

UV-B Radiation Definition and Characteristics

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Introduction

It could be simply stated that UV-B radiation is that portion of the electromagnetic spectrum from 290-320 nanometers. This definition would be meaningful and sufficient for those who have an adequate science background. However, for many, this explanation will have little meaning. Therefore the following is designed to lead the reader through a discussion of solar radiation and its characteristics in order to better understand the relationship of UV-B to that portion of the electromagnetic spectrum we refer to as “ultraviolet”, “visible” and “infrared” radiation (see Figure 1). Also discussed will be how ozone affects the UV-B portion of solar radiation reaching the earth’s surface as well as the relationship of UV-B to the sensitivity of biological organisms.

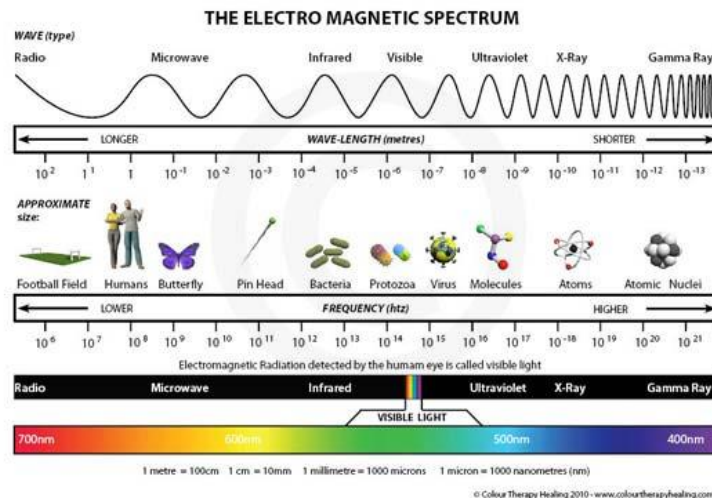


Figure 1 Visible portion of Solar Radiation

The Solar Radiation Spectrum

UV-B radiation refers to a specific portion of the sun's energy reaching the earth's surface. To understand how this is defined, we need to understand the general nature of solar energy. The energy of the sun reaching the earth is known as electromagnetic radiation. If we were to observe the sun above the earth's atmosphere, it would be found that the electromagnetic radiation consisted of the many forms of energy we recognize as visible light, infrared, ultraviolet, X-rays, etc. These terms simply define different portions of electromagnetic radiation with which we associate specific phenomena such as sight (light), heat (infrared), medical examinations (X-rays). They are all portions of the electromagnetic radiation that differ from one another in "energy".

The more energetic photons of the spectrum are at smaller or shorter wavelength. In the very limited portion of the total electromagnetic spectrum shown in the Figure 1, it is noted that ultraviolet is found at the short wavelength end (higher energy) and infrared at the long wavelength end (lower energy). At wavelengths longer than the infrared you will find microwaves and radio waves. At wavelengths much shorter than ultraviolet you will find X-rays and gamma rays. You will probably recognize that X-rays are very energetic since they can penetrate solid matter that visible light cannot penetrate which cannot "see through". Of critical importance to life on earth are the ultraviolet, visible and infrared spectral regions. For example, infrared and visible energy is that portion of the sun's spectrum that is responsible for heating the earth.

Table 1 Distribution of Solar Irradiance Energy

Spectral Region	Wavelength	% of Total Energy
Infrared	>700 nm	49.4
Visible	400-700 nm	42.3
UV-A	400-320 nm	6.3
UV-B	320-290 nm	1.5
UV-C	< 290 nm	0.5

It should be noted that UV radiation represents a very small portion of the total radiation from the sun that reaches the earth's surface. Much is filtered out by our atmosphere.

Table 1 lists the various regions of the solar spectrum, indicating the percentage of total solar energy in each region. UV radiation (represented by UV-A, UV-B and UV-C which will be defined in a following section) makes up only a little over 8% of the total. Most of the solar radiation is in the visible and infrared. The wavelength is defined as the length of one cycle (smallest segment that can be repeated to generate a continuous wave). For visible light, wavelength is usually expressed in nanometers (nm) ($1 \text{ nm} = 10^{-9}$ centimeters) or Angstroms (\AA) ($1 \text{ \AA} = 10^{-8}$ centimeters). Visible light ranges from 380 to 770 nanometers (nm) or 3,800 to 7,700 Angstroms (\AA) (see Figure 1).

