The History of the Universe

<table>
<thead>
<tr>
<th>Event</th>
<th>Planck Time</th>
<th>Planck Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{43} sec</td>
<td>10^{42} K</td>
<td></td>
</tr>
<tr>
<td>10^{38} sec</td>
<td>10^{37}</td>
<td></td>
</tr>
<tr>
<td>10^{32} sec</td>
<td>10^{31}</td>
<td></td>
</tr>
<tr>
<td>10^{27} sec</td>
<td>10^{26}</td>
<td></td>
</tr>
<tr>
<td>10^{15} sec</td>
<td>10^{14}</td>
<td></td>
</tr>
<tr>
<td>10^{37} yrs</td>
<td>10^{36}</td>
<td></td>
</tr>
<tr>
<td>10^{100} yrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Now</td>
<td>1.4 x 10^{10} yrs</td>
<td></td>
</tr>
</tbody>
</table>

### Degenerate Era
- 10^{14} – 10^{37} yrs.
- Almost no further radiation from stars.
  - Cold, dark universe.
- But...
  - Occasional collisions between brown dwarfs $\rightarrow$ new low-mass stars (10 to 100 in existence per galaxy at any given time).
  - Occasional collisions of degenerate stars $\rightarrow$ supernova.

### Black Hole Era
- 10^{37} – 10^{100} yrs.
- Degenerate stars have all disappeared through proton decay (maybe)
  - $p \rightarrow e^+$, neutrinos, gamma rays
  - No more atoms
- Dark matter previously swept into degenerate stars and annihilated (??????)
- Only black holes are left.
- But black holes also evaporate
  - Hawking radiation: very slow conversion of gravitational energy back to particles or photons.

### Dark Era
- Essentially nothing left except hugely redshifted CMB photons.

(Extremely speculative: See *Sky & Telescope* magazine, August 1998)
What’s outside the Universe?

• Other universes, not intersecting with our Universe??
• Some magic numbers:
  • At $t=1$ second, our Universe defined by:
    • Ratios of
      – **Numbers of particles**. Photons:Normal-matter:Dark-matter
    • Amplitude of density fluctuations $\sim 10^5$
  • Imprinted by Planck Time: ratios of physical constants.
    • Example: electrostatic force $10^{36}$ x stronger than gravitational force.
  • Different values in other universes?

• **Anthropic Principle**: our particular universe is suitable for us to live in because otherwise we would not be alive to know about it.

Good book: *Before the Beginning*, by Martin Rees

---

Announcements

**Final Exam.**
• Monday December 13.
• 8-10 PM.
  (PM = in the evening!!).
• In the usual classroom
  (Natural Resources 158).
• Counts as 1.5 midterms.
• 70 questions.
• 2/3 over material since Midterm 3.
• 1/3 over earlier material.
  • reworded midterm questions.
  • + a few new general questions.
  • + a few about **telescopes**.

---

**Homework.**
• Set 8 now open.
  • due late at night
    Friday, Dec 10
    (3AM Saturday Nov. 11)
• Set 7 answers on course web site.

**Review for Final.**
• **Right Now!**

**Course Evaluation.**
https://rateyourclass.msu.edu

---

Galaxies

• Composed of 100 billion stars or more.
• Main types are
  • Ellipticals
  • Spirals
    • Regular spirals
    • Barred spirals
  • Irregulars
• Our galaxy (the Milky Way) is a spiral with a weak bar.
• Mass of galaxies dominated by Dark Matter.
  • Detected by studying motions of stars around galactic centers.

Spiral Arms

• Density wave
  • Spiral arms have higher density than space between arms
  • Excess gravitational attraction slows down gas, stars when they pass through spiral arm in course of their orbits.
  • => spiral arms are a traffic jam
• But also some effect due to differential rotation.
  => natural tendency of big star-forming regions to just get wound up into spiral shapes.
Galaxy Formation:

Top-Down Model
- Collapse ➔ rotating disk
- Halo (Globular clusters & halo stars) formed during collapse.
- Once formed, stars don’t collide.

Bottom-Up Model
- Small structures form first
  - Dwarf galaxies
  - Globular Clusters
- Galaxies grow by cannibalism
- Ellipticals formed by mergers of spirals (?)

The Cosmic Distance Ladder
- Parallax
  - Out to 65 LY
  - Calibrate luminosities of Pulsating Variables
- Use pulsating variables to map rest of Milky Way and out to M31.
- In M31, Measure luminosities of
  - Brightest stars 10,000 L☉
  - Brightest globular clusters 100,000 L☉
  - Brightest H II regions 100,000 L☉
  - Etc.
  - ➔ can now measure distances to more distant galaxies

The distribution of matter.
- Structure upon Structure.
  - Local Supercluster
  - Bubbles & Voids.
- The Cosmic Web.
  - Structure determined by evolution of dark matter.

<table>
<thead>
<tr>
<th>Location</th>
<th>Fraction of critical density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas within galaxies</td>
<td>0.001</td>
</tr>
<tr>
<td>Gas in galaxy clusters</td>
<td>0.003</td>
</tr>
<tr>
<td>Stars within galaxies</td>
<td>0.004</td>
</tr>
<tr>
<td>Gas between galaxy clusters</td>
<td>0.014</td>
</tr>
<tr>
<td>Dark Matter</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Total normal matter = 0.022
Big Bang Nucleosynthesis predicts 0.03

About 90% of all matter is dark matter.

