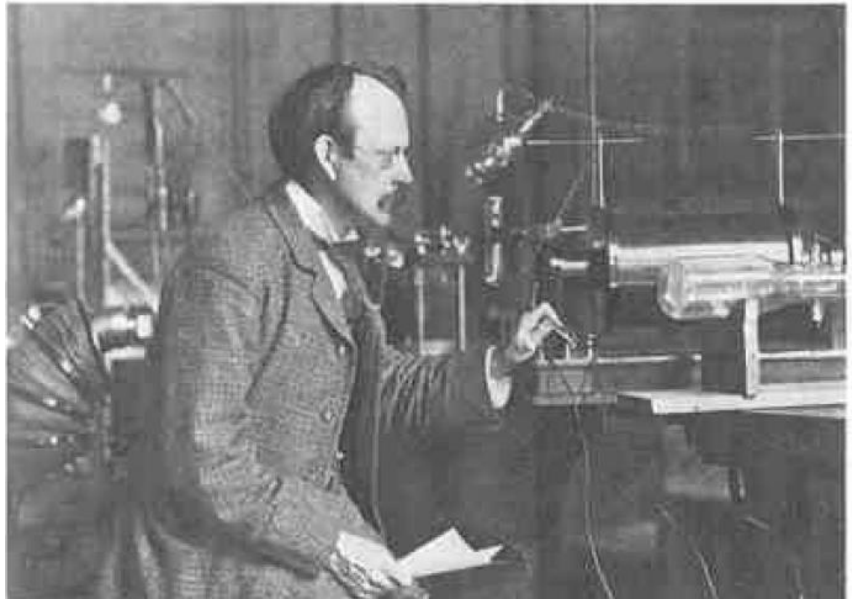
Chapter 3

Quantization of Charge, Light, and Energy

Discovery of the Electrons



- J. J. Thomson in 1897. Before that, people already know “charge” and “current”. Also, scientists know “cathode” could emit “cathode rays” and they are negative electric charge.

Cathode rays in magnetic field

$$\vec{F} = q\vec{v} \times \vec{B}$$

In circular motion

$$F = qvB = ma = m\frac{v^2}{R}$$

$$\frac{q}{m} = \frac{v}{RB}$$

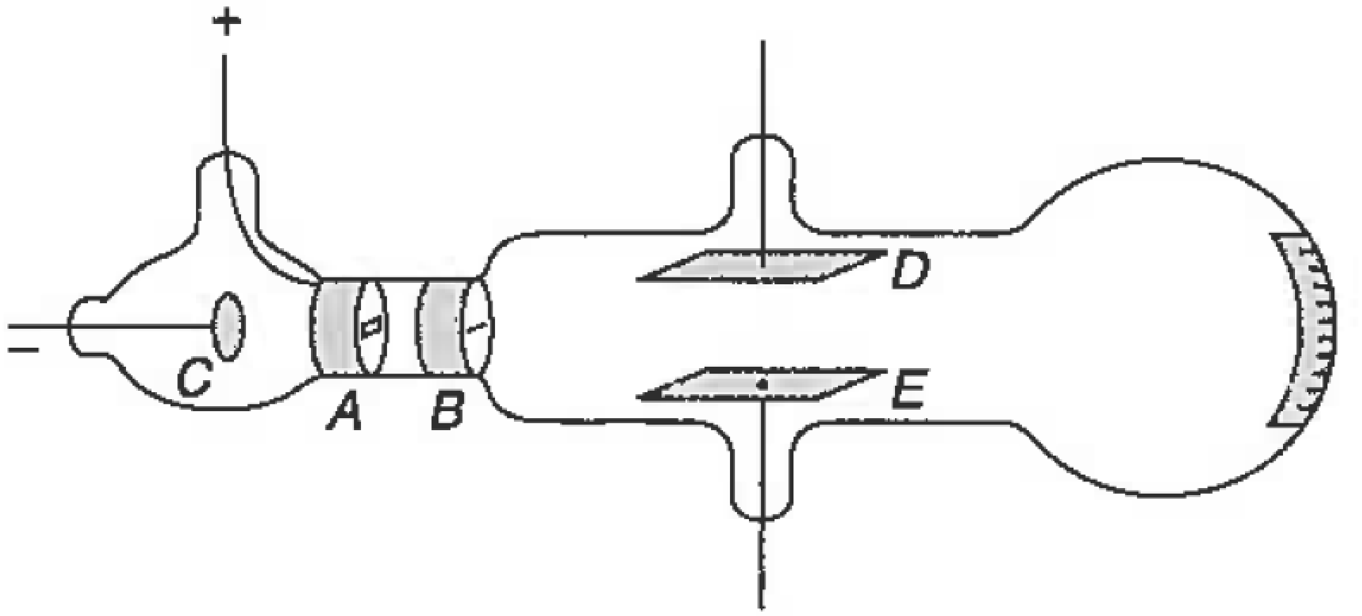
Discovery of the Electrons (1897)

Make the particles move straight by adjusting E and B

$$\vec{F}_{tot} = \vec{F}_E + \vec{F}_B = 0$$

$$qE = qvB$$

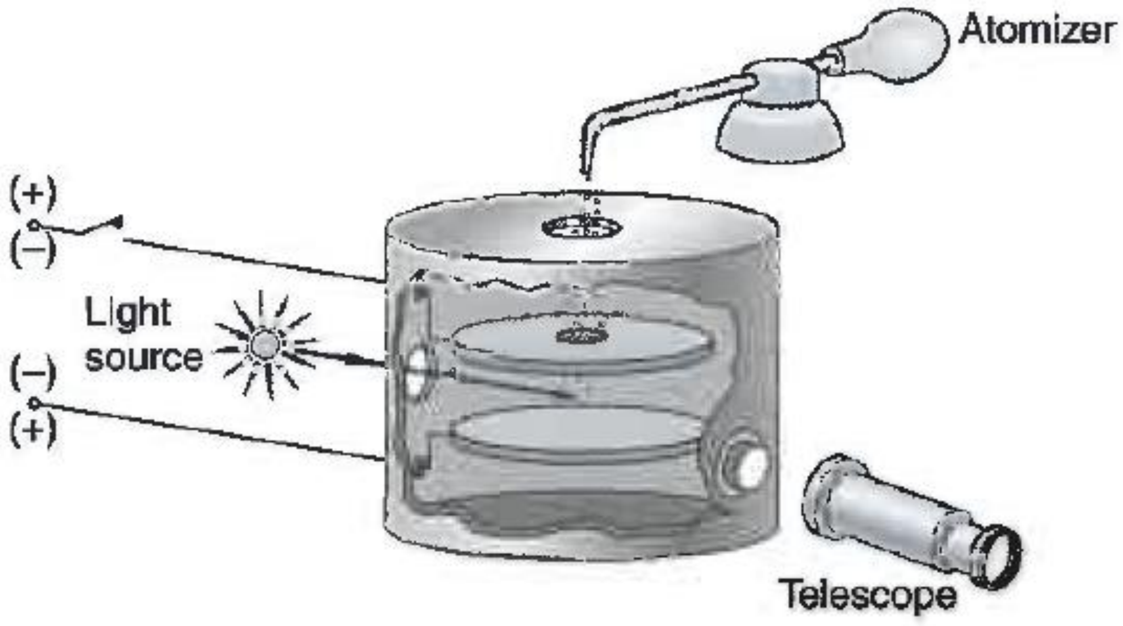
$$v = \frac{E}{B}$$



$$\frac{q}{m} = 0.7 \times 10^{11} C/kg$$

Millikan's Experiment (1909): Measuring the Electric Charge

- Use oil spray. The oil droplets are charged due to the friction before coming out of the nozzle.
- The droplets are in the electric field produced by capacitor.
- The motion of the droplets were measured and the charge were found to be always in integer multiples of a fundamental unit, e.