Another way of expressing the nature of electromagnetic radiation is by its frequency which is defined as the number of cycles per second or hertz.

Continuous Wave

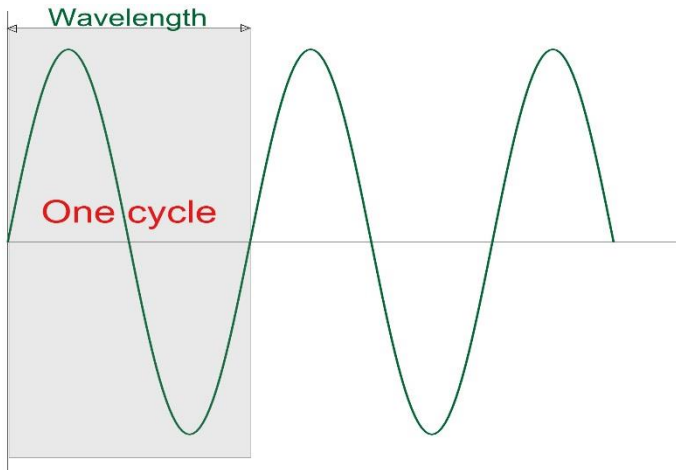


Figure 2 Sine wave showing definition of wavelength.

For radio waves, frequency is the usual designation rather than wavelength. Since radiation travels at the speed of light (approximately 3.0×10^{10} cm per second) and if we know the wavelength, the frequency in cycles (see cycle in Figure 2) per second can be calculated by dividing speed of light by the wavelength. This is expressed by the equation below where ν is the frequency, c is the rate at which radiation travels (3.0×10^{10} centimeters per second) and λ is the wavelength in centimeters.

$$\nu = \frac{c}{\lambda} \quad \text{Eq. 1}$$

Energy and Photons

Treating electromagnetic radiation as a wave, while explaining many of the phenomena associated with its behavior, is not satisfactory when describing many of its interaction with matter. It is necessary to describe it in terms of a particle called a “photon”. In other words, radiation has a dual nature - some phenomena related to its wave nature and other phenomena associated with its particle nature. It is the particle nature which we need to understand in order to explain the interactions of radiation with ozone and biological organisms which will be discussed later.

It is now necessary to define the energy of the photons occurring at various wavelengths or frequencies. An early German physicist, Max Planck, determined that the energy of radiation or photons at a given frequency was simply expressed as a constant times the frequency or:

$$E = h \cdot \nu = \frac{h \cdot c}{\lambda} \quad \text{Eq. 2}$$

E is the energy expressed in units called “ergs” and h is Planck’s constant which is 6.63×10^{-27} erg sec. From this expression it can be seen that as frequency increases and wavelength decreases the energy of the photons increase. For example, photons associated with ultraviolet radiation are more energetic than those associated with infrared radiation. Thus, short wavelength radiation is more energetic than long wavelength radiation.

Interactions of Radiation with Matter

We observe the interaction of matter and light all around us. The grass is green because “red and blue” photons are absorbed by the plants chlorophyll or a car is red because blue-green light is absorbed by the paint. Matter can also emit photons (as opposed to absorption) if it heated to high enough temperature or “excited”. The light from fluorescent lamps is a result of the excitation of mercury vapor by high energy electrons, which then emits photons (actually in the UV) which in turn interact with a “phosphor” coated on the tube walls to emit the bluish visible light. The yellowish street lamps are the result of photons emitted by hot or “excited” sodium vapor. Thus, the interaction between matter and electromagnetic

radiation can result in either the absorption or emission of photons depending on the phenomena being observed.

