feature article

Infrared radiation and planetary temperature

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Infrared radiative transfer theory, one of the most productive physical theories of the past century, has unlocked myriad secrets of the universe including that of planetary temperature and the connection between global warming and greenhouse gases.

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In a single second, Earth absorbs 1.22×10^{17} joules of energy from the Sun. Distributed uniformly over the mass of the planet, the absorbed energy would raise Earth's temperature to nearly 800 000 K after a billion years, if Earth had no way of getting rid of it. For a planet sitting in the near-vacuum of outer space, the only way to lose energy at a significant rate is through emission of electromagnetic radiation, which occurs primarily in the subrange of the IR spectrum with wavelengths of 5–50 μm for planets with temperatures between about 50 K and 1000 K. For purposes of this article, that subrange is called the thermal IR. The key role of the energy balance between short-wave solar absorption and long-wave IR emission was first recognized in 1827 by Joseph Fourier,[1,2] about a quarter century after IR radiation was discovered by William Herschel. As Fourier also recognized, the rate at which electromagnetic radiation escapes to space is strongly affected by the intervening atmosphere. With those insights, Fourier set in motion a program in planetary climate that would take more than a century to bring to fruition.

Radiative transfer is the theory that enables the above to be made precise. It is a remarkably productive theory that builds on two centuries of work by many of the leading lights of physics. Apart from its role in the energy balance of planets and stars, it lies at the heart of all forms of remote sensing and astronomy used to observe planets, stars, and the universe as a whole. It is woven through a vast range of devices that are part of modern life, from microwave ovens to heat-seeking missiles. This article focuses on thermal IR radiative transfer in planetary atmospheres and its consequences for planetary temperature. Those aspects of the theory are of particular current interest, because they are central to the calculations predicting that global climate disruption arises from anthropogenic emission of carbon dioxide and other radiatively active gases.

An atmosphere is a mixed gas of matter and photons. Radiative transfer deals with the nonequilibrium thermodynamics of a radiation field interacting with matter and the transport of energy by the photon component of the atmosphere. Except in the tenuous outer reaches of atmospheres, the matter can generally be divided into parcels containing enough molecules for thermodynamics to apply but small enough to be regarded as isothermal and hence in local thermodynamic equilibrium (LTE).

The local radiation field need not be in thermodynamic equilibrium with matter at the local temperature. Nonetheless, the equations predict that the radiation field comes into thermodynamic equilibrium in the limiting case in which it interacts very strongly with the matter. For such blackbody radiation, the distribution of energy flux over frequency is given by a universal expression known as the Planck function $B(\nu,T)$, where ν is the frequency and T is the temperature.

Integrating the Planck function over all directions and frequencies yields the Stefan–Boltzmann law for the flux F exiting from the surface of a blackbody, $F = \sigma T^4$, where $\sigma = 2\pi^5 k_B^4/(15c^2h^3) \approx 5.67 \times 10^{-8}$ W m^{-2} K^{-4}. Here, k_B is the Boltzmann thermodynamic constant, c is the speed of light, and h is Planck's constant. The fourth-power increase of flux with temperature is the main feedback allowing planets or stars to come into equilibrium with their energy source. Since such bodies are not actually isothermal, there is a question as to which T to use in computing the flux escaping to space. Radiative transfer is the tool that provides the answer.

The appearance of h and c in the Stefan–Boltzmann constant means that relativity and quantization—the two nonclassical aspects of the universe—are manifest macroscopically in things as basic as the temperatures of planets and stars. It is intriguing to note that one can construct a universe that is classical with regard to quantization but nonetheless is well behaved with regard to the thermodynamics of radiation only if one also makes the universe classical with regard to relativity. That is, σ remains fixed if we let $h \to 0$ but also let c tend to infinity as $h^{-3/2}$.

A few fundamentals

At planetary energy densities, photons do not significantly interact with each other; their distribution evolves only through interaction with matter. The momentum of atmospheric photons is too small to allow any significant portion of their energy to go directly into translational kinetic energy of the molecules that absorb them. Instead, it goes into changing the internal quantum states of the molecules. A photon with frequency ν has energy $h\nu$, so for a photon to be absorbed or emitted, the molecule involved must have a transition between energy levels differing by that amount.