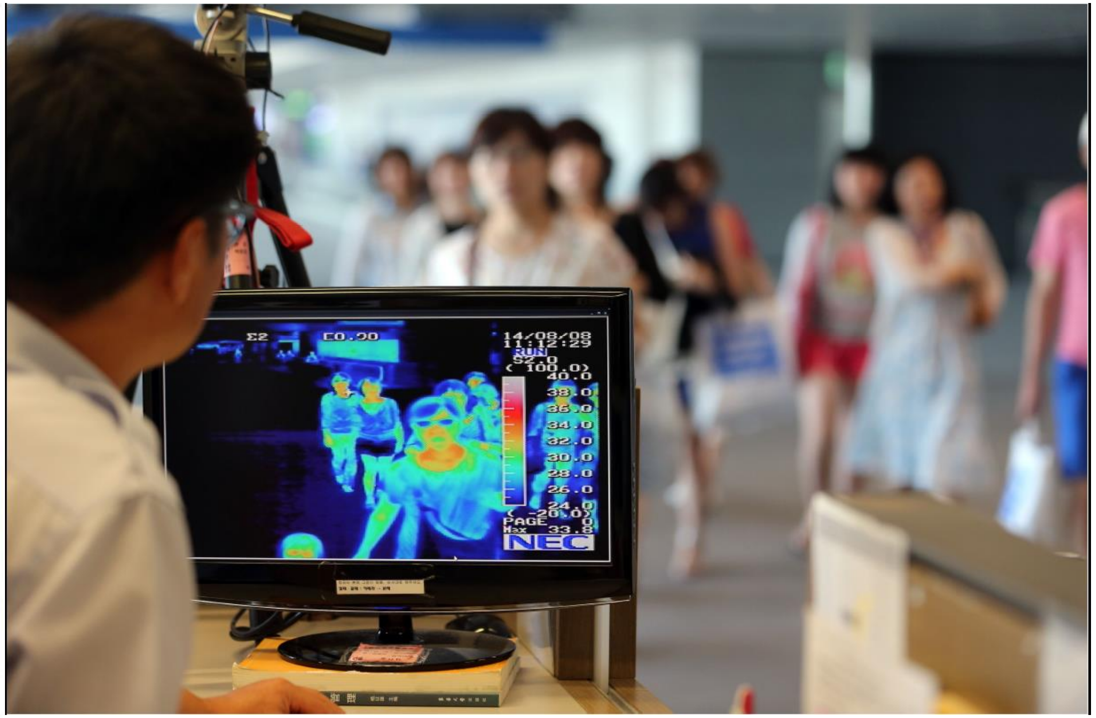


$$e = 1.601 \times 10^{-19} C$$

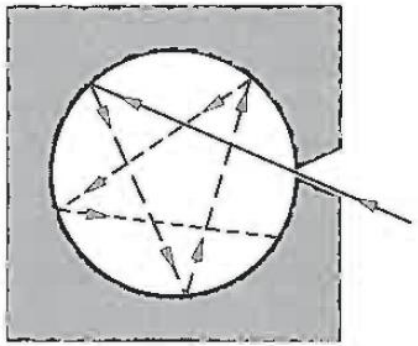
$$e = 1.60217653 \times 10^{-19} C$$

Thermal Radiation

Temperatupa, °C	Color
550	
630	
680	
740	
770	
800	
850	
900	
950	
1000	
1100	
1200	
1300	



Blackbody Radiation



- A body that absorbs all radiation incident on it is called an “ideal blackbody”.

Stefan-Boltzmann Law (1879) $R = \sigma T^4$ $\sigma = 5.6703 \times 10^{-8} W/m^2K^4$

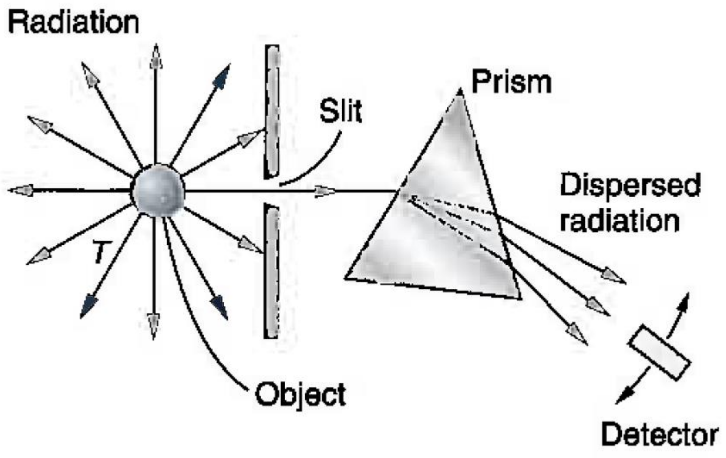
Radiation power

- Object not ideal blackbodies:

$$R = \epsilon\sigma T^4$$

Emissivity, always less than 1.

