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Blackbody and Blackbody Radiation

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Synonyms

Blackbody (specific terms) – Black body, Full radiator, Planckian radiator, Natural object

Blackbody (alt. terms) – Ideal black surface, Ideal emitter, Ideal thermal radiator

Blackbody radiation – Black-body radiation, Cavity radiation

Blackbody locus – Planckian locus

Definition

A *blackbody* is an ideal thermal radiator that absorbs completely all incident radiation whatever the wavelength, the direction of incidence, or the polarization [1]. This radiator has, for any wavelength and any direction, the maximum spectral concentration of radiance for a thermal radiator in thermal equilibrium at a given temperature.

Blackbody radiation is radiant energy emitted by an ideal black surface (blackbody) whose spectral power distribution is only governed by its own temperature.

Blackbody color is the temperature of a true blackbody emitter which to the human eye is a close match to the color of an incandescent object, which is not a blackbody.

Blackbody locus is the locus of points in a chromaticity diagram that represents chromaticities of the radiation of Planckian radiators at different temperatures.

Description

All bodies at nonzero temperature absorb and emit radiation. If a body is at thermal equilibrium, it is because the amount of radiation that is emitted per second is equal to the amount absorbed. A blackbody (or ideal Planckian or black radiator) is a body that can completely absorb radiation at any wavelength and completely emit radiation at any wavelength so that it emits more radiant power at each wavelength than any other object at the same temperature. A blackbody is not only an ideal emitter but also a diffuse emitter, which means that the emitted radiation is isotropic or independent of direction [2]. It gets its name because of the fact that, at room temperature, it appears visibly black.

In the late nineteenth century, Kirchhoff [3] and other experimental physicists found that an ideal blackbody, in thermodynamic equilibrium, emitted radiant energy whose spectrum was continuous and a function only of its wavelength and temperature, independent of the nature of the blackbody. However, this behavior could not be explained using thermodynamics or classical

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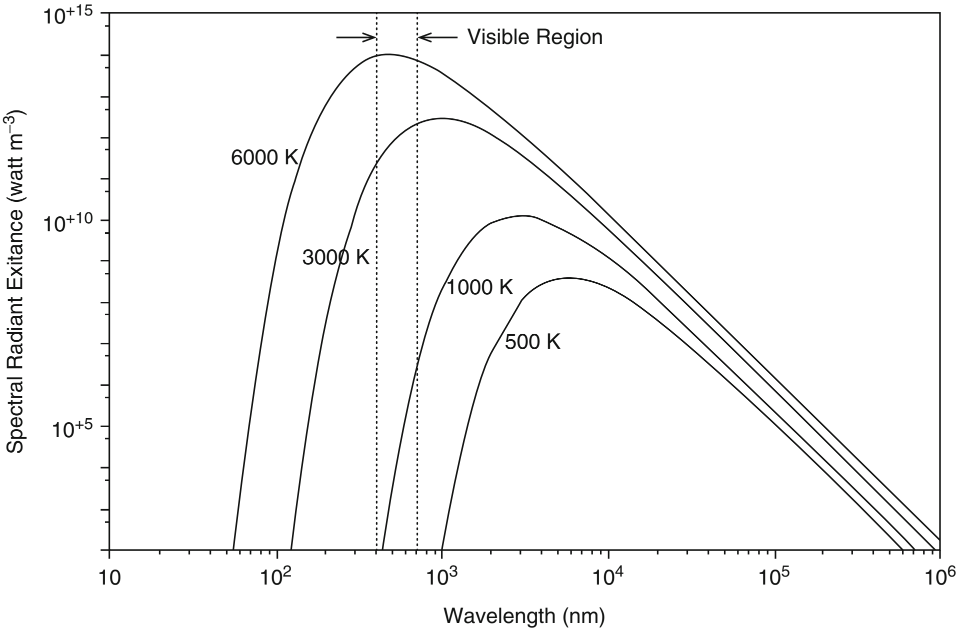


Blackbody and Blackbody Radiation, Fig. 1 Blackbody spectral exitance curves for several temperatures

statistical mechanics. It was not until Einstein introduced the idea that light could be quantized that Planck formulated his blackbody radiation law based upon this principle [4]. This is generally known as *Planck's law* and gives the amount of power emitted by a blackbody in equilibrium at a temperature T according to:

