Sunlight and science: the elements of optical radiation

Light is more than a life force; it makes possible the technologies of electro-optics.

Thomas V. Higgins, Contributing Editor

BACK TO BASICS

Light is a mesmerizing force of nature. It pervades our art, our literature, our mythology, and our science. Francis Bacon called it "God's first creature." And Albert Einstein once declared, "I want to reflect on light for the rest of my life." The reflections of Einstein and others on the nature of light have enhanced our understanding of the world and enabled us to develop technologies that enrich our lives.

This is the first article of a monthly series intended to explore the fundamentals of light and the technologies developed to control it, technologies collectively called electro-optics. Electro-optics is the flagstone for the much-touted "Information Superhighway" now under construction throughout the world. It will make interactive multimedia possible on a grand scale. In fact, electro-optical inventions such as lasers, light-emitting diodes, fiberoptic devices, detectors, modulators, video cameras, flat-panel displays, and even light bulbs have touched off revolutionary changes in science, industry, medicine, communications, entertainment, and society.

Light as energy

What is it about light that makes it so important to our prosperity? In a word, light is energy—pure energy. Any source of light, then, is also a source of energy. And in our world the most energetic of all light sources is the sun.

This thermonuclear furnace continuously bathes us in oceans of energy—more than enough to drive our weather and sustain all life on Earth. Altogether, the sun pumps out nearly 4×10^{26} J of radiant energy every second, a tiny fraction of which we capture here on Earth. If all that energy could be collected somehow and converted directly into mechanical force, it could accelerate a fully loaded space shuttle to half the speed of light in about 50 μs (relativistic effects being ignored here). But the vast majority of sunlight dissipates into space, where it eventually becomes starlight for other planetary systems. The energy fans out in all directions, speeding through the vacuum at 300,000 km/s.

One way to picture sunlight is to look at a fixed amount of it. Imagine, for example, 4×10^{33} ergs of energy leaving the sun packed inside an ever-expanding spherical shell 300,000 km thick (see Fig. 1). This represents one second of sunlight. As the shell expands, its volume balloons, but the total energy content remains unchanged; therefore, energy density (ergs/m^3) declines.

When the outer surface of the shell reaches Earth, the volume is about 8.5×10^{31} m^3 and the corresponding energy density is 47 ergs/m^3 (4×10^{33} ergs/8.5×10^{31} m^3). By the time the energy shell reaches Mars (1.5 times farther away than Earth), the volume has mushroomed to almost 2×10^{32} m^3 and energy density has dropped to 20.4 ergs/m^3. The expansion has diluted the energy density in the shell to 43% of its previous value at Earth, or 1/2.3.

It is no coincidence that 1/2.3 can also be written as $1/(1.5)^2$. This agrees with the inverse-square law, which states that light intensity is inversely proportional to the square of the distance from the source. The principle is a direct consequence of the geometry of space and the law of conservation of energy.

This relationship holds exactly for infinitesimal point sources and is approximately correct for extended light sources viewed from appreciable distances, such as the sun seen from Earth. For an infinitely extended source, however, light intensity would fall off in direct proportion to distance. When applying the inverse-square law, a good rule of thumb is that the source width not exceed 10% of its distance from the observer.

