EELE408 Photovoltaics
Lecture 03: Characteristics of Sunlight

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Wave – Particle Duality

- Light behaves as both a wave and a particle
  - Wave Properties
    - Refraction
    - Diffraction
    - Interference
  - Particle Properties
    - Emission and Absorption of Light
    - Blackbody Radiation
    - Photoelectric effect

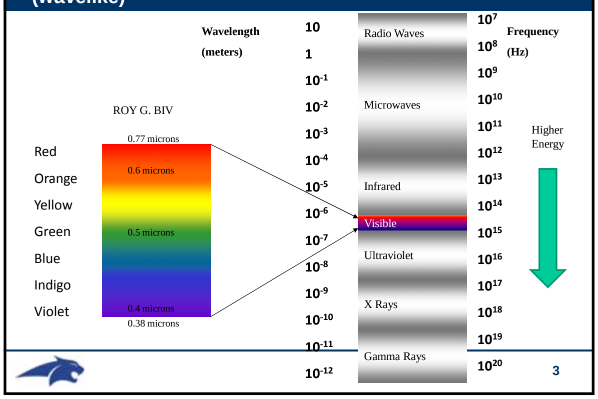
$$c = \nu\lambda = f\lambda$$

c: speed of light
n: frequency
l: wavelength
E: Energy
h: Planck's Constant

$$E = h\nu$$

$$c = 3\times10^{8}(m/s)$$
$$h = 6.636\times10^{-34}(J-s) = 4.136\times10^{-15}(eV-s)$$

Electromagnetic Spectrum (wavelike)



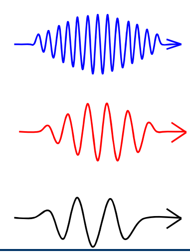
Photon Energy (Particle Like)

$$E = h\nu = \frac{hc}{\lambda} \Rightarrow E(eV) = \frac{1.24}{\lambda(\mu)}$$

High energy photon for blue light

Low energy photon for red light

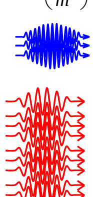
Very low energy photon for infrared (invisible)



Photon Flux & Energy Density

$$\text{Photon Flux} = \frac{\text{Number of Photons}}{(\text{second})(\text{Area})} = \Phi$$

$$\text{Energy Density}: (\text{Photon Flux})(\text{Energy per Photon}): H\left(\frac{W}{m^2}\right) = \Phi\left(\frac{hc}{\lambda}(J)\right)$$



For the same intensity of light shorter wavelengths require fewer photons, since the energy content of each individual photon is greater

Radiant Power Density

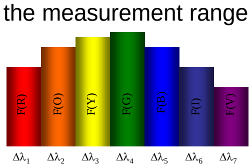
$$H\left(\frac{W}{m^2}\right) = \frac{\#\,photons}{\sec - m^2}\times\frac{E(J)}{photon} = \Phi\times E(J) = \Phi\frac{hc}{\lambda}$$

Radiant Power Density

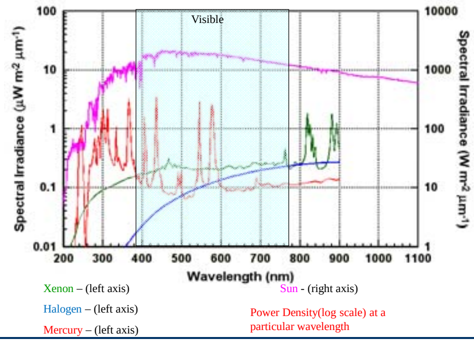
- The total power density emitted from a light source

$$H = \int_0^\infty E(\lambda)d\lambda \Rightarrow \sum_{i=0}^{N} E(\lambda_i)\Delta\lambda_i$$

- The spectral irradiance is multiplied by the wavelength range for which is was measured and summed over the measurement range