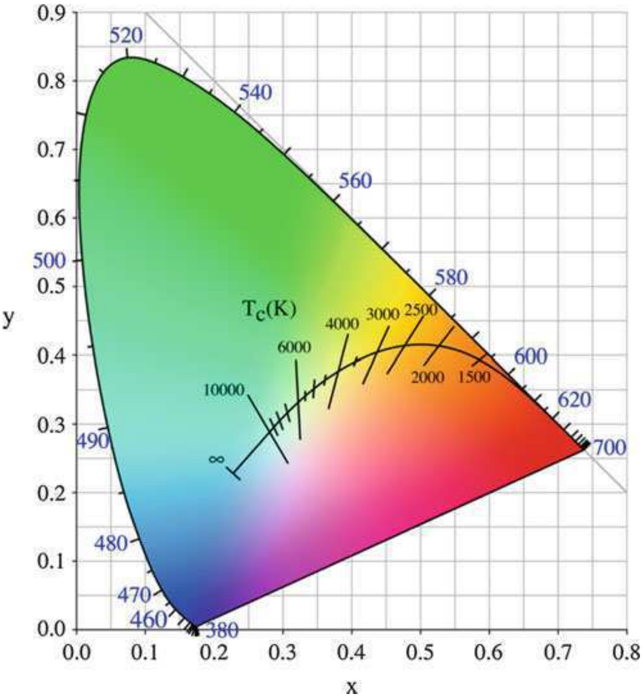
$$M_e(\lambda, T) = \frac{c_1}{\lambda^5}\left(\frac{1}{e^{c_2/\lambda T} - 1}\right)$$

where $M_e(\lambda, T)$ is the spectral radiant exitance (power per unit area per unit wavelength interval), λ is the wavelength in meters, and T is the absolute temperature in kelvins. The constants c_1 and c_2 are known as Planck's radiation constants and have the values:$c_1 = 2\pi hc^2 = 3.7415 \times 10^{-16}$ W m^2; $c_2 = hc/k = 1.4388 \times 10^{-2}$ m K, where h is Planck's constant, c is the speed of light in vacuum, and k is Boltzmann's constant.

The spectral power distributions of some blackbody radiators at different temperatures are shown in Fig. 1. It can be seen that the peak of the blackbody radiation curve shifts to shorter wavelength and higher energy with increasing temperature. At room temperature (300 K), the peak of the curve is at about 10 mm, and the emission is largely thermal in the infrared region. As discussed above, this room-temperature blackbody that has essentially no emission in the visible region appears black. However, as the temperature of the blackbody source rises through the range shown, it increasingly emits in the visible region, and its color changes continuously from black to red through orange and yellow to white and finally a bluish white.

The color coordinates of these blackbody sources at different temperatures can be plotted on a chromaticity diagram. This is shown in Fig. 2, which shows that as the temperature of the blackbody radiator increases, its CIE chromaticity coordinates (xy) move along a curved line in the CIE 1931 chromaticity diagram. This curve is known as the *blackbody* or *Planckian locus*. For white light sources for general lighting applications, they are designed so that their CIE chromaticities (u´v´) are located near this Planckian locus, when plotted on a Uniform Color Scale (UCS) diagram (u´v´).

For colorimetric applications, the International Commission on Illumination (CIE) has defined a standard illuminant A, which is



Blackbody and Blackbody Radiation, Fig. 2 CIE 1931 chromaticity diagram showing the locus of blackbody radiators calculated for Planckian temperatures from 1500 K to infinity; the Planckian temperature that provides the smallest chromaticity difference between an artificial source and this blackbody locus is its correlated color temperature, T_c

representative of illumination under incandescent lighting [5] and whose values of relative spectral power distribution are that of a Planckian radiator at a temperature of approximately 2856 K. It is important to note that while the original CIE standard illuminant A was defined in 1931 in terms of a relative spectral power distribution of a Planckian radiator at a temperature of 2848 K, the Planckian radiation constants, c_1 and c_2, have changed several times since then (in 1948, 1968, and 1990) with changes in the International Temperature Scale (ITS), causing a corresponding change in the associated temperature. For this reason, the CIE Standard which currently defines CIE standard illuminant A is no longer a function of temperature [5]. However, for an artificial source that is representative of CIE standard illuminant A, the concept of *correlated color temperature* is used, which is the temperature of the Planckian radiator having a chromaticity along the Planckian locus nearest the chromaticity calculated for the spectral distribution of the test source. There are also many artificial white light sources whose spectral power distribution is very different from a blackbody source, such as fluorescent lamps and sources based on light-emitting diodes. However, the concept of correlated color temperature is still used to describe the colorimetric properties of these types of white light sources.