In discussing the interactions of UV-B radiation with biological organisms we are primarily concerned with the absorption phenomena. Keep in mind that the source of this radiation is the sun which is hot enough to emit photons with a wide range of energies. In this discussion, the concern is with the range of photon energies referred to as UV which, through absorption, can damage biological organisms. On the other hand, it should be kept in mind that the absorption of visible radiation by plants, particularly photons in the blue and red region (400-500 and 650-780 nm) is the source of energy driving photosynthesis. Since our interest is with UV radiation, the following discussions will focus on its ability to be absorbed by and break the bonds between atoms in molecules which, in the case of biological organisms, may result in permanent damage.

Ultraviolet Radiation Absorption

Up to now the discussion has been of electromagnetic radiation in general. The following will focus on that portion of the spectrum designated as UV radiation. In Figure 3 the UV portion of the spectrum is divided into UV-A, UV-B and UV-C. These designations are somewhat arbitrary, but they are convenient divisions for the discussion of the interaction of UV radiation with ozone and biological organisms.

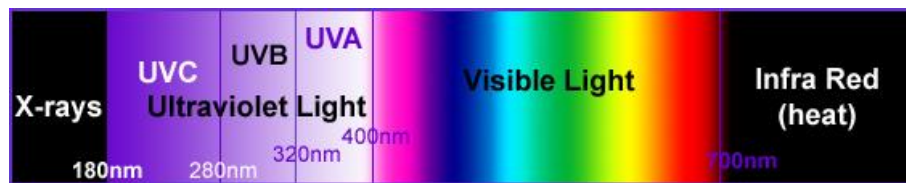


Figure 3 Diagram showing ultraviolet portion of solar spectrum.

The UV-B and UV-C radiation represents that portion of the spectrum that is capable of damaging biological organisms and is also that portion absorbed by the ozone layer above the earth. High energy UV-C photons (wavelengths shorter than 290 nm) are almost completely absorbed by ozone and very few reach the earth's surface. This is fortunate since life as we know it would not exist if this were not the case. For example, UV-C radiation is emitted from "germicidal" lamps which are used to kill biological organisms. UV-B radiation (wavelengths between 290 and 320 nm) is only partially absorbed by the ozone layer and can damage biological organisms while UV-A (wavelengths greater than 320 nm) is not absorbed by ozone and generally is not damaging to biological organisms. These relationships will be discussed in more detail in a later section.

Intensity of Radiation

Another consideration in evaluating the effects of UV radiation is the intensity or "flux" at the earth's surface. That is, how much radiation of a given wavelength is reaching the earth's surface. You might think of flux in terms of a 20 watt light bulb and a 100 watt light bulb. Both emit roughly the same spectral range of wavelengths - both are "white" visible light. However, there is a large difference in intensity and thus in the amount of light or radiation "flux". The term used to define the flux of solar radiation is "irradiance". The solar irradiance at the earth's surface varies greatly depending on factors such as latitude, time of day, time of year, cloud cover, and haze (aerosols). In the case of the UV irradiance, additional factors are

ozone and elevation above sea level. The units in which irradiance is expressed are watts per meter squared - the amount of light falling on a horizontal square meter of surface and measured in watts. If the radiation is separated into its spectrum, the irradiance at a specific wavelength can be expressed as watts per meter squared per nanometer of wavelength. It should be obvious that in the interaction of radiant energy with biological organisms, we have to consider both wavelength and irradiance. For example, in the case of photosynthesis an increasing irradiance in the visible may increase the photo synthetic rate depending on the plant. Thus when discussing the potential negative effects of UV-B radiation on biological organisms, not only is the wavelength and energy of the photons important but also the radiation flux or irradiance levels.

Impact of Ozone on UV-B Irradiance

As previously stated, the protection of the earth's living systems from UV-B and UV-C radiation is a result of the absorption of this radiation by ozone. While there is some ozone in the lower atmosphere (troposphere), it is small compared to the amount in the stratosphere. (It is not the purpose of this presentation to discuss the chemistry which has resulted in reductions of stratospheric ozone but to describe how changes in the ozone layer can affect the UV irradiance). The most important factor is the total amount of ozone that solar radiation encounters before reaching the earth's surface. This is referred to as "column ozone" since it is the total amount of ozone in a column between the earth's surface and the top of the stratosphere. This is normally expressed as "Dobson Units" and abbreviated as "DU".