Rudiments of radiometry

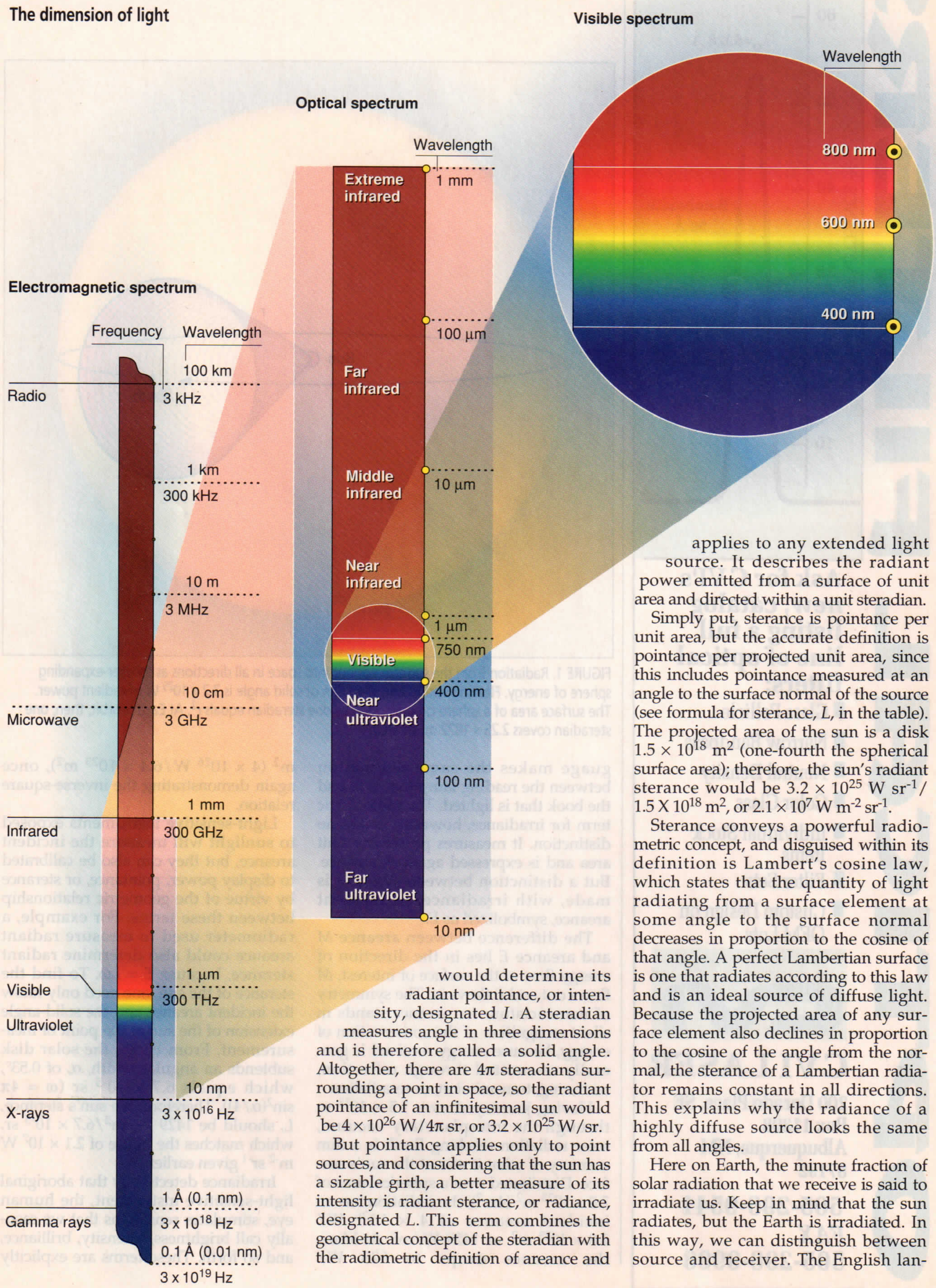
The detection and measurement of radiant energy defines the science of radiometry, which has given us remarkable insight into the physical world. Just recently, for example, precise radiometric measurements of background radiation from the Big Bang helped uncover vital new clues about the genesis of our universe. And nearly a century ago it was radiometric data that guided Max Planck to the first formulation of quantum mechanics.

Radiometry offers a useful, standardized system for characterizing radiant energy. Moreover, the International System of Units now includes SI units for radiometry that have helped dispel much of the confusion surrounding earlier nomenclature.

Specific radiometric terms address the geometry of radiant energy (see the table on p. 68), and several of them are implied in the description of sunlight given above. For example, the 4×10^{26} J of radiant energy, Q, that escape the sun every second define its radiant power or flux, ϕ, in watts. This is represented by the total energy contained within the light shell one light-second thick.

Given that the sun is a radiant sphere with 6.1×10^{18} m^2 of surface area, the energy radiating from each unit of area defines its radiant areance, or exitance, and is designated by M. Assuming the sun radiates evenly over its entire surface, that means every square meter emits 4×10^{26} W/6.1×10^{18} m^2 or 6.6×10^7 W.

