Solar Heating of Objects

Planck or Black Body Radiation

The Planck radiation spectrum from the 5800 K surface of the sun is shown in Figure 1 as consisting of predominantly visible and near infrared light, whereas, the spectra of the progressively cooler bodies in Figures 2 and 3 are dominated by infrared radiation. Notice how rapidly the intensity of the radiation decreases with temperature by comparing the scales on the three graphs. If the emission from one object is recorded at two temperatures, the intensity at any particular wavelength for the lower temperature will always be less than the intensity at the same wavelength for the higher temperature. The total power radiated by an object is proportional to the area beneath the spectrum in one of these figures, so the power radiated at the higher temperature will be greater than that radiated at the lower temperature.

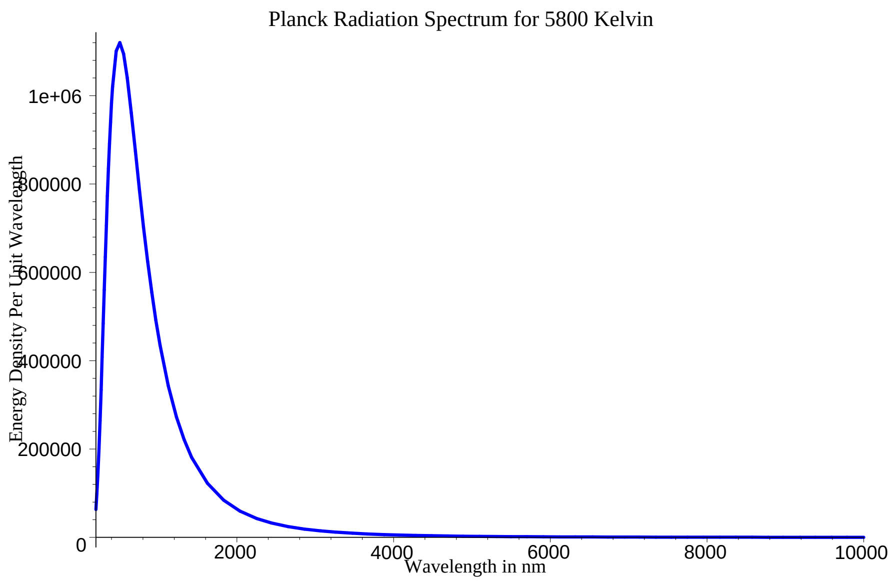

Figure 1: The Planck black body radiation spectrum from an object at a temperature of 5800 K.

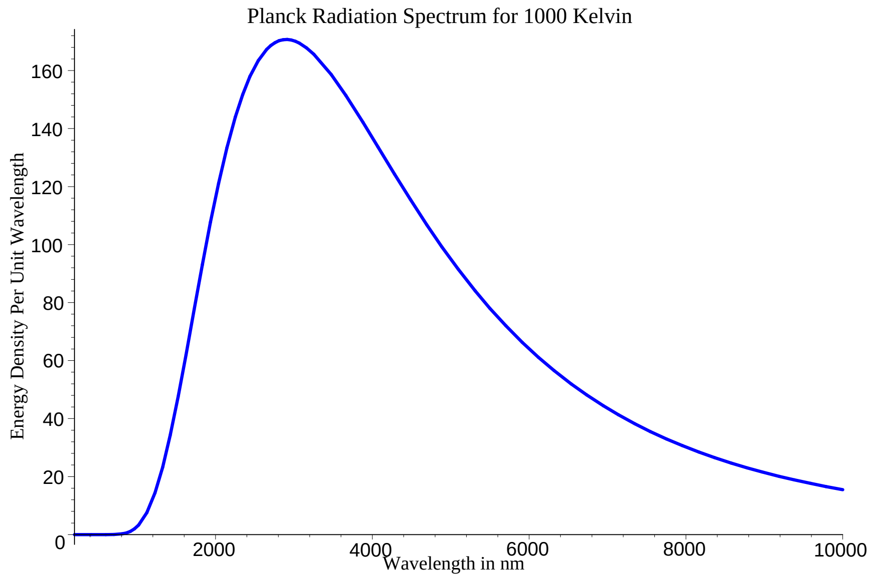

Figure 2: The Planck black body radiation spectrum from an object at a temperature of 1000 K.

