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Black Body Radiation

Any body at any temperature above absolute zero will radiate to some extent, the intensity and frequency distribution of the radiation depending on the detailed structure of the body. To begin analyzing heat radiation, we need to be specific about the body doing the radiating: the simplest possible case is an idealized body which is a perfect absorber, and therefore also (from the above argument) a perfect emitter. For obvious reasons, this is called a “black body”. But we need to check our ideas experimentally: so how do we construct a perfect absorber? OK, nothing’s perfect, but in 1859 Kirchhoff had a good idea: a small hole in the side of a large box is an excellent absorber, since any radiation that goes through the hole bounces around inside, a lot getting absorbed on each bounce, and has little chance of ever getting out again. So, we can do this in reverse: have an oven with a tiny hole in the side, and presumably the radiation coming out the hole is as good a representation of a perfect emitter as we’re going to find. Kirchhoff challenged theorists and experimentalists to figure out and measure (respectively) the energy/frequency curve for this “cavity radiation”, as he called it (in German, of course: hohlraumstrahlung, where hohlraum means hollow room or cavity, strahlung is radiation). In fact, it was Kirchhoff’s challenge in 1859 that led directly to quantum theory forty years later!

What Was Observed:

Two Laws The first quantitative conjecture based on experimental observation of hole radiation was: Stefan’s Law (1879): the total power P radiated from one square meter of black surface at temperature T goes as the fourth power of the absolute temperature:

$$P = \sigma T^4, \qquad \sigma = 5.67 \times 10^{-8} \text{ watts/sq.m./K}^4.$$

Five years later, in 1884, Boltzmann derived this T 4 behavior from theory: he applied classical thermodynamic reasoning to a box filled with electromagnetic radiation, using Maxwell’s equations to relate pressure to energy density. (The tiny amount of energy coming out of the hole would of course have the same temperature dependence as the radiation intensity inside.) See the accompanying notes for details of the derivation.

Exercise: the sun’s surface temperature is 5700K. How much power is radiated by one square meter of the sun’s surface? Given that the distance to earth is about 200 sun radii, what is the maximum power possible from a one square kilometer solar energy installation? Another important finding was Wien’s Displacement Law: As the oven temperature varies, so does the frequency at which the emitted radiation is most intense. In fact, that frequency is directly proportional to the absolute temperature:

$$f_{max}\, T \propto .$$

(Wien himself deduced this law theoretically in 1893, following Boltzmann’s thermodynamic reasoning. It had previously been observed, at least semi-quantitatively, by an American astronomer, Langley.) The formula is derived in the accompanying notes. In fact, this upward shift in f_{max} with T is familiar to everyone—when an iron is heated in a fire, the first visible radiation (at around 900K) is deep red, the lowest frequency visible light. Further increase in T causes the color to change to orange then yellow, and finally blue at very high temperatures (10,000K or more) for which the peak in radiation intensity has moved beyond the visible into the ultraviolet. This shift in the frequency at which radiant power is a maximum is very important for harnessing solar energy, such as in a greenhouse. The glass must allow the solar radiation in, but not let the heat radiation out. This is feasible because the two radiations are in very different frequency ranges—5700K and, say, 300K—and there are materials transparent to light but opaque to infrared radiation. Greenhouses only work because f_{max} varies with temperature.