Lecture 33: Einstein's Universe

Readings: Sections 28-1 and 28-2

Key Ideas:

Cosmological Principle:

- The Universe is *Homogeneous* and *Isotropic* on Large Scales
- No special places or directions

General Relativity predicts an expanding Universe

Einstein's Greatest Mistake (?)

Cosmology

Cosmology is the study of the Universe

- Physics of the Universe
- Distribution of objects on all scales
- Motions of objects in the Universe
- Evolution of the Universe
- Age, Origin, and Fate of the Universe

The Universe in 1917

Einstein explored the cosmological implications of General Relativity

Observational State in 1917

- Kapteyn model of the Milky Way was favored by some (but not all) astronomers.
- No agreement on the "spiral nebulae"
- First good calibrations of the P-L relations for Cepheids and RR Lyrae variables

The Cosmological Principle

The Universe is Homogeneous and Isotropic on the Largest Scales

Critical assumption underlying Cosmology.

Homogeneous

- No special places in the Universe

Isotropic

No special directions

<u>Largest Scales</u>

Average out small-scale details

Homogeneity

When viewed on the largest scales:

The average density of matter is about the same in all places in the Universe

The Universe is fairly smooth on large scales

Does *not* apply locally:

We see planets, stars, galaxies in regions nearby in space

The Universe is locally rather "lumpy"

Example from the Distribution of Galaxies about the scales we are talking about (~100 Mpc)

Isotropy

When viewed on the largest scales:

The Universe looks the same to all observers

The Universe looks the same in all directions as viewed by a particular observer

Does *not* apply locally

We see different numbers of local objects in different directions.

The Dynamic Universe

Einstein applied the Cosmological Principle to General Relativity and got a surprise:

The spacetime of the Universe could not be static and unchanging

The Universe *must* either expand or contract!

In 1917, astronomers assured him that no such general motion was observed

The Cosmological Constant

To make the Universe static, Einstein added a new term to his equations:

The Cosmological Constant, Λ :

Repulsive gravitation-like force term

Arises from empty space
Balances the effects of gravity

At this time, there was no physical reason to introduce a Cosmological Constant

Cosmic Expansion

1914-22: Vesto Slipher, Lowell Observatory measured the radial velocities of the brightest "spiral nebulae"

Results:

21 out of 25 spirals showed a systematic redshift

Systematic motion away from us
Some velocities are large: > 2000 km/sec

Einstein's Greatest Blunder…

1920s:

DeSitter corrects an error in Einstein's math, showing that the Λ Universe was unstable

Friedmann & Lemaitre showed that without Λ, GR predicts that the Universe expands.

Edwin Hubble firmly established cosmic expansion observationally in 1929.

State of the Art

Einstein's guess about the homogeneity and isotropy of the Universe was brilliant and far ahead of the scanty empirical data of his time.

Modern observations bear out large-scale homogeneity & isotropy on average

Large-scale galaxy surveys
Cosmic Microwave Background

Modern Cosmological Constant

In modern cosmology, Λ reappears in modified form as the "vacuum energy" of space:

Quantum ground-state of empty space

Acts as an extra pressure on the Universe

Distinction

Actually accelerates the expansion!

Increasing observational evidence that Λ, or something very like it, may be real