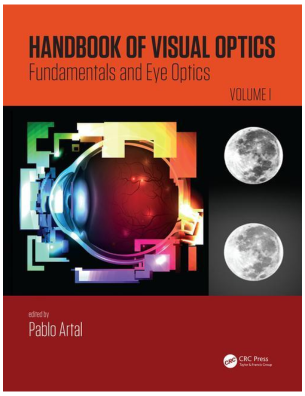

Handbook of Visual Optics

Pablo Artal

6 Photometry

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6 Photometry

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Contents

6.1 INTRODUCTION

Photometry is the measurement of light, which is electromagnetic radiation detectable by the human visual system in the wavelength range from 360 to 830 nm. Photometry is needed in many applications where light as observed by human eyes is evaluated, for example, in evaluation of products in lighting, displays, and traffic signs. In photometry, optical radiation is measured with spectral weighting by the standardized spectral response of the human eye. Photometry normally uses optical radiation detectors that mimic the spectral response of the eye, or spectroradiometry incorporating appropriate calculations for weighting by the spectral response of the eye. Typical photometric quantities include luminous flux (unit: lumen), luminous intensity (unit: cd), illuminance (unit: lux), and luminance (unit: candela per square meter).

Similar to photometry, the measurement of the entire optical radiation spectrum (and often involves spectrally resolved measurements) is called "radiometry," and a similar set of quantities is used, such as radiant flux, radiant intensity, and irradiance. Photometry and radiometry are closely related; thus, some principles in radiometry are also important for photometry.

Measurement of color is often regarded as a part of photometry, as it also involves measurement of visible radiation. Measurement of color is also important in evaluating many industrial products. Colorimetry is the measurement science used to quantify and describe physically the human color perception. The basis of colorimetry was established by Commission Internationale de l'Éclairage (CIE) in 1931, and it evolved much since then.

In this chapter, the fundamentals of photometric quantities and units, some important principles in photometry and radiometry, and the fundamentals of color quantities are described. The terminology used in this chapter follows international standards and recommendations [1,2].

6.2 BASIS OF PHYSICAL PHOTOMETRY

6.2.1 SPECTRAL LUMINOUS EFFICIENCY FUNCTION

The relative spectral responsivity of the human eye was first standardized by the CIE in 1924 [3] and redefined as part of the colorimetric standard observers in 1931 [4]. It is called "the spectral luminous efficiency function for photopic vision," or the $V(\lambda)$ function, defined in the region from 360 to 830 nm, and is normalized to one at its peak, 555 nm (Figure 6.1). The values were republished by CIE in 1983 [5] and adopted by Comité International des Poids et Mesures (CIPM) in 1983 [6] to supplement the 1979 definition of the candela. The tabulated values of the function at 1 nm increments are republished in a CIE standard [7]. In most cases, the region from 380 to 780 nm suffices for calculation with negligible errors because the value of the $V(\lambda)$ function falls below 10^{-4} outside this region. Thus, a photodetector having a spectral responsivity matched to the $V(\lambda)$ function achieves the role of human eyes in photometry.

The $V(\lambda)$ function is defined for the *CIE standard photometric observer for photopic vision*, which assumes a 2° field of view at relatively high luminance levels (higher than approximately 1 cd/m^2). The human vision in this level is called photopic vision.

The spectral response of human vision deviates significantly at very low levels of luminance (less than approximately 10^{-3} cd/m^2). This type of vision is called scotopic vision. Its spectral responsivity, peaking at 507 nm, is designated by the $V'(\lambda)$ function, which was defined by CIE in 1951 [8], recognized and republished by CIPM in 1982 [9]. The human vision in the region between photopic vision and scotopic vision is called mesopic vision. The spectral luminous efficiency functions for mesopic vision was published recently by CIE [10]. However, it has not yet been adopted as official photometric units. In current practice, almost all photometric quantities are given in terms of photopic vision, even at low light levels. Quantities in scotopic vision are seldom used except for special calculations in research purposes.

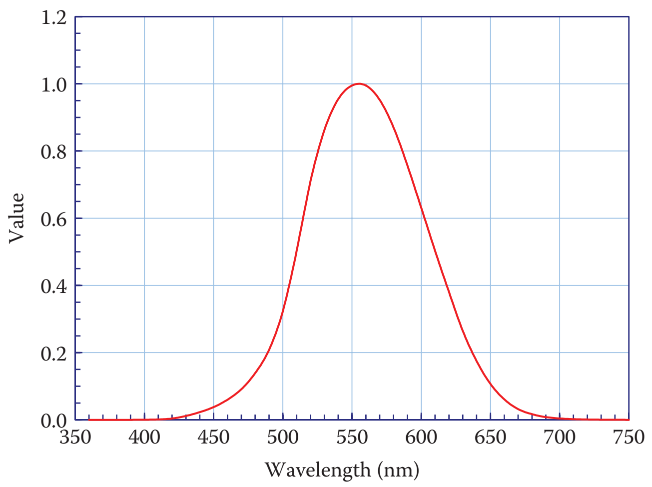

Figure 6.1 CIE $V(\lambda)$ function.

