

7 Visible Light and UV Radiation

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7.1 Introduction

The sun is the most important source of visible and ultraviolet (UV) radiation. Even though the distance from the sun to the Earth is large – about 150×10^6 km – the fluence rate of solar radiation on Earth, the solar constant, is about 1360 W/m^2 . Approximately 40% of this radiation is reflected back into space. The remaining 60% is the driving force of all life on Earth. A number of pigments have been developed by life to harvest solar energy: *chlorophyll a* (350-700 nm), *phycoerythrin* (45-580 nm), *phycocyanin* (460-650 nm), *bacteriochlorophyll a* (750-850 nm) and *bacterio-chlorophyll b* (950-1050 nm) are some of the most important ones. Furthermore, animals have developed visual pigments, the *rhodopsins*, to see light. By its action on DNA, UV radiation from the sun has induced mutations to speed up generation and development of new species. UV radiation acts positively and negatively on the human immune system, e.g. induces cancer and takes part in the production of vitamin D.

This chapter reviews some of the basic facts about visible and UV solar radiation: spectra and their variations with the phases of the solar cycle, ozone level, time, latitude, altitude, albedo (reflection), and sky cover. Furthermore, scattering and absorption of optical radiation in the atmosphere and in human skin are discussed. Finally, there is a review of the action spectra for erythema, skin cancer of different types, effects on the human immune system and photoreactivation (light-induced repair of DNA damage). The biology of these phenomena will be dealt with in Chapter 31 'Effects of UV Radiation and Visible Light'.

7.2 The spectrum of the sun

Visible light and infrared radiation constitute the major fraction of solar radiation reaching the atmosphere of the Earth (Fig. 7-1). Approximately 40 % of the radiation energy is visible light of wavelengths between 400 and 700 nm. Ultraviolet radiation is divided into different bands: Radiation of wavelengths between 200 nm and 280 nm is called *UVC*, radiation between 280 nm and 320 nm is called *UVB*, and between 320 and 400 nm is called *UVA*. About 8% of the radiation energy reaching the Earth's atmosphere is within the UV spectrum. At sea level, about 6% of the radiation is UV radiation, about 50% is visible radiation and about 40% is infrared radiation. UVA is 10 to 100 times more abundant than UVB. UVC is practically absent, as it is absorbed in the atmosphere. Due to differences in scattering and absorption, the ratio of UVB to UVA depends on several factors: latitude, zenith angle, cloud-cover and thickness of the ozone layer.

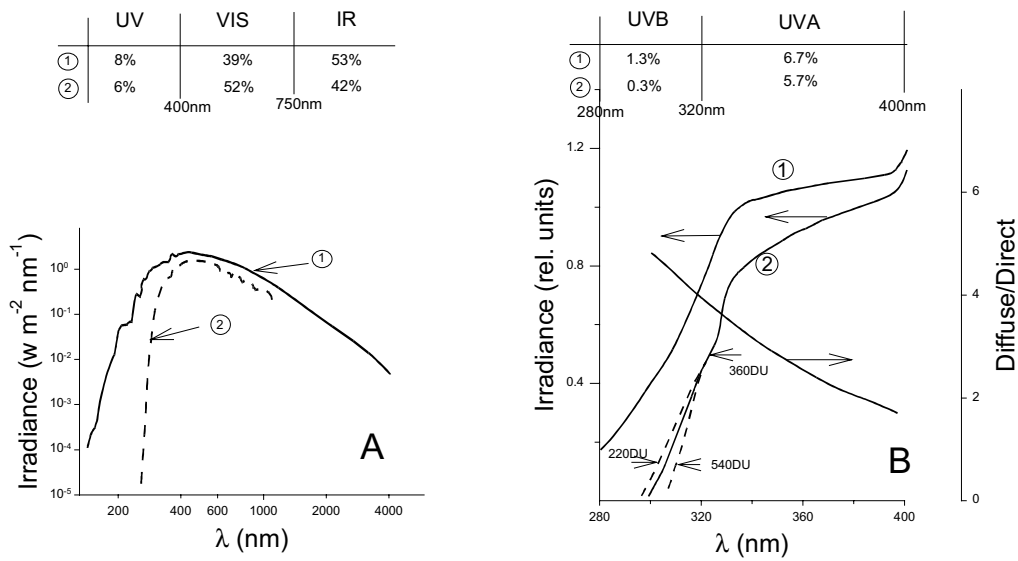


Fig. 7-1. A: Left panel: The spectrum of solar radiation, 1: outside the atmosphere and 2: at sea level. B: Right panel: The UVB and UVA region of the solar spectrum, 1: outside the atmosphere and 2: at sea level. The ratio of diffuse to direct radiation is also shown on the figure referring to the right-hand ordinate. The percentage of the radiation falling within the UVB, the UVA, the visible and the infrared region is given on top of the figure. Spectra for different ozone values are shown.

7.3 Scattering and absorption in the atmosphere – Why are the skies blue?

Scattering plays an important role in the penetration of solar radiation through the atmosphere, since it causes an increase of the path lengths of the photons and thus, makes absorption more likely.

Essentially, atmospheric scattering can be classified as either *Rayleigh scattering* or *Mie scattering*. Nitrogen and oxygen molecules are much smaller than the wavelengths of UV and visible radiation and cause Rayleigh scattering. The probability that a photon will be scattered by an angle θ with respect to its initial path is:

$$I_s = K \cdot \lambda^{-4} \cdot \sin^2 \cdot (\pi / 2 - \theta) \tag{7-1}$$

where K is a constant. Thus, the ratio of scattering of blue light ($\lambda = 450 \text{ nm}$) to scattering of red light ($\lambda = 600 \text{ nm}$) is $(450/600)^{-4} \approx 3$ and the ratio of scattering of UVB at 300 nm to that of UVA at 360 nm is $(300/360)^{-4} \approx 2$. The ratio of diffuse to direct radiation decreases with increasing wavelength as shown in Fig. 7-1B. Rayleigh scattering explains why the clear sky is blue since 'blue' photons are more scattered than 'green', 'yellow' and 'red' ones.

