When Radiation Ruled—24 Oct

- Homework 7 is due on Wed, not Mon.
- Picture of Penzias & Wilson’s equipment in Deutsches Museum, Munich, Germany (Thanks to Joel Adelsberg)

At present, radiation from the Big Bang is weak
- $T = 2.7$ K
- Has no affect on history of universe

In past, radiation from the Big Bang was
- Hot enough to change matter
- Denser than matter

Temperature and expansion
$$\frac{T}{T_{\text{now}}} = \frac{1}{a}$$
$$a = \frac{\text{Dist}}{\text{Dist}_{\text{now}}}$$

Expansion stretches wavelength of light

1. When the U was half the present size, what was the wavelength at the peak intensity?
   - A. 0.5 mm
   - B. 1 mm
   - C. 2 mm

2. What was the temperature of the radiation?
   - A. 1.3 K
   - B. 2.7 K
   - C. 5.4 K

Wavelength of radiation stretches by the same factor as the universe expands.

1. When the U was half the present size, what was the wavelength at the peak intensity? 0.5 mm
2. What was the temperature of the radiation? 5.4 K

Key idea: When the universe was smaller (when the distance between us and some object was smaller), the temperature was hotter.
Book-burning Universe

- Key idea: When the universe was smaller (when the distance between us and some object was smaller), the temperature was hotter. There is no obvious limit to the temperature.
- At one time, the universe was too hot to have paper. (Paper burns.)
  - Occurs at 451 F = 500 K.
  - (In reality, there was no carbon and no paper at that time.)
- Define the expansion parameter $a$ to be
  - $a = \frac{\text{distance between two objects}}{\text{present distance}}$
2. Hoag’s object is 300 Mpc from the Milky Way. How far was it when the universe was just hot enough to burn paper? A. 30 Mpc, $a = 1/10$, $T = 2.7 \times 10^3 K$
   B. 10 Mpc, $a = 1/30$
   C. 3 Mpc, $a = 1/100$
   D. 1 Mpc, $a = 1/300$

What other familiar things were not possible at one time? What other reactions might have occurred when the universe was smaller & hotter.

- U was too hot to have stars.
- U was too hot to have molecules.
- U was so hot that atoms were ionized.
- U was too hot to have nuclei other than hydrogen.

Other reactions:
- First stars formed
  - When U cooled enough, gravity was able to overcome pressure.
- Recombination: U changed from opaque to transparent
  - Ionization & recombination
  - Free $p + e \rightarrow$ hydrogen atom
- Production of the first nuclei other than H
  - Nuclear reaction
  - Free protons + neutrons $\rightarrow$ helium nucleus
Expansion parameter & redshift

- Expansion parameter
  \[ a = \text{distance between two galaxies} / \text{present distance} \]
  - The expansion parameter \( a \) changes from 0 at the Big Bang to 1 at the present.
- Universe expand the same as wavelength of light.

1. When the light that we see left galaxy 0140+326 RD1, its wavelength was 1215 Å (121.5nm). When the light that we see now left the galaxy, the expansion parameter of the universe was
   A. less than 1
   B. 1
   C. greater than 1.

   - We see its wavelength to be 7710Å.宇宙 expands by a factor of 6.35 since the time the light left that galaxy.
   - \[ a = \frac{1215}{7710} = \frac{1}{6.35} \]

   - Redshift \( z \)
     \[ z = 1/a - 1 \]
     Speed = \( z \times \text{speed of light} \) (for small \( z \))

   - For galaxy 0140+326 RD1,
     \[ z = \frac{7710}{1215} - 1 = 6.34 - 1 = 5.34 \]