Solar radiation & physical principles of light

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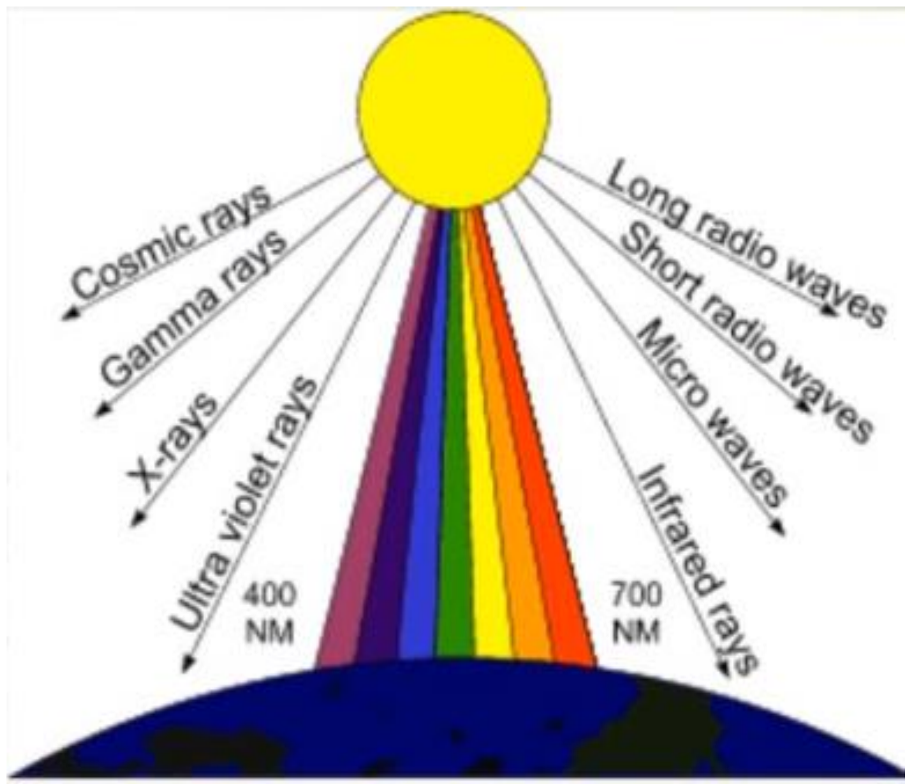
The propagation of electromagnetic energy is often referred to as radiation.

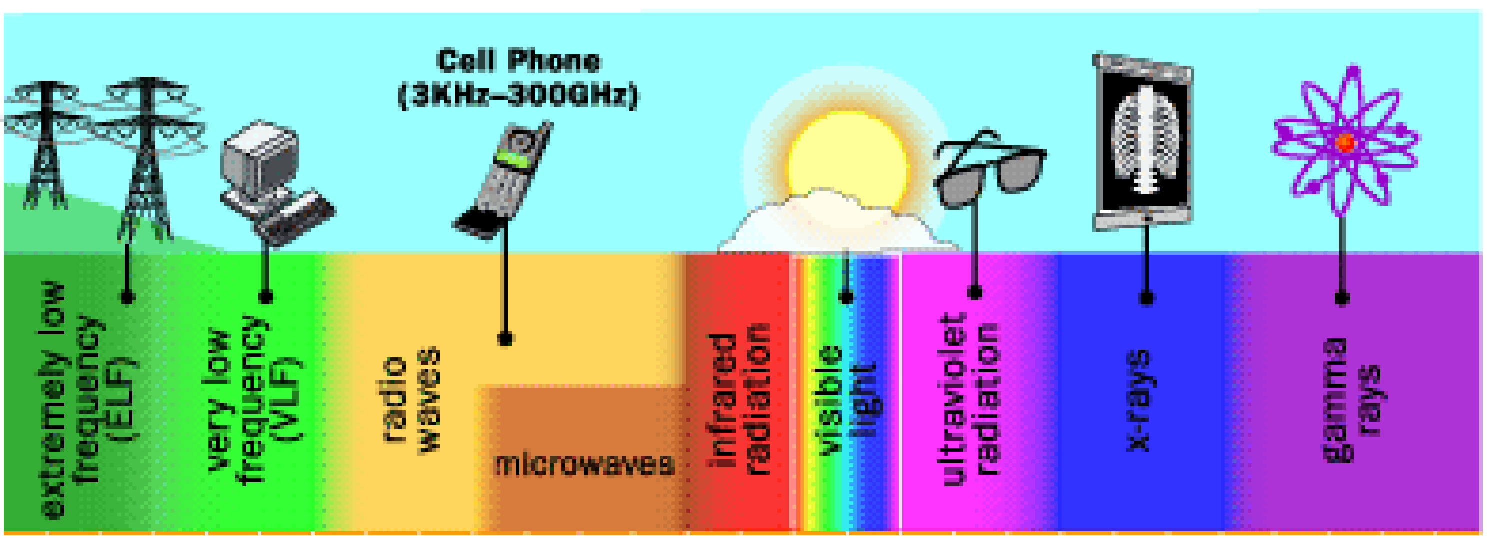
Electromagnetic solar radiation is a phenomenon by which energy escapes from the Sun in the form of a wave. The Sun emits radiation from cosmic rays to radio waves.



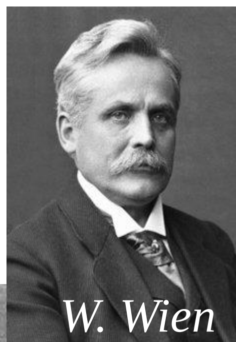
*The term **"LIGHT"** means "Visible light" that is just one type of electromagnetic radiation. "Light" is a very small component of the electromagnetic spectrum and is the part that can be perceived by the human eye.*

The "light" that we see everyday is only a fraction of the total energy emitted by the sun incident on the Earth.

*Instead of "light" it is more correct to speak about "**radiation**" as a form of "electromagnetic radiation" and about "visible light" as a small subset of the electromagnetic spectrum.*

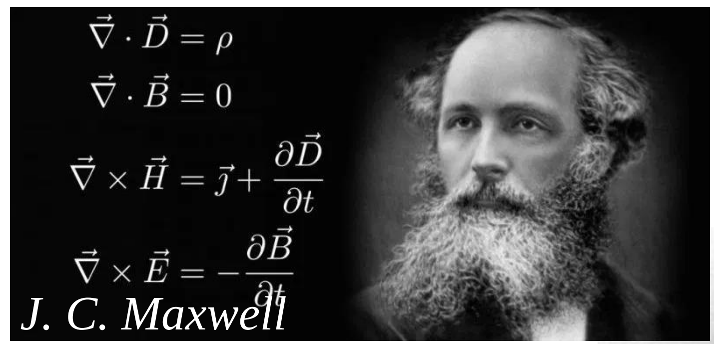


Magnetic and electrical energy studies were carried out during the 19th century and into the early 20th century through experimentation and mathematical reasoning by scientist such as Hans Christian Oersted, Michael Faraday, and James Clerk Maxwell, Gustav Kirchoff, Josef Stefan, Ludwig Boltzmann, Wilhelm Wien, and Max Planck.