Coupled vibrational and rotational states are the key players in IR absorption. An IR photon absorbed by a molecule knocks the molecule into a higher-energy quantum state. Those states have very long lifetimes, characterized by the spectroscopically measurable Einstein A coefficient. For example, for the CO_2 transitions that are most significant in the

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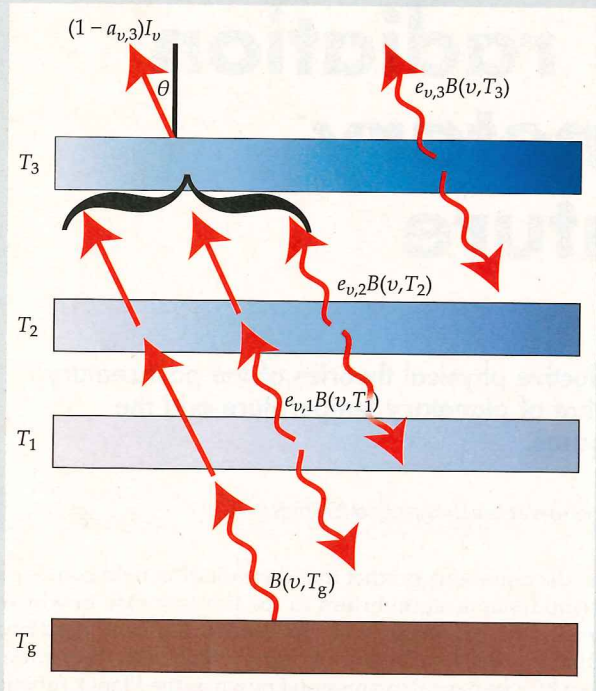

Figure 1. Three isothermal layers model the atmosphere in this illustration of upward-moving electromagnetic radiation with frequency ν. The radiation, assumed not to scatter, propagates at an angle θ with respect to the vertical and emerges from layer 3, the topmost atmospheric slice. The ground below the atmosphere emits as an ideal blackbody, characterized by the Planck function B. Each layer, at its own temperature T, emits with its own emissivity e_ν and, by Kirchhoff's law, absorbs a proportion $a_\nu = e_\nu$ of the incident radiation. The radiation flux distribution incident on layer 3 is I_ν. It is the sum of the thermal emission from the ground, layer 1, and layer 2, attenuated by absorption in the intervening layers 1 and 2. Squiggly arrows indicate thermal emission; straight arrows indicate transmitted radiation.

thermal IR, the lifetimes tend to range from a few milliseconds to a few tenths of a second. In contrast, the typical time between collisions for, say, a nitrogen-dominated atmosphere at a pressure of 10^4 Pa and temperature of 250 K is well under 10^{-7} s. Therefore, the energy of the photon will almost always be assimilated by collisions into the general energy pool of the matter and establish a new Maxwell–Boltzmann distribution at a slightly higher temperature. That is how radiation heats matter in the LTE limit.

According to the equipartition principle, molecular collisions maintain an equilibrium distribution of molecules in higher vibrational and rotational states. Many molecules occupy those higher-energy states, so even though the lifetime of the excited states is long, over a moderately small stretch of time a large number of molecules will decay by emitting photons. If that radiation escapes without being reabsorbed, the higher-energy states are depopulated and the system is thrown out of thermodynamic equilibrium. Molecular collisions repopulate the states and establish a new thermodynamic equilibrium at a slightly cooler temperature. That is how thermal emission of radiation cools matter in the LTE limit.

Now consider a column of atmosphere sliced into thin horizontal slabs, each of which has matter in LTE. Thermal IR does not significantly scatter off atmospheric molecules or the strongly absorbing materials such as those that make up Earth's water and ice clouds. In the absence of scattering, each direction is decoupled from the others, and the linearity of the electromagnetic interactions means that each frequency can also be considered in isolation. If a radiation flux distribution I_ν in a given propagation direction θ impinges on a slab from below, a fraction a_ν will be absorbed, with $a_\nu \ll 1$ by assumption. The slab may be too thin to emit like a blackbody. Without loss of generality, though, one can write the emission in the form $e_\nu B(\nu,T)$; here $e_\nu \ll 1$ is the emissivity of the slab (see figure 1). Both a_ν and e_ν are proportional to the number of absorber–emitter molecules in the slab.

The most fundamental relation underpinning radiative transfer in the LTE limit is Kirchhoff's law, which states that $a_\nu = e_\nu$. Gustav Kirchhoff first formulated the law as an empirical description of his pioneering experiments on the interaction of radiation with matter, which led directly to the concept of blackbody radiation. It can be derived as a consequence of the second law of thermodynamics by requiring, as Kirchhoff did, that radiative transfer act to relax matter in a closed system toward an isothermal state. If Kirchhoff's law were violated, isolated isothermal matter could spontaneously generate temperature inhomogeneities through interaction with the internal radiation field.

