APOD/Announcements for February 17, 2010:

HW #2 Due NOW
Quiz #2 - MONDAY 2/22, covers ALL material through today
Office hours Sunday (online - mhcastronomy) 8-9:15pm
Monday 9:15-10 am, 12:15-1:15
This Week: Discovery of the Universe!

- Historical Perspective
- Big Breakthroughs - Distance to Andromeda, velocities of galaxies
- Hubble’s Law, Age, Expansion
- Big Bang Model (Wednesday)
  - Development
  - Observational Proof!
  - Timeline for $t=0$ through $t=300,000\text{yrs}$
This Week: Discovery of the Universe!

Big Bang: Learning Goals

1. What is it?
2. What is the evidence for it?
3. What (& how) does it tell us about the history of the Early Universe?
Recession velocity of galaxies is proportional to their distance

\[ v = H_0 \times d \]

implying that the Universe is expanding!!

...and has a finite age!!
Original Theory of the Universe:

Newton (ca 1700)

The Universe is Static & Infinite

Problem: Olber’s Paradox (ca 1800)

Why is the night sky dark?
Original Theory of the Universe:

Newton:
The Universe is Static & Infinite

Problem #2: Einstein & Cosmological Constant (1915)

• General Relativity could not produce a static Universe...

• ...without inserting a “fudge factor” into equations.

“My biggest blunder”
**Big Bang Theory (1927):**

- Space, time, matter & energy were created ~14 billion years ago in a violent event called the **BIG BANG**

- Universe has been **expanding** ever since

**Steady State Theory (1700+):**

*Newton (1700)*

Universe is Static & Infinite

*Bondi, Gold & Hoyle (1948)*

Universe has no beginning, no end, and looks the same from every spot in it *at all times*
Big Bang vs. Steady State - Pros for Big Bang

• Solves Olber’s Paradox

• Explains observed Expansion of Universe

• Agrees with Einstein’s General Relativity (without needing Cosmological Constant)
Big Bang Theory: 3 Major Predictions

(Lemaitre/Gamow 1927-1948)

1. **The Universe should be expanding**

2. **There should be ~25% Helium abundance**

3. **There should be observable radiation EVERYWHERE left over from the Big Bang**

*Were Hubble/Lemaitre/Gamow Right?*
Origins: Back to the Beginning
Chapter 2
Big Bang Theory: 3 Major Predictions

(Lemaitre/Gamow 1927-1948)

1. The Universe should be expanding
   (consequence of Big Bang itself)

2. There should be ~25% Helium abundance
   (consequence of temperatures and particle interactions
    in early universe)

3. There should be observable radiation
   EVERYWHERE left over from the Big Bang

Were Hubble/Lemaitre/Gamow Right?  YES!!
Penzias & Wilson - Evidence for BIG BANG!!

- Cosmic Microwave Background Radiation (CMB)
  - Radiation left over from beginnings of the transparent universe
  - Blackbody @ T=3000K

Where should we observe it (why)?

Nobel Prize!!
Cosmic Microwave Background:

Blackbody @ 3000K REDSHIFTED to look like 3K

![Cosmic Microwave Background](image)

*Temperature: T = 2.728 K*

**Spectrum of the Cosmic Microwave Background**

Frequency (GHz)

![Spectrum Graph](image)

*Temperature: T = 2.725 ± 0.001°K*
Cosmic Microwave Background:

CMB is REDSHIFTED RADIATION from Big Bang!!

Blackbody @ 3000K REDSHIFTED to look like 3K

Spectrum of the Cosmic Microwave Background

Frequency (GHz)

Intensity (MJy/sr)

100 200 300 400 500

1 0.2 0.1 0.07 0.05

T = 2.725 ± 0.001°K
After the Bang... a Mystery!

Smooth Background??

$T = 2.728 \text{ K}$
Origins: Back to the Beginning
Chapter 2
(33:00-36:00)
a blackbody at ~2.7 K

2006 Nobel Prize!
After the Bang... a Mystery Solved!

COBE Satellite: Revealed structure in early universe!!

Gravity Acts on this structure to form stars & planets!
After the Bang... a Mystery Solved!

WMAP Satellite: DETAILED structure

ALLOWS US TO CONSTRAIN EARLY HISTORY!
Big Bang Timeline: The Beginning

- Universe was **infinitely dense, small, & hot**

- **Four forces of the Universe** (gravity, electromagnetism, strong & weak nuclear forces) **were unified**

**Current laws of physics cannot describe these conditions!**
As space expands, the Universe cools....

...forces separate ("freeze out")
Big Bang Timeline: Early Universe

**PLANCK ERA:**
\[ \text{time} < 10^{-43} \text{ s, } T = 10^{34} \text{ K} \]
- Universe was pure energy
- superforce!

**GUT ERA** (Grand Unified Theories):
\[ t = 10^{-43} \text{ s, } T = 10^{27} \text{ K} \]
- Gravity drops out of superforce
- matter & energy interchangeable

**INFLATION ERA:**
\[ t = 10^{-35} - 10^{-32} \text{ s, } T = 10^{27} \text{ K} \]
- Strong force drops out \( \rightarrow \) inflation
  - Rapid Expansion of Universe
- matter (& antimatter) appears
Era of Inflation

Space inflates $>10^{30}$ ... in $<10^{-30}$ sec.

Space created in Big Bang

Our Universe

Time

Space
Big Bang Timeline: Early Universe

QUARK/ELECTROWEAK ERA
\( t = 10^{-32} \text{s}, \ T = 10^{22} \text{K} \)
- Matter/Antimatter Annihilate
- Quarks & Exotic Particles only

PARTICLE ERAs
\( t = 10^{-12} \text{s}, \ T = 10^{15} \text{K} \)
- Remaining forces separate, current laws of physics apply
- Protons, Neutrons, & Electrons form
Big Bang Timeline: the first few minutes

NUCLEOSYNTHESIS ERA

• t=1s-200s, T=10^{10} K

• Big Bang Nucleosynthesis - fusion of atomic nuclei & formation of 98% of Universe’s Helium

• Predicts a specific Helium abundance for the Universe: 25%
Big Bang: the first few (thousand) years

**OPAQUE ERA**
- $t=200$ seconds - 380,000 years, $T=10^8$ K (100 million degrees)
  - Photons & matter are coupled (light can’t escape)
  - Hydrogen & Helium IONS

![Diagram showing protons, electrons, and photons before recombination](image)
Big Bang Timeline: first few (thousand) years

RECOMBINATION!!!!
- $t = 380,000$ years, $T = 3000$ K (still toasty!)
  - Protons & Electrons Recombine
  - Matter & Radiation decouple - Light escapes!

Residual radiation should be observable!
Big Bang: 3 Major Predictions

1. **The Universe should be expanding**
   (consequence of Big Bang itself)

2. **There should be ~25% Helium abundance**
   (consequence of temperatures and particle interactions in early universe)

3. **There should be observable radiation EVERYWHERE left over from the instant the universe became transparent**
   (photons are now free)
Big Bang: Evidence

1. The Universe should be expanding  
   (consequence of Big Bang itself)

   Hubble Law, Einstein’s General Relativity

2. There should be \( \sim 25\% \) Helium abundance  
   (consequence of temperatures and particle interactions in early universe)

   Measured Abundances are 75\% H, 25\% He

3. There should be observable radiation EVERYWHERE left over from the instant the universe became transparent  
   (photons are now free)

   Cosmic Microwave Background
After the Bang... a Mystery Solved!

Big Bang created this....

....Gravity acts on this to form galaxies, stars, planets & us!