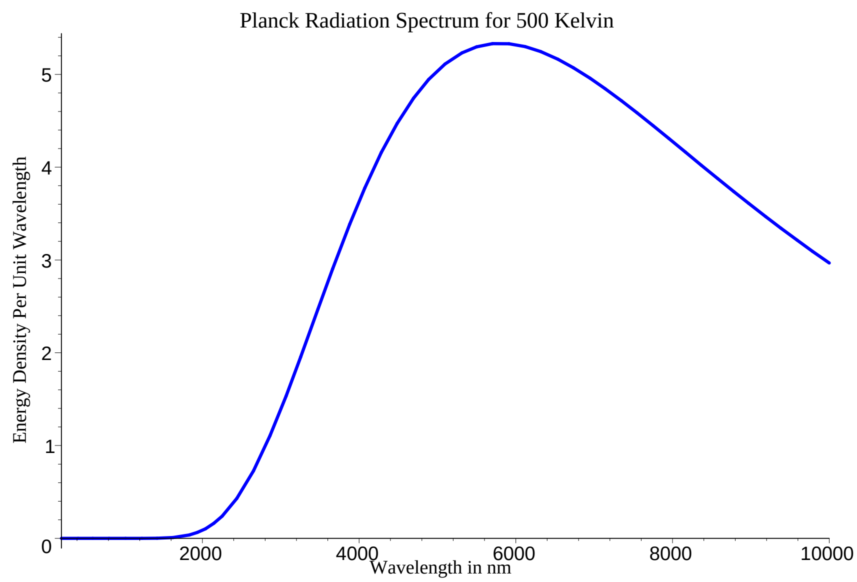

Figure 3: The Planck black body radiation spectrum from an object at a temperature of 500 K.

The variation in the peak of the spectrum with temperature is displayed in Figure 4 which shows normalized graphs at four temperatures. The mathematical expression for the peak wavelength for any temperature is called the Wien Displacement Law,

$$\lambda_{max} = \frac{2.897769 \times 10^{-3} m/K}{T} = \frac{2897.769 \mu m/K}{T},$$

where T is in Kelvin. This is graphed in Figure 5.

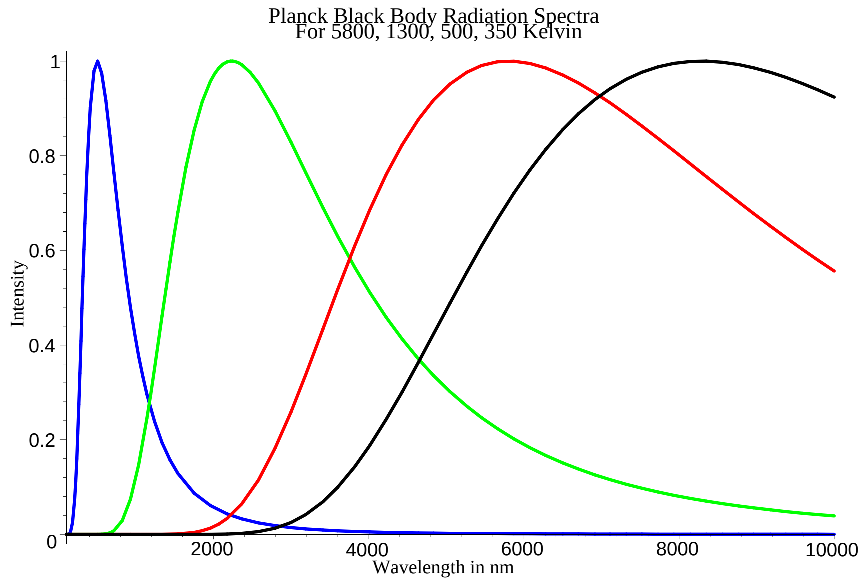

Figure 4: Planck radiation spectrum at four temperatures. The higher the temperature, the shorter the wavelength at the position of the peak.