Given Kirchhoff's law, the change in the flux distribution across a slab is $\Delta I_\nu = e_\nu[-I_\nu + B(\nu,T)]$, assuming $e_\nu \ll 1$. The radiation decays exponentially with rate e_ν, but it is resupplied by a source $e_\nu B$. The stable equilibrium solution to the flux-change iteration is $I_\nu = B(\nu,T)$, which implies that within a sufficiently extensive isothermal region the solution is the Planck function appropriate to a blackbody. The recovery of blackbody radiation in that limit is one of the chief implications of Kirchhoff's law, and it applies separately for each frequency.

In the limit of infinitesimal slabs, the iteration reduces to a linear first-order ordinary differential equation for I_ν. Or, as illustrated in figure 1, one can sum the contributions from each layer, suitably attenuated by absorption in the intervening layers. The resulting radiative transfer equations entered 20th-century science through the work of Karl Schwarzschild (of black hole fame) and Edward Milne, who were interested in astrophysical applications; Siméon Poisson published a nearly identical formulation of radiative transfer[3] in 1835, but his equations languished for nearly 100 years without application.

Spectroscopy of greenhouse gases

Because of its numerous uses throughout science and technology, gaseous spectroscopy is a highly developed subject. The application of gaseous spectroscopy to atmospheric constituents began with John Tyndall, who discovered in 1863 that most of the IR opacity of Earth's atmosphere was attributable to two minor constituents—CO_2 and water vapor. All spectral absorption lines acquire a finite width by virtue of a number of processes that allow a molecule to absorb a photon even if the energy is slightly detuned from that of an exact transition. For reasonably dense atmospheres, the most important of those processes is collisional broadening, which borrows some kinetic energy from recent collisions to make up the difference between the absorbed photon's energy and a transition.

Databases of spectral-line properties lie at the foundations of all calculations of IR radiative transfer in gases. The HITRAN database,[4] culled from thousands of meticulously cross-validated, published spectroscopic studies, provides line properties for 39 molecules; it has been extensively used

