LECTURE 24: THE BIG BANG THEORY

24.1 EXPANSION AND COOLING

As the universe expands, it cools (like the envelope of a star).

The expansion observed today implies that the universe in the past was denser and hotter.

24.2 THE BIG BANG THEORY

Summary form: The universe has expanded from a very dense, very hot state, which existed at some finite time in the past.

The big bang theory follows from the assumptions that

(1) General relativity is correct on cosmic scales
(2) the universe is homogeneous and isotropic
(3) the energy of the vacuum is small, or zero

These assumptions are plausible, and they have some empirical support. However, they don't *have* to be true — the real test of the big bang theory is to see whether it explains the observed universe.

24.3 EXPANSION AND REDSHIFT

In our 2-dimensional analogy (23.4), the universe is like the surface of an expanding spherical balloon, whose radius R_u is the "radius of the universe"

The expansion of space carries matter with it:
R_u doubles $\longrightarrow$ separations between galaxies double

The expansion of space stretches wavelengths of photons, $\lambda \propto R_u$:
R_u doubles $\longrightarrow$ wavelengths double

Light travels at a finite speed, so we see distant objects as they were when the universe was younger and *smaller*.

Photons from more distant objects have been stretched (redshifted) more.

The expansion of space exactly predicts Hubble's law, $v = Hd$, if v is much smaller than the speed of light.

The universe might be infinite, in which case an expanding infinite sheet would be a better analogy than an expanding balloon.

24.4 THE CRITICAL DENSITY

The cosmic expansion is slowing down because galaxies (and all mass in the universe) attract each other by gravity.

If the average density of mass in the universe is high enough, then gravity will eventually halt the expansion and the universe will start to contract.

If the average density of mass isn't high enough, the expansion will continue forever.

The value of the density that separates these two cases is called the *critical density.*

24.5 THE COSMOLOGICAL DENSITY PARAMETER, Ω

The cosmological density parameter is the ratio of the average density of mass in the universe to the critical density,

$$\Omega = \frac{\text{average density of universe}}{\text{critical density}}.$$

The ultimate fate of the universe depends on the value of Ω.

$\Omega > 1$: bound universe
$\Omega < 1$: unbound universe
$\Omega = 1$: balanced universe

A bound universe ends in a "big crunch."
An unbound universe expands forever.
A balanced universe expands forever, but at an ever decreasing speed.

A variety of observational and theoretical arguments suggest that Ω lies in the range 0.2 to 1.

24.6 THE AGE OF THE UNIVERSE

Something moving at an average speed v_{avg} for a time t covers a distance $d = tv_{\text{avg}}$. Thus, $t = d/v_{\text{avg}}$.

Hubble's law says that a galaxy at distance d is receding at speed $v = Hd$.

If the present speed is close to the average speed, then the expansion must have been going for a time

$$t = d/v_{\text{avg}} = d/(Hd) = 1/H.$$

For $H = 70$ km/s/Mpc, $1/H = 14$ billion years. This is encouragingly close to the estimated age of the oldest globular clusters.

If Ω is close to 1, then gravity has been slowing down the expansion. Galaxies were receding faster in the past, so the age of the universe is smaller than $1/H$.

For $\Omega = 1$, the age is $(2/3) \times (1/H)$, which for $H = 70$ km/s/Mpc is about 9.5 billion years.

9.5 billion years is younger than the estimated age of the oldest globular clusters, so either:

- Ω is much smaller than 1, or
- H is smaller than 70 km/s/Mpc, or
- the estimated globular cluster ages are wrong, or
- the big bang theory is still missing something important, or
- some combination of the above.

24.7 SUMMARY

The Big Bang Theory: The universe has expanded from a hot, dense state, which existed at some finite time in the past. Follows from plausible assumptions.

The expansion of space stretches the wavelengths of photons $\longrightarrow$ the big bang theory predicts Hubble's law.

The density parameter Ω is the ratio of the average density of the universe to the critical density required to halt the cosmic expansion.
$\Omega > 1$: bound universe, big crunch
$\Omega < 1$: unbound universe, expands forever
$\Omega = 1$: balanced universe

For $H = 70$ km/s/Mpc, the "expansion age" of the universe, $t = 1/H = 14$ billion years, agrees quite well with the estimated ages of the oldest globular clusters.

When we look at very distant objects (billions of light years away), we see them as they were when the universe was younger. In this way, powerful telescopes can act as "time machines."

The most distant *observable* objects are about 14 billion light years away, the distance that light can travel over the age of the universe. Presumably there are also much more distant objects, but light from them has not yet had time to reach us.