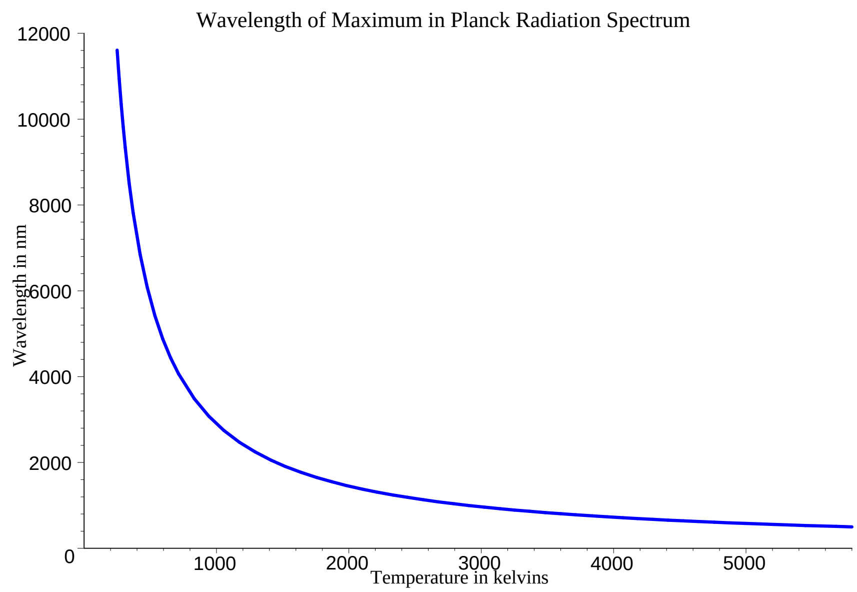

Figure 5: Planck radiation spectrum at four temperatures. The higher the temperature, the shorter the wavelength at the position of the peak.

Steady-State Temperature of an Object Absorbing Solar Radiation

When an object absorbs visible radiation, the object is said to be "black", and if it reflects all visible radiation the object is said to be "shiny" or "white". However, with solar radiation and the radiation from a hot object, near infrared (NIR) and infrared (IR) regions of the spectrum will be subject to different *absorptivities (a)*. An object can be black in the visible ($a = 1$), but white in the IR ($a = 0$). So, a, which must be between 0 and 1, depends upon wavelength.

The emission property of a hot object depends upon the *emissivity* (ϵ), a number between 0 and 1. At any particular wavelength a and ϵ are numerically equal though they govern different processes.

When subject to an incident *insolation (S)*, or power per unit area (W/m^2), an object will reach a steady state temperature. Convection, thermal conduction to objects in contact and radiation are the three heat loss mechanisms. For this discussion, it will be assumed that the object is insulated such as to eliminate convection and conduction.

A flat plate which is insulated on the bottom and subject to incident sunlight on the top will reach a steady-state temperature when the total incident power absorbed is equal to the power radiatedas depicted in Figure 6. The radiated power is given by the Stefan-Boltzmann law

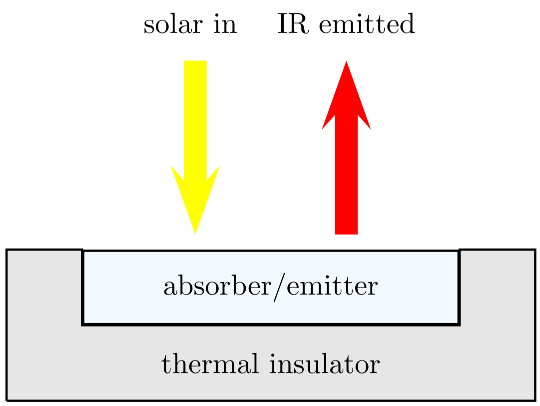

Figure 6: Steady state temperature is reached when the input power absorbed by the object equals the power emitted.

$$P_{rad} = \epsilon\sigma AT^4,$$

where A is the area in m^2, T is the temperature in K, ϵ is the average emissivity over the spectrum of the emitted radiation and $\sigma = 5.670 \times 10^{-8}$W/m^2/K^4 is the Stefan-Boltzmann constant. The absorbed power is approximately

$$P_{abs} = aAS,$$

where a is the average absorptivity of the spectrum of incident radiation. Thus, the steady-state temperature is determined from the equation

$$P_{abs} = P_{rad} \rightarrow aAS = \epsilon\sigma AT^4 \rightarrow T^4 = \frac{aS}{\epsilon\sigma}.$$

Clearly, to reach a high temperature we must have $a \approx 1$ and $\epsilon \approx 0$ over the incident and radiated spectra. This condition is depicted in Figures 7 through 9 for three different temperatures of the hot object.

