Einstein's Reality

Space and Time in Modern Physics

Ross Dempsey

Department of Physics and Astronomy
Johns Hopkins University

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Outline

Henrietta Leavitt

- 1868–1921
- Worked as a "computer" for Edward Pickering
- Analyzed photographic plates of variable stars

Period-Luminosity Relationship

- Leavitt discovered a close link between the period and the brightness of Cepheid variable stars
- Revolutionized astronomy - **why?**

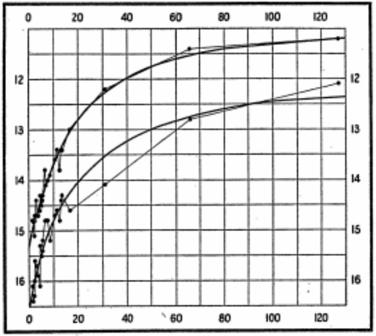


FIG. 1.

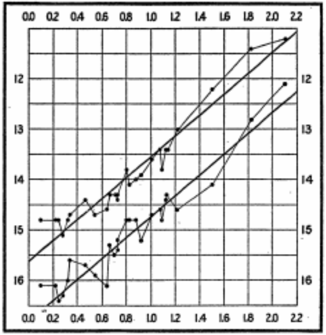


FIG. 2.

Cosmic Distance Ladder

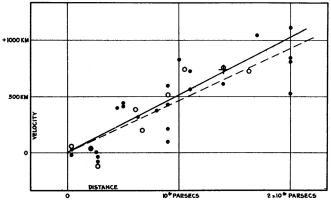
- Leavitt's discovery allowed distances to Cepheids to be determined
- Other tools:
  - Trigonometric parallax
  - Photometric parallax
  - Type 1a supernovae
  - Redshift

Edwin Hubble

- 1889–1953
- Used Cepheids to find distances to Andromeda and Triangulum
- Concluded that they must be outside the Milky Way

Hubble's Law

- Objects moving towards or away from us have their spectra shifted
- Hubble measured velocities using redshifts
- Discovered that more distant galaxies are receding faster



Big Bang Cosmology

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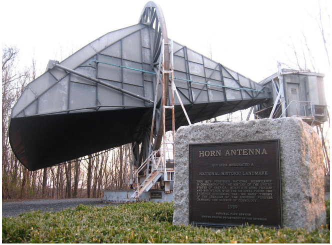
- Entire universe began in so-called Big Bang

Penzias and Wilson

- Penzias and Wilson were using a sensitive antenna to test faint radio signals from satellites
- Needed to remove all sources of noise
- One persistent source: the cosmic microwave background



Friedmann Equations

- Uniform expansion is oversimplified
- We model the universe as a homogenous, isotropic gas

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

- Observations indicate an essentially flat universe: $k = 0$

Critical Density

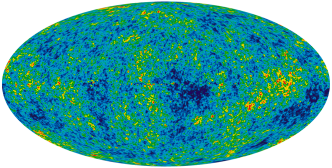
- What density ρ allows the flat ($k = 0$) universe to continue expanding at a constant rate?

$$\rho_c = \frac{3H^2}{8\pi G}$$

- This corresponds to 5 atoms of hydrogen per cubic meter
- We observe about 0.2 atoms of hydrogen per cubic meter – where's the rest?

WMAP

- Chuck Bennett (JHU) and WMAP team observed the CMB
- Determined the densities of different components of the universe
  - Ordinary matter: $\Omega_b = 0.05$
  - Dark matter: $\Omega_c = 0.23$
  - Dark energy: $\Omega_\Lambda = 0.72$



What caused the Big Bang?

Step 1: Singularity

- Extrapolating backwards indicates a primordial singularity
- No physical theory is adequate for handling this epoch
- Lasted about 10^{-43} seconds

Step 2: Inflation

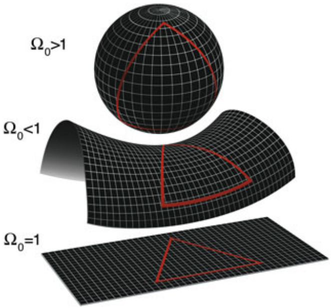
- Universe expanded exponentially for 10^{-32} seconds
- Quantum fluctuations became large-scale structure
- Baryogenesis: unknown process led to matter/antimatter asymmetry

Step 3: Cooling

- As the universe expanded, particles lost energy, moving closer to the energy scales we see today
- 10^{-6} seconds: protons and neutrons form
- 1 second: electrons annihilate positrons
- Few minutes: nucleosynthesis
- 379,000 years: cosmic microwave background

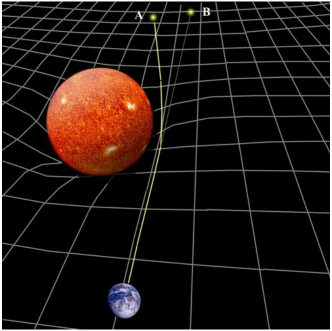
Curved Space

- What was the curvature k in the Friedmann equation?
- Spacetime can be curved, like the surface of the Earth
- What is the area of a triangle on Earth?



Local Spacetime Curvature

- "Spacetime tells matter how to move; matter tells spacetime how to curve." – John Wheeler
- General relativity explains gravity in terms of changes to the structure of space
- Light follows straight-line paths, but matter changes what "straight" means



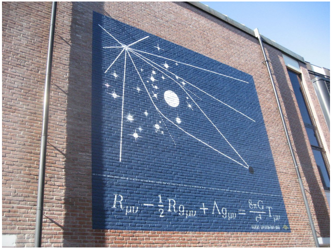
Einstein's Field Equations

- The ideas of general relativity are made precise in Einstein's equations
- Represents 10 coupled nonlinear partial differential equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}.$$

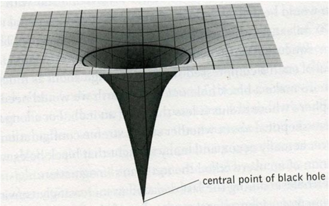
Gravitational Lensing

- Astronomers use lensing to detect massive objects
- Light is bent around the object, producing two images of an object behind it



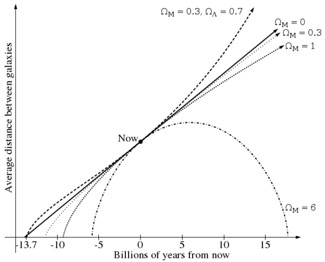
Schwarzschild Solution

- Easiest case for the Einstein equations is a single point mass
- Equations predict a singularity in spacetime
- Schwarzschild radius: $r_s = \frac{2GM}{c^2}$



Friedmann Solutions

- The trajectory of the universe depends on its density
- A flat universe with dark energy will expand forever at an increasing rate



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- Universe reaches a state of maximum entropy

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- Universe expands faster than the speed of light, more falls over the horizon
- Expansion pulls apart objects until they disintegrate into particles