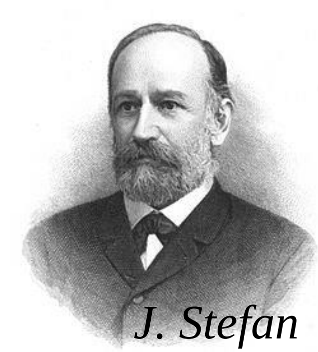


W. Wien

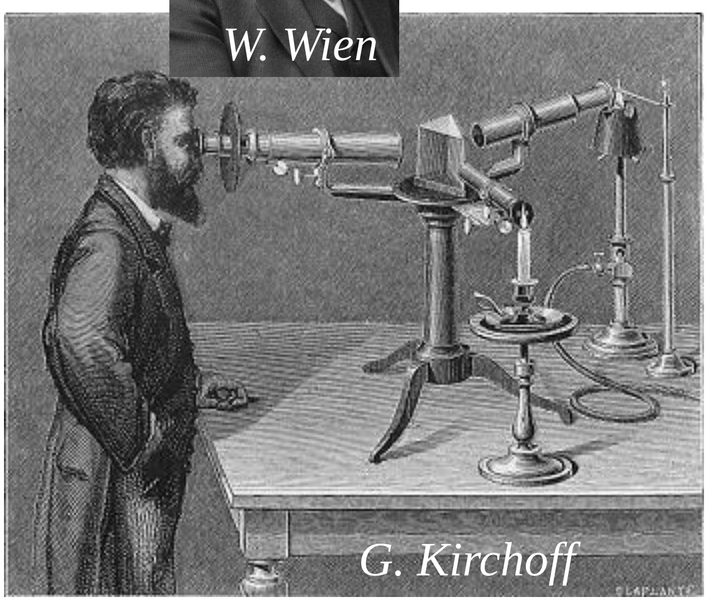
H.C. Ørsted



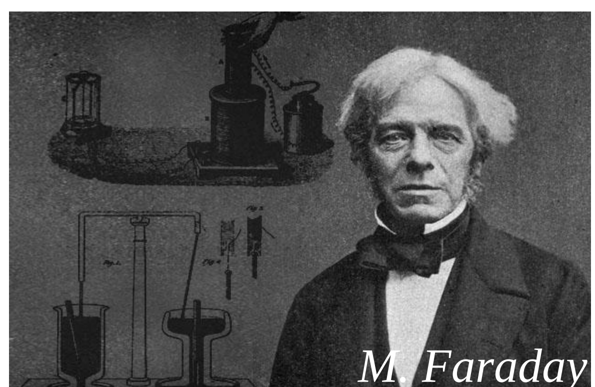
J. C. Maxwell



J. Stefan



G. Kirchoff



M. Faraday

L. Boltzmann

Electromagnetic radiation can be expressed in terms of:

- *Wavelength or frequency.*
- *Energy*

Each of these quantities for describing electromagnetic radiation are related to each other in a precise mathematical way.

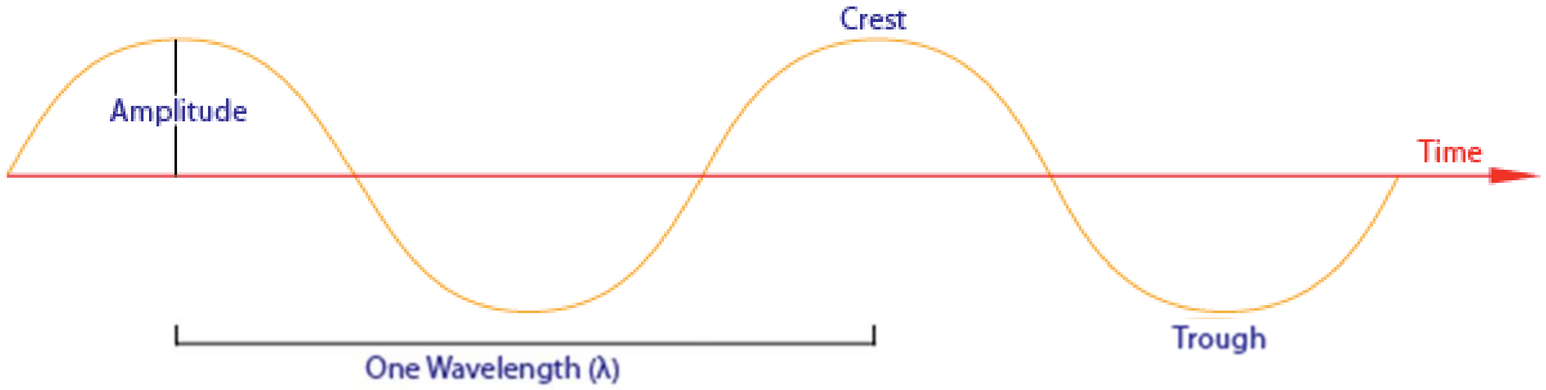
Frequency is measured in cycles per second, or Hertz.
Wavelength is measured in meters.
Energy is measured in electron volts.

Electromagnetic solar radiation travels in wave. A wave has a trough (lowest point) and a crest (highest point).

*The horizontal distance between two consecutive troughs or crests is known as the **wavelength of the wave**.*

In the ranges typical to climate the wavelength is usually measured in microns (or micro meters μm with 1 $\mu m = 10^{-6}$ m) and is denoted by lambda (λ).

The vertical distance between the tip of a crest and the wave's central axis is known as its amplitude. This is the property associated with the brightness, or intensity, of the wave. The wave energy is proportional to the square of the wave amplitude.

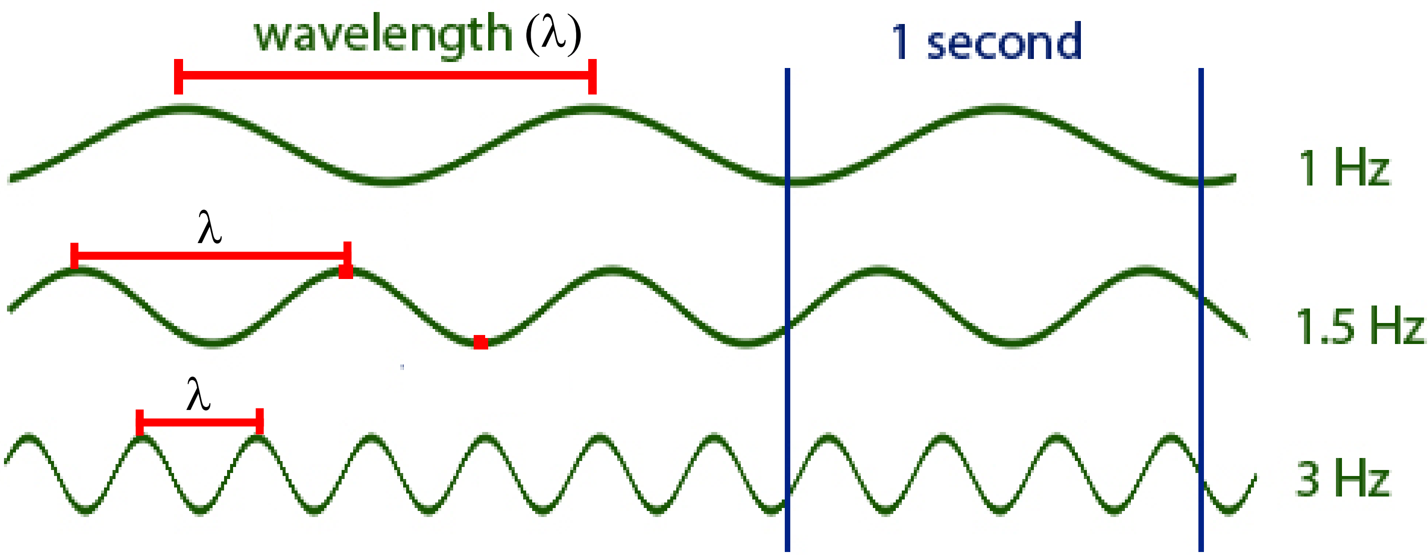


Another wave property is its ***frequency*** *denoted by nu (v).*

Electromagnetic waves oscillate in space, and therefore they are oscillating at a given position as time passes. The quantity known as the wave's frequency refers to the number of full wavelengths that pass by a given point in space every second.

The SI unit for frequency is Hertz (Hz), which is equivalent to "per seconds".

1 Hz= s^{-1}



The product of wavelength and frequency has units of speed and is referred to as the ***wave speed****, denoted by the latin letter c.*

$$c=\lambda \nu$$

where ***c is the speed of electromagnetic waves*** *(also known as the «speed of light»), λ is the wavelength and ν is the frequency.*

The speed of electromagnetic waves is a constant: $c = 3 \times 10^{8}\ m\ s^{-1}$.

All electromagnetic radiation, regardless of wavelength or frequency, travels at the speed of light.

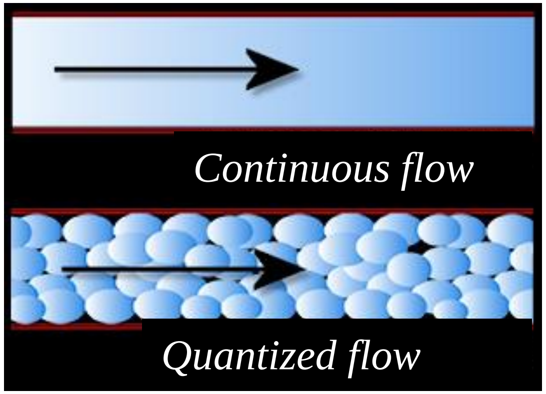
Wavelength and frequency are inversely proportional: that is, the shorter the wavelength, the higher the frequency, and vice versa.