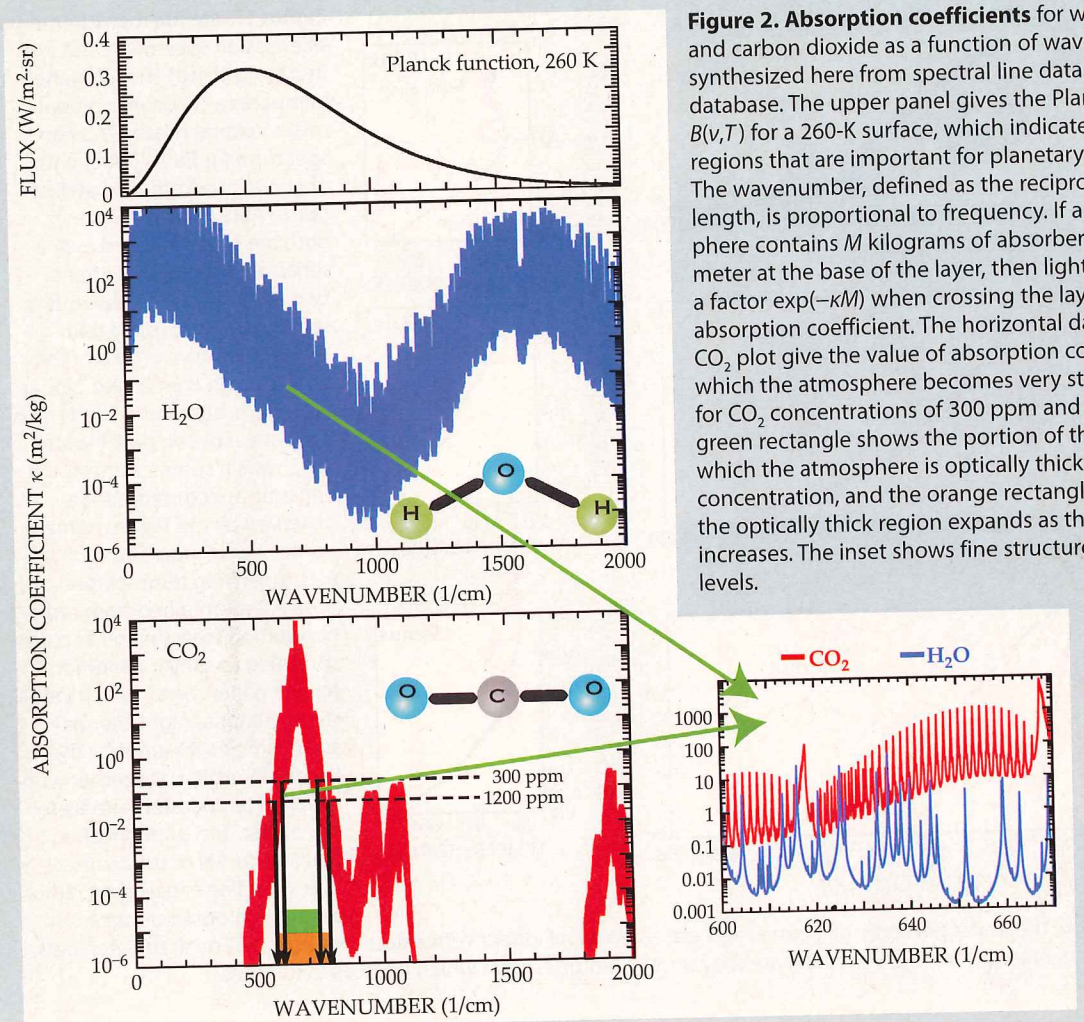

Figure 2. Absorption coefficients for water vapor and carbon dioxide as a function of wavenumber are synthesized here from spectral line data in the HITRAN database. The upper panel gives the Planck function $B(\nu,T)$ for a 260-K surface, which indicates the spectral regions that are important for planetary energy balance. The wavenumber, defined as the reciprocal of the wavelength, is proportional to frequency. If a layer of atmosphere contains M kilograms of absorber for each square meter at the base of the layer, then light is attenuated by a factor $\exp(-\kappa M)$ when crossing the layer, where κ is the absorption coefficient. The horizontal dashed lines on the CO_2 plot give the value of absorption coefficient above which the atmosphere becomes very strongly absorbing for CO_2 concentrations of 300 ppm and 1200 ppm; the green rectangle shows the portion of the spectrum in which the atmosphere is optically thick for the lower concentration, and the orange rectangle indicates how the optically thick region expands as the concentration increases. The inset shows fine structure due to rotational levels.

for applications across engineering and atmospheric sciences. The database is freely available at http://www.cfa.harvard.edu/hitran. A simple, flexible Python-language interface to HITRAN is included in the online software supplement to reference 5, available at http://geosci.uchicago.edu/~rtp1/PrinciplesPlanetaryClimate.

Measurements of absorption cross sections allow one to relate the absorption–emission properties of a layer of atmosphere to its composition. Figure 2, for example, shows absorption cross sections for CO_2 and water vapor as a function of wavenumber, which is proportional to frequency; the thermal IR ranges from 200 cm^{-1} to 2000 cm^{-1}. The spectra there are computed from the HITRAN database with lines broadened by collision with air at a pressure of 5×10^4 Pa, which corresponds to about the middle of Earth's atmosphere by mass. The CO_2 molecule has four main groups of absorption features in the thermal IR, of which the most important for Earthlike conditions is the one with the wavenumber near 667 cm^{-1}. (The corresponding wavelength is 15 μm.) The feature arises from vibrational bending modes of the linear triatomic molecule, which are given a fine structure by mixing with rotational transitions; the inset to figure 2 shows the corresponding lines. Water vapor is a polar molecule, and its richer set of vibrational and rotational modes allows it to absorb effectively over a much broader range of frequencies than CO_2.

Gases exhibit continuum absorption, as does the condensed matter making up clouds of all kinds. In some cases continua result from the overlap of nearby lines, but in other cases continua appear where no lines are in the vicinity. Loosely speaking, those continua arise because, over the finite duration of a collision, a pair of colliding molecules acts somewhat like a single, more complex molecule with transitions of its own. Equivalently, they result from the overlap of the tails of remote collisionally broadened lines. The statistical mechanics governing the far regions of long line tails is not at all well understood;[6] nonetheless, the continua have been quite well characterized, at least for those cases relevant to radiative transfer in Earth's atmosphere. For present-day Earth, the only important continuum is the water vapor continuum in the window around 1000 cm^{-1}. Carbon dioxide continua are unimportant for conditions that have prevailed on Earth during the past several billion years, but they are important for plugging the gaps in the line spectra for the dense CO_2 atmospheres of Venus and early Mars. Diatomic homoatomic molecules like N_2, which are transparent to IR in Earthlike conditions, have collisional continua that become important in cold, dense atmospheres. For example, the continuum makes N_2 one of the most important greenhouse gases on Saturn's largest moon, Titan.