6.2.2 PHOTOMETRIC BASE UNIT, THE CANDELA

While the $V(\lambda)$ was defined in 1924, the physical standard for photometry evolved later. Until 1948, the flame of a specially fabricated candle or oil lamp was used as a unit of luminous intensity. In 1920, *the international candle* was adopted by the CIE. In 1948, to realize more stable and reproducible standards, the Conférence Générale des Poids et Mesures (CGPM) (the General Conference on Weights and Measures) adopted a definition based on a platinum blackbody at its freezing temperature and adopted the "candela" (Latin name of candle).

The candela was then redefined in 1979 by the CGPM [11], which is still the current definition. The candela is defined in terms of a specific amount of optical power of a monochromatic radiation at a specific wavelength as

> The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.

The value of K_m (683 lm/W) was determined based on measurements by several national laboratories in such a way that consistency was maintained with the prior unit so that the magnitude of one candela did not change. Technical details on the redefinition of the candela are available in references [12,13]. The key point of this 1979 redefinition is the establishment of an explicit link between the photometric units and the radiometric units.

It should be noted that the 1979 definition is given only at one wavelength where the $V(\lambda)$ function peaks and did not refer to the $V(\lambda)$ function itself. This was because, at that time, it was considered that the values of $V(\lambda)$ would be changed often and then the definition of the candela would not have to be revised.

To fill in this incompleteness of the definition, the CIPM supplemented the definition of the candela in 1983 [6], in which a photometric quantity X_v is defined in relation to the corresponding radiometric quantity $X_{e,\lambda}$ by the equation:

$$X_v = K_m \int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} X_{e,\lambda} V(\lambda)\, d\lambda. \tag{6.1}$$

The constant, K_m, relates the photometric quantities and radiometric quantities and is called the "maximum spectral luminous efficacy (of radiation) for photopic vision." The value of K_m is given by the 1979 definition of candela, which defines the spectral luminous efficacy of light at the frequency 540×10^{12} Hz (at the wavelength 555.016 nm in standard air) to be 683 lm/W. The value of K_m is calculated as $683 \times V(555.000\ \mathrm{nm})/V(555.016\ \mathrm{nm}) = 683.002$ lm/W [5]. K_m is normally rounded to 683 lm/W with negligible errors.

Fundamentals

6.3 PHOTOMETRIC QUANTITIES AND UNITS

In 1960, the Système International (SI) was established, and the candela became one of the seven SI base units [14]. For further details on the SI units, Refs. [15–17] can be consulted.

Several quantities and units, defined in different geometries, are used in photometry and radiometry. Table 6.1 lists the photometric quantities and units, along with corresponding quantities and units for radiometry.

While the candela is the SI base unit, the luminous flux (lumen) is perhaps the most fundamental photometric quantity, as the other photometric quantities are defined in terms of lumen with an appropriate geometric factor. The definitions of these photometric quantities are described as follows. The definitions of some terms given here are simplified from those given in Ref. [1], which provides the official, rigorous definitions.

6.3.1 LUMINOUS FLUX

Luminous flux (Φ_v) is the time rate of flow of light as weighted by $V(\lambda)$. The unit of luminous flux is the lumen (lm). It is defined as

$$\Phi_v = K_m \int_\lambda \Phi_{e,\lambda} V(\lambda) \mathrm{d}\lambda, \quad (6.2)$$

where $\Phi_{e,\lambda}$ is the spectral concentration of radiant flux as a function of wavelength λ. The term, luminous flux, is often used in the meaning of total luminous flux in photometry.

6.3.2 LUMINOUS INTENSITY

Luminous intensity (I_v) is the luminous flux from a point source emitted per unit solid angle in a given direction, as defined by

$$I = \frac{\mathrm{d}\Phi}{\mathrm{d}\Omega}, \quad (6.3)$$

where $\mathrm{d}\Phi$ is the luminous flux leaving the source and propagating in an element of solid angle $\mathrm{d}\Omega$ containing the given direction. The unit of luminous intensity is the candela (cd = lm sr^{-1}) (Figure 6.2).

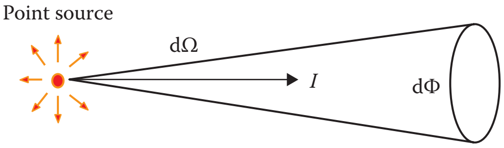

Figure 6.2 Luminous intensity.