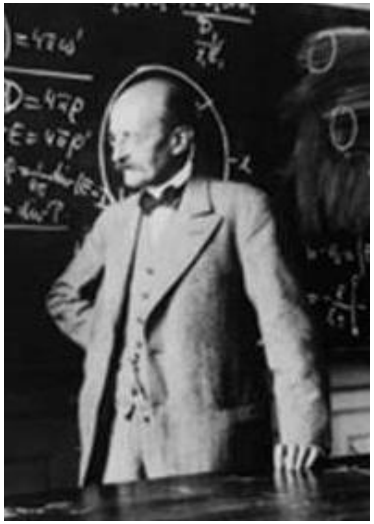
Max Planck suggested in 1900 the quantum theory.

The energy of electromagnetic waves is quantized rather than continuous. Planck revolutionized the field of physics by discovering that energy does not flow evenly but is instead released in discrete packets. Energy, which appears to be emitted in wavelengths, is actually discharged in small packets, called "quanta".

The energy of radiation that a system may possess is limited to a discrete set of values.

The difference between two of the allowed energies also has a specific value, called quantum of energy.





Max Planck

Planck postulated that the energy of a quantum of electromagnetic radiation is proportional to the frequency of the radiation: the higher the frequency the greater the energy.

The equation that explained the results of these tests is:

$$E = h\,\upsilon = \frac{hc}{\lambda}$$

E = energy in electron Volts (eV)

h = Plank's constant (6.626068×10^{-34} m^2 kg s^{-1})

v= frequency in Hertz (Hz = s^{-1})

c = the speed of light (2.998×10^{8} m s^{-1})

λ = wavelength in meters (m)

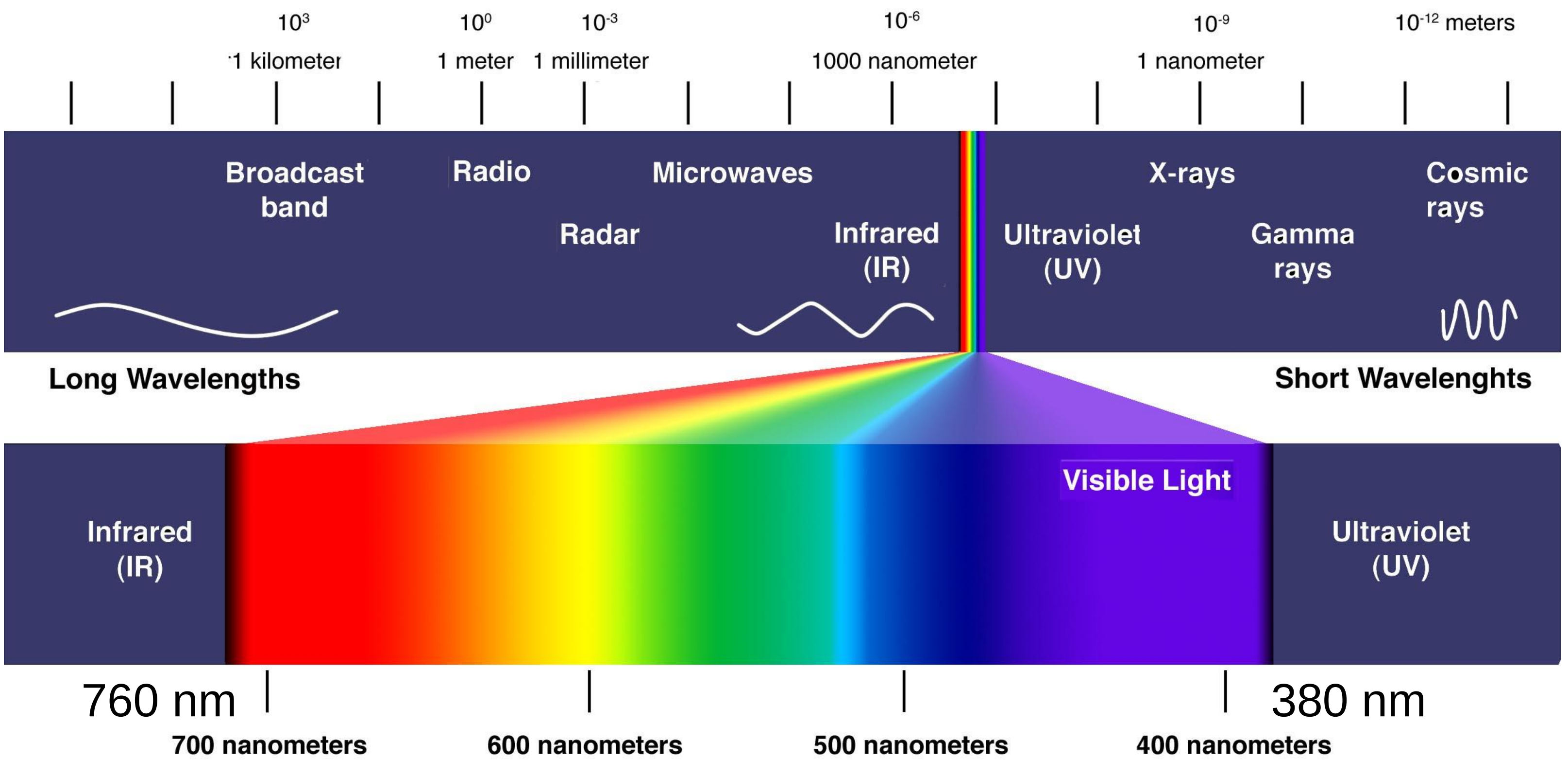
$c=\lambda\, v$

$$E = h\,\upsilon = \frac{hc}{\lambda}$$

The Planck's law highlights that:

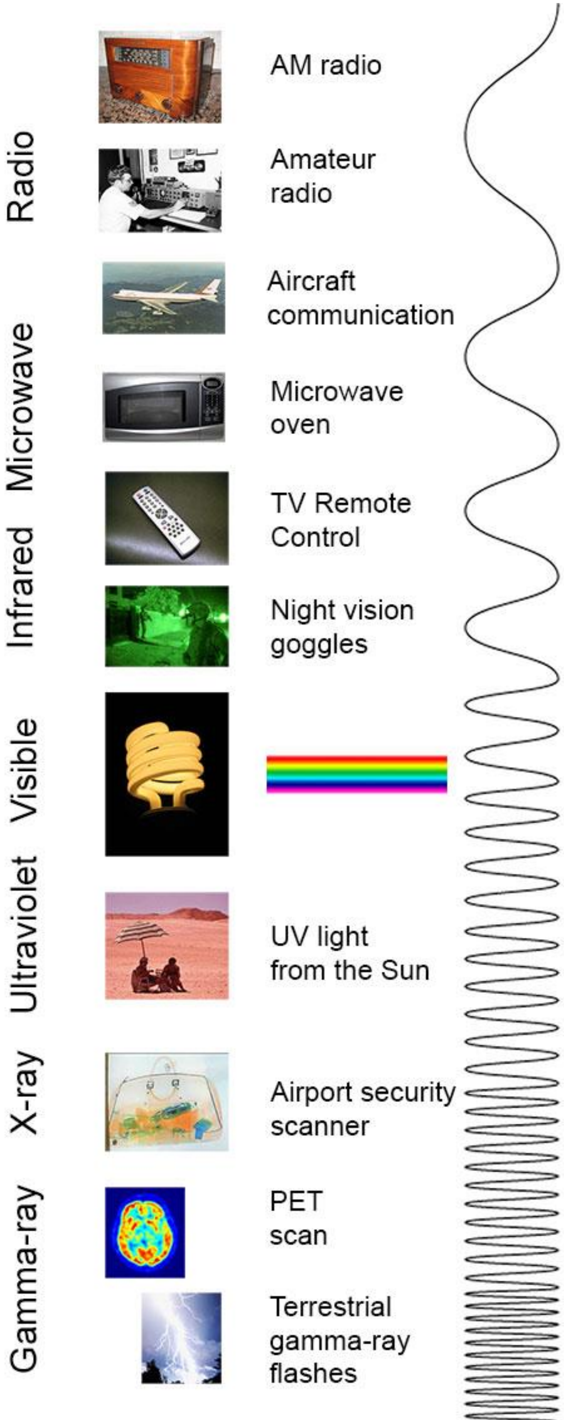
- *the Energy (E) and the frequency (v) of an electromagnetic wave are directly related*
- *the wavelength (λ) and the energy (E) are inversely related.*

The electromagnetic spectrum



Electromagnetic energy travels in waves and spans a broad spectrum from very long radio waves to very short gamma rays.

