Mon. Feb. 26, 2018

• Midterm exam date:
  – Mon. Mar. 5 or Wed. Mar 7 (decide today in class)

• Reading: Sabins Ch. 5 (Thermal)

• Finish:
  – Theory of mineral absorptions (not in text)
    • Use slides posted for last Monday

• Thermal Remote Sensing
Use previously posted slides for Absorption Theory
Thermal Radiation Intro.

• Thermal Emission – Application (mostly Monday)
  – Direct measurements of temperature (volcanoes, weather, etc.)
  – Mineral composition through “emissivity” (how well it radiates thermal IR)
  – Indirect information from heating & cooling rates (thermal inertia)

• Thermal Emission – Theory
  – Planck Blackbody formula
  – Stefan-Boltzmann law and Wien displacement law
  – Kilauea Aster examples
  – Emissivity
    • Emissivity spectra of silicates and other minerals
    • Emissivity mapping of Mars
  – Thermal Inertia (Monday.)
Temperature and Heat

• Thermal energy is “kinetic energy” of moving atoms and molecules
• Want temperature scale where energy is proportional to T
  – Celsius scale is “arbitrary” (Fahrenheit even more so)
    • 0°C = freezing point of water
    • 100°C = boiling point of water
  – By experiment, available energy = 0 at “Absolute Zero” = –273°C (-459.7°F)
  – Define “Kelvin” scale with same step size as Celsius, but 0K = -273°C = Absolute Zero

• Use Kelvin Scale for most of work in this course
  – Available energy is proportional to T, making equations simple
  – 273K = freezing point of water
  – 373K = boiling point of water
  – 300K approximately room temperature
Thermal Energy Transfer

• Conduction
  • molecule – to – molecule (contact)

• Convection
  • motion of material carrying heat

• Radiation
  • electromagnetic radiation
Planck “Black Body Radiation”

- Hot objects glow (emit light)

- Reason for name “Black Body Radiation”
  - A material which reflects light also has trouble emitting it:
    - reflectance + absorbance + transmission = 1
    - reflectance + absorbance = 1 if transmission negligible
  
  - A black material in one which readily absorbed all wavelengths of light. These turn out to be the same materials which also readily emit all wavelengths when hot.
    - reflectance + emissivity + transmission = 1
    - reflectance + emissivity = 1 if transmission negligible
    - \( r + \varepsilon = 1 \quad \text{ (at given } \lambda) \)
    - In thermal infrared, most materials are opaque so this rule holds (and usually \( r \ll 1, \varepsilon \approx 1 \))

- The hotter the material the more energy it emits as light
  - As you heat up a filament or branding iron, it glows brighter and brighter

- The hotter the material the more readily it emits high energy (blue) photons
  - As you heat up a filament or branding iron, it first glows dull red, then bright red, then orange, then if you continue, yellow, and eventually blue
Planck and other Formulae

- **Planck formula** gives intensity of light at each wavelength

\[
B(\lambda, T) = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)} - 1}
\]

  - It is complicated. Often we’ll use two simpler formulae which can be derived from it.

- **Wien’s law** tells us what wavelength has maximum intensity

\[
\lambda_{\text{Max}} = \frac{3,000,000 \text{ nm K}}{T} = \frac{3,000 \text{ \mu m K}}{T}
\]

- **Stefan-Boltzmann law** tells us total radiated energy per unit area

\[
F = \sigma T^4 \text{ where } \sigma = 5.67 \times 10^{-8} \text{ W/}(m^2 \text{ K}^4)
\]

From Horizons, by Seeds
Landsat TM has Band 6 at ~10 μm
120 m resolution on TM

60 m resolution on ETM+ (Landsat 7)

Aster has bands 10-14, 90 m resolution
Big Island of Hawaii

Hot objects glow (emit light)
Big Island of Hawaii

Kilauea

Landsat Mosaic
Planck Blackbody Curves

\[ B(\lambda, T) = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)} - 1} \]

Units of I (or B)

Watts m\(^{-2}\) \(\mu m\)^{-1} str\(^{-1}\)
Color Temperature vs. Brightness Temperature

- If you measure intensity at many wavelengths, find \( \lambda \) where \( I \) is maximum (i.e. intensity \( I_{\text{max}} \)) then use Wien’s law to solve for \( T \)
  \[
  \lambda_{\text{Max}} = \frac{3,000 \, \mu\text{m} \, \text{K}}{T} \quad \frac{3,000 \, \mu\text{m} \, \text{K}}{\lambda_{\text{Max}}}
  \]

- Examples – Room T, Volcanic T
  \[
  T = \frac{3,000 \, \mu\text{m} \, \text{K}}{10 \, \mu\text{m}} = 300 \, \text{K} \quad T = \frac{3,000 \, \mu\text{m} \, \text{K}}{3 \, \mu\text{m}} = 1000 \, \text{K}
  \]

- Advantage of color T: Don’t need to know area of source.
- Even if you just know \( I \) at two \( \lambda \) you can find color T because ratio \( I_1/I_2 = B(\lambda_1, T)/B(\lambda_2, T) \) doesn’t depend on area
  Can solve (complicated equation) for \( T \)
  \[
  B(\lambda, T) = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda \, T)} - 1}
  \]
Color Temperature vs. Brightness Temperature