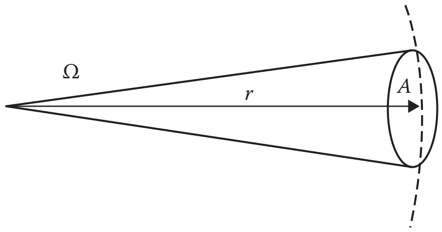

Figure 6.3 Solid angle.

6.3.2.1 Solid angle

The solid angle (Ω) of a cone is defined as the ratio of the area (A) cut out on a spherical surface (with its center at the apex of that cone) to the square of the radius (r) of the sphere:

$$\Omega = \frac{A}{r^2}. \quad (6.4)$$

The unit of solid angle is steradian (sr), which is a dimensionless unit (Figure 6.3).

6.3.3 ILLUMINANCE

Illuminance (E_v) is the density of incident luminous flux at a point on a surface and is defined as luminous flux per unit area:

$$E = \frac{\mathrm{d}\Phi}{\mathrm{d}A}, \quad (6.5)$$

where $\mathrm{d}\Phi$ is the luminous flux incident on an element $\mathrm{d}A$ of the surface containing the point. The unit of illuminance is lux (lx = lm m^{-2}) (Figure 6.4).

Table 6.1 Quantities and units used in photometry and radiometry

PHOTOMETRIC QUANTITY	UNIT	RELATIONSHIP WITH LUMEN	RADIOMETRIC QUANTITY	UNIT
Luminous flux	lm (lumen)		Radiant flux	W (watt)
Luminous intensity	cd (candela)	lm sr^{-1}	Radiant intensity	W sr^{-1}
Illuminance	lx (lux)	lm m^{-2}	Irradiance	W m^{-2}
Luminance	cd m^{-2}	lm sr^{-1} m^{-2}	Radiance	W sr^{-1} m^{-2}
Luminous exitance	lm m^{-2}		Radiant exitance	W m^{-2}
Luminous exposure	lx s		Radiant exposure	W m^{-2}
Luminous energy	lm s		Radiant energy	J (joule)
Total luminous flux	lm (lumen)		Total radiant flux	W (watt)
Color temperature	K (kelvin)		Radiance temperature	K

Fundamentals

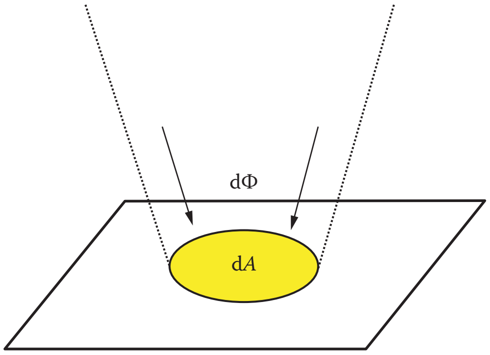

Figure 6.4 Illuminance.

6.3.4 LUMINANCE

Luminance (L_v) is the luminous flux per unit solid angle emitted from a surface element in a given direction, per unit projected area of the surface element perpendicular to the direction. The unit of radiance is W sr^{-1} m^{-2}, and that of luminance is cd/m^2. These quantities are defined by

$$L = \frac{d\Phi}{d\Omega \cdot dA \cdot \cos\theta}, \tag{6.6}$$

where
- dΦ is the radiant flux (luminous flux) emitted (reflected or transmitted) from the surface element and propagating in the elementary solid angle dΩ containing the given direction
- dA is the area of the surface element
- θ is the angle between the normal to the surface element and the direction of the beam

The term dA cosθ gives the projected area of the surface element perpendicular to the direction of measurement (Figure 6.5).

Note that the Equations 6.3, 6.5, and 6.6 are not mathematical derivatives but quotients (see note in ILV luminance definition [1]).

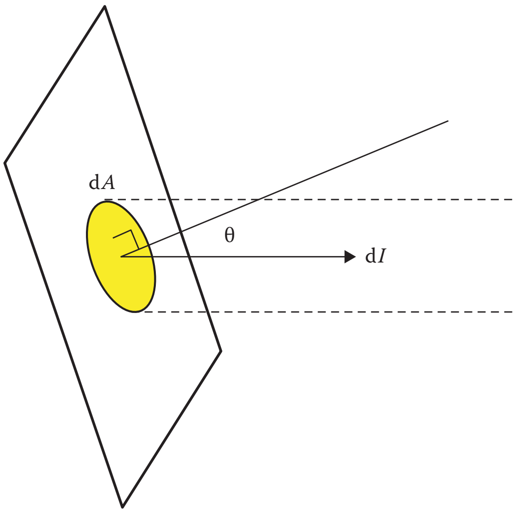

Figure 6.5 Luminance.

6.3.5 LUMINOUS EXPOSURE

Luminous exposure (H_v) is the time integral of illuminance $E_v(t)$ over a given duration Δt:

$$H = \int_{\Delta t} E(t)\,dt. \tag{6.7}$$

The unit of luminous exposure is lux · second (lx · s).