The human eye can only detect only a small portion of this spectrum called ***visible light***



Type of Radiation	*Wavelenght range (nm)*
Radio waves	26000 - 100000
Microwave	0.3-1 mm
Long infrared (LWIR)	2500-26000
Mid Infrared (MWIR)	1000-2500
Short- infrared (SWIR)	760-1000
Visible	380-760
Ultraviolet A (UVA)	315-380
Ultraviolet B (UVB)	280-315
Ultraviolet C (UVC)	100-280
X-ray	1-15
Gamma ray	0.001-0.14
Cosmic ray	0.00005

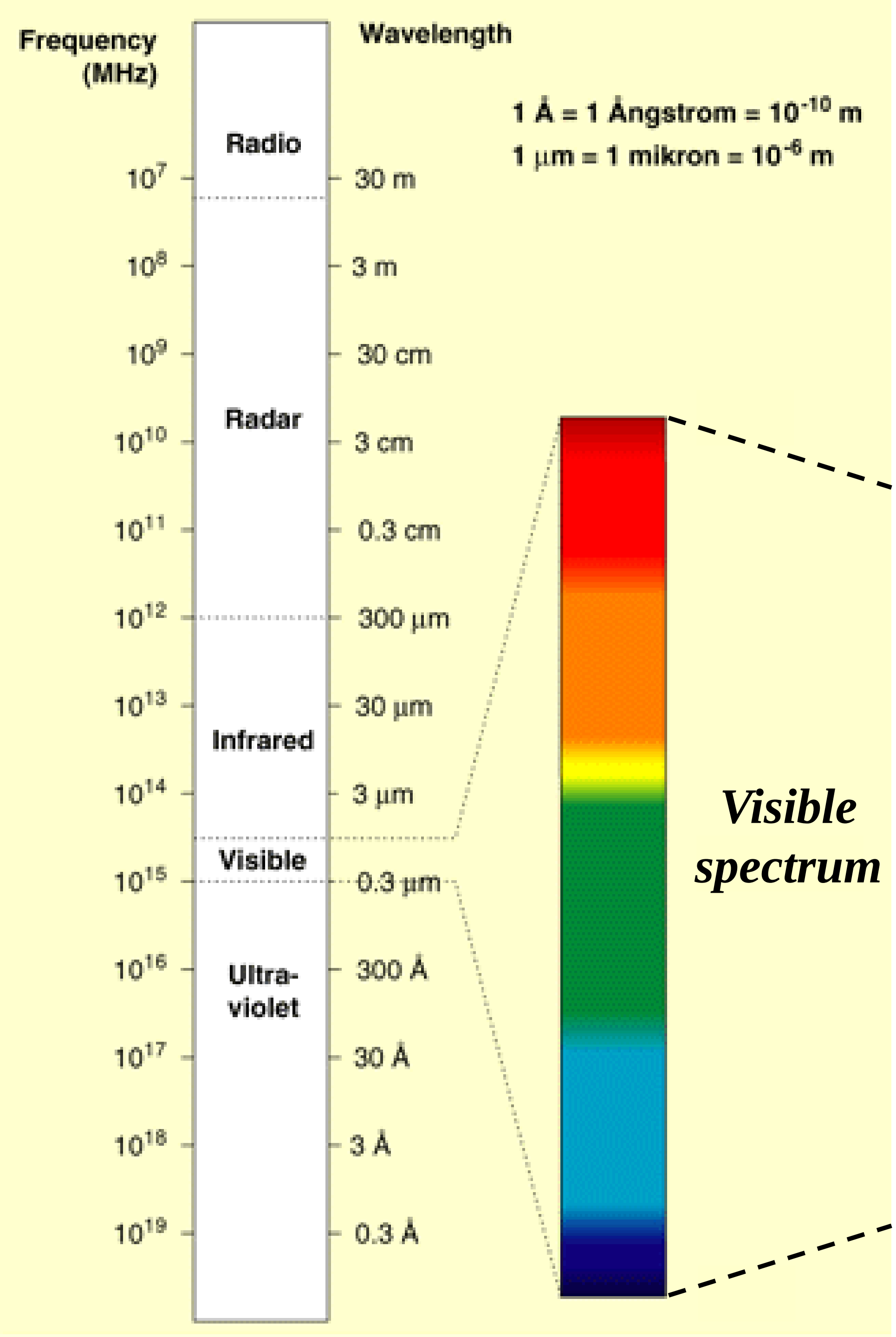
(1 nm = 10^{-9} m)

The electromagnetic spectrum from lowest energy/longest wavelenght (at the top) to highest energy/shortest wavelength (at the bottom).

Scientists don't like to use numbers any bigger or smaller than they have to. They use whatever units are easiest for the type of electromagnetic radiation they work with.

Unit	Symbol	Length (m)	Type of radiation
Angstrom	Å	10^{-10}	X-ray
Nanometer	nm	10^{-9}	UV, Visible
Mikrometer	μ	10^{-6}	Infrared
Milimeter	mm	10^{-3}	Infrared
Centimeter	cm	10^{-2}	Micro wave
Meter	m	1	TV, radio

Using nanometers *(0.0000001 cm, or 10^{-7} cm) violet, blue, green, yellow, orange, and red radiation have wavelengths between 400 and 700 nanometers.*



Bands with shorter wavelengths produce higher frequencies.

Red: 625 – 760 nm

Orange: 595 – 625 nm

Yellow: 570 – 595 nm

Green: 495 – 570 nm

Blue: 440 – 495 nm

Violet: 380 – 440 nm

Solar Radiation

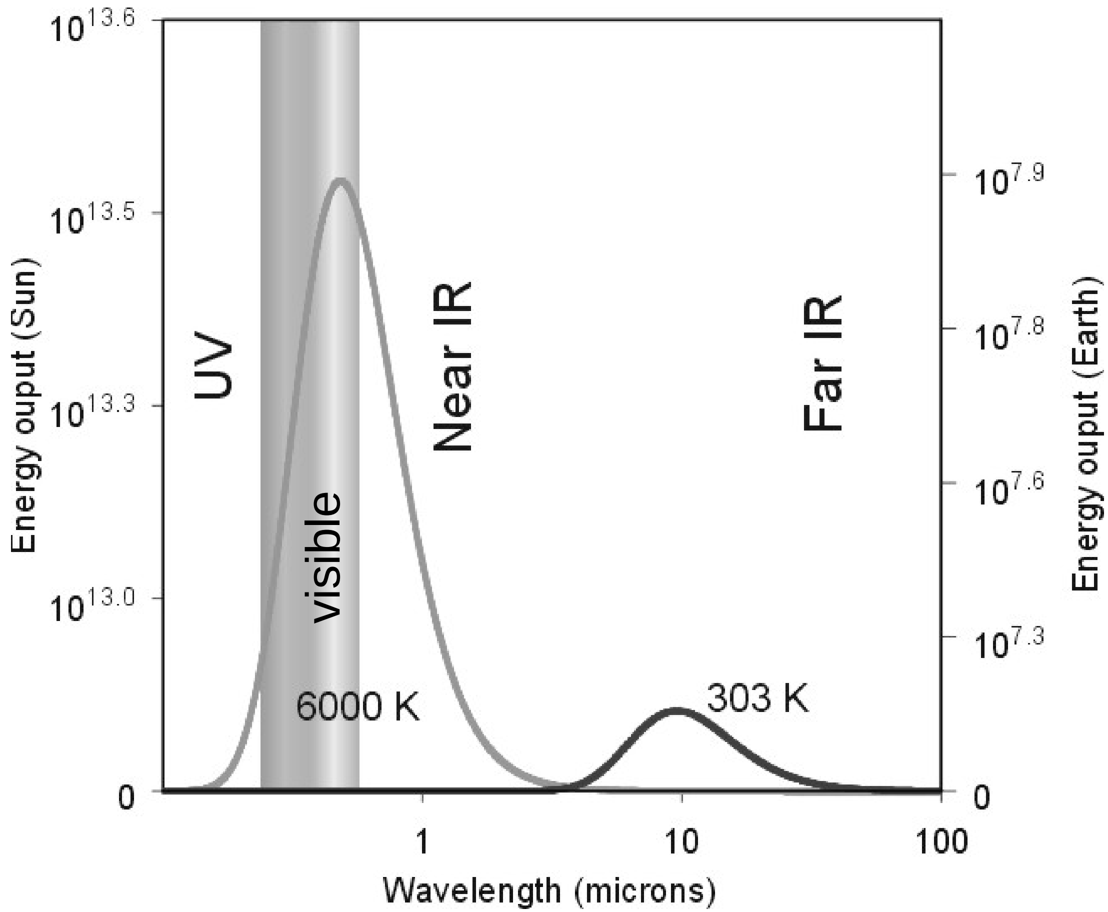
The Sun behaves as a blackbody for T » 5800 K and the maximum of the solar emission occurs in the visible range (λ » 0.5 μm).