If the sun were a point source, the radiant power streaming out into space within a cone angle of one steradian


The dimension of light

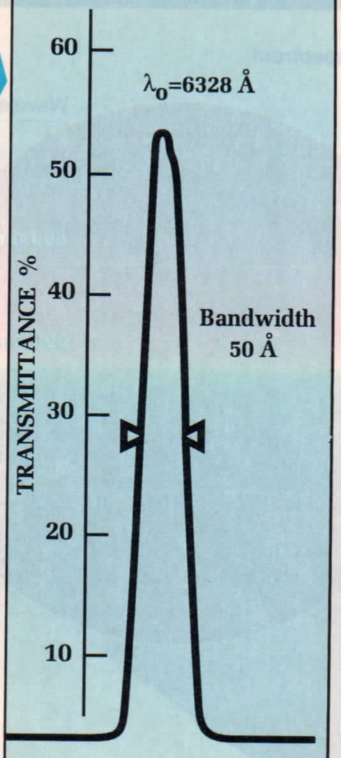
would determine its radiant pointance, or intensity, designated *I*. A steradian measures angle in three dimensions and is therefore called a solid angle. Altogether, there are 4π steradians surrounding a point in space, so the radiant pointance of an infinitesimal sun would be 4×10^{26} W/4π sr, or 3.2×10^{25} W/sr.

But pointance applies only to point sources, and considering that the sun has a sizable girth, a better measure of its intensity is radiant sterance, or radiance, designated *L*. This term combines the geometrical concept of the steradian with the radiometric definition of areance and applies to any extended light source. It describes the radiant power emitted from a surface of unit area and directed within a unit steradian.

Simply put, sterance is pointance per unit area, but the accurate definition is pointance per projected unit area, since this includes pointance measured at an angle to the surface normal of the source (see formula for sterance, *L*, in the table). The projected area of the sun is a disk 1.5×10^{18} m^2 (one-fourth the spherical surface area); therefore, the sun's radiant sterance would be 3.2×10^{25} W sr^{-1}/ $1.5 \text{ X } 10^{18}$ m^2, or 2.1×10^7 W m^{-2} sr^{-1}.

Sterance conveys a powerful radiometric concept, and disguised within its definition is Lambert's cosine law, which states that the quantity of light radiating from a surface element at some angle to the surface normal decreases in proportion to the cosine of that angle. A perfect Lambertian surface is one that radiates according to this law and is an ideal source of diffuse light. Because the projected area of any surface element also declines in proportion to the cosine of the angle from the normal, the sterance of a Lambertian radiator remains constant in all directions. This explains why the radiance of a highly diffuse source looks the same from all angles.

Here on Earth, the minute fraction of solar radiation that we receive is said to irradiate us. Keep in mind that the sun radiates, but the Earth is irradiated. In this way, we can distinguish between source and receiver. The English lan-



