Medical Equipment II - 2010
Chapter 14: Atoms and Light (2,3)

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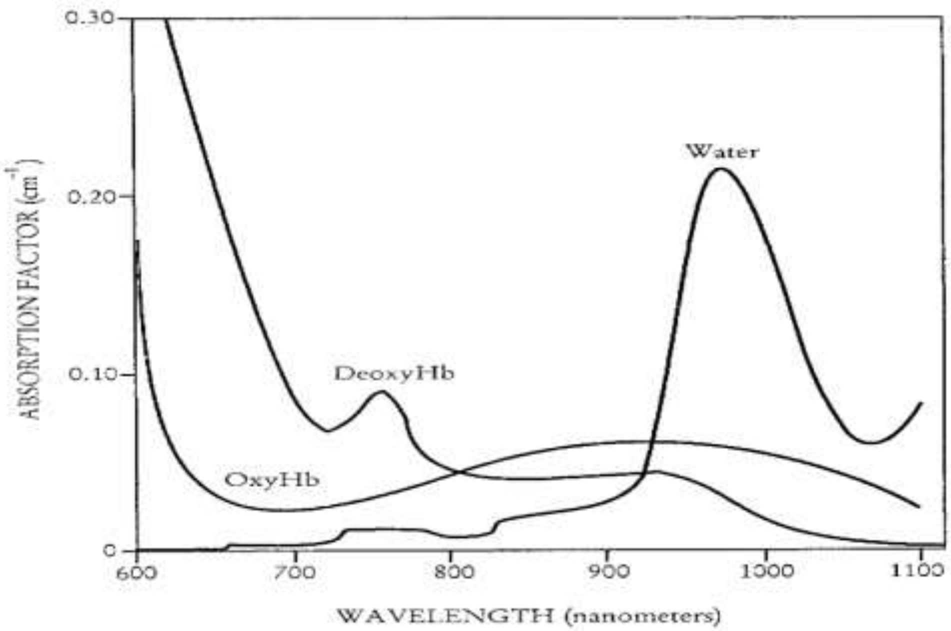
Web: http://ymk.k-space.org/courses.htm

Applications of NIR: Blood Oximetry

- NIR (600–1000 nm) is used to measure the oxygenation of the blood
  - Measure absorption at two different λ's
  - Isosbestic point
  - Calibration

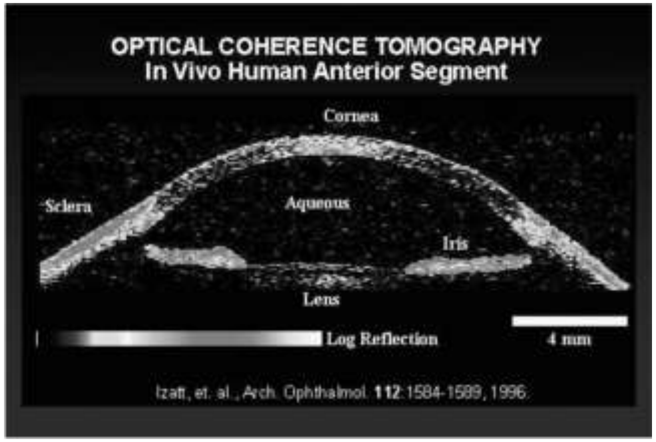


Optical Coherence Tomography (OCT)

