589 nm; high-pressure sodium lamps, which emit a more continuous spectrum by extending the width of the emission lines of the low-pressure sodium lamp; and metal halide lamps. Figure 3.25 shows the wavelengths emitted by the discharge from mercury, sodium, and other gases. Metal halide lamps, which can have prescribed spectral distributions according to their intended use are now employed for general illumination in addition to their professional uses. Figure 3.26 shows the spectral distribution of typical metal halide lamps for use in general illumination (Shimogaki 1987).

3.9 STANDARD AND SUPPLEMENTARY ILLUMINANTS

The tristimulus values X, Y and Z, which define an object color, are obtained by Equation 3.12, and it is clear that the values depend on the spectral distribution $P(\lambda)$ of the illuminant. In other words, even for the same object color, various tristimulus values can be obtained depending on the type of illuminant. This is inconvenient in quantitatively expressing colors. Thus, the CIE established several types of standard illuminants (CIE standard illuminants) and artificial light sources (CIE standard sources) for realizing the standard illuminants (CIE 1998a, 2004a). A standard illuminant is a light specified by a (relative) spectral distribution $P(\lambda)$, and a standard source is an artificial apparatus, such as an incandescent light bulb, that realizes the standard illuminant in practice. Thus, the terms each have a different meaning and must be distinguished from each other. A standard illuminant has its spectral distribution specified numerically in a table, and is used only for the calculation of the tristimulus values. The word 'illuminant' is derived from the old English word 'illume' (light up) by adding a noun suffix '-ant' (who does. . .), and it signifies a light-radiating body.

The CIE has selected incandescent lamp light and daylight as standard illuminants, representing the most common illuminating lights in daily life, and has recommended representative spectral distributions. Standard illuminant A represents the light emitted from an incandescent light bulb and has a black-body distribution with a correlated color temperature of approximately 2856 K. Standard illuminant D_{65}, which has a correlated color temperature of approximately 6500 K, is selected from the series of CIE daylight illuminants defined above. An older CIE illuminant, known as CIE illuminant C, is still used in some applications to represent daylight, although it is not as good a representation as D_{65}, especially in the ultraviolet region of the spectrum. Although the use of fluorescent lamps is very common in daily life, no fluorescent lamp is yet designated as a standard illuminant. In addition to the standard illuminants, the CIE has also defined some supplementary illuminants for use in colorimetry. There are three types of supplementary illuminants, known as D_{50}, D_{55}, and D_{75}, with correlated color temperatures of 5000, 5500, and 7500 K, respectively. There is also another older standard illuminant, known as standard illuminant B, which is now deprecated. If necessary, other black-body radiations or CIE daylight illuminants may be used as well, but the standard or supplementary illuminants are preferred for simplicity. The spectral distributions of the standard and supplementary illuminants are given in Figures 3.27 and 3.28, and also in Table A3 in the Appendix. The colorimetric values of these illuminants, calculated for a wavelength interval of 5 nm in a wavelength range of 380–780 nm, are given in Table A4 in the Appendix. Figure 3.29 shows the chromaticity points of the standard and supplementary illuminants together with the Planckian locus. It can be seen that that these illuminants represent a wide range of typical illuminating lights.