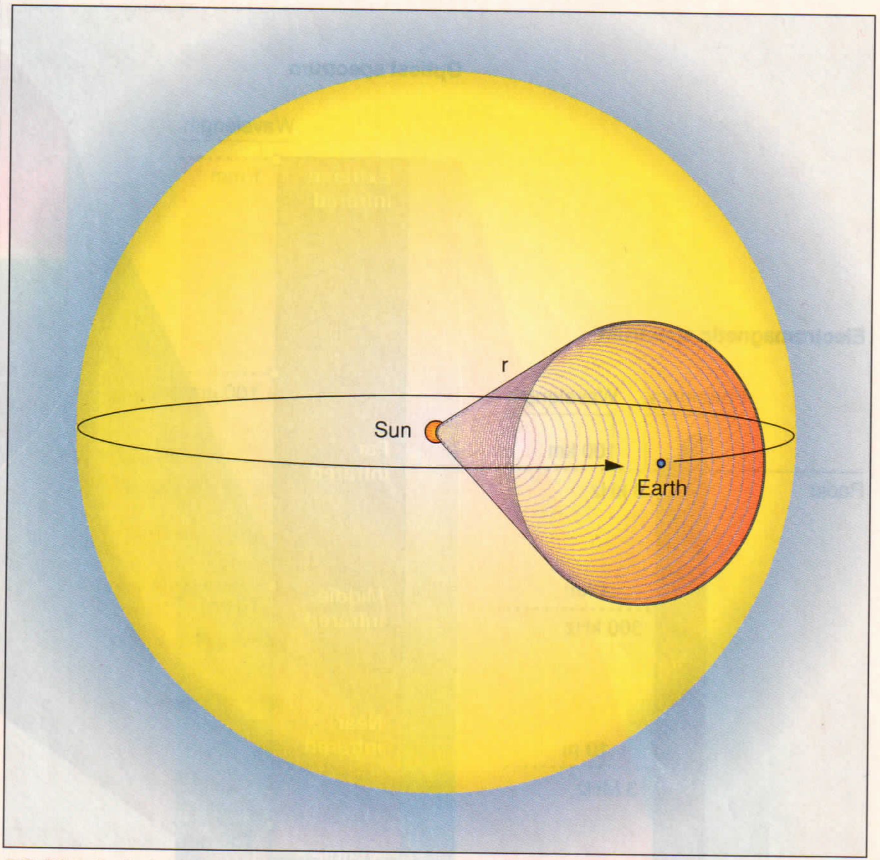


FIGURE 1. Radiation from the sun streams out into space in all directions as an ever-expanding sphere of energy. Flowing within one steradian of solid angle is 3.2×10^{25} W of radiant power. The surface area of a sphere circumscribed by one steradian equals r^2. At Earth's orbit, then, one steradian covers 2.25 × 1022 m^2 of area.

guage makes the same distinction between the reading lamp that is lit and the book that is lighted. The radiometric term for irradiance, however, makes no distinction. It measures power per unit area and is expressed again as areance. But a distinction between symbols is made, with irradiance, or incident areance, symbolized as *E*.

The difference between areance *M* and areance *E* lies in the direction of energy flow at the surface of interest. *M* flows out and *E* flows in. The symmetry of nomenclature for areance stands in silent recognition of the conservation of energy, because energy received is generally re-emitted through reflection, scattering, transmission, or reradiation.

Having journeyed over 1.5×10^{11} m through the interplanetary vacuum, solar radiation reaching Earth is a dim memory of what it was at the sun's surface. Distributed over a spherical area of 2.8×10^{23} m^2 ($4\pi r^2$), the radiation has an incident areance of 4×10^{26} W/2.8×10^{23} m^2, or 1429 W/m^2. At Mars, the areance drops to 625 W/m^2 (4×10^{26} W/6.4×10^{23} m^2), once again demonstrating the inverse-square relation.

Light-sensitive instruments exposed to sunlight will measure the incident areance, but they can also be calibrated to display power, pointance, or sterance by virtue of the geometric relationship between these terms. For example, a radiometer used to measure radiant areance could also determine radiant sterance, because $E = L\omega$. To find the sterance of the sun, one need only know the incident areance and the solid-angle extension of the sun at the point of measurement. From Earth, the solar disk subtends an angular width, α, of 0.53°, which equals 6.7×10^{-5} sr ($\omega = 4\pi \sin^2(\alpha/4)$). Therefore, the sun's sterance, *L*, should be 1429 W/m^2/6.7×10^{-5} sr, which matches the figure of 2.1×10^7 W m^{-2} sr^{-1} given earlier.

Irradiance detected by that aboriginal light-sensitive instrument, the human eye, stimulates sensations that we casually call brightness, intensity, brilliance, and so forth. These terms are explicitly addressed in a subdivision of radiometry called photometry (see "Measuring visible light," below). Photometry concerns itself solely with visible radiation.

The blackbody radiator

That visible radiation should exist at all, as apart from invisible radiation, suggests that the radiant energy of the sun is distributed over a range of energies (see spectrum, p. 63). And in fact, anyone who has seen a rainbow has witnessed a colorful display of the sun's visible-energy distribution. But how is the total energy from the sun distributed? And how much of it is invisible? In the last decade of the 19th century, some of the finest scientific minds were trying to find an answer to these questions, and the solution turned the world of physics upside down.

Previous work by James Maxwell, Heinrich Hertz, and others had shown that an oscillating electric charge generates radiant energy that propagates outward from the charge at the speed of light. They also found that the energy radiates as a wave with a frequency matching that of the oscillator. Meanwhile, the science of thermodynamics—particularly the statistical mechanics cultivated by Ludwig Boltzmann—had contributed powerful new insights into the molecular structure of matter and its relationship to temperature and heat. Theoretical physicists such as Max Planck, John Rayleigh, James Jeans, and Wilhelm Wien began to sense a funda-

Measuring visible light

To be strictly accurate, the word light refers only to that portion of radiant energy that we can actually see. Radiometry applied to this visible radiation is called photometry.

