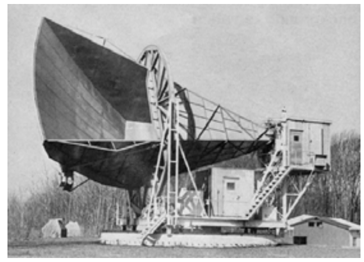
When Radiation Ruled—6 Nov

- 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

  $T / T_{now} = 1/a$

  $a = Dist / Dist_{now}$



Universe now

Universe at 3min

Matter: 0.1mg $T=0.8\times10^9$K

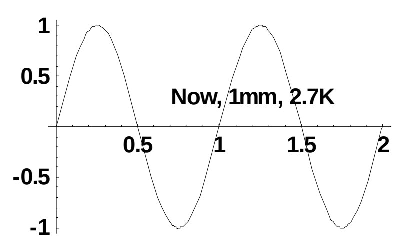
Rad: 0.6kg $T=0.8\times10^9$K

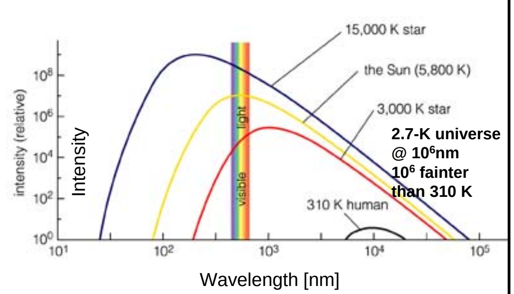
Expansion stretches wavelength of light

- We see black-body radiation with T=2.7 K, and wavelength at the peak intensity λ_{max}= 1 mm.

  λ_{max} = 2.7mm-K / T (Wein's Law)
- Principle: 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?
   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





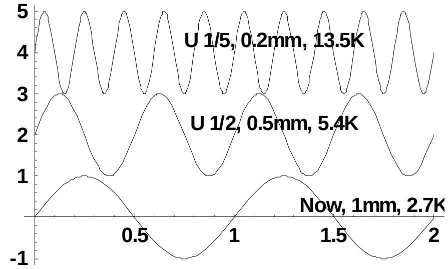
Expansion stretches wavelength of light and cools the radiation from the Big Bang

- Wavelength of radiation stretches by the same factor that the universe expands.

  λ_{max} = 2.7mm-K / T (Wein's Law)

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.

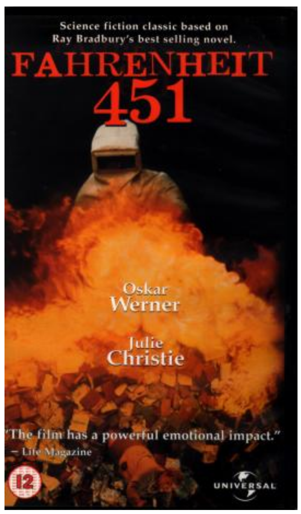


Book-burning Universe

- 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 at 451 F = 500 K.
  - In reality, there was no carbon and no paper at that time.
- Define the expansion parameter a

  a = (distance between two objects) / (present distance)
  - Two objects must be moving apart with the expansion of the universe.
  - a = 1/(1+z)

1. The value of the expansion parameter is
   - A. 1 at BB and 0 at present.
   - B. 1 at present and 0 at BB
   - C. 1 at both present time and at BB.
   - D. None of other answers are correct.



Book-burning Universe

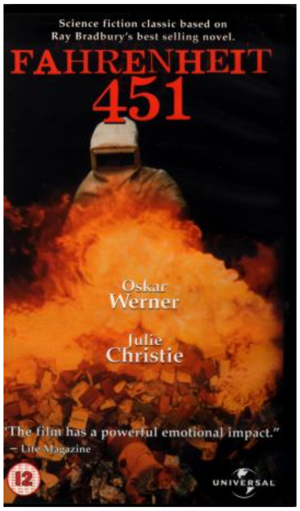
- Key idea: When the universe was smaller (when the distance between us and some object was smaller), the temperature was hotter. There is no obvious limit to the temperature.
- At one time, the universe was too hot to have paper.
  - Paper burns at 451 F = 500 K.
  - In reality, there was no carbon and no paper at that time.
- Define the expansion parameter a

  a = (distance between two objects) / (present distance)

  Two objects must be moving apart with the expansion of the universe.