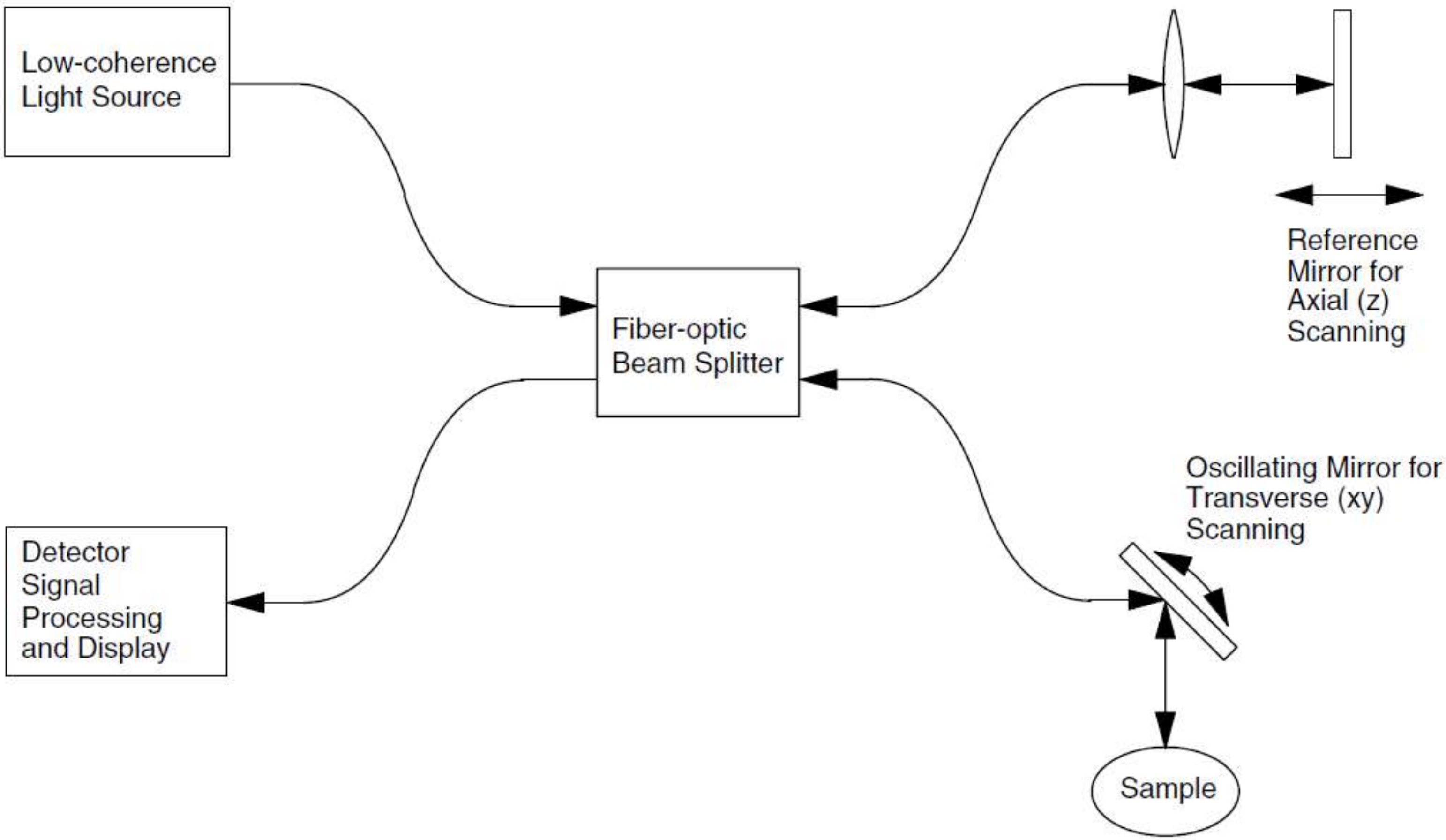
- Optical range measurements using the time delay of reflected or backscattered light from pulses of a few femtosecond (10^{-15} s) duration can be used to produce images similar to those of ultrasound A- and B-mode scans.
  - Spatial extent of a 30 fs pulse in water ~7 μm.
  - Difficult to measure delays that short

- OCT system design:

  Use interference principles to solve problem with simple method



OCT System Diagram



OCT Theory

- Wave received: $A \sin \frac{2\pi}{\lambda}(x - c_n t)$
- Detector: intensity averaged over time

$$y \propto A^2 \overline{\sin^2 \omega(x/c_n - t)} = A^2/2.$$

- Split wave and add two waves before detection : Interferometry

$$y \propto (A/2)^2 \overline{[\sin \omega(x_1/c_n - t) + \sin \omega(x_2/c_n - t)]^2}$$
$$= \frac{A^2}{4}\left(1 + \cos \frac{\omega}{c_n}(x_2 - x_1)\right).$$

  - Change position of reference beam to get position of the reflector and use to form image

