Plan of Lecture

The Cosmic Microwave Background

The most precise available tool for understanding cosmology.

Prediction and discovery.

Fluctuations and COBE.

Power spectra.

The present and future of CMB observations.

Supernovae and cosmic concordance.

Prediction of the CMB

In 1948, George Gamow and student Ralph Alpher considered the early universe.

Run expansion backwards.

Early: dense and opaque.

Their focus was actually on whether the conditions early on produced all elements.

They don't (for reasons to be discussed later), but another prediction came true.

Nearly uniform glow.

Predicted 5 K; not bad!

Added Hans Bethe to author list; Alpher, Bethe, Gamow!

More Physics of the CMB

Why should the temperature be well-defined? Why not range?

Key: in very early universe, matter was largely ionized.

Many free electrons.

Lots of scattering.

However, at a redshift $z \sim 1100$, universe had cooled down enough for atoms to be neutral.

Few free electrons.

Photons travel freely; decoupling!

We see back to the “surface of last scattering”.

Discovery of the CMB

In 1965, Alpher and Gamow work basically forgotten.

Robert Dicke led Princeton group to detect CMB.

Jim Peebles presented work at JHU.

Word got to Holmdel, NJ, where...

Arno Penzias and Robert Wilson (Bell Labs) were trying to track down an annoying “hiss”.

Cleaned out pigeon droppings!

When they heard the report about Dicke’s group, they knew what they had discovered.

Both papers published.

Penzias and Wilson got Nobel.

Implications of the CMB

Before discussing the fine detail of the CMB, let's take stock of what the background means.

This is a clear prediction of the Big Bang model.

Early hot, dense universe.

Not predicted in the Steady State model.

To the end of his life, Hoyle suggested other mechanisms.

Scattering off metallic "whiskers".

However, the CMB is one of the major pieces of evidence that the universe was different long ago.

Fluctuations and Structure Formation

If the universe were *perfectly* smooth at $z = 1100$, no structure could ever form!

On scales of several degrees, was predicted that fluctuations couldn't be less than $\sim 10^{-5}$.

Smaller scales, bigger bumps.

Therefore, strong test of models would be to detect this variation in the background. But how?

The Cosmic Background Explorer

In 1989, COBE was launched.

Its purpose of observing the CMB had several goals.

- **Show spectrum is blackbody.**
- **Measure temperature accurately.**
- **Find fluctuations.**

This is technically challenging.

- **Key: differential radiometer.**
- **Compare nearby fields.**

This is complicated by foreground sources.

- **Milky Way sources.**
- **Dipole: we're moving!**

But after subtraction, the fluctuations were found at roughly the expected level.

Power Spectra

More information can be gleaned from details of the CMB.

Useful tool: power spectra.

Imagine many adjacent patches on the sky.

Pick size for the patches.

How much does patch flux vary?

Repeat for many patch sizes.

Then, plot fluctuation level versus patch size.

More commonly, 1/size.

Can do other things (square fluctuation level, normalize, etc.), but this produces *power spectrum*.

Expectations for Power Spectra

Consider early universe; various “sound” waves.

Waves of the right frequency are especially strong.

Resonant cavity.

The extra sloshing of matter means Doppler shifts.

Also, extra density means extra gravitational redshifts.

Net result: at resonant frequencies when decoupling occurred, get strong variations.

Series of peaks!

Impossible to see with COBE.

Information From Power Spectra

The CMB peaks contain tons of information.

Why? Angular scales, strengths of peaks are affected by fundamental parameters:

- **Curvature of universe.**
- **Amount of dark matter.**
- **Dark energy?**
- **Neutrino number, mass.**

Combined with other cosmological information, much of the "initial conditions" is well-understood.

The WMAP Era

Peaks in the CMB power spectra have been seen with many instruments, but we'll focus on one.

WMAP: Wilkinson Microwave Anisotropy Probe.

Launched in 2001, much more sensitive and much better angular resolution than COBE.

First year data released: consistent with flat universe, standard cosmology.

Second year data coming out soon.

Provides anchor point for cosmological simulations.

Supernovae as Cosmological Probes

Type Ia supernovae appear to be standard candles (after some small corrections).

Really bright; can see out to $z \sim 1 - 2$.

Surprise: distant ones appear dimmer than expected.

Absorption? Scattering? Intrinsic differences? Gravitational "antilensing"?

All detailed suggestions fail.

Remaining possibility: expansion is accelerating!

Small effect, but very significant. Dark energy?

Cosmic Concordance

CMB and supernovae are complementary.

E.g., CMB measures $\Omega_\Lambda + \Omega_m$.

Supernovae measure $\Omega_\Lambda - \Omega_m$.

Combine this information, as well as info from large scale surveys and other data.

Self-consistent parameters?

Yes! "Cosmic concordance".

Current best values (neglecting error bars).

$\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$.

$\Omega_{\text{baryon}} = 0.04$

Other parameters agree as well.

Summary

The cosmic microwave background comes from the last scatterings of early photons.

Peaks in the power spectrum encode valuable information.

Other cosmological data (e.g., supernovae) mesh well with CMB.

Challenge: at what redshift would the CMB have been at room temperature?