Terrestrial Daylight

6

Lars Olof Björn

6.1 Introduction

Natural light at the surface of the Earth is almost synonymous with light from the sun. Light from other stars has, as far as is known, photobiological importance only for navigation by night-migrating birds and some beetles Dacke et al. (2013).

Moonlight, which originates in the sun, is important for the setting of some biological rhythms. A full moon may perturb the photoperiodism of some short-day plants and also synchronize rhythms in some marine animals.

However, the majority of photobiological phenomena are ruled by daylight, and we shall devote the remainder of this chapter to this topic. We shall treat the shortest wavelength components of daylight, UV-B radiation, at the end of this chapter, as special problems are involved with this wave band.

6.2 Principles for the Modification of Sunlight by the Earth's Atmosphere

As mentioned earlier, the radiation from the sun (Fig. 6.1) is spectrally very similar to blackbody radiation of 6,000 K (above 700 nm 5,777 K). There are, however, deviations both in the basic shape and due to reabsorption (Fraunhofer lines) of some light by gases in the higher, cooler layers of the sun.

The Earth's atmosphere reflects, refracts, scatters, and partially absorbs the radiation from the sun and thereby changes its spectral composition considerably. Part of the absorption and Rayleigh scattering is due to the main gases in the atmosphere, the concentration of which can be regarded as constant. Another part is due to ozone and water vapor (see Stomp et al. 2007), which occur in highly variable amounts. A third part is due to aerosol, which is also highly variable. The absorption causes loss of light, while scattering causes some light to be lost to space, while another part appears as diffuse light (skylight). Light is also reflected by clouds and thereby mostly lost to space, but this will not be considered in detail here. Light reflected from the ground is partly scattered downward or reflected from clouds and again appears at the surface as diffuse light, and for this reason, the ground reflectivity has some effect on skylight.

Daylight is also strongly dependent on the elevation of the sun above the horizon (90° minus the solar elevation is called the zenith angle of the sun and often symbolized by the Greek letter theta, θ), because the lower the sun, the more air the rays must pass before they reach the ground. Daylight can be considered as composed of two components—direct sunlight and scattered light. The scattered light is in most cases dominated by skylight, while some may reach the observer as scattered from the ground, trees, etc.

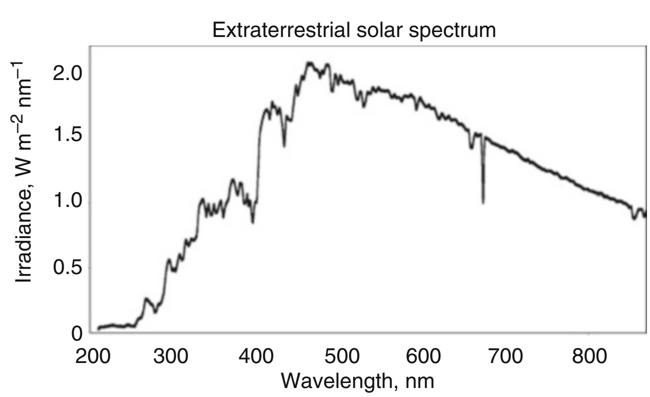

Fig. 6.1 The spectrum of sunlight on a plane perpendicular to the direction to the sun, outside the Earth's atmosphere

L.O. Björn
School of Life Science, South China Normal University, Guangzhou, China

Department of Biology, Lund University, Lund, Sweden
e-mail: Lars_Olof.Bjorn@biol.lu.se

L.O. Björn (ed.), *Photobiology: The Science of Light and Life*,
DOI 10.1007/978-1-4939-1468-5_6, © Springer Science+Business Media New York 2015

6.3 The UV-A, Visible, and Infrared Components of Daylight in the Open Terrestrial Environment Under Clear Skies

Accurate methods for computational modeling of daylight depart from the radiative transfer theory described by Chandrasekhar (1950). However, the fundamental formulas usually cannot be used directly; different approximations have to be used for various cases, and this is nothing for the average biologist to work with. However, as long as we are dealing with clear skies (no clouds) and relatively long wavelengths (near-infrared, visible, and UV-A radiations) and as long as we stay above water and vegetation, daylight can be well described by methods that are more easily handled.