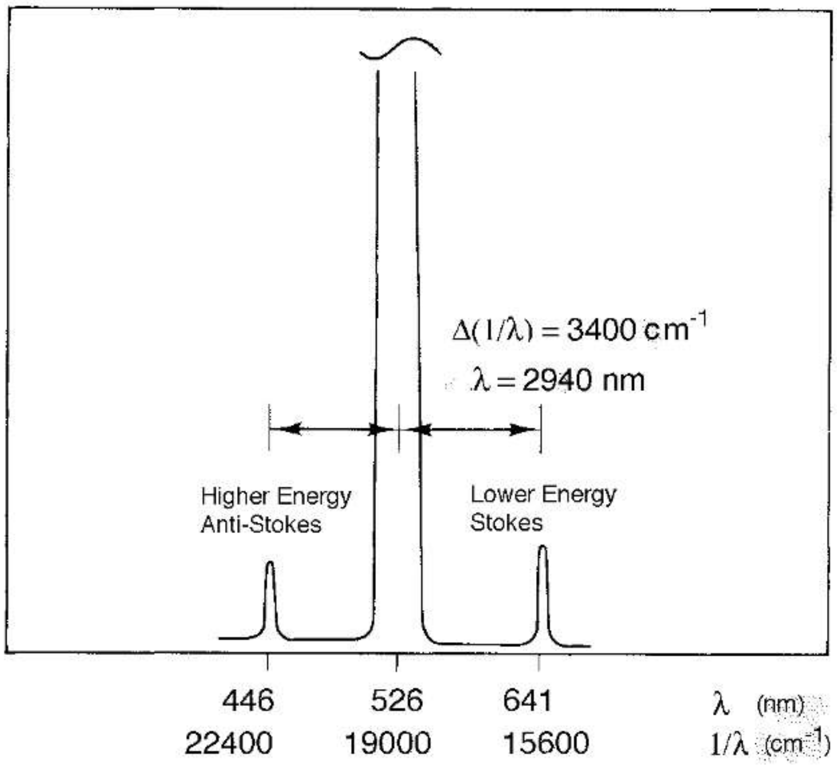
OCT: Coherence of Source

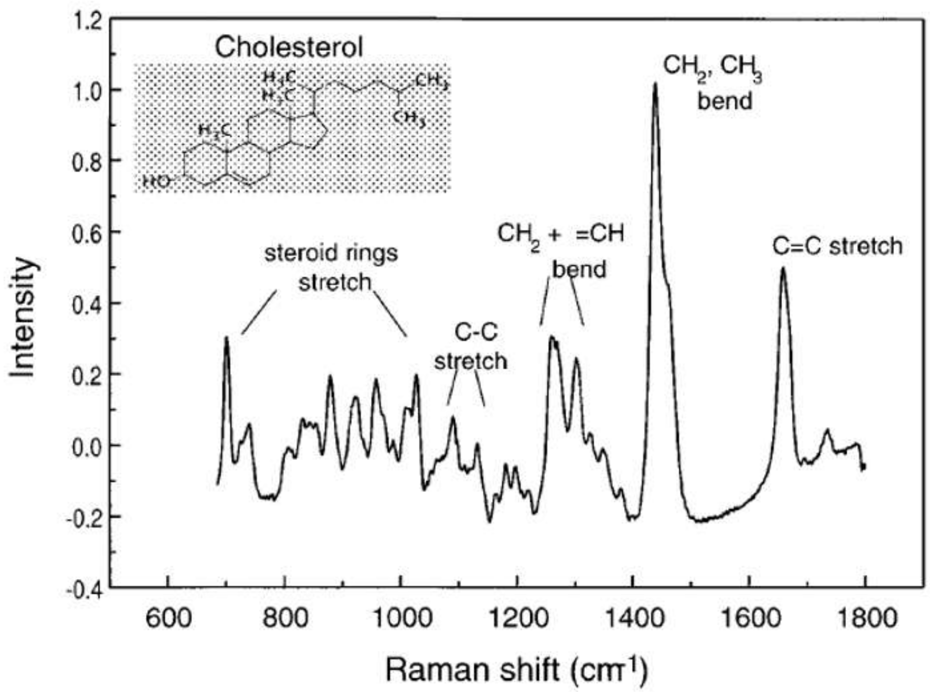
- Coherence of the light beam
  - number of cycles over which the phase of the wave does not change.
- When an atom emits light, wave lasts for a finite time, τ_{coh} ($\sim 10^{-8}$ s).
  - When another atom emits light, the phase is unrelated to the phase of light already emitted.
- If $(x_2 - x_1)/c_n > \tau_{coh}$, time average will go to 0
  - Distance measured when $\boxed{x_2 - x_1 < c_n \tau_{\text{coh}}.}$
  - Hi Res: use light source with short τ_{coh}

Raman Spectroscopy

- Scattering of light in which the scattered photon does not have its original energy, but has lost or gained energy corresponding to a rotational or vibrational transition.
- Raman scattering can be done with light of any wavelength, from infrared to ultraviolet

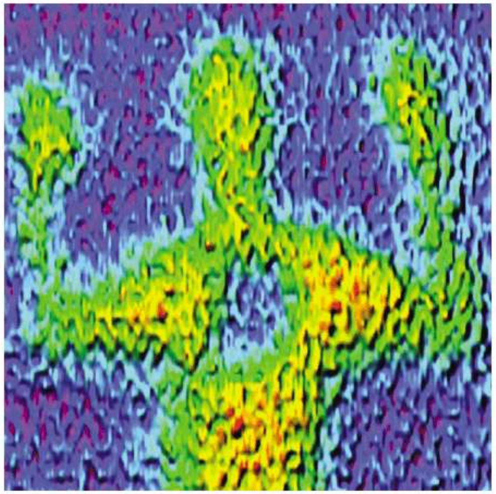
Raman Scattering





Far Infrared or Terahertz Radiation

- Medical use of THz radiation (“T rays”)
- Polarization is important
- High attenuation
  - Restricted to superficial applications
- Applications
  - Spectroscopy
  - Imaging



