The Tools of Cosmology

Andrew Zentner
The University of Pittsburgh
Part Two: The Contemporary Universe
Contents

- Review of Part One
- The Pillars of Modern Cosmology
  - Primordial Synthesis of Light Nuclei
  - The Cosmic Microwave Background
  - Dark Matter and Galaxies in the Universe
  - The Appearance of Distant Supernovae
  - The Arrangement of Matter in the Universe
Basic Questions

- What are the contents of the Universe?
- What is the “shape” of the Universe? or What are the rules of geometry on cosmic scales?
The Homogeneous Universe
The Expanding Universe

1915 - Einstein: Theory of Gravity

1927 - Georges Lemaître: Expanding Universe
The Expanding Universe

- The Expansion requires no notion of "center"
- All point recede from all other points
1929 - Edwin Hubble made a plot of the distance to galaxies against the velocities that galaxies were receding.

Today the Hubble expansion rate is 22 (km/s) for every million light years of distance.
“Later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder of his life.”

- George Gamow
Cosmic Timeline

1 sec. to 20 min: Light Element synthesis

400,000 yr: CMB Produced

200 Million Years: First Stars

13.7 Billion Years: Today
Early Universe Synthesis of Light Nuclei

Dashed lines show range of observed values

→ 4% of energy in the universe is in “normal” baryonic matter
Correctly deduced that heavy elements are synthesized in stars, but never supported the Lemaître “Big Bang” Model.
The Geometry of the Universe

Closed: Angles Sum To $> 180^\circ$

Open: Angles Sum To $< 180^\circ$

FLAT (EUCLIDEAN)

http://casa.colorado.edu/~ajsh
The Cosmic Microwave Background
Observing the CMB

WMAP  http://map.gsfc.nasa.gov
Observing the CMB

The Universe is Flat ➔ The total density is the critical density for flatness
The Contents of the Universe

Normal Matter
(stars 0.4%, gas 3.6%)

Dark Matter
(suspected since 30s, “known” since 70s)

“Dark Energy”
(suspected since 1980s, “known” since 1998)
Dark Matter in the Coma Cluster of Galaxies

Fritz Zwicky
The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\bar{M} \geq 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_\odot.$$  \hspace{1cm} (36)

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about $8.5 \times 10^7$ suns. According
Dark Matter in the Andromeda Galaxy

- The rotation speed of the Andromeda disk (~250 km/s) is much larger than expected from its light output (Rubin & Ford 1970)
Dark Matter in Disk Galaxies

Velocities: Observed vs. Expected from Light

Rotation Curve of F571-8

Baryonic Contribution

Distance from Galactic Center

- This problem of excessive rotation speeds is typical of disk galaxies
Dark Matter and the Stability of Disk Galaxies

Hohl 1970: Disk galaxies will evolve into strong bars in millions of years → puzzling for a 14 Billion year old Universe
Dark Matter and the Stability of Disk Galaxies

Hohl 1970: Disk galaxies will evolve into strong bars in millions of years → puzzling for a 14 Billion year old Universe

Ostriker & Peebles 1973: This problem could be mitigated if galaxies sit in halos of dark matter
The Modern Era

<table>
<thead>
<tr>
<th>Curved Universe</th>
<th>Matter only Universe</th>
<th>Matter only &amp; slow expansion</th>
<th>Matter &amp; Dark Energy</th>
</tr>
</thead>
</table>

*Large calculations predict the patterns of galaxies that we should observe*

- $z=3$, 11 billion year ago
- $z=1$, 8 billion year ago
- Today
The Modern Era

Observatories can map out the positions of millions of galaxies

The Sloan Digital Sky Survey (Pitt. is part of the collaboration) in New Mexico
The Sloan Digital Sky Survey has mapped the positions of millions of galaxies.
Galaxy Clustering Patterns

- Comparing the patterns in the way galaxies are distributed throughout the Universe
The CMB Bump in Galaxies