Spectral Irradiance



Solar Radiation

Blackbody Radiation

- Ideal absorber and emitters of electromagnetic radiation
  - The hotter the body the more radiation emitted
  - The hotter the body the higher the energy of the spectrum peak
- Classical physics unable to explain blackbody radiation
  - 1900-Max Planck: Quantization of Energy Radiation
  - 1905-Albert Einstein: Photoelectric Effect

Planck's Formula

$$E(\nu) = \frac{8\pi h\nu^3}{c^3\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]} d\nu \left(\frac{J-s}{m^3}\right)$$

Integrate over all energies to get the intensity emitted into a hemisphere

$$H = \frac{c}{4}\int_0^\infty E(\nu)d\nu = \sigma T^4$$

H: intensity of radiation (W/m^2)
Stefan-Boltzmann Constant s = 5.67x10-8 (W/(m^{2}K^4))

- A body in thermal equilibrium emits and absorbs radiation at the same rate
- A body that absorbs all the radiation incident on it is an ideal **blackbody**
- The power per area radiated is given by the **Stefan-Boltzmann Law**

$$H = \sigma T^4 \left(W/m^2\right) \qquad \sigma = 5.6704\times10^{-8}\left(\frac{W}{m^2K^4}\right)$$

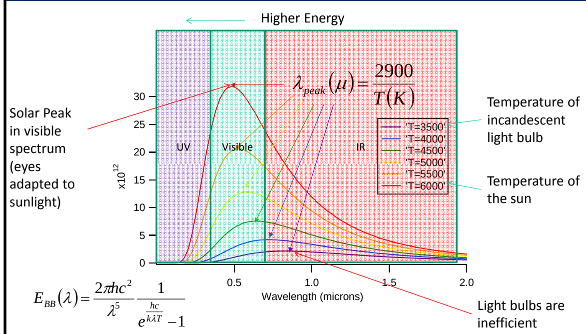
- This function has a maximum given by **Wien's Displacement Law**

$$\lambda_{peak}(\mu) = \frac{2900}{T(K)}$$

- The spectral irradiance of a blackbody radiator is given by **Planck's Law**

$$E_{BB}(\lambda,T) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{k\lambda T}}-1}$$

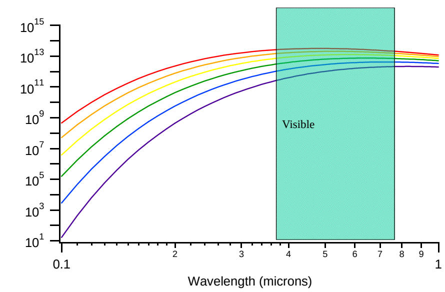
Plot of Planck's Law



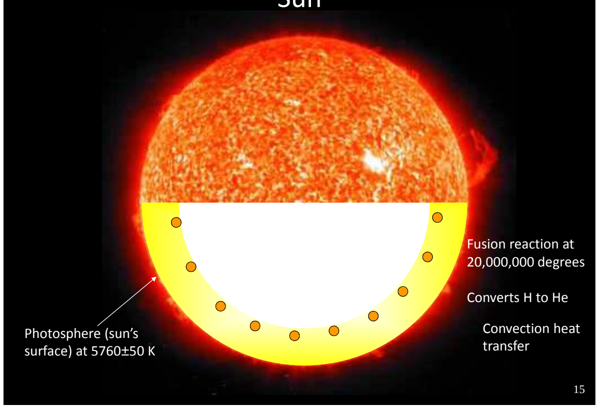
$$\lambda_{peak}(\mu) = \frac{2900}{T(K)}$$

$$E_{BB}(\lambda) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{k\lambda T}} - 1}$$

