Cosmology II

What I’m Going to Talk About

• The Big Bang Theory of the Formation of the Universe
  – Radiation, Matter and the Physical Laws
  – Kirchhoff’s Spectroscopic Laws
  – Planck’s Radiation Curve
  – Stefan-Boltzmann Law
  – Newton’s Law of Motion
  – Maxwell’s Equations for Electromagnetism
  – Hubble’s Law
  – Einstein’s Special Theory of Relativity
  – Einstein’s General Theory of Relativity

• The Formation of Galaxies and Stars
  – The Nebular Condensation Theory and the Formation of the Solar System
  – The Formation of the Earth
  – The Precursors of the Formation of Life

The Big Bang Begats

• Macrocosmos
• Quantum Fluctuation
• Electromagnetic Radiation
• Phonons
• Higgs Bosons
• Inflation
• Cosmological Principle
• Strong Force
• Nuclear Fusion
• Beta Radioactivity
• Gas
• Electric Charge
• Rocks
• Life
• Humans

Some Basic Physics

• Kirchhoff’s Spectral Laws
  – Continuous Spectrum
    • any body (ideal blackbody) that is at a temperature above 0 K
  – Emission Spectrum
    • any low pressure gas that you place a high voltage across
  – Absorption Spectrum
    • any low pressure gas placed between a blackbody and the observer

Bohr’s Atom

• Best described the workings of the Hydrogen atom
  – one proton and one electron “around” the proton moving in orbits that are discretized (quantized) so that no intermediate orbits are allowed

“Unity in the Whole Structure”

• “…How is it possible by any methods of observation yet known to the astronomer to learn anything about the universe as a whole? It is possible only because the universe, vast though it is, shows certain characteristics of a unified and bounded whole. …science shows unity in the whole structure, and diversity only in details.”
  — Simon Newcomb, 1906
Planck’s Radiation Curves
• A way to depict frequency (inverse of wavelength) versus intensity

Wien’s Law
• Peak wavelength is inversely proportional to the temperature of the blackbody

Stefan-Boltzmann Law
• Energy radiated by blackbody is proportional to the temperature to the 4th power
  \[ E = \sigma T^4 \]

Kepler’s Laws
• Kepler’s First Law of Planetary Motion
  – planets orbit sun in an ellipse with sun at one focus
• Kepler’s Second Law of Planetary Motion
  – planets sweep out equal areas in equal times
    • travel faster when closer, slower when farther
• Kepler’s Third Law of Planetary Motion
  – orbital period squared is proportional to semi-major axis cubed
  \[ P^2 \propto a^3 \]

Newton’s Laws I
• Newton’s First Law of Motion
  – body at rest tends to stay at rest and body in uniform motion will stay in straight line
    uniform motion unless acted upon by an outside force
• Newton’s Second Law of Motion
  – the acceleration of a body is proportional to the force being applied
  \[ F = m a \]

Newton’s Laws II
• Newton’s Third Law of Motion
  – for every force there is an equal and opposite force (action and reaction)
• Newton’s Law of Gravitational Attraction
  – force is proportional to masses and inversely proportional to the distance squared
  \[ F = \frac{G m M}{r^2} \]
Doppler Shift

- A change in measured frequency caused by the motion of the observer or the source
  - classical example of pitch of train coming towards you and moving away

Maxwell’s Electromagnetism

- Electricity according to Gauss
  - relates electricity to electric charge
- Faraday’s Law
  - relates electric fields to magnetic fields
- Magnetism according to Gauss
  - relates magnetism to electricity
- Ampere-Maxwell Law
  - relates magnetic field to electricity

Einstein’s Relativity Theories

- Special Theory of Relativity
  - speed of light constant in all reference frames
    - time dilation and simultaneity
    - length and mass
    - addition of velocities
- General Theory of Relativity
  - Principle of Equivalence
  - curvature of space-time

Hubble’s Law

- The further away a galaxy is, the greater its recessional velocity and the greater its spectral red shift

\[ v = H_0 d \]