- The “Bump” in the CMB Anisotropy Spectrum leaves an imprint on the pattern of galaxies
The CMB Bump in Galaxies

The “Bump” in the CMB Anisotropy Spectrum leaves an imprint on the pattern of galaxies.
The CMB Bump in Galaxies

- The “Bump” in the CMB Anisotropy Spectrum leaves an imprint on the pattern of galaxies
The Oscillation Bump

**Amount of Matter in the Universe**

- With the rules of geometry fixed by the CMB, the size of the bump tells us the amount of matter in the Universe
Type Ia Supernovae

- Occur when a white dwarf accretes mass from a companion that pushes it up to 1.3 times the mass of the sun
- Because they always occur at this critical mass, they have a fixed luminosity
Objects with a fixed luminosity are called “standard candles”

They measure effective distances in the Universe
The Accelerating Universe

- Supernova appear dimmer than naively expected
  ➔ The Universal Expansion is Accelerating!
The Accelerating Universe

Amount of Dark Energy

- $\frac{H_0\rho_0}{63 \text{ km s}^{-1} \text{Mpc}^{-1}} = 19 \text{ Gyr}$
- $14.3 \text{ Gyr}$
- $11.9 \text{ Gyr}$
- $9.5 \text{ Gyr}$
- $7.6 \text{ Gyr}$

$\Omega_\Lambda$

$\Omega_M$

Amount of Matter in the Universe

accelerating
deaccelerating
The Accelerating Universe

Amount of Matter in the Universe

Given the evidence from supernovae and other observations, it is clear that the expansion of the universe is accelerating. The discovery of this acceleration, known as the Hubble Expansion, has led to significant changes in our understanding of the universe's composition and history. The amount of dark energy in the universe is estimated to be about 68% of the critical density, with the rest attributed to dark matter and baryonic matter. The relationship between the density of these components and the expansion rate of the universe is shown in the figure below.

The figure illustrates the relationship between the density of dark energy ($\Omega_\Lambda$) and the density of ordinary matter ($\Omega_M$) in the universe. The line labeled "accelerating" indicates the conditions required for the universe to have an accelerating expansion, while the line labeled "decelerating" indicates the conditions for a decelerating expansion. The region between these two lines represents the range of possible values for the universe's density parameters that are consistent with current observations.

The flat universes, which have a zero curvature and are consistent with the cosmological principle, lie on the horizontal line in the plot. This line corresponds to the condition where the sum of the densities of dark energy and dark matter equals the critical density of the universe. The age of the universe and the Hubble parameter are also indicated on the plot, providing a means to estimate the age of the universe and the rate of expansion at different epochs.

The discovery of the accelerating universe has had profound implications for our understanding of the universe's evolution and the nature of gravity and dark energy. It has also led to new theories and models that attempt to explain the mysterious components of the universe and their role in the universe's evolution.
The Accelerating Universe

Galaxy Data Say We Are Here

Flat Universes Lie Here

Amount of Matter in the Universe
The Full Pie

**Normal Matter**
$\Omega_{\text{BARYON}} = 0.04$

**Dark Matter**
$\Omega_{\text{DM}} = 0.26$

**“Dark Energy”**
$\Omega_{\text{DE}} = 0.70$

- The Universe is FLAT When $\Omega_{\text{BARYON}} + \Omega_{\text{DM}} + \Omega_{\text{DE}} = 1$
Lensing Support for Dark Matter
Lensing Support for Dark Matter
The Future

- Both Dark Energy and Dark Matter effect the efficiency of gravitational lensing

- Detailed surveys measuring the effects of gravitational lensing on galaxies will hopefully give us clues to the properties of Dark Matter and Dark Energy
The Future
Summary

- We have good evidence that:
  - The Universe is only 4% normal matter
  - The Universe is 24% dark matter
  - The Universe is 72% dark energy
  - The Universe is flat
  - Structure in the Universe has been around for only about 13.7 Billion years
  - We can trace most of this history reliably!
- This is an impressive achievement
- The future will lead to more fundamental insights into the nature of the dark stuff