1. The value of the expansion parameter is
   A. 1 at BB and 0 at present.
   B. 0 at present and 1 at BB
   C. 1 at both present time and at BB.
   D. None of other answers are correct.
2. Hoag's object is 300 Mpc from the Milky Way. How far was it when the U was just hot enough to burn paper?
   A. 30 Mpc, a=1/10, T=2.7 * 10 = 27K
   B. 10 Mpc, a=1/30
   C. 3 Mpc, a= 1/100
   D. 1 Mpc, a= 1/300

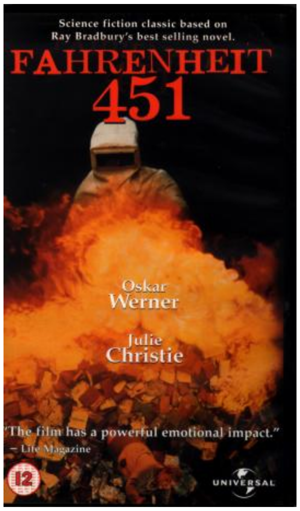
- We derived temperature T = 2.7K/a.



Book-burning Universe

- Key idea: When the universe was smaller (when the distance between us and some object was smaller), the temperature was hotter. <u>There is no obvious limit to the temperature.</u>
- At one time, the universe was too hot to have paper.

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

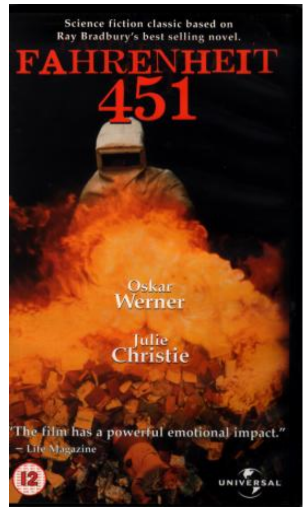


Book-burning Universe

- 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.

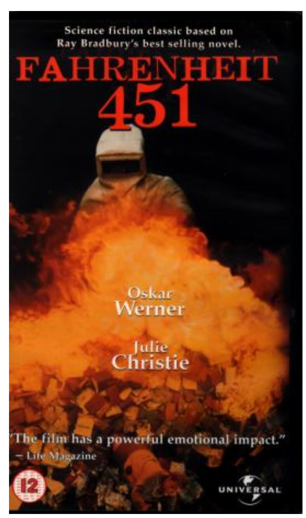
1. What other familiar things were not possible at one time? What other reactions might have occurred when the universe was smaller & hotter.

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



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.
- What other reactions might have occurred when the universe was smaller & hotter?
- Events in the universe's life
- 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 → hydrogen atom
- Production of the first nuclei other than H
  - Nuclear reaction
  - Free protons + neutrons → helium nucleus



How mass density changes

- Fill a 2-L bottle with an average of the present universe
- Matter
  - Mass = 2×10^{-27}kg
    - Same mass as hydrogen atom
- Radiation (Light) has mass because gravity pulls on radiation as if the mass is $m=E/c^2$.
  - A photon, a particle of light, has energy E
  - A photon generates gravity and pulls on

Matter: 2×10^{-27}kg
Rad: 4×10^{-32}kg

How mass density changes

5. The matter in the 2-L bottle used to occupy a smaller volume. When universe half the present size (a= ½), how much volume did the matter in the present-day 2-L bottle fill?
   A. Same
   B. ½
   C. ¼
   D. 1/8

Then

Matter: 2×10^{-27}kg
Rad: 4×10^{-32}kg

How mass density changes

Then

5. The matter in the 2-L bottle used to occupy a smaller volume. When universe half the present size (a= ½), how much volume did the matter in the present-day 2-L bottle fill?
   A. Same
   B. ½
   C. ¼
   D. 1/8

- Mass density = mass/volume.
- The mass density of matter changes as $\rho=a^{-3}$.
- The mass density of radiation changes as $\rho=a^{-4}$. There is a extra factor of a because the wavelength (and energy) of radiation changes as universe expands.

Matter: 2×10^{-27}kg
Rad: 4×10^{-32}kg

How mass density changes

Then

- Mass density = mass/volume.
- The mass density of matter changes as $\rho=a^{-3}$.
- The mass density of radiation changes as $\rho=a^{-4}$.

Matter: 0.1mg
$T=0.8\times10^{9}$K

Rad: 0.6kg
$T=0.8\times10^{9}$K

Universe at 3min

Matter: 2×10^{-27}kg
Rad: 4×10^{-32}kg

Summarizing questions

- Your parents ask, “Why does the universe cool?”
- What are 4 important things that did not exist when the universe was younger?
- Why did a 2-L bottle of the U have so much mass when the U was 3min old? Why did radiation have more mass than matter?