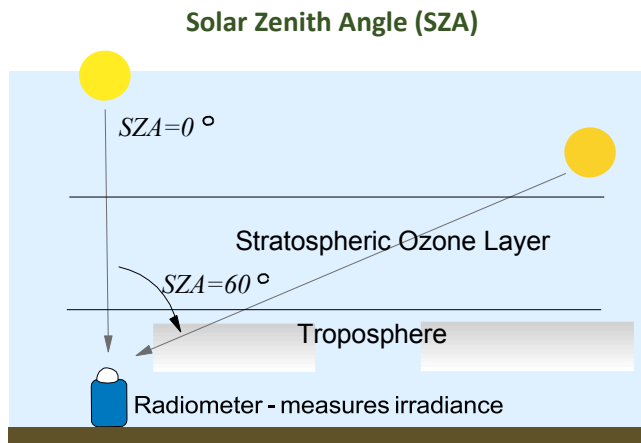


Figure 4 Path length through atmosphere and SZA

The amount of ozone the radiation passes through is dependent not only on its concentration in the atmosphere but is also dependent on the elevation above sea level and the angle of the sun with respect to a point on the earth's surface. The higher the elevation above sea level, the shorter the path through the atmosphere that the radiation has to travel. This results in increasing irradiance. The lower the sun is in the sky, the longer the path through the atmosphere (see Figure 4) and the greater the amount of ozone the radiation encounters

as it passes to the earth's surface thus lowering the irradiance. The angle of the sun depends on three factors - the latitude, the time of year, and the time of day. This angle is referred to as the "solar zenith angle" (SZA) and is the angular difference in degrees between directly overhead and the sun's actual position. If the sun were directly overhead the SZA would be zero. This can occur only at latitudes between 23.5° north and 23.5° south. Thus, in the northern and southern latitudes greater than 23.5°, the sun never reaches a SZA of zero degrees.

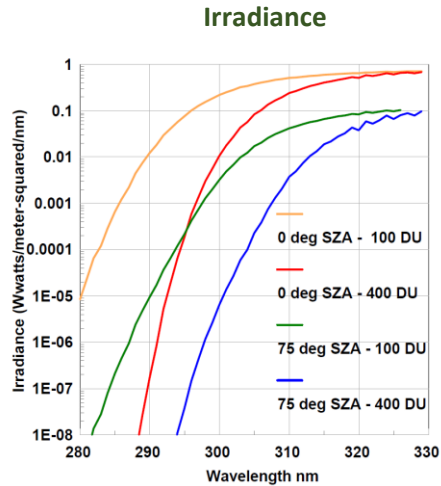


Figure 5 Effect of sun's angle and ozone on irradiance.

The relationship between the solar UV irradiance at the surface, the solar zenith angle and the total ozone column is displayed in the graphs in Figure 5. For illustration, solar irradiance is plotted (logarithmic scale) versus wavelength at column ozone amounts of 100 DU and 400 DU (normal levels for the U. S. latitudes are 260-350 DU) and SZAs of 0° and 75° on a clear day (role of clouds will be considered later). The sun angle of 0° could represent a location at 23.5° north latitude (for example La Paz, Mexico) at solar noon on the 21st of June (day sun is farthest north). The sun angle of 75° could represent approximately 6:00 AM or 6:00 PM on the same day. There are obviously many combinations of time of day, day of the year and geographical locations (between 23.5° south and 23.5° north) which would produce these conditions. If farther north or farther south than 23.5°, the sun will never be overhead or at 0° SZA.

