VII. The Cosmic Microwave Background

Reading: Chapter 9.

"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 $p + e^- \to H$ 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 $p + e^- \to H$ 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 $p + e^- \to H$ 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.

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 provides constraints on processes in the universe back to $z \sim 10^7$.

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%).

Gravitational instability and structure formation

Today's universe shows structure on scales from individual galaxies to galaxy groups and clusters up to superclusters of galaxies that can extend to 100 Mpc or more.

If the universe is smooth but not perfectly smooth, then gravity will cause structure to grow, by drawing matter into regions that start slightly above the average density (and out of regions that start slightly below the average density).

For this process to work, there must have been small-amplitude inhomogeneities present in the early universe, the "seeds" for the gravitational growth of structure.

These inhomogeneities should cause slight non-uniformities in the CMB.

In the simplest models with only baryonic matter, the predicted flucuations in the CMB are roughly one part in 10^3.

With non-baryonic dark matter, it is possible to lower the level of CMB anisotropies to $\sim 10^{-5}$ and remain consistent with gravitational growth of today's structure.

Measurement of CMB anisotropy

The "dipole" anisotropy of the CMB, which is just the reflex of the earth's peculiar velocity (which is largely due to the motion of the Milky Way), was detected in the 1970s.

The first detection of the *intrinsic* anisotropies of the CMB, reflecting structure in the universe at $z_{\rm rec}$ rather than the motion of the earth today, was obtained by the COBE satellite in 1992.

The variations are only a part in 10^5, so measuring them requires extremely high sensitivity and extremely good control of systematic errors, like contamination of the signal from other sources.

Since COBE, there have been a number of measurements of CMB anisotropy with higher resolution and sensitivity, from the ground, balloons, and, most recently, the WMAP satellite (Wilkinson Microwave Anisotropy Probe).

The Planck satellite, to be launched later this year, will map the CMB with higher resolution and higher sensitivity than WMAP.

Characterizing the CMB anisotropy

Suppose that we smooth a CMB map over an angular scale θ. (Any real map will automatically be smoothed at some minimum angular scale determined by the diffraction limit of the telescope used to make it, and we can subsequently smooth the map over larger scales.)

We can then plot a histogram of the fractional temperature variations $\Delta T/T$ in the smoothed map and measure the root-mean-square width of this histogram.

To characterize the structure in the map, we can plot $(\Delta T/T)_{\rm rms}$ against the smoothing scale θ.

If the map consisted of randomly placed hot and cold spots, we would expect $(\Delta T/T)_{\rm rms}$ to decline in proportion to the square-root of the sky area ($\propto 1/\theta$) because of $\sqrt{N}$ averaging of random variables.

In fact, hot and cold regions are correlated over large scales, and $(\Delta T/T)_{\rm rms}$ declines much more slowly than $1/\theta$.

The most widely used statistical measure of structure in CMB maps is the angular power spectrum, C_l, derived from a decomposition of the map into spherical harmonics.

Roughly speaking, $l(l+1)C_l$ is the square of $(\Delta T/T)_{\rm rms}$ on the scale $\theta = 200/l$ degrees.

Physics of CMB anisotropy

It is not surprising that if the density of the universe is slightly inhomogeneous at $z_{\rm rec}$, then the CMB will be slightly non-uniform.

There are several effects that link the inhomogeneities of the matter distribution to the CMB anisotropies:

- Adiabatic temperature fluctuations. Where the density is higher, the photon temperature is hotter.
- Doppler shifts. The gravitational perturbations caused by the density fluctuations induce peculiar velocities, and photons are blueshifted or redshifted if they last scattered off electrons with peculiar velocities toward us or away from us, respectively.
- Gravitational redshifts, as the photons climb out of the dark matter potential wells, or blueshifts as they fall off of potential hills. This effect makes the photons coming out of denser regions redder (cooler temperature).

Different processes dominate on different scales, so if we can measure CMB anisotropy over a wide range of scales we can separate them to some degree.

Acoustic oscillations

As long as the universe is ionized, so that photons are tightly coupled to the electrons and baryons, the photons and baryons behave like a single, high-pressure fluid with a "sound speed" of approximately $c/\sqrt{3}$.

An overdense region may start to collapse under its own gravity, but eventually the buildup of pressure will halt and reverse the expansion.

If there is enough time, a perturbation can contract and re-expand several times, a cycle of "acoustic oscillations."

Because of this effect, there is a preferred scale on which the temperature fluctuations are largest. This is the scale for which an overdense region has had just enough time to collapse to maximum compression when the universe recombines.

CMB Polarization

CMB anisotropies are polarized, i.e., they have slightly different amplitudes when measured in orthogonal polarizations.

The polarized signal is only about 10% of the full signal (which is only 10^{-5} in the first place), and the polarization from foreground contaminants is hard to remove, so these measurements are tough.

First detections in 2005, consistent with predictions from inflation (discussed in next section).

Roughly speaking, polarization doubles (or even triples) the information content of CMB anisotropies and better pins down what is causing anisotropy on a given scale.

These effects can produce only particular kinds of statistical patterns, known as "E-mode" polarization.

"B-mode" polarization can be produced by gravitational lensing of the E-mode pattern by clustered matter at low redshifts.

B-mode polarization can also be produced by gravity waves created in the early universe, a.k.a. "tensor fluctuations."

Detection of B-mode polarization, especially from gravity waves, is the current holy grail of experimental CMB research.

The Planck satellite will significantly advance polarization measurements. Future ground-based and balloon experiments can do significantly better than Planck, while a future CMB polarization satellite would provide the ultimate in sensitivity.

CMB Anisotropy: Bottom Lines

If we specify the statistical properties of the density fluctuations present at $z_{\rm rec}$, and the matter and energy contents of the universe ($\Omega_{r,0}$, $\Omega_{m,0}$, $\Omega_{\Lambda,0}$, H_0, etc.), then we can predict the full pattern of CMB anisotropy.

Model predictions can be tested against measurements, and the measurements can be used to infer the properties of the primordial fluctuations and the matter and energy contents of the universe.

The interplay between gravity and pressure introduces a preferred scale, the acoustic oscillation scale, on which CMB fluctuations are strongest.

This scale, which is approximately the speed of light times the age of the universe at recombination (and which can be computed exactly once the cosmological parameters are specified), provides a "standard ruler," whose apparent angular size can be used to measure the geometry of space.

More generally, CMB measurements in concert with other data provide powerful constraints on cosmological parameters *and* powerful tests of inflation, which is the leading theory for the origin of the primordial fluctuations.