Big Bang, Black Holes, No Math

ASTR/PHYS 109

Dr. David Toback

Lectures 17 & 18

Evidence for the Big Bang

Topic 3: Photons and Hydrogen in the Universe
Was due Today – L18

• Reading:
  - Unit 4
• Pre-Lecture Reading Questions (PLRQ)
  - Unit 3 Revision, Stage 1: Due before class Wednesday
  - Unit 4, Stage 1: Due before class Wednesday
• End-of-Chapter Quizzes:
  - Chapter 11
• Papers:
  - Paper 2 Revision (if desired), Stage 1: Due before class Wednesday
    • Turn in to both CPR and turnitin on eCampus even if the text is the same (that way we know that it’s the same)
  - Paper 3, Stage 1: Due before class, Next Wednesday
Paper 3: The Assignment

• **Abbreviated Description:** What is the evidence for the Big Bang?
  - Explain it to someone who isn’t taking the class (no jargon)

• Make sure you read ALL the instructions in CPR
Two Different Pieces of Evidence

When we look at the stuff in the Universe, we see that

1. ~90% of the atoms are hydrogen, ~10% are helium and there is very little of everything else
   - The Earth is very different than the rest of the Universe in many ways

2. Lots of photons uniformly distributed with a Temperature of 2.7 Kelvin
   - Cosmic Background Radiation
Outline

• A ridiculously brief history of time
• The Early Universe and its Particles
• Nuclei and atoms and their reactions in the Early Universe
• The stuff in the Early Universe
• As the Universe expands and cools
Ridiculously Brief History of Time

• It all started with a Big Bang

• Then the Universe got Bigger, Older and Colder

• We look at the evidence today
The Early Universe

If there was a Big Bang, what would the Universe look like a second after the Big Bang?

1) Very small
2) All the particles would have high energies
3) Lots of free particles

Let's address each of these issues one at a time.
Free Particles in the Early Universe

Many things COULD happen if we just had lots of free particles

Start by describing how they combine

• Quarks could combine to form protons and neutrons
• Protons/neutrons could combine to form nuclei
• Nuclei and electrons could combine to form atoms
Forming Protons

\[
\text{Nuclear Reaction} \quad qqq \rightarrow \text{Proton}
\]

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Proton + Proton \rightarrow Deuterium + Anti-Electron + Neutrino

Forming Heavy Nuclei

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Forming Atoms

Proton + electron → Hydrogen Atom + photon
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Proton

Electron

High Energy Photon Breaks up Atoms quickly

⇒ Free electrons and protons

Electromagnetic Reaction

⇒ Hydrogen Atom

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Nuclei in the Early Universe

Photon Breaks up Nucleus before it can find an electron to create an Atom or find another nucleon to form a bigger nucleus.

- Free protons and neutrons

Nuclear Reaction

Deuterium
Bottom Line

- As time progresses all the particles, including the photons, will have lower energies
  - Lower temperatures
  - Bigger, older and colder...
- The interactions between the particles are very different at different energies
Later Times: Atoms and Low Energy Photons

Low energy photons typically only “bump” atoms or excite them.

ElectroMagnetic Reaction → Hydrogen Atom

Proton

Electron

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Nuclei and Low Energy Photons

Low energy photons only "bump" nuclei

Deuterium

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Proton + Deuterium \rightarrow \text{Helium}_3 + \text{Photon}

Can Now Build Up Heavier Heavy Nuclei
Creating Stable Helium

**Equation:**

Helium$_3$ + Helium$_3$ $\rightarrow$ Helium$_4$ + 2 Protons

- This is why we have ~90% hydrogen and ~10% helium. More on this later...

**Diagram:**

- Helium$_3$
- Helium$_4$
- Protons

**Explanation:**

Creating stable helium through nuclear reactions is a key process in understanding the composition of the universe. The reaction shown involves the fusion of two helium-3 nuclei to form a helium-4 nucleus, releasing two protons as a byproduct. This process helps explain the observed abundance of hydrogen and helium in the universe.

**Further Reading:**

- Evidence for the Big Bang
- Black Holes, No Math

**Topic:**

- Topic 3: Photons and Hydrogen in the Universe
Evidence: Hydrogen

• We can see how to build up heavier nuclei... Should have lots of each. No?

• Observed facts:
  - 91% of all the atoms in the universe are hydrogen
  - Most of the rest are helium
  - In comparison, almost nothing of heavier types

• Why is this?
Why so few atoms Heavier than Helium?