Photometric nomenclature differentiates itself from radiometric terminology by using the adjective luminous to modify the term of interest. For example, radiant energy becomes luminous energy and radiant power becomes luminous power. Photometric terms can be converted into radiometric ones and vice versa if the characteristic sensitivity of the human eye is known.

In brightly lighted surroundings, the human eye is most sensitive to light with a wavelength of 555 nm. This is called photopic vision. At night, or in low-light conditions, the eye sees best at 510 nm. This is classified as scotopic vision. At the blue and red extremes of human vision, sensitivity drops dramatically; therefore, a blue or red light source with the same radiance as a yellow one would nevertheless appear much dimmer (see figure).

To gain a quantitative yardstick for the brightness of a luminous object, luminous efficiency must be factored in to compensate for the nonlinear sensitivity of the eye. At maximum photopic sensitivity (555 nm), the luminous efficiency of the eye is 100% and 1 W of radiant power is defined as 673 lumens. Therefore, a 2000-lm light bulb would give off a total of 2000 lm/673 lm/W, or about 3 W of visible radiant power.

At other visible wavelengths, luminous efficiency drops off; the luminous power of, say, a 1-mW He-Ne laser at 633 nm can be found by multiplying the radiant power by 673 lm/W(0.265), where 0.265 is the luminous efficiency factor at 630 nm. Thus the 1-mW HeNe would emit about 0.18 lm of luminous power.

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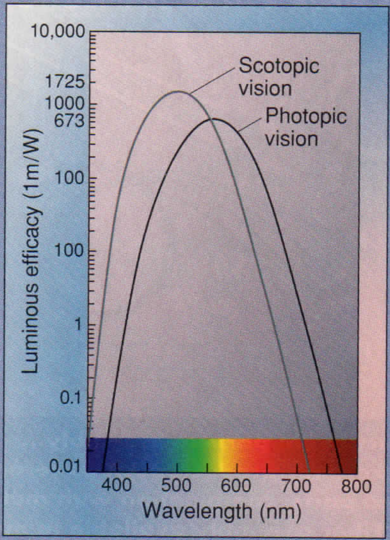


The human eye has two sensitivity curves, one for daylight conditions ("photopic" vision) and one for nighttime settings ("scotopic" vision). Shown here in units of luminous efficacy (lm/W), the two curves help quantify the efficiency of the eye as it perceives a 1-W light source at various wavelengths (colors).

