electromagnetic radiation with the same temperature as the matter.

Because the early universe was dense, matter should have been able to absorb and emit photons very efficiently.

The radiation background should therefore have a specific distribution of photon energies known as a *blackbody spectrum*, because it is the spectrum that would be emitted by an object that is perfectly efficient at absorbing light that falls on it.

When the universe was 10 billion degrees, the typical photons would have been gamma rays, with wavelength comparable in size to an atomic nucleus.

These photons don't disappear, but the universe has expanded enormously since then, so the photon wavelengths have stretched by an enormous factor, and the temperature has dropped by an enormous factor.

Gamow and his students estimated that the temperature today would be a few degrees Kelvin.

However, they didn't comment on whether this background of radiation (microwaves, with wavelength of about 1 mm) might be observable.

**Recombination and the opaque early universe**

Continuing the calculation with the BBT, one finds that the temperature of the universe would have been 3000°K at $t = 400,000$ years.

At this time, the radiation background would have been at the boundary between red and infrared, casting a hot orange glow.

Before that time, the universe was too hot for neutral hydrogen atoms to exist.

Instead, there were protons, helium nuclei, and free electrons (not bound into atoms).

Free electrons are very good at scattering photons, much like water molecules in a fog.

Before $t = 400,000$ years, therefore, the universe was opaque, in the same sense that a fog is opaque — photons couldn't go very far before being scattered into another direction.

When the universe cooled to 3000°K, protons and electrons quickly combined to form neutral hydrogen atoms, leaving almost no free electrons.

(Neutral here means electrically neutral, with no electric charge. A proton without an electron would be considered an ionized hydrogen atom, with positive electric charge.)

Neutral hydrogen atoms do *not* scatter visible light photons (or infrared or microwave or radio photons), so since $t = 400,000$ years the universe has been mostly transparent — a typical photon can go forever without ever being absorbed or scattered.

This transition at $t \approx 400,000$ years, temperature $T \approx 3000°$K is referred to as *the epoch of recombination*, because of electrons and protons combining to make neutral hydrogen.

(The "re" in recombination is a misnomer, since the electrons and protons had never been combined in the first place.)

**The cosmic microwave background (CMB)**

In the early 1960s, two groups (one Russian, one American) retraced Gamow's steps, independently and more accurately.

They realized that there should be a detectable background of microwave radiation today and again predicted its temperature to be a few degrees Kelvin, with characteristic wavelength of about 1 mm.

One group based in Princeton built a small microwave telescope to search for it.

However, before they found it, the *cosmic microwave background* was discovered serendipitously, in 1965, by Arno Penzias and Robert Wilson, using a microwave telescope at Bell Laboratories in New Jersey.

Penzias and Wilson were characterizing this telescope, which had originally been built for experiments in satellite communication, and they found a faint microwave/radio “hiss” from all directions on the sky, which they could not get to go away.

This “hiss” is in fact the faded glow of the hot early universe, stretched in wavelength by a factor of 1000 since the epoch of recombination, and a factor of a billion since the epoch of nucleosynthesis.

Its almost perfect uniformity across the sky (uniform to better than 0.01 percent) is the first indication of its cosmic origin.

The second indication is its near-perfect blackbody spectrum, which demonstrates an origin in the dense early universe rather than starlight or emission from warm interstellar dust.

In 1990, the *Cosmic Background Explorer* satellite showed that the CMB matches a blackbody spectrum to better than 0.001 percent.

The temperature of the spectrum is 2.7°K.

If you take a lump of coal (or anything else) into intergalactic space, it will cool off by emitting radiation, but if it gets down to 2.7°K it won’t cool any further because of the warming glow of the CMB.

In the universe as a whole, there are about two billion CMB photons for every atom.

If you go out to sunbathe, each square inch of your skin is hit by a few trillion CMB photons every second.