Fundamental Observations

Pillars of Modern Cosmological Paradigm

- Universe is homogeneous and isotropic
- Night Sky is Dark
- Linear Expansion
- Light Element Abundances
- Microwave Background Radiation
  +
- Statistics of Large-Scale Structures
Cosmological Principle

On large scales, the universe is homogeneous and isotropic.

redshift $z=0.05$

$\sim 200 \text{ Mpc}$

$\sim 1000 \text{ galaxies (1982)}$
Cosmological Principle

- A logical outcome of Copernican revolution: no special place or direction
- Time dimension included in a stronger variant called the "perfect cosmological principle"
- These remain assumptions: ongoing debate on largest scales (e.g. a fractal?)
~1 billion galaxies
Sloan Digital Sky Survey
Michael Blanton (NYU)
The Cosmic Microwave Background (CMB)

Wilkinson Microwave Anisotropy Probe: February 13, 2003
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2. The Night Sky is Dark

Is this a problem?

- Not if stars are points of light stuck onto a dome

- But yes, in post-Copernican models
  - stars are scattered through space
  - (or galaxies are…)

The Simplest Model

- Universe infinitely large
- Uniformly filled with stars
- Infinitely old
Surface Brightness of the Sky

- Sum over all stars: $J$ is infinitely large

$$J = \frac{1}{4\pi} \int_0^\infty \frac{L}{4\pi r^2} n(4\pi r^2 dr) = \frac{nL}{4\pi} \int_0^\infty dr = \infty$$

- Sum up to “crowding” distance $d = 1/(n\pi R^2)$

$$J = \frac{nL}{4\pi} \int_0^d dr = \frac{nL}{4\pi} \frac{1}{n\pi R^2} = \frac{L}{4\pi^2 R^2}$$

Still as bright as the disk of an individual star
What does this imply?

- One or more of the assumptions are wrong
  - recognized to be a problem already in 1576 by Thomas Digges (vs Copernicus 1543)

- Obscuring stars by dust does not work
  - proposed as a solution in 1744 by de Chesaux and in 1826 by Heinrich Olbers

- Infinitely old, infinitely large, Euclidean universe is self-contradictory.
  - innocuous-looking puzzle lasts into 20th century!
    until discovery of the expansion of the universe
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3. Linear Expansion

- Slipher (1912) starts measuring redshifts, interprets $z = (\lambda_{\text{obs}} - \lambda_{\text{em}}) / \lambda_{\text{em}}$ as due to motion of galaxies.

- Edwin Hubble* proclaims linear expansion in 1929 using redshift vs distance to 20 galaxies – Cepheids!

(*) Georges Lemaitre (1927)
**Redshift**

spectrum of a **nearby star** vs a **galaxy traveling at 12,000 km/s**

![Graph showing redshift between a nearby star and a galaxy traveling at 12,000 km/s](image)
Linear Expansion

- Hubble constant: \( H_0 = \frac{v}{r} = 500 \text{ km/s/Mpc} \)

- Modern value: 70±7 km/s/Mpc (HST key project)

- Expansion not linear at large distance
What does this imply?

- Galaxies recede from us ("explosion")
  - would imply center to the Universe

- Uniform expansion of Universe
  - consistent with cosmological principle
  - extrapolated estimate for age: $1/H_0 = 14$ Gyr
    consistent with ages of oldest stars
  - solves Olbers’ paradox (redshift, finite age)

- Inconsistent with Perfect Cosmological Principle
  - inspired steady-state model.
    requires $d\rho/dt = 3H_0 \rho = 6\times10^{-28}$ kg/m$^3$/Gyr ($= 1$ proton/m$^3$/yr)
Universe is ACCELERATING!