6.3.6 LUMINOUS ENERGY

Luminous energy (Q_v) is the time integral of the luminous flux (Φ) over a given duration Δt:

$$Q = \int_{\Delta t} \Phi(t)\,dt. \tag{6.8}$$

The unit of luminous energy is lumen · second (lm · s).

6.3.7 TROLAND

Troland is a unit of the retinal illuminance when a surface with a luminance of 1 cd/m^2 is viewed through the eye's entrance pupil with an area of 1 mm^2. The troland value, T, for the luminance, L (cd/m^2), of an external field and the pupil size, p (mm^2), is given by

$$T = L \cdot p \tag{6.9}$$

This unit is not an SI unit, not used in metrology; however, it is introduced here because this unit is commonly used by vision scientists.

6.4 PRINCIPLES IN PHOTOMETRY

Several important theories in practical photometry and radiometry are introduced in this section.

6.4.1 INVERSE SQUARE LAW

Illuminance E (lx) at a distance d (m) from a point source having luminous intensity I (cd) is given by

$$E = \frac{I}{d^2}. \tag{6.10}$$

For example, if the luminous intensity of a lamp in a given direction is 1000 cd, the illuminance at 2 m from the lamp in this direction is 250 lx. Note that the inverse square law is valid only when the light source is regarded as a point source. Sufficient distances relative to the size of the source are needed to assume this relationship.

6.4.2 LAMBERT'S COSINE LAW

The luminous intensity of a Lambertian surface element is given by (Figure 6.6)

$$I(\theta) = I_n \cos\theta. \tag{6.11}$$

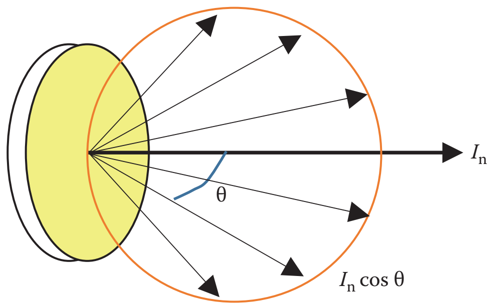

Figure 6.6 Lambert's cosine law.

6.4.2.1 Lambertian surface

A surface whose luminance is the same in all directions of the hemisphere above the surface.

6.4.2.2 Perfect (reflecting/transmitting) diffuser

A Lambertian diffuser with a reflectance (transmittance) equal to 1.

6.4.3 RELATIONSHIP BETWEEN ILLUMINANCE AND LUMINANCE

The luminance L (cd/m^2) of a Lambertian surface of reflectance ρ, illuminated by E (lx) is given by (Figure 6.7)

$$L = \frac{\rho \cdot E}{\pi}. \tag{6.12}$$

6.4.3.1 Reflectance (ρ)

The ratio of the reflected flux to the incident flux in a given condition. The value of ρ can be between 0 and 1.

In the real world, there is no existing perfect diffuser or perfectly Lambertian surfaces, and Equation 6.12 does not apply. For real object surfaces, the following terms apply.

6.4.3.2 Luminance factor (β)

Ratio of the luminance of a surface element in a given direction to that of a perfect reflecting or transmitting diffuser, under specified conditions of illumination. The value of β can be larger than 1. For a Lambertian surface, reflectance is

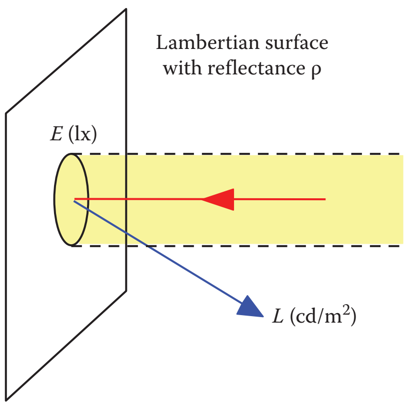

Figure 6.7 Relationship between illuminance and luminance.

equal to the luminance factor. Equation 6.12 for real object is restated using β as

$$L = \frac{\beta \cdot E}{\pi}. \tag{6.13}$$

6.4.3.3 Luminance coefficient (q)

Quotient of the luminance of a surface element in a given direction by the illuminance on the surface element, under specified conditions of illumination, is

$$q = \frac{L}{E}. \tag{6.14}$$

Using q, the relationship between luminance and illuminance is thus given by

$$L = q \cdot E. \tag{6.15}$$

Luminance factor corresponds to radiance factor, and luminance coefficient corresponds to radiance coefficient in radiometry. Bidirectional reflectance distribution function is also used for the same concept as radiance coefficient.

