Thermal Flux Is a Broadband Continuum of Energy

Peter L. Ward, US Geological Survey retired
peward@wyoming.com 307-413-4055

Planck's law, developed empirically to describe observed thermal radiation, shows that thermal energy in radiation and therefore in matter consists of a very broadband continuum of frequencies of oscillation, each with a unique amplitude of oscillation. A body, to be warmed, must absorb radiation from a hotter body with higher amplitudes of oscillation, especially at higher frequencies of oscillation. Heat flows via resonance, increasing the amplitude of oscillation at every frequency of oscillation, especially at higher frequencies. Thermal flux, therefore, varies by frequency and cannot be summarized accurately as a single number of watts per square meter.

The purpose of this paper is to examine the observed physical basis for temperature and the observed physical properties of thermal electromagnetic radiation to explore what thermal energy is and how it flows. At the microscopic level, thermal energy in joules increases over many orders of magnitude as a function of increasing frequency of oscillation of all the molecular bonds. At the macroscopic level, therefore, thermal radiation is a very broad continuum of these microscopic energies that, when absorbed, raises the temperature of the absorbing matter. Thermal flux, the rate at which thermal energy flows, varies with frequency and actually decreases as the absorbing matter approaches its final temperature.

Temperature is a measure of how fast the atoms and molecules in a material are moving (Grossman, 2014). The lower the average velocity of the atoms and molecules, the lower the thermal energy, and the lower the temperature of the material, with velocity and energy approaching zero as temperature approaches absolute zero. In a gas, the atoms and molecules are free to move in any direction until they collide. Temperature of an ideal gas, therefore, is proportional to the average kinetic energy of translation over all the atoms and molecules, each of which has a kinetic energy $E= \frac{1}{2} mv^2$ where m is the mass and v is its velocity.

In matter, however, atoms and molecules are constrained by the bonds or pressures holding matter together. These bonds oscillate at higher and higher frequencies as their temperature increases until the bonds come apart. Temperature of matter, therefore, is primarily proportional to the kinetic energy of oscillation of all the degrees of freedom of all the bonds or pressures holding matter together.

Radiation is a broad continuum of frequencies of oscillation: All bodies of matter spontaneously emit thermal radiation with physical properties that are a function of the temperature of the body. This electromagnetic radiation has two observable physical properties: frequency of oscillation, which is color in the visible spectrum, and radiance, which is how intense or bright a specific color appears. Radiation is unique among measurable physical properties, though, because it is made up not just of one frequency, but of a continuum of all physically possible frequencies ranging from less than cycles per second to greater than ten million trillion cycles per second. In air and space, all frequencies coexist without interacting in any way except when in the immediate presence of matter.

Frequencies travel through air and space without change except for Doppler effects, while radiance is clearly observed to decrease inversely proportional to the square of the distance travelled—objects look dimmer at a distance. Thus, in principle, all physically possible frequencies of oscillation coexist all the time in air and space, but the radiance at many frequencies on either end of this continuum are typically far too small to be physically relevant.

A black body is an idealized absorber of all incident radiation no matter the angle of incidence or the frequency. A black body is also an ideal diffuse emitter of all frequencies where the energy is radiated isotropically, independent of direction. A black body at thermal equilibrium, which means it is at the same temperature throughout, is observed to emit a broad continuum of frequencies described by Planck's law, an equation derived empirically by Max Planck in 1900 to fit laboratory data (Figure 1). Planck's law specifies the radiance at each frequency observed to be radiated by a black body at a specific absolute temperature that has reached thermal equilibrium.

Note in Figure 1 that a warmer body has greater radiance than a cooler body at every frequency of oscillation and especially at the higher frequencies of oscillation. The Planck curves at lower frequencies actually merge toward zero radiance as temperature approaches absolute zero. The shape of the Planck curves at higher frequencies is determined by the fact that radiance is proportional to frequency cubed but is also limited at higher frequencies by the exponential term in the denominator causing a rapid decrease in radiance with higher frequency.

