10. The Cosmic Microwave Background

Reading: Chapter 8, sections 8.0-8.3. (We will cover 8.4 and 8.5 later.)

"Re"combination

After Big Bang Nucleosynthesis, the universe was still much too hot for the formation of neutral atoms.

As expansion continued, the background radiation photons redshifted and the temperature dropped.

Naively, one would expect $p + e^- \rightarrow H$ when $kT \sim 13.6\text{eV}$.

Just as with deuterium synthesis, however, the high value of n_γ/n_b implies that the exponential tail of the photon distribution can dissociate hydrogen atoms.

Less naively, we expect $p + e^- \rightarrow H$ when $kT \sim 13.6\text{eV}/(-\ln \eta) \sim 0.65\text{eV}$, corresponding to $(1 + z) \approx 2700$.

A more accurate version of this argument given in the textbook (section 9.3) yields a predicted redshift of $(1 + z) \approx 1370$ for hydrogen formation.

In practice, there are several complicating factors, e.g., any recombination direct to the ground state produces a photon that can immediately ionize another neutral atom unless the photon survives long enough to be redshifted below 13.6 eV.

A proper, somewhat tricky calculation of cosmic recombination shows that there is a fairly rapid transition from a free electron fraction $x_e \approx 1$ to $x_e \approx 0$ at $z \approx 1100$, with most of the transition occuring over a redshift range $\Delta z \approx 80$.

In the laboratory, or in regions ionized by hot stars or quasars or shocks, the process $p + e^- \rightarrow H$ is usually referred to as "recombination."

In the early universe, the protons and electrons were never in the form of hydrogen to begin with, so this process should arguably be called "combination" rather than "recombination."

But "combination" sounds rather silly, so "recombination" is still the standard term for this transition.

The Last Scattering Surface

Free electrons are good at scattering photons, with the Thomson cross section $\sigma_T = 6.6 \times 10^{-25}\text{cm}^2$.

Before recombination, the universe was "opaque," in the sense that a photon would travel a distance much shorter than ct before scattering off a free electron.

(At order-of-magnitude level, $n_e = 10^{-6}\text{cm}^{-3} \times (10^3)^3 = 10^3\text{cm}^{-3}$, implying a photon mean free path $(n_e\sigma_T)^{-1} = 10^{21}\text{cm} = 10^3$ light years.)

Neutral hydrogen atoms are good at absorbing Lyman-α and other resonance-line photons, but their cross section for scattering continuum photons is very low.

After recombination, therefore, the universe was transparent to visible/infrared photons — a typical photon can travel for the entire future history of the universe without ever being absorbed or scattered.

The last interaction a typical CMB photon experienced was scattering off a free electron at $z \approx 1100$.

We can thus think of the CMB as coming from a spherical "last scattering surface" that surrounds us at a distance corresponding to $z \approx 1100$.

Since recombination is not instantaneous, it is more accurate to call this a "last scattering layer," but since $\Delta z / z_{\rm rec} \sim 80/1100 \ll 1$, this layer is thin.

Where do the photons come from?

Thomson scattering does not create or destroy photons, it just changes their directions.

In the very early universe, photons were continually created and destroyed, by many different interactions.

Most of the photons that are in the CMB today were created by Bremsstrahlung ($e^- + \text{ion} \rightarrow e^- + \text{ion} + \gamma$) or double Compton scattering ($e^- + \gamma \rightarrow e^- + \gamma + \gamma$) at redshifts $z \sim 10^7$ (recall that BBN is at $z \sim 10^9$).

The blackbody nature of the CMB spectrum, now measured to a precision of about 0.01%, provides constraints on processes in the universe back to $z \sim 10^7$.

For example, if decay of an unknown particle species at $z = 10^6$ increased the number of photons by 0.1%, this would show up today as a distortion of the blackbody spectrum.

Energy redistribution (without change of photon number) remains efficient down to about $z = 10^5$.

Discovery of the CMB

The discovery of the CMB is a complicated and interesting story, told well by Steven Weinberg in *The First Three Minutes*.

Very briefly:

George Gamow and his students/collaborators Alpher and Herman worked out the basic ideas of big bang nucleosynthesis in the late 1940s and early 1950s.

They got some things right (elements forged in hot early universe, early universe was radiation dominated) and some things wrong (they thought initial conditions were 50% neutrons and that all elements up to iron could be made).

They predicted that there should be a radiation background with a temperature of a few degrees Kelvin, but didn't note that it might be observable.

The understanding of BBN developed gradually over the next decade, and by the early 1960s people realized that mainly helium would be produced.

A group at Princeton, led by Robert Dicke, began investigating element synthesis in the hot early universe, independent of Gamow's earlier work.

They predicted that there should be an observable microwave background, and they built an instrument to look for it.

Before they found it, Penzias and Wilson of Bell Laboratories, using a microwave antenna that they had adapted for radio astronomy, discovered a uniform microwave background that they were unable to interpret.

Chance encounters put them in contact with the Princeton group, and the two groups published back-to-back papers in *The Astrophysical Journal*, one on the measurement and one on the interpretation.

Further observations, by these two groups and others, confirmed that the microwave background had the properties of uniformity and a blackbody spectrum predicted by the big bang model.

In 1990, a special purpose instrument on the COBE satellite (Cosmic Background Explorer) confirmed the blackbody shape of the CMB spectrum to exquisitely high precision (about 0.01%).

The black body shape is the key demonstration that the CMB formed in a state of thermal equilibrium, requiring the dense, hot conditions of the big bang theory.

In 1992, COBE made the first detection of anisotropies (i.e., temperature variations as a function of direction) in the CMB, at a level of about 0.001-percent. These provide a tremendous trove of cosmological information, as we will come to later.