The intricate variation of absorption with frequency makes it difficult to efficiently solve the radiative transfer equations. In line-by-line models, the equations are solved

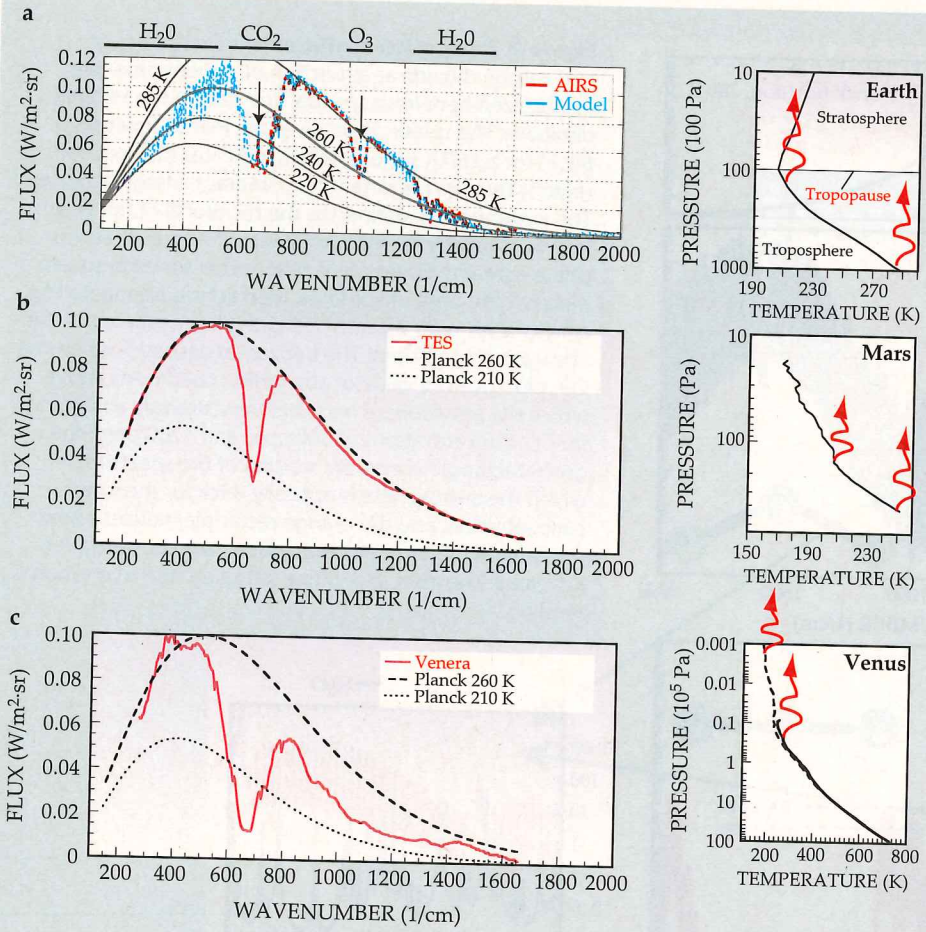

Figure 3. Satellite measurements of emission spectra are not limited to Earth. **(a)** The left panel compares a computed global-mean, annual-mean emission spectrum for Earth (blue) with observations from the satellite-borne AIRS instrument (red); both are superimposed over a series of Planck distributions. Two arrows point to absorption spikes discussed in the text. The temperature profile to the right, also an annual and global average, is based on in situ measurements. **(b)** The panel to the left shows a summer-afternoon emission spectrum for Mars observed by the TES instrument on the *Mars Global Surveyor*. Its accompanying temperature profile was obtained from radio-occultation measurements corresponding to similar conditions. **(c)** The panels here show a Venusian equatorial night thermal spectrum as measured by the *Venera 15* orbiter[14] together with a typical temperature profile for the planet. The upper portion (dashed curve) of the temperature sounding is based on radio-occultation observations from the Magellan mission; the lower portion (solid curve) was observed by a Pioneer Venus descender probe. For all three planets, squiggly arrows on the temperature profiles indicate the range of altitudes from which IR escapes to space.