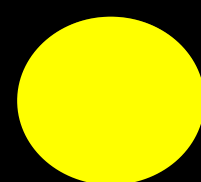
Sun's maximum at visible spectrum



Sun



Sunlight in Space

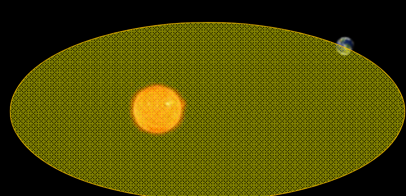


The energy is emitted from the surface of the sun as a sphere of light

The size of the sphere grows as the light moves farther from the sun causing the power density to reduce

$$H(D) = \frac{4\pi R_{sun}^2}{4\pi D^2} H_0 = \frac{R_{sun}^2}{D^2} H_0 \Rightarrow H_{EarthOrbit} = 1367\left(W/m^2\right)$$

Sunlight at Earth's Orbit



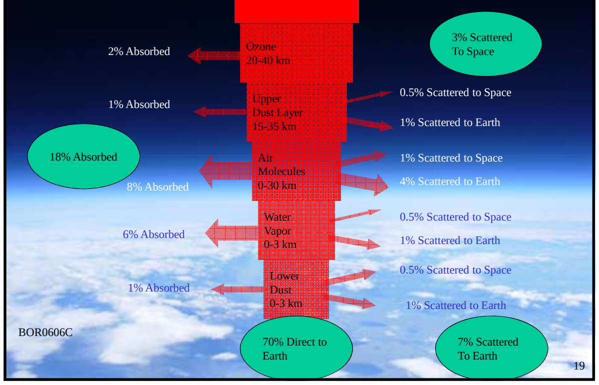
$$H_{EarthEllipticalOrbit} = 1367\left[1 + 0.033\cos\left(\frac{360(n-2)}{365}\right)\right]\left(W/m^2\right)$$

n is the day of the year

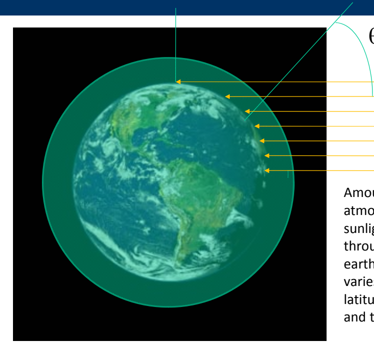
Sunlight at Earth's Surface

- Atmospheric Effects
  - Absorption
  - Scattering
  - Local Variations
    - Clouds
    - Pollution
    - Weather
- Latitude
- Season of Year
- Time of Day

Clear Sky Absorption & Scattering



Air Mass



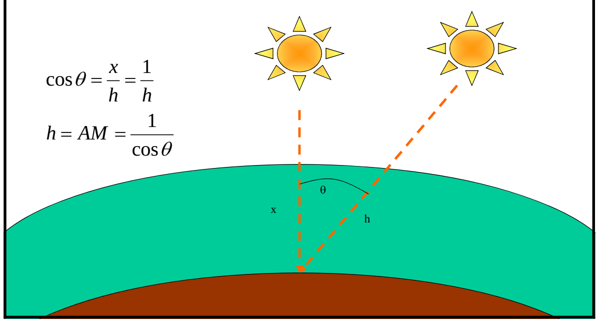
Amount of atmosphere the sunlight has to go through to reach earth surface varies with latitude, season and time of day

Calculating Air Mass

- The path length that light takes through the atmosphere normalized to the shortest possible path length

$$\cos\theta = \frac{x}{h} = \frac{1}{h}$$

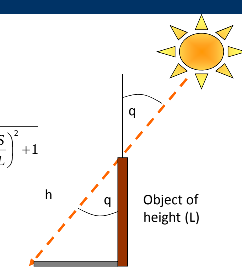
$$h = AM = \frac{1}{\cos\theta}$$



Measuring the Air Mass

$$\cos\theta = \frac{L}{h} \Rightarrow$$

$$AM = \frac{1}{\cos\theta} = \frac{h}{L} = \frac{\sqrt{S^2 + L^2}}{L} = \sqrt{\left(\frac{S}{L}\right)^2 + 1}$$



