EE580 – Solar Cells
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- Lecture 03
- Nature of Sunlight

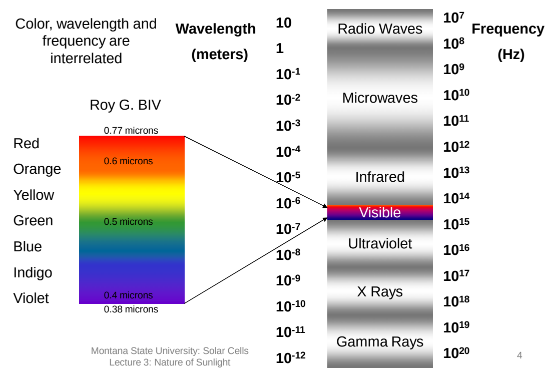
Wave-Particle Duality

- Light acts as
  - Waves: electromagnetic radiation
    - Refraction - bending of light through a prism
    - Diffraction - bending of light around an edge
    - Interference – adding of light waves
  - Particles: photons – individual packets of energy
    - Photoelectric Effect
    - Blackbody Radiation

Properties of Light

- Sunlight contains photons of many different frequencies (we see as different colors)
- Visible Light
  - 0.38 microns – 0.77 microns (10^{-6} meters)
  - Blue - Red
- Frequency (f) and Wavelength (λ) are inversely related: $f = 1/\lambda$
  - High Energy → High Frequency → Short Wavelength
  - Low Energy → Low Frequency → Long Wavelength

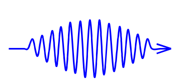
Electromagnetic Spectrum



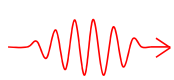
Photon Energy

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

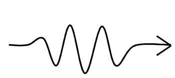
High energy photon for blue light



Low energy photon for red light



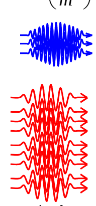
Very low energy photon for infrared (invisible)



Photon Flux & Energy Density

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

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



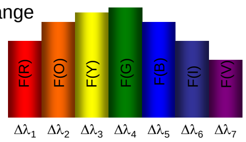
For the same intensity of light shorter wavelengths require fewer photons, since the energy content of each individual photon is greater

Radiant Power Density

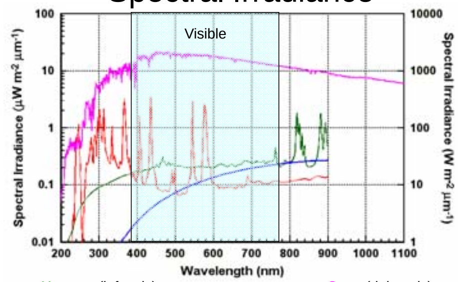
- The total power density emitted from a light source

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

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



Spectral Irradiance



Xenon – (left axis)
Sun - (right axis)
Halogen – (left axis)
Mercury – (left axis)
Power Density at a particular wavelength

Solar Radiation

Blackbody Radiation

- 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**

$$H = \sigma T^4$$

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

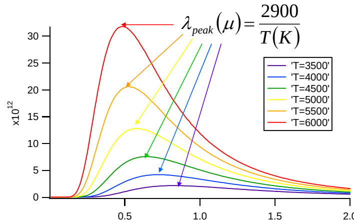
$$\lambda_{peak}(\mu) = \frac{2900}{T(K)}$$

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

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

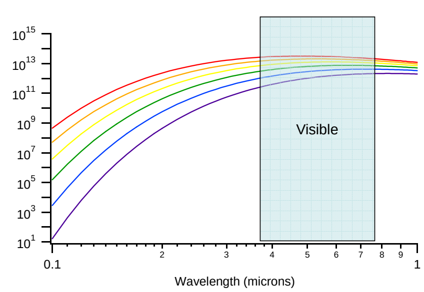
Plot of Planck's Law

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

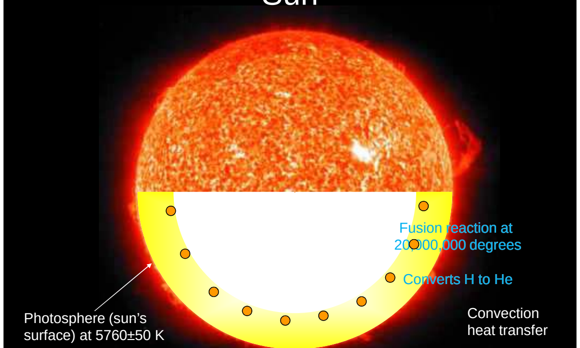


$$F_{BB}(\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{k\lambda T}} - 1}$$

