Wave – Particle Duality

- Light behaves as both a wave and a particle
  - Wave Properties
    - Refraction
    - Diffraction
    - Interference $c = v \lambda = f \lambda$
      - $c$: speed of light
      - $v$: frequency
      - $\lambda$: wavelength
      - $f$: Planck's Constant
  - Particle Properties
    - Emission and Absorption of Light
    - Blackbody Radiation
    - Photoelectric effect
      
      $E = hf$
      
      $c = 3 \times 10^8 \text{m/s}$
      $h = 6.626 \times 10^{-34} (J \cdot s) = 4.136 \times 10^{-15} (eV \cdot s)$

Electromagnetic Spectrum (wavelike)

<table>
<thead>
<tr>
<th>Wavelength (meters)</th>
<th>10^-10</th>
<th>10^-9</th>
<th>10^-8</th>
<th>10^-7</th>
<th>10^-6</th>
<th>10^-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
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<tr>
<td>Orange</td>
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<tr>
<td>Yellow</td>
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<tr>
<td>Green</td>
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<tr>
<td>Blue</td>
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<tr>
<td>Indigo</td>
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<tr>
<td>Violet</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Visible</td>
<td>4.08</td>
<td>700</td>
<td>589</td>
<td>492</td>
<td>430</td>
<td>380</td>
</tr>
<tr>
<td>Infrared</td>
<td>1000</td>
<td>1200</td>
<td>1000</td>
<td>880</td>
<td>750</td>
<td>650</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>1000</td>
<td>1200</td>
<td>1000</td>
<td>880</td>
<td>750</td>
<td>650</td>
</tr>
<tr>
<td>X-rays</td>
<td>1000</td>
<td>1200</td>
<td>1000</td>
<td>880</td>
<td>750</td>
<td>650</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>1000</td>
<td>1200</td>
<td>1000</td>
<td>880</td>
<td>750</td>
<td>650</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>1000</td>
<td>1200</td>
<td>1000</td>
<td>880</td>
<td>750</td>
<td>650</td>
</tr>
</tbody>
</table>

Photon Energy (Particle Like)

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

- High energy photon for blue light
- Low energy photon for red light
- Very low energy photon for infrared (invisible)

Photon Flux & Energy Density

- Photon Flux = Number of Photons (second/Area) = $\Phi$
- Energy Density = Photon Flux × Energy per Photon:
  
  $\Phi \left( \frac{W}{m^2} \right) = \Phi \left( \frac{hc}{\lambda} \right) \times E(\nu \lambda) = \Phi \frac{hc}{\lambda}$

Radiant Power Density

$H \left( \frac{W}{m^2} \right) = \frac{\# \text{ photons}}{\text{sec} \cdot m^2} \times E(\nu \lambda) = \Phi \frac{hc}{\lambda}$

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
  \[ H = \int_{\lambda} E(\lambda) \, d\lambda \Rightarrow \sum_{\lambda} E(\lambda) \, d\lambda \]
- The spectral irradiance is multiplied by the wavelength range for which it was measured and summed over the measurement range.

Spectral Irradiance

- Visible Spectrum
- Xenon – (left axis)
- Sun – (right axis)
- Halogen – (left axis)
- Mercury – (left axis)

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-Planck: Quantization of Energy Radiation
  - 1905-Einstein: Photoelectric Effect

Planck’s Formula

- 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
  \[ H = \sigma T^4 \left( W/m^2 \right) \]
- This function has a maximum given by Wien’s Displacement Law
  \[ \lambda_{\text{max}}(T) = \frac{2900}{T(K)} \]
- The spectral irradiance of a blackbody radiator is given by Planck’s Law
  \[ E_{\lambda}(\lambda, T) = \frac{2 \pi h c^2}{\lambda^5 (e^{\frac{hc}{\lambda kT}} - 1)} \]

H: intensity of radiation (W/m²)
Stefan-Boltzmann Constant \( \sigma = 5.67 \times 10^{-8} \text{ W/(m²K⁴)} \)
Sun's maximum at visible spectrum

Solar Peak in visible spectrum (eyes adapted to sunlight)

\[ E_n(\lambda) = \frac{2\pihc}{\lambda^4} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \]

Higher Energy

Temperature of incandescent light bulb

Temperature of the sun

Light bulbs are inefficient

Temperature of the sun

\[ T = 5000 \]

\[ T = 5500 \]

\[ T = 6000 \]

\[ T = 3500 \]

\[ T = 4000 \]

\[ T = 4500 \]

Visible

Wavelength (microns)

\[ \lambda_{peak} \]

\[ K \]

\[ h \]

\[ c \]

\[ E_n \]

\[ \pi \]

\[ \lambda \]

\[ k \]

\[ T \]

\[ c \]

\[ h \]

\[ E \]

\[ \pi \]

\[ \lambda \]

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\[ k \]

\[ T \]

\[ c \]

\[ h \]

\[ E \]
### Clear Sky Absorption & Scattering

- 18% Absorbed
- 10% Absorbed
- 5% Absorbed
- 2% Absorbed

### 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.

\[ \cos \theta = \frac{x}{h} \]

\[ h = AM = \frac{1}{\cos \theta} \]

### Measuring the Air Mass

\[ AM = \frac{1}{\cos \theta} \frac{L}{\sqrt{L^2 + h^2} - h} \]

Neglects the curvature of the earth’s atmosphere.

