Midterm Exam

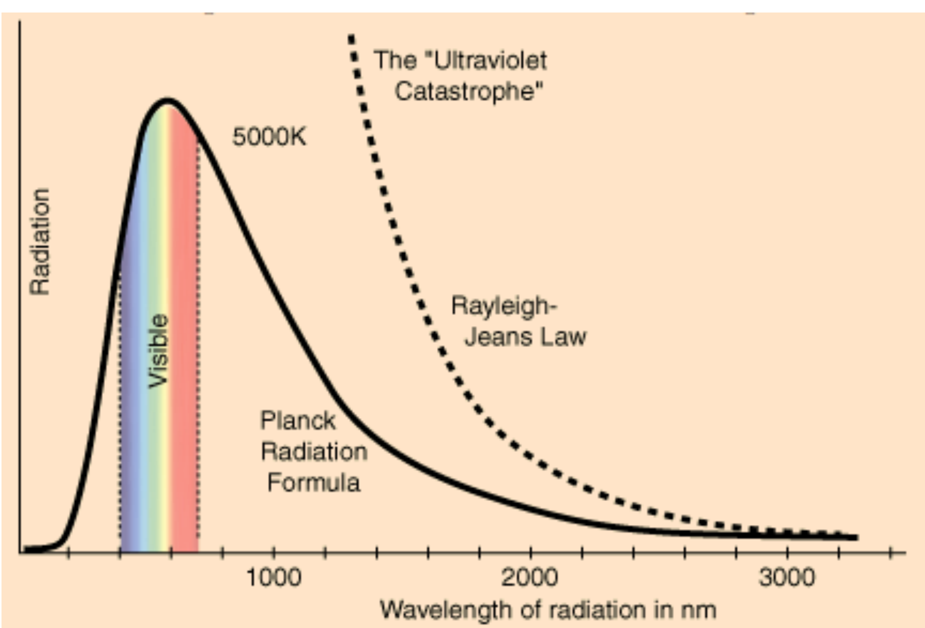
- Promptly at 8 am on Thursday February 7.
- Please bring student IDs.
- Covers chapters 1-4.
- 5 questions.
- Physical constants given, formulas given.
- Formula sheet will be provided and is posted online.
- Only pen or pencil and student ID, and non-programmable calculator allowed at desk.
- **No backpacks, purses, cell phones, ipods, ipads, notebooks, books, laptops, etc.**
- **If your cell phone is within reach, you will receive a zero on the exam.**
- Seat list available online, linked off course schedule.

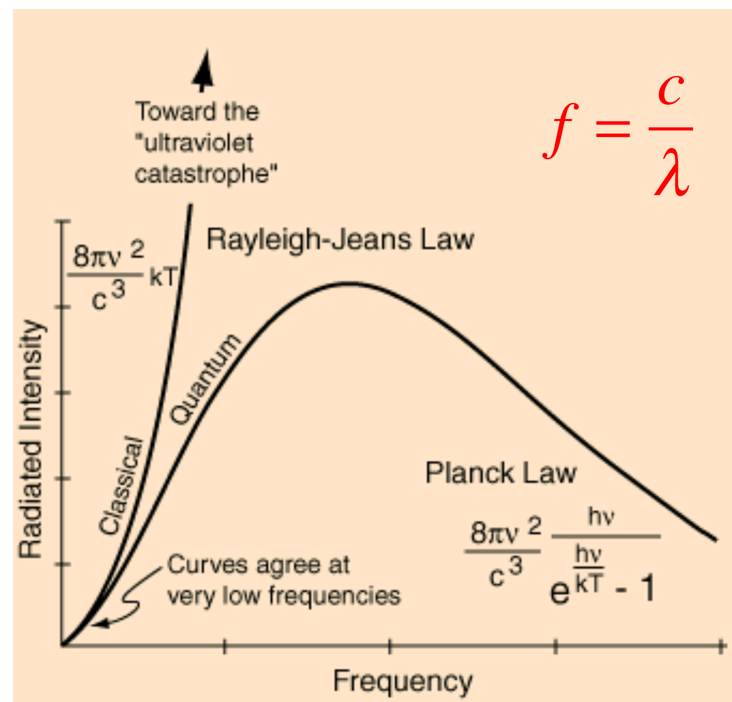
Chapter 4: Quantization of light

- “Quantized” means it can occur only in certain discrete amounts
- Quantized is the opposite of continuous
- Examples: Eggs are quantized, gasoline is not. Nor is butter. Black beans are quantized (but divisible).
- Electric charge is quantized. The charge on an electron is the lowest we see in nature.

