Chapter 16
Dark Matter, Dark Energy, &
The Fate of the Universe

16.1 Unseen Influences

Dark Matter: An undetected form of mass that emits little or no light but whose existence we infer from its gravitational influence.

Dark Energy: An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate.

Contents of Universe

- “Normal” Matter: ~ 4.4%
  - Normal Matter inside stars: ~ 0.6%
  - Normal Matter outside stars: ~ 3.8%
- Dark Matter: ~ 25%
- Dark Energy: ~ 71%

What do we mean by dark matter and dark energy?

- Dark matter and dark energy have never been directly observed, but each has been proposed to exist because it seems the simplest way to explain a set of observed motions in the universe.
- Dark matter is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds.
- Dark energy is the name given to whatever may be causing the expansion of the universe to accelerate.
16.2 Evidence for Dark Matter

Our Goals for Learning

• What is the evidence for dark matter in galaxies?
• What is the evidence for dark matter in clusters of galaxies?
• Does dark matter really exist?
• What might dark matter be made of?

Rotation curve

A plot of orbital velocity versus orbital radius

Solar system’s rotation curve declines because Sun has almost all the mass

Rotation curve of Milky Way stays flat with distance
Mass must be more spread out than in solar system
Mass in Milky Way is spread out over a larger region than the stars
Most of the Milky Way’s mass seems to be dark matter!

Mass within Sun’s orbit:
$1.0 \times 10^{11} \, M_{\text{Sun}}$

Total mass:
$\approx 10^{12} \, M_{\text{Sun}}$
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

We can measure rotation curves of other spiral galaxies using the Doppler shift of the 21-cm line of atomic H.

Spiral galaxies all tend to have flat rotation curves indicating large amounts of dark matter.

Observations first made by Vera Rubin.

Broadening of spectral lines in elliptical galaxies tells us how fast the stars are orbiting.

Elliptical galaxies also have dark matter.
We can measure the velocities of galaxies in a cluster from their Doppler shifts. Almost every object is a galaxy in this picture.

The mass we find from galaxy motions in a cluster is about 50 \textit{times} larger than the mass in stars.

Fritz Zwicky discovered dark matter in galaxy clusters.

Clusters contain large amounts of X-ray emitting hot gas. Temperature of hot gas (particle motions) tells us cluster mass:

- 85\% dark matter
- 13\% hot gas
- 2\% stars

Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster’s mass.
A gravitational lens distorts our view of things behind it

All three methods of measuring cluster mass indicate similar amounts of dark matter
Do dark matter really exist?

Our Options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction
2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter

Because gravity is so well tested, most astronomers prefer option #1

How dark is it?

… not as bright as a star.

What might dark matter be made of?

Two Basic Options

• Ordinary Dark Matter (MACHOS)
  – Massive Compact Halo Objects:
    dead or failed stars in halos of galaxies

• Extraordinary Dark Matter (WIMPS)
  – Weakly Interacting Massive Particles:
    mysterious neutrino-like particles
Two Basic Options

- Ordinary Dark Matter (MACHOS)
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  - Weakly Interacting Massive Particles: mysterious neutrino-like particles

Why Believe in WIMPs?

- There’s not enough ordinary matter
- WIMPs could be left over from Big Bang
- Models involving WIMPs explain how galaxy formation works

16.4 The Universe’s Fate

Our Goals for Learning
- Will the universe continue expanding forever?
- Is the expansion of the universe accelerating?

Does the universe have enough kinetic energy to escape its own gravitational pull?

Canon ball analogy

Fate of universe depends on amount of dark matter
The fate of the universe depends on the amount of dark matter. Lots of dark matter suggests an eternal expansion. Not enough dark matter indicates a recollapsing universe. The amount of dark matter is approximately 25% of the critical density, implying eternal expansion. However, expansion appears to be speeding up. Dark Energy could be the missing component.
Estimated age depends on dark matter and dark energy

Is the expansion of the universe accelerating?

Brightness of distant white-dwarf supernovae tell us how much universe has expanded since they exploded

Accelerating universe is best fit to supernova data