From Figure 5 it can be seen that the irradiance varies strongly with wavelength and at 400 DU and at 0° sun angle, the irradiance at 290 nm is only one-one hundred millionth of that at 320 nm. This illustrates the important role ozone plays in filtering out radiation at wavelengths shorter than 320 nm. As the solar angle increases to 75° late in the day, the path through the atmosphere has increased and the irradiance has decreased significantly as a result of increased ozone absorption as well the fact the sun is at a more oblique angle with respect to the earth's surface. If the column ozone were reduced from 400 DU to 100 DU it is obvious that there is a large effect on UV absorption. At a solar angle of 0° the absorption at 290 nm has increased by a factor of one hundred thousand (A column ozone value of 100 DU in the northern and southern mid-latitudes is entirely unrealistic and was chosen for illustration purposes only). A value as low as 100 DU has occurred over the Antarctic continent as a result of the "ozone hole" but the SZA is never less than 55 degrees at this latitude. Interesting, and little noticed, are the implications of SZA and latitude for UV-B irradiance. Where you live has a large effect on the UV-B dose you may receive for a given exposure time. To illustrate this, if you live in Las Cruces, NM at 32.6° north latitude, on June 21st on a clear day with an ozone level of 300 DU, you would receive a UV-B dose 1.24 times that which you would receive in Seattle, WA at 47.7° north under the same atmospheric conditions. This would be equivalent to increasing the ozone levels by about 50 DU to 350 DU at Las Cruces. This results from the fact that the sun does not rise as high in the sky as you move farther north.

Clouds, Aerosols and Air Pollution

It should come as no surprise that clouds have a large effect on irradiance at the earth's surface. Clouds and aerosols scatter radiation while air pollutants such as sulfur dioxide absorb and scatter UV. Absorption of UV by gasses other than ozone is generally a small factor except in highly polluted areas. The illustration in Figure 6 depicts the three factors which affect the transmission of solar radiation to the earth's surface. These are absorption in the atmosphere (f_A) by ozone and air pollutants, scattering back to space (f_s) by molecules, clouds and aerosols (haze), and absorption by the ground (f_G). If the ground is covered by snow or ice, absorption is low. The reflectivity of the ground is expressed as the "albedo". The albedo of clean

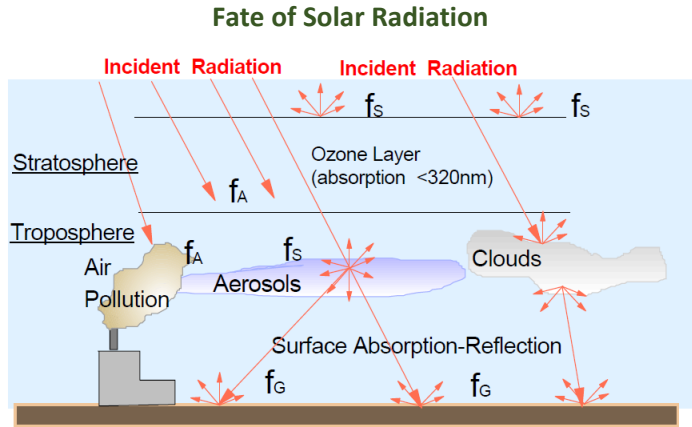


Figure 6 Interaction of radiation and the earth's atmosphere.

snow is almost one (100% reflection) reflecting a large portion of the radiation. For example, the reflective nature of snow greatly increases the exposure of a skier to UV-B thus increasing the severity of sunburn and possibly resulting in “snow blindness” if not wearing goggles. Blacktop, on the other hand, would have an albedo approaching zero. The sum of absorption and scattering ($f_A + f_s + f_G$) is equivalent to the total radiation entering the atmosphere.

To illustrate these effects (primarily for clouds), the plots in Figure 7 are actual field measurements of UV irradiance at 305 nm on a clear day and cloudy day in Texas on March 28 (clear) and 30 (cloudy). While there is cloud cover the entire day on the 30th, the UV-B irradiance is still significant. As is illustrated in the previous figure, thin clouds actually scatter a significant portion of the UV-B toward the earth while thick clouds scatter most back to space. Thus, clouds are not necessarily good protection from sun-burn.