Blackbody Radiation Distribution

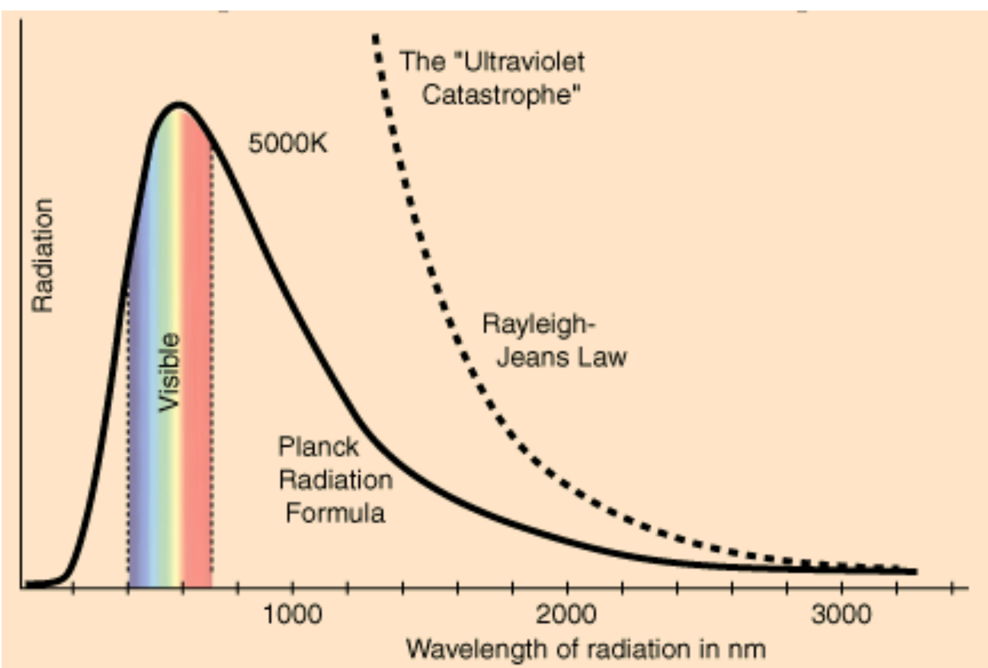
- Electromagnetic radiation from a body in thermal equilibrium
- "A blackbody is any body that is a perfect absorber of radiation, and blackbody radiation is the radiation given off by that body when heated." (Think of an oven.)
- Before Planck (Classical Electromagnetism):
  - Classical distribution matched at long-wavelengths (Rayleigh-Jeans)