With the sun at its zenith, about 10% of the total solar radiation and about 30% of UVB and UVA is diffuse. For a solar elevation angle of 20° about 20% of the total radiation, 70% of UVA and almost 80% of UVB, is diffuse.

Water droplets (in clouds), aerosols and dust particles are much larger than the wavelengths of UV and visible light and scatter light independently of the wavelength like small mirrors. This so-called Mie scattering is predominantly forward scattering, in contrast to Rayleigh scattering, which is isotropic. The grey-white colour of the clouds is due to Mie scattering. The probability that a photon is scattered by a particle is maximal if the particle size is similar to the wavelength of the photon.

7.4 Variations of the spectrum and fluence rate of solar radiation

Variations of the fluence rate and of the spectrum of solar radiation reaching the atmosphere of the Earth

The astronomical variations of the orbit of the Earth (of the tilt of the Earth's axis on the ecliptic, ((period 41 000 years), of the precession of the axis (period 22 000 years) and of the eccentricity (period 100 000 years)) are related to the periodic appearance of ice ages according to the Milankovitch theory, but such considerations are beyond the scope of this text. Of more significance are the variations of the solar energy exposure with the 11-year cycle of sunspot activity, the annual variation of the sun-Earth distance, the 27-day apparent rotation of the sun and occasional solar flares.

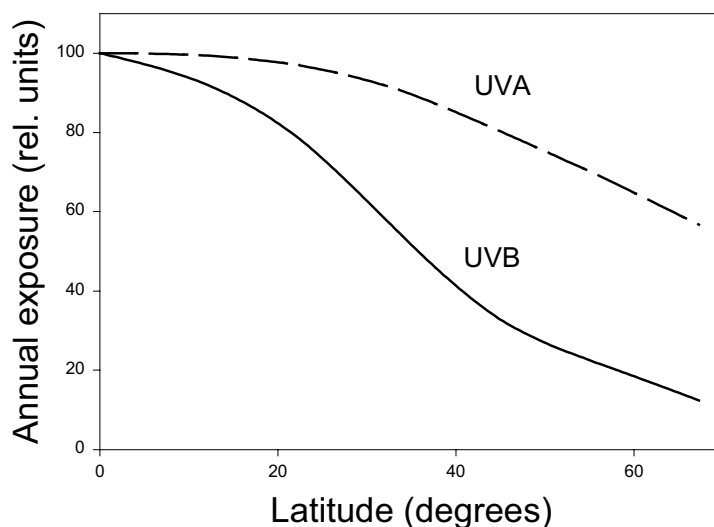


Fig. 7-2. The annual exposure of UVA at about 360 nm (denoted CMM) and of UVB at about 310 nm (denoted CIE) as functions of the latitude.

A number of phenomena, among them a periodic variation in skin cancer incidence rates and longevity of humans, have been related to the sunspot cycle. However, such 'relationships' are usually mere coincidences. Thus, even though the solar irradiance varies over the solar cycle by a factor of 2 at 120 nm, with 10% at 200 nm and with 5% at 250 nm, it varies less than 1% at wavelengths relevant for life on Earth, *i.e.* wavelengths longer than 300 nm. This is far less than variations caused by cloud-cover and ozone.

The sun-Earth distance is 3.4% smaller at perihelion on 3th January than at aphelion on 5th July. Thus, the solar constant is 6.9% larger in the summer of the Southern Hemisphere than in the summer of the Northern Hemisphere. This may be just on the border of significance as far as skin cancer is concerned.

Variations of UV fluences with latitude

The annual fluence of UVB varies more with latitude than annual fluences of UVA and visible light. This is due to absorption of UVB by the ozone layer. The annual fluence of UVB radiation at 310 nm at 60°, 45° and 30° latitude are respectively 20%, 40% and 65% of the annual fluence at the Equator (Fig. 7-2). The corresponding numbers for 60°, 45° and 30° latitude for UVA at 360 nm are 60%, 80% and 92%, respectively.

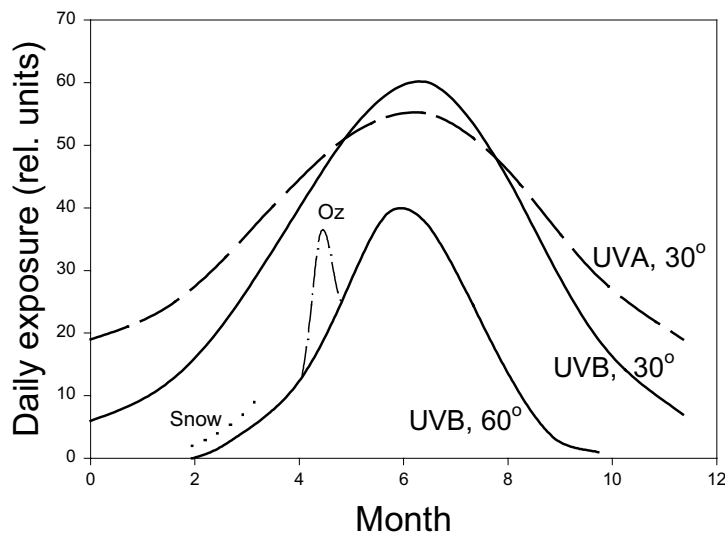


Fig. 7-3. The relative annual variation of UVA and UVB at a latitude of 30°, and that of UVB at a latitude of 60°. An ozone depletion, similar to what has been observed in the Antarctic spring, leads to a peak marked Oz in the UVB curve. Snow doubles the UVB exposure.