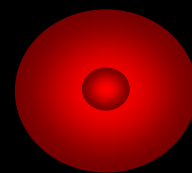
Sun's maximum at visible spectrum



Sun



Sunlight in Space

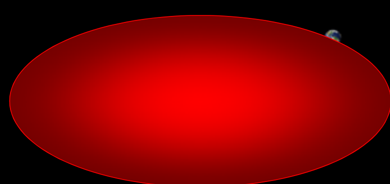


The energy is emitted from the surface of the sun as a sphere of light

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

$$H(D)=\frac{4\pi R_{sun}^2}{4\pi D^2}H_0=\frac{R_{sun}^2}{D^2}H_0 \Rightarrow H_{EarthOrbit}=1353\left(W/m^2\right)$$

Sunlight at Earth's Orbit



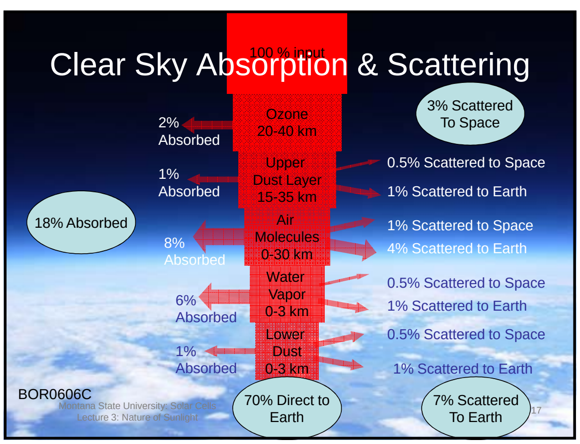
$$H_{EarthEllipticalOrbit}=1353\left[1+0.033\cos\left(\frac{360(n-2)}{365}\right)\right]\left(W/m^2\right)$$

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

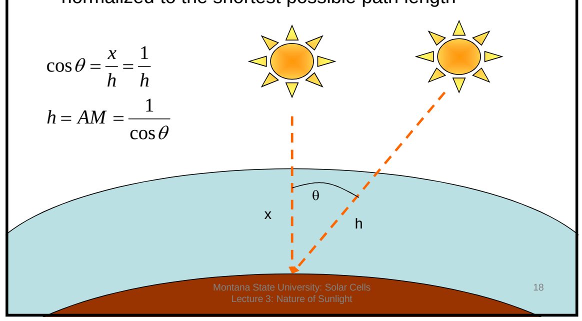


Air Mass

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

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

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

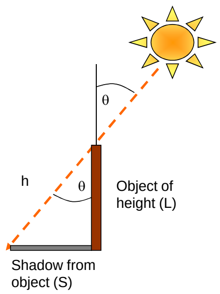


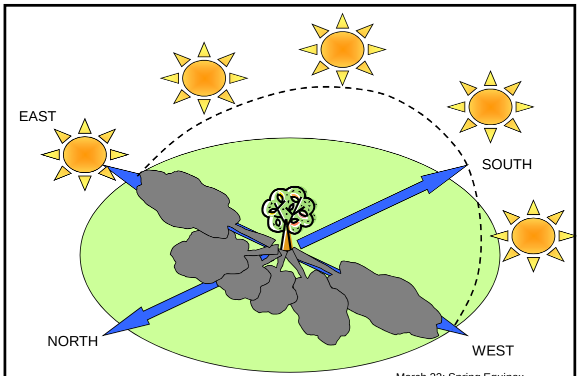
Measuring the Air Mass

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

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

Neglects the curvature of the earth's atmosphere





What time of year is this image true?