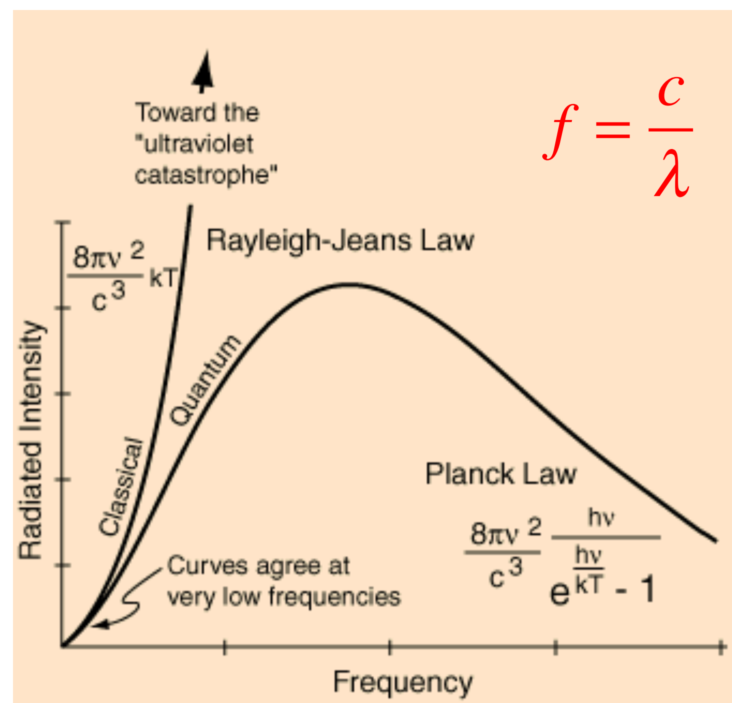




Planck's Idea: Radiation energies are quantized

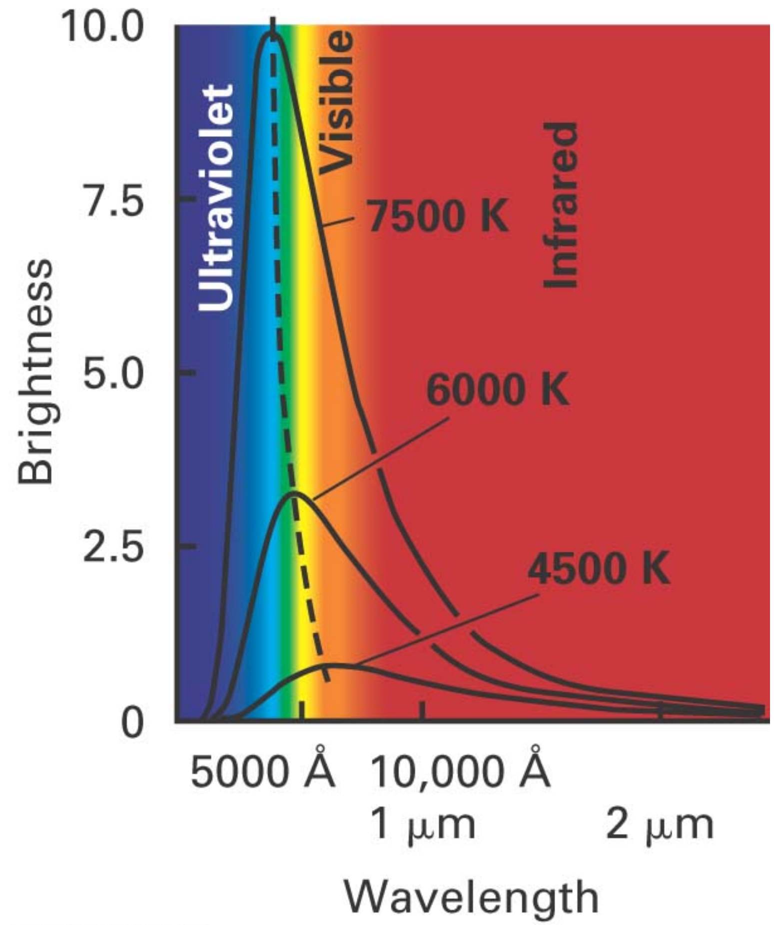
- Planck derived exact formula by making the radical assumption that photon energies are quantized; radiation of frequency f can be emitted only in integer multiples of f: E=0, 1hf, 2hf, 3hf,...
- h = Planck's constant=6.63 x 10^{-34} J s





Blackbody radiation and temperature

- Hotter bodies emit bluer light
  - “red hot” a misnomer, in a sense
  - Things colder than “red hot” emit in infrared
  - Blow torch is blue; hotter than candle flame
- Cosmic Microwave Background Radiation from the Big Bang has a blackbody radiation spectrum for T=2.7 K.