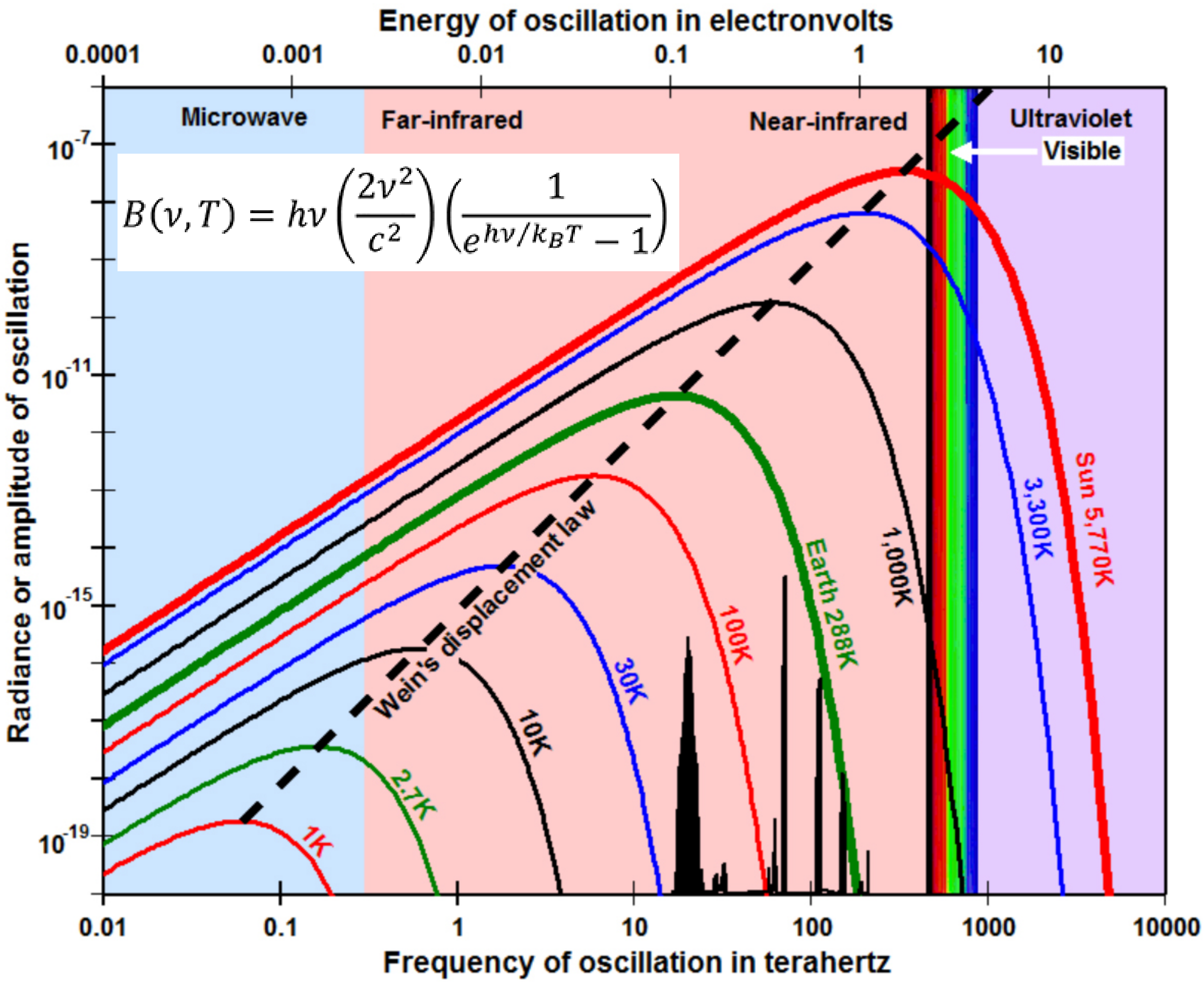

Figure 1. Planck's law shows that radiation from a warmer body has higher radiance or amplitudes of oscillation at all frequencies than does radiation from a cooler body and exhibits its greatest amplitude at a higher frequency, following Wien's displacement law (black dashed line). Each solid line shows the amplitude of oscillation radiated from a body at thermal equilibrium for the temperature shown. 3300 K is the temperature of the filament of an incandescent light bulb. 2.7 K is the temperature of the cosmic microwave background (Fixsen, 2009). The black vertical lines show frequencies absorbed by carbon dioxide.

The most important observation from Figure 1 is that higher temperatures are the result of higher frequencies of oscillation as shown more clearly by plotting frequency on the x-axis along a linear scale in Figure 2. Thus, radiance at higher frequencies of oscillation can only be increased naturally by absorbing radiation from a hotter body of matter. In other words, a body of matter can only be heated via radiation by absorbing radiation from a hotter body of matter, essentially the second law of thermodynamics.