Thermal Radiation

- Any atomic gas emits light if it is heated to a few thousand kelvin.
  - Light consists of a line spectrum.
  - Example: famous yellow line of sodium

$$\lambda = 589.2 \text{ nm},$$

$$\nu = c/\lambda = 5.092 \times 10^{14} \text{ Hz},$$

$$E = h\nu = hc/\lambda = 3.38 \times 10^{-19} \text{ J} = 2.11 \text{ eV}.$$

Thermal Radiation

- At any temperature, ratio of excited sodium atoms to those in ground state is given by Boltzmann ratio:,

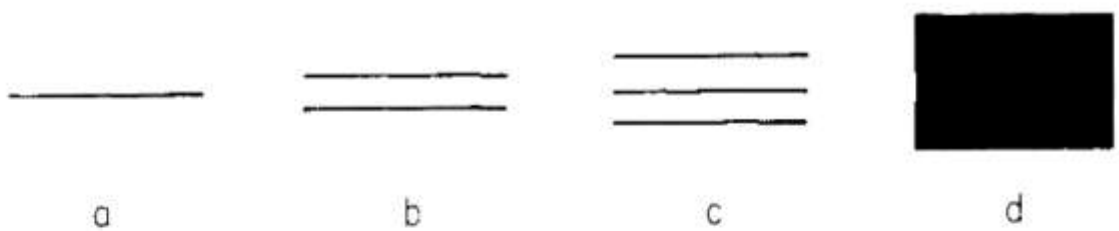
$$\frac{P_{\text{excited}}}{P_{\text{ground}}} = e^{-E/k_B T}$$

- At room temperature 3.8×10^{-36} (negligible)
- At 1500 K 8×10^{-8} (enough atoms give off light)

Thermal Radiation

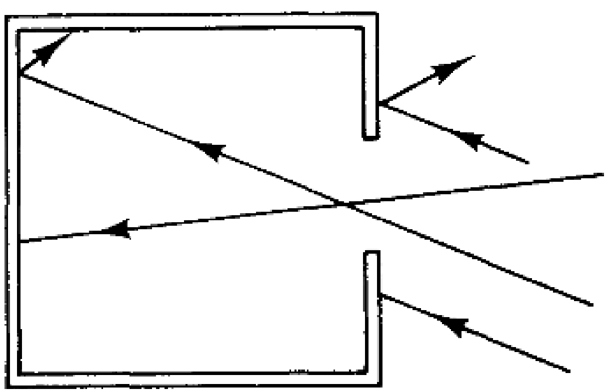
- Heating a piece of iron
  - Splitting
  - Shifting
  - Bands

Color	T (K)
Red, just visible in daylight	750–800
"Cherry" red	975–1175
Yellow	1200–1505
White	1425-1800
Dazzling (bluish) white	1900



Blackbody

- A substance that has so many closely spaced levels that it can absorb every photon that strikes it appears black.
- Ideal not practical
  - Hole in cavity wall approximation