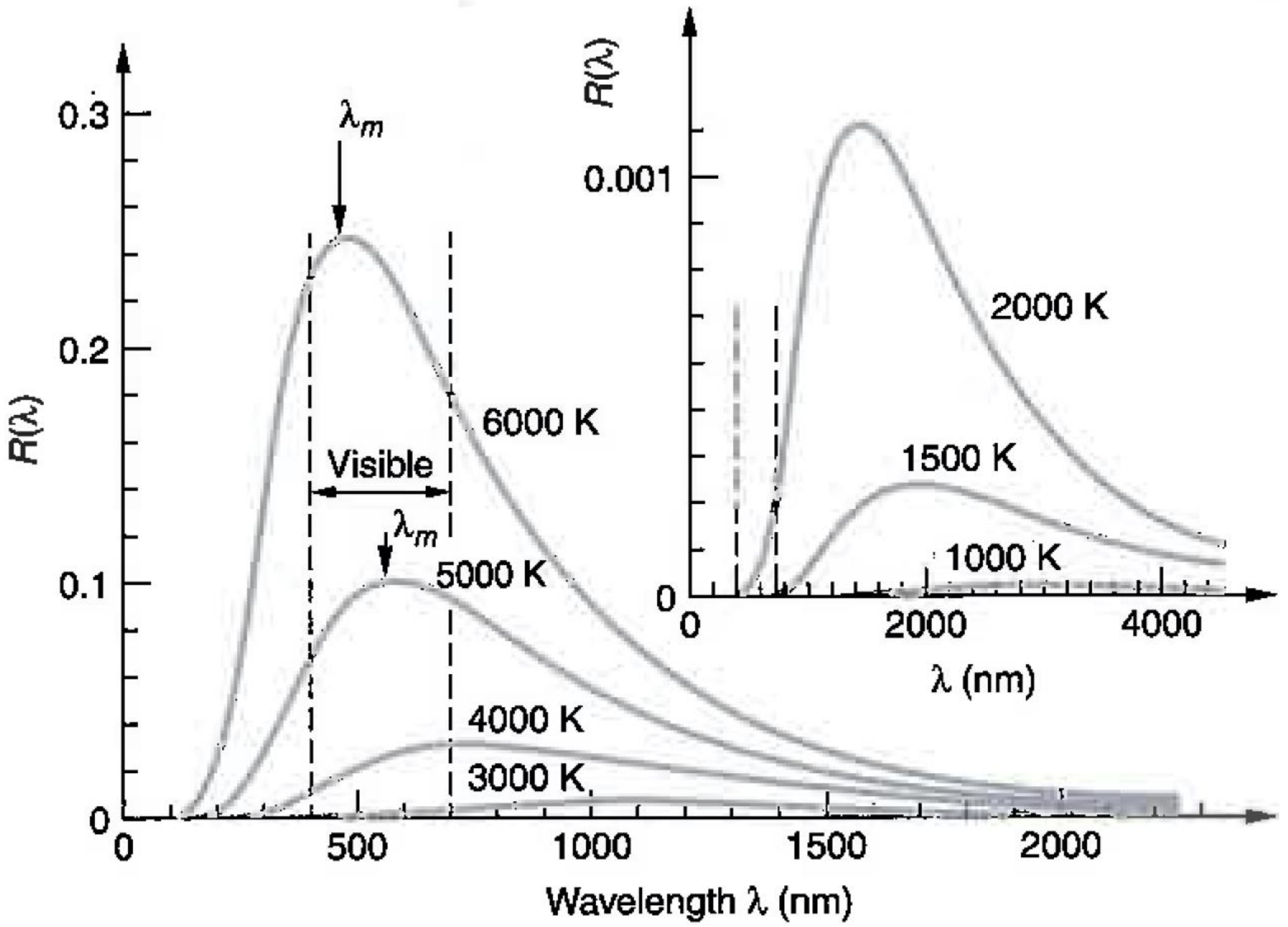
Blackbody Radiation Spectrum



$$\lambda_m \propto \frac{1}{T}$$

or

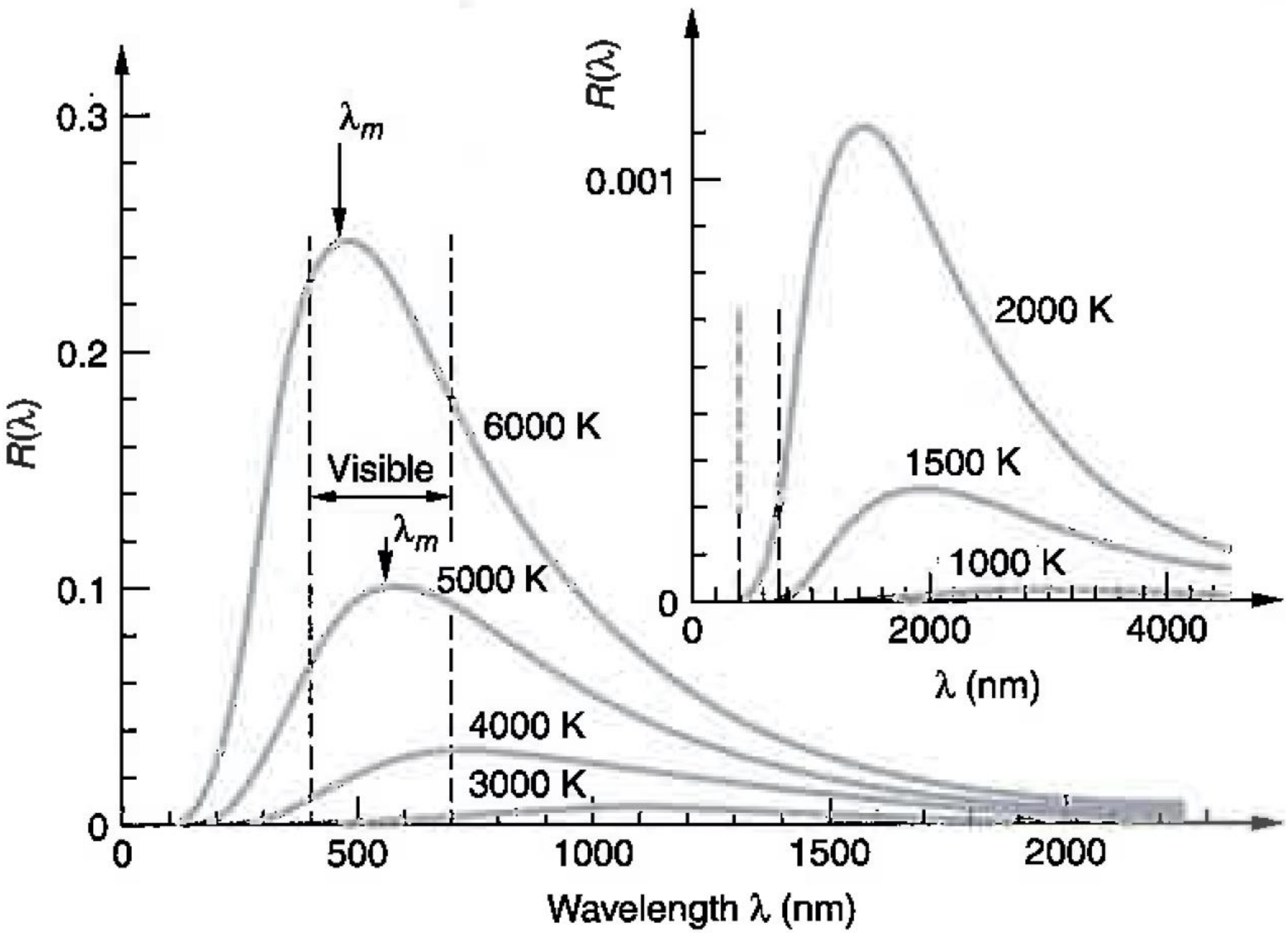
$$\lambda_m T = 2.898 \times 10^{-3} m \cdot K$$



Example

- Measurement of $R(\lambda)$ from a certain star shows the $\lambda_m = 950\ nm$. If the star is also found to radiate 100 times the power $P_\odot$ radiated by the Sun, how big is the star? (The symbol ⊙ = Sun) The Sun's surface temperature is 5800 K. Express the answer as how many times of Sun's radius, $r_\odot$. Hint: you may need to find the surface temperature of the star. Hint #2: power, P, is the total energy radiated per unit time; while R (in Stefan-Boltzmann Law) is the power radiated per unit area.

How to understand this?



Classical Kinetic Theory – Rayleigh-Jeans Equation

$$R(u) \propto u(\lambda)$$

Energy density due to E&M wave

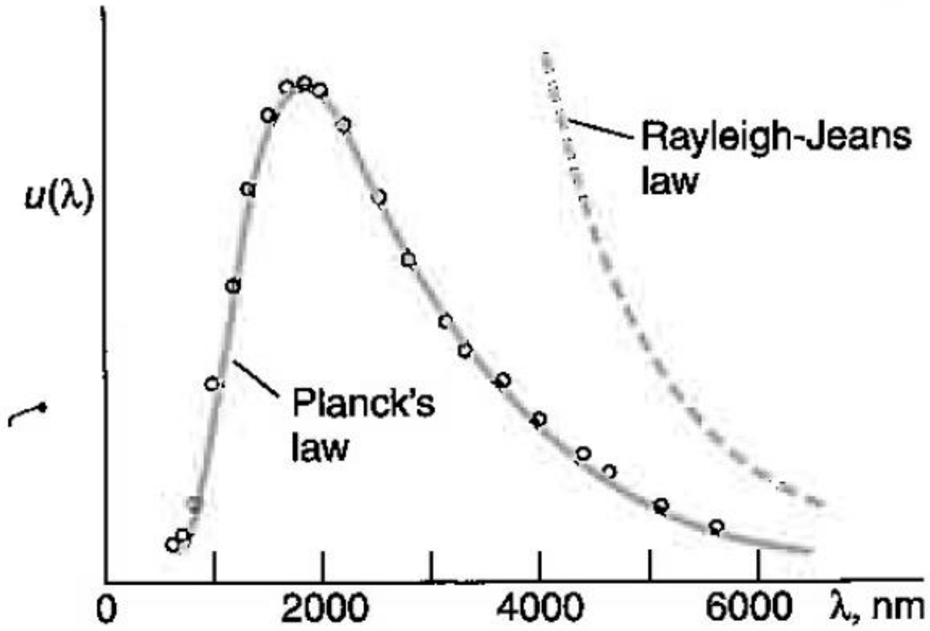
$$u(\lambda) = \bar{E}n(\lambda)$$

Average energy per mode   Number of modes per unit volume

$$n(\lambda) = 8\pi\lambda^{-4}$$

$$\bar{E} = kT$$

$$u(\lambda) = kT8\pi\lambda^{-4}$$



Planck's Law

Average Energy in Classical Kinetic Theory

$$\bar{E} = \int_0^\infty E f(E) dE \qquad 1 = \int_0^\infty f(E) dE$$

Probability function (distribution function)

$$f(E) = Ae^{-E/kT}$$ Maxwell-Boltzmann distribution function ⇒ $$\bar{E} = kT$$

Planck's assumption:

$$E_n = n\epsilon = nhf \qquad n = 0,1,2,\ldots$$

$$\bar{E} = \sum_{n=0}^{\infty} E_n f(E_n) \qquad 1 = \sum_{n=0}^{\infty} f(E_n) \qquad \bar{E} = \frac{hc/\lambda}{e^{hc/\lambda kT} - 1}$$