Neglects the curvature of the earth's atmosphere

Curvature compensated

$$AM = \frac{1}{\cos\theta + 0.50572(96.07995 - \theta)^{-1.36364}}$$

Air Mass Values

Theta (θ)	$\frac{1}{\cos\theta}$	Air Mass
0°	1	AM1.0
48.2°	1.5	AM1.5
60°	2	AM2.0
75°>	Not Accurate	

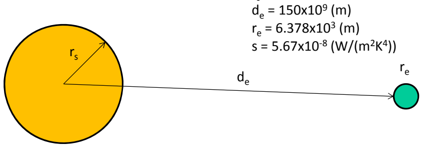
Sun Radiation

- The sun is approximately a blackbody radiator at 6000K
- Earth is approximately a blackbody radiator at 300K
- Total output of the sun is 4×10^{26} W
- Power reaching earth is 1.72×10^{11} W
- AM0 = 1353 W/m^2
- AM1.5 = 1000 W/m^2 → Used as Standard

Earth Temperature Calculation

Assume the sun at 6000K is a blackbody radiator, then calculate the earth temperature if it radiates all the solar energy it captures as a blackbody.

r_s = 6.955x10^8 (m)
d_e = 150x10^9 (m)
r_e = 6.378x10^3 (m)
s = 5.67x10^{-8} (W/(m^{2}K^4))



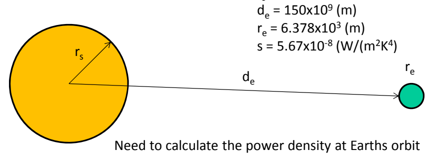
$$H = \sigma T^4 \left(W/m^2\right) = 5.67\times10^{-8}(6000)^4 = 7.35\times10^7\left(W/m^2\right)$$

$$P = H\left(4\pi r_s^2\right) = 7.35\times10^7(4\pi)\left(6.955\times10^8\right)^2 = 4.5\times10^{26}(W)$$

Power Radiated from the sun

Earth Temperature Calculation 2

r_s = 6.955x10^8 (m)
d_e = 150x10^9 (m)
r_e = 6.378x10^3 (m)
s = 5.67x10^{-8} (W/(m^{2}K^4))



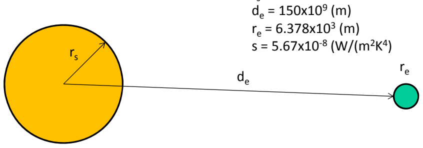
Need to calculate the power density at Earths orbit

$$P = 4.5\times10^{26}(W) = H(4\pi)d_e^2 \Rightarrow H = \frac{4.5\times10^{26}}{(4\pi)\left(150\times10^9\right)^2} = 1590\left(W/m^2\right)$$

Power density at Earths orbit

Earth Temperature Calculation 3

r_s = 6.955x10^8 (m)
d_e = 150x10^9 (m)
r_e = 6.378x10^3 (m)
s = 5.67x10^{-8} (W/(m^{2}K^4))



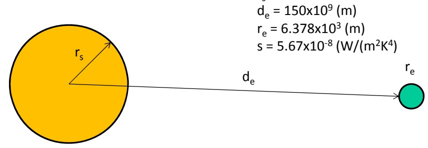
Need to calculate the power captured by the earth

$$H = 1590\left(W/m^2\right) \Rightarrow P = H\left(\pi r_e^2\right) = 1590(\pi)\left(6.378\times10^3\right)^2 = 2\times10^{11}(W)$$

Power captured by earth

Earth Temperature Calculation 4

r_s = 6.955x10^8 (m)
d_e = 150x10^9 (m)
r_e = 6.378x10^3 (m)
s = 5.67x10^{-8} (W/(m^{2}K^4))



Assume the earth is radiating like a blackbody

$$H = \frac{2\times10^{11}(W)}{(4\pi)r_e^2} = \sigma T^4 \Rightarrow T = \left(\frac{2\times10^{11}}{(4\pi)\left(6.378\times10^3\right)^2\left(5.67\times10^{-8}\right)}\right)^{\frac{1}{4}} = 288K$$

Temperature of earth

Planet Temperatures

$$P = (\sigma)T_S^4\frac{(4\pi)r_s^2}{(4\pi)d_e^2}\frac{(\pi)r_e^2}{(4\pi)r_e^2} = (\sigma)T_e^4 \Rightarrow T_s\left(\frac{r_s^2}{4d_e^2}\right)^{1/4} = T_e$$

Planet	Distance to Sun (10^9)	Calculated Temperature	Average Temperature
Mercury	57	469K	452K
Venus	108	340K	740K
Earth	150	288K	288K
Mars	227	235K	210K

Why the big discrepancy?

