RADIATION HEAT TRANSFER FUNDAMENTALS

BASIC RADIATION PHYSICS

- RADIATION IS A FORM OF ELECTROMAGNETIC ENERGY TRANSFER
- MAY BE WAVE TRANSFER
- MAY BE PHOTONS OR QUANTA
- SURFACE OR VOLUMETRIC PHENOMENON
- CAN BE GENERATED FROM A SOLID OR LIQUID SURFACE
- CAN BE GENERATED IN A GAS

BASIC RADIATION PHYSICS

- PRIMARY RELATIONSHIPS ARE WAVELENGTH AND FREQUENCY
- WHERE Co IS THE SPEED OF LIGHT IN A VACUUM
- ENERGY OF A PHOTON IS BASED ON PLANCK'S CONSTANT .

$$\lambda = \frac{C_0}{\upsilon}$$

$$C_0 = 2.998 * 10^8 \frac{m}{sec}$$

$$e = h\upsilon = h\frac{C_0}{\lambda}$$

THERMAL RADIATION

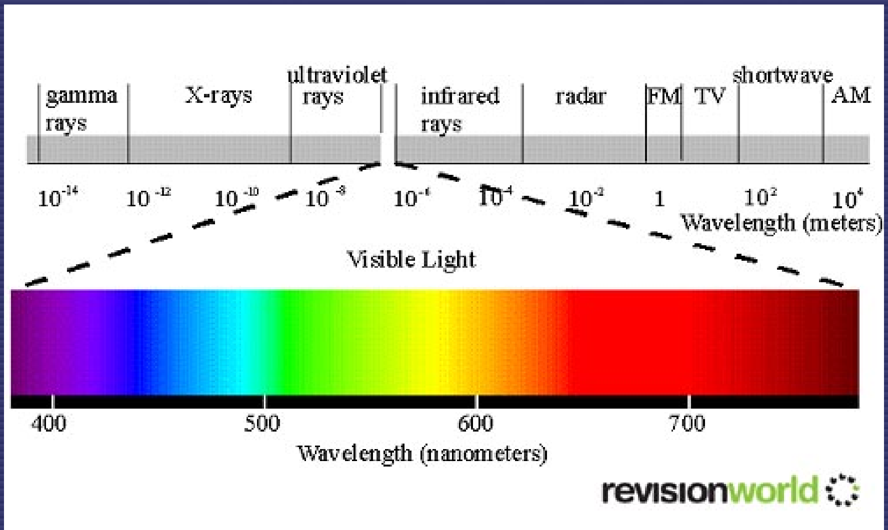
- OVERALL ELECTROMAGNETIC SPECTRUM

	Wavelength (m)	Frequency (Hz)	Energy (J)
Radio	$> 1 \times 10^{-1}$	$< 3 \times 10^{9}$	$< 2 \times 10^{-24}$
Microwave	$1 \times 10^{-3} - 1 \times 10^{-1}$	$3 \times 10^{9} - 3 \times 10^{11}$	$2 \times 10^{-24} - 2 \times 10^{-22}$
Infrared	$7 \times 10^{-7} - 1 \times 10^{-3}$	$3 \times 10^{11} - 4 \times 10^{14}$	$2 \times 10^{-22} - 3 \times 10^{-19}$
Optical	$4 \times 10^{-7} - 7 \times 10^{-7}$	$4 \times 10^{14} - 7.5 \times 10^{14}$	$3 \times 10^{-19} - 5 \times 10^{-19}$
UV	$1 \times 10^{-8} - 4 \times 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{16}$	$5 \times 10^{-19} - 2 \times 10^{-17}$
X-ray	$1 \times 10^{-11} - 1 \times 10^{-8}$	$3 \times 10^{16} - 3 \times 10^{19}$	$2 \times 10^{-17} - 2 \times 10^{-14}$
Gamma-ray	$< 1 \times 10^{-11}$	$> 3 \times 10^{19}$	$> 2 \times 10^{-14}$

URL: http://imagine.gsfc.nasa.govfc.nasa.gov/docs/science/know_l1/spectrum_chart.html