Fig. 7-3 shows how the daily UV exposure changes during the year at two latitudes, 30° and 60°. Due to absorption of UVB by the ozone layer, the annual variation of UVB is significantly larger than that of UVA.

For the same reason, UVB varies relatively more at high latitudes than at low latitudes. Furthermore, maximal ozone depletion, similar to that observed around the Antarctic region, leads to a large increase of UVB in the spring. So far, no such depletion has been observed in the Northern Hemisphere. If snow is present on the ground, UV exposure will be almost doubled (Fig. 7-3).

Variations of UV fluence rates during the day – effect on sunburn

Fig. 7-4 shows how UVA and UVB vary during a day in the middle of the summer at 50° latitude. The variation of UVB is more prominent than that of UVA. Thus, UVB is halved about 2.5 hours after noon, while UVA is halved about 4 hours after noon. In the autumn, UVB varies more during the day than at midsummer and is halved about 2 hours after noon.

Clouds have a strong influence on the fluence rates of visible light and UV radiation. Since scattering by air molecules increases with decreasing wavelengths, UVB is more scattered on a clear day than UVA and visible light. Therefore, the effect of clouds, which is added to the scattering by air molecules, is relatively larger for visible light and UVA than for UVB. The effect of a cloud passing the sun at about noon is demonstrated by the arrows (A for visible light and B for UVB) in Fig. 7-4. Since our eyes cannot 'see' UVB, it is impossible to evaluate the effect of clouds and hazy weather on the fluence rate of sunburn (erythemogenic) from UVB radiation without using spectrometers, filter instruments or chemical actinometers.

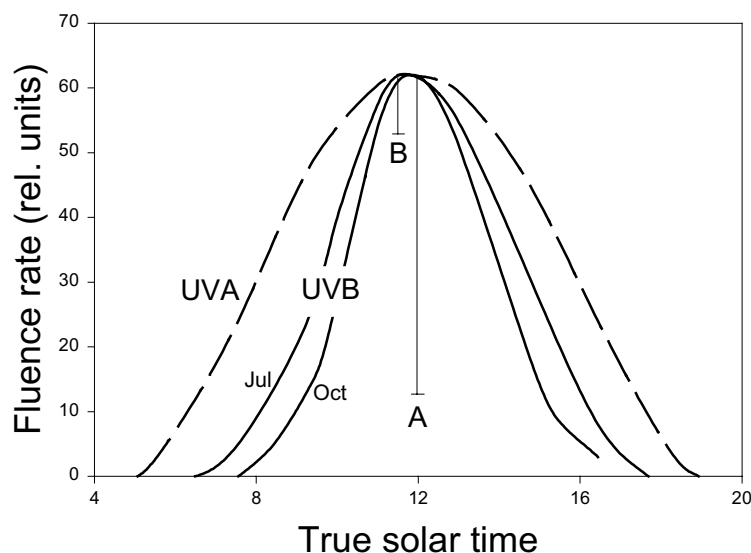


Fig. 7-4. Relative variations of UVA and UVB during a day. For UVB the curves for July and October are significantly different, while for UVA the corresponding curves are almost overlapping. The effect of a small cloud covering the sun is much smaller for UVB than for UVA, as shown by the lines marked B and A.

The effects of altitude and reflection (albedo) on UV fluence rates

The fluence rate of UV radiation changes with altitude. This is related to scattering by water vapour, dust particles and air molecules and to absorption by ozone. The increase is dependent on wavelength and solar elevation. For a solar elevation angle of 20° , the fluence rate of UVA increases by about 12% per 1 000 m and that of UVB at 305 nm by about 20%. For a solar elevation angle of 60° , the fluence rate of UVA increases by about 9% per 1 000 m and that of UVB by about 14%. The percentage of incident radiation reflected by different surfaces, the so-called albedo, is also slightly dependent on the wavelength. Snow reflects between 20 and 100% of all wavelengths (depending on whether the snow is dry, wet, new, old, dirty etc). Water reflects 6-12% of visible light and 4-7% of UVB and grassland reflects 15-30% of visible light but only 2-5% of UVB. The reflection by snow deserves special attention since it may lead to a prominent increase of the fluence rate of erythemogenic UVB radiation. In clear weather, snow with a surface albedo of 80% increases the fluence rate of UVB by a factor of 2 for a solar zenith angle of 45° (Fig. 7-5). On a cloudy day, the fluence rate of UVB may, under otherwise similar conditions, be increased by up to a factor of 4.