There is a simple linear relationship between the distance a galaxy is from the Earth and, the redshift of that galaxy (which is a measure of the speed with which a galaxy is moving away from the Earth)

The value of the Hubble constant, \( H_0 \), is not known with certainty but best value today is approximately 67 km/s/Mpc

\[ \text{Distance (Mpc)} \]

\[ \text{Velocity (km/s)} \]

(a) Five galaxies spaced 100 Mpc apart

(b) The expansion of the universe spreads the galaxies apart
Hubble’s Conclusion

- From Hubble’s Law we can calculate a time in the past when universe was a point
- Big bang occurred about 13-15 billion years ago
  - big bang formally proposed by Gamow based upon such evidence
    - Big bang theory progenitors existed in looser manner

Gamow’s Big Bang and Hoyle’s Steady State

- Steady State Universe
  - universe looks same and will look same
    - continuous creation
- Big Bang Universe
  - universe began in “big bang” or “ylem”
    - single point of creation

“In The Beginning”

- “In the beginning, God created the particles and the antiparticles. Now the temperature was high, and the particles and the antiparticles were in equilibrium…And God said, ‘Let there be light’…and He separated the photons from the particles and antiparticles. God called the photons “bosons” and the particles and antiparticles He called “fermions.” And there was pair production and there was photon creation -- the first $10^{-43}$ seconds.”
  - Eric Schulman from “A Briefer History of Time”

Details of the Big Bang

- The littlest of physics
- The Big Bang & ensuing Cosmic Eras
  - The Vacuum Era
  - The Planck Epoch and The Inflationary Epoch
  - The Radiation Era
  - Light and Baryons
  - The Electroweak Epoch and The Strong Epoch
  - Decoupling and the creation of matter
  - The Matter Era
  - Transition to matter
    - Galaxy Formation Epoch and Stellar Epoch
  - The Degenerate Dark Era
    - Dead Star Epoch and Black Hole Epoch
  - Whither the future?

The Littlest of Physics

- Space, Time, Matter and Forces
- Types of Matter
  - Quarks -> Baryons
    - protons, neutrons
  - Electrons -> Leptons
    - electrons, neutrinos, muons
- Types of Forces
  - gravity, electromagnetism, strong, weak

Back to the Beginning

- The universe began as an infinitely dense cosmic singularity which began its expansion in the event called the Big Bang, which can be described as the beginning of time
- During the first $10^{-43}$ second after the Big Bang, the universe was too dense to be described by the known laws of physics
The Vacuum Era

- The Planck Epoch
  - \(< 10^{-43}\) sec. and about \(10^{19}\) GeV (1 GeV \(\approx 10^{13}\) K)
  - We just don’t know
- The Inflationary Epoch
  - \(> 10^{-43}\) sec., \(< 10^{-10}\) sec.
  - Expansion driven by “repulsive gravity”

Inflation was one of several profound changes that occurred in the very early universe.

Four basic forces explain all the interactions observed in the universe.

<table>
<thead>
<tr>
<th>Force</th>
<th>Relative strength</th>
<th>Particles exchanged</th>
<th>Particles or which the force can act</th>
<th>Range</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>1</td>
<td>Gluons</td>
<td>Quarks</td>
<td>(10^{-17}) m</td>
<td>Holding protein, matter, and nuclei together</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>1/e</td>
<td>Photons</td>
<td>Charged particles</td>
<td>Infinite</td>
<td>Holding atoms together</td>
</tr>
<tr>
<td>Weak</td>
<td>(10^{-8})</td>
<td>Intermediate vector bosons</td>
<td>Quarks, electrons, neutrinos</td>
<td>(10^{-13}) m</td>
<td>Radiative decay</td>
</tr>
<tr>
<td>Gravitational</td>
<td>(6 \times 10^{-39})</td>
<td>Gravitons</td>
<td>Everything</td>
<td>Infinite</td>
<td>Holding the solar system together</td>
</tr>
</tbody>
</table>

- Grand unified theories (GUTs) are attempts to explain three of the forces in terms of a single consistent set of physical laws.
- A supergrand unified theory would explain all four forces.
- GUTs suggest that all four physical forces were equivalent just after the Big Bang.