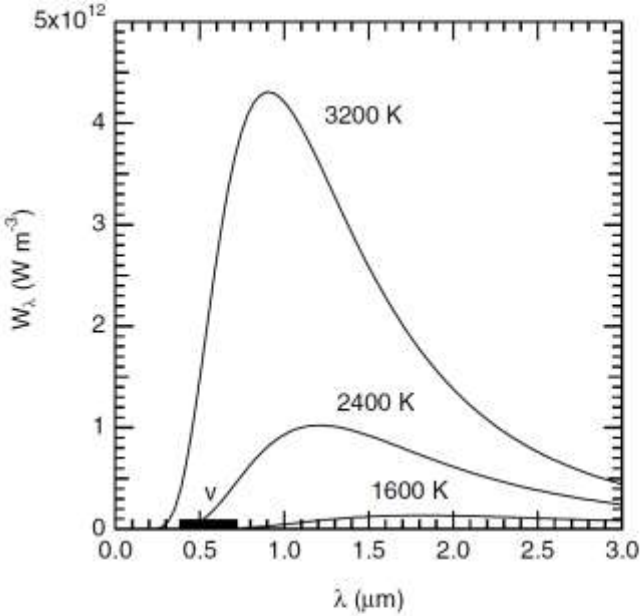
Emissivity

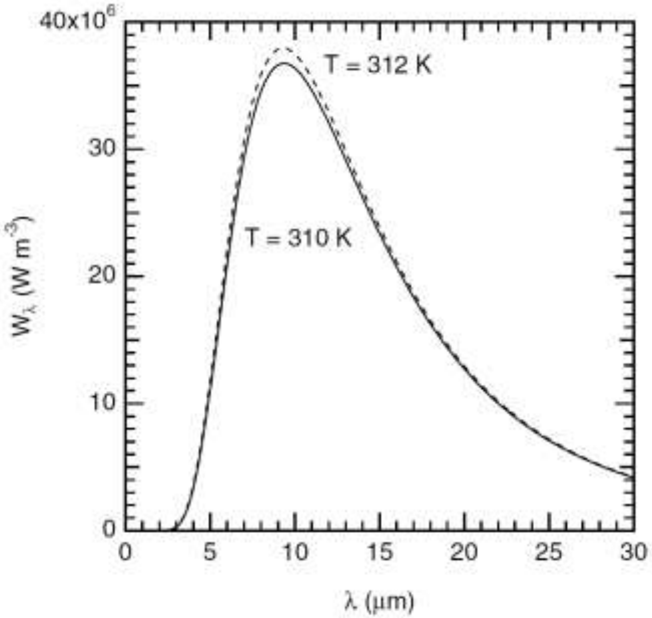
- If the surface is not completely absorbing, we define the emissivity $\varepsilon(\lambda)$, which is the fraction of light absorbed at wavelength λ
  - $\varepsilon = 0$ for transparent or reflective material
  - $\varepsilon = 1$ for complete absorption
  - $\varepsilon(\lambda) = 1$ for a blackbody
  - $\varepsilon(\lambda) = \text{constant} < 1$ for a “gray body”
- When a blackbody is heated, the light given off has a continuous spectrum because the energy levels are so closely spaced.

Blackbody Radiation Function

- The spectrum of power per unit area emitted by a completely black surface in wavelength interval between λ and λ+dλ (units W/m^3)

$$W_\lambda(\lambda, T)d\lambda$$





Blackbody Radiation Function

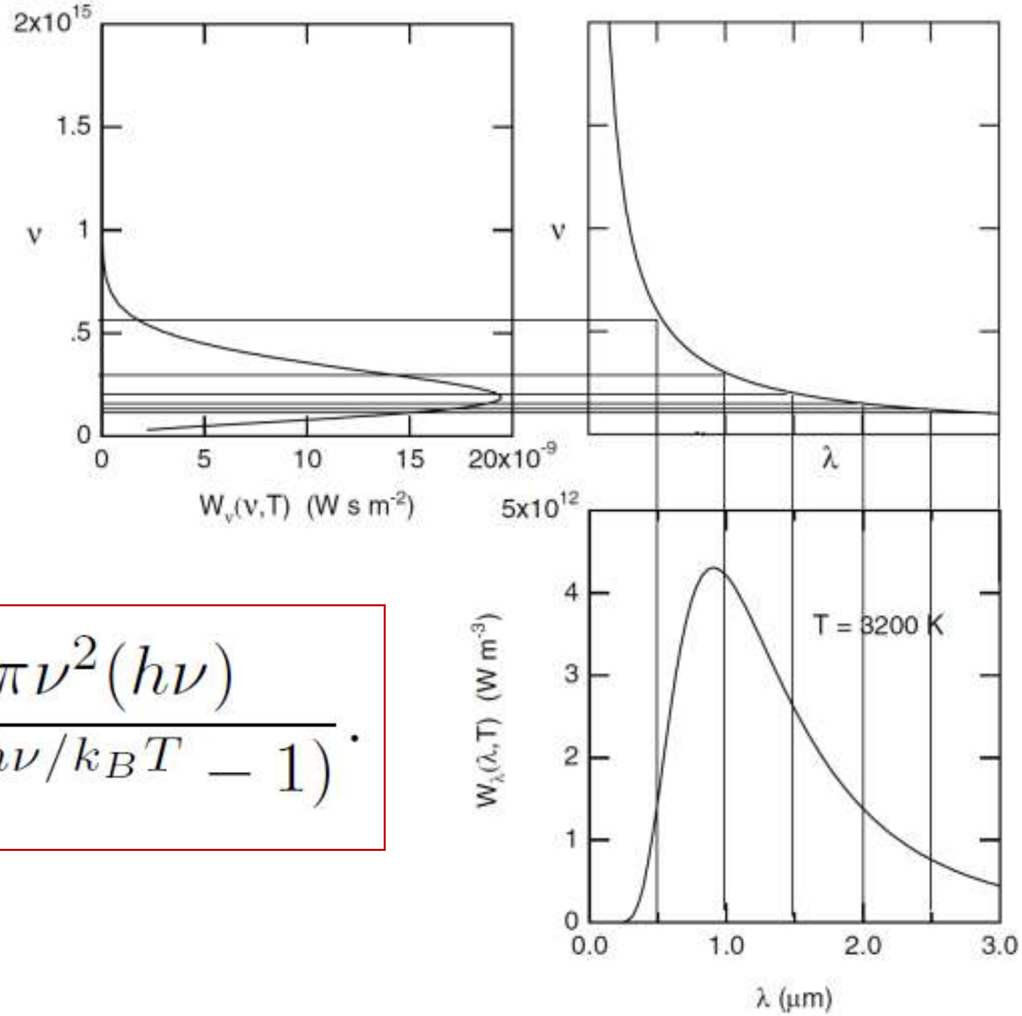
- Total power from Planck's theoretical formula