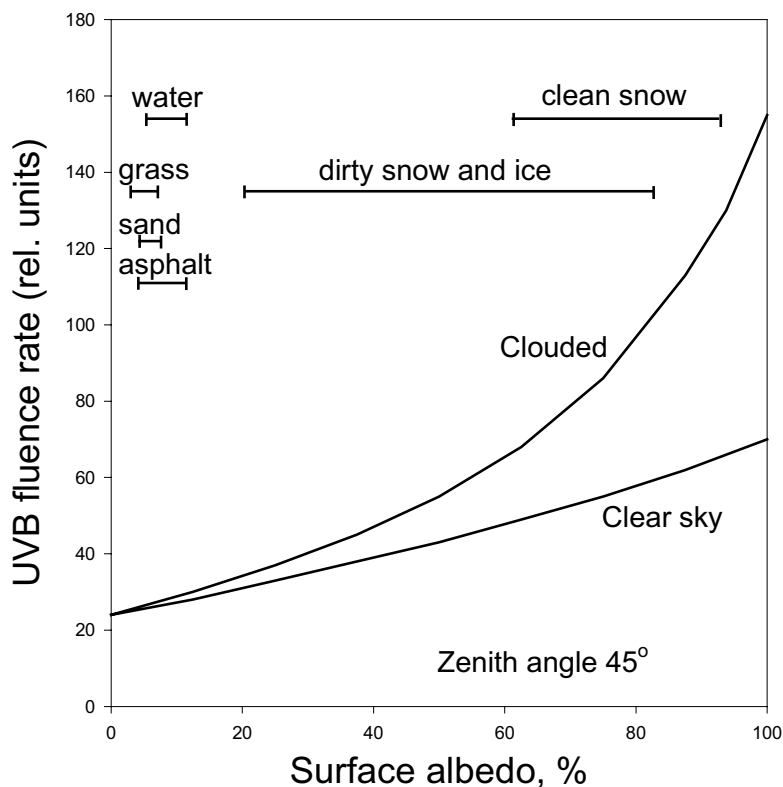


Fig. 7-5. The fluence rate of UVB for a zenith angle of 45° as a function of surface albedo. The albedo plays a greater role on cloudy days than on clear days. Typical albedos for different surfaces are given on top of the figure.

Effects of the ozone layer

Ozone, O_3 , is produced when oxygen, O_2 , in the upper atmosphere absorbs UVC ($\lambda < 245 \text{ nm}$). This absorption completely eliminates UVC from the solar radiation and dissociates oxygen molecules to oxygen atoms. When an oxygen atom reacts with an oxygen molecule, ozone is produced. More O_3 is produced around the Equator than at high latitudes per unit volume of atmosphere. Nevertheless, because of atmospheric convection, there is more O_3 at higher latitudes than at the Equator as Fig. 7-6 shows. O_3 is measured in *Dobson Units*, *DU*. One DU unit corresponds to an ozone column of 0.01 mm. An O_3 level of 300 DU means that if the O_3 in a vertical column of the atmosphere is collected and brought to sea level at normal air pressure (101 kPa), the column of pure O_3 would be 3 mm high. This small amount of O_3 absorbs a large fraction of biologically damaging solar UVB radiation and is a protective shield for life on the Earth. Its absorption spectrum is located in the same spectral region as that of DNA.

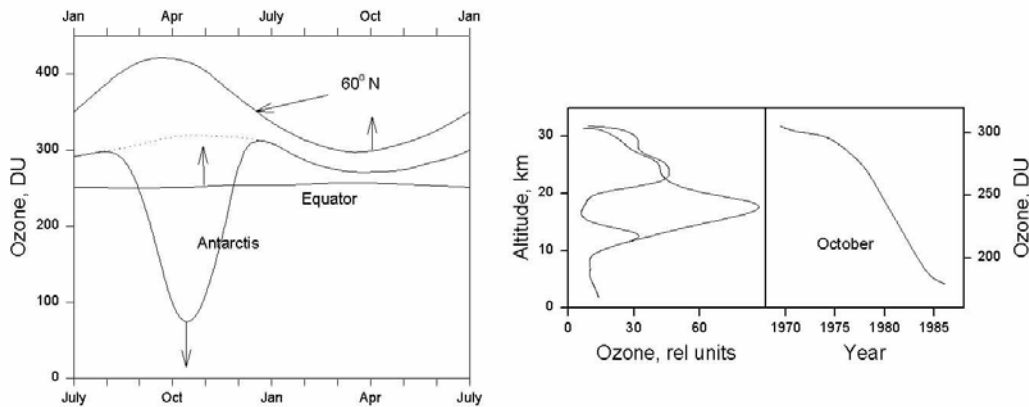


Fig. 7-6. The annual variation of the ozone layer at 60 °N, at the Equator and at Antarctica (top). The dotted curve indicates how the ozone level would vary if no depletion took place. The left lower part of the figure shows the ozone concentration as a function of altitude for no ozone depletion and for a depletion corresponding to what is observed over Antarctica in October. The right lower part of the figure shows the October ozone values for Antarctica for the period 1970-1986.

Variations of the O_3 layer and of UVB

The fluctuations of the fluence rate of UVC reaching the upper atmosphere with the sunspot cycle (with 10% at 200 nm and 5% at 250 nm) cause a fluctuation of the ozone layer. This fluctuation is small, of the order of $\pm 1\%$ and the corresponding fluctuation

of the fluence rate of UVB is hardly observable since the average cloud-cover changes randomly from year to year.

Additionally, there is a random variation of the ozone layer leading to a corresponding random variation of the average annual UVB fluence. The latter O₃ related fluctuation of UVB fluence amounts to about ±3%, while the annual fluctuation of UVB related to the average cloud-cover is significantly larger, of the order of ±10%.

Degradation of ozone layer due to man-made activities

Since about 1970, a significant decrease of the October values of O₃ in the Antarctic region has been observed (Fig. 7-6). The transient depletion of O₃ in October is related to an atmospheric low temperature at an altitude of 15-20 km combined with increasing UV exposure at this time of the year. It is likely that the depletion is related to *anthropogenic chlorofluorocarbons*, CFCs. These molecules give rise to chlorine which catalyses the UV induced breakdown of O₃ under conditions where small crystals of ice form in the troposphere between 15 and 20 km. These small crystals in the polar stratospheric clouds provide surfaces for heterogeneous photochemical reactions that release chlorine, Cl₂, into the atmosphere from the reservoir species HCl and ClONO₂. F-11 (CFCl₃) and F-12 (CF₂Cl₂) used to be two of the major anthropogenic CFCs. The concentrations of these species in the atmosphere were increasing until quite recently. Their lifetimes in the atmosphere can range from years to decades. The concentration of substances containing chlorine in the atmosphere increased from 0.6 ppb (0.6 parts per billion by volume) in 1960 to about 3.5 ppb in 1992 due to human activities. A few of the reactions involved in formation and degradation of O₃ are summarised in Fig. 7-7. CFCs produced at ground level are carried by atmospheric convection to high altitudes, above the O₃ layer, where they are photolysed by UVC and halogen atoms are formed. As these atoms gradually enter the O₃ layer, they catalyse O₃ breakdown. Nitrogen oxides are also present in the atmosphere, partly as a result of human activities, and participate in recovering reactive chlorine back to its reservoir ClONO₂: $\text{NO}_2 + \text{ClO} \Rightarrow \text{ClONO}_2$.

