• Problem set #1 due. Solutions will be posted.
  – From now on, late work is not accepted unless we pre-arrange something.
• Read “The Lives of Stars (Part I)” for Wed.
  – Quiz at beginning of class
• Problem set #2 due Wed 16th.
  – Large online problem.
• Reminder: need approval of article for final presentations by Wed 16th.
Early History of the Universe (Part II)

Kathy Cooksey

AY5 Introductory Astronomy

Monday, July 7, 2008
Blackbody Radiation (revisited)

- Peak wavelength is defining characteristic
  - Depends on temperature (Wien’s Law)
- Higher temperature means more light at every wavelength.

This is very important for understanding early Universe.
Timeline of Big Bang

1 billion years:
- First galaxies form.

500,000 years:
- Atoms form; photons fly free and become microwave background.

3 minutes:
- Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.

0.001 seconds:
- Matter annihilates antimatter.

10^{-10} seconds:
- Electromagnetic and weak forces become distinct.

10^{-38} seconds:
- Strong force becomes distinct, perhaps causing inflation of universe.

10^{-43} seconds:
- GUT Era
- Elementary particles
- 10^{-43} seconds: Planck Era
- ????

Particulate Era:
- Protons, neutrons, electrons, neutrinos (antimatter rare)

Era of Nucleosynthesis:
- Plasma of hydrogen and helium nuclei plus electrons

Era of Nuclei:
- Elementary particles (antimatter common)

Era of Atoms:
- Atoms and plasma (stars begin to form)

Cosmic Perspective

(proton, neutron, electron, antiproton, neutrino, antineutrino, antineutron, antielectron, quark)
Planck Era

- 0 s to $10^{-43}$ s
- Local Universe $\sim 10^{-35}$ m ($= c t_P$)
- Four fundamental forces unified
  - Do not understand physics of first $10^{-43}$ s
  - “Theory of Everything”: supersymmetry, superstrings, quantum gravity
## Fundamental Forces

<table>
<thead>
<tr>
<th>Force</th>
<th>Exchange Particle</th>
<th>Relative Strength</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Nuclear</td>
<td>gluon</td>
<td>$10^{38}$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>photons</td>
<td>$10^{36}$</td>
<td>Infinite</td>
</tr>
<tr>
<td>Weak Nuclear</td>
<td>W, Z bosons</td>
<td>$10^{25}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Gravitational</td>
<td>graviton</td>
<td>1</td>
<td>Infinite</td>
</tr>
</tbody>
</table>
Grand Unified Theory Era

• $\approx 10^{-43}$ s to $10^{-35}$ s
• Ends with $T \approx 10^{28}$ K
  – Strong nuclear force separates from electroweak force
  – Suspected cause of inflation
Inflationary Era

- $\approx 10^{-34}$ s to $10^{-32}$ s
- $T \approx 10^{27}$ K throughout
  - Universe reheated.
- Expansion faster than speed of light
  - $10^{-50}$ m to 1 m
- **Isotropic and homogeneous** expansion
- Regions originally in *causal contact* pushed outside cosmic horizon
- Universe **flattened** (spatial density $\approx$ critical).
Causal Contact

Age of Universe and (finite) speed of light defines observable Universe.

(Cosmic Perspective)
A and B not in causal contact but can be similar.

A and B in causal contact and had knowledge of each other.

(Cosmic Perspective)
Flat Universe

(Cosmic Perspective)
Critical Density

(Cosmic Perspective)
Isotropic and Homogeneous

Isotropic: uniform in all directions
Homogeneous: same composition throughout

Is the Universe so?
Isotropic and Homogeneous

• Is the Universe so?
  – No. We can see that in each other.
  – On large scales the symmetry improves.
  – CMB is very smooth.

• Inflation stretched quantum fluctuations to structure size so Universe could evolve.
  – To be revisited later
Electroweak Era

- $\approx 10^{-32}$ s to $10^{-11}$ s
- Ends with $T \approx 10^{15}$ K
  - Weak nuclear force separates from electromagnetic force
  - Fundamental particles gain mass from Higgs mechanism
Particle Era

• ≈ 10^{-12} s to 10^{-3} s
  – Physics understood (even reproduced in particle accelerators)
• At ~10^{-4} s, quarks form into neutrons, protons, etc.
  – Neutrons, protons formed here (make up us).
• Ends with T ≈ 10^{12} K
  – Spontaneous production of neutrons, protons no longer possible
• As many particles as photons
  – Electrons, neutrinos, quarks
Intro to Particle Physics

How do matter and energy work?
Particle Accelerators

- “Recreating” Big Bang
- High energy collisions reproduce processes of early Universe

Compact Muon Solenoid, CERN
Standard Model of Particle Physics

- **Quarks**: indivisible units of most common matter.
- **Baryons**: ordinary matter (3 quarks)
  - Proton (uud), neutron (udd)
- **Neutrinos**: signature of high-energy processes.
- **Anti-particles** exist.
Pair Production

• Matter and energy are interchangeable.
  – Law of conservation of energy/matter
• Create e.g., electron-positron pairs
• Boltzmann constant \( k = 1.381 \times 10^{-23} \text{ J/K} \)
  \( = 8.617 \times 10^{-5} \text{ eV/K} \)

\[ E = mc^2 \]

\[ E \approx kT \]

(Cosmic Perspective)
Blackbody Radiation: Source of Energy

- $T = 12,000 \, \text{K}$: $\lambda_m \approx 250 \, \text{nm}$
- $T = 6000 \, \text{K}$: $\lambda_m \approx 500 \, \text{nm}$
- $T = 3000 \, \text{K}$: $\lambda_m \approx 1000 \, \text{nm}$