A simple and for most purposes adequate procedure for this has been published by Bird and Riordan (1986). Their model, SPCTRAL2, has become very popular, and their paper had been cited over 340 times when this is being written. An alternative approach for part of the spectrum is that of Green and Chai (1988). We shall use the approach of Bird and Riordan (1986) here to show how the direct component (sunlight) and the component scattered by the atmosphere (skylight) vary with the solar elevation (i.e., with the zenith angle). The same algorithm can be used also for visualizing how other factors, such as air pressure, air humidity, aerosol, ozone column, and ground albedo, affect daylight. We show the result only from 300 to 800 nm, but the paper by Bird and Riordan (1986) can be used to model radiation up to 4 µm, i.e., 4,000 nm. Hulstrom et al. (1985) have published values for airmass 1.5 (i.e., a solar elevation of 41.8° above the horizon for a standard atmosphere).

Figure 6.2 shows three spectra, representing the direct sunlight, the skylight (diffuse radiation), and their sum, the so-called global radiation (the total daylight). Note that the skylight has its maximum moved toward shorter wavelengths compared to the direct sunlight. This corresponds to the fact that the sky appears blue in color and also to the fact that Rayleigh scattering is inversely proportional to the fourth power of the wavelength.

Figure 6.3 shows the irradiance on a horizontal plane and the one for the irradiance on a vertical plane in the compass direction (azimuth) toward the sun. These spectra are rather different. The sunset sunlight is of course much stronger in the horizontal direction (on a vertical plane). The scattered light is now not only skylight but also light scattered from the ground, and therefore, it contains much more long-wave components. Note also how deep the absorption bands for water vapor and oxygen have become, because the light must pass so much air when the sun is so low in the horizon. We can see from this that the concept "daylight spectrum" has no meaning if the geometry of measurement is not specified. We would get a third set of spectra for the fluence rate. The fluence rate can also be readily calculated using the algorithm of Bird and Riordan (1986), slightly modified: the diffuse component should be doubled, and the factor cosinus of incidence angle should be dropped in the expression for the direct component (sunlight).

The algorithm of Bird and Riordan (1986) assumes the skylight to come equally from all over the sky, or, in other words, the sky *radiance* is uniform. This is an approximation, and other more accurate descriptions exist. A model based on radiative transfer theory has been published by Liang and Lewis (1996), while the group of R. H. Grant (Grant and Heisler 1997; Grant et al. 1996a, b, 1997), based

