LECTURE 23: EXPANSION OF THE UNIVERSE

23.1 EINSTEIN TURNS TO COSMOLOGY

In 1917, two years after completing the theory of general relativity (GR), Einstein began to explore the implications of his theory for cosmology.

He started by introducing a key assumption, the *cosmological principle*:
The universe is homogeneous and isotropic.
In other words: the universe has no "special" places and no "special" directions.

The cosmological principle does not apply locally, since the sun, the Milky Way, and nearby galaxies all mark "special" directions.

In 1917, no empirical evidence supported the cosmological principle because "maps" of the universe didn't extend very far.

Today deep maps of the universe provide excellent evidence that the cosmological principle applies on very large scales. Einstein made a brilliant guess.

23.2 A STATIC UNIVERSE?

Einstein also introduced another assumption (almost without realizing that it was an assumption):
The universe is static (not expanding or contracting).

He found that he must add another term to the equations of GR — a "repulsive force," exerted by empty space, that balances the attraction of gravity — to make such a universe possible.

Einstein called this term the "cosmological constant"; today physicists usually call it *vacuum energy*, energy of empty space.

In the 1920's, Friedmann and Lemaitre showed that *without* a cosmological constant, GR implies that a homogeneous universe must expand.

23.3 THE DISCOVERY OF COSMIC EXPANSION

1910-1920: Slipher measures Doppler shifts of bright spiral nebulae.
He finds that they are moving fast, up to $\sim$ 2000 km/s, nearly all *away* from the Milky Way

1923: Hubble finds Cepheids in Andromeda $\Longrightarrow$ spiral nebulae are spiral galaxies

1923-1929: Hubble estimates distances to $\sim$ 20 galaxies, using Cepheid variables and brightest stars. He also develops his classification scheme for galaxies.

1929: Hubble announces a new discovery – a galaxy's recession velocity (and hence its Doppler shift) is proportional to its distance.

Implication: the universe is expanding, in a systematic way.

Hubble's 1929 data were rather marginal. Hubble's law is now very well established, through later efforts of Hubble and many astronomers since.

IMPORTANT EQUATIONS

7: HUBBLE'S LAW

In symbols:

$$v = Hd.$$

v = recession velocity, measured from Doppler shift [km/s]
d = distance [Mpc]
H = Hubble's constant [km/s/Mpc]

In words: A galaxy's recession velocity, which can be measured from its Doppler shift, is proportional to its distance. The constant of proportionality is Hubble's constant H.

Comments:

- Hubble's law is an empirical relation, discovered through observation, and it is not exact. It has a natural interpretation within the Big Bang theory.
- Hubble's constant is difficult to measure. The best current estimate is $H \approx 70$ km/s/Mpc, but within the observational uncertainties, H could be as high as 90 or as low as 50. A better measurement of H is a major goal of observational cosmology.

Examples:

(1) What is the recession velocity of a galaxy 10 Mpc away, assuming $H = 70$ km/s/Mpc?

The velocity is $v = Hd = (70 \text{ km/s/Mpc}) \times (10 \text{ Mpc}) = 700$ km/s.

(2) By measuring a galaxy's Doppler shift, I determine that it is receding from the earth at 7000 km/s. How distant is the galaxy, assuming $H = 70$ km/s/Mpc?

The distance is $d = v/H = (7000 \text{ km/s})/(70 \text{ km/s/Mpc}) = 100$ Mpc.

23.4 THE NATURE OF THE EXPANSION

Since distant galaxies are moving away in every direction, it seems as though we're in the center of the universe.

We're not. Observers in other galaxies would also see distant galaxies (including our own) receding from them, also obeying Hubble's law.

There is no "center" of the expansion. The Hubble flow is an expansion *of* space not an expansion *into* space. Galaxies are carried along by the expansion, like corks in a current.

A 2-dimensional analogy

Represent galaxies by points on a spherical balloon.

As the balloon inflates (expansion of space), galaxies are carried apart.

The expansion has no center; every galaxy sees others moving away, with velocity proportional to distance.

Note: In the real universe, galaxies move apart from each other, but the galaxies themselves do not expand because gravity holds them together.

23.5 PECULIAR VELOCITIES

Hubble's law is not a perfect description. In addition to moving with the expansion of space, a galaxy can have a *peculiar velocity*, caused by the gravitational pull of nearby galaxies.

A more accurate formula is

$$v = Hd + v_{\rm pec}.$$

Typical peculiar velocities are 100–1000 km/s. When the distance is large, Hd is always much bigger than $v_{\rm pec}$.

Andromeda is close (small d), and is actually moving towards us.

In terms of the balloon analogy, peculiar velocities correspond to small motions of galaxies along the balloon's surface.

Hubble's law also breaks down when the implied velocity v approaches the speed of light. We'll need a more sophisticated interpretation of redshift for these cases (lecture 24).

Bottom line: $v = Hd$ is very accurate for v between 5000 km/s and 50,000 km/s, pretty accurate for v between 1000 km/s and 100,000 km/s.

23.6 REDSHIFT DISTANCES, REDSHIFT MAPS

Since a receding galaxy's spectral lines are Doppler shifted to the red, a galaxy's recession velocity is often called its *redshift.*

To discover the $v = Hd$ relation, Hubble needed galaxies with measured redshifts *and* distances.

A galaxy's distance is hard to measure directly, but its redshift is relatively easy to measure from its spectrum.

[Note, however, that the fractional change in the wavelength of light is only v/c, so except for the most distant galaxies, the redshift does not significantly change a galaxy's color.]

Once we know Hubble's law, we can use it to infer a galaxy's distance from its redshift:

$$d = v/H.$$

By measuring galaxy spectra, we can map the distribution of galaxies in 3 dimensions. The largest such maps today have about 20,000 galaxies.

These maps show that galaxies and clusters lie in enormous sheets and filaments, separated by gigantic voids.

Shortcomings of the redshift approach:
- Peculiar velocities affect inferred distance.
- We don't know the absolute scale of the maps well, because the value of H is uncertain.

23.7 SUMMARY

The cosmological principle: the universe is homogeneous and isotropic.

General relativity, combined with the cosmological principle, predicts an expanding universe.

Doppler shifts show that distant galaxies are receding.

Hubble's law: $v = Hd$. Space is expanding.

The Hubble constant H is an important number for cosmology, but it's difficult to measure. The best current estimate is about 70 km/s/Mpc.

Peculiar velocities $\Longrightarrow$the expansion is not perfectly smooth: $v = Hd + v_{\text{pec}}$.

Knowing Hubble's law, we can determine a galaxy's distance from its redshift: $d = v/H$.