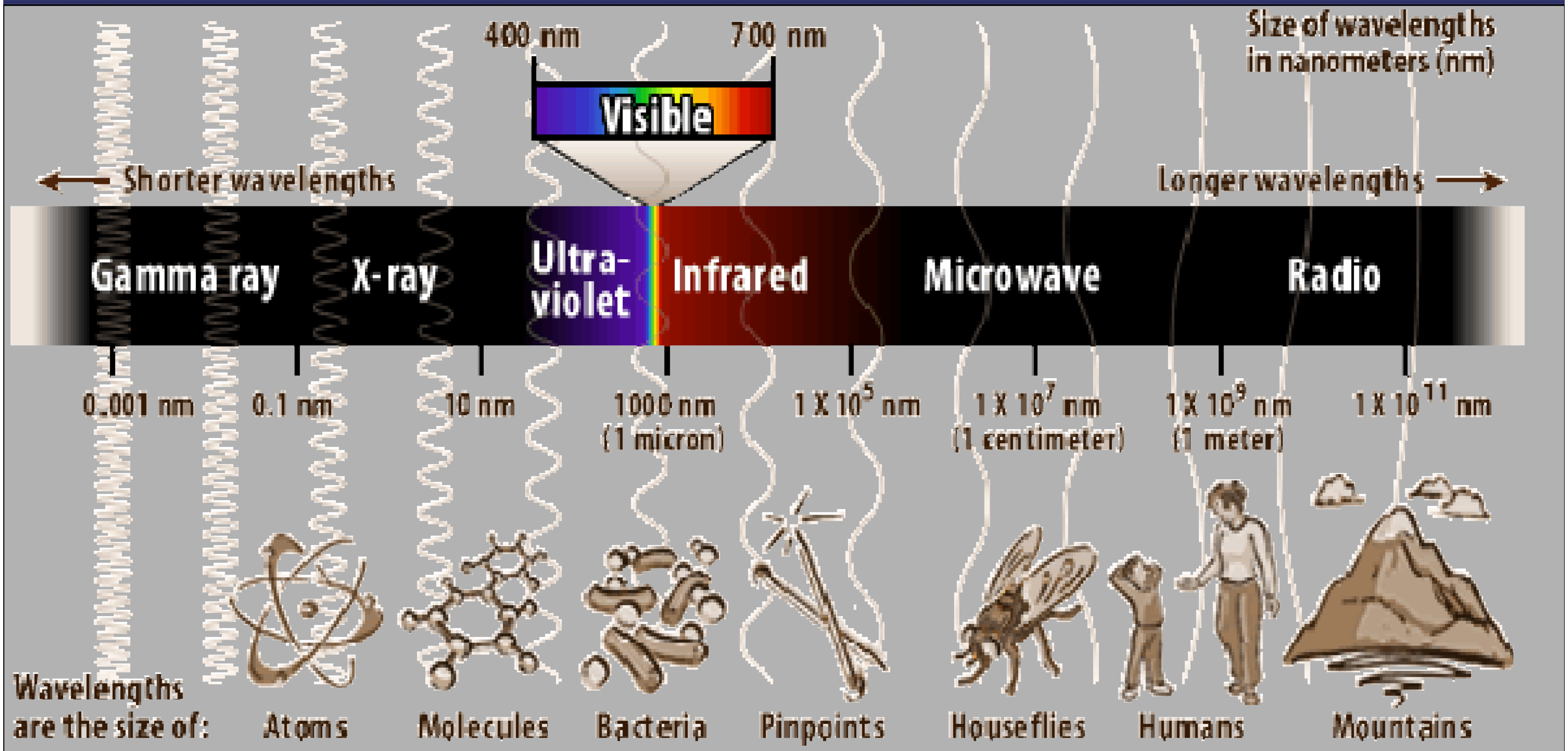
THERMAL RADIATION

- DEFINED OVER A RANGE OF THE ELECTROMAGNETIC SPECTRUM FROM λ = 0.1 μm TO λ = 100 μm
- VISIBLE IS A SECTION OF THE THERMAL SPECTRUM



http://www.onpointlasers.com/media/upload/image/EMwave(2).jpg

THE ELECTROMAGNETIC SPECTRUM



http://amazing-space.stsci.edu/news/archive/2005/03/graphics/em_chart.gif

WAVELENGTH RESONANCE

- MICROWAVE ENERGY IS USED FOR COOKING
- HAS A WAVELENGTH RANGE OF $102 < \lambda < 105$
- IS ABSORBED WITH A HIGH EFFICIENCY BY WATER MOLECULES IN THIS RANGE