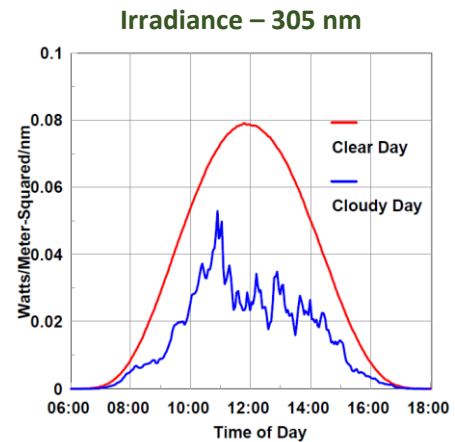


Figure 7 Irradiance for a clear and cloudy day.

Response of Biological Organisms

The last step in our discussion is the relationship of UV radiation to biological organisms. Again, it is necessary to look at the nature of this interaction in terms of its dependence on wavelength. As stated previously, photons of sufficiently high energy can break the bonds between atoms in molecules and thus destroy the molecule. The higher the energy of the photon, the more likely that the interaction will be destructive. Also, the larger the number of photons or the higher the irradiance, the greater the damage. We saw in the previous section that as the wavelength decreases, the photons have higher energy but there are fewer of them because of the absorption by ozone (red curve in Figure 8). On the other hand, the sensitivity of biological organisms increases as the wavelength becomes shorter (green curve Figure 8) because of the higher photon energy. Thus, there will be some wavelength which causes the greatest damage based on organism sensitivity and irradiance level. We can determine the most destructive wavelengths if we can experimentally determine the amount of damage to a given organism as a function of wavelength or photon energy. Such a function is called an “action spectra” and is specific for a given organism. If action spectra are compared for a variety of biological organisms, while they will all be different, there is not a great deal of variation.

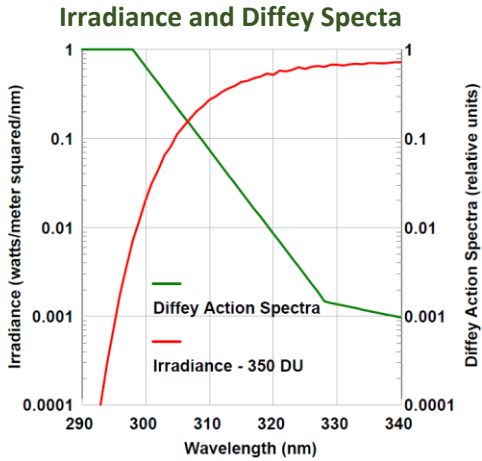


Figure 8 Modeled irradiance (350 DU and 0 SZA) and Diffey action spectra.

For purposes of this discussion, the action or damage spectra for sun-burn was chosen (Diffey action spectra). This is plotted as a function of wavelength (green curve) on the graph in Figure 8 and represents the relative response of human skin to UV-B as a function of wavelength (action spectra are expressed in relative units - one representing the highest sensitivity). To determine the skin’s response, the number of photons to which the skin is exposed is essentially the same at each wavelength. You will note that as the wavelength is decreased, the damage increases logarithmically (changing by factors of ten) and that the sensitivity of skin at 290 nm is a thousand times that at 340 nm.

At the same time, the sun’s irradiance or number of photons (red curve) is decreasing logarithmically as a result of ozone absorption. In order to determine the wavelengths where greatest damage occurs, we simply multiply the two functions together (the values in the Diffey curve times those in the irradiance curve). The result is shown in Figure 9. This process is called “weighting”. We see that the most destructive wavelengths are around 305 nm. At shorter wavelengths, there are not enough photons and at longer wavelengths, the photon energy is not high enough to cause as much damage. It turns out that for most biological organisms the most destructive wavelengths are between 305 and 310 nm.

