The Early Universe
Chapter 12 – Hawley/Holcomb
“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
What I’m Going to Talk About

• The Big Bang Theory of the Formation of the Universe
  – Radiation, Matter and the Physical Laws
    • Kirchoff’s Spectroscopic Laws
    • Planck’s Radiation Curves
    • Stefan-Boltzmann Law
    • Newton’s Law of Motion
    • Maxwell’s Equations for Electromagnetism
    • Hubble’s Law
    • Einstein’s General Theory of Relativity
  – Bohr’s Atom
  – Wien’s Law
  – Kepler’s Laws of Planetary Motion
  – Newton’s Law of Universal Gravitation
  – Doppler Effect
  – Einstein’s Special Theory of Relativity
  – Gamow’s Big Bang

• The Beginning?
• The Cosmological Timescale
  – Eras and Epochs
• Spacetime Inflation
• The Formation of Galaxies
• Evidence
Some Basic Physics

- Kirchoff’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
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
    \[ P^2 = a^3 \]
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

\[
\nabla \cdot E = \frac{1}{\varepsilon_0} \rho \\
\n\nabla \times E = -\frac{\partial B}{\partial t} \\
\n\n\nabla \cdot B = 0 \\
\n\n\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \\
\n\n\]
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
The value of the Hubble constant, $H_0$, is not known with certainty but best value today is approximately 71 km/s/Mpc.

There is a 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 straight line that best fits the data corresponds to $H_0 = 71$ km/s/Mpc.

$v = H_0 d$
(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, 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 = $\sim10^{13}$K)
  – we just don’t know

• The Inflationary Epoch
  – $>10^{-43}$ sec., $<10^{-10}$ sec.
  – expansion driven by “repulsive gravity”
The newborn universe may have undergone a brief period of vigorous expansion

- A brief period of rapid expansion, called inflation, is thought to have occurred immediately after the Big Bang
- During a tiny fraction of a second, the universe expanded to a size many times larger than it would have reached through its normal expansion rate
Inflation was one of several profound changes that occurred in the very early universe.

Had inflation not taken place, the present-day observable universe would have had to have been relatively large just after the Big Bang.

Once the inflationary epoch had ended, the universe continued to expand in a more gradual way down to the present day.

In the inflationary model, the present-day observable universe was very tiny just after the Big Bang. This region, as well as the rest of the universe, then underwent a tremendous expansion during the inflationary epoch.
Recall The Isotropy Problem

Our cosmic light horizon

Cosmic light horizon for A

Cosmic light horizon for B

Earth

A

B

Radiation from A takes 13.7 billion years to reach us

Radiation from B takes 13.7 billion years to reach us
Inflation helps explain why the universe is so nearly flat and the 2.725 K microwave background is almost perfectly isotropic.

As the sphere is inflated, its curvature eventually becomes undetectable and its surface appears flat.
Four basic forces came out of the Big Bang and explain all the interactions observed in the universe.
Grand unified theories (GUTs) are attempts to explain the physical forces in terms of a single consistent set of physical laws.

Some reserve the term “supergrand” unified theory would explain all four forces, some “theory of everything” (TOE).

Strong suggestion that all four physical forces were equivalent just after the Big Bang.
More on Forces

• As yet, we have no satisfactory supergrand unified theory or theory of everything, so we cannot say anything about the nature of the universe during this period before the Planck time ($t = 10^{-43}$ s after the Big Bang)
• At the Planck time, gravity froze out to become a distinctive force in a spontaneous symmetry breaking
• During a second spontaneous symmetry breaking, the strong nuclear force became a distinct force
• This transition triggered the rapid inflation of the universe
• A final spontaneous symmetry breaking occurred which separated the electromagnetic force from the weak nuclear force; from that time on, the universe behaved as it does today
During inflation, all the mass and energy in the universe burst forth from the vacuum of space.

- Heisenberg’s uncertainty principle states that the amount of uncertainty in the mass of a subatomic particle increases as it is observed for shorter and shorter time periods.
- Because of the uncertainty principle, particle-antiparticle pairs can spontaneously form and disappear within a fraction of a second.
- These pairs, whose presence can be detected only indirectly, are called virtual pairs.
As the early universe expanded and cooled, most of the matter and antimatter annihilated each other.

- A virtual pair can become a real particle-antiparticle pair when high-energy photons collide.
- In this process, called pair production, the photons disappear, and their energy is replaced by the mass of the particle-antiparticle pair.
- In the process of annihilation, a colliding particle-antiparticle pair disappears and high energy photons appear.
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 Origin of Matter

- During the Radiation Era, the universe began to fill with particles and antiparticles formed by pair production and with numerous high-energy photons formed by annihilation.
- A state of thermal equilibrium existed in this hot plasma.
- As the universe expanded, its temperature decreased.
- When the temperature fell below the threshold temperature required to produce each kind of particle, annihilation of that kind of particle began to dominate over production.
- Matter is much more prevalent than antimatter in the present day universe because particles and antiparticles were not created in exactly equal numbers just after the Vacuum Era.
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?
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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

• Recall 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.
Galaxies formed from density fluctuations in the early universe
Hexagons indicate objects at $z = 3.04$.

High-redshift objects that lie within a filament.
Illustration of the filament

Filament

To Earth

Objects shown in (a)
IR 1916 cannot be seen at visible wavelengths...

...but is observable at longer wavelengths.

Determined the redshift of IR 1916

\[
\begin{align*}
\lambda &= 540 \text{ nm} \\
\lambda &= 1260 \text{ nm} \\
\lambda &= 1650 \text{ nm} \\
\lambda &= 2160 \text{ nm}
\end{align*}
\]
Galaxies are grouped into clusters rather than being scattered randomly throughout the universe.
Models based on dark energy and cold dark matter give good agreement with details of the large-scale structure.

(a) A flat universe with dark energy:
$\Omega_m = 0.3, \Omega_\Lambda = 0.7$

(b) A open universe without dark energy:
$\Omega_m = 0.3, \Omega_\Lambda = 0$

(c) A flat universe without dark energy:
$\Omega_m = 1.0, \Omega_\Lambda = 0$
String Theories Attempt to Unify Physical Forces

- The search for a theory that unifies gravity with the other physical forces suggests that the universe may have 11 dimensions (ten of space and one of time), seven of which are folded on themselves so that we cannot see them
  - This is from string theory / M theory / brane theory
- The idea of higher dimensions has motivated alternative cosmological models
- There is no evidence to support such string theories at this time
What I Talked About and Jargon

• The Big Bang and Everything Within
• The Four Eras of the Cosmological Timescale
• The Evidence for the Big Bang
  – Hubble’s Law
  – Cosmic Microwave Background
  – Abundance of chemical elements
• A touch of strings
  • annihilation
  • antimatter
  • antiparticle
  • antiproton
  • cold dark matter
  • cosmic light horizon
  • density fluctuation
  • deuterium bottleneck
  • electroweak force
  • elementary particle physics
  • false vacuum
  • flatness problem
  • gluon
  • grand unified theory (GUT)
  • graviton
  • Heisenberg uncertainty principle
  • hot dark matter
  • inflation
  • inflationary epoch
  • intermediate vector boson
• isotropy problem (horizon problem)
• Jeans length
• Kaluza-Klein theory
• Lamb shift
• M-theory
• nucleosynthesis
• pair production
• positron
• quantum electrodynamics
• quantum mechanics
• quark
• quark confinement
• spontaneous symmetry breaking
• strong force
• supergrand unified theory
• theory of everything (TOE)
• thermal equilibrium
• threshold temperature
• virtual pairs
• weak force