Chlorine gas is dissociated photochemically to Cl atoms, which react with O₃ and form ClO. Then dimers (Cl₂O₂) are formed and decomposed to Cl + Cl + O₂. In this manner, each Cl atom can catalytically destroy of the order of 100 000 O₃ molecules.

The Arctic stratosphere is slightly warmer than the Antarctic stratosphere (Antarctica is a mountain area and a 'highland' while the Arctic is ice floating on water), and less polar stratospheric clouds are formed. Thus no significant O₃ hole has been observed in the Arctic region so far. In the Antarctic region, the O₃ layer can change quite fast and substantially. For instance, in Punta Arenas, the ozone level was about 210 DU on 15th October 1994. On 16th October, it was only 150 DU and 240 DU on 17th October.

When the O₃ hole appears in the Antarctic spring (in October), the fluence rate of UVB rapidly increases to midsummer values, which are about double the normal spring values. In spring, after the long Antarctic winter, plants, fish and micro-

organisms may be unprepared for high fluence rates of UVB. Protective substances, like carotenoids, may not have had time to be formed. It is too early to say if this will have serious adverse effects.

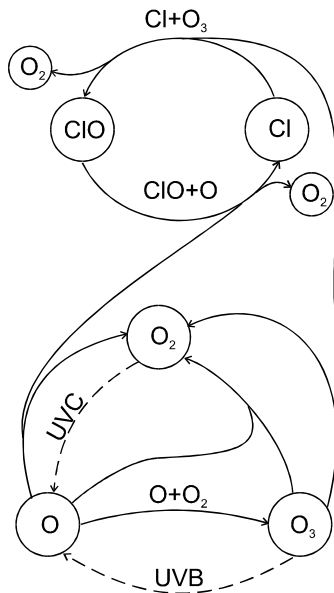


Fig. 7-7

Some of the reactions involved in the production and degradation of O_3 in the atmosphere.

Natural variations of the ozone layer

Not all factors related to O_3 depletion are related to human activities, however. Volcanic eruptions, like El Chichon in 1982 and Mt. Pinatubo in 1991 led to reductions of the O_3 layer by about 20 DU the following year.

As can be seen from Fig. 7-6, there is also some O_3 in the lower atmosphere (the troposphere). With respect to UVB absorption, this tropospheric O_3 plays a larger role than the figure indicates since the troposphere contains much larger concentrations of scattering elements (water vapour, dust, etc.) than the stratosphere. Thus, the photon path length per km of vertical distance is larger in the troposphere than in the stratosphere, and the absorption of UVB per concentration unit of O_3 is larger there as well. Furthermore, in unclean air and in air containing large amounts of nitroxides, increased UVB fluence rates lead to increased O_3 production. Because of its strong oxidative effect, O_3 is poisonous to plants and animals.

7.5 Artificial light sources

Incandescent lamps, halogen lamps and fluorescent tubes are the most commonly used light sources in homes and work places.

Incandescent lamps give practically no UV radiation, while halogen lamps operate at a higher temperature and give small fluence rates of UVA radiation. It has been speculated that these lamps might have a photocarcinogenic effect, but in view of their small fluence rates of UVA, the risk is probably negligible compared to the carcinogenic effect solar exposure has on people. The same is true for common fluorescent tubes. These tubes contain mercury vapour, which gives a typical line spectrum when current is passed through it. The strongest lines are located at 254 nm, 313 nm, 405 nm, 436 nm, 546 nm and 577 nm. The UV lines are partly filtered out by the glass of the tubes and partly converted to visible radiation with a broad spectrum by a fluorescent layer on the inner surface of the tubes. Some of the tubes that are intended to produce pure visible light give small yields of the mercury lines in the UV region. Different types of fluorescent layer give different emission spectra. Tubes for solaria emit mainly in the UVB and UVA region. Some years ago it was believed that exposure to UVA, leading to a given skin pigmentation, was less carcinogenic and erythemogenic than exposure to UVB leading to the same degree of pigmentation. Thus, a large number of UVA solaria came into use worldwide. However, all UVA solaria also contain some UVB and since UVB is much more potent than UVA in producing both pigmentation and erythema, the effect of UVA solaria is to a large extent a UVB effect. It should be kept in mind that recent research indicates that UVA may be more photocarcinogenic than earlier believed (see the action spectra given in Fig. 7-12). Generally, solaria contain less visible radiation than solar radiation. This may have an adverse effect since visible light removes some of the carcinogenic effect of UV radiation in a process called photoreactivation (see below).