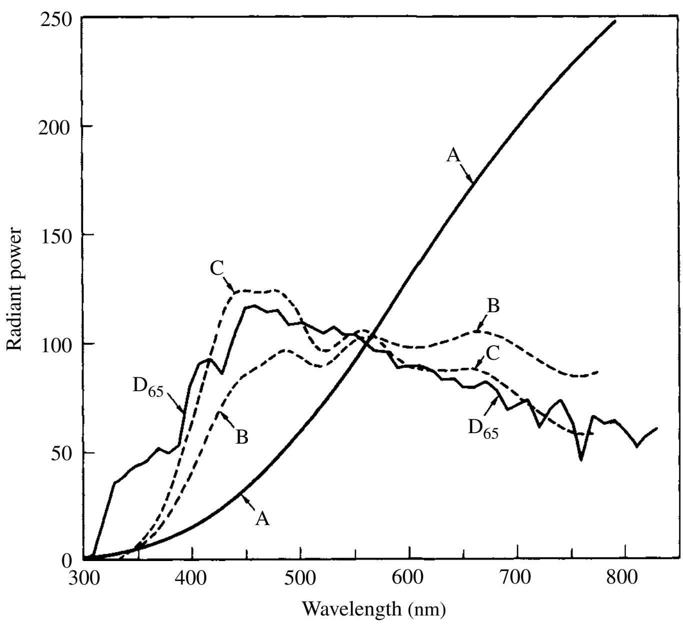

Figure 3.27 Spectral distribution of CIE illuminants A, B, C, and D_{65}

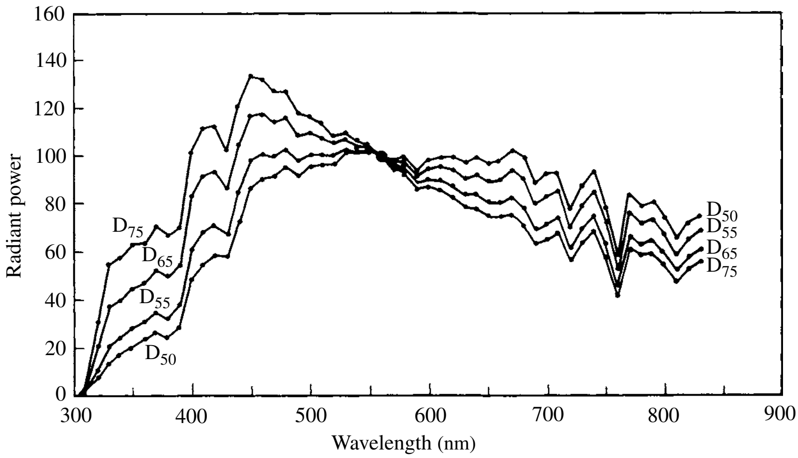

Figure 3.28 Spectral distribution of CIE standard illuminant D_{65}, and supplementary illuminants D_{50}, D_{55}, and D_{75} (normalized to 100 at a wavelength of 560 nm)

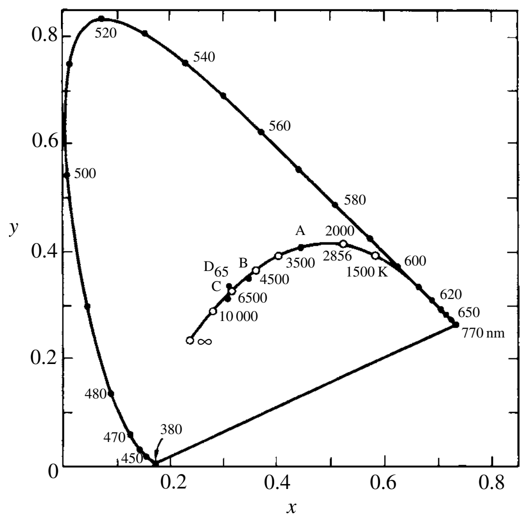

Figure 3.29 Planckian locus (open circles) and chromaticity points for CIE standard and supplementary illuminants (filled circles)

The CIE recommendations for illuminants and sources are as follows.

1. *Standard illuminant A and standard source A.* Standard illuminant A represents an incandescent light bulb. It has the spectral

distribution specified in Table A3 in the Appendix, and a correlated color temperature of about 2856 K. To realize standard illuminant A, a gas-filled tungsten lamp with a colorless transparent bulb is recommended as standard source A.