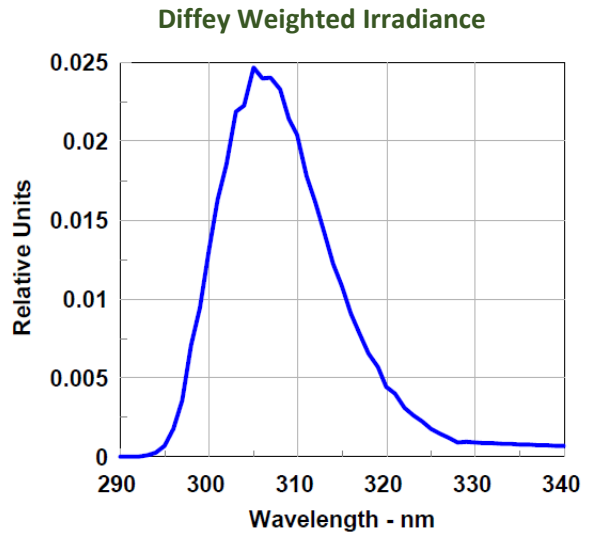


Figure 9 Product of the irradiance and Diffey action spectra as shown in Figure 7.

Researchers during the past decades have verified that the health benefits of exposure to solar UV-B (290–320 nm), the primary source of cutaneous production of vitamin D3, now include reduced risk for bone diseases, many types of cancer and, to a lesser extent, autoimmune diseases like multiple sclerosis and infectious diseases such as tuberculosis and influenza. Solar UV-B may also have a beneficial role in other diseases and conditions and it is still used as a treatment in several hospitals around the world.

The adverse health effects include skin cancer and melanoma, cataract development, premature skin aging and other sun related effects. However, some research suggests that the risk of melanoma seems to be due primarily to UV-A (320–400 nm), while the use of sunscreen that successfully blocks erythema UV but does not provide effective absorption of UV-A seems to be associated with both reduced production of vitamin D and an increased risk of melanoma.

A simple UV Index

In order to describe the levels of UV irradiance that reaches the earth's surface in a more comprehensive way, a simple index was adopted. The UV index (UVI) is a linear indicator that has values starting from 1. The higher the UVI values; the greater the risk of sunburn, thus protective measures should be taken (Figure 10).

HOW TO PROTECT YOURSELF	UV RATING 1-2 LOW	UV RATING 3-4 MODERATE	UV RATING 5-7 HIGH	UV RATING 8-10 VERY HIGH	UV RATING 11+ EXTREME
Wear UV-blocking sunglasses					
Use sunscreen					
Wear a hat					
Wear protective clothing					
Stay in the shade near midday					
Stay in the shade reduce time in the sun					
Try to avoid the sun between 11-4pm					

Figure 10 Protection measures based on the UV index for skin type I.

Apart from the knowledge of the UVI that can be obtained from several online tools and/or cell phones applications as a prognostic parameter; the skin type should also be identified. In the figure below you can find a rough description of how one can determine his/her own susceptibility in UV exposure by checking the skin colour in conjunction with the frequency of sunburn incidences. If someone has a dilemma between two skin types, then he/she should pick the one that is more sensitive to UV exposure.

NATURAL SKIN COLOUR	Very fair, pale white, often freckled	Fair, white skin	Light brown	Moderate brown	Dark brown	Deeply pigmented dark brown to black
UV SENSITIVITY & TENDENCY TO BURN	Highly sensitive Always burns, never tans	Very sensitive Burns easily, tans minimally	Sensitive Burns moderately, usually tans	Less sensitive Burns minimally, tans well	Minimal sensitivity Rarely burns	Minimal sensitivity Never burns
SKIN CANCER RISK	Greatest risk of skin cancer	High risk of skin cancer	High risk of skin cancer	At risk of skin cancer	Skin cancers are relatively rare, but those that occur are often detected at later, more dangerous stage. Increased risk of low vitamin D levels.	Skin cancers are relatively rare, but those that occur are often detected at later, more dangerous stage. Increased risk of low vitamin D levels.

Figure 11 Characteristics of each skin type

A recent study by Chang et al, 2010⁽¹⁾ showed a strong positive association between the skin cancer incidence rate and the annual UVI exposure with the existence of a latent period between the UVI exposure and cancer diagnosis. In figure 12 the annual skin cancer incidences across multiple states are presented.