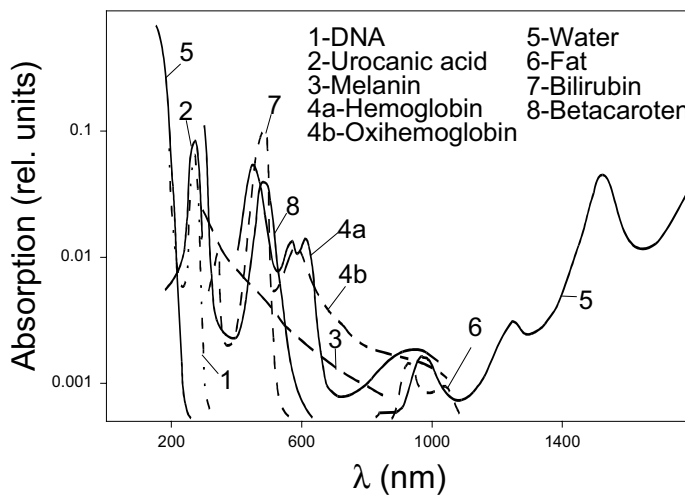


Fig. 7-8. Absorption spectra of some of the chromophores in human tissue.

7.6 Penetration of light and UV radiation through human skin

The penetration of UV radiation and light into human tissue is limited by scattering and absorption. Just as in the atmosphere, the scattering in tissue follows the rules for Mie scattering (cells, blood vessels, fibres, granules, etc.) and Rayleigh scattering (organelles, molecules). The main absorbers of visible light in tissue are haemoglobin and its degradation products, melanins, flavins and carotenoids. Aromatic amino acids and nucleic acids are absorbers in the UVB region. Fig. 7-8 shows the absorption spectra of some of these chromophores and Fig. 7-9 shows the wavelength dependency of the penetration depth of UV radiation and visible light into human tissue.

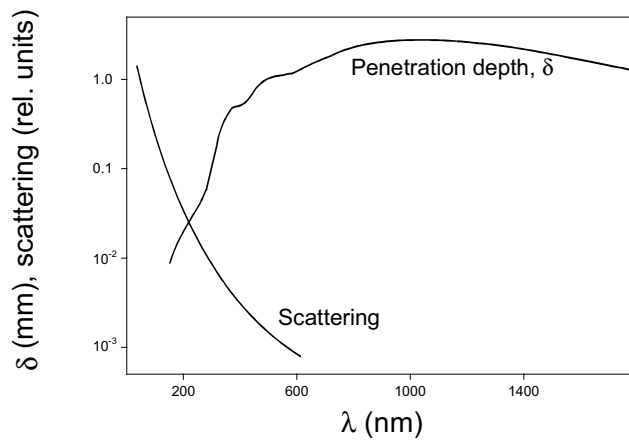


Fig. 7-9. The penetration spectrum of light and UV radiation into human tissue. The scattering increases with decreasing wavelength.

The penetration depth is defined as the distance into the tissue at which the space irradiance of a wide, parallel beam of radiation is reduced to e^{-1} of its value close to (below) the surface.

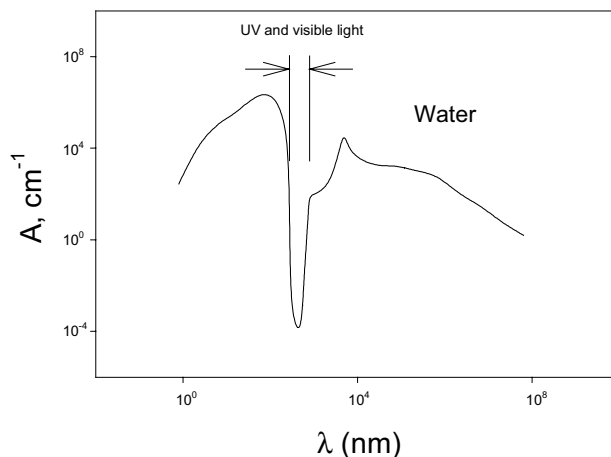


Fig. 7-10. The absorption spectrum of water

Since the absorbing molecules are randomly oriented in biological, scattering media, the space irradiance determines the effect. Space irradiance is defined as the fluence rate falling on an infinitesimally small sphere from all angles divided by the cross section area of the sphere.

Fig. 7-10 shows a curious feature in that the penetration spectrum of water: A window in the UV and visible range. This property of water has certainly played a great role in the development of life on Earth and in sustaining it.

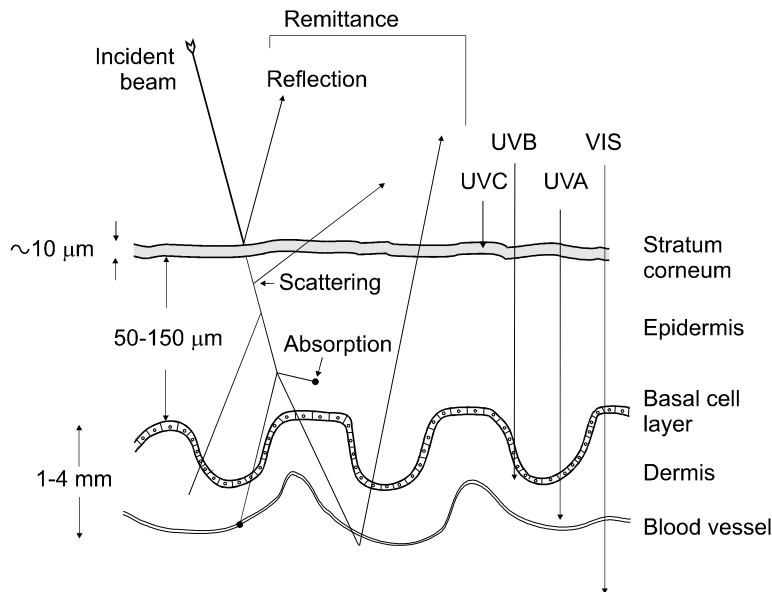


Fig. 7-11. An illustration of absorption and scattering in skin. The penetration depths for different wavelength regions are indicated.

