Plan of Lecture

Infinity and the Future of the Universe

Time for some more mind-blowing...

Consequences of an infinite universe.

The anthropic principle.

The future of the universe.

Is the Universe Infinite?

In standard cosmology, if the universe is flat or open it is spatially infinite.

However, we currently see only a finite portion.

Is the universe infinite? Maybe, but:

Cosmic variance can skew.

Weird compact open geometries!

Some of this can be tested with the CMB.

"Rings" on the sky.

No evidence for them yet.

What are the consequences if the universe is spatially infinite?

First, let's approach another question...

The Anthropic Principle

What allows us to exist?

We'd have problems with any number of modifications.

Changes in c, G, $\hbar$, etc.

Changes in physical law.

Little things; properties of water!

How is it that everything is "just so"?

Maybe it isn't; perhaps complexity always arises from interlinking laws.

Maybe life only exists where life can exist!

An Infinite Universe, Part I

Assuming an infinite universe, what then? Tegmark discusses this in Scientific American.

Type I: all laws and constants same everywhere.

Consider the current visible universe.

Finite volume, time, particles.

Infinite number of such volumes.

There are only a finite number of combinations of particles and their histories.

All happen infinitely often!

This would imply a universe in which everything was identical to this one!

Maybe all possible variants.

An Infinite Universe, Part II

Type II: all laws the same, but fundamental constants differ.

Could provide an answer to anthropic questions.

Only universes with constants allowing life would evolve life to wonder about itself!

This might include universes wildly different from our own.

Are *all* combinations of constants okay?

Large $G \Rightarrow$ closed universe!

Isolated universes?

An Infinite Universe, Part III

Type III: laws and constants differ.

All bets are off!

Satisfies anthropic principle assuming all possible laws, constants are allowed.

But "all" is a lot; some would be self-contradictory.

I have no idea how to test all this...

The Future of our Universe

Let's return to the safety of what we can see!

In a standard cosmological scenario, what will happen in the near and far future?

We'll start locally, then move out. Fred Adams has examined this in detail.

For the Solar System:

Moon moves out (Gyrs).

Sun evolves (∼5 Gyr).

Otherwise stable in that time.

Evolution of Sun will eventually boil oceans, engulf Mercury and Venus.

Maybe Earth as well.

Earth certainly will melt.

Stars and Galaxies

In a few billion years, Andromeda will hit Milky Way.

Copious star formation.

Many supernovae.

Use or ejection of gas.

Even without this, $\sim 5\,M_\odot\ \mathrm{yr}^{-1}$ of star formation, $\sim 3\,M_\odot\ \mathrm{yr}^{-1}$ returned to ISM.

Gas is being depleted.

Star formation will die out.

With time, remaining stars are lower and lower mass.

Galaxies become redder.

Longest-lived stars exist for $\sim 10^{13}$ yr.

Afterwards, only remnants.

Compact Remnants

Suppose every star has evolved. What then?

Husks: white dwarfs, neutron stars, black holes.

In solar system, remaining planets (Mars on out, plus maybe Earth) orbit white dwarf.

Similar stories elsewhere.

Does this remain stable forever?

Longer-Term Evolution

At this stage, we have compact objects and planets orbiting in a galaxy of dead stars.

What happens next?

Gravitational forces are somewhat grainy, so orbits will be perturbed.

$\sim 10^{15}$ **yr for galactic center.**

$\sim 10^{17}$ **yr for full disk.**

$\sim 10^{19}$ **yr for halo.**

Central regions become denser; outer regions more diffuse, and some stars start escaping.

Binary formation may allow three-body processes, kicking out some stars.

Most objects thrown out of galaxy.

Central core remains.

Gravitational Radiation

Will a binary remain stable forever?

No! Gravitational radiation will eventually bring it in.

Time scale for merger:

$T \approx 6 \times 10^{17}$ yr$(M_\odot^3/mM^2)(a/1 \text{ AU})^4$.

Roughly 10^{23} yr for Earth-Sun.

Ultimately, all binaries will merge (if nothing else happens first!).

Therefore, even in empty space, expect only single stars eventually.

Decay of Particles

Suppose you have a solitary white dwarf or neutron star. Will it last forever?

Maybe and maybe not!

Some attempts to unify forces propose that protons will decay into other particles.

Analogy: $n \rightarrow p + e^- + \bar{\nu}_e$**.**

However, if this happens, it will take a long time!

$T > 10^{32}$ **yr!**

Can test with water tanks!

Stars might eventually fall apart.

Drifting sea of particles...

If truly stable, could last forever.

Black Holes

What about the black holes?

These emit Hawking radiation.

Mostly photons.

$T \approx 10^{65}$ yr$(M/M_{\odot})^3$**.**

Even the largest black holes ($\sim 10^{10}\,M_{\odot}$!) won't last forever.

If universe expands forever, have redshifted photons and increasingly distant particles.

Heat death of the universe.

In ekpyrotic scenario, branes might collide again after some time, forming another Big Bang!

Summary

The universe might expand forever and be infinite.

Or maybe not!

In the very far future, we might find a listless sea of particles...

Challenge: what observations could bear on this?