The Radiation Era

- Creation of light
- Creation of baryonic matter
- Electroweak epoch
- Strong epoch
- Decoupling of weak interaction
- Creation of nuclei of the light elements
- Decoupling of radiation spectrum

When the temperature of the radiation fell below \(3000\) K, protons and electrons could combine to form hydrogen atoms and the universe became transparent.
The Matter Era

- Transition from radiation domination to matter domination
- Last scattering
- Dark Ages
- Galaxy Formation Epoch
- Bright Ages

The Degenerate Dark Era

- Whither the future?
  - death of stars
  - black hole domination
  - What will happen to the remaining matter in the universe
    - Ultimately sucked into black holes?
    - Ultimately all black holes combine?
    - Ultimately all spit out in a new big bang?

Summary Timescale

<table>
<thead>
<tr>
<th>Era</th>
<th>Epochs</th>
<th>Main Event</th>
<th>Time after bang</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Vacuum Era</td>
<td>Planck Epoch</td>
<td>Quantum fluctuation</td>
<td>&lt;10^{-43} sec.</td>
</tr>
<tr>
<td></td>
<td>Inflationary Epoch</td>
<td>Inflation</td>
<td>&lt;10^{-10} sec.</td>
</tr>
<tr>
<td>The Radiation Era</td>
<td>Electroweak Epoch</td>
<td>Formation of leptons, bosons, hydrogen, helium and deuterium</td>
<td>10^{-10} sec. - 10^{-4} sec. - 1 sec. - 1 month</td>
</tr>
<tr>
<td></td>
<td>Strong Epoch</td>
<td>Decoupling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Matter Era</td>
<td>Galaxy Epoch</td>
<td>Galaxy formation</td>
<td>1-2 billion years</td>
</tr>
<tr>
<td></td>
<td>Stellar Epoch</td>
<td>Stellar birth</td>
<td>2-15 billion years</td>
</tr>
<tr>
<td>The Degenerate Dark Era</td>
<td>Dead Star Epoch</td>
<td>Death of stars</td>
<td>20-100 billion yrs.</td>
</tr>
<tr>
<td></td>
<td>Black Hole Epoch</td>
<td>Black holes</td>
<td>100 billion - ????</td>
</tr>
</tbody>
</table>

A Thoughtful Break

- "The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms."
  - Albert Einstein, 1950

The Evidence So Far

- Evidence for a "Big Bang"
  - expansion of the universe
    - galaxies receding from us
    - everywhere the same
  - remnants of the energy from the "Big Bang"
    - a very hot body that has cooled
    - 2.7 K cosmic background radiation
  - the primordial abundance of chemical elements

What CMB means?

- Cosmic Microwave Background
  - Remember Wien’s Law
  - Remember Doppler
  - COBE results
Cosmic Background

- How hot would the cosmic background radiation be?
  - close to 3 K
    - first detected by Penzias and Wilson of Bell Labs
    - Didn't know what it was
    - Explained by Robert Dicke of Princeton
    - Didn't get a piece of the Nobel Prize with Penzias and Wilson
  - confirmed by COBE satellite

Putting it into context

- Taking the perspective of the universe with you at the center

The CMB remainder...

- Using COBE DIRBE data for examining the fine differences
  - fine structure of the universe
  - led to the galaxies and their location

Astronomers use supercomputers to simulate how the large-scale structure of the universe arose from primordial density fluctuations

Linking the CMB to the Galaxies

Galaxies are grouped into clusters rather than being scattered randomly throughout the universe
String Theories Attempt to Unify Physical Forces

- The search for a theory that unifies gravity with the other physical forces suggests that the universe actually has 11 dimensions (ten of space and one of time), seven of which are folded on themselves so that we cannot see them
- The idea of higher dimensions has motivated alternative cosmological models
- No evidence to support string theories at this time

What I Talked About

- The Big Bang and Everything Within
- The Evidence for the Big Bang
  - Hubble’s Law
  - Cosmic Microwave Background
  - Abundance of chemical elements
- A touch of strings