Fig. 7-11 indicates the penetration depths of UV and visible light into human skin. The main action of UVB is believed to take place in the epidermis and in the basal cell layer, while UVA can also have a dermal effect. About 5% of the radiation is reflected from the outer surface of the skin, *i.e.* from the dead layer called *stratum corneum*. The radiation coming back from the skin is composed of reflected radiation and radiation scattered in the epidermis and dermis, and is called remitted radiation. Some of the absorption characteristics of melanin and haemoglobin/oxyhaemoglobin contribute to the shape of the spectrum of the remitted radiation. Because of back-scattering, the space irradiance close to the surface of the tissue is larger than the fluence rate of the incident radiation. Radiation transfer in a scattering and absorbing medium is often approximated by the so-called Kubelka-Munk model. If the inward fluence rate, *i.e.* that in the direction of the incident radiation, is I , and the diffuse, back-scattered fluence rate is J , then:

$$dI = (-KI - SI + SJ) dx \quad (7-2)$$

and

$$-dJ = (-KJ - SJ + SI) dx \quad (7-3)$$

where S is the scattering coefficient
 K is the absorption coefficient
 x is the distance into the tissue

Solving these simultaneous differential equations gives:

$$K/S = [(1 + R^2 - T^2) / 2R] - 1 \quad (7-4)$$

where R is the remittance J_o/I_o
 T is the transmission I/I_o

If $K = 0$, i.e. the tissue has no absorption, then:

$$R + T = 1 \quad (7-5)$$

Eq. 7-5 indicates that no radiation is lost.

For a thick sample, where $T \approx 0$:

$$K/S = (1 - R^2) / 2R \quad (7-6)$$

which means that the remittance of a thick sample depends only on the ratio of the absorption and scattering coefficient.

Melanin plays the major role in penetration of UVB and UVA through the epidermis. Thus, the transmittance at 300 nm is 2-3 orders of magnitude larger for white epidermis than for the darkly pigmented epidermis. Thickening (hyperplasia) of the epidermis is one of the reactions of human epidermis to UV. For UVB, even mild hyperplasia plays a large protective role. However, for UVA and visible light, hyperplasia offers little protection compared to melanogenesis. Melanin is present through the entire epidermis. Negroid *stratum corneum* contains melanin particles, melanosomes, while Caucasian, white *stratum corneum* contains only broken melanosomes, melanin 'dust'. This difference may be significant as far as the K/S ratio is concerned.

Urocanic acid is present in the epidermis of all people. It has an absorption spectrum in the same spectral region as DNA and may play a protective role. Furthermore, it is believed that this substance is a main chromophore for UV effects on the immune system.

Haemoglobin is present only in the vessels of the dermis, but one of its break-down products, the lipophilic substance bilirubin, binds to fat and is present in the whole skin, even in the *stratum corneum*. This is also true for ingested betacaroten. These substances may act in two ways: partly as sunscreens and partly as antioxidants.

For Caucasian skin, the remittance is about 0.1 at 300 nm, 0.2 at 360 nm and about 0.5 at 600 nm. The corresponding numbers for dark, Negroid skin are 0.02 at 300 nm, 0.09 at 360 nm and 0.2 at 600 nm.

7.7 Action spectra

The spectrum of solar light is wide. Radiation of different wavelengths contributes to different degrees in biological processes. Sometimes, it is difficult to identify the chromophores for a given process. The chromophore for a process can be defined as the molecule that absorbs the photon that initiates the process. For instance, in many plants, chlorophyll is the main chromophore for photosynthesis.

Action spectra provide fundamental information about photobiological processes.

Quantum yields

The efficiency of a radiation-initiated process is given by the quantum yield ϕ . The quantum yield ϕ_p for a process P can be defined as $\phi_p = \text{number of } P\text{-events taking place per absorbed photon}$. Usually, only one chromophore is involved. It is necessary to determine the number of photons absorbed by this chromophore. When dealing with scattering media, like skin or cell suspensions, the determination of absorption spectra can be quite complicated. Spectrometers with integrating spheres that collect a large fraction of the light transmitted by the sample, are frequently used. Otherwise, spectra can be estimated by use of ordinary spectrophotometers if equal and strongly scattering quartz plates are introduced behind both the sample cuvette and the reference cuvette. Thus, both sample and reference beams are scattered to almost the same extent and the scattering of the sample is 'drowned' in the scattering of the plates.

Sometimes, it is of interest to determine the efficiency of a process per incident photon. This is the case when the chromophore is localised below an absorbing layer.

Action spectroscopy

The action spectrum for a process gives the wavelength dependency of its quantum yield. Conventionally, this is determined as follows: the sample is exposed to $n(\lambda)$ photons at the wavelength λ to produce a given effect, for instance generation of a given concentration of a photoproduct. Then, the wavelength and the photon number are varied in such a way that the same effect is produced at all wavelengths. The action spectrum is then $\Phi(\lambda) = K/n(\lambda)$, where K is a constant.

If only one chromophore is present and if this chromophore is in an unbound and monomeric state, the action spectrum will have a shape identical to that of the absorption spectrum of the chromophore. In samples with many absorbing molecules, action spectroscopy is a powerful tool in identifying the chromophore for the process of interest. For instance, this could be photosynthesis, generation of erythema, melanogenesis, induction of skin cancer etc. If free monomeric chromophore molecules are present together with bound or aggregated molecules, the situation is more complicated. Aggregated or bound molecules usually have distorted or shifted spectra as compared with monomeric molecules, but are usually less efficient in initiating photochemical processes.