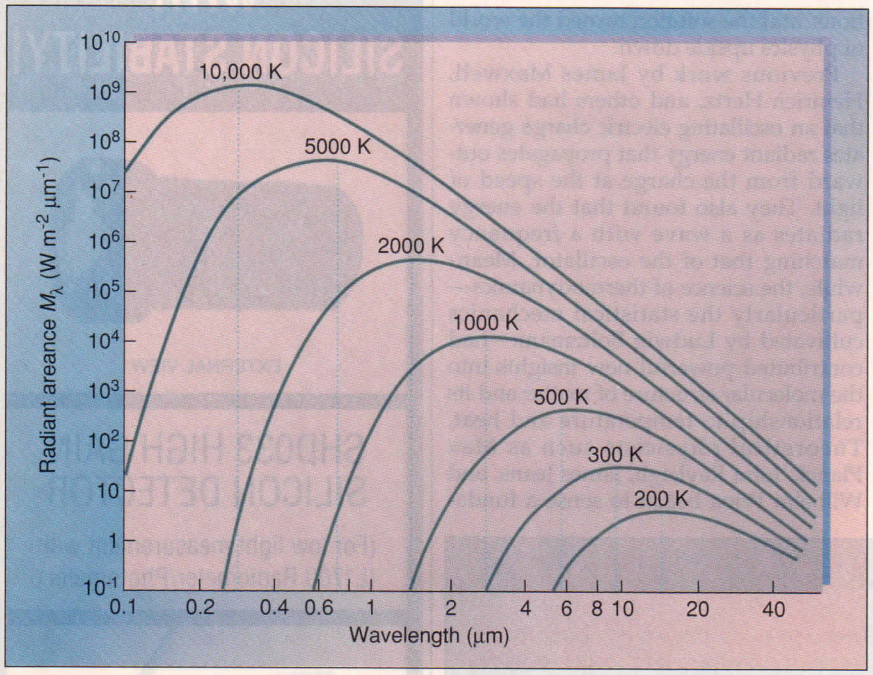


FIGURE 2. Blackbody radiation displays a distinct spectral distribution of energy that peaks at a unique value of wavelength and areance. The position of that peak depends only on temperature and is described by the Wien displacement law. A true blackbody emits energy at all wavelengths.

mental connection between the radiation of oscillating charges and the characteristic radiation emitted by glowing-hot objects.

Radiometric measurements of objects heated to different temperatures revealed a distinctive distribution of radiant energy. Data plots of wavelength vs. spectral areance (that is, radiant areance emitted from a source within a narrow wavelength range) traced a bell-shaped curve decidedly skewed to the shorter wavelengths (see Fig. 2). At higher temperatures the spectral areance, M_λ, peaked at higher levels and at shorter wavelengths, but at any given temperature the overall shape of the curve stayed the same.

To better understand the physical mechanisms behind this phenomenon, theorists developed the concept of the perfect radiator—a body that emits the maximum possible radiant energy at all wavelengths, in all directions, and at any given temperature. The thermodynamic considerations of Gustav Kirchhoff, expressed as Kirchhoff's Law, showed that if such a body were to

Radiometric and photometric terms*

Term	Symbol	Unit	Formula
Energy	Q		
Radiant	Q_e	J	—
Luminous	Q_v	lm-s	
Power (flux)	ϕ		
Radiant	ϕ_e	W	Q/t
Luminous	ϕ_v	lm	
Areance (exitance)	M		
Radiant	M_e	W/m^2	ϕ/A
Luminous	M_v	lm/m^2	
Pointance (intensity)	I		
Radiant	I_e	W/sr	ϕ/ω
Luminous	I_v	lm/sr	
Sterance	L		
Radiant (radiance)	L_e	$W/m^2 \cdot sr$	$\phi/A\cos\theta(\omega)$
Luminous (luminance)	L_v	$lm/m^2 \cdot sr$	or $I/A\cos\theta$
Areance (irradiance/ illuminance)	E		ϕ/A
Radiant	E_e	W/m^2	I/r^2
Luminous	E_v	lm/m^2	or $L\omega$

*Radiant = radiometric term; luminous = photometric term

remain in thermal equilibrium, it also would have to be a perfect absorber of energy. The idealization became known as the blackbody.

Blackbodies have some very useful features. First, a blackbody emits more radiant energy than any real object at the same temperature. Second, two blackbodies at the same temperature will have exactly the same radiant energy distribution. Third, the distribution of radiant energy from a blackbody is continuous. Fourth, a blackbody absorbs all incident radiation from any direction and at any wavelength (no reflection, no transmission). And fifth, the sterance of a blackbody is perfectly Lambertian. These qualities make the blackbody an important radiometric standard with which to compare real light sources.

Planck's insight

To theoretically simulate the unique properties of a blackbody radiator, Planck and his contemporaries considered the radiant energy contained in a thermally isolated box known as Jeans' cube. If the hypothetical box is truly isothermal it acts like an ideal thermos bottle and the radiation stays in the cavity forever, being perpetually absorbed and re-emitted by the walls. The question then becomes: What does the radiation in the box look like for a given temperature?

Based on thermodynamic arguments, Boltzmann derived a simple expression that related the total areance of the blackbody radiation to the fourth power of temperature:

$$M = \sigma T^4 \ \mathrm{W/m^2} \qquad \text{[Eq. 1]}$$

This important relationship has become known as the Stefan-Boltzmann Law in recognition of Josef Stefan who earlier proposed it and Boltzmann who derived it. But the constant, σ, had to be experimentally determined, and the equation says nothing about spectral areance as a function of wavelength.

Wien, Rayleigh, Jeans, and Planck attacked the problem of spectral energy distribution by first counting up the number of radiation modes (standing waves) that can exist between the walls of the box and within a given wavelength (frequency) interval, which is a little like determining how many notes a bugler can play within a single octave (see Fig. 3). If the average energy of each mode could also be established, then knowing the number of modes within the cavity would yield the average energy density for the given wavelength range. And from this information the spectral areance can be deduced.