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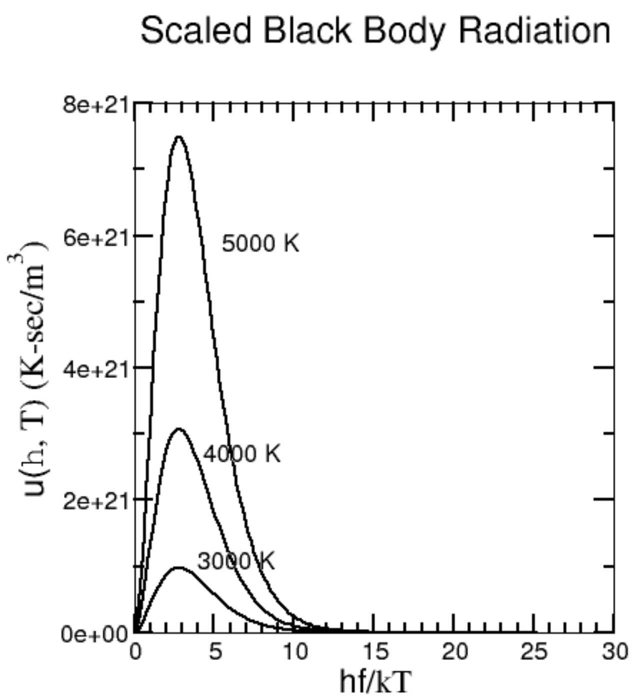
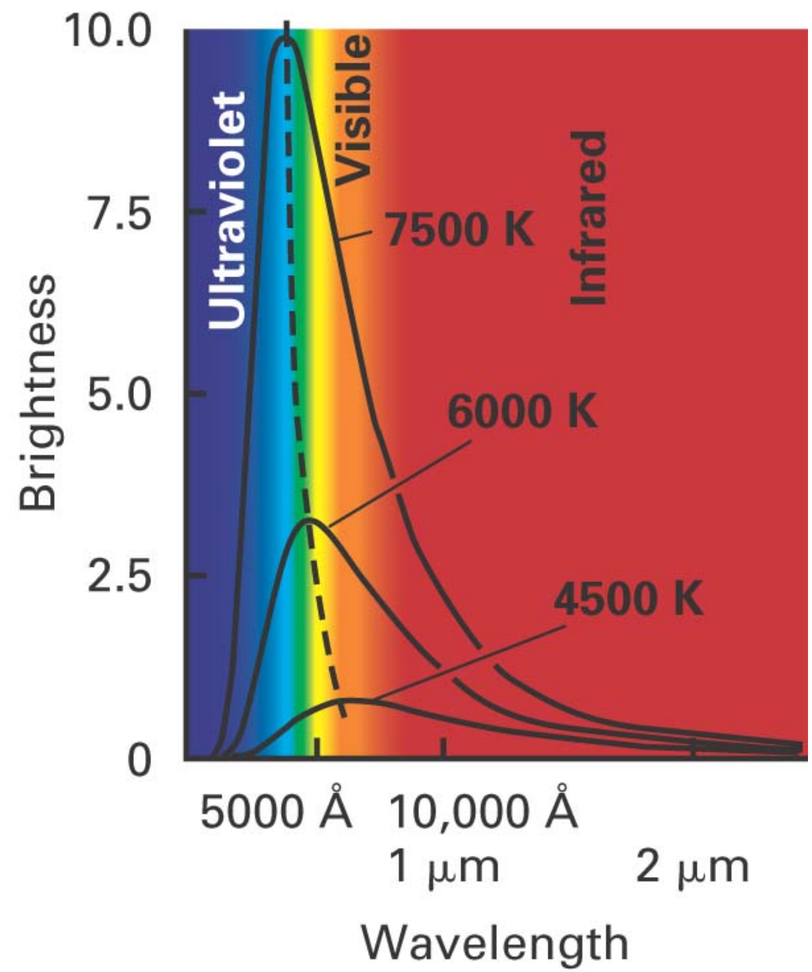
Which is hottest?

a. The surface of a star that glows primarily in the infrared,
b. the surface of a star that glows primarily in the ultraviolet,
c. a burner that is glowing red,
d. a purple flame of a blow torch,
e. the surface of the yellow sun.

Blackbody radiation and temperature

- wavelength of peak of spectrum depends on temperature
- $\lambda_{max} T = 2.9 \times 10^7$ Å K
- same as before: hotter object emits bluer light with shorter wavelength





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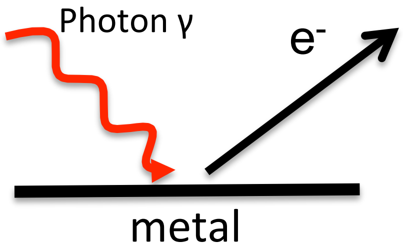


Photoelectric effect

- Hertz discovered photoelectric effect in 1887
- a metal exposed to light ejects electrons from its surface
- not explainable in classical electromagnetism
  1. If the intensity of the incident light increases, the number of electrons that are ejected increases, but the kinetic energy of each electron stays the same.
  2. If the frequency, f, goes below a certain critical value, f_0, no electrons are ejected.
  3. As the frequency, f, increases above f_0, the maximum kinetic energy of the ejected electrons increases.
- Quantized explanation (Einstein, 1905): Energy in a single quantum or photon is hf. Each electron is ejected because of being struck by a single photon. Below f_0, the photon doesn't have enough energy to eject the electron. As f increases above f_0 the photons impart $hf-hf_0$ = kinetic energy of the electron. This is the excess energy above that required for ejection. Analgous to posting bail to set a prisoner (electron) free.
- Work function of a metal $\Phi = hf_0$

$$K_{max} = hf - hf_0 = hf - \phi$$

Planck's constant, photon energies

- Can determine Planck's constant h by fitting Planck's formula to blackbody radiation, and from a fit of K_{max} vs. f to the photoelectric effect. Both techniques give the same value for h.

$$K_{\max} = hf - hf_0 = hf - \phi$$

- Wave: c=f λ (speed of light = frequency x wavelength).
- Wavelength of visible light: 400 nm to 650 nm

Example 1

- Energy of 550 nm (visible) photon:
  - E=hf=hc/λ=(6.63 x 10^{-34} J s)(3 x 10^{8} m/s)/(550 x 10^{-9} m)
    =3.62 x 10^{-19} J
  - Can also use hc=1240 eV nm
  - So E=hf=hc/λ=1240 eV nm/550 nm = 2.3 eV
  - 1 eV = 1.6 x 10^{-19} J
- How many photons hit our eye per sec from moon?