A black body is an idealized body which is a perfect absorber, and therefore also a perfect emitter.

*The **UV radiation** (~7%) is the more energetic band of radiation.*

*The **visible radiation** (~ 45%) allows us to see and is essential for photosynthesis.*

*The **IR radiation** (~48%) is responsible for warming Earth's surface and it's necessary for energy balance of the body.*



The Sun is the energy source for the Earth. The energy captured by the Earth is about two billionths of the total radiant energy emitted by the Sun.

Solar radiation provides heat, light, and energy necessary for all living organisms. Infrared radiation supplies heat to all habitats, on land and in the water.

The amount and intensity of solar radiation depends on a variety of factors, such as latitude, season, time of day, cloud cover and altitude. Not all radiation emitted from the sun reaches Earth's surface.

Not the entire electromagnetic spectrum is of use to the plants.

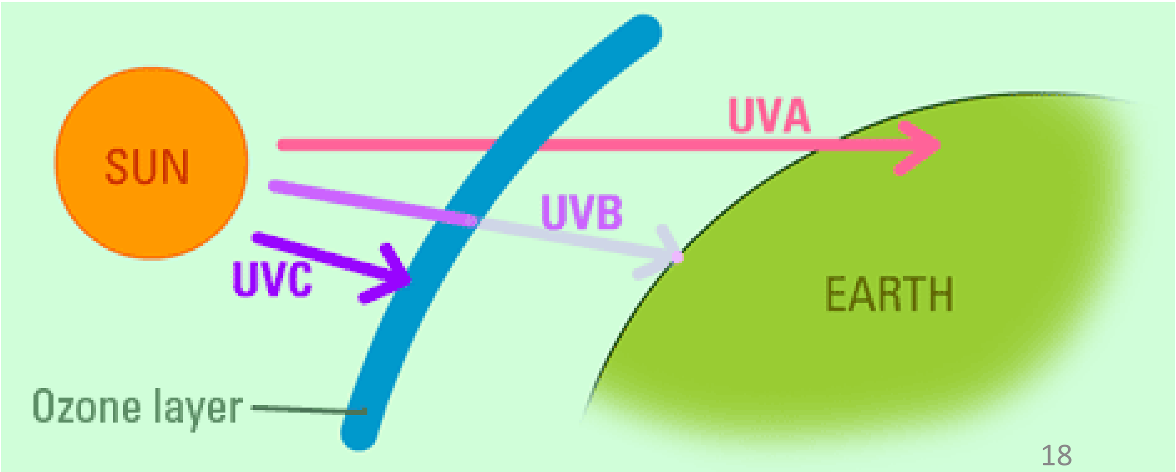
The Sun is a source of the full spectrum of ultraviolet radiation, which is commonly subdivided into UV-A, UV-B, and UV-C.

Ultraviolet (UV) radiation has shorter wavelengths than visible light. Although UV waves are invisible to the human eye, some insects, such as bumblebees, can see them.

UV-C rays are the most harmful and are almost completely absorbed by our atmosphere.

UV-B rays are the harmful rays that cause sunburn. Fortunately, about 95% of UV-B rays are absorbed by ozone in the Earth's atmosphere.

UV-A rays reach the Earth all the time.



UV-B radiations are known to cause many anatomical and morphogenic changes in crop plants, including smaller leaf size, folding, discoloration and browning, reduced hypocotyls, and increased thickness of leaves that lead to plant stunting.

These effects are elevated when PAR levels are reduced.

Further alterations in height, stem diameter, length of internodes, leaf area, stomatal number and length, as well as changes in floral morphology have also been observed.

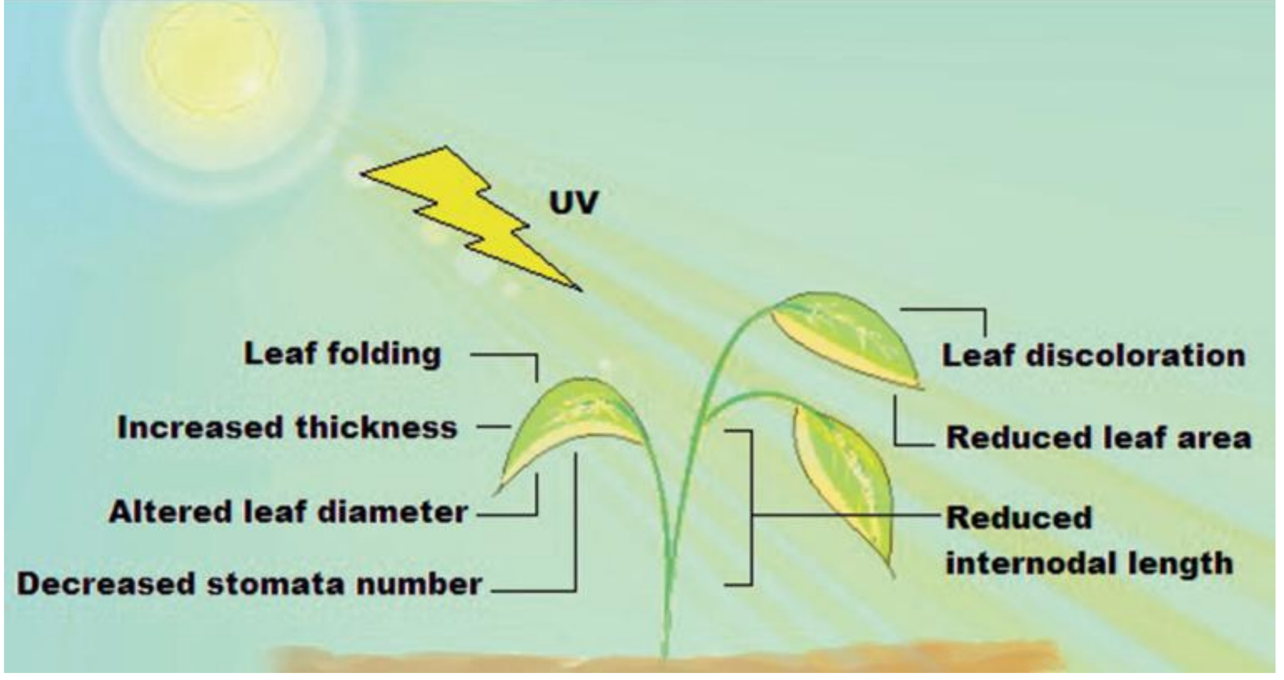
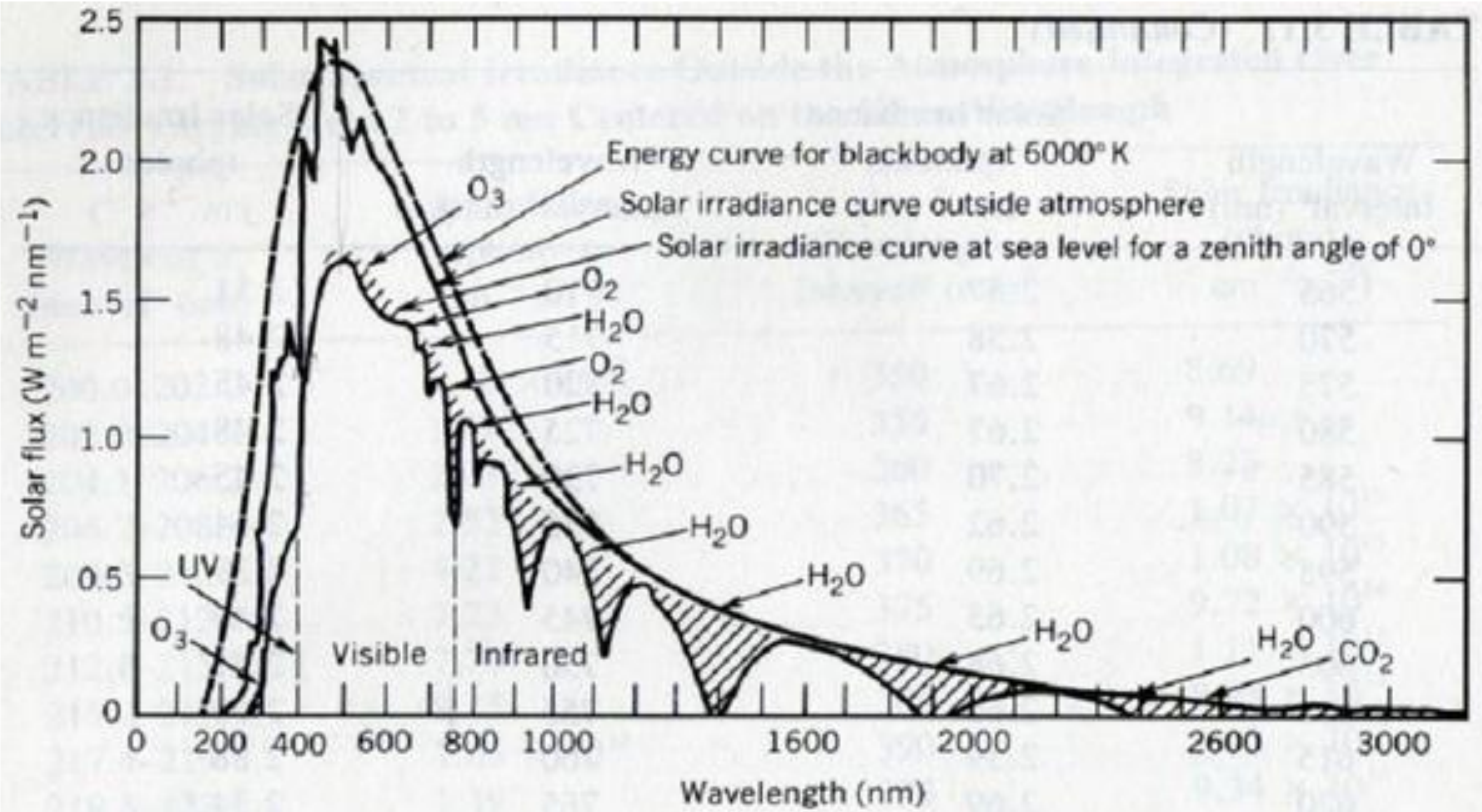