When calculating the average modal energy contained in each wavelength interval, Wien, Rayleigh, and Jeans naturally assumed that the energy of molecular vibrations in the walls of the cavity could take on any value in a continuum of possible energies. Wien's resultant formulation for spectral areance fit the radiometric data at short wavelengths or low temperatures but missed the mark at longer wavelengths. Rayleigh and Jeans devised a theorem that agreed with the data at longer wavelengths but blew up at shorter ones.

Planck, however, hit the bullseye with a theorem that made a startling assumption: the energies of molecular oscillations can only take on discrete values. His formula for spectral areance fit the data at all wavelengths. Planck presented his results at the Christmas meeting of the German Physical Society in 1900 — a timely gift for the 20th century:

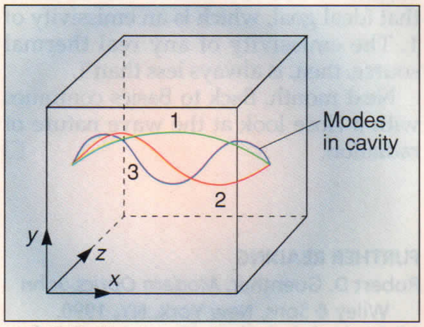
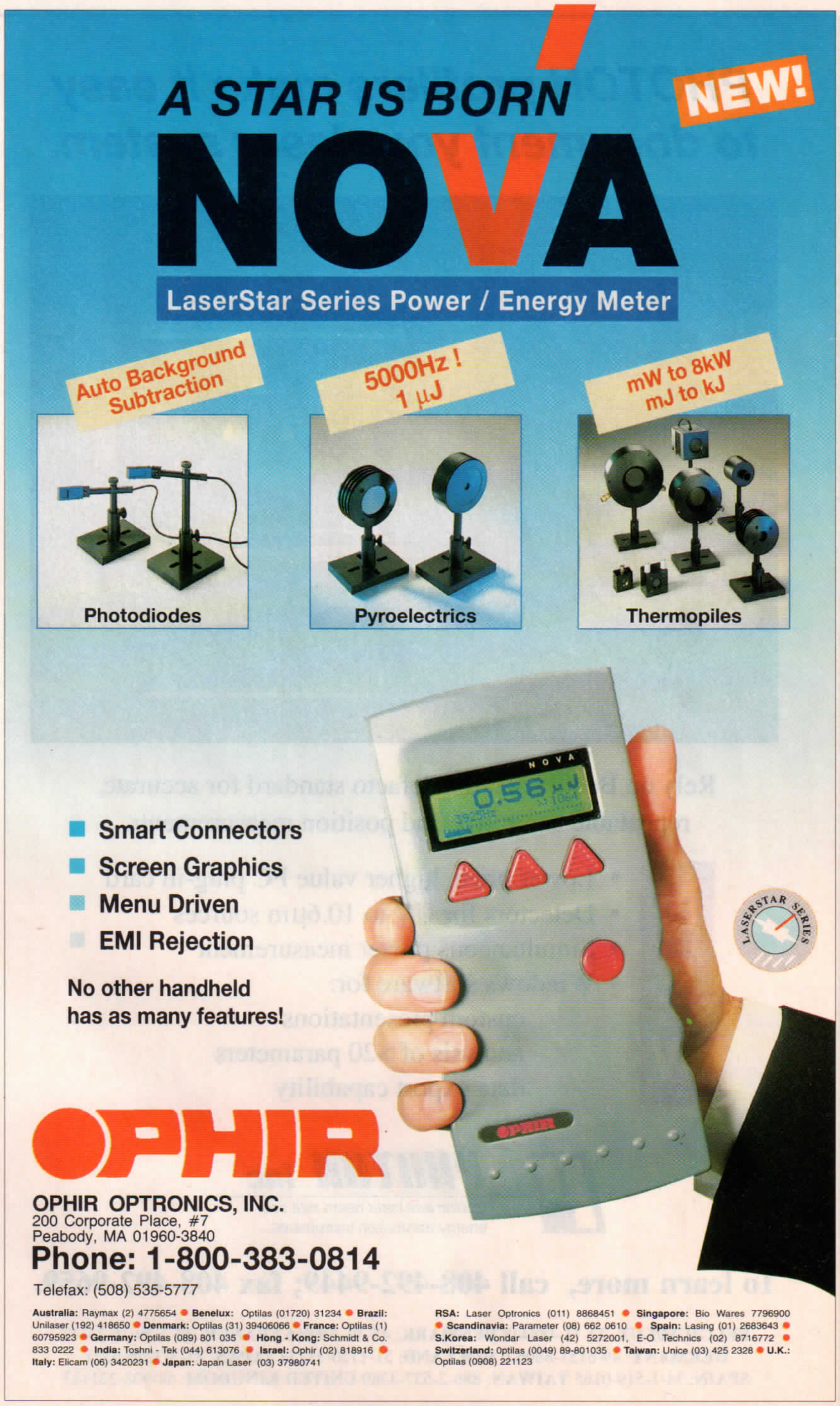