Planck's Law

$$u(\lambda) = \bar{E}n(\lambda)$$

$$n(\lambda) = 8\pi\lambda^{-4}$$

$$\bar{E} = \frac{hc/\lambda}{e^{hc/\lambda kT} - 1}$$

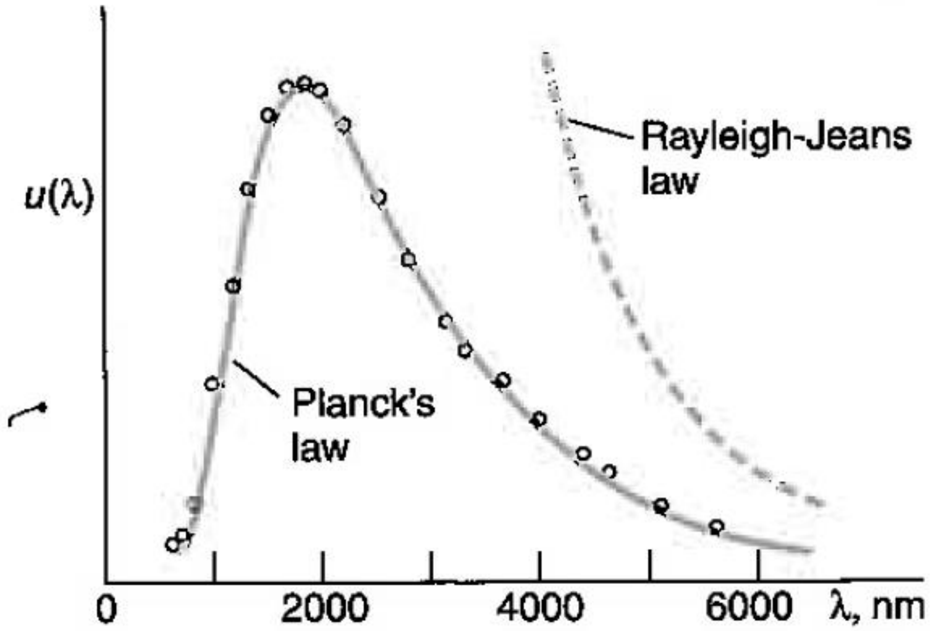
$$u(\lambda) = \frac{hc/\lambda}{e^{hc/\lambda kT} - 1} 8\pi\lambda^{-4} = \frac{8\pi hc/\lambda^5}{e^{hc/\lambda kT} - 1}$$