2. *Standard illuminant D_{65} and daylight simulator D_{65}*. Standard illuminant D_{65} represents average daylight. It has the spectral distribution specified in Table A3, and a correlated color temperature of about 6500 K (more accurately, 6504 K; the correlated color temperature of standard illuminant D_{65} was originally 6500 K, but a change in the international temperature scale changed the value of the constant c_2 of Planck's law of radiation from 1.4380×10^7 to 1.4388×10^7 nm K. Thus, the temperature of standard illuminant D_{65} was changed to $6500 \cdot 1.4388/1.4380 \simeq 6504$ K in order to maintain the same spectral distribution. Similarly, the color temperature of standard illuminant A, which was originally set at 2848 K when the value of c_2 was 1.4350×10^7 nm K, is now $2848 \cdot 1.4388/1.4350 \simeq 2856$ K). No standard source D_{65} is yet developed, but lamps such as xenon lamps are often used as simulators to provide an approximate standard source.
3. *Illuminants D_{50}, D_{55}, and D_{75}*. Illuminants D_{50}, D_{55} and D_{75} represent daylight with correlated color temperatures of about 5000, 5500 and 7500 K, respectively (more accurately, 5003, 5503 and 7504 K). Their spectral distributions are specified in Table A3 in the Appendix. As with D_{65}, no standard source is formally recommended to realize these illuminants. However, daylight simulators have been developed that provide approximate standard sources.
4. *Illuminant C and source C*. Illuminant C represents average daylight. It has the spectral distribution specified in Table A3 in the Appendix, and a correlated color temperature of about 6774 K. To realize illuminant C, standard source A covered with a color temperature conversion filter is recommended. A so-called *Davis-Gibson filter*, comprising two chemical solutions is used as the color temperature conversion filter. A Davis–Gibson filter has poor durability because it is a chemical solution, and it requires a complicated procedure to reproduce it. Accordingly, solid filters are often used instead. Compared with real daylight at the same correlated color temperature, illuminant C has a smaller relative spectral distribution in the ultraviolet wavelength region. Thus, it cannot be used to express the color of an object that emits fluorescent light when excited by ultraviolet radiation. Accordingly, illuminant C is being replaced in most applications by standard illuminant D_{65}.

5. *Illuminant B.* CIE illuminant B was previously recommended as a representation of direct sunlight. It has the spectral distribution specified in Table A3 in the Appendix, and a correlated color temperature of about 4874 K. To realize illuminant B, source A together with another Davis–Gibson filter was recommended. As with illuminant C, CIE illuminant B has less power in the ultraviolet wavelength range than does direct sunlight of the same correlated color temperature. Thus, it should not be used for object colors that emit fluorescent light when excited by ultraviolet radiation. Accordingly, illuminant B is replaced by illuminant D_{50} in most applications and the CIE has already discarded its recommendation for illuminant B.

A daylight simulator is a light source that realizes a D illuminant approximately. Simulators can be produced by using an incandescent lamp with a suitable filter or by other sources with or without filters. However, as can be seen from Figure 3.28, the spectral distribution of CIE daylight is not smooth and has many indentations. Thus, in a strict sense, there is little possibility of establishing a series of standard D sources. Accordingly, daylight simulators with good (but not perfect) approximation must be used. As is described in Section 7.2, the CIE has specified a method for evaluating the spectral distribution of such simulators.

On the other hand, there is also a proposal that accepts the impossibility of realizing the current CIE daylight illuminants, and instead proposes replacing them with more practical sources. For instance, Hunt (1992) proposes employing a tungsten light bulb, a xenon lamp, and a filtered fluorescent lamp as standard illuminants D_T, D_X, and D_F, respectively.

NOTE 3.1 DERIVATION OF COLOR MATCHING FUNCTIONS FROM GUILD AND WRIGHT'S RESULTS

When color matching a monochromatic light $[F_\lambda]$, the following relation holds from Equation 2.6

$$[F_\lambda] = \bar{r}(\lambda)[R] + \bar{g}(\lambda)[G] + \bar{b}(\lambda)[B] \tag{3.31}$$

However, since the quantitative relation between $[F_\lambda]$ and the reference stimuli [R], [G] and [B] was not known, Guild and Wright's experiments were actually performed according to the following relation

$$[F_\lambda] = K(\bar{r}(\lambda)[R] + \bar{g}(\lambda)[G] + \bar{b}(\lambda)[B]) \tag{3.32}$$