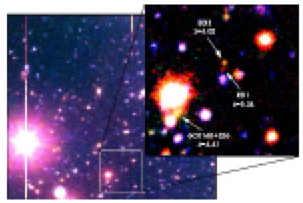
When Radiation Ruled—31 Oct

- Mass of radiation was more than mass of matter at early times
  - Stars & galaxies cannot form because of pressure of radiation.
  - Like trying to make a ball of light collapse.
- Recombination: when matter became free.



Galaxy 0140+326 RD1 at z=5.35 or a=1/6.35
http://antwrp.gsfc.nasa.gov/apod/ap980324.html

How mass density of radiation changes

Then

- Mass of radiation = 4×10^{-32}kg
  - Same mass as 1/50,000 hydrogen atom
- Mass density of matter changes as
  - $\rho = \rho_{now}\, a^{-3}$
  - One power for each dimension
- Photons have mass
  - $E = m c^2$
  - Energy of a photon is proportional to temperature

1. (2 pts.) The radiation in the 2-L bottle used to occupy a smaller volume. When universe half the present size, how much volume did the radiation in the 2-L bottle fill? The mass density at that time was ___ that of the present mass density.

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

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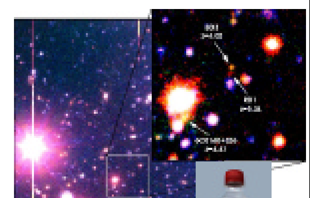
- Mass of a photon decreases as universe expands
  - $E = m c^2$.
  - Mass $\propto$ E $\propto$ T $\propto$ $1/\lambda$ (Wien)
- Mass density of radiation changes as
  - $\rho = \rho_{now}\, a^{-4}$
  - One power for each dimension and one power for mass

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

Mass density of matter & radiation

- In a 2-L bottle
  - Mass of radiation = 4×10^{-32}kg
  - Same mass as 1/50,000 hydrogen atom
  - Mass of matter = 2×10^{-27}kg
  - Same mass as 1 hydrogen atom
- Mass density changes as
  - $\rho = \rho_{now}\, a^{-3}$ for matter
  - $\rho = \rho_{now}\, a^{-4}$ for radiation
- When the light that we see left Galaxy 0140+326 RD1, its wavelength was 1215 Å (121.5nm). We see its wavelength to be 7710Å. U has expanded by a factor of 6.35 since the time the light left that galaxy. a=1/6.35 when light left galaxy.

2. (2 pts.) How much greater was the mass of the matter in 2LB when LLG? How much greater was the mass of radiation…?



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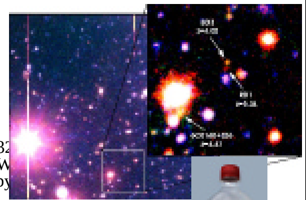
- Radiation dominated matter when U was young
  - $M_{matter} = 6.35^3$=260
  - $M_{rad} = 6.35^4$ =260*6.35 =1600
  - At a=1/6.35, radiation gains by a factor of 6.35.
  - When a=1/50,000, mass of radiation matched mass of matter.



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Pressure of radiation

- Can a star or galaxy form? Battle: Pressure vs. gravity
  - If gravity wins, star of galaxy forms.
  - If pressure wind, no star, no galaxy.
- Pressure on a balloon comes from gas particles hitting balloon and transferring momentum.
  - Interpret PV=nRT as P=n/V RT = number density× mass × speed²
  - P = mass density × speed².
- Pressure of radiation dominates when mass density of matter & radiation are close.
  - For matter (H atoms) at 3000K, v=6 km/s.
  - For radiation v=300,000 km/s.
  - Pressure of radiation is bigger by $(300{,}000/6)^2=2.5\times10^9$.
- How can star form?
  - When matter no longer interacts with radiation
  - p + e → hydrogen atom

When stars and galaxies form

- Pressure of radiation is bigger by 2.5×10^9.
- How can star form?
- When matter was ionized
  - Gravity pulls matter together; ionized electrons hit radiation and get pushed back apart.
- After recombination (at a=1/1200.)
  - p + e → hydrogen atom

3. Modify the statement “Gravity pulls matter together; ionized electrons hit radiation and get pushed back apart.” so that it applies to the universe after recombination.

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- When matter was ionized
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- After recombination (at a=1/1200.)
  - p + e → hydrogen atom
- After recombination: Gravity pulls matter together; without ionized electrons to hit, radiation does not exert pressure on matter. Pressure drops by a factor of 10^{11}.
- Gravity wins and pulls more. Stars and galaxies form.