For large λ

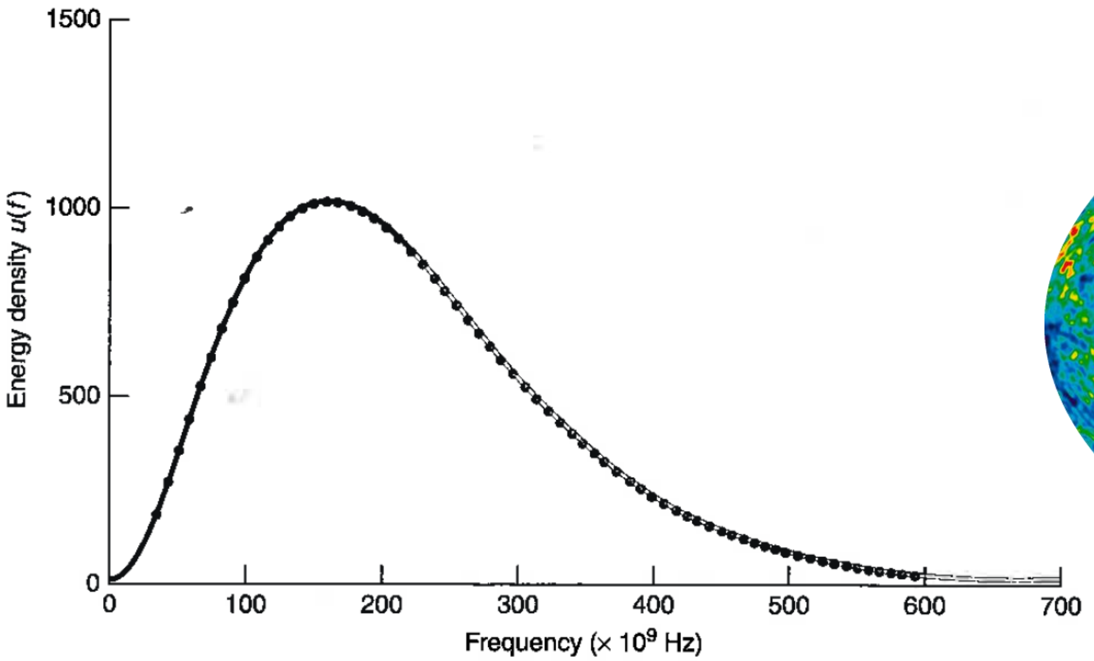
$$u(\lambda) = kT 8\pi\lambda^{-4}$$

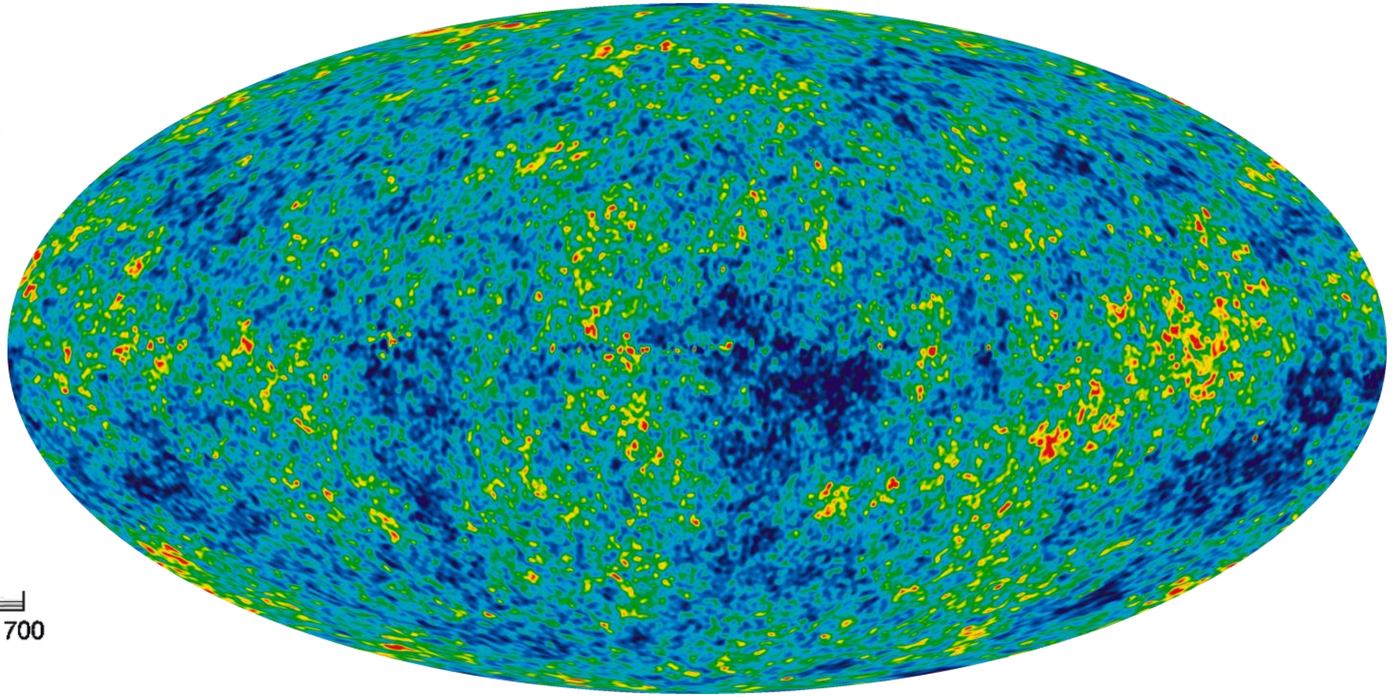
Rayleigh-Jeans Equation

$$h = 6.626 \times 10^{-34} J \cdot s$$



Cosmic microwave background radiation





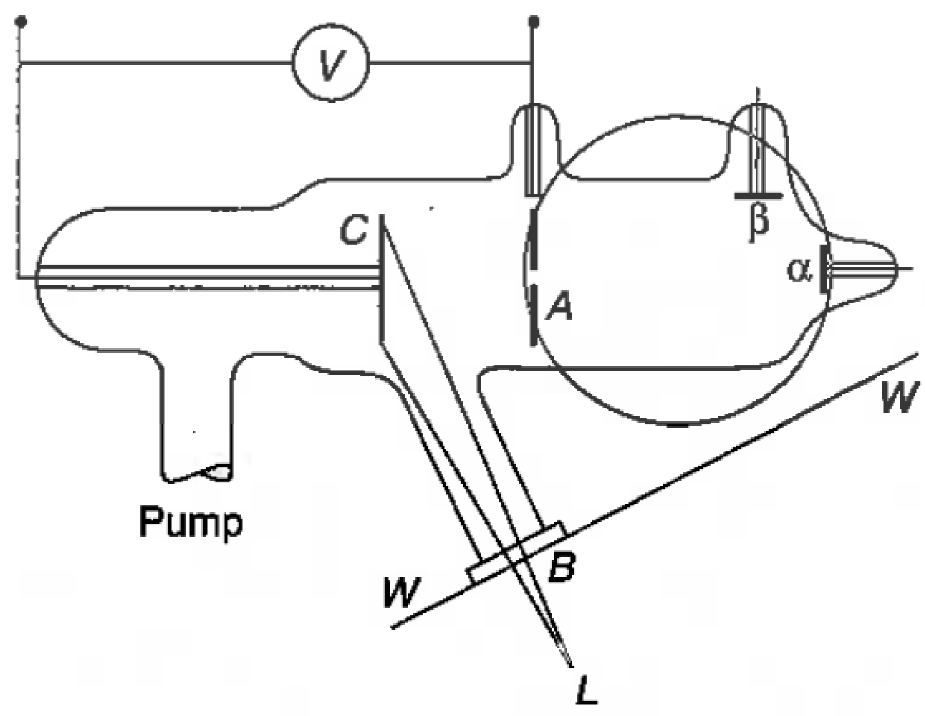
T = 2.725 K

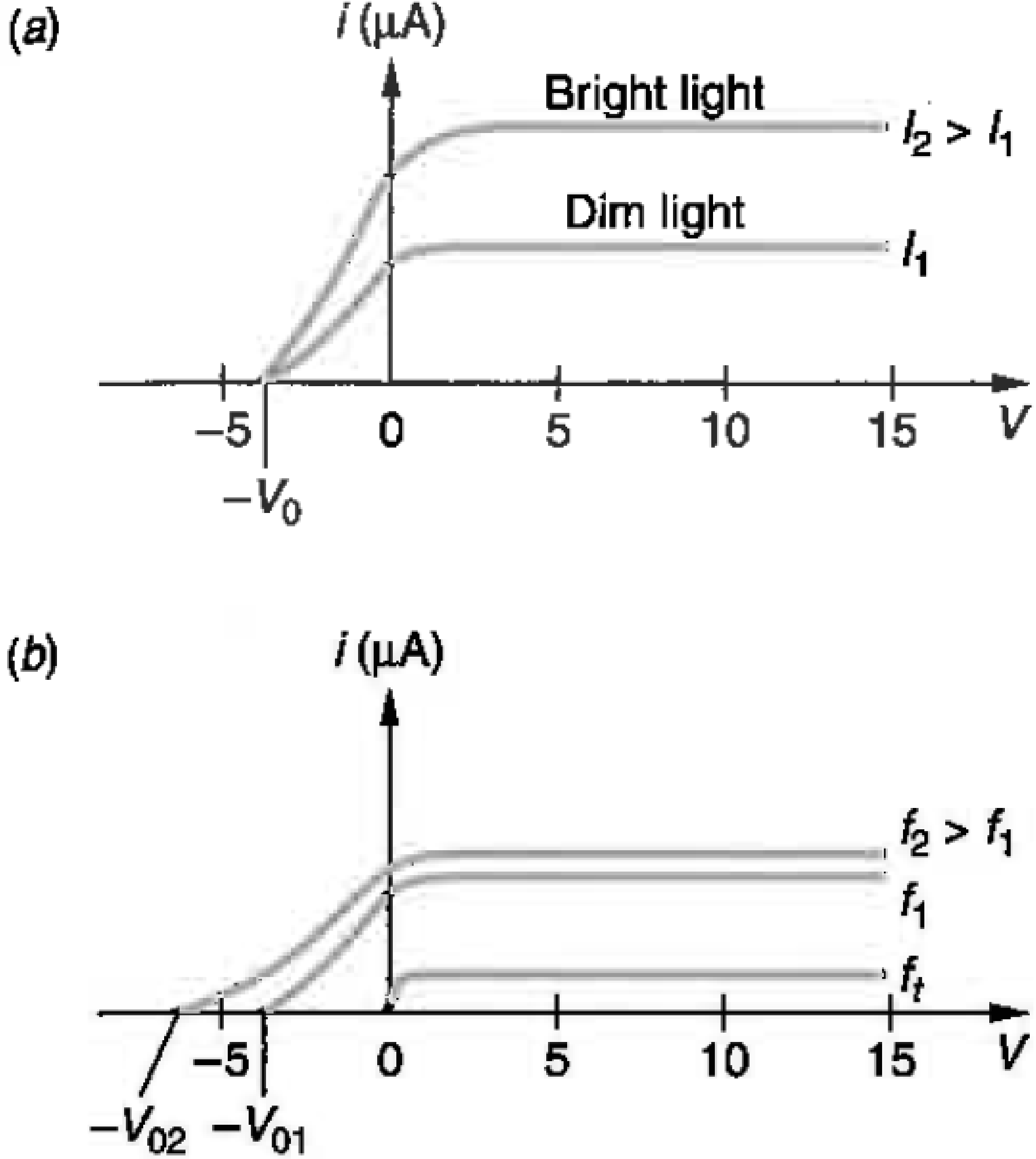
All-sky map of the CMB, created from 9 years of WMAP data.

Example

- With the energy density per volume, $u(\lambda)$, calculated by Planck, find the temperature dependence of the total energy density, U.

Photoelectric effect



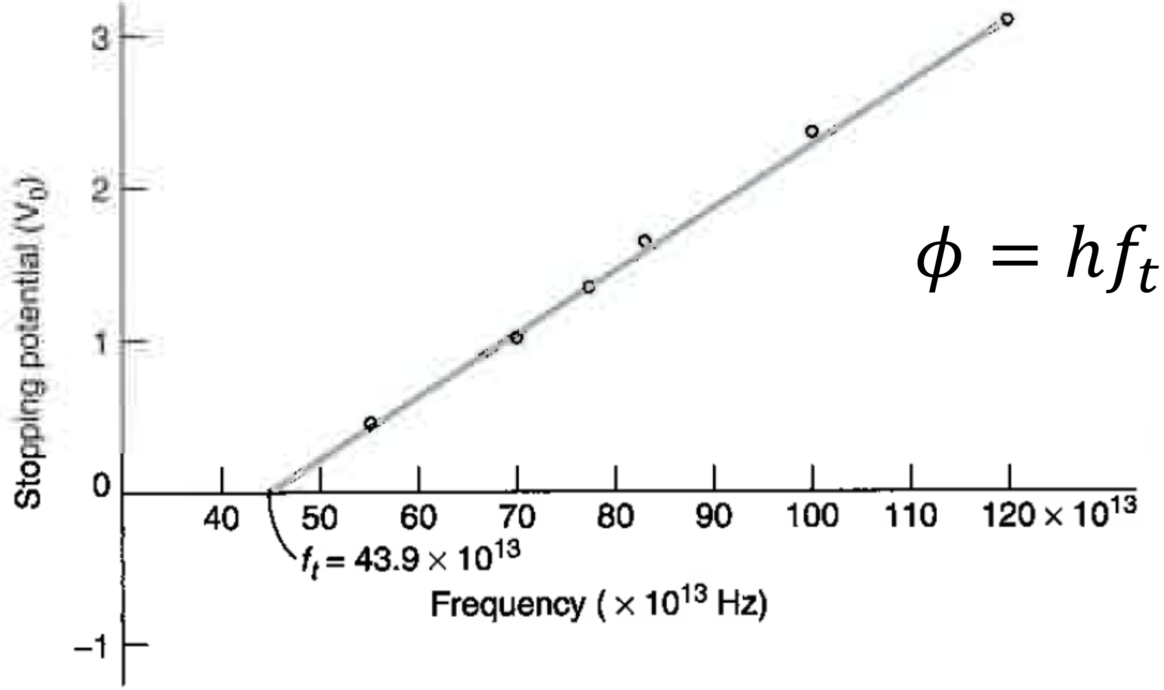


- Stopping voltage infers to the maximum kinetic energy of electrons
- Higher current infers to more electrons reached the electrode.