Curvature compensated

\[ AM = \frac{1}{\cos \theta} \frac{L}{\sqrt{L^2 + h^2} - h} \]

Object of height (L)

Shadow from object (S)

### Air Mass Values

<table>
<thead>
<tr>
<th>Theta (θ)</th>
<th>( \frac{1}{\cos \theta} )</th>
<th>Air Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1</td>
<td>AM1.0</td>
</tr>
<tr>
<td>48.2°</td>
<td>1.5</td>
<td>AM1.5</td>
</tr>
<tr>
<td>60°</td>
<td>2</td>
<td>AM2.0</td>
</tr>
<tr>
<td>75°&gt;</td>
<td>Not Accurate</td>
<td></td>
</tr>
</tbody>
</table>

### 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 \( 4 \times 10^{26} \) W
- Power reaching earth is \( 1.72 \times 10^{11} \) W
- \( AM0 = 1353 \) W/m²
- \( AM1.5 = 1000 \) W/m² → 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.

\[
\begin{align*}
rs &= 6.955 \times 10^8 \text{ (m)} \\
\text{de} &= 150 \times 10^9 \text{ (m)} \\
re &= 6.378 \times 10^3 \text{ (m)} \\
s &= 5.67 \times 10^{-8} \text{ (W/(m}^2\text{K}^4)}
\end{align*}
\]

\[
H = \sigma T^4 \left( \text{W/m}^2 \right) = 5.67 \times 10^{-8} \left( 6000 \right)^4 = 7.35 \times 10^5 \left( \text{W/m}^2 \right)
\]

\[
P = H \left( 4\pi r_e^2 \right) = 7.35 \times 10^5 \left( 4\pi \left( 6.378 \times 10^3 \right)^2 \right) = 4.5 \times 10^{10} \left( \text{W} \right)
\]

Power Radiated from the sun

Need to calculate the power density at Earth’s orbit

\[
P = 4.5 \times 10^{10} \left( \text{W} / \text{m}^2 \right) = H \left( 4\pi k_e^2 \right) \Rightarrow H = \frac{4.5 \times 10^{10}}{\left( 4\pi \left( 150 \times 10^9 \right)^2 \right)} = 1590 \left( \text{W/m}^2 \right)
\]

Power density at Earth’s orbit

Earth Temperature Calculation 2

Need to calculate the power captured by the earth

\[
H = 1590 \left( \text{W/m}^2 \right) \Rightarrow P = H \left( 4\pi \right) = 1590 \left( 4\pi \left( 6.378 \times 10^3 \right)^2 \right) = 2 \times 10^5 \left( \text{W} \right)
\]

Power captured by earth

\[
T = \left( \frac{2 \times 10^5}{4\pi \left( 6.378 \times 10^3 \right)^2 \left( 5.67 \times 10^{-8} \right) \left( 150 \times 10^9 \right)^2} \right)^{1/4} = 288 \text{K}
\]

Temperature of earth

Earth Temperature Calculation 4

Green House Effect

- Venus atmosphere is 98% CO₂
  - The carbon dioxide captures the incoming radiation energy and prevents
  it from radiating
- Pre-1860→Pre-Industrial Revolution
  - CO₂ concentration = 280 ppm
  - Found by analyzing ice core samples from the Arctic and Antarctic
- Today
  - CO₂ 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 $\lambda \sim 4-7 \mu$.
- Carbon Dioxide absorbs at $\lambda \sim 12-19 \mu$.
- Most energy escapes in the band $\sim 7-13 \mu$.
- Delicate balance of energy in = energy out.
- Disruption in balance create temperature changes $\Rightarrow$ Climate Changes.

**Sun Light Attenuation (70%)**
- Rayleigh Scattering by molecules in the atmosphere ($\sim \lambda^{-4}$ dependence).
- Significant at short wavelengths.
- Scattering by aerosols and dust.
- Absorption by atmospheric gases.

**Solar Light Distribution**

<table>
<thead>
<tr>
<th>AM Global</th>
<th>AM Direct</th>
<th>AM Diffuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- 2 Components of sunlight
- Overcast Day $\Rightarrow$ 100% diffuse
- 100% = 90% + 10% at AM0
- Diffuse increases with increasing AM.

**Direct and Diffuse Radiation**

**Intensity Based on Air Mass**
- The intensity of direct sunlight can be experimentally fit to the equation:
  
  $$I_D = 1.367(0.7)^{AM_{0.7}} (kW/m^2)$$
- $I_D$: 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.
Intensity with Altitude Adjustment

- The intensity of direct sunlight increases with altitude:
  \[ I_D = 1.367 \left( 1 - ah \right) \left( 0.7 \right)^{ah} + ah \left( kW/m^2 \right) \]

- 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:

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