- If you know area of source so you have measured I or F then you can solve for Brightness Temperature using either Stefan-Boltzmann equation or Planck’s Equation

\[
F = \sigma \, T^4 \quad \text{where} \quad \sigma = 5.67 \times 10^{-8} \, \text{W/(m}^2 \text{K}^4) \\
T = (F/\sigma)^{1/4} \\
T = \left(\frac{459 \, \text{W} \, \text{m}^{-2}}{5.67 \times 10^9 \, \text{W} \, \text{m}^{-2} \, \text{K}^{-4}}\right)^{1/4} = (8.1 \times 10^9 \, \text{K}^4)^{1/4} = 300 \, \text{K}
\]

\[
B(\lambda, T) = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)}} - 1 \\
T = \frac{C_2}{\lambda \ln\left|\frac{C_1}{(I \lambda^5) + 1}\right|}
\]
Planck Blackbody Curves

\[ B(\lambda, T) = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)} - 1} \]

Units of I (or B)
Watts m\(^{-2}\) \(\mu\)m\(^{-1}\) str\(^{-1}\)
Actual Thermal Emission Curves

\[ B(\lambda, T) = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)} - 1} \]

\[ \varepsilon(\lambda) = 1 - r(\lambda) \]

\[ \varepsilon(\lambda) + r(\lambda) = 1 \]

Example where emissivity = 0.9 over all wavelengths
Actual Thermal Emission Curves

Actual emission

Planck blackbody

Emissivity $\varepsilon$

$B(\lambda, T) = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)}} - 1$

$\varepsilon(\lambda) = 1 - r(\lambda)$

$\varepsilon(\lambda) + r(\lambda) = 1$

Example where emissivity drops below 1 from 9 to 14 $\mu$m
Emissivity of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity, $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>water, distilled</td>
<td>0.99</td>
</tr>
<tr>
<td>water</td>
<td>0.92 – 0.98</td>
</tr>
<tr>
<td>water with petroleum film</td>
<td>0.972</td>
</tr>
<tr>
<td>concrete</td>
<td>0.71 – 0.90</td>
</tr>
<tr>
<td>asphalt</td>
<td>0.95</td>
</tr>
<tr>
<td>un/scene</td>
<td>0.97</td>
</tr>
<tr>
<td>loamy soil, dry</td>
<td>0.92</td>
</tr>
<tr>
<td>loamy soil, wet</td>
<td>0.95</td>
</tr>
<tr>
<td>soil, sandy</td>
<td>0.90</td>
</tr>
<tr>
<td>brick, red and rough</td>
<td>0.93</td>
</tr>
<tr>
<td>vegetation, closed canopy</td>
<td>0.98</td>
</tr>
<tr>
<td>vegetation, open canopy</td>
<td>0.96</td>
</tr>
<tr>
<td>grass</td>
<td>0.97</td>
</tr>
<tr>
<td>wood, planed oak</td>
<td>0.90</td>
</tr>
<tr>
<td>deciduous forest</td>
<td>0.97 – 0.98</td>
</tr>
<tr>
<td>coniferous forest</td>
<td>0.97 – 0.99</td>
</tr>
<tr>
<td>stainless steel</td>
<td>0.16</td>
</tr>
<tr>
<td>aluminum, foil</td>
<td>0.05</td>
</tr>
<tr>
<td>aluminum, polished</td>
<td>0.08</td>
</tr>
<tr>
<td>aluminum, paint</td>
<td>0.55</td>
</tr>
<tr>
<td>polished metals</td>
<td>0.16 – 0.21</td>
</tr>
<tr>
<td>oxidized steel</td>
<td>0.70</td>
</tr>
<tr>
<td>granite</td>
<td>0.86</td>
</tr>
<tr>
<td>durite</td>
<td>0.78</td>
</tr>
<tr>
<td>basalt, rough</td>
<td>0.95</td>
</tr>
<tr>
<td>snow</td>
<td>0.83 – 0.85</td>
</tr>
<tr>
<td>paint</td>
<td>0.90 – 0.96</td>
</tr>
<tr>
<td>human skin</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Emissivity minimum and silica %

<table>
<thead>
<tr>
<th></th>
<th>SiO$_2$%</th>
<th>Quartz %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leucogranite</td>
<td>70.8</td>
<td>29.5</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>67.8</td>
<td>31.9</td>
</tr>
<tr>
<td>Quartz Monzonite</td>
<td>64.0</td>
<td>23.7</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>60.4</td>
<td>18.8</td>
</tr>
<tr>
<td>Diorite</td>
<td>54.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Anorthosite</td>
<td>49.7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Silica content, % vs. Emissivity minimum, µm

TIMS bands
Emissivity for other minerals
Mars “TES” Results

![Graph showing emissivity against wavelength for Mars Surface, Terrestrial Sample, Basalt, and Andesite.](image1)

![Map showing TES Andesite Abundance with color scale from 0% to 80%](image2)

![Map showing TES Basalt Abundance with color scale from 0% to 80%](image3)