RADIATION DIRECTIONALITY

- RADIATION IS NORMALLY EMITTED IN ALL DIRECTIONS FROM A SOURCE, THOUGH IT MAY HAVE A PREFERENTIAL DIRECTION

- RADIATION ALSO IS EMITTED IN PREFERRED WAVELENGTHS, PRODUCING SPECTRA THAT CAN BE USED TO IDENTIFY MATERIALS

BLACKBODY RADIATION

- THE BLACKBODY IS THE IDEAL EMITTER
- THE INTENSITY OF BLACKBODY RADIATION AS A FUNCTION OF WAVELENGTH IS DEFINED BY PLANCK'S LAW:

$$E_{\lambda,b}(\lambda,T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]}$$

$$WHERE: \quad C_1 = 3.742x10^8 \frac{W\,\mu m^4}{m^2}$$

$$AND \;\; C_2 = 1.439x10^4\,\mu m K$$

MAXIMUM RADIATION INTENSITY

- THE MAXIMUM INTENSITY AT ANY WAVELENGTH IS OBTAINED BY DIFFERENTIATING PLANCK'S LAW WITH RESPECT TO λ AND CALCULATING THE ROOT FOR THE MAXIMUM

$$C_3 = (\lambda T)_{MAX} = 2897.8\,\mu m\,K$$

- THIS IS WIEN'S DISPLACEMENT LAW
- THIS RELATIONSHIP CAN BE USED TO CALCULATE THE TEMPERATURE OF STARS USING THE HIGHEST INTENSITY WAVELENGTH

TOTAL BLACKBODY EMISSIVE POWER

- INTEGRATION OF PLANCK'S LAW OVER THE RANGE OF λ, YIELDS THE TOTAL BLACKBODY EMISSIVE POWER FOR A GIVEN TEMPERATURE

$$E_b(T) = \int_0^\infty \frac{C_1}{\lambda^5[\exp(C_2 / \lambda T) - 1]} d\lambda$$

$$E_b(T) = \sigma T^4$$

$$WHERE: \ \sigma = 5.67x10^{-8} \frac{W}{m^2 K^4}$$

EMISSION BY WAVELENGTH

- INTENSITY FOR DIFFUSE BLACKBODY RADIATION

$$I = \frac{E_b}{\pi}$$

- BAND EMISSION OVER A RANGE OF WAVELENGTHS CAN BE CALCULATED WITH PLANCK'S LAW
- IS SUMMARIZED IN TABLE 12-2 AS A FUNCTION OF λT

EMISSION BY WAVELENGTH RANGE

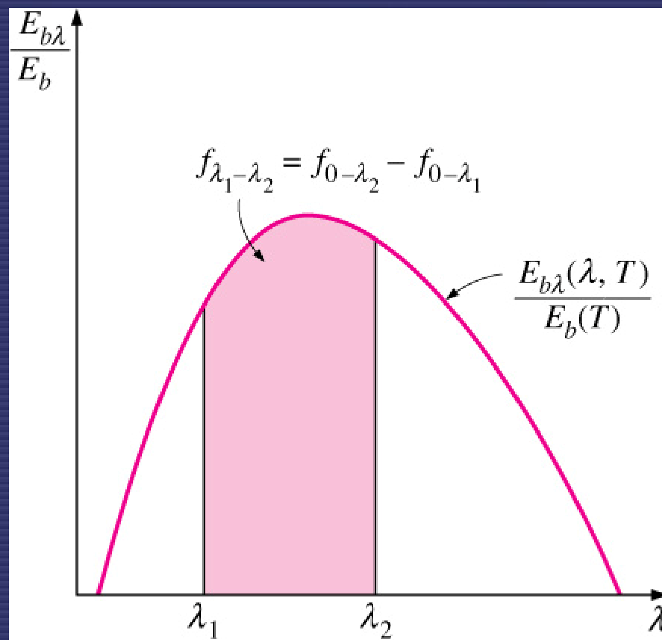


FIGURE 12–14
Graphical representation of the fraction of radiation emitted in the wavelength band from λ_1 to λ_2.

