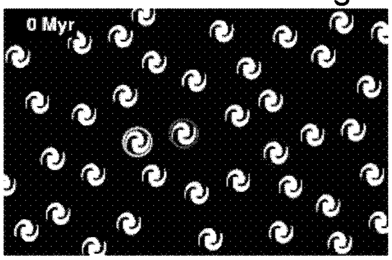
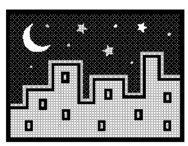
Photons, Electrons, & the Cosmic Microwave Background



Monday, November 2

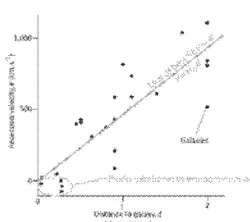
Evidence in favor of the **Big Bang** model for the universe.

1) The night sky is dark.



Implication: universe is of finite age; light from distant galaxies hasn't reached us.

2) Galaxies show a **redshift** proportional to their distance.



Implication: space is expanding; light from farther galaxies is stretched more.

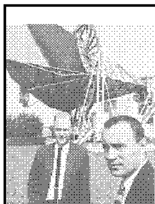
3) The universe is filled with a **Cosmic Microwave Background**.

The Cosmic Microwave Background (**CMB**) was discussed briefly in Section 5.3 of the textbook.

The time has come to talk of the CMB.

What is the Cosmic Microwave Background?

Why does it arise naturally in a Big Bang model?

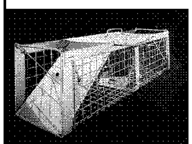


In the early 1960s, two astronomers, Wilson & Penzias, were working with a microwave antenna at Bell Labs.

(Microwaves are electromagnetic waves with wavelengths from 1 millimeter to 10 centimeters.)

Wilson & Penzias were plagued by static.

Wilson & Penzias did everything they could to eliminate "noise" in their antenna.



…including trapping pigeons that had left "a white dielectric material" on the antenna.

Conclusion: "static" or "noise" actually came from outer space, not from pigeon poop.

Microwave radiation picked up by Wilson & Penzias was nearly isotropic.

(That is, it doesn't come from a single source, like the Sun.)

Because they come from everywhere, the microwaves from space are called the **Cosmic** Microwave Background.

Penzias & Wilson won the Nobel Prize.

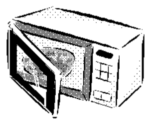
Physicists and astronomers thought that discovering the CMB was really important!

WHY?

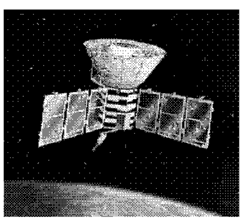
Consider the spectrum of the CMB.

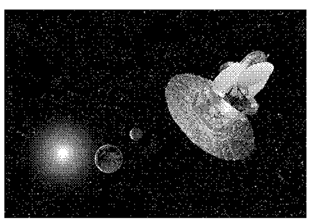
Measuring the CMB spectrum is hard to do from the Earth's surface.

Water is very good at absorbing microwaves.

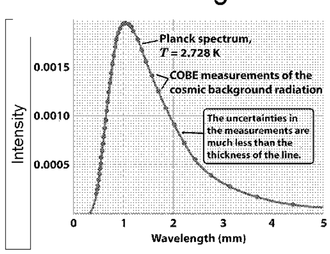


Astronomers observe the CMB from above the Earth's damp atmosphere with artificial satellites.



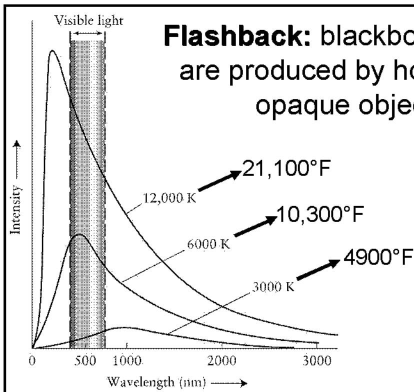


What do these orbiting satellites find?

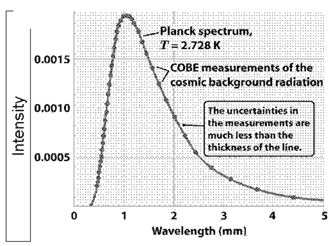


The Cosmic Microwave Background has a **blackbody** spectrum.

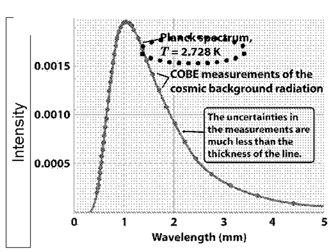
Flashback: blackbody spectra are produced by hot, dense, opaque objects.



