Blackbody radiation
Applications to astronomy / astrophysics

Max Plank
1858-1947
Nobel Prize Physics 1918
• Known since centuries that **when a material is heated, it radiates heat and its color depends on its temperature**

• Example: heating elements of a stove:
  – Dark red: 550°C
  – Bright red: 700°C
  – Then: orange, yellow and finally white (really hot !)

• The emission spectrum depends on the material

• Theoretical description: simplifications necessary

  ➔ **Blackbody**

 Thermal images taken before and after the zombie apocalypse
A material is constantly exchanging heat with its surrounding (to remain at a constant temperature):
- It absorbs and emits radiations
- Problem: it can reflect incoming radiations, which makes a theoretical description more difficult (depends on the environment)

A blackbody is a perfect absorber:
- Incoming radiations is totally absorbed and none is reflected

- Blackbody = a cavity, such as a metal box with a small hole drilled into it.
  - Incoming radiations entering the hole keep bouncing around inside the box with a negligible chance of escaping again through the hole → Absorbed.
  - The hole is the perfect absorber, e.g. the blackbody
    - Radiation emission does not depend on the material the box is made of → Universal in nature
Blackbody radiation

The graph shows the relative intensity of blackbody radiation as a function of wavelength for different temperatures. The peak wavelength, $\lambda_{\text{max}}$, shifts to shorter wavelengths as the temperature increases. The curves represent temperatures of 900 K, 1200 K, 1500 K, and 1800 K.
• The intensity $I(\lambda, T)$ is the total power radiated per unit area per unit wavelength at a given temperature

• **Wien’s displacement law:** The maximum of the distribution shifts to smaller wavelengths as the temperature is increased.

$$\lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{ m} \cdot \text{K}$$

Originally an empirical formula
Wilhem Wien – Nobel Prize (Physics) 1911

Visible light: 400 – 700 nm
Ultra-violet: <400 nm
Infrared: >700 nm
Exercise - blackbody

- Dominant color of a blackbody at:
  - $T=4000^\circ C$ \( \lambda = 678 \text{ nm} \) RED
  - $T=5000^\circ C$ \( \lambda = 549 \text{ nm} \) GREEN
  - $T=6000^\circ C$ \( \lambda = 461 \text{ nm} \) BLUE
The total power radiated per unit area increases with the temperature:

$$R(T) = \int_0^\infty \mathcal{L}(\lambda, T) d\lambda = \varepsilon \sigma T^4$$

This is known as the Stefan-Boltzmann law, with the constant $\sigma$ experimentally measured to be $5.6705 \times 10^{-8}$ W / (m$^2$ · K$^4$).

The emissivity $\varepsilon$ ($\varepsilon = 1$ for an idealized blackbody) is simply the ratio of the emissive power of an object to that of an ideal blackbody and is always less than 1.
Power radiated at a given frequency for a given blackbody temperature:

\[ I(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \]

Planck’s radiation law

Quantum theory needed!
Why is blackbody radiation relevant to astronomy & astrophysics?

• A blackbody is a perfect absorber: incoming radiations is totally absorbed and none is reflected.

• The Sun (and any other stars) can be approximated to a Black Body:
  • Almost a perfect absorber
  • (Near) thermal equilibrium

At the top of the atmosphere
CLASSIFICATION:

TEMPERATURE (K):

Hertzsprung-Russell (H-R) diagram
Luminosity vs temperature

Luminosity: \[ L = 4\pi R^2 \sigma T^4 \]

where
- \( R \) the radius of the star
- \( T \) the temperature of the star
- \( \sigma \) the Stefan-Boltzmann constant (\( \sigma = 5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4} \))
The Cosmic Microwave Background (CMB)

- The CMB suggests that, at some point, the Universe was extremely dense and hot, and filled with radiation in THERMAL EQUILIBRIUM = Blackbody.
- After the “time of last scattering” (T~3000K - when the universe becomes transparent to radiation), the radiation “cools off” (redshift) due to the expansion of the Universe (now: T~2.728K)
A black hole may well be the perfect absorber. Famous astrophysicist Stephen Hawking suggests that a black hole can radiate energy with a thermal spectrum due to quantum effects (Hawking radiation). Let's consider a black hole as a sphere with a radius of 30km radiating $8.8 \times 10^{-31}$ W of such thermal radiation. What would be the temperature of this black hole (in K)? [Hint: remember that the power is radiated from the surface of the black hole].