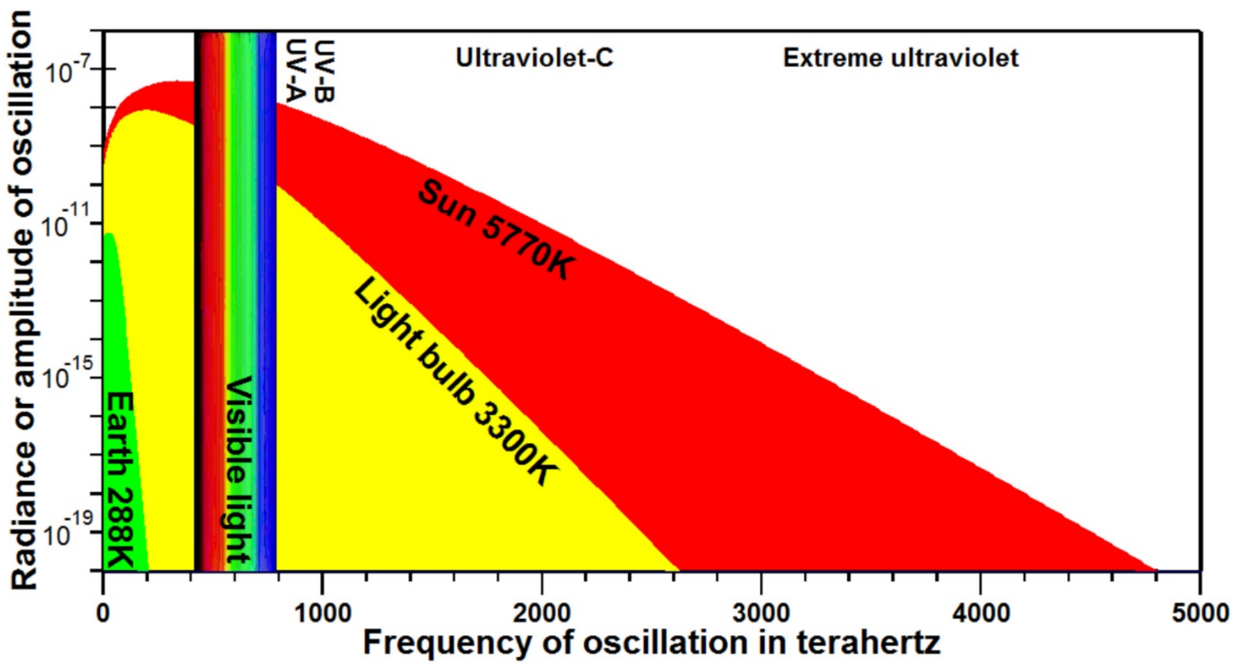

Figure 2. This plot of Planck's law with a linear x-axis for frequency, shows how radiation from warmer bodies contains considerably more high frequencies of oscillation than radiation from cooler bodies.

A body may absorb thermal energy at any number of locations around the body from any number of sources with any distribution of frequencies of oscillation, but as the body approaches thermal equilibrium, absolute temperature throughout the body approaches a fixed value and the distribution of radiance at every frequency approaches a Planck curve for that specific temperature. Temperature can, in fact, be defined from the zeroth law of thermodynamics as "that which is equal when heat ceases to flow between systems in thermal contact" (Grossman, 2014). Therefore, macroscopic temperature is only defined precisely at or very close to thermal equilibrium.

Microscopic thermal energy of oscillation in matter: The microscopic atomic and molecular bonds holding matter together are not rigid. Thermal energy in matter is well observed to be the oscillation of all the degrees of freedom of motion of all the bonds holding matter together. The greater the number of degrees of freedom within the bonds, the higher the heat capacity of the matter (Grossman, 2014), and the greater the amount of thermal energy required to raise the temperature of the matter.

Each vibration oscillates around a potential-energy minimum (Figure 3). Electrodynamic forces attract atoms when they are close and other electrodynamic forces repel atoms when they are too close, typically modeled as a Morse potential energy function. As temperature increases, amplitude of oscillation increases, increasing level of thermal energy of oscillation. When the level of thermal energy of oscillation reaches a certain level of thermal energy (E_{max}), the bond comes apart, freeing an electron in the photoelectric effect or by ionization, or freeing an atom by dissociation of the molecule. Because the force of repulsion increases much more rapidly than the force of attraction decreases, the length of each bond increases with temperature, meaning the volume of material increases with temperature, as is well observed.

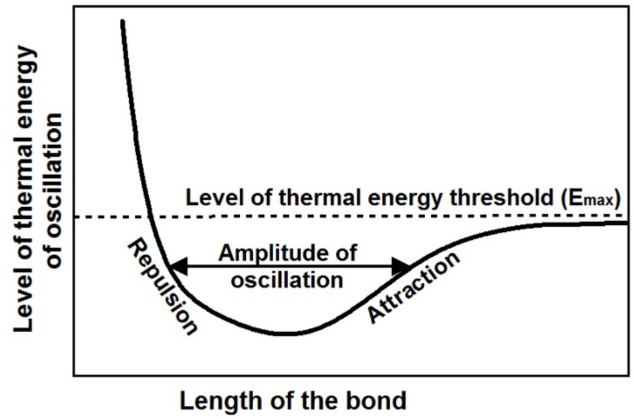

Figure 3. Each degree of freedom of each bond oscillates around a potential-energy minimum between electrodynamic forces that attract atoms when they are close and other electrodynamic forces that repel atoms when they are too close. When the level of thermal energy is increased, the amplitude of oscillation can be increased to a level of thermal energy where the bond comes apart, E_{max}.