6.4.4 PLANCK'S LAW

The spectral radiance of a blackbody at a temperature T (K) is given by

$$L_e(\lambda, T) = c_1 n^{-2} \pi^{-1} \lambda^{-5} \left[\exp\left(\frac{c_2}{n\lambda T} \right) - 1 \right]^{-1}, \tag{6.16}$$

where

- $c_1 = 2\pi hc^2 = 3.7417749 \times 10^{-16}$ W · m^2
- $c_2 = hc/k = 1.438769 \times 10^{-2}$ m · K (1986 CODATA from Ref. [18])
- h is Planck's constant
- c is the speed of light in vacuum
- k is the Boltzmann constant
- n (=1.00028) is the refractive index of standard air [19]
- λ is the wavelength in standard air

6.5 COLORIMETRIC QUANTITIES

6.5.1 COLOR MATCHING FUNCTIONS AND TRISTIMULUS VALUES

The basis of colorimetry was established by CIE in 1931 based on a number of visual experiments that defined a set of three spectral weighting functions [4]. These functions, shown in Figure 6.8, are called the "CIE 1931 XYZ color matching functions (CMFs)" denoted as $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$. These functions were derived from a linear transformation of the original set of color matching functions in such a way that $\bar{y}(\lambda)$ is equal to $V(\lambda)$. The tabulated values of the 1931 CMFs at 5 nm interval are available in Ref. [20] and at 1 nm interval in Ref. [21].

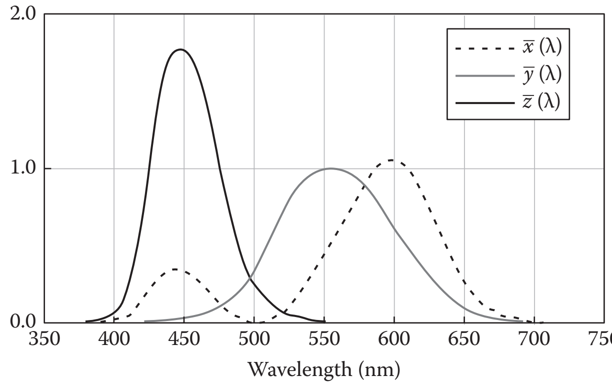

Figure 6.8 CIE 1931 *XYZ* color matching functions.

By using the CMFs, light stimuli having any spectral power distribution $\phi_\lambda(\lambda)$ can be specified for color by three values:

$$X = k\int_\lambda \phi_\lambda(\lambda)\bar{x}(\lambda)\mathrm{d}\lambda$$

$$Y = k\int_\lambda \phi_\lambda(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda \tag{6.17}$$

$$Z = k\int_\lambda \phi_\lambda(\lambda)\bar{z}(\lambda)\mathrm{d}\lambda,$$

where
$\phi_\lambda(\lambda)$ is the spectral distribution of light stimulus
k is a normalizing constant

These integrated values are called "tristimulus values." Two light stimuli having the same tristimulus values have the same color even if the spectral distributions are different. For light sources and displays, $\phi_\lambda(\lambda)$ is given in quantities such as spectral irradiance and spectral radiance. If $\phi_\lambda(\lambda)$ is given in an absolute unit (such as W m^{-2} nm^{-1}, W m^{-2} sr^{-1} nm^{-1}) and $k = 683$ lm/W is chosen, Y yields an absolute photometric quantity such as illuminance (in lux) or luminance (in cd/m^2).

For object colors, $\phi_\lambda(\lambda)$is given as

$$\phi_\lambda(\lambda) = R(\lambda)S(\lambda), \tag{6.18}$$

where
$R(\lambda)$ is the spectral reflectance factor of the object
$S(\lambda)$ is the relative spectral distribution of the illumination

and

$$k = \frac{100}{\int_\lambda S(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda}, \tag{6.19}$$

so that $Y = 100$ for a perfect diffuser and Y indicates the luminance factor of the object surface. To calculate color of objects from spectral reflectance factor $R(\lambda)$, one of the standard illuminants (see Refs. [20,22]) is used.

Tristimulus values can be obtained either by numerical summation of Equation 6.17 from the spectral data $\phi_\lambda(\lambda)$ obtained by a spectroradiometer or spectrophotometer or by broadband measurements using detectors having relative spectral responsivity matched to the color matching functions. Such a device using three (or four) detector channels is called "tristimulus colorimeter."

When applying colorimetric data for real visual color matching, it should be noted that the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ color matching functions are based on experiments using 2° field of view and applicable only to narrow fields of view (up to 4°). Such an ideal observer is called the "CIE 1931 standard colorimetric observer." In 1964, the CIE defined a second set of standard color matching functions for a 10° field of view, denoted as $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$, to supplement those of the 1931 standard observer. This is called the "CIE 1964 supplementary standard colorimetric observer" and can be used for a field of view greater than 4°. The 2° observer is used in most applications for colorimetry of light sources. The 10° observer is often used in object color measurements. For further details of colorimetry and color science, refer to official CIE publications [20–22] and other general references [23].