$$N = \frac{\text{Intensity} \times \text{Area}}{\text{Energy}} = \frac{IA}{E} \approx \frac{\left(3\times10^{-4}\,\text{W/m}^2\right)\left(3\times10^{-5}\,\text{m}^2\right)}{\left(3.62\times10^{-19}\,\text{J}\right)} \approx 2.5\times10^{10}\ \text{photons/sec}$$

Photon relationships: particle/wave "duality"

- $E = hf = h\,c/\lambda$
- $E = pc$ (chapter 2)
- Thus, for a photon: $p=h/\lambda$

- Compton effect shows that photons have this momentum
- Compton effect involves x-rays

Photon relationships: particle/wave "duality"

- $E = hf = h\, c/\lambda$
- $E = pc$ (chapter 2)
- Thus, for a photon: $p=h/\lambda$
- If $E=pc$, what is m for a photon?

a. pc/c^2,

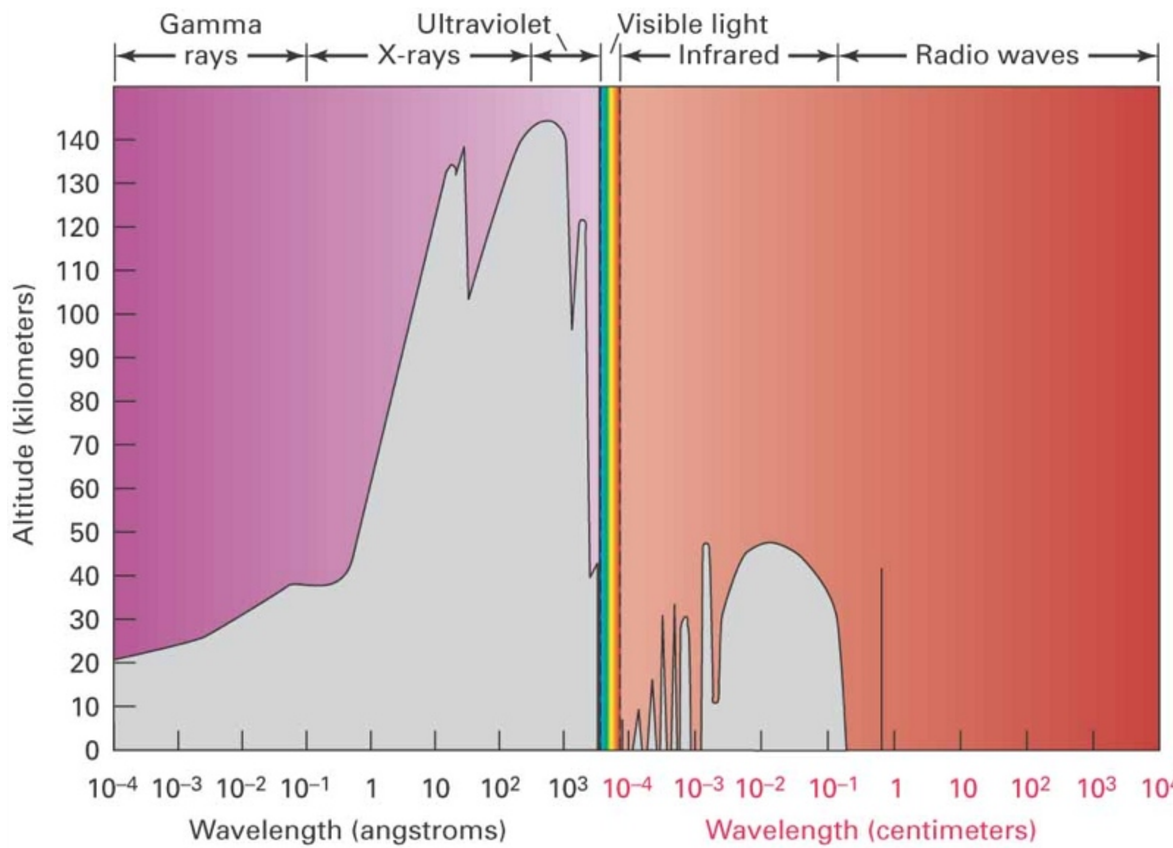
b. 0,

c. impossible to tell.