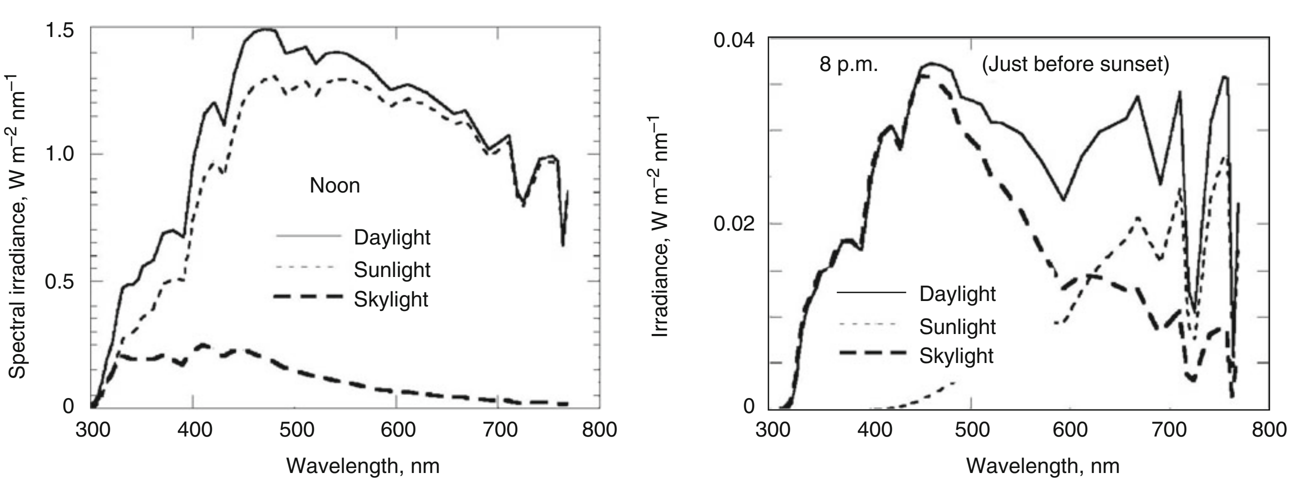

Fig. 6.2 Irradiance at noon (*left*) and just before sunset (*right*) from above on a horizontal plane in Lund (south Sweden, 55.7°N, 13.4°E) on July 15, 2002, as computed using the algorithm of Bird and Riordan (1986). The ozone column was assumed to be 300 Dobson units and the ground albedo 0.2, aerosol 0, and air pressure 1,000 mbar

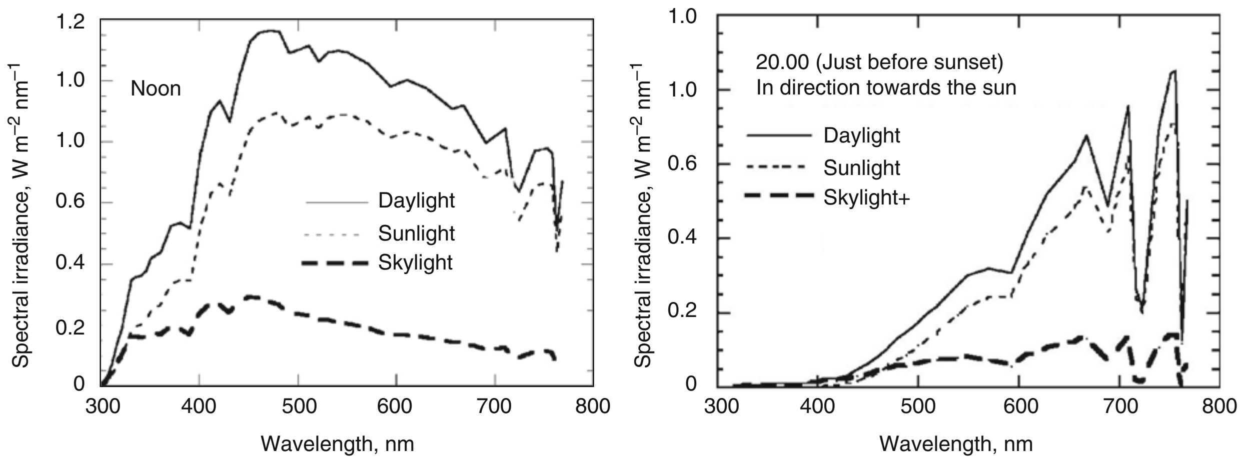

Fig. 6.3 Same as Fig. 6.2, except that the plane is vertical and pointed in the compass direction of the sun

on measurements, has developed a set of very simple models for various cloud conditions.

The paper by Bird and Riordan (1986), as stated in its title, deals only with clear skies. In modeling the diffuse skylight, it assumes the sky to have uniform (isotropic) radiance. This latter approximation works very well as long as we are interested only in the irradiance on a horizontal or nearly horizontal plane. For some other purposes, it may be of interest to model more exactly the variations in sky radiance, and how this can be done (in a relative sense also for cloudy conditions and for UV-B radiation) in a simple way has been described by Grant et al. (1996a, b, 1997) and Grant and Heisler (1997) in a series of papers, with a summary presently available at http://shadow.agry.purdue.edu/research.model.skyrad.html.

For direct sunlight, another method that is said to have some advantages (although not tested by the present author) has been published by Oke et al. (2010). In one test, under stable cloud-free conditions, it agreed well with the model of Bird and Riordan (1986), while in another, under frequently changing clouds test, it agreed much better with measured data than the older model did. This is not a pure calculation method, but requires for each occasion normalization against a pyrheliometer measurement, which explains the better agreement with spectroradiometer measurements under changing cloud conditions.

Sky radiance distribution, i.e., distribution of brightness across the sky, depends on several factors, including the position of the sun, cloudiness, and wavelength. The reader is referred to Román et al. (2012) for information about measurement and computer modeling of this.