- Gravity always attractive: causes deceleration

- BUT see modern Hubble diagram, based on using supernovae as calibrated “light-bulbs”

- Implies the presence of “something with large negative pressure”
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* everything else is called a “metal”

* universe expands and cools rapidly, no time to fuse any other nuclei

* rest of the elements are fused later, inside long-lived stars
4. Light Element Abundances

- Observed abundances of light elements
  - Hydrogen 75%
  - Helium 24%
  - Others 1%

- Helium problem:
  - stars would fuse He into C, N, O, etc
  - if universe started from 100% hydrogen,
    we would expect 75% H, 13% He, 12% others
  - problem solved if universe starts out with H + He
Measuring Light Element Abundances

Helium abundance:
- measured in stellar spectra
  (Helium discovered & named after Sun)
- He can be produced in stars, too
- extrapolate to zero metalicity to subtract He from stellar nucleosynthesis

Lithium abundance:
- measured in stellar spectra
- Li is depleted in stars by mixing
- find plateau at high stellar mass (these stars have little mixing)
Deuterium Abundance

• Destroyed easily in stars

• Must look for gas that has never cycled through a star

• quasar absorption lines:
  - low-density gas
  - far back in time
  - extra neutron makes electron slightly more tightly bound
  - possible only with 10m telescopes (Keck)
  - $D/H = 10^{-5}$
Measuring the Density of the Universe

• Big Bang Nucleosynthesis (BBNS)
  - can make precise calculations for relative abundances of light elements
  - turns out very sensitive to baryon density

• Current results:
  - imply 0.2 hydrogen atoms per cubic m
  - a small fraction (≈4 percent) of the so-called critical density:

$$\Omega_{\text{baryons}} \sim 0.04$$
Dark Matter

There are several other ways to measure mass density of the universe

- Motions of stars in galaxies
- Motions of galaxies in clusters
- Large-scale cosmic flows

\[ \Omega_{\text{total gravitating matter}} \sim 0.30 \pm 0.1 \]
What does this imply?

- Light element abundances strongly support nucleosynthesis in “hot” big bang.
- Presence of dark matter that cannot be baryonic (i.e. cannot affect nuclear reactions) weakly interacting massive particle (WIMP)?
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5. Cosmic Microwave Background

- Hot radiation from the big bang, which has cooled to ~3 Kelvin by present epoch
- Predicted in 1948 (Alpher & Herman)
- First observed in 1965 (Penzias & Wilson)
- Extremely smooth, but seeds of structure discovered by COBE satellite (1992)
- Accounts for 3% of the static on your TV screen!
COBE 1992 Temperature Map of CMB
Cosmic Microwave Background: WMAP

1965
Penzias and Wilson

1992
COBE

2001
MAP (Simulated)
Spectrum of CMB (from COBE)

![Graph showing the spectrum of CMB from COBE with wavelength (mm) on the x-axis and intensity (MJy/sr) on the y-axis, including FIRAS data with 400σ error bars and a 2.725 K blackbody curve.]
Thermal Spectrum

- Extremely accurately measured quantity
- The most precisely measured example of a black-body spectrum

\[ \varepsilon(f) df = \frac{8\pi h}{c^3} \frac{f^3 df}{\exp(hf / kT) - 1} \]

- Implies thermal equilibrium
- Temperature measured to be \( T = 2.725 \pm 0.001 \) K
- Too cold and dilute to achieve equilibrium today
  - real puzzle outside the big bang model
  - natural by product of hot dense phase
What does this imply?

Supports:

• Cosmological principle (isotropy)
• Laws of nature not varying even over cosmic scales
• Universe expanded
• Universe was much hotter in the past
• A puzzle: horizon problem. Inflation?
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CMB Anisotropies

- CMB angular and frequency structures contain a wealth of cosmological information.
- Amplitude & statistics of temperature fluctuations consistent with gravitational structure formation.
- This wealth of detail (to be discussed in future lectures) is all consistent with the hot big bang + cold dark matter structure formation model.
- Hard feat for alternative to replicate / postdict!
6. Large-Scale Structures

Modern Pillars of Standard Model: based on inhomogeneities

- CMB anisotropies – e.g. power spectrum
- Galaxy distribution – e.g. power spectrum
- Abundance of galaxy clusters
- Weak gravitational lensing statistics
- Lyman alpha forest absorption statistics
~1 billion galaxies
Sloan Digital Sky Survey
Michael Blanton (NYU)
Cosmological Principle

~10 billion particles
Millennium simulation
Volker Springel, MPA
Galaxy Power Spectrum
Galaxy Cluster Abundance

Large X-ray survey with Chandra (Vikhlinin et al. 2009)
Weak Gravitational Lensing

Abell 1689
Weak Gravitational Lensing Power Spectrum

Forecast by Song & Knox (2006); recently measured by COSMOS survey by HST (2011)