The atomic dimensions of these oscillators are very small, a bond length being typically 100 to 200 picometers (10^{-12} meters), so their natural frequencies of oscillation are very high. In the visible light spectrum, for example, they range from 430 to 770 terahertz (10^{12} cycles per second).

The energy (E) of any one of these atomic or molecular oscillators is equal to the Planck constant (h) times its frequency of oscillation (ν, the Greek letter nu). Thus, $E=h\nu$, the Planck-Einstein relation, where the Planck constant (h) is the energy contained in an oscillation of one cycle per second. The unit “cycles” is often omitted from definitions of the Planck constant, leading to imprecise thinking. The unit “cycles” is critical to make it clear that the kinetic energy we are talking about is the kinetic energy of oscillation, which is a continuum of values, not a single value like the kinetic energy of translation with which we are much more familiar. The Planck constant can be estimated easily in a high school physics laboratory using four different colored LEDs with four different frequencies of oscillation, which by $E=h\nu$ are four different levels of energy (Rute and Sérgio, 2014).

Note that thermal energy ($E=h\nu$) of an atomic oscillator is not a function of mass, is not a function of bond length, and is not a function of the number of oscillators. Thermal energy is physically frequency of oscillation. The Planck constant (h) is simply the number of joules per unit frequency. As frequency approaches zero, thermal energy of oscillation approaches zero, and the resulting absolute temperature approaches zero.

One atomic oscillator is one quantum of thermal energy, the smallest physical thing making up thermal energy. The smaller the oscillator, the higher the frequency of oscillation, and, therefore, the higher the thermal energy. This is why atomic bonds contain more energy than molecular bonds. Such atomic oscillators pervade matter at the atomic level so that their energy is an intensive physical property that is not additive. This is very different from kinetic or potential energy of a body of matter, where energies are additive. At the microscopic level, there is no physical way to join two atomic oscillators together to give twice the amount of energy. The oscillators simply coexist.

Macroscopic thermal energy of oscillation in matter: If $E=h\nu$ and frequency (ν) is a continuum, then a constant (h) times a continuum (ν) must be a continuum of energies of oscillation of an ensemble of microscopic oscillators. Therefore, radiant thermal energy (E) at the macroscopic level is not a single number, it is a very broad continuum of values that coexist, somewhat like an infinite series with commas instead of plus signs, except it forms a continuum, not discrete values. While there may be a finite number of oscillators, oscillating at a finite number of frequencies, the effect of thermal conduction in matter appears to smear out all frequencies into a continuum of frequencies of oscillation in which each frequency has its own radiance. These oscillations, on the surface of matter, induce an electric field by charge-acceleration and/or dipole oscillation, which induces a magnetic field, which induces an electric field, etc. forming electromagnetic radiation that is observed to contain a continuum of frequencies. This radiation adds to the surrounding electromagnetic field, which includes radiation from any number of bodies of matter within line of sight.

The hotter the body, the more high-frequencies of oscillation have substantial radiance and the broader the frequency continuum of the radiation. Plus, the hotter the body, the higher the frequency (ν_{max}) of the peak amplitude of oscillation shown by the dashed black line in Figure 1, known as Wien's displacement law where $T=9.67*10^{-12}*\nu_{max}$. Thus, temperature is primarily a function of all frequencies of oscillation—the higher the temperature, the higher the frequencies of oscillation, and the higher the frequencies of oscillation, the higher the temperature. Radiance is also a function of temperature. The higher the temperature, the higher the radiance shown by Planck's law (Figure 1), the brighter or more intense the radiating body appears. This is why we see stars in the sky even though they are a long distance away and radiance decreases with the square of distance.

Note that all frequencies in the continuum are important for defining macroscopic temperature. If any of these frequencies are missing or if their radiance is less than or more than the value calculated by Planck's law, the body is not at thermal equilibrium.

Radiation carries the ability to raise the temperature of the absorbing body to the temperature of the radiating body provided enough radiation is absorbed, provided the radiating and absorbing bodies are close to each other, and provided the absorbing body is not losing energy at the same rate or faster than it is absorbing it. Note that Planck's law (Figure 1) is not a function of the nature of the material making up either body, although certain materials may need to absorb more radiation to reach the same temperature. In this way, we can think of radiation as "having" a temperature where ultraviolet radiation is "hotter" than violet radiation, which is "hotter" than green radiation, which is "hotter" than red radiation, which is "hotter" than infrared radiation.