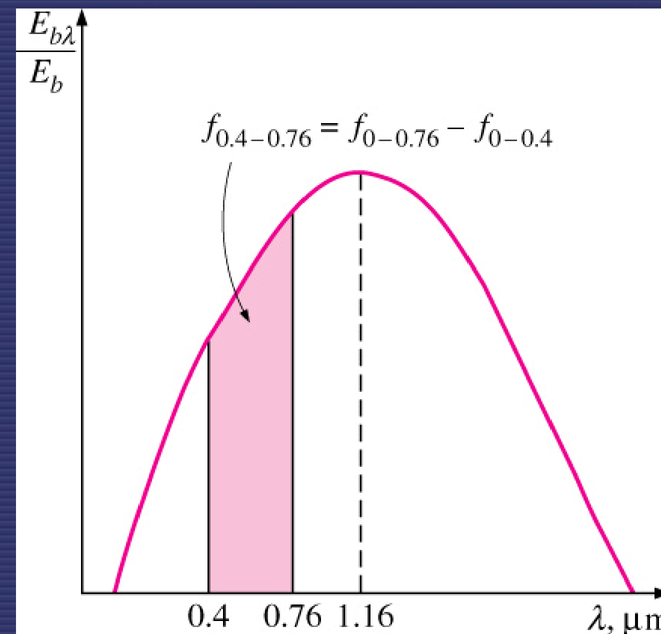


FIGURE 12–15
Graphical representation of the fraction of radiation emitted in the visible range in Example 12–2.

BLACKBODY EMISSION BY λ

- THE RELATIONSHIP FOR THE FRACTION OF EMISSIVE ENERGY FOR A BLACKBODY WITHIN A SPECIFIC RANGE OF WAVELENGTHS IS:

$$f_{\lambda 1-\lambda 2} = \frac{\int_0^{\lambda 2} E_{\lambda,b}\, d\lambda - \int_0^{\lambda 1} E_{\lambda,b}\, d\lambda}{\sigma T^4} = f_{0\to\lambda 2} - f_{0\to\lambda 1}$$

SOLID ANGLES

- EMISSION IN A PARTICULAR DIRECTION FROM A SOURCE, dA, IS EVALUATED RELATIVE TO THE ZENITH θ AND AZIMUTH φ ANGLES
- THE SOLID ANGLE, ω, IS DEFINED BY THE SECTION, dS, SWEPT OUT ON A HEMISPHERE AT A SPECIFIC RADIUS, r.

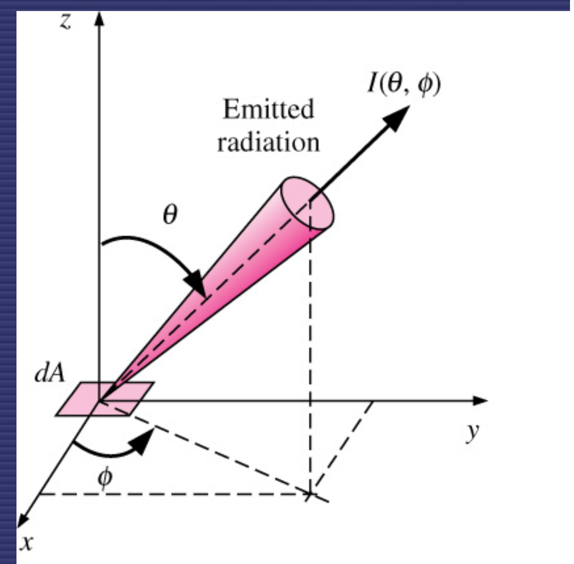


FIGURE 12–16
Radiation intensity is used to describe the variation of radiation energy with direction.

DIFFERENTIAL SOLID ANGLE

- DEFINED IN TERMS OF THE ANGLES AS:

$$d\omega = \frac{dS}{r^2} = \sin\theta \, d\theta \, d\phi$$

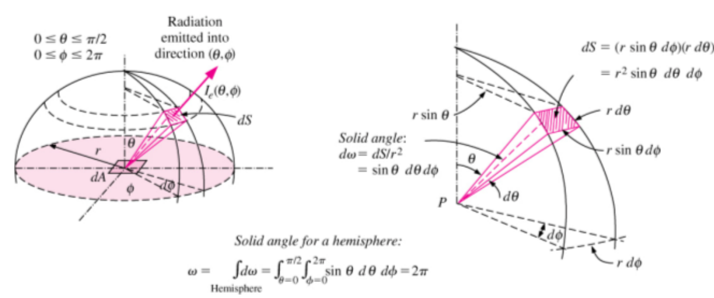
WHERE dS IS NORMAL TO THE AXIS OF THE ANGLE

DIFFERENTIAL EMISSIVITY

- THE SOLID ANGLE HAS UNITS OF STERADIANS
- THE PROJECTION OF dA AT A DISTANCE r FROM THE SOURCE AND ON A ZENITH OF φ IS A COSINE RELATIONSHIP