Skylight is elliptically polarized (i.e., partly plane polarized), which is important for some animals who are able to determine the direction of polarization and use it for orientation (see, e.g., Labhart 1999). The degree of polarization can be approximated by $p = p_o \cdot \sin\mu/(1+\cos^2\mu)$, where μ is the angular distance from the sun. The value of p_o is never more than 94 %, usually lower, depending on aerosol in the air, reflection from the ground, etc. The direction of the major electrical vector is approximately along the circumference of "circles" on the sky with the sun in the center (e.g., Schwind and Horváth 1993). A few comments should be added to this simplified description (again, a more exact mathematical description can be obtained using the radiative transfer theory). Thus, the polarization is increased in the spectral bands where the terrestrial atmosphere absorbs strongly (Aben et al. 1999). When the sun is higher than about 20° above the horizon, there are two points within 20° of the sun, one above and one below, where polarization is zero. When the sun is less than about 20° above the horizon, one such point is located about 20° above the antisolar point (Bohren 1995, 2004).

6.4 Cloud Effects

Clouds usually decrease both the irradiance and the degree of polarization of daylight. However, under some circumstances, clouds can cause the irradiance above the values it would have had without clouds. This effect is particularly pronounced when most of the sky is overcast but the sun is not in clouds and when the ground is snow covered or otherwise highly reflecting.

6.5 Effects of Ground and Vegetation

Reflection from the ground is particularly important in the ultraviolet, since ultraviolet light reflected upward by the ground is partially scattered downward again by the atmosphere and the ground cover thus affects also downwelling radiation. The effect of reflection from the ground is greatest when it is covered by snow. Reflection from the ground can be quite important for the visible spectrum and for plant growth, as shown by Hunt et al. (1985) and Kasperbauer and Hunt (1987).

Penetration of light into the ground is important for the germination of seeds. Soil transmission generally increases with increasing wavelength, thus giving buried seeds a far-red-biased environment (Kasperbauer and Hunt 1988).

Plant canopies absorb visible light and ultraviolet radiation but reflect and transmit far-red light and near-infrared radiation. Light in or under green vegetation is therefore strongly biased toward the longer wavelengths, a fact that is of paramount importance to the plants subjected to this regime. The plant-filtered light forces the phytochrome system to the Pr (inactive) state (Holmes and Smith 1977; Kasperbauer 1971, 1987; Smith 1986).

It is now possible to measure light *inside* plants and animals (Marijnissen and Star 1987; Star et al. 1987; Vogelmann 1986).

6.6 The UV-B Daylight Spectrum and Biological Action of UV-B

At the short-wavelength end of the daylight spectrum is the UV-B spectral band, 280–315 nm. This band is of particular interest because it is highly biologically active (mostly inhibitory). It is more difficult to measure than visible light and UV-A radiation because irradiance and fluence rate are lower. It is also more difficult to model than other daylight, because the spectral irradiance at ground surface is highly variable and dependent on other factors in addition to those influencing the longer wavelength components. The main factors influencing UV-B spectral irradiance at ground level are the elevation of the sun above the horizon and the amount of ozone in the atmosphere (Fig. 6.4).

A computer program to study the effects of these and other factors on the UV-B spectral irradiance and estimate the biological action was designed by Björn and Murphy (1985) based on Green (1983) and is further described by Björn (1989) and Björn and Teramura (1993). A more accurate code that can also be used for visible light and is based on radiative transfer theory is that of S. Madronich, presently available on the Internet (http://cprm.acd.ucar.edu/Models/TUV/).

UV-B is more highly scattered than longer daylight components, and even under clear skies, much of it reaches the ground as skylight rather than direct sunlight. Thus, the fluence rate can be appreciable even in shadow. If the ground is snow covered and especially if the snow is fresh, much radiation can reach the observer from snow. Snow also increases the ultraviolet component of skylight, because radiation reflected from the ground is to an appreciable extent scattered down again by the atmosphere.

Also, underwater ultraviolet radiation has its special measuring and modeling problems. In freshwater bodies and coastal water, the amount of UV-B-absorbing dissolved substances is usually so high that UV-B radiation does not penetrate very far. Exceptions are some Alpine lakes. But in clear ocean water, such as that in the Southern Ocean, UV-B radiation can be measured down to 60 m, and biological effects can be recorded at a depth of 20 m.