6.5.2 CHROMATICITY COORDINATES

While the tristimulus values can specify color, it is difficult to associate what color it is from the three numbers. By projecting the tristimulus values onto a unit plane ($X + Y + Z = 1$), color of light can be expressed on a two-dimensional plane. Such a unit plane is known as the *chromaticity diagram*. The color can be specified by the *chromaticity coordinates* (x, y) defined by

$$x = \frac{X}{X+Y+Z}; \quad y = \frac{Y}{X+Y+Z} \tag{6.20}$$

The diagram using the chromaticity coordinates (x, y), as shown in Figure 6.9a, is referred to as the *CIE 1931 (x, y) chromaticity diagram*, or the *CIE (x, y) chromaticity diagram*. The boundaries of this horseshoe-shaped diagram are the plots of monochromatic radiation (called the "spectrum locus").

The (x, y) chromaticity diagram is significantly nonuniform in terms of color difference. The minimum perceivable color differences in the CIE (x, y) diagram, known as the "MacAdam ellipses," are shown in Figure 6.9a. To improve this, in 1960, CIE defined an improved diagram—*CIE 1960 (u, v) chromaticity diagram* (now obsolete), and in 1976, a further improved diagram—*CIE 1976 uniform chromaticity scale (UCS) diagram*, or the CIE (u', v') diagram, as shown in Figure 6.9b, with its chromaticity coordinate (u', v') given by

$$u' = \frac{4X}{X+15Y+3Z}; \quad v' = \frac{9Y}{X+15Y+3Z}. \tag{6.21}$$

While the (u', v') chromaticity diagram is a significant improvement from the (x, y) diagram, it is still not satisfactorily uniform. Both of these diagrams are widely used. Note that these chromaticity diagrams are intended to present color of light sources (emitted light) and not color of objects (reflected light). Presentation of object colors requires a three-dimensional color space that incorporates another dimension—lightness (black to white). Refer to Ref. [20] for the details of object color specification.

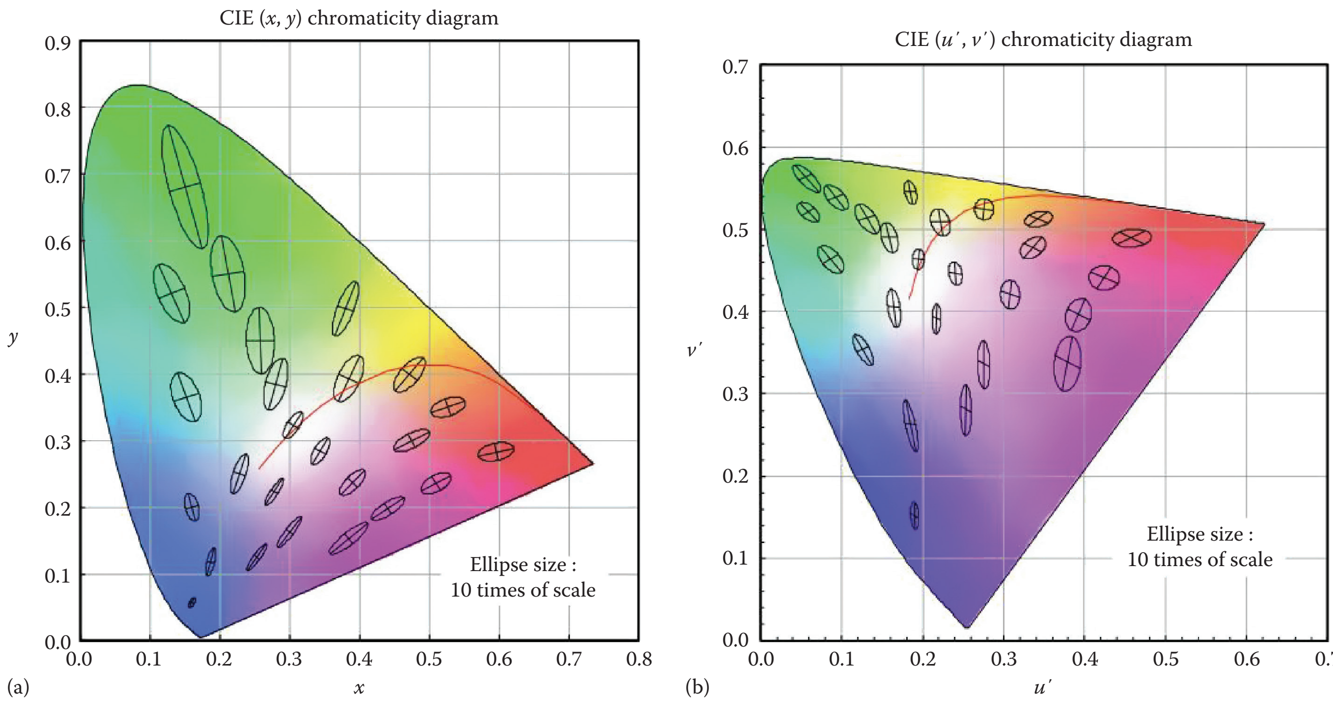

Figure 6.9 (a) MacAdam ellipses on CIE 1931 (*x*, *y*) diagram and (b) MacAdam ellipses on the CIE 1976 (*u*′*v*′) diagram. The ellipses are plotted 10 times their actual size. The curve near the center region is the Planckian locus.