Relativity
- Special Relativity
  - The Principal of Relativity. The laws of physics are the same in all inertial reference frames.
  - The constancy of the speed of light. Light travels through a vacuum at a speed c which is independent of the light source.
- General Relativity
  - The Principle of Equivalence
    - Can’t tell difference between gravity & acceleration
    - …or between freefall & no gravity.
    - So any experiment should give same answer in either case.
  - Gravity Upwards acceleration, no gravity.
  - Falling due to gravity No gravity

Predicted and then observed effects of Special Relativity:
- E = mc²
- Time Dilation
**Curved Space**

- Everything finds shortest path in spacetime.
- Photons (light) find shortest path of all, because they move the fastest.

![Diagram of a photon's path around the Sun showing the shortest path in spacetime.](image)

**Proofs of General Relativity**

- Rapid precession of Mercury’s orbit.
  - Phenomenon known before.
  - G.R. offered the explanation.
- Bending of light rays passing near Sun.
  - First measured in 1919
- Time dilation in gravitational fields.
  - Measured using real clocks, on Earth.
- Gravitational redshift in strong gravitational fields
  - Observed in spectra of white dwarfs.

![Diagram of light bending around a massive object, showing time dilation and gravitational redshift.](image)

**Quasars**

- Large redshift ➔ large distance
  
  \[ F = \frac{L}{4\pi d^2} \]
  
  - Measured flux + distance ➔ huge luminosity
    - Up to 1000 x luminosity of an entire galaxy of stars.
  - Rapid flux variability ➔ small volume.

Some luminous quasars vary in *few days* ➔ same size as solar system.

**High density ➔ Strong Gravitational Field ➔ Black Hole**

- Escape Velocity:
  
  \[ v_{\text{escape}} = \frac{\sqrt{2GM}}{R} \]

- Schwarzschild radius:
  
  \[ R_s = \frac{2GM}{c^2} \]

- Located in centers of galaxies.
- Happened early in lives of galaxies.

And also:
- Located in centers of galaxies.
- Happened early in lives of galaxies.

![Diagram showing escape velocity and Schwarzschild radius of a black hole.](image)
Nearby Galaxies with Mini-Quasars in Center
- Small fraction of nearby galaxies have huge outflows of particles moving at nearly speed of light.
- Massive black holes in most nearby galaxies, but not currently accreting gas.
- Orbits of stars → million solar-mass black hole at center of Milky Way Galaxy.

- Matter falls onto accretion disk.
- Disk heats up & glows.

Giant blobs of charged particles, seen at radio wavelengths.

Accretion Disk forms around Black Hole.

The Expanding Universe
Hubble’s Law:
- Galaxies all recede from us.
- Velocity proportional to distance.
  \[ v = H_0 \cdot d \]
- We are unlikely to be at exact center.
  \[ \Rightarrow \] Scale of the whole universe is expanding.

Distance = R(time) x (comoving distance)

Summary:
How do we know the universe is expanding from a very much smaller size?

- Hubble’s Law
  - Everything is moving away from everything else.

- Cosmic Microwave Background (CMB)
  - Universe used to be much hotter than it is now \( \Rightarrow \) it has changed and evolved.
A Canon Ball

$v_{\text{escape}} = \sqrt{\frac{2GM}{R}}$

“critical” curve: cannon ball has exactly escape velocity.

$v_{\text{escape}} = \sqrt{\frac{2GM}{R}}$
The Expanding Universe

Hubble’s law:
\[ v = H_o \cdot d \]

Distance = travel time = \[ \frac{d}{v} \] = \[ \frac{1}{H_o} \]

Which Universe Do We Live in?
Distance = light travel time \( \rightarrow \) lookback time \( \Delta t \)

What we can measure for supernovae:
- Redshift
- Distance

The Accelerating Universe
Distance = light travel time \( \rightarrow \) lookback time \( \Delta t \)

Acceleration due to Dark Energy pushing outwards.

Structure in the Cosmic Microwave Background

What does it tell us?
- Sound waves permeated universe just before decoupling of CMB.
- Linear size of largest structure = (speed of sound) x (age of universe at that time)
- Distance to surface emitting CMB depends strongly on cosmological model.
- Angular size depends on cosmological model.
Structure in the CMB

- The result:
  - The universe is FLAT.

Line shows predicted result for flat universe
Points show measured values

What is the Universe Made Of?

73% Dark Energy (using $E = mc^2$)
23% Dark Matter
4% Normal Matter

This is the only part we see.

We infer these are there, but we don’t know what they are.

Some Key Numbers

<table>
<thead>
<tr>
<th>What?</th>
<th>Value</th>
<th>How do we know?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of Solar System (&amp; Earth)</td>
<td>4.54 billion years</td>
<td>Direct radioactive decay dating of oldest meteorites.</td>
</tr>
<tr>
<td>Lifetime of Sun</td>
<td>10 billion years</td>
<td>Computer simulations of stars.</td>
</tr>
<tr>
<td>Age of Universe</td>
<td>13.7 billion years</td>
<td>Recent measurements that Universe is flat and accelerating.</td>
</tr>
<tr>
<td>% of mass of Solar System that is in the Sun.</td>
<td>99.8%</td>
<td>Measuring mass of Sun &amp; planets using Newton’s/Kepler’s laws.</td>
</tr>
<tr>
<td>Number of stars in our Milky Way Galaxy</td>
<td>100 billion</td>
<td>We can count them.</td>
</tr>
<tr>
<td>Number of observable galaxies similar to Milky Way</td>
<td>100 billion or more</td>
<td>We can see them with big telescopes.</td>
</tr>
<tr>
<td>% of all matter that is unseen Dark Matter</td>
<td>90%</td>
<td>Gravitational effect on normal matter &amp; on path of light.</td>
</tr>
<tr>
<td>% of content of Universe that is not any kind of matter</td>
<td>73%</td>
<td>Recent measurements that Universe is flat and accelerating.</td>
</tr>
</tbody>
</table>