Blackbody Radiation

Unit: Quantum and Particle Physics

NGSS Standards/MA Curriculum Frameworks (2016): N/A

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 15.4.A, 15.4.A.1, 15.4.A.2, 15.4.A.3, 15.4.A.3.i, 15.4.A.3.ii, 15.4.A.3.iii

Mastery Objective(s): (Students will be able to…)

- Describe the electromagnetic radiation emitted by an object due to its temperature.

Success Criteria:

- Calculations are correct

Language Objectives:

- Be able to explain and draw & label representations of an atom.

Tier 2 Vocabulary: atom, charge, nucleus

Notes:

As discussed in the *Thermodynamics* topic starting on page 109, matter contains internal thermal energy, *U*, based on its temperature:

$$U = \tfrac{3}{2}nRT = \tfrac{3}{2}Nk_BT$$

where:

- U = internal thermal energy (J)
- n = number of moles of substance (mol)
- N = number of particles
- R = the gas constant = $8.31\,\frac{\text{J}}{\text{mol·K}}$
- K_B = Boltzmann's constant = $1.38\times10^{-23}\,\frac{\text{J}}{\text{K}}$
- T = temperature (K)

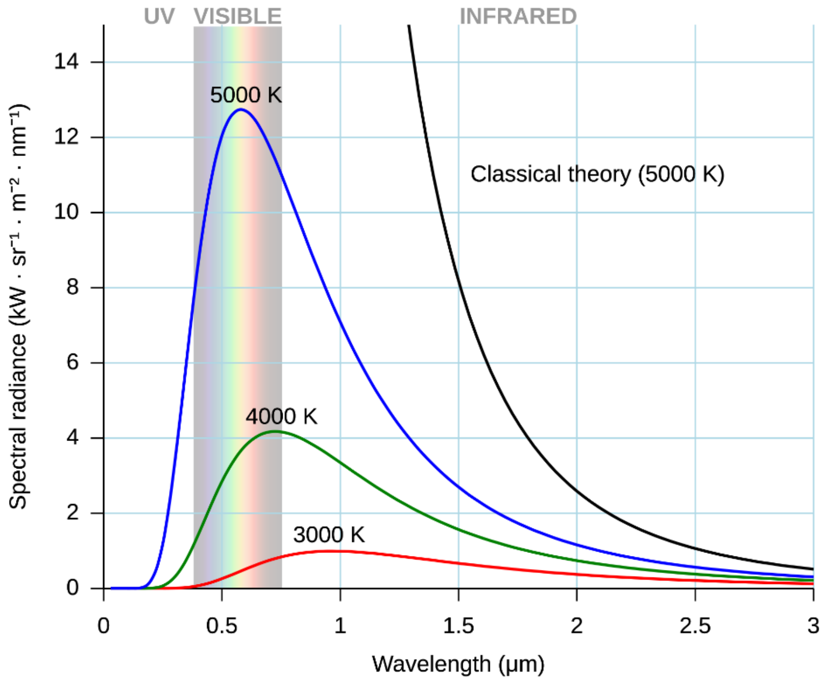
Matter spontaneously converts some of its internal thermal energy into electromagnetic energy, which radiates from it.

<u>blackbody</u>: an object that absorbs all of the heat energy that comes in contact with it (and reflects none of it).

<u>blackbody radiation</u>: the process of absorbed energy being emitted by a perfect blackbody.

Because a blackbody absorbs all of the radiation energy that falls onto it, if it is in thermal equilibrium (constant temperature), it must emit the same amount of energy as blackbody radiation.

A blackbody emits a continuous spectrum of light, but the amount of light emitted varies with the wavelength.



(Note that a wavelength of 0.5 μm equals 500 nm.)

Notice that the wavelength at which the blackbody radiates the most radiation decreases as the temperature increases. The colors of the lines on the graph are the colors that correspond with the wavelength of maximum emission.

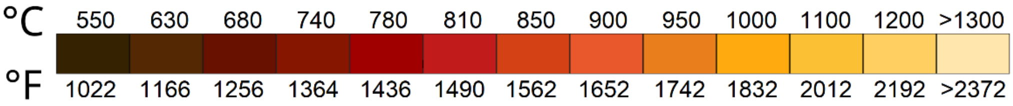
This wavelength of maximum emission is given by Wien's law, named for German physicist Wilhelm Wien who discovered it in 1893:

$$\lambda_{max} = \frac{b}{T}$$

where:

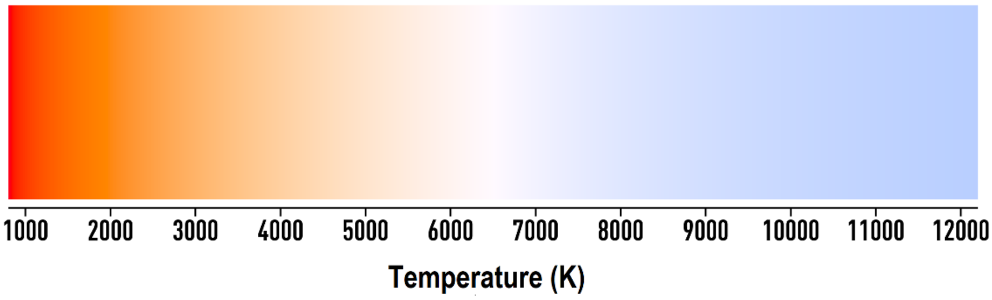
- λ_{max} = wavelength of maximum emission
- b = Wien's constant = 2.897×10^{-3} m·K
- T = temperature (K)

Although Wein discovered this relation in the late 19th century, blacksmiths have been using color temperatures for much longer. This blacksmith's chart shows the colors of metals at different temperatures, up to the melting point of steel:



This is the origin of phrases like "red hot."

Blackbody radiation colors can also be used to estimate the temperatures on the surface of stars. This chart covers the range from 880 K to 12 200 K:



In recent years, these temperatures are used to describe the colors of household lighting fixtures and computer monitors. Fortunately, these devices are not actually at these temperatures!

The rate at which energy is emitted from a blackbody is proportional to the surface area of the body and to temperature to the fourth power, as described by the Stefan-Boltzmann law, which was derived theoretically by Ludwig Boltzmann and empirically by Josef Stephan in 1900:

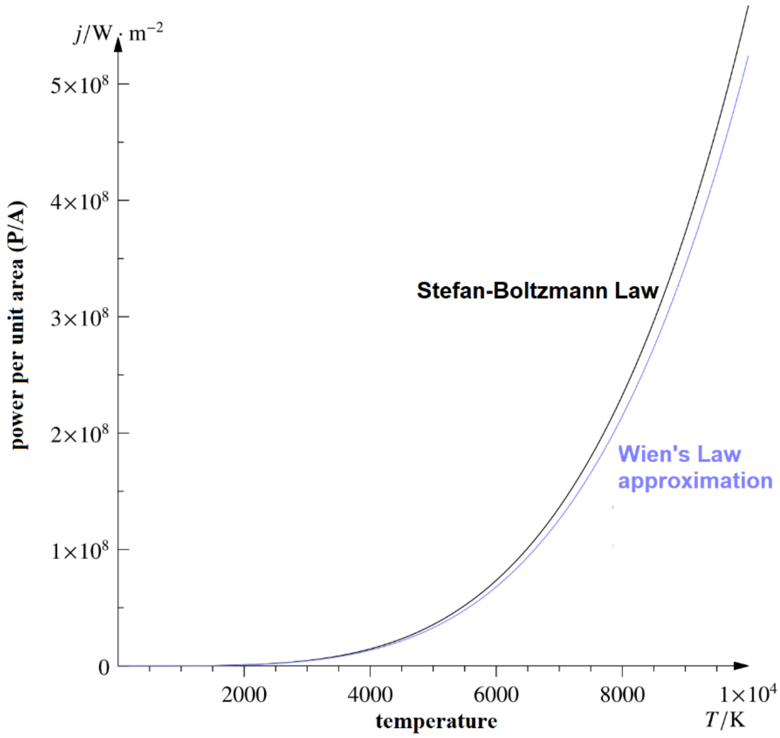
$$P=\frac{Q}{t}=\sigma A T^4$$

where:

- P = power (W)
- Q = heat (J)
- t = time (s)
- σ = Stefan-Boltzmann constant $\left(\sigma=5.67\times10^{-8}\,\frac{\text{W}}{\text{m}^2\cdot\text{K}^4}\right)$
- A = area (m^2)
- T = temperature (K)

Stefan-Boltzmann constant (σ): the constant that makes the above equation come out in watts. Note that the Stefan-Boltzmann constant is defined from other constants:

$\sigma=\frac{2\pi^5 k_B^4}{15h^3c^2}$, where k_B is the Boltzmann constant, h is Planck's constant, and c is the speed of light in a vacuum.



honors (not AP®)

As described in the subsection "Calculating Heat Transfer by Radiation" on page 46, when energy is radiated by a substance that is not an ideal blackbody, we define a material-specific constant called emissivity.

emissivity (ε): a ratio of the amount of heat radiated by a substance to the amount of heat that would be radiated by a perfect "blackbody" of the same dimensions.

Emissivity is a dimensionless number (meaning that it has no units, because the units cancel), and is specific to the substance.

This gives the equation for radiation from a non-blackbody substance:

$$P = \frac{Q}{t} = \varepsilon \sigma A T^4$$

where ε is the emissivity, and the other variables are as described above.