Plan of Lecture
Cosmology

Take a deep breath. We're going to start considering the universe as a whole.

Olbers' paradox.

Is the universe infinite?

Symmetries and philosophies.

Isotropy and homogeneity.

The Copernican principle.

Expansion of the universe.

The Big Bang.

Why is the Sky Dark at Night?

One of many fundamental questions: is the universe finite or infinite?

Ancient days: clearly finite.

Medieval: clearly infinite.

What if it were infinite and eternal?

Every line of sight meets a star.

Sky would be blazing bright.

Wrongly called Olbers' paradox.

What are ways out?

Dust, absorption?

A Finite Universe?

How far would we have to go to equal Sun's brightness?

Assume all stars same as Sun.

Number density $n = 1$ **pc**$^{-3}$**.**

Spherical symmetry.

Solid angle at r is $\pi(R_\odot/r)^2$.

Number in shell of thickness dr at r is $4\pi r^2 dr\, n$.

Total solid angle: $\int_0^R \pi(R_\odot/r)^2 4\pi n r^2 dr$, or $4\pi^2 R_\odot^2 R n$.

Sun is $\pi(0.25\ \mathrm{deg})^2 = 6 \times 10^{-5}$ **ster.**

Need $R \approx$ **size of visible universe!**

Resolution of Olbers

Olbers himself thought that dust, gas would extinguish light.

But in an infinite, eternal universe, the dust would heat up to the temperature of stars!

Finite lifetime of stars? No! If stars continually produced, it amounts to same thing.

Redshift? If every star or galaxy has *finite* redshift, it *still* amounts to same thing!

Take maximum redshift $z_{\rm max}$**.**

Reduces flux by $1/(1+z_{\rm max})^2$**.**

Still adds up to infinite flux.

Need finite size or age or both for *visible* universe.

Philosophy in Cosmology

When thinking of the whole universe, there is too much to explain in detail.

Simplification is needed.

Generalization of Copernicus: we are not in special place in universe.

Thus, homogeneity: on a very large scale, matter is spread uniformly through space.

On small scale, obviously false!

Isotropy: on large scale, all directions look same.

Universality: all basic laws apply everywhere.

Difference from Greeks? These lead to testable, quantitative predictions.

Confirmation of Basic Picture

For homogeneity and isotropy, clear confirmation on very large scales.

Cosmic microwave background.

Very large scale surveys.

Not available in 1920s!

But how do we know that the same laws apply everywhere?

Orbits of Sirius A, B.

Spectroscopy.

Microwave background predictions.

Expansion of the Universe

As we saw before, Hubble found that more distant galaxies are redshifted more.

If we interpret redshift as velocity away from us, it means galaxies are rushing away!

Are we in center of an explosion?

No. Other galaxies see same.

Instead, spacetime itself is expanding.

Into what? Into nothing, we think.

Must think in 4 dimensions.

Expansion is really into future.

Einstein's theory predicted dynamicism of universe.

The Steady State Model

In 1950s, Fred Hoyle and others proposed the "perfect cosmological principle".

Uniform in space, time!

Spacetime is expanding, but new matter is created to fill the gaps.

1 H atom per m^3 per 10^9 yr!

Infinite universe, infinite time.

What could test this model?

Tests of Uniformity

One prediction of this model is that at all cosmic epochs the universe should have been similar to now.

In 1950s, Martin Ryle and others observed radio sources.

More distant ones had different properties.

Brighter, more common.

Serious blow to steady state.

In reality, some selection effects exaggerated the evidence.

Nonetheless, this started rift between Hoyle and most of the community.

The Big Bang

Another option. If the universe is expanding...

Run the film backwards.

Universe had an explosive origin.

In this model, the universe was once extremely hot and dense.

Exploded from a point.

Getting bigger, cooler ever since.

How can we test this?

Key: ***look-back time*****.**

Light travels at finite speed. Light from distant galaxies started off when the universe was younger.

Distant quasar: 6% current age.

We see the universe when it was younger.

Spacetime Geometry

Looked at with general relativity, the universe has an overall "geometry".

Closed: eventually recollapses.

Open: expands forever.

Flat: barely expands forever.

Contributions of components are normalized to *critical density*.

Energy-density of flat universe.

Matter: Ω_m; dark energy: Ω_Λ; curvature: Ω_R. If other things negligible, $\Omega_m + \Omega_\Lambda + \Omega_R = 1$.

Different Distances

The curvature of spacetime means that there are different ways to define distance.

Equivalent in Euclidean geometry!

Distance between two objects as measured by a ruler (spacetime frozen).

Proper distance.

Distance in Euclidean space that would make object as dim as it appears.

Luminosity distance.

Distance in Euclidean space that would make angular size what it is.

Angular size distance.

For $z \ll 1$, all are the same.

Many Open Questions

The overall picture is well-confirmed, but with lots of questions.

Most of the mass in the universe appears to be invisible.

Dark matter?

Modified gravity?

Most of the universe appears not to be matter of any kind.

Dark energy?

What happened in the extremely early universe, before light elements were formed?

Quark-gluon phase transition?

Inflationary epoch?

Cause of the Big Bang?

Summary

Dark night skies imply a finite universe.

Cosmological principles:

Homogeneity.

Isotropy.

Universality.

Expansion means universe had a beginning.

The Big Bang.

Challenge: what observations might probe the extremely early universe?