Lecture 6 - Distance and Dark Matter

In this lecture, we extend our cosmic exploration into how astronomers measure vast interstellar distances and uncover the mysterious presence of dark matter. The key focus is on the methods used to build our "cosmic distance ladder" and the accumulating evidence for unseen mass shaping the universe.

Measuring Distance with Globular Clusters

- Globular clusters: tightly bound groups of about a million stars
- These orbit the galactic center and help pinpoint the galaxy's mass and shape
- Their motions provide data on average velocities using root-mean-square (RMS) analysis to cancel directional effects

The Inverse Square Law of Light

- Apparent brightness (“flux”) drops off with the square of the distance
- Luminosity distance = tool to infer how far stars and galaxies are based on their intrinsic brightness and measured flux

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Cepheid Variables and Henrietta Swan Leavitt

- Cepheids: pulsating stars whose brightness varies in a regular cycle
- Leavitt's Law (period-luminosity relationship): longer pulsation period = greater intrinsic luminosity
- Allows astronomers to determine distance based on the period alone

The Magellanic Clouds

- Small and Large Magellanic Clouds: satellite galaxies of the Milky Way
- Provided a relatively uniform population of Cepheids to calibrate Leavitt's Law
- Enabled comparison with other galaxies

Hubble and the Discovery of Other Galaxies

- 1923: Edwin Hubble discovers a Cepheid in the Andromeda "Nebula"
- Using Leavitt's Law, he determines it's 15x farther than the Milky Way—proving Andromeda is its own galaxy
- This launched extragalactic astronomy and confirmed the universe is filled with galaxies beyond our own

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Hubble's Classification of Galaxies

- Spiral galaxies (e.g. Milky Way, Andromeda)
- Elliptical galaxies: older, featureless, often result from galactic mergers
- Hubble Tuning Fork: categorizes galaxy evolution from spirals to ellipticals

Galactic Collisions and Dark Matter Halos

- When galaxies merge (e.g. Milky Way + Andromeda in 5 billion years), stars rarely collide but their gravitational fields and dark matter halos interact
- Surrounding every galaxy is a massive halo of invisible "dark matter"

Vera Rubin and Galaxy Rotation Curves

- Observed flat rotation curves: star velocity does not decrease with distance from galactic center (as predicted by Newtonian mechanics)
- Implies presence of unseen mass = **dark matter**

Evidence for Dark Matter

- Mass estimates from visible stars fall short (only ~10% of total mass inferred by gravitational behavior)
- Galaxy rotation curves, galaxy clusters, cosmic microwave background (CMB), and simulations all require dark matter

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MACHOs vs. WIMPs

- **MACHOs** (Massive Compact Halo Objects): e.g. black holes, dead stars
- Detected via gravitational lensing (light bending due to gravity)
- Too rare to explain full dark matter component
- **WIMPs** (Weakly Interacting Massive Particles): hypothetical particles
- Interact only via gravity and weak force
- Could account for much of the missing mass

Neutrinos: Known Dark Matter Candidates

- Trillions pass through us daily; they have mass and interact weakly
- But mass is too low to explain total dark matter

Simulations of Dark Matter Structure

- Galaxies sit in web-like filaments of dark matter
- Simulations including dark matter reproduce observed structures

Dark Matter Detection Experiments

- Underground labs (e.g. xenon tanks) attempt to capture rare dark matter interactions
- If dark matter interacts only via gravity, it's nearly impossible to detect in labs

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Gravitational Lensing

- Mass bends light — an effect predicted by Einstein
- Clusters of galaxies act as cosmic lenses, magnifying background objects
- Used to map the distribution of dark matter

Looking Ahead

- Telescopes act as time machines
- In the next lecture, we explore the expansion of the universe and the discovery of the cosmic microwave background
- We'll also touch on the earliest moments after the Big Bang and how hydrogen and other elements came into existence

"You're not just made of star stuff. You're made of Big Bang stuff."

Stay curious.