We shall return to UV-B radiation later, especially in Chaps. 21, 22, 23, 24, and 25.

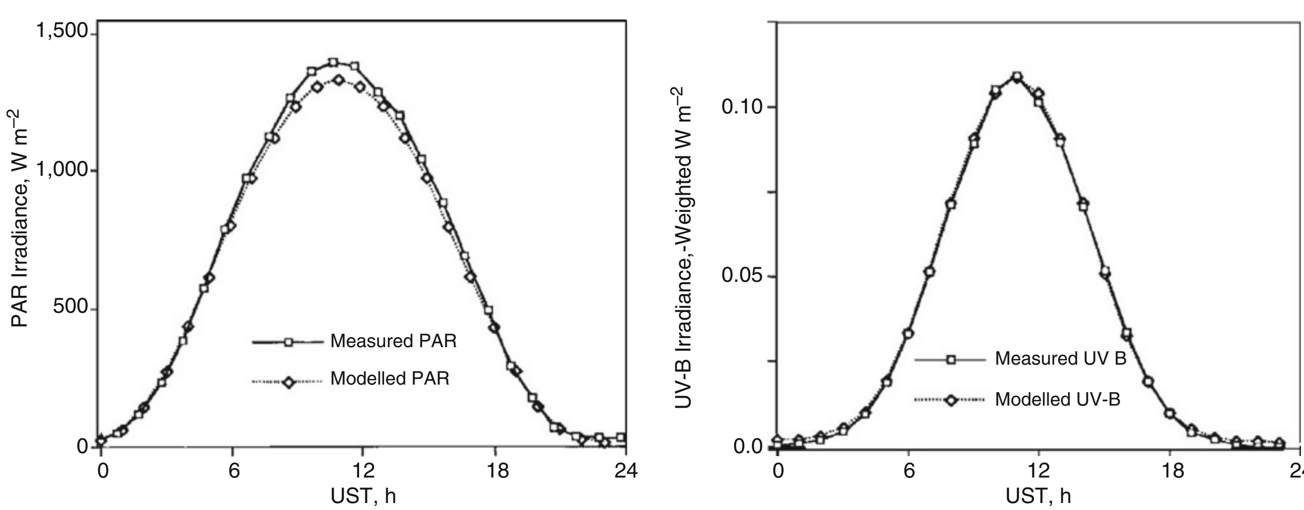

Fig. 6.4 The variation of daylight during a cloud-free day (July 5, 1994) at Abisko in northern Sweden (68.35°N, 18.82°E). The *left panel* shows photosynthetically active radiation (PAR, 400–700 nm), the *right panel* UV-B radiation. The UV-B radiation was weighted with a mathematical function to enhance the biologically more active shorter wavelength components. The *horizontal axis* shows Universal Standard Time. Note that the UV-B is more concentrated toward the middle of the day than is PAR (From Björn and Holmgren 1996)

References

Aben I, Helderman F, Stam DM, Stamnes P (1999) Spectral fine-structure in the polarisation of skylight. Geophys Res Lett 26:591–594

Bird RE, Riordan C (1986) Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the earth's surface for cloudless atmospheres. J Clim Appl Meteorol 25:87–97

Björn LO (1989) Computer programs for estimating ultraviolet radiation in daylight. In: Diffey BL (ed) Radiation measurement in photobiology. Academic, London, pp 161–169

Björn LO, Holmgren B (1996) Monitoring and modelling of the radiation climate at Abisko. Ecol Bull 45:204–209

Björn LO, Murphy TM (1985) Computer calculation of solar ultraviolet radiation at ground level. Physiol Vég 23:555–561

Björn LO, Teramura AH (1993) Simulation of daylight ultraviolet radiation and effects of ozone depletion. In: Young AR, Björn LO, Moan J, Nultsch W (eds) UV Photobiology. Plenum Press, New York, pp 41–71

Bohren CF (1995) Optics, atmospheric. In: Trigg GL (ed) Encyclopedia of applied physics, vol 12. VCH Publishers, New York, pp 405–434

Bohren CF (2004) Atmospheric optics. In: Brown TG (ed) The optics encyclopedia: basic foundations and practical applications, vol 1. Wiley, Hoboken, pp 53–91