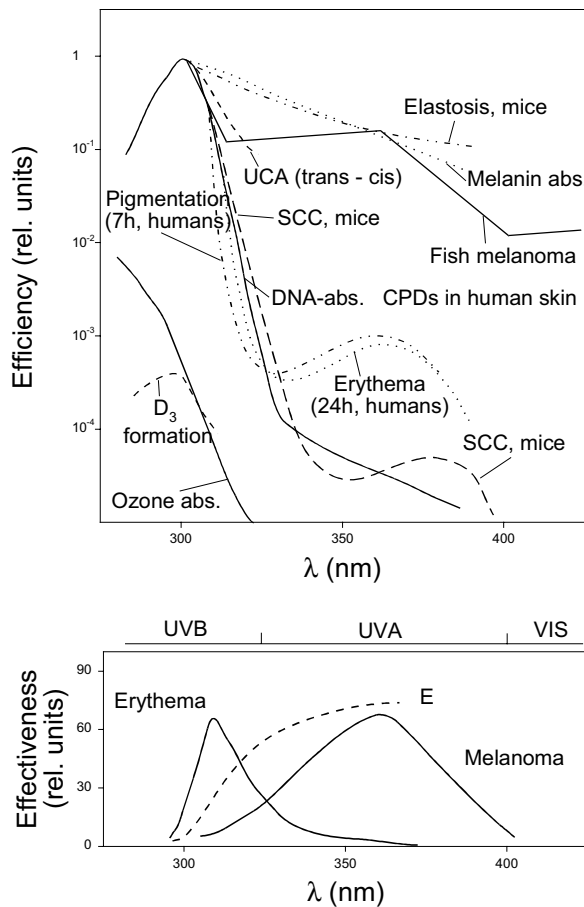


Fig. 7-12. Some important action spectra (upper panel). Effectiveness spectra, are obtained by use of the action spectra for fish melanoma and erythema, respectively, and the emission spectrum for solar radiation, E (lower panel).

Action spectra for some photobiological processes

Action spectroscopy can give the answer to many important photobiological questions, such as:

1. Is skin cancer due to UVA or UVB?
2. Can a light source be constructed that gives skin pigmentation (melanogenesis) without any risk of inducing skin cancer?
3. What light source should be used to stimulate vitamin D synthesis?
4. What is an optimal spectrum for light therapy of infants with hyperbilirubinemia?
5. Do UVA solarium give a UVA or a UVB effect?
6. Do such solarium contain enough visible light to photoreactivate DNA damage that can lead to skin cancer?

The answers to some of these questions can be read from the action spectra sketched in Fig. 7-12. Since the action spectrum of melanogenesis is quite similar to that for erythema (in humans) and for non-melanoma skin-cancer in mice, it is likely that a given melanogenesis is accompanied by a given risk of sunburn and of non-melanoma

skin cancer. The efficiency spectrum of a radiation source producing a given biological effect is constructed by multiplying the spectrum of the light source with the action spectrum for the effect, wavelength by wavelength, as demonstrated in Fig. 7-12. This data indicates that it is mainly the UVB fraction of the solar radiation that gives erythema, melanogenesis, vitamin D synthesis, and non-melanoma skin cancer, while melanoma is likely to be caused by UVA.

Amplification factors

Many photobiological processes are complex and not linearly dependent on the number of photons absorbed. Repair, oxygen depletion, photon-induced movement of chromophores, generation of protecting molecules and skin thickening (hyperplasia) are some of the complicating processes. It is then relevant to ask the question: If the number of incident photons is increased from n to $n + \Delta n$, *i.e.* by a fraction $\Delta n/n$, how large will the increase in the interesting effect be? For instance, if a population has a probability of R (per person and per year) of getting skin cancer when it is exposed to n UVB photons per year, what will the probability be if the number of photons is increased, for instance by ozone depletion, to $n + \Delta n$? In this context, the *biological amplification factor* A_B is introduced and defined by the equation:

$$\Delta R / R = A_B (\Delta n / n) \quad (7-7)$$

If A_B is constant throughout the entire relevant range of photon numbers n , then:

$$\ln R = A_B \ln n + \text{constant} \quad (7-8)$$

This turns out to be a good approximation of the real relationship between incidence rates R and UV exposure n . For all skin cancer forms, A_B is equal to about 2.

If the ozone amount in the atmosphere decreases, the fluence rate of UVB will increase. The *radiation amplification factor* A_R (by some authors called *RAF*) is defined by the equation:

$$\Delta F / F = A_R \Delta C / C \quad (7-9)$$

where F is the fluence rate of UVB
 C is the amount of ozone in the atmosphere

A_R is equal to about 1, and thus, if the ozone amount in the atmosphere decreases by 1%, the fluence rate of erythemogenic UVB radiation increases by about 1%. For practical purposes, a more complicated calculation needs to be performed. Instead of considering the UVB fluence rate F , the annual exposure of UVB n has to be calculated or measured. To study erythema, the action spectrum of erythema in the

determination of the annual exposure should be used, and to study skin cancer, the corresponding action spectrum should be used.

A question often asked in the media is – 'how much will the incidence rate of skin cancer increase if the ozone amount (integrated over one year) is reduced by 1%?'

The answer is given by the magnitude of the total amplification factor $A_t = A_B \cdot A_R$. This follows directly from the equations above:

$$\Delta R / R = A_B (\Delta n / n) = A_B \cdot A_R (\Delta C / C) \quad (7-10)$$

Thus, an ozone depletion of 1% will result in an $A_B \cdot A_R = 2\%$ increase of the incidence rates of skin cancer using the approximate numbers of A_R and A_B mentioned above.

7.8 Further reading

- Andwes, A. *et al.* (1995) Action spectrum for erythema in humans investigated with dye lasers. *Photochem. Photobiol.* vol. 61, pp 200-205
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- Regan, J. D. & Parrish, J. A. (Eds.) (1993) *The Science of Photomedicine*. Plenum Press, New York and London
- Young, *et al.* (1993) *Environmental UV Photobiology* Plenum Press, New York and London