For astronomical applications, the electromagnetic radiation from stars and planets is sometimes characterized in terms of an *effective temperature*, the temperature of a blackbody that would emit the same total flux of electromagnetic energy. However, stars are observed at a depth inside the atmosphere (the photosphere), so it is more typical to describe a star's visual surface by its *photospheric temperature* (see entry on ▶ Apparent Magnitude, Astronomy).

There are several other important properties of blackbody sources that are given by the following three laws [6]:

Stefan-Boltzmann Law: This law states that the total radiant exitance, M of a blackbody, determined by integrating the spectral radiant exitance curve, $M_e(\lambda)$, for all wavelengths, λ, is proportional to the fourth power of its absolute temperature:

$$M = \sigma T^4$$

where σ is Stefan's constant (=0.56686 × 10–7 $\mathrm{Wm^2K^{-4}}$). No surface at thermal equilibrium can emit more than this amount of energy.

Kirchhoff's Law of Thermal Radiation: This law states that, at each wavelength, the emissivity of the blackbody, $\varepsilon(\lambda)$, at thermal equilibrium is equal to its absorptivity, $\alpha(\lambda)$:

$$\varepsilon(\lambda) = \alpha(\lambda)$$

Wien's Displacement Law: This law states that the curves of the spectral power distribution of the blackbody radiation are peaked at a wavelength, λ_{peak}, given by:

$$\lambda_{peak} = \frac{2898}{T}$$

This can be simply shown by differentiating the Planckian spectral power distribution with respect to wavelength and solving the derivative when it equals zero.

Examples

Since the last century, blackbody radiation has been of great interest for use as a primary (calculable) source because the properties are universal and independent of the particular material substance. A good laboratory implementation of a blackbody is a small hole in the wall of an otherwise opaque cavity [7]. The light that enters the cavity through the hole will undergo so many reflections before it can escape from the hole that the light will be effectively absorbed and the hole will appear black. Until 1979, a blackbody like this, heated to the temperature of melting platinum, was the basis of the definition and realization of the SI base unit for photometry, the candela [8].

The earliest types of artificial light were based on heating an object until it was red hot or hotter and was able to emit visible light. These types of artificial light sources are referred to as *incandescent*. Examples of incandescent objects are fire, candles, carbon arcs, and tungsten-filament lamps. They emit radiation with approximately the same spectral power distribution as a blackbody but with an intensity reduced by a factor called the *emissivity*, ε. If the emissivity does not vary with wavelength, the source is called a *gray body* or *nonselective radiator*. An incandescent tungsten-filament lamp is close to being a gray body with an emissivity of approximately 0.40 [7]. The temperature of a blackbody that is closest in color to this gray body source is often used as an index of its color. This is referred to as the *correlated color temperature*, T_c. An alternative index is the *distribution temperature*, which is the temperature of a blackbody whose relative spectral power distribution is closest to that of the source in question. However, all three terms should be used with caution as they do not give a full picture of the actual spectral distribution [9]. Typical tungsten-filament lamps have correlated color temperatures and distribution temperatures in the range 2500–3000 K.

However, these incandescent lamps emit not only visible light but a significant amount of infrared radiation which makes them inefficient as light sources compared with more modern lighting technologies, such as solid-state lighting which can be designed to emit optical radiation only in the visible range.

There are many examples of everyday materials that behave like blackbodies but emit significant thermal radiation. The human body is one example of a blackbody radiator which emits at roughly 300 K. Another obvious example is the Sun, whose surface is roughly 6000 K. The Earth is also considered to be a blackbody radiator, but it is less than ideal.

Cross-References

- ▶ Apparent Magnitude, Astronomy
- ▶ CIE Chromaticity Coordinates, xyY
- ▶ Spectral Power Distribution
- ▶ UCS Diagrams; Uniform Chromaticity Scales; Yu'v'

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