$$W_\lambda(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5 \left(e^{hc/\lambda k_B T} - 1\right)}.$$

$$\begin{aligned} W_{\text{tot}}(T) &= \int_0^\infty W_\lambda(\lambda, T)\, d\lambda \\ &= \frac{2\pi^5 k_B^4}{15 c^2 h^3} T^4 = \sigma_{SB} T^4. \end{aligned}$$

Stefan-Boltzmann law with σ_{SB} defined as Stefan-Boltzman constant $\sigma_{SB} = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}.$

Blackbody Radiation Function



$$W_\nu(\nu, T) = \frac{2\pi\nu^2(h\nu)}{c^2(e^{h\nu/k_BT} - 1)}.$$

The transformation from $W_\lambda(\lambda, T)$ to $W_\nu(\nu, T)$

Blackbody Radiation Function: Peak Location

- Differentiate and equate by 0

$$\lambda_{\max} T = \frac{hc}{4.9651 k_B} = 2.90 \times 10^{-3} \text{ m K}.$$

$$\frac{\nu_{\max}}{T} = \frac{2.82144 k_B}{h} = 5.88 \times 10^{10} \text{ K}^{-1} \text{ s}^{-1}.$$

$$\lambda_{\max} \nu_{\max} = 1.705 \times 10^{8} \text{ m s}^{-1} = 0.57 c.$$

- General case (not blackbody)

$$\boxed{\epsilon(\lambda) W_\lambda(\lambda, T).}$$

Infrared Radiation from The Human Body

- Emissivity of human skin:

$$\text{for } 1\ \mu\text{m} < \lambda \leq 14\ \mu\text{m},\ \epsilon(\lambda) = 0.98 \pm 0.01$$

- Assuming surface area of 1.73m2, temperature of 33 °C, total power radiated is

$$w_{\text{tot}} = SW_{\text{tot}} = S\sigma_{SB}T^4 = 860\ \text{W}$$

  - 9 times basal metabolic rate of 100W
  - Error: assuming surroundings at 0 °K

Infrared Radiation from The Human Body

- Assume surrounding temperature T_s=20°C

$$w_{\mathrm{tot}} = S\sigma_{SB}(T^4 - T_s^4).$$

$$w_{\mathrm{tot}} = (1.73)(5.67 \times 10^{-8})(306^4 - 293^4) = 137 \text{ W}.$$

  - Subject has to exercise to keep body temperature
- Radiation to a cold window
  - Glass has high emissivity in infrared region
  - Heat from body to glass window more than from
  - Application to infant incubator near window

Infrared Imaging

- Illumination and imaging of shallow structures
- Thermal imaging of the body
- Body temperature measurement
- Atherosclerotic coronary heart disease (ACHD) diagnosis
  - Temperature sensor (thermistor)
  - Raman spectroscopy and near infrared spectroscopy

Blue and Ultraviolet Radiation

- The energy of individual photons of blue and ultraviolet light is high enough to trigger chemical reactions in the body.
  - Can be both harmful and beneficial.
  - Beneficial: treatment of neonatal jaundice
  - Harmful: sunburn, skin cancer, and premature aging of the skin

Treatment of Neonatal Jaundice

- Neonatal jaundice occurs when bilirubin builds up in the blood
  - Bilirubin is a toxic waste product of decomposition of hemoglobin from dead RBCs.
  - Insoluble in water and cannot be excreted through either the kidney or the gut.
  - It is excreted only after being conjugated with glucuronic acid in liver (become water soluble). through bile and leave via the gut.
  - Occurs when newborns have immature livers or with increased rate of hemolysis