separately on a grid of millions of frequencies and the results are summed to obtain net fluxes. Climate models, however, require greater computational efficiency; one needs to compute the frequency-averaged radiation flux at each of several thousand model time steps for each of several thousand grid boxes covering a planet's atmosphere. Modelers use various approximations to represent the aggregate effects of spectral lines averaged over bands about 50 cm^{-1} wide. Such approximations are validated against line-by-line codes that have, in turn, been validated against laboratory and atmospheric observations. When averaged over a broad band, radiative flux decays algebraically rather than exponentially with distance traversed, because the progressive depletion of flux at strongly absorbed frequencies leaves behind flux at frequencies that are more weakly absorbed.[5]

Confirmation by observed spectra

The Sun radiates approximately like a blackbody having a temperature of 6000 K, even though the temperature of the solar interior is many millions of degrees. That's because the visible-wavelength and IR photons that predominate in solar radiation can escape from only the cooler outer layers of the Sun. Similarly, the 2.7-K cosmic microwave background radiation gives the temperature of the radiating layer of the very early universe, redshifted down from its original, much higher temperature.

The radiating layer of a planet is the IR equivalent of the Sun's photosphere. When a planet is viewed from above, the emission seen at a given frequency originates in the deepest layer that is optically thin enough for significant numbers of photons to escape. The effective emission temperature for that frequency is a suitably weighted average temperature of that layer. If the atmospheric temperature varies with height, variations of the absorption coefficients of atmospheric constituents with frequency show up in planetary emission spectra as variations of emission temperature; the more transparent the atmosphere is, the deeper one can probe.

For atmospheres heated partly from below—either as a consequence of solar absorption at the ground as in the case of Earth, Mars, and Venus, or due to internal absorption and escaping interior heat as with Jupiter and Saturn—the lower layers of the atmosphere are stirred by convection and other fluid motions, and the constant lifting and adiabatic cooling establish a region whose temperature decline with height approximates that of an adiabat. That region is the troposphere. At higher altitudes, heat transfer is dominated by radiative transfer instead of fluid motions; the corresponding region is the stratosphere. Stratospheric temperature is constant or gently decaying with height for pure IR radiative equilibrium, but in situ absorption of solar radiation can make the stratospheric temperature increase with height. Ozone facilitates such absorption on Earth, and organic hazes have a similar effect on Titan. Typical temperature profiles for Earth, daytime Mars, and Venus are shown in the right-hand column of figure 3.

The top panel of figure 3 compares global-mean, annual-

mean, clear-sky spectra of Earth observed by the Atmospheric Infrared Sounder (AIRS) satellite instrument with spectra calculated after the radiative transfer equations were applied to output of a climate model driven by observed surface temperatures.[7] The agreement between the two is nearly perfect, which confirms the validity of the radiative transfer theory, the spectroscopy used to implement it, and the physics of the climate model. The AIRS instrument covers only wavenumbers above 650 cm^{-1}, but the theory and spectroscopic data sources used for radiative transfer at lower wavenumbers do not differ in any significant way from those used in the wavenumber range probed by AIRS. Numerous observations—notably, downward-looking radiation measurements from high-altitude aircraft—have confirmed the validity of radiative transfer models in the low-wavenumber water-vapor region.[8]

In the window region from roughly 800 to 1300 cm^{-1}, Earth radiates to space at very nearly the mean temperature of the ground, except for a dip due to ozone near 1050 cm^{-1}. At higher wavenumbers, one can see the reduction of radiating temperature due to water-vapor opacity. The main CO_2 absorption group leads to a pronounced reduction of radiating temperature in a broad region centered on 667 cm^{-1}. The emission spike at the center of the feature arises because CO_2 absorbs so strongly that the radiating level is in the upper stratosphere, which is considerably warmer than the tropopause; the ozone feature exhibits a similar spike. The spectrum thus reveals the presence of CO_2, water vapor, ozone, and other gases not discussed here. We can infer that the planet has a stratosphere in which temperature increases with height, indicating the presence of an upper-level solar absorber. We can determine that temperatures of the atmosphere and ground range at least from 220 K to 285 K. But absent additional information, we cannot tell that the high end of that range actually comes from the ground.

Climate scientists routinely use spectral inferences such as those discussed above to monitor the state of Earth's atmosphere from space. Every time you see an IR weather satellite image, you are seeing radiative transfer in action. Earth's liquid or frozen water clouds act essentially as blackbodies. They emit at the cloud-top temperature, which is cold if the clouds are deep. On an IR satellite image, clouds appear as regions of weak emission, though by convention IR weather satellite images are usually presented with an inverted gray scale that makes clouds look white, as one expects from everyday experience. Weather forecasting centers worldwide use such images many times every day, as they show cloud patterns even on Earth's night side and, unlike visible-light images, allow forecasters to determine the height of cloud tops. Observations in selected IR and microwave bands are routinely used to retrieve temperature profiles and patterns of atmospheric constituents such as water vapor and CO_2.