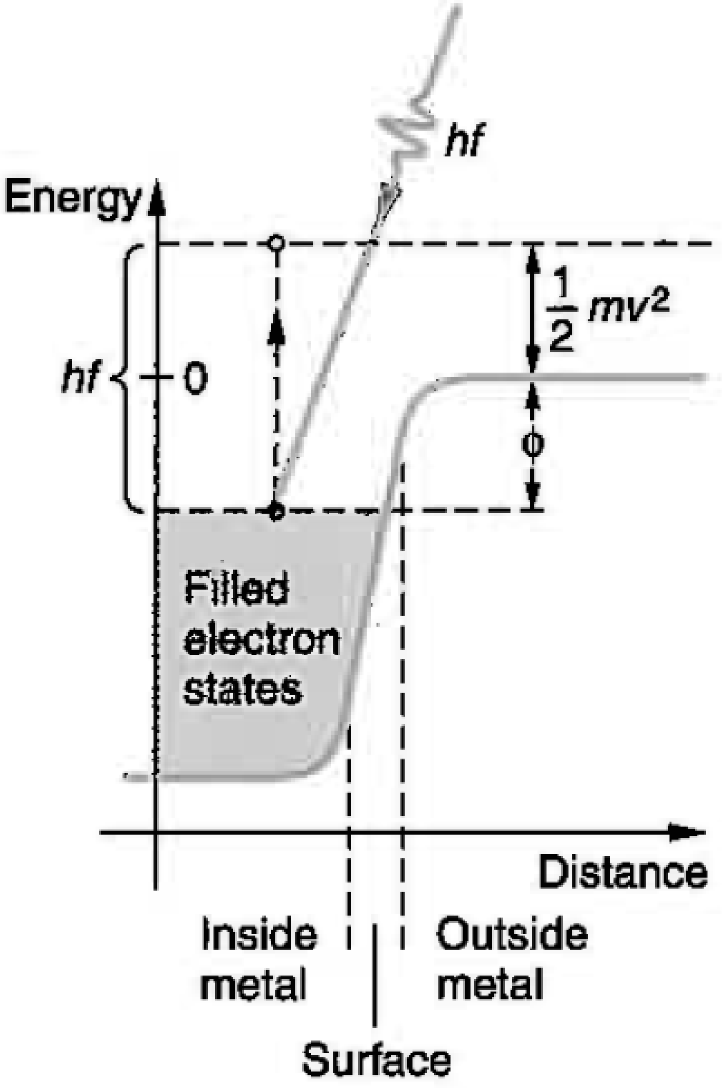
Einstein's Photoelectric effect theory

$$E_{k,max} = eV_0 = hf - \phi$$

ϕ is the "workfunction" of the material. See table 3-1 on page 134



$$\phi = hf_t = \frac{hc}{\lambda_t}$$

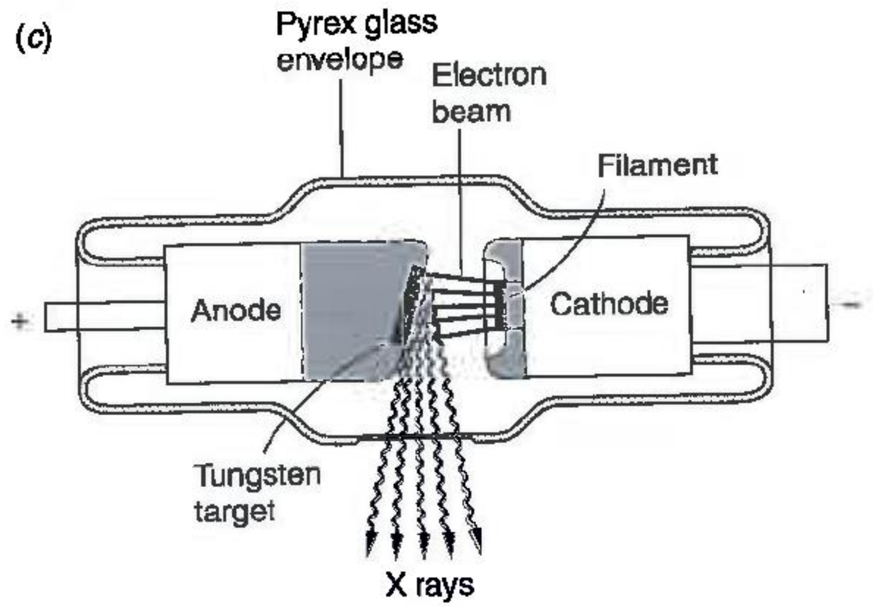


Example

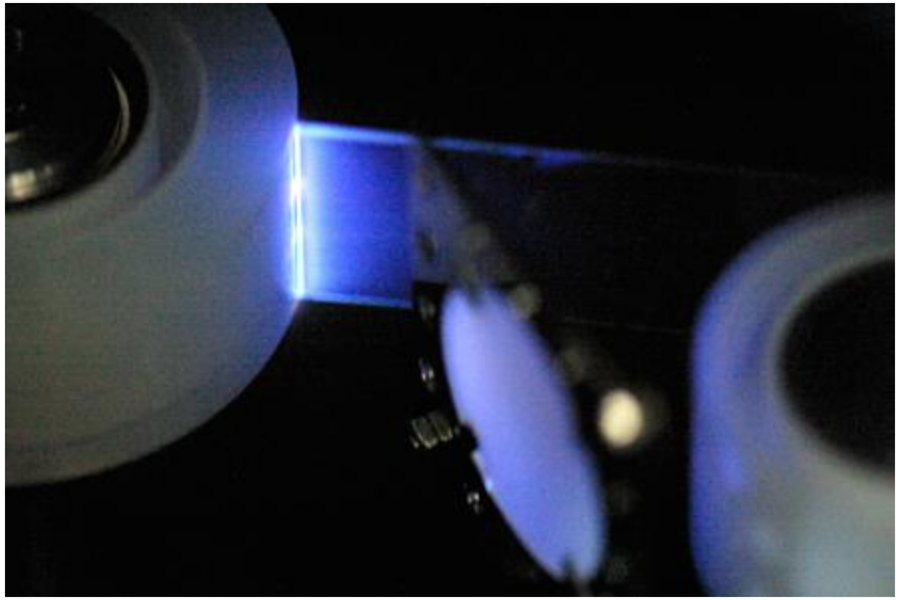
- Use the table 3-1, fine the threshold wavelength of sodium (Na). What is the stopping voltage when light of 400 nm is incident on sodium (Na)?

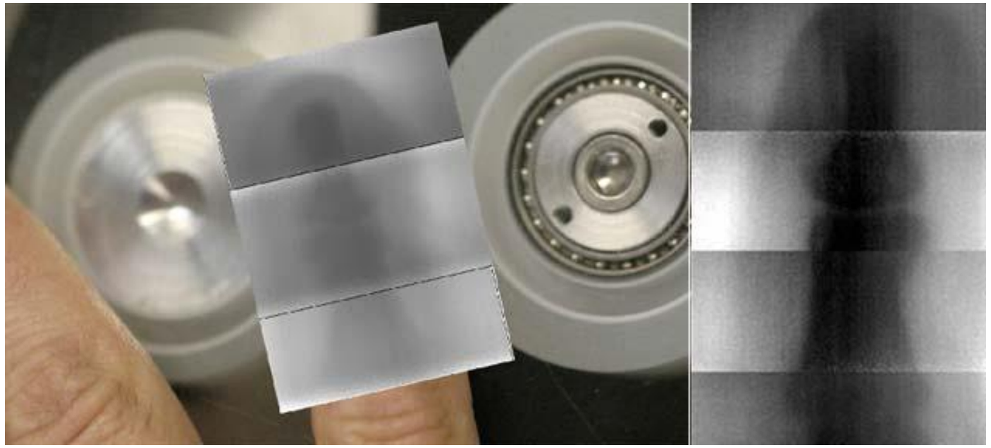
- For a light with wavelength of 400 nm, and intensity of 0.01 W/m^2, how many photons are incident per second per square meter on to a surface.