Radiance is amplitude of oscillation not flux of thermal energy: At the microscopic level, a particular oscillator has a specific frequency of oscillation (v), a specific energy of oscillation ($E=hv$), and a specific amplitude of oscillation that increases with increasing frequency of oscillation and, therefore, increasing energy of oscillation as shown in Figure 3. An ensemble of atomic oscillators forms a broad continuum of amplitudes of oscillation, which together determine the thermal effect of all oscillations. To raise a body at temperature 100 K to the temperature of Earth at 288 K, the body must absorb radiation described by the area between the 100 K and the 288 K Planck's law curves in Figure 1. This area is described by a continuum of amplitudes of oscillation as a function of a continuum of frequencies of oscillation with values calculated using the Planck's-law function for temperature equaling 288 K minus the Planck's law function for temperature equaling 100 K.

Planck's law was formulated empirically to explain measurements in the laboratory collected by many different physicists (e.g. Ångström, 1892; Langley, 1883; Langley, 1888; Rubens and Aschkinass, 1898) who separated the radiation of interest into a rainbow spectrum, using a glass prism for visible and ultraviolet frequencies or a halite prism for infrared frequencies that are not energetic enough to penetrate glass. They then placed a temperature sensor within each narrow spectral band, measuring the increase in temperature of a small piece of mass within the sensor. They were, therefore, measuring the thermal effect of this narrow band of radiation on a small piece of matter. Based on Maxwell's wave theory for radiation, they thought they were measuring the amount of energy required to cause this thermal effect in units including watts per square meter on the y-axis as a function of frequency of oscillation in cycles per second on the x-axis.

Yet microscopic energy ($E=h\nu$) in both matter and radiation is equal to the Planck constant (h) times frequency of oscillation (ν) so that energy should be plotted on an alternative x-axis, the upper x-axis in Figure 1, not on the y-axis. What they were measuring in volts and thinking of as flux in watts was actually a proxy for amplitude of oscillation along a continuum. Amplitude of oscillation needs to be calibrated experimentally in the laboratory. That is why no units for amplitude of oscillation are shown on the logarithmic y-axes in Figures 1 and 2, only orders of magnitude. As shown in these figures, macroscopic temperature is determined by a broad continuum of microscopic frequencies of oscillation, each with a specific microscopic amplitude of oscillation calculated using Planck's law. This continuum of microscopic energy is best represented at the macroscopic level by a single number for temperature, the result of all these microscopic energies after the ensemble of oscillations reaches thermal equilibrium.

Planck's law shows that the natural, normal amplitude of bond oscillation at a particular temperature has a particular value at each frequency. This normal amplitude of oscillation can be increased by adding more energy, for example by creating a laser, by creating high-energy fields such as in a microwave oven, by moving closer to the emitting surface, or by using a magnifying lens to cause diverging rays to converge.

Heat flows primarily by resonance: Atomic/molecular oscillators are frictionless. Therefore, the only way they can share energy is by resonance. This is an extremely important observation for understanding why resonance provides the physical basis for how heat flows at the microscopic level in matter and via electromagnetic radiation.

Resonance is a phenomenon by which one oscillating system can send energy to, or receive energy from, another system that is oscillating at nearly the same frequency. Within matter, resonance is enabled by physical contact. Through air and space, resonance is enabled by an electromagnetic field along the shortest path via line of sight.

The "energy" that two resonant oscillators share is actually amplitude of oscillation at their common frequency of oscillation. The result of resonance is to average the amplitudes of oscillation so that both oscillators end up with the same amplitude of oscillation. Thus, the oscillator with the greatest amplitude of oscillation loses amplitude to the oscillator with the lesser amplitude of oscillation. The exchange of amplitude of oscillation is at the atomic/molecular level from one oscillator within a bond to another oscillator within a neighboring bond. How much amplitude is shared is determined by the difference in amplitudes of the two bonds, not by any other boundary conditions.

How close the frequencies of the two oscillators must be to share amplitudes is typically quantified using a quality factor (Q-factor). The higher the Q-factor, the closer the two frequencies must be. The Q-factor is likely to change with the physical properties of the matter, but clearly from Figure 1, the Q-factor is generally low enough to allow “smearing out” of discrete frequencies along a continuum.

At the microscopic level, resonance determines flux of thermal energy. The flux, the rate of amplitude transfer, is different at every frequency and is largest at the higher frequencies, those near and above the frequency with the greatest amplitude, specified by the Wien approximation, the dashed black line in Figure 1. Thermal energy cannot flow between systems with the same amplitudes of oscillation at all frequencies of oscillation, the zeroth law of thermodynamics. Resonance conserves energy, the first law of thermodynamics. Amplitude of oscillation can only “flow” from higher amplitude to lower amplitude, from higher temperature to lower temperature, the second law of thermodynamics. Because amplitudes are averaged, temperatures can approach absolute zero but will never reach absolute zero, the third law of thermodynamics.