Gosh! The universe (mostly transparent) is filled with nearly isotropic blackbody radiation (characteristic of opaque objects).



Double gosh! The temperature of the isotropic blackbody radiation is only **2.7 Kelvin**.



Key questions:

Why is the universe full of isotropic blackbody radiation (the CMB)?

Why is the temperature of the CMB so low?

Why is the universe full of isotropic blackbody radiation (the CMB)?

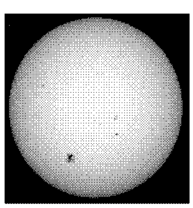
Let's suppose that the universe was **very hot** as well as **very dense** when it started expanding.

This hypothesis (hot, dense beginning) is called the **Hot Big Bang** model.

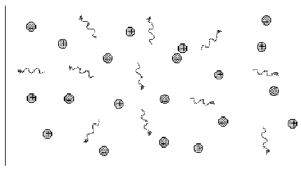
If the temperature of the early universe was $T > 3000$ K, then hydrogen was ionized.

Why does this matter?

Dense ionized gases are opaque. (You can't see through the Sun!)



Ionized gases are opaque because they contain free electrons that scatter photons of any energy.

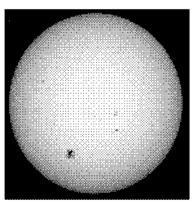


Photons (squiggles) don't move freely through space, because they collide with electrons (purple dots).

Why does it matter whether the early universe was opaque?

Hot, dense, opaque objects emit light!

Today, we call hot, dense, opaque objects that emit light "**stars**".

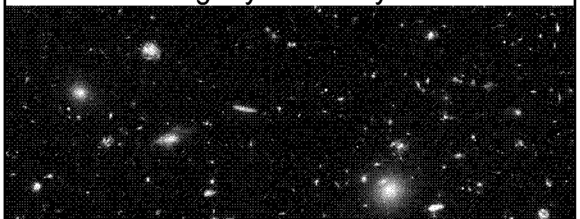


Soon after the Big Bang, the **entire universe** was glowing.

Imagine yourself **inside** a star, surrounded by a luminous, opaque "fog", equally bright in all directions.

Early universe was like that – sort of monotonous…

The universe is **NOT** opaque today. We can see galaxies billions of light-years away.



The universe is **NOT** uniformly glowing today. The night sky is dark, with a few glowing stars.

Gases cool as they expand.

(This accounts for the relative unpopularity of spray deodorants.)

As the hot, dense, ionized hydrogen expanded, it cooled.

When its temperature dropped below 3000 K, protons & electrons combined to form neutral H atoms.

The universe became transparent.

The universe became transparent at a temperature T ≈ 3000 K.

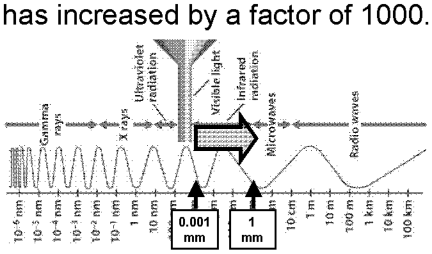
But…objects at T ≈ 3000 K produce **visible & infrared** light (think “lightbulb filament”), not **microwave** light.

Why is the temperature of the CMB so low?

How did its temperature drop from **3000 K** to **3 K**?

How did the cosmic background change from **visible & infrared** light ($\lambda \approx 0.001$ mm) to **microwave** light ($\lambda \approx 1$ mm)?

Wavelength of cosmic background light has increased by a factor of 1000.



Why? Because the universe has expanded by a factor of 1000 since the time it became transparent.

Flashback:

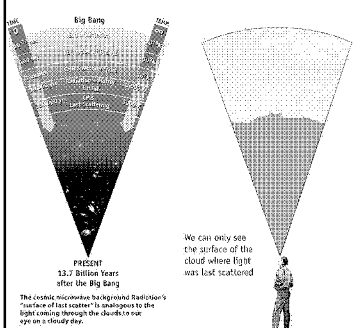
Wavelength of peak emission for a blackbody is **inversely** related to temperature.

$$\lambda_{\text{peak}} = \frac{2.9 \text{ millimeters}}{T}$$

$$\lambda_{\text{peak}} = \text{wavelength of maximum emission}$$
$$T = \text{temperature (Kelvin)}$$

Longer λ_{peak} implies smaller T.

The CMB has highest redshift of **anything** we can see ($z \approx 1000$).



When we look at the CMB, we look at the surface of the glowing "fog" that filled the early universe!

Wednesday's Lecture:

More Fun with Microwaves!

Reminders:

Have you read chapters 1 – 8 ?

Have you picked up your corrected problem sets and midterm?