Figure 3 also shows emission spectra for Mars and Venus. The Martian spectrum, obtained on a summer afternoon, mainly takes the form of blackbody emission from a 260-K surface, but as with Earth's spectrum, it has a region centered on the main CO_2 absorption band where the radiating temperature is much colder. As far as one can tell from its IR spectra, nighttime Venus looks about as cold as daytime Mars. However, based on microwave emissions (to which the atmosphere is largely transparent), Venera landers, and Pioneer descenders, we now know that Venus has an extremely hot surface, a nearly pure CO_2 atmosphere, and a surface pressure of nearly 100 Earth atmospheres. Because of the thick atmosphere, essentially all the IR escaping from Venus originates in the top region of the atmosphere, where the pressure is less than 2.5×10^4 Pa. The highest-temperature radiating surface in that layer is primarily attributable to CO_2 continuum absorption, which fills in the transparent regions of the line spectrum shown in figure 2. Sulfuric-acid clouds and trace amounts of water vapor also contribute to plugging the gaps.

Saturation fallacies

The path to the present understanding of the effect of carbon dioxide on climate was not without its missteps. Notably, in 1900 Knut Ångström (son of Anders Ångström, whose name graces a unit of length widely used among spectroscopists) argued in opposition to his fellow Swedish scientist Svante Arrhenius that increasing CO_2 could not affect Earth's climate. Ångström claimed that IR absorption by CO_2 was saturated in the sense that, for those wavelengths CO_2 could absorb at all, the CO_2 already present in Earth's atmosphere was absorbing essentially all of the IR. With regard to Earthlike atmospheres, Ångström was doubly wrong. First, modern spectroscopy shows that CO_2 is nowhere near being saturated. Ångström's laboratory experiments were simply too inaccurate to show the additional absorption in the wings of the 667-cm^{-1} CO_2 feature that follows upon increasing CO_2. But even if CO_2 were saturated in Ångström's sense—as indeed it is on Venus—his argument would nonetheless be fallacious. The Venusian atmosphere as a whole may be saturated with regard to IR absorption, but the radiation only escapes from the thin upper portions of the atmosphere that are not saturated. Hot as Venus is, it would become still hotter if one added CO_2 to its atmosphere.

A related saturation fallacy, also popularized by Ångström, is that CO_2 could have no influence on radiation balance because water vapor already absorbs all the IR that CO_2 would absorb. Earth's very moist, near-surface tropical atmosphere is nearly saturated in that sense, but the flaw in Ångström's argument is that radiation in the portion of the spectrum affected by CO_2 escapes to space from the cold, dry upper portions of the atmosphere, not from the warm, moist lower portions. Also, as displayed in the inset to figure 2, the individual water-vapor and CO_2 spectral lines interleave but do not totally overlap. That structure limits the competition between CO_2 and water vapor.

Energy balance and surface temperature

The same considerations used in the interpretation of spectra also determine the IR cooling rate of a planet and hence its surface temperature. An atmospheric greenhouse gas enables a planet to radiate at a temperature lower than the ground's, if there is cold air aloft. It therefore causes the surface temperature in balance with a given amount of absorbed solar radiation to be higher than would be the case if the atmosphere were transparent to IR. Adding more greenhouse gas to the atmosphere makes higher, more tenuous, formerly transparent portions of the atmosphere opaque to IR and thus increases the difference between the ground temperature and the radiating temperature. The result, once the system comes into equilibrium, is surface warming. The effect is particularly spectacular for Venus, whose ground temperature is 730 K. If the planet were a blackbody in equilibrium with the solar radiation received by the planet, the ground temperature would be a mere 231 K.

The greenhouse effect of CO_2 on Earth and Mars is visually manifest as the ditch carved out of the Planck spectrum near 667 cm^{-1}. That dip represents energy that would have escaped to space were it not for the opacity of CO_2. On Venus, the CO_2 greenhouse effect extends well beyond the ditch,

owing to the opacity of the continuum associated with so much CO_2. In the Earth spectrum, one can also see a broad region in which water vapor has reduced the radiating temperature to a value well below the surface temperature.