X-ray



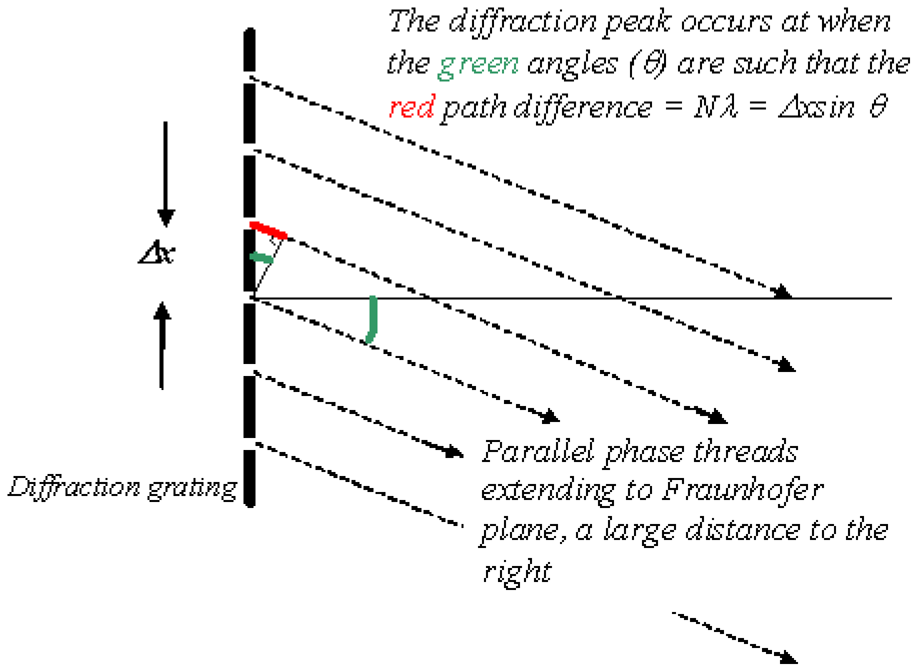
1895





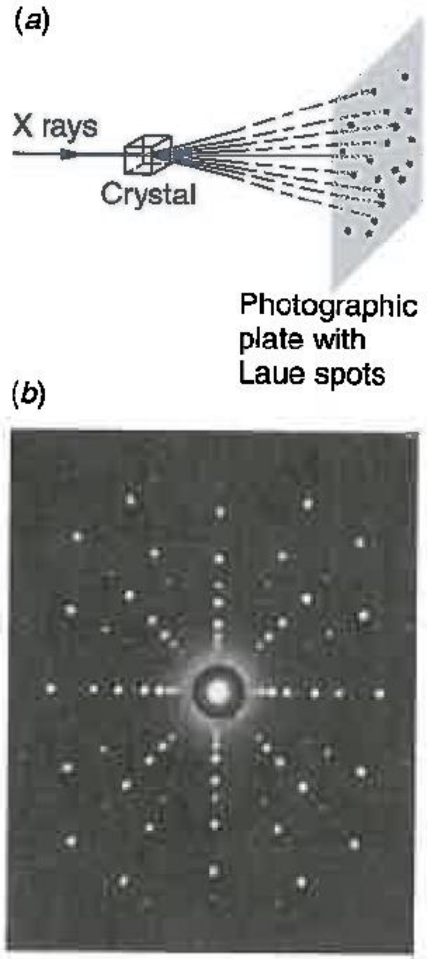
2008

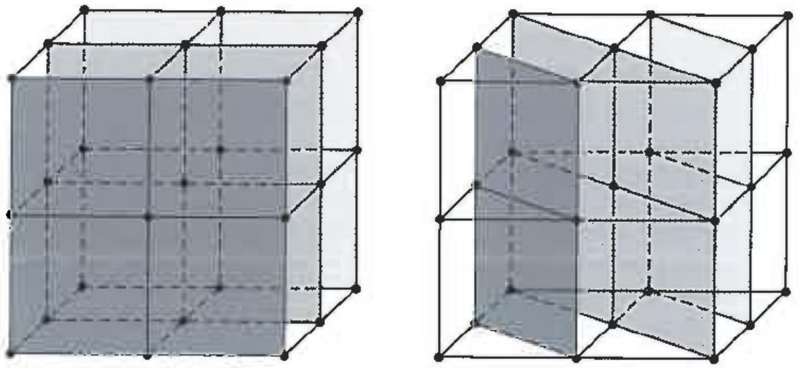
X-ray



$$2dsin\theta = n\lambda$$

Wavelength of the light has to be comparable to the slit distance (scattering source distance).