The spectrum of EM radiation

- We see different wavelengths of light as colors
- Visible light wavelength range is 400-650 nm = 4000 - 6500 Å
- (1 Å = 1 Angstrom = 10^{-10} m)

x-rays



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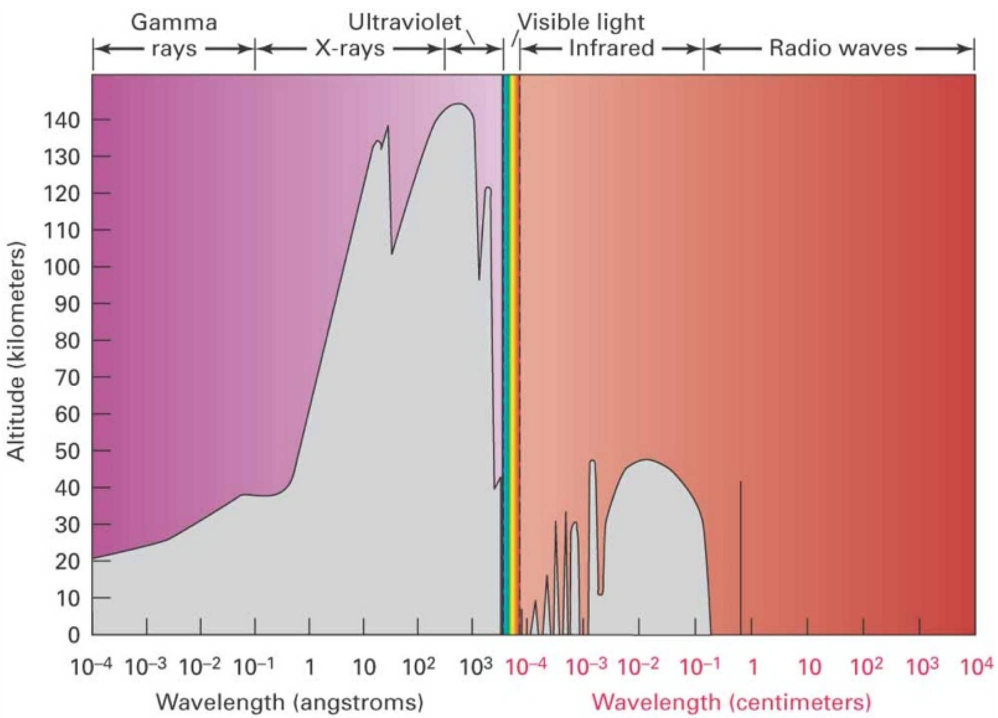
Water

Water vapor in our atmosphere blocks most of the harmful rays from the sun, e.g., ultraviolet radiation. Fortunately, however, it is transparent to visible light. Otherwise the sky would be dark all the time.



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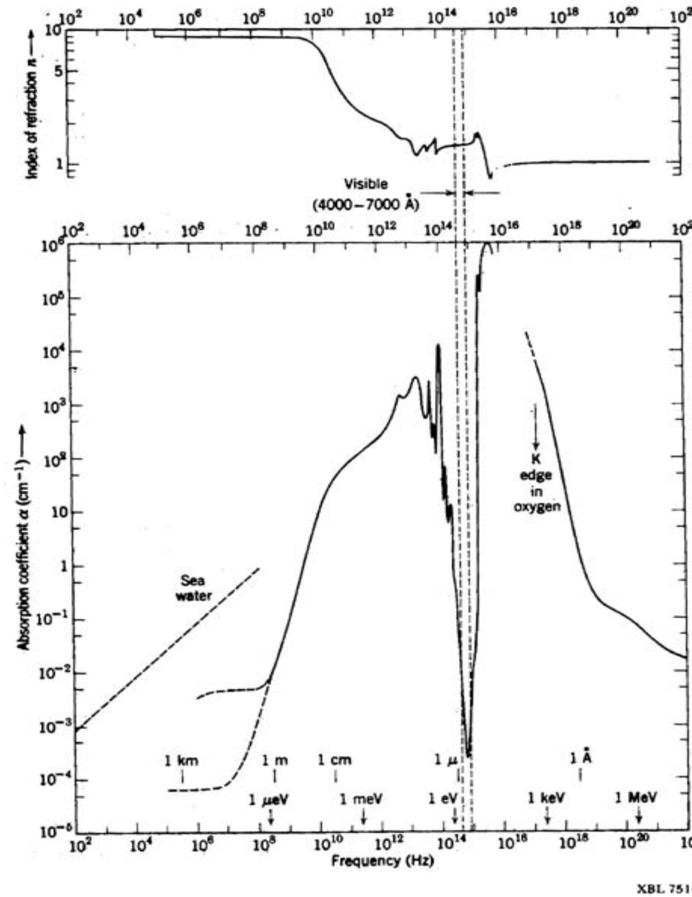

Fig. 7.9 The index of refraction (top) and absorption coefficient (bottom) for liquid water as a function of linear frequency. Also shown as abscissas are an energy scale (arrows) and a wavelength scale (vertical lines). The visible region of the frequency spectrum is indicated by the vertical dashed lines. The absorption coefficient for sea water is indicated by the dashed diagonal line at the left. Note that the scales are logarithmic in both directions.