Details concerning the flow of thermal energy: The greater the difference in macroscopic temperature, the greater the difference in microscopic amplitude of oscillation, which means the greater the flux of amplitude via resonance.

In matter, resonance is enabled by physical contact. Think of it as conductive resonance. Thermal conductivity is determined by the way the molecules are bound together. Furthermore, air bubbles or voids in a material would interrupt conductive resonance, decreasing thermal conductivity.

In space, amplitude is not shared because there are no physical oscillators—there are no bonds to oscillate. Energy is contained in the oscillations of the electromagnetic field but this energy is not available until a small piece of matter is provided. Introduce just one tiny molecule of a gas, and the resonant frequencies of all the bonds holding the gas molecule together will resonate with the electromagnetic field, extracting amplitudes of oscillation at just those frequencies of oscillation. Spectral physicists utilize these spectral lines of absorption to identify the chemical composition of molecules from close at hand to the far reaches of the universe (Rothman et al., 2013).

When radiation is absorbed via resonance by matter, what changes on the surface of the absorbing matter is an increase in the amplitude of oscillation at every frequency. There is still the same distribution of physical atomic oscillators on the surface of the matter. Then the oscillators on the surface share this new energy by resonance with nearby oscillators at the same frequency, increasing and decreasing their amplitude of oscillation and so on via conductive resonance until thermal equilibrium is reached.

To transfer energy via resonance through space, a specific oscillator on the surface of the radiating body must resonate with a specific oscillator on the surface of a distant body visible by line of sight, which is the shortest path. On a clear night, that body is somewhere in cold space so the difference in amplitudes of oscillation is very large and heat is conducted rapidly into space. If there are clouds in the sky, that resonance body is a water molecule in the cloud, the difference in amplitude of oscillation is small, and heat is not radiated efficiently away from Earth.

During the day, the amplitude of oscillation from Sun, even corrected for distance traveled, is much, much higher than the amplitude of oscillation for the same frequency on the surface of Earth, so energy flows from Sun to Earth very efficiently. If a cloud is in the way, the amount of energy that flows to Earth is dependent on the temperature of the cloud. The amount of energy that flows into the shade of a tree is dependent on the temperature of the tree. Therefore, flux, as we experience it, varies widely, but it only goes in one direction at a time between a particular pair of oscillators—from higher amplitude of oscillation to lower amplitude of oscillation at nearly the same frequency.

Flux is a very local thing. It is molecule to molecule and, therefore, even in an extremely varied distribution of thermal energy, flux will flow to homogenize that energy, to approach thermal equilibrium.

Amplitude of oscillation is well observed to decrease inversely proportional to distance squared. Why? The apparent surface density of oscillators available at a distance to resonate with a local oscillator with a higher amplitude of oscillation decreases inversely proportional to distance squared. Therefore, the number of oscillators available to resonate decreases with distance and the amplitude absorbed must now be shared among other oscillators, decreasing both intensity and the net new amplitudes transferred.

Macroscopic thermal energy of radiation: $E=hv$ describes energy at the microscopic level. How do we describe energy of radiation at the macroscopic level? Thermal energy is the physical property that must be transferred to an object in order to heat the object. Thus, a body must absorb the radiation described on a plot of Planck's law by the difference between a Planck curve for the final temperature T_2 minus the Planck curve for the beginning temperature T_1. This difference is a continuum of frequencies, each with their own amplitude after the body has reached thermal equilibrium. Energy to warm a body could come in any arbitrarily narrow spectrum of frequencies, but when the body reaches thermal equilibrium, the energy transferred will be described accurately by the difference between the two Planck curves.

Heat is a macroscopic term for the amount of thermal energy flowing from one body to another spontaneously due to their temperature difference. Because heat is an amount of energy flowing, it has been customary in physics not to use the word heat as a noun and not to say that a body contains heat. It is also customary, however, to talk of a body of matter containing internal thermal energy. The continuum of microscopic frequencies and amplitudes making up internal energy is described by a Planck's law curve for whatever temperature the body it at. The Planck's law curve thus is a description of heat contained by this body, and the difference in Planck's law curves describes the heat transferred from the hotter body to the cooler body.