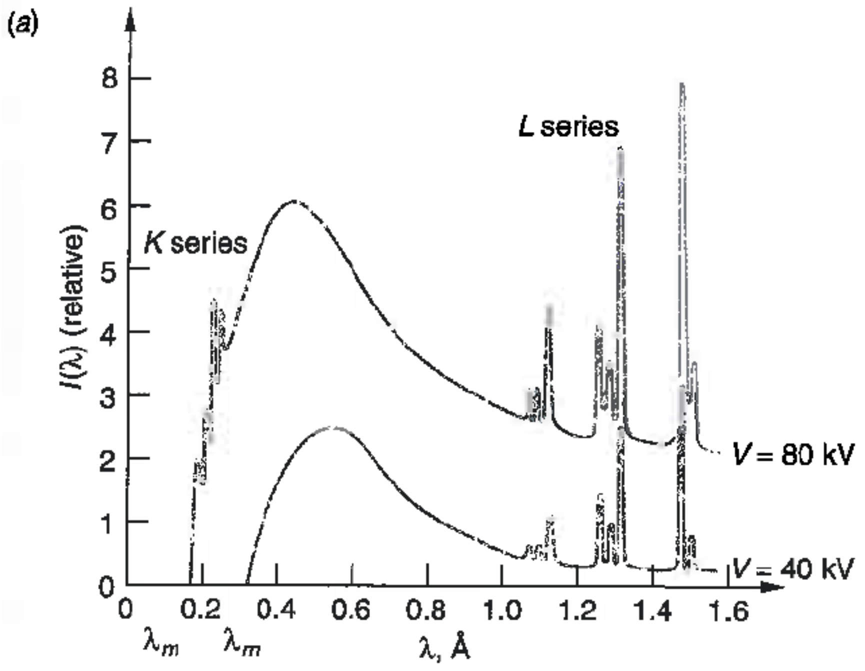


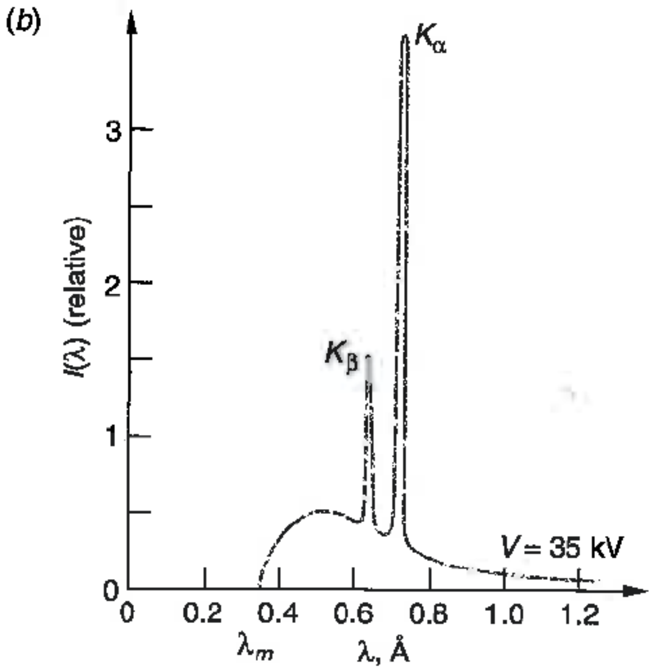


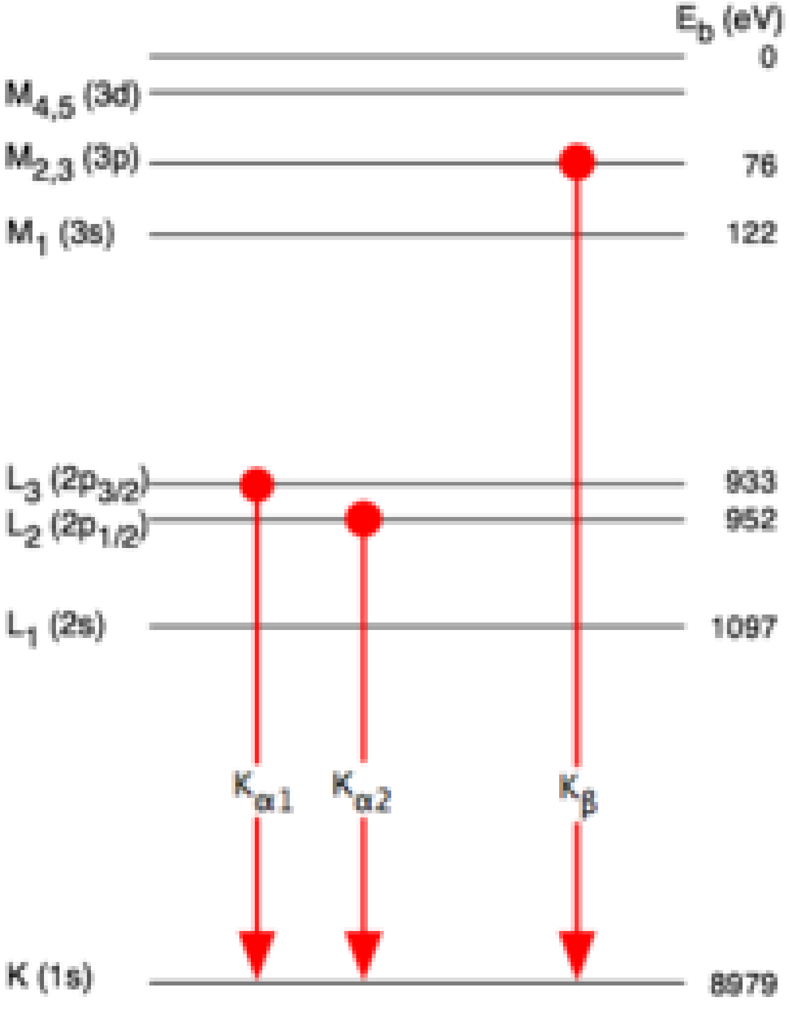
NaCl crystal. Lattice constant: 0.56 nm

$$\lambda \approx 10^{-10} m = 0.1\ nm$$

X-ray spectrum produced by vacuum tube



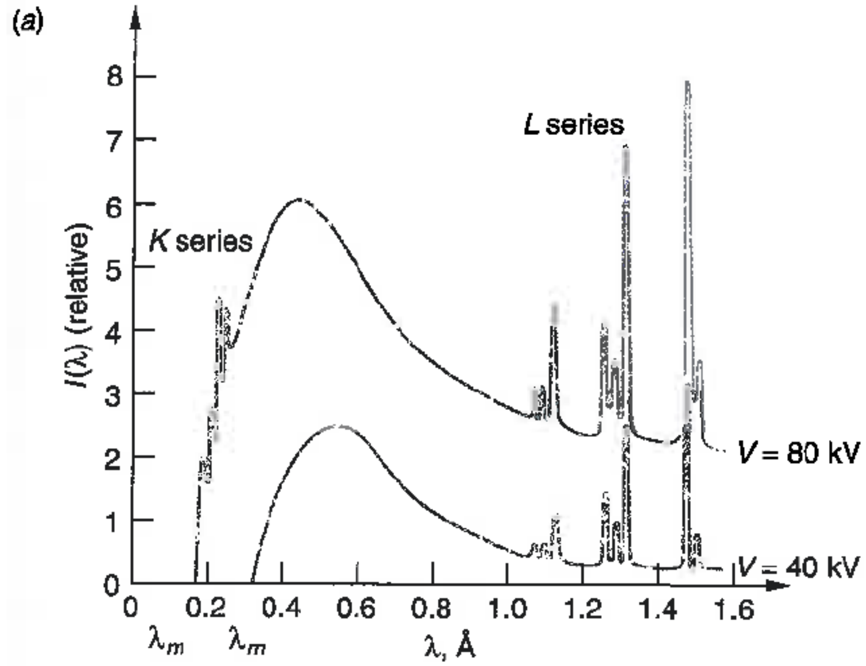




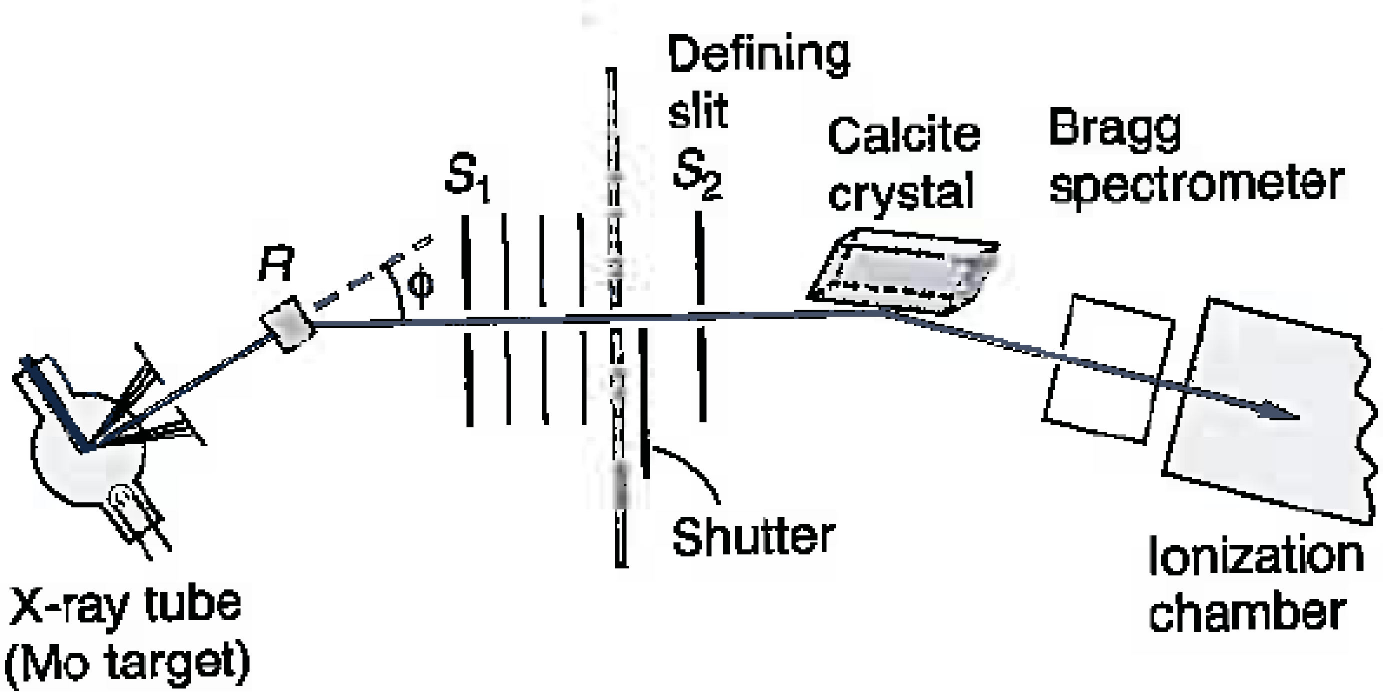
X-ray spectrum produced by vacuum tube

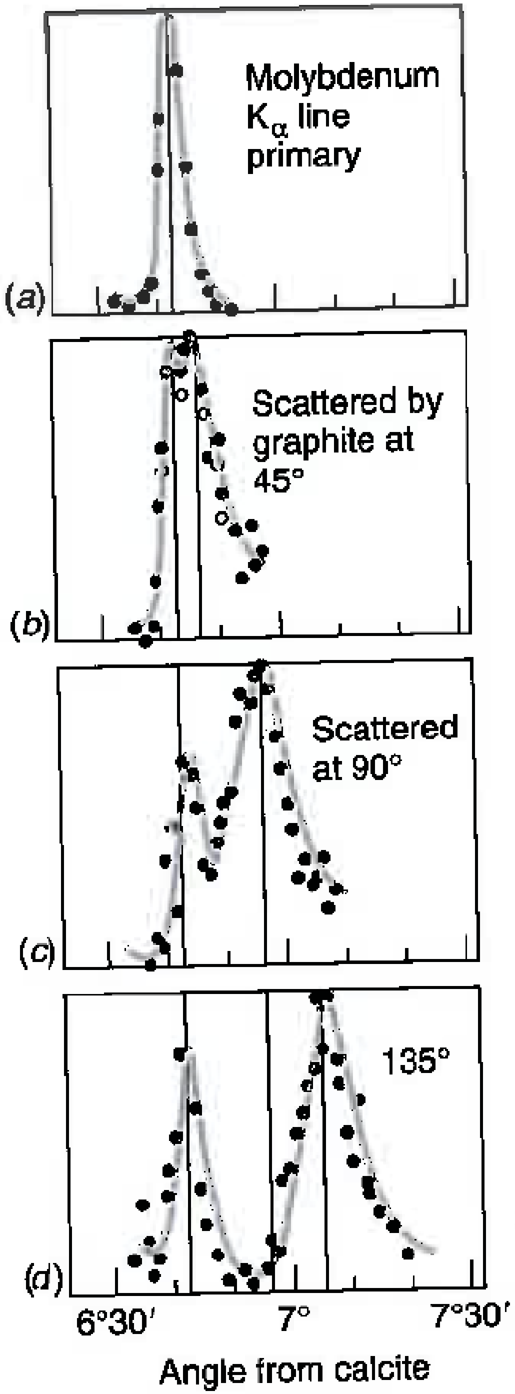
$$E_{Max} = \frac{hc}{\lambda_{min}} = eV$$

$$\lambda_{min} = \frac{hc}{eV} \approx \frac{1240}{V}$$



Compton Effect





Compton Effect – inelastic collision between photon and electron

$$\lambda_2 - \lambda_1 = \frac{h}{mc}(1 - cos\theta)$$