Table 6. Summary of the effects of solar ultraviolet radiation on plants (Teramura 1983).

Plant characteristic	Enhanced UVR
Photosynthesis	Decreases in many plants
Leaf conductance	No effect in many plants
Water use efficiency	Decreases in most plants
Dry matter production and yield	Decreases in many plants
Leaf area	Decreases in many plants
Specific leaf weight	Increases in many plants
Crop maturity	No effect
Flowering	May inhibit or stimulate flowering in some plants
Interspecific differences	Species may vary in degree of response
Intraspecific differences	Response varies among cultivars
Drought stress	Plants become less sensitive to UV but not tolerant to drought



Solar radiation peaks in the visible range of wavelengths and is maximum in the green (λ = 500 nm). About half of total solar radiation is at infra-red wavelengths (IR; λ > 760 nm) and a small fraction is in the ultraviolet (UV; λ < 380 nm).

The solar radiation flux at sea level is weaker than at the top of the atmosphere, in part because of reflection by clouds. There are also major absorption features by O_2 and O_3 in the UV and by H_2O in the IR.

The part in the spectrum that meets the energy requirements for photosynthesis is in the region known as the ***Photosynthetically Active Radiation (PAR)*** *which ranges from wavelenghts of about 400 to 700 nm. This range is also the part of electromagnetic spectrum that is visible to humans.*

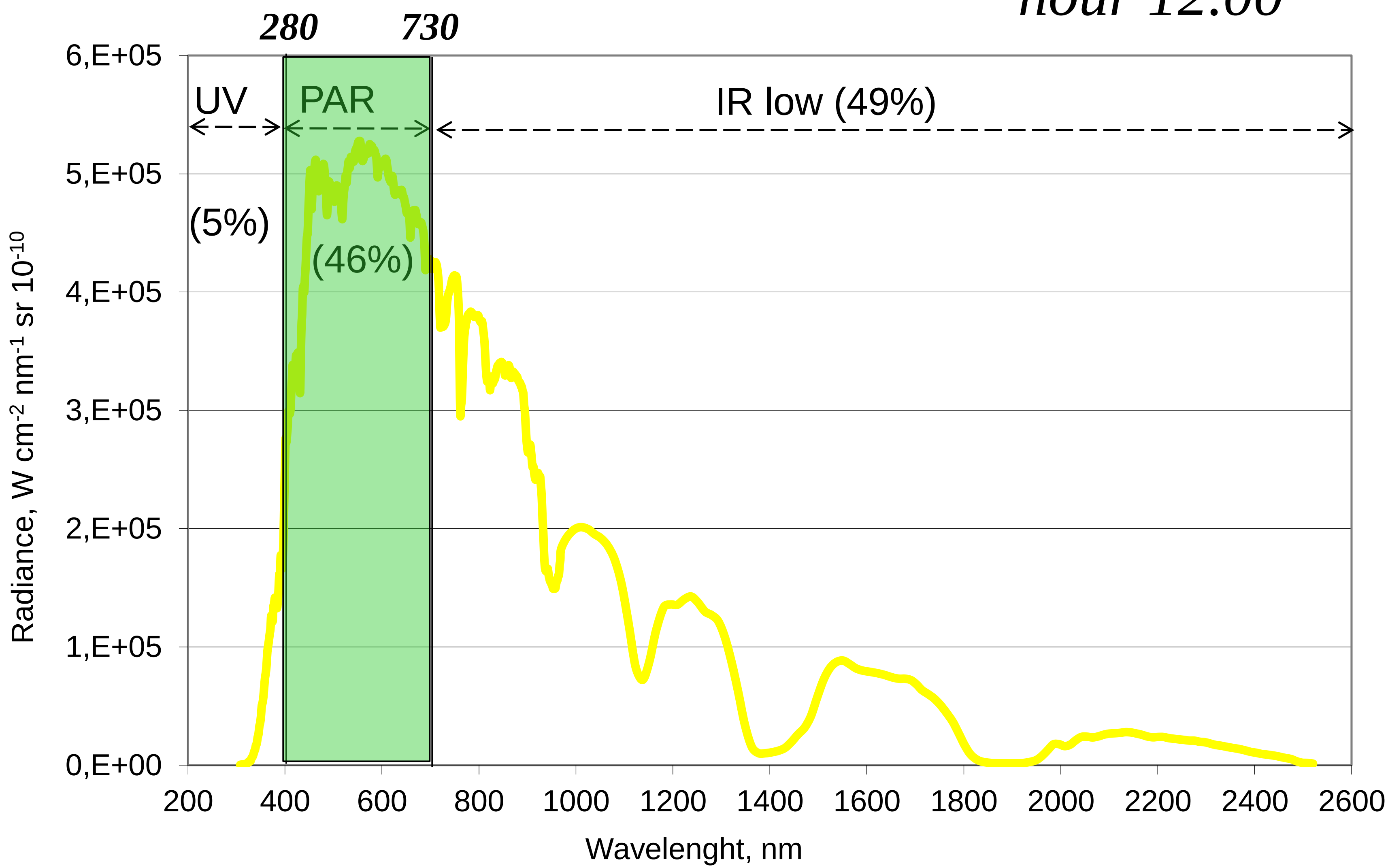
*Plants use different spectra for different life functions. For example, a plant in the seedling stage may utilize radiation in the 450 nm (**blue**) range of the spectrum. However, as the plant transitions into a flowering phase, it relies more heavily on radiation in the 660 nm (**red**) area of the spectrum. A right mix of these varying wavelengths will produce the most vigorous and fruitful plants in the shortest amount of time.*