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Jackson, *Classical Electrodynamics*

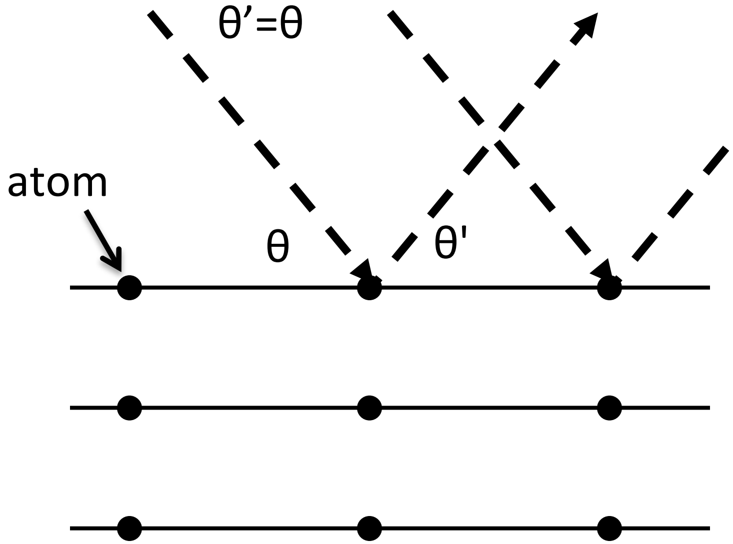
x-rays

- X-rays: short wavelengths: 0.001-1 nm; discovered c. 1895 by Roentgen. He put cathode ray tube in black carton to exclude light and found a fluorescent screen lit up even if it was 2 m away.
- He didn't know what they were and called them "x-rays". (made an x-ray of his wife's hand)
- For reference, visible is 400-650 nm; ("optical" typically 300-1000 nm in astronomy)
- Energies are high, above 1 keV; can be MeV
- Produced when accelerated electrons from a cathode (negatively charged metal) slam into a metal anode (positively charged metal)
- Can penetrate solids: used for medicine before people knew what they were
- YouTube (How are x-rays produced?) http://www.youtube.com/watch?v=Bc0eOjWkxpU

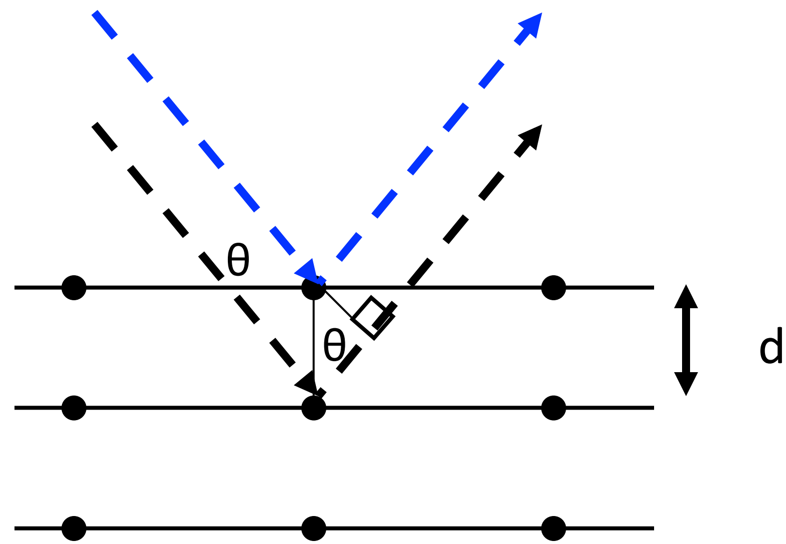
X-ray production

- X-rays are produced by bremsstrahlung (braking) radiation in which electrons decelerate when they hit the anode.
- X-rays are produced when an inner electron near the nucleus is removed and the other electrons cascade down in energy to fill the hole. As these electrons make transitions between energy levels, photons are produced. The high energy photons are x-rays.