Chandrasekhar S (1950) Radiative transfer theory. Oxford University Press. Reprinted (1960) by Dover Publications, New York

Dacke M, Baird E, Byrne M, Scholtz, CH, Warrant EJ (2013) Dung beetles use the milky way for orientation. Curr Biol 23:298–300

Grant RH, Heisler GM (1997) Obscured overcast sky radiance distributions for UV and PAR wavebands. J Appl Meteorol 36: 1336–1345

Grant RH, Gao W, Heisler GM (1996a) Photosynthetically active radiation: sky radiance distributions under clear and overcast conditions. Agric For Meteorol 82:267–292

Grant RH, Heisler GM, Gao W (1996b) Clear sky radiance distributions in ultraviolet wavelength bands. Theor Appl Climatol 56:123–135

Grant RH, Gao W, Heisler GM (1997) Ultraviolet sky radiance distributions of translucent overcast skies. Theor Appl Climatol 3–4:129–139

Green AES (1983) The penetration of ultraviolet radiation to the ground. Physiol Plant 58:351–359

Green AES, Chai S-T (1988) Solar spectral irradiance in the visible and infrared regions. Photochem Photobiol 48:477–486

Holmes MG, Smith H (1977) Spectral distribution of light within plant canopies. In: Smith H (ed) Plants and the daylight spectrum. Academic, New York, pp 147–158

Hulstrom R, Bird R, Riordan C (1985) Spectral solar irradiance data sets for selected terrestrial conditions. Solar Cells 15:365–391

Hunt PG, Kasperbauer MJ, Matheny TA, Kasperbauer MJ (1985) Effect of soil surface color and *Rhizobium japonicum* strain on soybeen seedling growth and nodulation. Agron Abstr 85:157

Kasperbauer MJ (1971) Spectral distribution of light in a tobacco canopy and effects of end-of-day light quality on growth and development. Plant Physiol 47:775–778

Kasperbauer MJ (1987) Far red light reflection from green leaves and effects on phytochrome-mediated assimilate partitioning under field conditions. Plant Physiol 85:350–354

Kasperbauer MJ, Hunt PG (1987) Soil color and surface residue effects on seedling light environment. Plant Soil 97:295–298

Kasperbauer MJ, Hunt PG (1988) Biological and photometric measurement of light transmission through soils of various colors. Bot Gaz 149:361–364

Labhart T (1999) How polarization-sensitive interneurones of crickets see the polarization pattern of the sky: a field study with an optoelectronic model neurone. J Exp Biol 202:757–770

Liang SL, Lewis P (1996) A parametric radiative transfer model for sky radiance distribution. J Quant Spectrosc Radiat Transf 55: 181–189

Marijnissen JPA, Star WM (1987) Quantitative light dosimetry *in vitro* and *in vivo*. Lasers Med Sci 2:235–242

Oke S, Fukushige N, Kemmoku Y, Takikawa H, Sakakibara T, Araki K (2010) A new simple model of direct spectral irradiance with easily observable atmospheric parameters. IEEJ Trans 5:548–552

Román R, Antón M, Cazorla A, de Miguel A, Olmo FJ, Bilbao J, Alados-Arboledas L (2012) Calibration of an all-sky camera for obtaining sky radiance at three wavelengths. Atmos Meas Technol 5:2013–2024

Schwind R, Horváth G (1993) Reflection-polarization pattern at water surfaces and correction of a common representation of the polarization pattern of the sky. Naturwissenschaft 80:82–83

Smith H (1986) The perception of light quality. In: Kendrick RE, Kronenberg GMH (eds) Photomorphogenesis in plants. Martinus Nijhoff Publishers, Dordrecht, pp 187–217

Star WM, Marijnissen HPA, Jansen H, Keijzer M, van Gemert MJC (1987) Light dosimetry for photodynamic therapy by whole bladder wall irradiation. Photochem Photobiol 46:619–624

Stomp M, Huisman J, Stal LJ, Matthijs HCP (2007) Colorful niches of phototrophic microorganisms shaped by vibrations in the water molecule. ISME J 1:271–282

Vogelmann TC (1986) Light within the plant. In: Kendrick RE, Kronenberg GMH (eds) Photomorphogenesis in plants. Martinus Nijhoff Publishers, Dordrecht, pp 307–337