The dominant role of resonance in nature: Resonance is not only central to what temperature is and how we sense it, but to how we see and hear the world around us. Visible light is visible precisely because the cone cells in our eyes have sizes that resonate at visible frequencies. A molecule on a green leaf resonates at a certain frequency of green in sunlight. When we look at that molecule, three cone cells in our eye, each most responsive to blue, green, or red light, all resonate with that molecule or, more likely, with nearby molecules. The three intensities or amplitudes of resonance are sent to our brain where the three signals are combined so that we perceive that molecule to have a specific shade of green. Our computer monitors do the same; certain amounts of red, green, and blue digital signals are converted in a computer monitor into a very specific color for each pixel.

From this point of view, every molecule on the surface of every piece of matter resonates at a particular frequency giving the molecule color. The brighter the sunlight, the greater the amplitude of oscillation. Thus, while light can be thought of as reflected by matter, light appears to cause molecules of matter to resonate, absorbing amplitude at that color, and then giving up some of this amplitude to the cones in our eyes. Apparent reflection by a water surface, the silver lining of a mirror, and such may simply be that those molecules can oscillate at any color or that in some way they enable resonance, a distinction to study in the laboratory.

In our inner ears, approximately 3500 hair cells, 10 to 50 micrometers in length, resonate at different frequencies of sound, sending electrical signals to our brain. These hair cells within the fluid-filled cochlear duct also send very low frequency signals of the "sloshing" of fluid in the cochlear duct related to balance and spatial orientation.

Resonance is all around us. A radio receiver, tuned to resonate at the frequency of a specific radio transmitter, extracts that small signal from the electromagnetic frequency continuum. The resonant frequencies of the bonds holding a gas molecule together extract, via resonance, energy for those specific frequencies from the frequency continuum of the electromagnetic field.

Resonance is the physical basis for what Einstein called "spooky action at a distance" (Born et al., 1971, p. 155), where something over there influences something over here, but there is no visible connection between them. Resonance is also the physical phenomenon that the mathematical theory of quantum entanglement seeks to explain.

The level of radiant energy drives atmospheric chemistry: Hertz (1887) discovered the photoelectric effect where shining light on surfaces of certain metals causes release of electrons. The metal must be very freshly cut, before oxidation of the surface. The peculiar thing about the photoelectric effect is that no electrons are observed to be released when the color of the light is below some minimum frequency in the blue to ultraviolet range, depending on the metal. No electrons are observed to be released no matter how great the amount of light, no matter how great the intensity of light, and no matter how long the light shines on the surface. Once the minimum frequency (level of energy of oscillation) is reached, electrons are released and the intensity of the light determines the rate of electron release. This minimum frequency, this minimum level of energy, cannot be explained by Maxwell's wave equations for electromagnetic radiation, the most widely respected theory of radiation at the time that is still part of greenhouse-warming theory today.

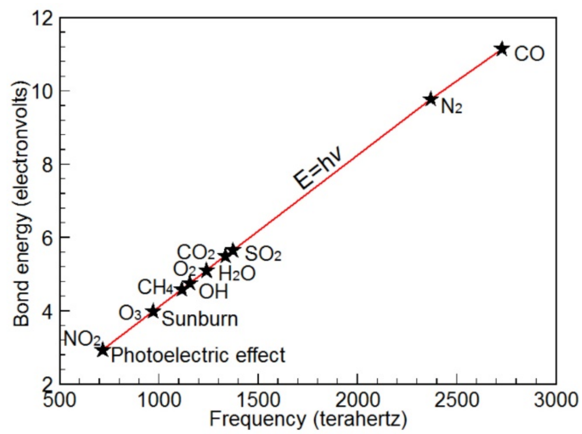

Figure 4. Levels of radiant energy required to dissociate many different molecules common in Earth's atmosphere, to cause the photoelectric effect, and to cause sunburn.

Einstein (1905), in studying the photoelectric effect, proposed that Planck's "energy element" (E=h*ν*) might better be thought of as a "light quantum", a quantity of energy large enough to break an electron loose. As the ideas of quantum mechanics developed, the "light quantum" became known as the photon (Lewis, 1926), the force carrier for electromagnetic force, where the energy of a photon is thought to be E=h*ν*. As discussed above, however, E=h*ν* at the microscopic level is the energy of a frictionless atomic oscillator and at the macroscopic level describes the continuum of electromagnetic energy (Figure 1). What Hertz (1887) discovered is that there is a certain level of this energy of oscillation of a bond required to break the bond holding an electron in place. There are other levels of energy required to cause dissociation of certain molecules, and other chemical reactions such as sunburn shown in Figure 4. Note that is takes very little energy to dissociate NO_2, explaining why, in atmospheric chemistry related to pollution, the generic term NO_X is often used to describe any one of many oxides of nitrogen because they are always changing. It takes a lot of energy to dissociate N_2, on the other hand, one of the reasons why N_2 makes up 78% of Earth's atmosphere.