6.5.3 CORRELATED COLOR TEMPERATURE

Figure 6.10 shows the trace of the (*x*, *y*) chromaticity coordinate of blackbody radiation (See 6.4.4) at its temperature from 1,600 to 20,000 K. This trace is called the "Planckian locus." The colors on the Planckian locus can be specified by the blackbody temperature in kelvin and is called *color temperature*. The colors around the Planckian locus from about 2,500 to 20,000 K can be regarded as *white*, 2,500 K and lower being reddish white and 20,000 K and higher being bluish white. The point labeled "Illuminant A" is the typical color of an incandescent lamp and "Illuminant D65" the typical color of daylight, as standardized by the CIE [22] as *CIE Standard Illuminants A and D65*. The colors of most of the traditional lamps for general lighting fall in the region between 2700 and 6500 K.

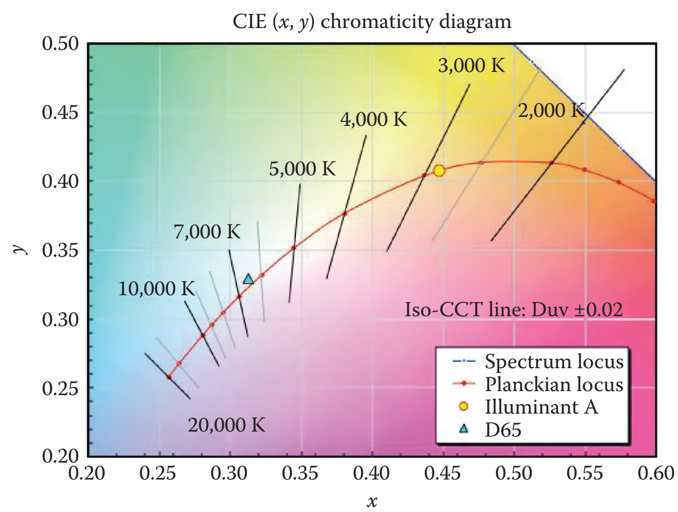

Figure 6.10 Planckian locus on (*x*, *y*) chromaticity diagram and iso-CCT lines.

By definition, color temperature cannot be used for colors away from the Planckian locus, in which case *correlated color temperature* (CCT) is used. CCT is defined as the temperature of the blackbody whose chromaticity is closest to that of the light source in question on the CIE (*u*′, 2/3 *v*′) coordinates [1]. The (*u*′, 2/3 *v*′) coordinate means the CIE 1960 (*u*, *v*) diagram, which is now obsolete. Based on the definition, the iso-CCT lines are perpendicular to the Planckian locus on the (*u*, *v*) diagram, but not perpendicular on the (*x*, *y*) diagram (see Figure 6.10) due to its nonuniformity. To calculate CCT, find the point on the Planckian locus that is at the shortest distance from the given chromaticity point on the (*u*, *v*) diagram. CCT is the temperature of the Planck's radiation at that point. Practical methods of computing CCT are available in Ref. [24].

CCT is widely used to specify the chromaticity of general illumination sources. However, CCT provides only one dimension of the chromaticity, which is a two-dimensional quantity. Another important dimension with respect to CCT is the shift of chromaticity from the Planckian locus. Duv (symbol: D_{uv}) is defined as the distance from the chromaticity coordinate of the test light source to the closest point on the Planckian locus on the CIE (*u*′, 2/3 *v*′) coordinates, with a plus sign for above and a minus sign for below the Planckian locus [25]. Duv is important when the color quality of illumination sources is evaluated. Further details and calculation methods for Duv are available in Ref. [24].

6.5.4 COLOR QUANTITIES FOR SINGLE-COLOR LIGHTS

In addition to chromaticity coordinates x, y and u', v', the following quantities are used to specify the color and spectrum of single-color sources such as LEDs. The definitions in this section follow Ref. [26].

Peak wavelength λ_p: The wavelength at the maximum of the spectral distribution.

Spectral bandwidth (*at half intensity level*) $\Delta\lambda_{0.5}$: Calculated as the width between the wavelengths at half of the peak of spectral distribution, as shown in Figure 6.11. It is also denoted as $\Delta\lambda$(FWHM).

