Dark Matter and Dark Energy I

Physics 113 Goderya

Chapter(s): 18
Learning Outcomes:

Overview

• Definition
• Current Understanding
• Detection Methods
• Cosmological Impact
**Definition of Dark Matter**

Matter that can be seen by its gravitational effects, but does not emit light.

- Dark Matter
- Not Dark Matter

**Hot or Cold?**

Dark matter comes in two forms:

- **Hot Dark Matter (HDM)**
  - very small particles (neutrinos)
  - relativistic velocities

- **Cold Dark Matter (CDM)**
  - more massive and slower
  - able to form smaller structures like galaxies

**Detection**

Galaxy Rotation - Missing Mass
Universal Composition

- Dark matter slows the universal expansion rate
- Density of dark matter affects the fate of the universe
  - Low density leads to accelerating expansion
  - High density leads to Big Crunch
- Dark matter density affects the universal geometry
  - Low density leads to open universe
  - High density leads to closed universe

Universal Overview

- Current measurements indicate a flat universe with accelerating expansion
- The existence of dark matter can explain these observations
- Detecting dark matter can confirm measurements
Inquiring into Dark Energy

Science is about Questions and Tools

• What are some questions we might ask?

• And what are the tools we might use?

What is Gravity?

• Einstein asked about the nature of gravity.
• He discovered that gravity is curved space-time.
  – His theory predicted that light would bend when passing near a massive object.
  ➡ Tool Used: 1919 Solar Eclipse verified Einstein's prediction.
How Far Away are “Spiral Nebulae”? 

• In 1920, astronomers pondered the distance to the “spiral nebulae.”
  
  ➤ Harlow Shapley and Heber Curtis debated whether they were within our own Galaxy or outside our Galaxy.
  ➤ The question was settled when Edwin Hubble determined the distance to Andromeda Galaxy.

Tools for answering “How Far Away are Spiral Nebulae?”

Cepheid Variables

• These stars vary in brightness due to pulsations.
• The period of brightness variation is related to star’s intrinsic luminosity.
• By measuring the observed luminosity, and knowing intrinsic luminosity we can determine distance

\[ L_o = L_i / r^2 \]

Tools for answering “How Far Away are Spiral Nebulae?”

• 100” Telescope at Mt Wilson, CA (commissioned 1917) – provided the added aperture and resolution to resolve the stars.
• Hubble determined distance to Andromeda to be 800,000 LY (actual distance is 2.8 million LY)
Consequence of asking “How Far Away are Spiral Nebulae?”

- Early observations showed the “nebulae” were red-shifted.
  - I.e. moving very fast away from us.
- Hubble put together the redshifts with their distances.
  
Is Universe a “Steady State” or Did it originate from a “Big Bang?”

- Steady State Theory: As universe expands, matter is created.
  - Creation rate - a few hundred atoms per year per galaxy
- Big Bang: running expansion backwards leads us to a point of high density and high temperature from which universe originated. (Create everything all at once)
Tool for Determining “Steady State” vs. “Big Bang”

- Penzias and Wilson were using a 20-foot horn detector to make radio observations of the Milky Way.
- Effort to reduce noise in the detector left them with a 3 K residual. But they didn’t know its origin.

Tool for Determining “Steady State” vs. “Big Bang”

- Peebles and Dicke (Princeton) had just calculated an estimate for the temperature of the residual background temperature, and found it was detectable in the microwave region.
- Peebles and Dicke were convinced that Penzias and Wilson had found it.

This solved the Steady State vs Big Bang question.

How Fast is the Expansion Slowing Down?

- Saul Perlmutter (UC Berkeley) wanted to determine the deceleration rate of the expansion.
- Amount of deceleration depends on average mass density.
  - So we’d be “weighing the universe”
- This would lead to determining the curvature of the universe and whether the universe is infinite or not.
Tools for Determining
“How Fast is the Expansion Slowing Down?”

- Compare a galaxy’s measured distance with its redshift.
- Get distance by comparing observed and intrinsic luminosity of an object in the galaxy.

Enter - Supernovae!
(But we need a special kind of supernova)

1. Create a White Dwarf

A dying star becomes a white dwarf.

2. Dump more mass onto it

The white dwarf strips gas from its stellar companion...
3. Until it explodes

...and uses it to become a hydrogen bomb. Bang!

4. Observe it in a distant galaxy

The explosion is as bright as an entire galaxy of stars....
...and can be seen in galaxies across the universe.

5. Compare its distance to its velocity

More distant galaxies recede from us more rapidly.

These supernovae are more distant than expected. Space-time has expanded more than expected.
Dark Energy Comprises 73% of Universe

Dark Energy
73%

Dark Matter
23%

“Normal Matter”
4%

“Normal Matter”
4%

Common Thread: Standard Candle!

• A Standard Candle is an object whose intrinsic brightness does not vary.
  – Measuring its observed brightness gives us its distance.

• A Standard Candle utilizes $1/r^2$ property of light.
  \[ L_o \propto L_i / r^2 \]

What is the Dark Energy?

Einstein introduced the Cosmological Constant to explain what was then thought to be a static Universe, “my biggest mistake . . .”

Empty space has energy. Its gravitational effect pushes the universe apart.

Need a form of energy that is elastic:
  • Vacuum energy (= Cosmol. Const.)
  • But it’s effect may be too large
  • Quintessence (particle field)
Dark Energy is an Unfinished Story

WE DON'T KNOW WHAT IT IS!

But it traces the story of our understanding of the nature of the universe.

- An ideal setting for illustrating the process of science:
  - Science is alive and on-going.
  - Our ideas change as the data changes.
  - Scientific debate differs from social/political debate.
  - Progress in science results from both individual and group efforts.