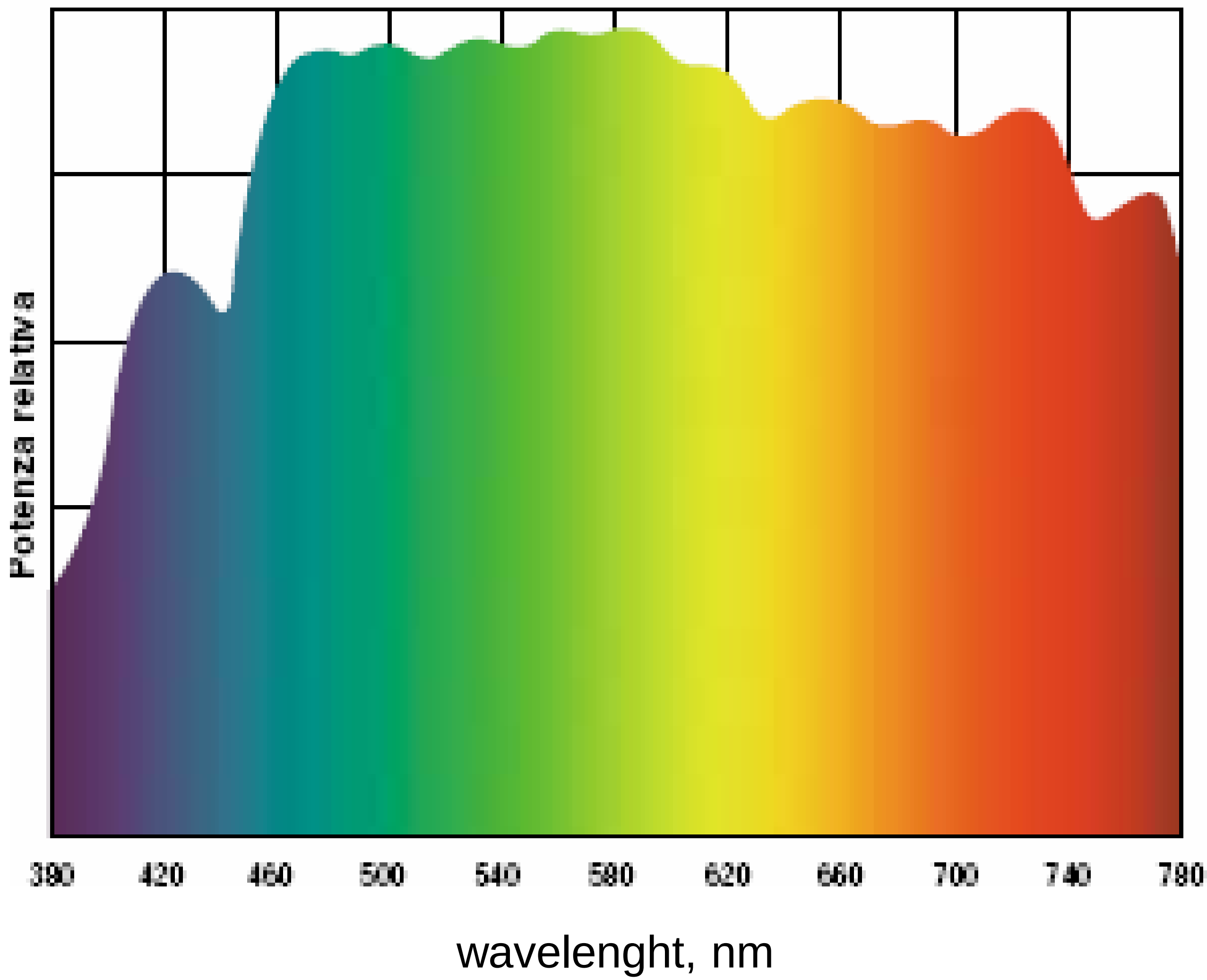
An additional consideration is crop type. The photosynthetic response to different levels of PAR varies with plant species and leaf position.

Spectral distribution of incident solar radiation

Bari, lat. 41° 05‘ N, *15 June 2009*

hour 12.00





The spectral distribution of solar radiation at noon shows how *solar radiation is a source well balanced with all the wavelengths of the visible spectrum present in an amount substantially equ*al.

Quantitative plants needs and spectral composition of the radiation

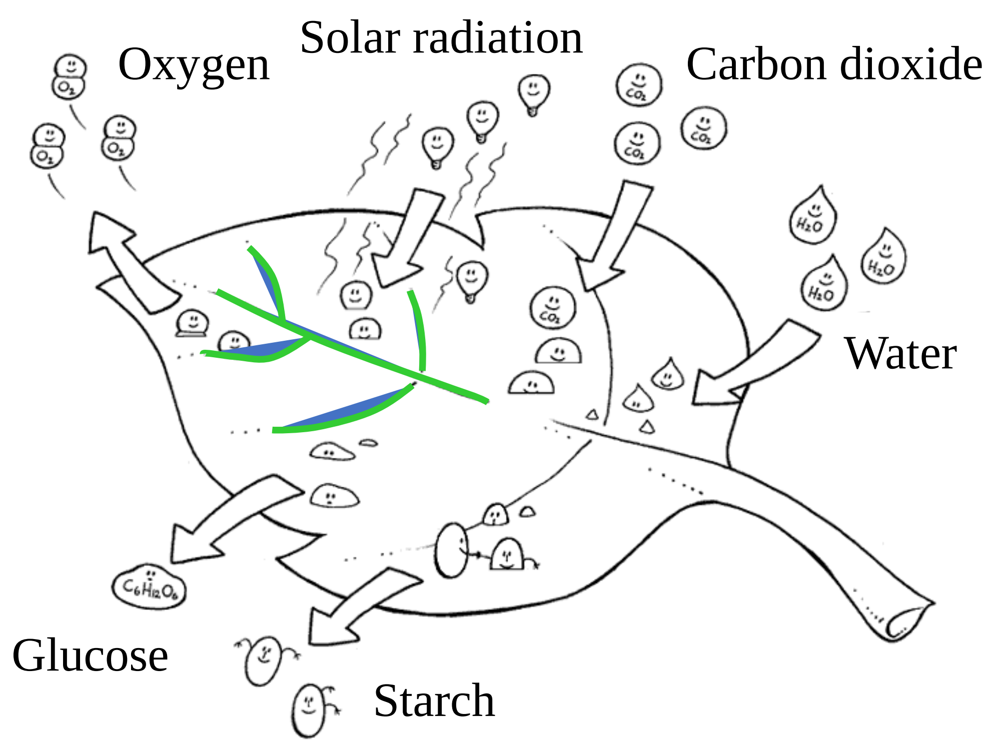
The main processes of plant development influenced by solar radiation are:

- *photosynthesis*
- *photomorphogenesis*
- *phototropism*
- *photoperiodism*

The quality, intensity, direction and duration of radiation are continuously monitored by the plant and the information gained is used to modulate all aspects of plant development.

Photosynthesis

During photosynthesis carbon dioxide interacts with water and, thanks to the energy of the solar radiation in the PAR and to the presence of chlorophyll, a green pigment, is transformed into organic compounds, mostly glucose, with release of oxygen.



*Based on plant demand of radiation intensity, the plants can be divided into **heliophilous** and **sciaphilous** species.*

Radiation intensity for photosynthesis activity	Heliophilous Specie (tomato, lettuce, cucumber, melon, carnation, tulip, peach, grape)	sciaphilous species (undergrowth plants, cyclamen, begonia, azalea, camellia, oak, juniper, holly)
minimum	2.000 lux	500 lux
mean	10.000 lux	3.800 lux
max	30.000 lux	10.000 lux

Greater values than the maximum values cause a decrease in photosynthetic activity.

In summer, in Bari (south Italy): solar intensity is 100000 lux

Photosynthetically active radiation (PAR) is defined as electromagnetic radiation over the spectral range of 400 nm to 700 nm that photosynthetic organisms are able to use in the process of photosynthesis to fix the carbon in CO_2 into carbohydrates.

*A common unit of measurement for PAR is **photosynthetic photon flux density (PPFD)** [μmol m^{-2} s^{-1}]. In this case, every absorbed photon, regardless of its wavelength (and hence energy), is assumed to contribute equally to the photosynthetic process.*

*The amount of solar radiation necessary for photosynthesis is reported as **PPFD** i.e the number of photons per second between 400 and 700 nm per unit area.*

A radiative source is considered a source that releases energy particles, called photons or quanta. The energy content of a photon is a function of its wavelength.