For Earth and Mars, the width of the CO_2 ditch corresponds approximately to the width of the spectral region over which the atmosphere is nearly opaque to IR. Increasing atmospheric CO_2 increases the width of the ditch and hence increases the CO_2 greenhouse effect. But the increase occurs in the wings of the absorption feature rather than at the center (see figure 2). That limitation is the origin of the logarithmic relation between CO_2 concentration and the resulting perturbation in Earth's energy budget. It has been a feature of every climate model since that of Svante Arrhenius in 1896. Per square meter of surface, Mars has nearly 70 times as much CO_2 in its atmosphere as Earth, but the low Martian atmospheric pressure results in narrower spectral lines. That weakens absorption so much that the Martian CO_2 ditch has a width somewhat less than Earth's.

The planetary warming resulting from the greenhouse effect is consistent with the second law of thermodynamics because a planet is not a closed system. It exchanges heat with a high-temperature bath by absorbing radiation from the photosphere of its star and with a cold bath by emitting IR into the essentially zero-temperature reservoir of space. It therefore reaches equilibrium at a temperature intermediate between the two. The greenhouse effect shifts the planet's surface temperature toward the photospheric temperature by reducing the rate at which the planet loses energy at a given surface temperature. The way that works is really no different from the way adding fiberglass insulation or low-emissivity windows to your home increases its temperature without requiring more energy input from the furnace. The temperature of your house is intermediate between the temperature of the flame in your furnace and the temperature of the outdoors, and adding insulation shifts it toward the former by reducing the rate at which the house loses energy to the outdoors. As Fourier already understood, when it comes to relating temperature to the principles of energy balance, it matters little whether the heat-loss mechanism is purely radiative, as in the case of a planet, or a mix of radiation and turbulent convection, as in the case of a house—or a greenhouse. Carbon dioxide is just planetary insulation.

For present Earth conditions, CO_2 accounts for about a third of the clear-sky greenhouse effect in the tropics and for a somewhat greater portion in the drier, colder extratropics (see reference 9, figure 12.1); the remainder is mostly due to water vapor. The contribution of CO_2 to the greenhouse effect, considerable though it is, understates the central role of the gas as a controller of climate. The atmosphere, if CO_2 were removed from it, would cool enough that much of the water vapor would rain out. That precipitation, in turn, would cause further cooling and ultimately spiral Earth into a globally glaciated snowball state.[10] It is only the presence of CO_2 that keeps Earth's atmosphere warm enough to contain much water vapor. Conversely, increasing CO_2 would warm the atmosphere and ultimately result in greater water-vapor content—a now well-understood situation known as water-vapor feedback.[9,11]

Though the first calculation of the warming of Earth due to CO_2 increase was carried out by Arrhenius in 1896, accurate CO_2 and water-vapor spectroscopy and a fully correct formulation of planetary energy balance did not come together until the work of Syukuro Manabe and Richard Wetherald in 1967.[2,12] With that development, the theory was brought to its modern state of understanding. It has withstood all subsequent challenges and without question represents one of the great triumphs of 20th-century physics.

Planets far and near

The foundations of radiative transfer were laid by some of the greatest physicists of the 19th and 20th centuries—Fourier, Tyndall, Arrhenius, Kirchhoff, Ludwig Boltzmann, Max Planck, Albert Einstein, Schwarzschild, Arthur Eddington, Milne, and Subrahmanyan Chandrasekhar—plus many more whose names are not well known, even among physicists, but probably deserve to be. The subject has had a century of triumphs (and, as the box on page 37 describes, some wrong turns)[13] and is about to go into high gear because of the dawning era of extrasolar planet discovery. What kind of atmospheres would render a planet in the potentially habitable zone of its star actually habitable,[13] and how would astronomers detect it? If they see a high-albedo object with CO_2 in its atmosphere, how will they determine if it is a snowball or a large Venus-like rocky planet?

Whatever the future holds for newly discovered planets, interest remains intense in maintaining the habitability of the planet likely to be our only home for some time to come. The contributions of fundamental physics to achieving that aim are clear. The CO_2 greenhouse effect is directly visible in satellite observations of the bite taken out of the IR spectrum near 667 cm^{-1}, a feature whose details agree precisely with results of calculations based on first-principles radiative transfer calculations. Laboratory spectroscopy demonstrates that the width of the bite will increase as CO_2 increases, and warming inevitably follows as a consequence of well-established energy-balance principles. The precise magnitude of the resulting warming depends on the fairly well-known amount of amplification by water-vapor feedbacks and on the less-known amount of cloud feedback. There are indeed uncertainties in the magnitude and impact of anthropogenic global warming, but the basic radiative physics of the anthropogenic greenhouse effect is unassailable.

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