Evidence for the Big Bang

Big Bang, Black Holes, No Math

ASTR/PHYS 109

Dr. David Toback

Lectures 17 & 18

Big Bang, Black Holes, No Math

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

- Reading:
  - Unit 4: Assigned at the end of class
- Pre-Lecture Reading Questions (PLRQ)
  - Unit 3: Let us know if you think you were misgraded
  - Unit 3 Revision (if desired): Due Tuesday before class
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- End-of-Chapter Quizzes:
  - Chapter 11
- Papers:
  - Apologies for the grades flopping
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  - Papers 1 and 2:
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    - Paper 2 Revision (if desired): Due Thursday Nov 1st 11:59PM
  - Paper 3: Will assign due dates Today if we finish Chapter 12
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 Peerceptiv
Overview

Evidence for the Big Bang?

• Finished:
  - The Exploding Universe
  - Expanding Space-Time

• This Time:
  - More evidence for a hot early Universe?
  - Photons and Hydrogen in the Universe today
Before we begin…

- The Cosmic Background Radiation provides, perhaps, the most compelling piece of evidence for the story of the Big Bang.
- Unfortunately, it's the hardest to explain to the non-scientist.
  - Radiation = Photons.
Two Different Pieces of Evidence

When we look at the atoms and photons 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 with a Temperature of 2.7 Kelvin coming from all directions
   - Cosmic Background Radiation
Prelude to the Story

• To understand why the photons and amount of hydrogen in the universe are important, we need to understand a little about the way the Universe changed over time.
  - It’s history

• How it changes over time is what we call the evolution of the Universe.
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
• What happens to the stuff as the Universe cools
Ridiculously Brief History of Time with 3 Time Steps

1. It all started with a Big Bang
2. The Universe gets Bigger, Older and Colder
3. We observe the evidence today
How the Universe Changes

• If the Big Bang theory is correct, that means that over time the universe has been getting
  - Bigger,
  - Older, and
  - Colder
**Why Colder?**

*Space-time is stretching*

- The wavelengths of the particles are stretching
- Longer wavelength particles
- Lower energy particles
- Temperature is dropping!
Evidence for the Big Bang

**Why Colder?**

The temperature simply “cools” as space expands
- Longer Wavelengths
- Lower energy
- Lower Temperature

**Time After Big Bang**

- Not yet
- ~2.5 billion years
- ~15 million years
- ~5 million years
- ~20,000 years
- ~200 years
- ~0 years

**Photon Wavelength**

- 10^3 m: Radio Waves
- 10^{-2} m: Microwaves
- 10^{-5} m: Infrared Light
- 10^{-6} m: Visible Light
- 10^{-8} m: Ultraviolet Light
- 10^{-10} m: X-rays
- 10^{-12} m: Gamma Rays

**Then**

- Photons and Hydrogen in the Universe

**Now**

- Why Colder?
Setting up to Tell the History

• Tell you the hypothesis of what the Universe would look like a short time after the Big Bang

• Say a little bit about how the Universe changed from “how-it-was-back-then” to “how-it-is-today”

• Then explain WHY we think it looked that way “back-then”
The Early Universe

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

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

Will address each of these issues one at a time.
If we hypothesize that the universe was small with lots of high energy free particles, how did it become what we observe today?

**Early Universe**
- Electron
- Proton
- Photon
- Neutron

**Today**
- Hydrogen
- Deuterium
- $^4$He
- Photon

**How did the universe get from to?**
Why Small?

If the universe has been expanding for billions of years, it would have been smaller billions of years ago.
Why **High Energy Particles?**

- If the universe has been expanding, then (according to General Relativity) it has been stretching the wavelengths of all the particles since then.
- Back then, when they were less-stretched, they must have been higher energy.
  - Long wavelength $\rightarrow$ Low energy (today)
  - Short wavelength $\rightarrow$ High energy (then)
Why **Free Particles in The Early Universe instead of Composite Particles like Atoms**?

