Lecture 35: The Whispers of Creation: Testing the Big Bang

Readings: Section 28-4, 28-5 and 29-5

Key Ideas

Fundamental Tests of the Big Bang
Primordial Nucleosynthesis
  Primordial Deuterium & Helium
  Primordial Light Elements (Li, B, Be)
Cosmic Background Radiation
  Relic blackbody radiation from Big Bang
  Temperature today: T=2.725 +/- 0.001K

The Three Pillars of the Big Bang

<u>Expansion of the Universe</u>
  Explains the observed Hubble Law
  Age is consistent with ages of the oldest stars
<u>Primordial Nucleosynthesis</u>
  Creation of the original light elements
  Deuterium (^{2}H), Helium, traces of Li, Be & B
<u>Cosmic Background Radiation:</u>
  Relic blackbody radiation from hot early phases

The Hot Big Bang

<u>What we see Now:</u>
  The Universe is cold & low density
  Galaxies (matter) are getting further apart as space expands between them.
  As the Universe expands, it cools further
<u>In the past:</u>
  Universe was smaller, hotter, & denser

Is there any evidence of this early hot, dense phase in the past?

Where Did Helium come from?

Metal-rich stars (such as the Sun)

- 70% H, 28% He & ~ 2% metals
- Metals come from earlier supernovae (& AGB stars)

Metal-poor stars (=old stars):

- 75% H, 25% He, & < 0.01% metals

Where did all the He in metal-poor stars come from?

- If from the first stars, where are all the metals that would have formed along with it?
- Haven't found a pure H star, cloud, anything. Always He as well.

Primordial Nucleosynthesis

When the Universe was only 1 second old:

- Temperature: 10 Billion K
- Too hot for atomic nuclei to exist
- Only protons, neutrons, electrons & photons
- 1 neutron for every 5 protons

General hot, dense soup of subatomic particles & photons

- As it expanded, it cooled off

Primordial Deuterium Formation

When the Universe was 2 minutes old:

- Temperature dropped to 1 Billion K

Neutrons & protons fuse into Deuterium (^2H)

- All of the free neutrons go into making deuterium nuclei
- Leftover protons stay free as ^1H nuclei
- Proportions: about 1 ^2H for every 4 protons (^1H)

Soup of mostly ^1H and ^2H along with a mix of photons, electrons & other particles.

Primordial Helium Formation

Most of the ^2H fuses to form ^4He nuclei

Other reactions make ^3He, Li, Be and B in very tiny quantities.

When the Universe was 4 minutes old:

Much of the deuterium turned in ^4He

Left with tiny traces of deuterium and other light elements

The Universe cooled so much that fusion stopped.

Aftermath

When Primordial Nucleosynthesis stopped:

Predictions

$^4He/H$-20-26%

D/H=0.0001-0.1%

Observations:

$^4He/H$=22-25%

D/H=0.001-0.02%

Agrees!

Information about Dark Matter

The amount of ^2H is extremely sensitive to the density of "baryonic"=ordinary matter

The higher the density of baryonic matter, the lower the predicted amount of ^2H out of the Big Bang

The relatively high amount of ^2H shows that all of the dark matter cannot be baryonic.

Current Status

Predictions of Primordial Nucleosynthesis agree well with current observations:

Observations:

Need refinement of the primordial abundances
Very difficult observations to make.
Need to look at high redshift or areas with little star pollution

Theory

Need to know average density of p&n
Light-element reaction rates need refinement

The Hot Early Universe

After Nucleosynthesis, the Universe stays hotter than 3000 K for a long time
Electrons & nuclei cannot combine to form neutral atoms
Universe remains *fully ionized*
Free electrons easily scatter photons

Universe is opaque to light during this time.
Filled with a hot ionized "fog" of ions & free electrons

Blackbody Radiation

The Early Universe is filled with a hot opaque ionized gas:
Has a perfect blackbody spectrum
With a characteristic temperature, T

As the Universe expands, it cools:
Photons *redshift*
The peak of the spectrum shifts *redward*
The blackbody temperature *drops*

Epoch of Recombination

When the Universe is ~300,000 years old
Temperature drops below 3000 K:
Electrons & nuclei combine to form atoms
Not enough free electrons to scatter photons

Universe suddenly becomes *transparent*:
Photons stream out through space
Photon Spectrum: 3000 K blackbody

Cosmic Background Radiation

After Recombination, the Universe is filled with diffuse, “relic” blackbody radiation.

As the Universe expands further:
- Blackbody photons *redshift*
- Spectrum peak shifts to *redder wavelengths,* and hence *cooler* temperatures

By today, the spectrum is redshifted by a factor ~1000 down to T~3K

Discovery

<u>1965:</u> Penzias & Wilson (Bell Labs)
- Mapping sky at microwave wavelengths
- Found a faint microwave background noise
- First thought it was equipment problems (noisy amplifiers, pigeons in the antenna)
- Finally determined it was cosmic in origin

Won the Nobel Prize in 1978 for discovering the Cosmic Background Radiation

But, is it Blackbody Radiation?

The Big Bang model makes very specific predictions:
- The spectrum is a *perfect blackbody*
- Characterized by a *single temperature*

Observations:
- Need to work with very cold instruments at the South Pole, high altitude or in orbit
- Experiments with balloons, rockets, radio antennas, and satellites

See Figure 28-7

Spectacular Confirmation

Current data all spectacularly confirm the predictions of the Big Bang

Perfect blackbody spectrum
A single temperature T=2.725=0.001K
Uniformly fills the Universe

Details

Fine structure at a part in 10^5 level is related to the large-scale structure we see in the galaxy distribution
Currently an object of intense study
See Figure 28-14

Evidence for the Big Bang

Expansion of the Universe: **CONFIRMED**

Hubble's Law
Age is consistent with the oldest stars

Primordial Nucleosynthesis: **CONFIRMED**

Deuterium & Helum in the right amounts

Cosmic Background Radiation: **CONFIRMED**

Perfect blackbody with a single temperature