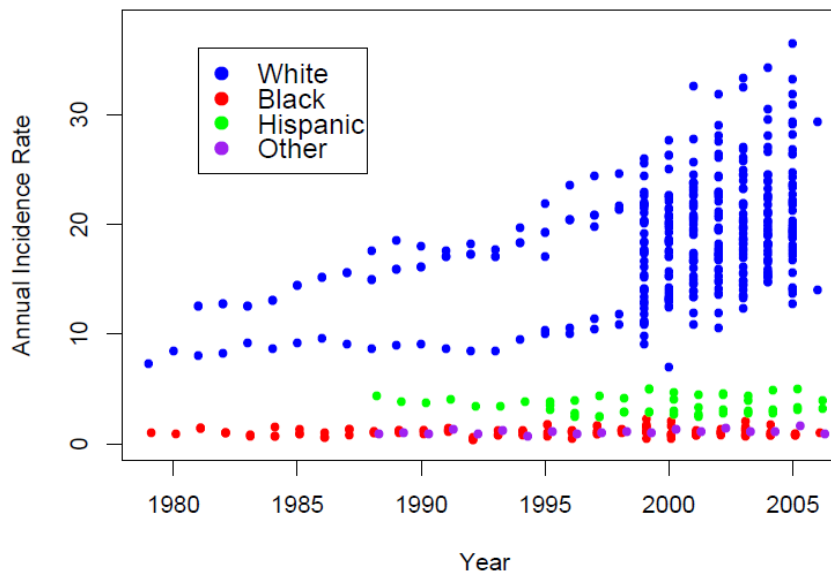


Figure 12 Race-specific incidence rates from 1979-2005 across multiple states.

It is important to emphasize that the effects of the exposure to UV solar radiation have an additive character. The human body cannot assimilate the energy absorbed by the UV radiation thus the importance of a preventive attitude is more than imperative even for the youngest ones.

Summary

We have seen that electromagnetic radiation spans wavelengths from long wavelength radio waves to short wavelength X-rays and gamma rays. Wavelength can be converted to frequency by dividing the speed of light by wavelength. Classical physics treats electromagnetic radiation as a wave while the particle nature of radiation is invoked to describe its absorption by matter. In this case, radiation is described in terms of photons which have an energy $E=h\nu$. This relation demonstrates that photon energy increases with increasing frequency and decreasing wavelength. Photons, depending on their energy, are capable of being absorbed by biological molecules and, at wavelengths shorter than 320 nm, breaking molecular bonds and causing damage which may be irreparable. On the other hand, at wavelengths less than 320 nm, ozone is absorbing the UV-B and UV-C radiation and greatly reducing the number or flux of these high energy photons reaching the earth's surface. In an earlier section it was noted that ozone may drop to 100 DU in the Antarctic during the ozone hole but at that latitude the solar angle is never less than 55°. Because of the low sun angle, the UV irradiance generally does not exceed normal values at mid-

¹Chang, N. B., Feng, R., Gao, Z. and Gao, W. (2010): Skin cancer incidence is highly associated with ultraviolet-B radiation history. *International Journal of Hygiene and Environmental Health*, **213**, 359-368.

latitudes. It should be pointed out, however, that this does represent abnormally high UV-B irradiance for the plants and animals that have evolved in this region of the world and in fact does represent a problem. There are demonstrated harmful effects of increased UV-B radiation on aquatic organisms in the Antarctic, particularly phytoplankton which is a critical component of the food chain. Skin cancer, increased incidence of cataracts, DNA damage, the negative response of phytoplankton and other plants are all related to elevated UV-B. These represent a few of the negative effects observed as a result of UV-B absorption by biological and geochemical systems which clearly illustrate the importance of maintaining normal ozone levels in the stratosphere thus increasing the absorption of the short wavelength UV radiation.

The cutaneous production of the Vitamin D3 is related to beneficial effects on humans. The main driver for the production of the pre-Vitamin D in the skin is the UV solar radiation. Thus one has to keep in mind the balance between the benefits and the detrimental effects of exposure in solar UV radiation.

SITES WITH UV-B RADIATION RELATED INFORMATION

For additional information on the UV-B radiation please follow the links bellow.

<http://sedac.ciesin.columbia.edu/ozone>

<http://pubs.rsc.org/en/content/articlehtml/2016/pp/c6pp90004f>