Brightness vs. Wavelength (nm)
Blackbody Radiation: Atoms in Motion

• Everything is composed of atoms that are constantly in motion.
Blackbody Radiation: Atoms & Temperature

- Hotter objects have atoms that move faster.
Atoms collide as they move around.
Collisions release energy.
But energy is radiation.
Blackbody Radiation: Source of Energy

- $T = 12,000 \text{ K}$: $\lambda_m \approx 250 \text{ nm}$
- $T = 6000 \text{ K}$: $\lambda_m \approx 500 \text{ nm}$
- $T = 3000 \text{ K}$: $\lambda_m \approx 1000 \text{ nm}$

Brightness vs. Wavelength (nm)
Particle Era (Recap)

• $\approx 10^{-12}$ s to $10^{-3}$ s
  – Physics understood (even reproduced in particle accelerators)
• At $\sim 10^{-4}$ s, quarks form into neutrons, protons, etc.
  – Neutrons, protons formed here make up us.
• Ends with $T \approx 10^{12}$ K
  – Spontaneous production of neutrons, protons no longer possible
• As many particles as photons
  – Electrons, neutrinos, quarks
Era of Nucleosynthesis

- $\approx 10^{-3}$ s to 3 min
  - Goldie Locks: temperature and density just right for nuclear fusion
- Universe dominated by radiation
- Ends with $T \approx 10^9$ K
  - Ordinary (baryonic) matter: 75% H, 25% He (0.01% D, $10^{-8}$% Li, Be) by mass
Big Bang Nucleosynthesis

Periodic Table of the Elements

(GPC)
Hydrogen and Helium

- Observed abundances evidence for Big Bang
- $T > 10^{11}$ K, equal numbers of neutrons and protons
- $10^{10} \text{ K} < T < 10^{11}$ K, protons outnumber neutrons
- $T \approx 10^9$ K, $^4\text{He}$ stable (less gamma rays)
- 7 protons for every 1 neutron
  - H is just proton when ionized.

(Cosmic Perspective)
Era of Nuclei

- ≈ 3 min to 500,000 yr
- Plasma of H and He nuclei and free electrons
  - Photons bounce around and never get far (unobservable)
- Ends with T ≈ 3,000 K
  - Cool enough for recombination
  - Photons stream away as cosmic microwave background
- Universe dominated by matter
  - Begin “Cosmic Dark Ages”
Cosmic Microwave Background

- Strongest evidence for Big Bang theory
  - Especially inflation
- 3,000 K redshifted to 2.725 K
- Isotropic (uniform) to one part in 100,000
- Remnant of last scattering surface (when H formed)

(WMAP)
z: Redshift

- Speed of light
  \( c = 3 \times 10^5 \text{ km/s} \)
  \( = 186,000 \text{ mi/s} \)
- Hubble’s constant
  \( H_0 = 70 \text{ (km/s)/Mpc} \)
- Distance \( D \)
  \( (1 \text{ Mpc} = 3.3 \times 10^6 \text{ light-year}) \)
- Wavelength \( \lambda \)
  (observed and emitted)
- Velocity \( v \)

\[
\begin{align*}
  c z & = H_0 D \\
  z & \equiv \frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}} - 1 \approx \frac{v}{c}
\end{align*}
\]
Redshift and Time

- Speed of light is finite.
- Distance (redshift) and time related.
- We observe distant objects as they were in the past.
Observing CMB

- Penzias and Wilson at Bell Labs, NJ (1965)
  - First detection
- Cosmic Background Explorer (COBE, 1989-1993)
  - First measure anisotropy
- Wilkinson Microwave Anisotropy Probe (WMAP, 2001-present)
  - Concordance cosmology

COBE (Physics Today)
First Stars

• $\approx 400,000 \text{ yr (} z \approx 1100)\}$
• Heat and reionize Universe
  – End of “Cosmic Dark Ages”
• Universe ionized by $\approx 1 \text{ Myr (} z \approx 6)\}$
Timeline of Big Bang

1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
$10^{-10}$ seconds
Electroweak Era
$10^{-38}$ seconds
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Planck Era

First galaxies form.
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 Plasma of hydrogen and helium nuclei plus electrons.
 Protons, neutrons, electrons, neutrinos (antimatter rare).
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 Elementary particles.
 Electromagnetic and weak forces become distinct.
 Strong force becomes distinct, perhaps causing inflation of universe.

(Cosmic Perspective)
Summary

• Universe expands and cools since Big Bang until first stars (~500,000 yr).
  – Inflation is exception.

• Evidence for Big Bang:
  – Cosmic Microwave Background
  – Expansion of Universe
  – Big Bang Nucleosynthesis: 75% H, 25% He

• Inflation “fixes” problem with Big Bang theory
  – Isotropy and homogeneity, critical density, flatness

• \[ z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}} - 1 \] (relates to distance and time)
Class Notes

- Problem set #1 due. Solutions will be posted.
  - From now on, late work is not accepted unless we pre-arrange something.
  - Quiz at beginning of class
- **Math quiz**, end of class Fri.
  - Review work from class and 1st problem set
  - Familiarize yourself with 2nd problem set
- Problem set #2 due Wed 16th.
  - Large online problem.
- Reminder: need approval of article for final presentations by Wed 16th.
Anthropic Principle: Why is the Universe the way it is?
Anthropic Principle

• “Why is the Universe the way it is?”
• “If the Universe was not as it is, there would be no life, and we would not even be here to answer this question.”
• Observational bias