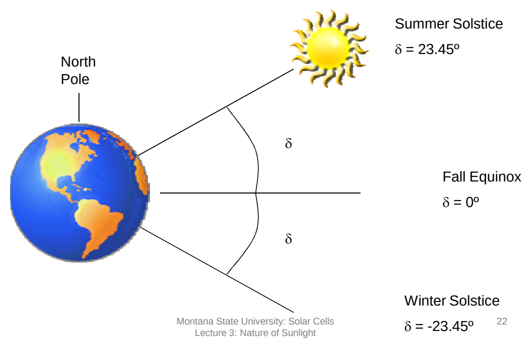
March 22: Spring Equinox

Sept 23: Fall Equinox

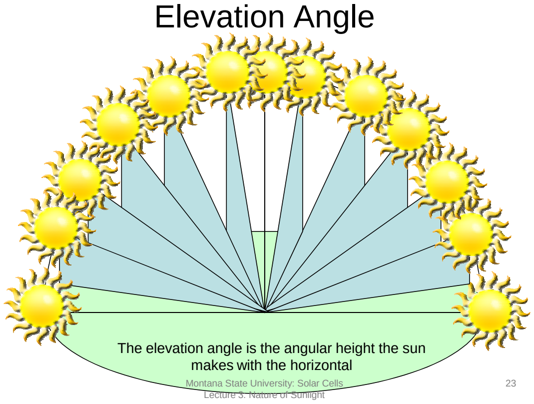
Declination Angle

$$\delta = 23.45^\circ \sin\left[\frac{360}{365}(d-81)\right]$$

Declination Angle of Sun

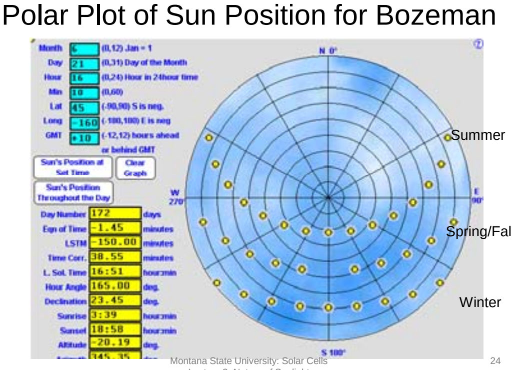


Elevation Angle

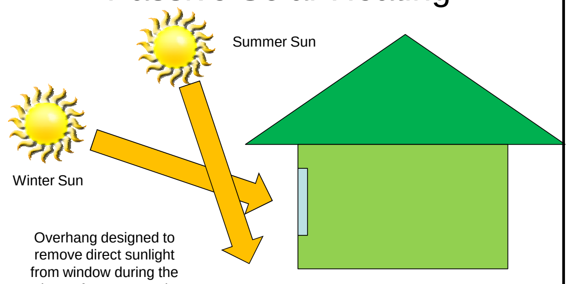


The elevation angle is the angular height the sun makes with the horizontal

Polar Plot of Sun Position for Bozeman



Passive Solar Heating



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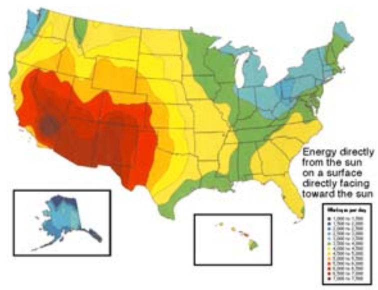
Insolation



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Solar Cell Land Area Requirements for the USA's Energy with Solar PV

- 100 miles by 100 miles in Nevada would provide the equivalent of the <u>entire</u> US electrical demand
- Distributed (to sites with less sun) it would take less than 25% of the area covered by US roads.

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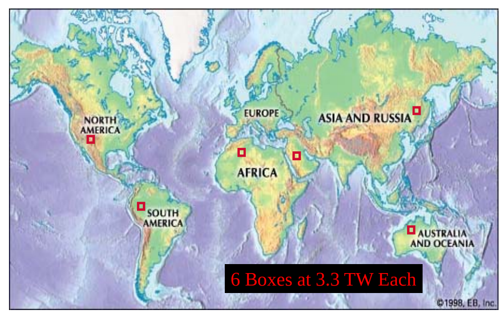
Solar Cell Land Area Requirements for the World's Energy with Solar PV



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