Treatment of Neonatal Jaundice

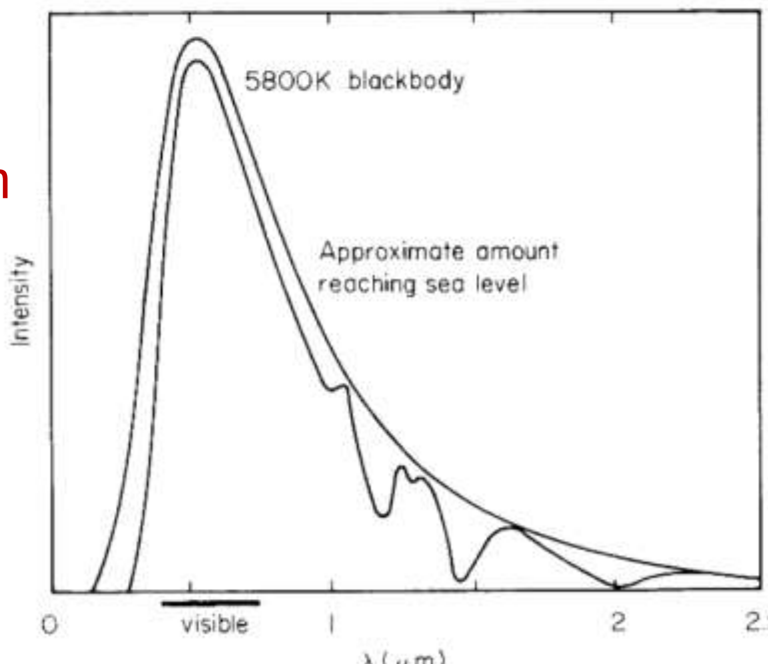
- When skin of a newborn with jaundice was exposed to bright light, jaundice went away.
  - Photons of blue light have sufficient energy to convert the bilirubin molecule into more soluble and apparently less harmful forms.
  - Photons of longer wavelength have less energy and are completely ineffective.

Treatment of Neonatal Jaundice

- Standard form of phototherapy used to be to place the baby “under the lights.”
  - Place eye patches to protect the baby’s eyes.
  - Baby placed in an incubator to keep warm
- Fiberoptic blanket
  - Wrapped around the baby’s torso under clothing
  - Still controversial

UV Spectrum

- UV can come from the sun or from lamps.
- Maximum intensity of solar radiation is in the green, at about 500 nm.
  - Sun emits approximately like a thermal radiator at a temperature of 5,800 °K.
  - O_3 absorbs 200-320 nm
  - Molecular O_2 absorbs <180 nm
- Solar constant
  - Theoretical 1,390 W m^{-2}
  - Satellite 1,372 W m^{-2}
  - Surface: 1,000 W m^{-2}



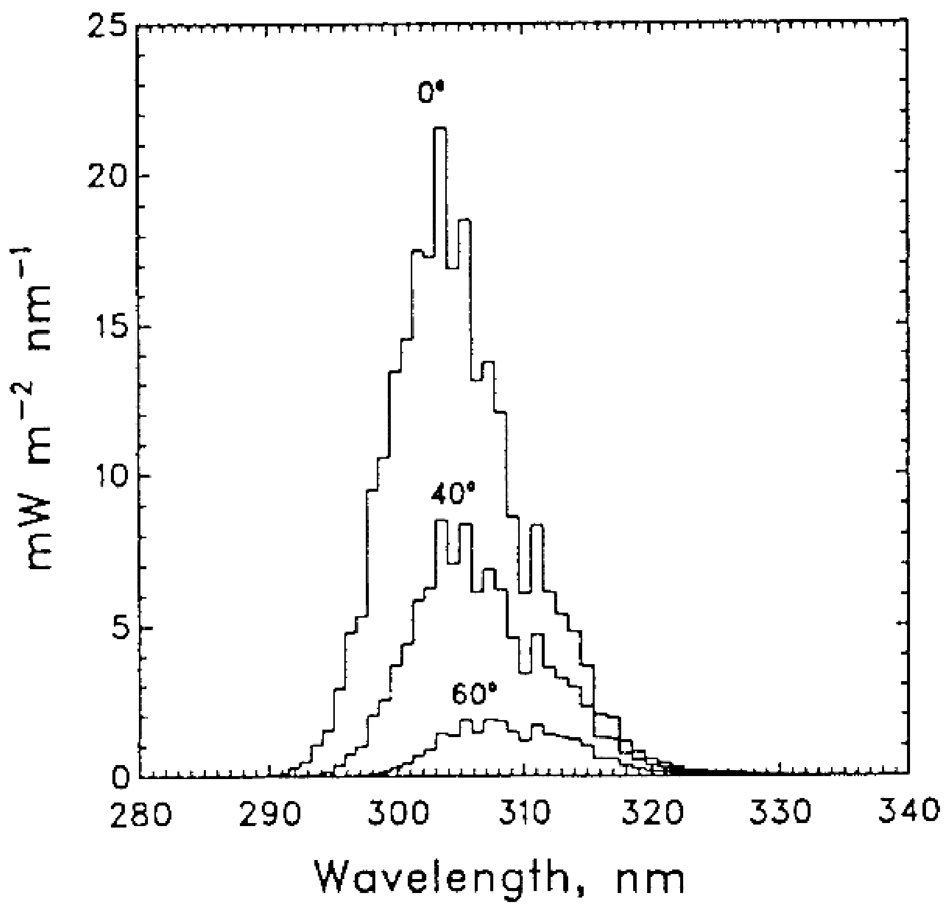
UV Spectrum

UVA	315–400 nm
UVB	280–315 nm[12]
UVC or middle UV	200–280 nm
Vacuum UV	<240 nm
Far UV	120–200 nm
Extreme UV	10–120 nm