The velocity of radiation: Maxwell (1865) formulated a set of partial differential equations showing that electric and magnetic fields in space can satisfy wave equations when you think of electromagnetic radiation as transverse waves traveling at some velocity. He derived an equation showing that this velocity was equal to one divided by the square root of the product of two physical constants: the vacuum permittivity (the resistance to forming an electric field) times the magnetic permeability (the ability to form a magnetic field) (Maxwell, 1873). Thus, the velocity of light appears to be proportional to the maximum rate at which an electric field can induce a magnetic field, which in turn can induce an electric field, ad infinitum. This very short increment in time would be a physical constant of nature and would affect how fast resonance can happen via an electromagnetic field.

Conclusions: Thermal energy within matter is observed to be a broad continuum of frequencies of oscillation of all the degrees of freedom of all the bonds holding matter together. These frequencies and amplitudes of oscillation on the surface of matter induce electromagnetic radiation that we think of as traveling through space at the speed of light. Electromagnetic radiation, however, simply enables resonance between two atomic oscillators within molecules of matter that are separated by any distance through air or space but are still within line of sight. These oscillators are oscillating at frequencies that are nearly the same. What is transferred is half the difference in amplitude of oscillation. The rate of transfer, the flux, increases as the difference in amplitude increases. Flux, therefore, varies for every resonant pair of molecules, increases with frequency of oscillation, and increases with the difference in temperature between the two molecules. Thermal flux, therefore, cannot be accurately quantified by a single number of watts per square meter as is done today by most scientists calculating the thermal effects of radiation.

References cited

Ångström, K., 1892, Untersuchungen über die spektrale Verteilung der Absorption im ultraroten Spektrum: Physikalische Revue, v. 1, p. 597-623.

Born, M., Einstein, A., and Born, H., 1971, Born-Einstein Letters: Freindship, politics, and physics in uncertain times, Macmillan, 235 p.:

Einstein, A., 1905, Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt: Annalen der Physik, v. 322, no. 6, p. 132-148.

Fixsen, D., 2009, The temperature of the cosmic microwave background: Astrophysical Journal, v. 707, no. 2, p. 916.

Grossman, J. C., 2014, Thermodynamics: Four laws that move the Universe, The Great Courses, Course 1291.

Hertz, H., 1887, Ueber einen Einfluss des ultravioletten Lichtes auf die electrische Entladung: Annalen der Physik, v. 267, no. 8, p. 983-1000.

Langley, S. P., 1883, The selective absorption of solar energy: American Journal of Science, v. 25, no. 147, p. 169-196.

Langley, S. P., 1888, LIX. The invisible solar and lunar spectrum: Philosophical Magazine Series 5, v. 26, no. 163, p. 505-520.

Lewis, G. N., 1926, The conservation of photons: Nature, v. 118, p. 874-875.

Maxwell, J. C., 1865, A dynamical theory of the electromagnetic field: Philosophical Transactions of the Royal Society of London, v. 155, p. 459-512.

-, 1873, A treatise on electricity and magnetism, Oxford, Clarendon Press, 560 p.:

Rothman, L. S., Gordon, I. E., Babikov, Y., Barbe, A., Benner, D. C., Bernath, P. F., Birk, M., Bizzocchi, L., Boudon, V., Brown, L. R., Campargue, A., Chance, K., Cohen, E. A., Coudert, L. H., Devi, V. M., Drouin, B. J., Fayt, A., Flaud, J.-M., Gamache, R. R., Harrison, J. J., Hartmann, J.-M., Hill, C., Hodges, J. T., Jacquemart, D., Jolly, A., Lamouroux, J., Roy, R. J. L., Li, G., Long, D. A., Lyulin, O. M., Mackie, C. J., Massie, S. T., Mikhailenko, S., Müller, H. S. P., Naumenko, O. V., Nikitin, A. V., Orphal, J., Perevalov, V., Perrin, A., Polovtseva, E. R., Richard, C., Smith, M. A. H., Starikova, E., Sung, K., Tashkun, S., Tennyson, J., Toon, G. C., Tyuterev, V. G., and Wagner, G., 2013, The HITRAN2012 molecular spectroscopic database: Journal of Quantitative Spectroscopy and Radiative Transfer, v. 130, p. 4-50.

Rubens, H., and Aschkinass, E., 1898, Observations on the absorption and emission of aqueous vapor and carbon dioxide in the infra-red spectrum: Astrophysical Journal, v. 8, p. 176-192.

Rute, M., and Sérgio, P., 2014, Bring discovery into the classroom and show students how to evaluate Planck’s constant using simple equipment: Science in School, no. 28, Spring, ScienceInSchool.org/sites/default/files/teaserPdf/issue28_planck.pdf.