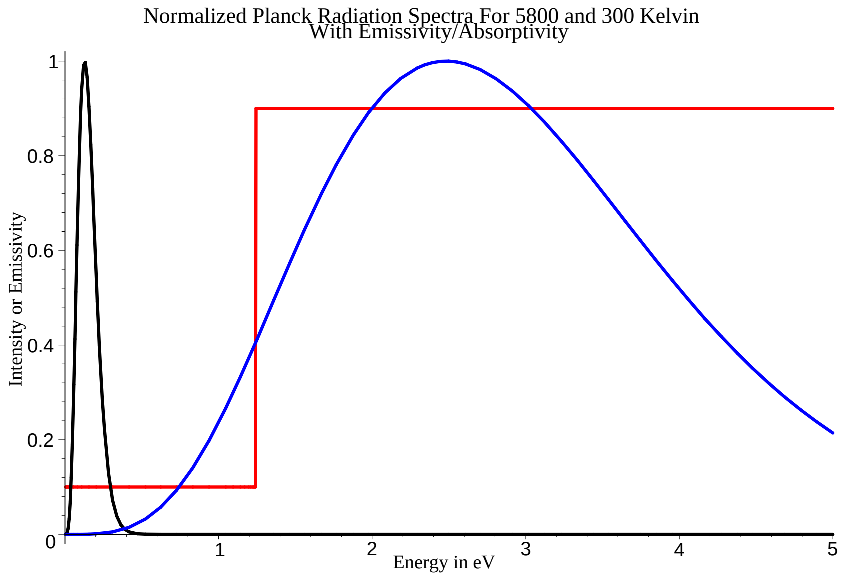

Figure 7: Spectra of the emitted and absorbed radiation for an object temperature of 300 K with a, for the absorbed radiation, and ϵ, for the emitted radiation plotted as an idealized step function.

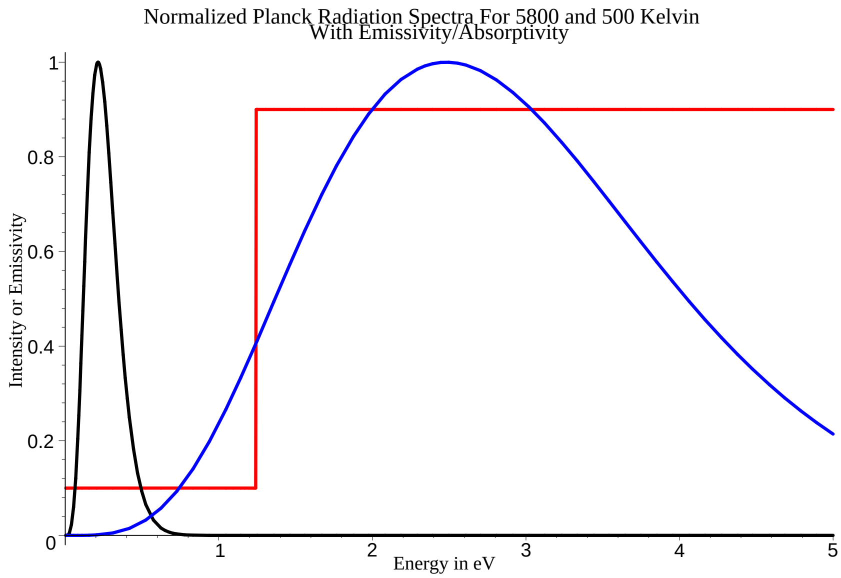

Figure 8: Spectra of the emitted and absorbed radiation for an object temperature of 500 K with a, for the absorbed radiation, and ϵ, for the emitted radiation plotted as an idealized step function.

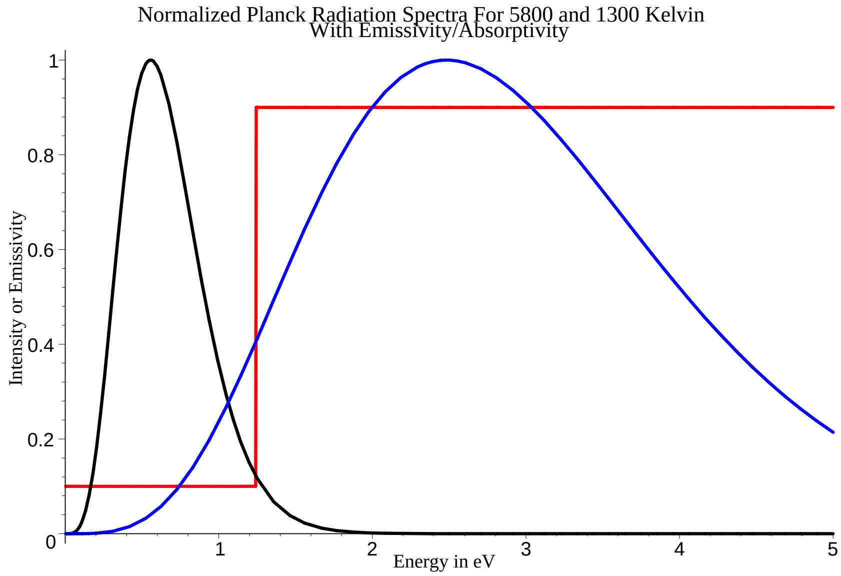

Figure 9: Spectra of the emitted and absorbed radiation for an object temperature of 1300 K with a, for the absorbed radiation, and ϵ, for the emitted radiation plotted as an idealized step function.