FIGURE 3. Planck and others determined the radiant energy density contained in an isothermal box by first adding up all the possible radiation modes (standing waves) between the walls of the cavity and within a given wavelength range. By multiplying the number of modes by the average energy per mode, the energy density is derived. Shown here are three possible modes in just one dimension.

$$M_\lambda = \frac{2\pi hc^2}{\lambda^5}\left[\frac{1}{\left(\exp(hc/\lambda kT)-1\right)}\right]\mathrm{Wm}^{-2}\mu\mathrm{m}^{-1} \qquad \text{[Eq. 2]}$$

Planck's famous formula shows that the spectral areance of a blackbody depends only on the temperature. But, more important, it also establishes that the energy of any radiation mode cannot fall below a certain minimum value defined by the quantity $h\nu$, where h = 6.63×10^{-34} J-sec and ν is the frequency. At the core of Planck's formula lies the first description of the photon:

$$E = h\nu \qquad \text{[Eq. 3]}$$



Furthermore, by finding the area under the curve generated from Planck's formula (in other words, by integrating Eq. 2 over all wavelengths), the Stefan-Boltzmann relation for total areance (Eq.1) is derived. The Stefan-Boltzmann constant, once experimentally determined, can now be expressed in terms of the more fundamental constant, *h*, known as Planck's constant.

If the sun were a perfect blackbody radiator, then according to Planck's formula, its spectral distribution would depend on temperature alone. Furthermore, we know that any two blackbodies at the same temperature will have exactly the same distribution. Therefore, if we heat a blackbody until its spectral distribution matches that of the sun, we should know the temperature of the sun.

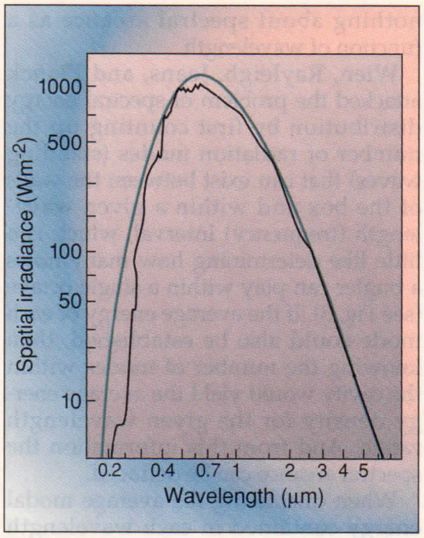


FIGURE 4. The spectral areance of a blackbody at 6000 K (dashed curve) and of the sun (solid curve) closely resemble one another, demonstrating that the sun is a reasonably good blackbody radiator.

In fact, the solar spectral areance shows a remarkable similarity to a blackbody at a temperature of 6000 K (see Fig. 4). The same principle can be used to characterize the color temperature of artificial thermal light sources, such as incandescent lamps, as well as distant stars.

It's important to remember that no thermal source of radiation exactly mimics the spectral areance of a blackbody, because the blackbody is a perfect radiator. Emissivity measures the degree to which a source falls short of that ideal goal, which is an emissivity of 1. The emissivity of any real thermal source, then, is always less than 1.

Next month, Back to Basics continues with a close look at the wave nature of radiation. ☐

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