$$dA_n = dA \cos\theta$$

$$I_e(\theta, \phi) = \frac{d\dot{Q}_e}{dA \cos\theta \cdot d\omega} = \frac{d\dot{Q}_e}{dA \cos\theta \sin\theta \, d\theta \, d\phi} \qquad (\mathrm{W/m^2 \cdot sr}) \qquad \textbf{(12–13)}$$



STEFAN-BOLTZMAN DERIVATION

- INTENSITY OF RADIATION FROM A BLACKBODY (PLANCK'S LAW)

$$I(\nu,T)=\frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

- Idv IS ENERGY IN FREQUENCY RANGE BETWEEN v AND v+dv, PER UNIT SURFACE AREA PER UNIT TIME PER UNIT SOLID ANGLE
- TOTAL POWER FROM A SURFACE AREA A, THROUGH SOLID ANGLE dΩ IS

$$Power = I(\nu,T)A\,d\nu\,d\Omega$$

STEFAN-BOLTZMAN DERIVATION

- OVER A HALF SPHERE RECEIVER, POWER PER UNIT AREA IS

$$\frac{P}{A} = \int_0^{\infty} I(\nu, T)\, d\nu \int_0^{2\pi} d\theta \int_0^{\pi/2} \cos\phi \sin\phi\, d\phi$$

$$= \pi \int_0^{\infty} I(\nu, T)\, d\nu = \frac{2\pi h}{c^2} \int_0^{\infty} \frac{\nu^3}{e^{\frac{h\nu}{kT}} - 1}$$

- THROUGH SOME SUBSTITUTIONS, THIS EXPRESSION INTEGRATES TO

$$\frac{P}{A} = \frac{2\pi^5 k^4}{15 h^3 c^2} T^4 = \left[5.67 * 10^{-8} \frac{W}{m^2 K^4} \right] T^4$$

RADIATION INTENSITY

- THE BLACKBODY, DIFFUSE EMITTED INTENSITY IS DEFINED IN TERMS OF THE SOLID ANGLE
- IRRADIATION, INCIDENT RADIATION, SEE FIGURE 12-20

$$I_b = \frac{\sigma T^4}{\pi} \frac{W}{m^2\, sr}$$

- IS A FUNCTION OF WAVELENGTH AND THE INCIDENT ANGLE:

$$G_\lambda(\lambda) = \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,i}(\lambda, \theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi$$

- OVER THE ENTIRE SPECTRUM OF WAVELENGTHS:

$$G = \int_0^\infty G_\lambda d\lambda$$

RADIATION INTENSITY

- IF THE INCOMING RADIATION IS DIFFUSE, THEN IT IS INDEPENDENT OF θ AND φ, SO THE EQUATIONS BECOME:

$$G_\lambda(\lambda) = \pi I_{\lambda,i}(\lambda)$$

$$G = \pi I_i$$

RADIOSITY

- REPRESENTS ***ALL*** THE RADIANT ENERGY LEAVING A SURFACE (SEE FIGURE 12-21)
- INCLUDES REFLECTED AND EMITTED ENERGY
- CAN BE EXPRESSED IN TERMS OF WAVELENGTH AND ANGLES AS:

$$J_\lambda(\lambda) = \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,e+r}(\lambda,\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi$$

- TOTAL RADIOSITY CAN THEN BE EXPRESSED AS:

$$J = \int_0^{\infty} \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,e+r}(\lambda,\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi\, d\lambda$$

DIFFUSE SURFACE

- IF THE SURFACE IS A DIFFUSE REFLECTOR AND A DIFFUSE EMITTER, THEN RADIOSITY IS INDEPENDENT OF θ AND φ, SO THE EQUATIONS BECOME (SEE CHAP 13)

$$J_{\lambda}(\lambda) = \pi I_{\lambda, e=r}(\lambda)$$

$$J = \pi I_{e+r}$$