Green House Effect

- Venus atmosphere is 96% CO_2
  - The carbon dioxide captures the incoming radiation energy and prevents it from radiating
- Pre-1860→Pre-Industrial Revolution
  - CO_2 concentration = 280 ppm
  - Found by analyzing ice core samples from the Arctic and Antarctic
- Today
  - CO_2 concentration = 335 ppm
  - Burning of Fossil Fuel: Trapped Organic Matter (Carbon)
  - Coal and Oil
  - What took 1 million years to form is used in 1 year.

Green House Effect 2

- Water absorbs in the band λ ~ 4-7μ
- Carbon Dioxide absorbs at λ ~13-19μ
- Most energy escapes in the band ~ 7-13μ
- Delicate balance of energy in = energy out
- Disruption in balance create temperature changes → Climate Changes

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Sun Light Attenuation (70%)

- Rayleigh Scattering by molecules in the atmosphere (~λ^{-4} dependence)
  - Significant at short wavelengths
- Scattering by aerosols and dust
- Absorption by atmospheric gases

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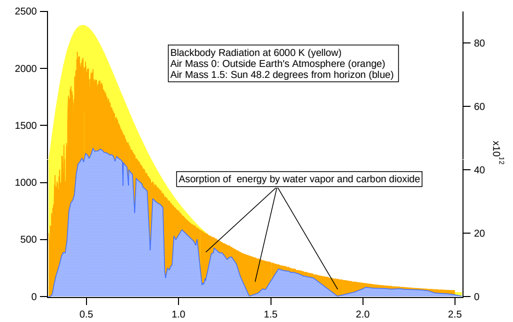
Solar Light Distribution



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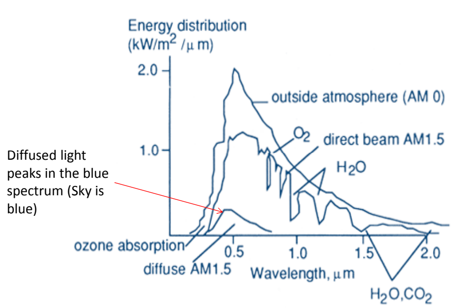
Diffused Light

- 2 Components of sunlight $AM_{Global} = AM_{direct} + AM_{diffuse}$
- 100%=90%+10% at AM0
- Diffuse Increases with increasing AM
- Overcast Day → 100% diffuse
- 20% of maximum possible

Direct and Diffuse Radiation



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Intensity Based on Air Mass

- The intensity of direct sunlight can be experimentally fit to the equation:

$$I_D = 1.367(0.7)^{\left(AM^{0.678}\right)}\left(kW/m^2\right)$$

- I_D: Intensity of direct sunlight
- 1.367 Solar Constant
- 0.7: 70% of the light reaches the Earth's surface
- 0.678 Experimental fit of the data which accounts for atmospheric variations

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Intensity with Altitude Adjustment

- The intensity of direct sunlight increases with altitude:

$$I_D = 1.367\left[(1-ah)(0.7)^{\left(AM^{0.678}\right)} + ah\right]\left(kW/m^2\right)$$

- a: empirical fit constant = 0.14
- h: height above sea level in kilometers

Estimate of Global Intensity

- The diffuse radiation is approximately 10% of the direct radiation
- The clear day global intensity is estimated as:

$$I_G = 1.1(I_D)\left(kW/m^2\right)$$