x-rays shown to be waves by their diffraction pattern



crystal lattice with incident x-rays; spacing is small



red and blue constructively interfere when $2d \sin\theta = n\lambda$

λ = wavelength

n= integer

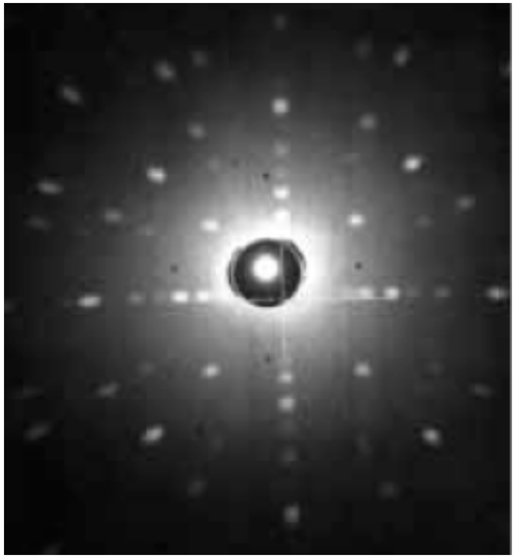
•allows measurement of λ or d

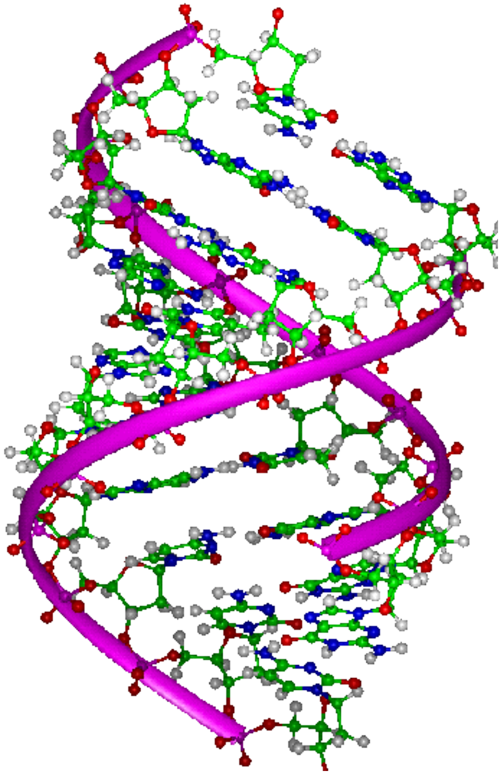
Bragg Law

Bragg Diffraction

x-ray crystallography

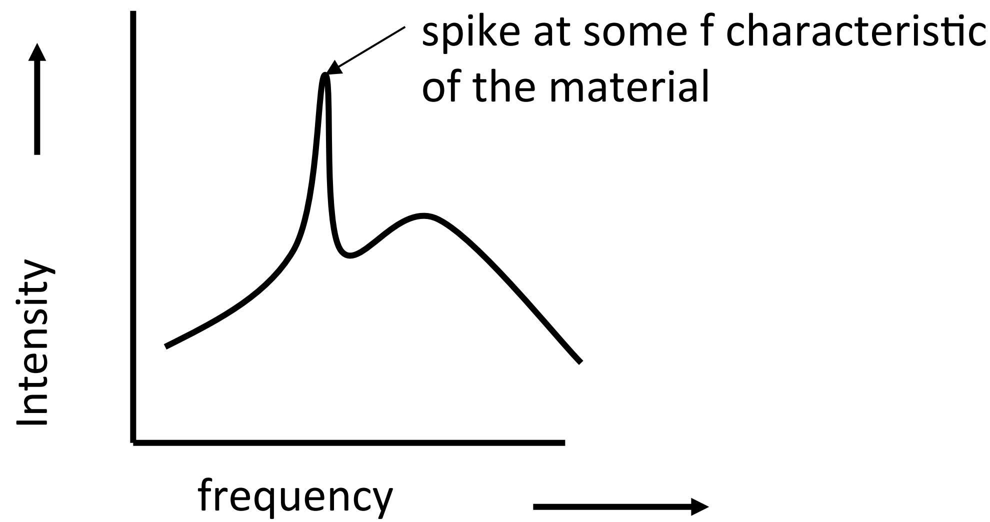
- x-ray interference patterns from Bragg Law allow reconstruction of the structures of crystals
- Important for structure of DNA (Rosalind Franklin's x-ray pictures led Watson and Crick to the structure of DNA) and proteins (protein crystals)





x-ray diagnostics

- x-ray spectra: have sharp spikes called "characteristic x-rays" (characteristic of metal used to make anode)
- Photon energy cannot be greater than the kinetic energy of electrons hitting the metal anode (Duane-Hunt law)
- $hf_{max} = K = V_0 e$



The Compton Effect

- See board notes.

Wave-Particle Duality

- Light has both a wave and a particle nature
- Experimental evidence from photelectric effect and Compton effect

$$E = hf \text{ and } p = \frac{h}{\lambda}$$