- This one is harder to understand
- Need to learn more about what happens when particles interact
- Need to explain how we got from lots of free particles then to lots of composite particles today
Free Particles in the Early Universe

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

Focus on 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

$$qqq \rightarrow \text{Proton}$$

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Forming Heavy Nuclei

Proton + Proton \rightarrow \text{Deuterium} + \text{Anti-Electron} + \text{Neutrino}

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Topic 3: Photons and Hydrogen in the Universe
Forming Atoms

Proton + electron
\[ \rightarrow \text{Hydrogen Atom + photon} \]
The Story

This is great... you can see that IF there were lots of free particles in the early Universe, they could combine to create the things we see today, like stars and galaxies.

Universe just slowly assembled over time

Lots of atoms combine to form stars, then galaxies, then us!

(more on this in later chapters, since it's not that simple)
But Why Only Free Particles in the Early Universe?

Things get broken up in high energy collisions (like at particle accelerators)

Examples:
Atoms in the Early Universe

High Energy Photon Breaks up Atoms quickly

- Free electrons and protons

Electromagnetic Reaction

- Hydrogen Atom

Proton

Electron

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Nuclei in the Early Universe

Photon

Proton

Nuclear Reaction ➔ Deuterium

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

High Energy Photon

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**Bottom line:**
Early Universe has Free Particles with Really High Energies

- In the early Universe we had many different types of free particles because high energy collisions can create all the different types
- Composite particles could get formed, but other high energy particles would bust them apart $\rightarrow$ we end up with only free particles
What else happens in collisions in the Early Universe?

High energy photons → lower energy photons

Low energy photons → higher energy photons
The Same Temperature

- All these high energy particles are quickly colliding in a small space.
- Eventually all the particles will (roughly) have the same energy.
  - Said better: The same Temperature.
Quick Aside: Not all energies are equal

They are all close to being the same, but they aren’t all the same

How many of each?

Average height

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Evident Topic 3: Photons and Hydrogen in the Universe
More detail than you wanted...

Not all atoms have exactly the same energy or speed.

If we have this special distribution of energies, we know the particles are in thermal equilibrium.

Can use the average to tell us what the temperature is.
Particles in a Hot Small Universe

Because of the way particles interact at high energies we get lots of photons, protons, neutrons and electrons.

Even if the universe didn’t start with lots of each of these particles, eventually there would be lots of them:

- Produced in collisions or in the decay of other particles.

Holes, No Math! Topic 3: Photons and Hydrogen in the Universe
Evidence for the Big Bang

Electron-Photon Soup in the Early Universe

Electron pairs and photon pairs interact and annihilate → electron and photon Soup
Then what happens?

What will happen later?

The Universe Expands and stretches the wavelengths of the particles

Universe cools... energies drop
Expanding Space Part 1

Photons in the Universe

Early Times $\rightarrow$ High Temperature, high energy particles
Expanding Space Part 2

Later Time $\rightarrow$ Space gets Bigger
$\rightarrow$ Wavelength gets Longer

$\rightarrow$ Temperature is Cooler, lower energy particles
Even later ➔ Even more red shifted

Even cooler, even lower energies
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

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

- **Proton**
- **Electron**
- **Low Energy Photon**
- **ElectroMagnetic Reaction**
- **Hydrogen Atom**

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**Topic 3: Photons and Hydrogen in the Universe**
Nuclei and Low Energy Photons

Low energy photons only "bump" nuclei

Deuterium
Proton + Deuterium $\rightarrow$ Helium$_3$ + Photon

Nuclear Reaction

Proton

Deuterium

Photon

$\rightarrow$ Helium$_3$
Creating Stable Helium

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

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

Helium$_3$, Proton, Helium$_4$, Proton, Proton

Evidence for the Big Bang, Black Holes, No Math
Topic 3: Photons and Hydrogen in the Universe
Evidence Today: 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
For Next Time - L18

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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