Centroid wavelength λ_c: Calculated as the "center of gravity wavelength," according to the equation

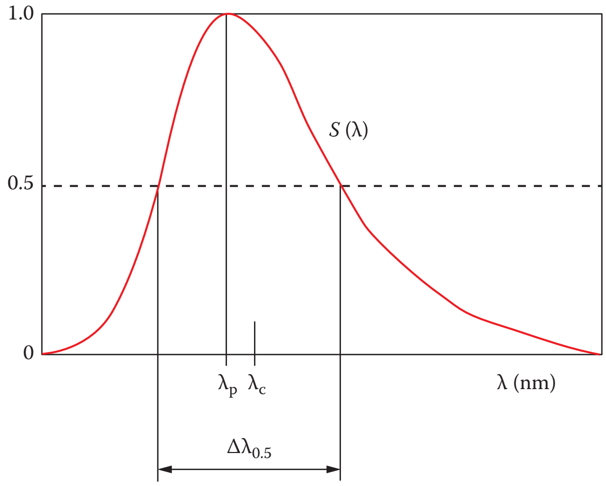

Figure 6.11 Typical relative spectral distribution of an LED.

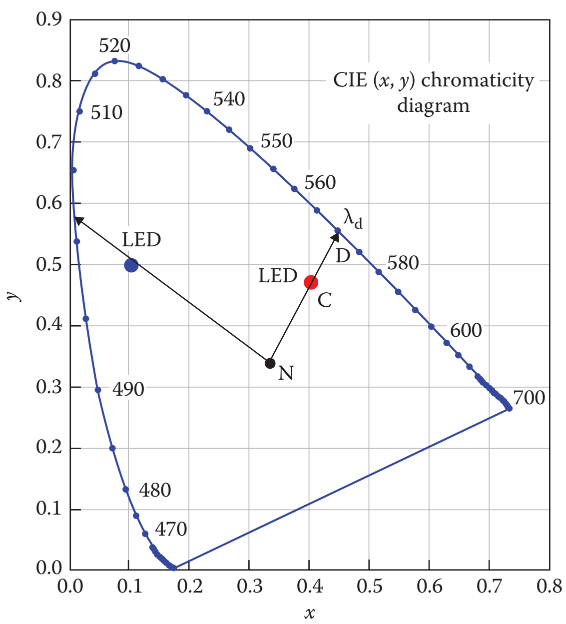

Figure 6.12 (x, y) chromaticity diagram showing the dominant wavelength and excitation purity.

$$\lambda_c = \frac{\int_\lambda \lambda \cdot S(\lambda) d\lambda}{\int_\lambda S(\lambda) d\lambda}. \tag{6.22}$$

Dominant wavelength λ_d: Wavelength of the monochromatic stimulus that, when additively mixed in suitable proportions with the specified achromatic stimulus, matches the color stimulus considered. Equal energy spectrum with $(x, y) = (0.3333, 0.3333)$ is used as the achromatic stimulus. See Figure 6.12, where N denotes the achromatic stimulus.

Excitation purity p_e: Defined as the ratio NC/ND in Figure 6.12. The value of excitation purity is unity if the chromaticity of the LED is on the spectrum locus.

6.6 FUTURE PROSPECT FOR PHOTOMETRY

The $V(\lambda)$ function was determined on the basis of experimental studies of photopic vision with a narrow field of view (about 4° or less). For situations where the visual target has an angular subtense larger than 4° or is seen off-axis, the CIE has defined the $V_{10}(\lambda)$ function [27], based on experimental studies for photopic vision with a 10° field of view. However, photometric units based on the $V_{10}(\lambda)$ function have not been adopted by CIPM. Such work is in progress.

It is also known that the $V(\lambda)$ underestimates the visual response in the blue region, and an improved function, known as $V_M(\lambda)$, was published by CIE as a supplement to $V(\lambda)$ [28]. The $V_M(\lambda)$ is not recognized by CIPM and might be used only for research purposes.

In real applications, perceived brightness and measured photometric quantities do not agree in some cases. However, at present there is no agreed photometric quantity that is more satisfactory than luminance or luminous intensity for quantifying the absolute brightness of luminous sources. CIE described a supplementary system of photometry that provides a more perceptually relevant approach for comparative brightness evaluation of lights at any level, including mesopic levels [29]. This system introduces the concept of equivalent luminance and develops a photometric model to calculate brightness-related equivalent luminance by using existing photometric and colorimetric quantities and introducing a chromatic contribution to brightness that depends upon the adaptation level.

In colorimetry, CIE recently published an improved color matching functions (CIE 2015 CMFs) [30] to define chromaticity coordinates that agree more accurately with visual perception. The new set of the CMFs, including new spectral luminous efficiency functions, has not been adopted as CIE standards nor recognized by the CIPM. With further application studies and support by the color and lighting community, these new functions may replace the current CMFs in the future. The proposed spectral luminous efficiency functions also require further application studies for a possible future update of the $V(\lambda)$ function.

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