Nuclear Physics
Can build up Hydrogen and Helium one at a time

→ Next possibility, $^5\text{He}$ or $^5\text{Li}$, isn’t stable

So What? Since $^5\text{He}$ and $^5\text{Li}$ decay quickly they don’t have enough time to find another proton to become $^6\text{Li}$ and be stable

→ Almost no elements heavier than helium are produced in the early Universe

• Will happen much later, and in stars
The Helium Story

- Able to predict the fraction of the atoms in the Universe that are Helium
  - 75% of atomic mass in hydrogen
  - 25% of observed mass in helium
    - Same as saying about 91% of the atoms are hydrogen
- Helium is the same in every direction because it was created everywhere
  - Entire Universe had the same temperature everywhere
  - If it was created mostly in stellar cooking we'd see it coming from the directions where there are more stars
    - I.e., the direction of galaxies
- More on this in Chapter 16
Hot Early Universe

The high-energy particles in a hot, small Universe would break apart heavy atoms and nuclei, and explains two pieces of experimental data

1. So much hydrogen and so little of other types of atoms except Helium

2. Lots of photons with the same temperature in all directions
Particles in the Universe

- Early times: Protons, Neutrons, Electrons, Positrons and Photons
- Later times: Photons and atoms
- Much later: Atoms combine to form stars and galaxies
  - More on this later

What happens to the photons?
Life as a Photon in the Universe

• If a photon is high enough energy to break a part an atom it will
• Any photon that isn’t high energy enough won’t interact again and will thus just travel forever
• Thus, the last thing a typical photon in the universe interacts with is an atom/electron
• Why does that matter? Essentially, they are unchanged since the time of “last interaction” except to be stretched by expanding space
  - Tells us about the Universe when they last interacted
What happens to the Photons?

The photons simply “cool” as space expands → Lower Temperature → Longer Wavelengths

- **Photon Type**: Photons simply “cool” as space expands, leading to a decrease in temperature and an increase in wavelength.

- **Photon Wavelength**:
  - $10^{-12}$ m: Gamma Rays, ~0 years
  - $10^{-10}$ m: X-rays, ~200 years
  - $10^{-8}$ m: Ultraviolet Light, ~20,000 years
  - $10^{-7}$ m: Infrared Light, ~5 million years
  - $10^{-5}$ m: Microwaves, ~15 million years
  - $10^{-3}$ m: Radio Waves, not yet

- **Time After Big Bang**:
  - ~0 years
  - ~200 years
  - ~20,000 years
  - ~5 million years
  - ~15 million years
  - ~2.5 billion years
  - not yet

- **Wavelength Change**:
  - Photons cool as space expands, resulting in lower temperatures and longer wavelengths.
Why should we believe this Story?

Should be able to observe this “remnant” of the Big Bang

Any evidence for photons with energies that look like a low temperature?
A Great Experiment

Arno Penzias and Robert Wilson in 1964 were doing high precision measurements of photons for radio waves. Notice “noise” in their system that turned out to be photons with a temperature of about 3 degrees above absolute zero. Not looking for these photons... but won the Nobel Prize anyway.
The same Temperature in all directions?

Look at the full sky in a single map

Temperature Map (i.e., different colors correspond to different temperatures)

Incredibly Uniform! 2.78 degrees Kelvin
Conclusion from the data?

- Data is exactly consistent with a Universe that was small and hot a long time ago... what we would expect with a Big Bang!

- No other reasonable explanation for where lots of photons with a specific temperature would come from, and be the same in all directions
Summary

1. We observe galaxies moving away from us in a manner that is consistent with an expansion of space-time.

2. Most of the atoms in the universe are hydrogen and helium and not much else.

3. We observe photons (the cosmic background radiation) uniformly distributed in all directions that have a temperature consistent with cooling for ~13.7 billion years.
Fun Way to think about things

- Look at things “far away” in space ➔ Backward in time
- Can see stars from millions of years ago
  - Look like stars today
- Look at galaxies from billions of years ago
  - Look like galaxies today
- Look at galaxies from about 13 billion years ago
  - Look like baby galaxies forming
- Look even “farther back”
  - No galaxies! Why? Because they haven’t even formed!
- Look further still... See the “white noise” of the cosmic background radiation and no evidence of any galaxies
  - Looking back at the earliest times we can “see” without the photons going through the “fog” of the early universe... Can’t see through the fog to earlier times... Then again, there isn’t much time before that anyway
How far can we look back in time?

All we can see is back a certain distance in TIME.

We can’t see anything “past” the background radiation.
Lecture on Chapter 12 now complete
What’s Next?

Unit 4: Evolution of the Universe

• The Early Universe
• After the First Three Minutes
Paper 3: The Assignment

• Abbreviated Description: What is the evidence for the Big Bang?
  - Explain it to someone who isn’t taking the class (no jargon)

• Make sure you read ALL the instructions
For Next Time - L18

- Let us know if you were misgraded on any CPR Assignment
- Reading:
  - (Unit 4)
- Pre-Lecture Reading Questions (PLRQ)
  - Unit 3 Revision, Stage 1: Due before class Wednesday
  - Unit 4, Stage 1: Due before class Wednesday
- End-of-Chapter Quizzes:
  - If we finished Chapter 12, then Chapter 12, parts a&b (if not, Chapter 11)
- Papers:
  - Paper 2 Revision (if desired), Stage 1: Due before class Wednesday
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Topic 3: Photons and Hydrogen in the Universe
Full set of Readings So Far

• Required:
  - BBBHNM: Chaps. 1-13

• Recommended:
  - TFTM: Chaps. 1-5
  - BHOT: Chaps. 1-7, 8 (68-76), 9 and 11 (117-122)
  - SHU: Chaps. 1-3, 4(77-86), 5(95-114), 6, 7 (up-to-page 159)
  - TOE: Chaps. 1 & 2