- Only the first three are of biological significance, because the others are strongly absorbed in the atmosphere

UV Spectrum

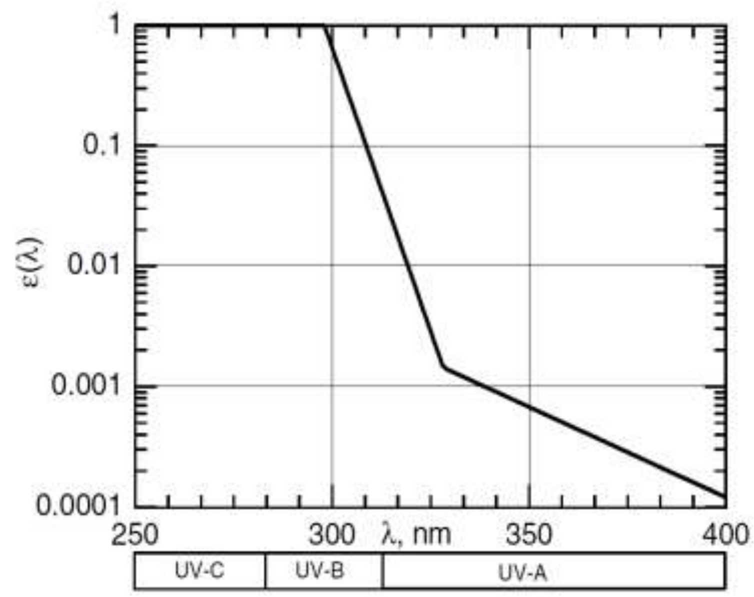
- Solar radiation reaching ground when sun is at different angles from the zenith weighted for DNA sensitivity.



Response of Skin to UV

- Acute (inflammatory) response
  - Erythema : reddening of the skin
  - Minimum erythemal dose
  - Erythema action spectrum: relative sensitivity of skin vs. wavelength

$$\epsilon(\lambda) = \begin{cases} 1.0, & 250 \leq \lambda \leq 298 \text{ nm} \\ 10^{0.094(298-\lambda)}, & 298 \leq \lambda \leq 328 \text{ nm} \\ 10^{0.015(139-\lambda)}, & 328 \leq \lambda \leq 400 \text{ nm} \end{cases}$$



Response of Skin to UV

- Chronic (prolonged) response
  - Abnormal cell growth
  - Hypertrophy or hyperplasia

TABLE 14.4. Abnormal changes in tissue

Metaplasia	A reversible change in which one cell type is replaced by another.
Dysplasia	Variation in size, shape, and organization of the cells. Literally, "deranged development."
Anaplasia	A marked, irreversible, and regressive change from adult cells that are differentiated in form to more primitive, less differentiated cells.

Ultraviolet Light Causes Skin Cancer

- Chronic exposure to UV causes premature aging of the skin.
  - Photoaged different from skin with normal aging
- UVA and UVB suppress the body's immune system
  - This plays a major role in cancer caused by UV

TABLE 14.5. Estimates of skin cancer incidence rates per 100,000.[a]

Cancer type	Population	Males	Females
Melanoma	White, New Orleans, 1983–87	6.9	5.3
	White, Hawaii, 1983–1987	22.2	14.9
SCC	White, U.S., 1994 (rough est.)	100	45
BCC	White, U.S., 1994 (rough est.)	400	200

Protection of Skin from UV

- Sunscreen (SPF: sun protection factor)
  - SPF is based on erythema (mainly UVB effect)
  - Some sunscreens do not protect against UVA
- Important for children
  - 3x exposure to sum + skin more susceptible

UV Damages the Eye

- Acute effects
  - Keratitis and conjunctivitis
  - Thickening of the cornea
  - Disruption of corneal metabolism.
  - Retina susceptible to trauma from blue light.
  - Low doses cause photochemical changes in tissues
  - High doses also cause thermal damage.
- Chronic exposure to UV causes permanent damage to the cornea

Ultraviolet Light Synthesizes Vitamin D

- Ultraviolet light has one beneficial effect: it allows the body to synthesize vitamin D.
- Brief exposures are sufficient to do that.
  - Remember exposure hazards
- Many foods are fortified with vitamin D, which has caused occasional overdoses

Problem Assignments

- Information posted on web site
- Chapter 14 Problems 1, 3, 5, 7, 8, 10, 14, 16, 17,18, 21, 23, 24, 25, 27, 29, 30