LECTURE 25: BIG BANG NUCLEOSYNTHESIS
AND THE COSMIC MICROWAVE BACKGROUND

25.1 PRIMORDIAL HELIUM

Stars fuse hydrogen $\longrightarrow$ helium
hydrogen, helium $\longrightarrow$ metals

Sun and Pop. I stars are about 70% hydrogen, 28% helium, 2% metals.

Oldest Pop. II stars are about 75% hydrogen, 25% helium, only 0.01% metals.

Metals in Pop. I could have come from earlier supernovae.

But where did the Pop. II helium come from? If it came from the very first stars, there should be lots of metals too.

25.2 BIG BANG NUCLEOSYNTHESIS: HELIUM

One second after the big bang, the temperature of the universe is about 10 billion °K, too hot for atomic nuclei to exist. The universe is filled with photons, electrons, protons, and neutrons.

Two minutes after the big bang, the temperature has dropped to about one billion °K, cool enough for deuterium nuclei (pn) to survive.

High density $\longrightarrow$ protons and neutrons collide frequently $\longrightarrow$ all free neutrons fuse into deuterium

High density and temperature $\longrightarrow$ almost all deuterium fuses into helium nuclei ($ppnn$).

By this time, the temperature is not hot enough for helium to fuse into heavier elements.

The remaining free protons are hydrogen nuclei
$\Longrightarrow$ ratio of helium/hydrogen just depends on the ratio of neutrons/protons $\sim$ 2 minutes after the big bang.

Putting in the known properties of protons and neutrons yields the prediction of the big bang theory: 25% helium!

25.3 BIG BANG NUCLEOSYNTHESIS: DEUTERIUM

Interstellar gas clouds have a measured deuterium/hydrogen ratio of about 0.002%.

In stellar nucleosynthesis, any deuterium is immediately fused to helium $\longrightarrow$ stars can't produce the observed deuterium.

Big bang nucleosynthesis occurs at lower density $\longrightarrow$ a small fraction of the deuterium isn't fused to helium.

Calculations of the leftover fraction (using nuclear physics and the big bang theory) show fair agreement with the observations.

25.4 THE STATUS OF BIG BANG NUCLEOSYNTHESIS

Current measurements of primordial abundances are quite uncertain:

helium/hydrogen: 22% – 25%
deuterium/hydrogen: 0.001% – 0.02%

Big bang nucleosynthesis predictions are also uncertain, because they depend on the average density of protons and neutrons in the universe, which is poorly known. For observationally acceptable values of this average density, the predictions are:

helium/hydrogen: 20% – 26%
deuterium/hydrogen: 0.0001% – 0.1%

Agreement between measurements and theoretical predictions looks good for now.

Requiring the theory to reproduce the observed abundances limits the acceptable range for the average density.

Better measurements of the primordial deuterium and helium abundances could lead to stronger tests of the big bang predictions.

25.5 BLACKBODY RADIATION IN THE EARLY UNIVERSE

After nuclei form, the universe is still too hot for electrons and nuclei to combine into neutral atoms.

Free electrons scatter photons efficiently, making the universe opaque.

Opaque, dense, hot gas $\Longrightarrow$ universe is filled with radiation (photons) having a blackbody spectrum.

As the universe expands, photon wavelengths stretch (redshift), the peak of the blackbody spectrum shifts, and the temperature drops.

When the temperature drops to 3,000°K (about 500,000 years after the big bang), electrons and nuclei can combine to form neutral atoms.

The universe suddenly becomes transparent, and blackbody photons stream through space unhindered, redshifting as the universe expands.

25.6 THE COSMIC MICROWAVE BACKGROUND

1965: Penzias and Wilson discover that the earth is being bombarded from all directions by microwaves, with a temperature of about 3°K (above absolute zero).

Dicke, Peebles, Roll, and Wilkinson argue that this microwave background is the relic background of photons from the big bang; the universe has expanded by ~ 1000 since becoming transparent, transforming 3000°K to 3°K.

Big bang theory makes strong prediction: cosmic microwave background should have highly accurate blackbody spectrum. Tested by many observations after 1965 discovery.

1978: Penzias and Wilson win Nobel Prize.

1990: COBE (COsmic Background Explorer) satellite confirms blackbody spectral shape with spectacular precision.

No proposed alternative to the big bang theory explains the perfect blackbody shape of the microwave background spectrum.

25.7 EVALUATION OF THE BIG BANG THEORY

The big bang theory follows from plausible, empirically supported assumptions. Direct empirical support for the big bang theory comes from:

Hubble's law $\longrightarrow$ expansion, of type predicted.

Changes in the populations of galaxies and quasars with redshift (distance, time) $\longrightarrow$ universe was different in the past.

Agreement between cosmic expansion age and inferred ages of oldest stars $\longrightarrow$ universe had a beginning.

Abundance of helium, deuterium $\longrightarrow$ early universe was hot and dense; tests theory back to a few seconds after the big bang (at moderate precision).

Cosmic microwave background $\longrightarrow$ early universe was hot, dense, and opaque; tests theory back to about 500 years after the big bang (at very high precision).

25.8 SUMMARY

Fusion of hydrogen$\longrightarrow$helium occurs in the hot early universe (temperature $\sim$ 1 billion °K, time $\sim$ 2 minutes).

The big bang theory predicts helium/hydrogen $\sim$ 25%, deuterium/hydrogen $\sim$ 0.001%, in agreement with observations.

For the first 500,000 years after the big bang, the temperature is higher than 3,000°K; atoms are ionized, and the universe is opaque and filled with blackbody radiation.

The redshifted blackbody photons are observed today as the cosmic microwave background.

The cosmic microwave background and the success of big bang nucleosynthesis provide strong evidence that the universe has expanded from a hot, dense state.