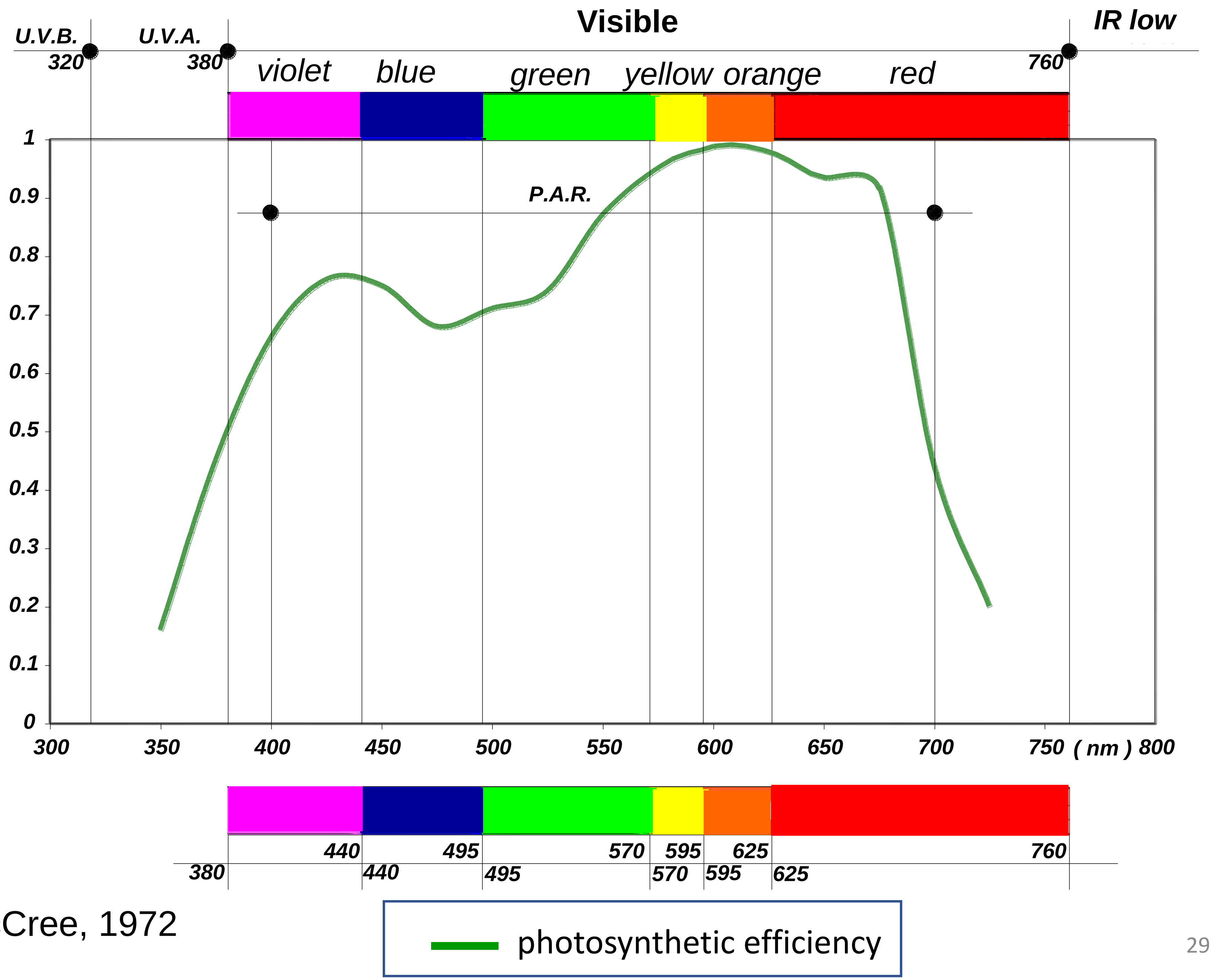
Simplified formula

***PPFD** [μmol m^{-2} s^{-1}] = PAR Solar radiation [W/m^2] * 4.56*

In Summer, in Apulia (south Italy), incident solar radiation = 900 W/m^2

PAR solar radiation (45%) = 400 W/m^2

PPFD= 1824 μmol m^{-2} s^{-1}



Visible
IR low
U.V.B.
U.V.A.
320
380
760
violet
blue
green
yellow orange
red
P.A.R.
1
0.9
0.8
0.7
0.6
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0.3
0.2
0.1
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550
600
650
700
750 (nm) 800
440
495
570
595
625
760
380
440
495
570
595
625
photosynthetic efficiency

McCree, 1972

Photomorphogenesis

The Photomorphogenesis concerns the change in form occurring in response to changes in the radiation environment.

As is expressed by the action of the photoreceptors (phytochrome, cryptochrome, etc.) in response to specific wavelength bands of the spectrum, the sensitivity of plants varies with the radiation wavelength band.

Variations in the ***red*** *(R; 650 - 670 nm),* ***far-red*** *(FR; 720 - 740 nm), and* ***blue*** *(B; 400 - 500 nm) wavelengths in the growing environment affect photomorphogenesis through the activation of photoreceptors such as phytochromes and cryptochromes.*

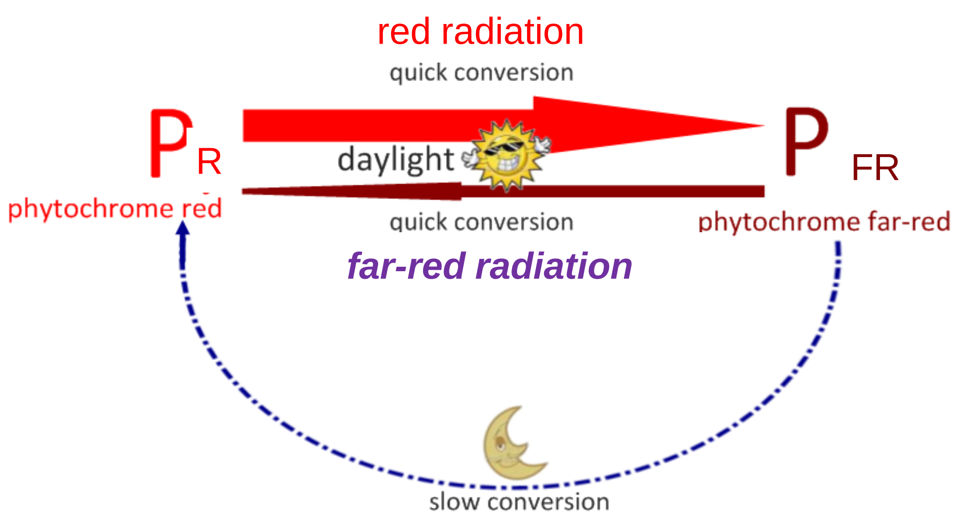
Plants make such adjustments by utilizing a ***blue-green*** *pigment called* ***phytochrome,*** *which exists in two interconvertible forms:* $\boldsymbol{P_R}$, *which absorbs* ***red radiation*** *(R; 660 nm), and* $\boldsymbol{P_{FR}}$, *which absorbs* ***far-red radiation*** *(FR; 730 nm). Each can convert to the other when they absorb radiation.*

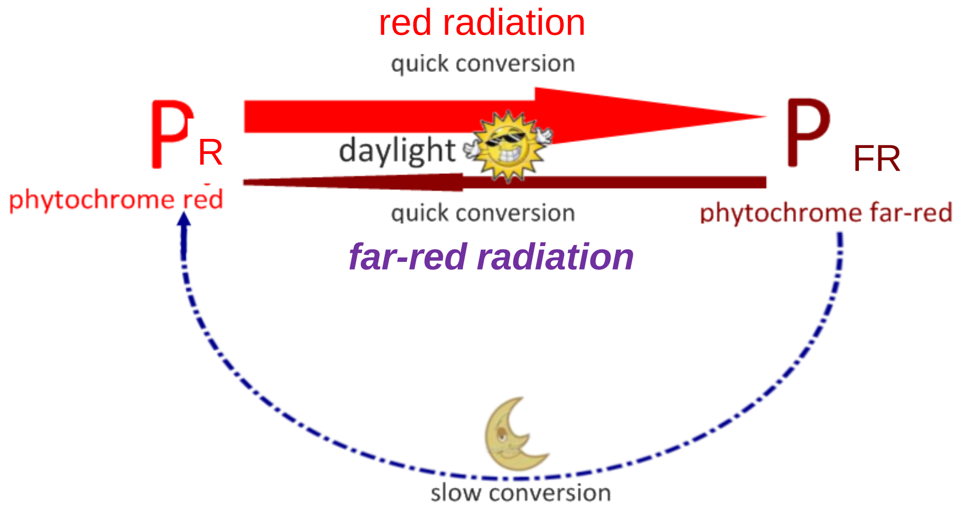
During the day, the two forms convert back and forth (P_R *becomes* P_{FR}*, and vice versa). During the night,* P_{FR} *slowly converts to* P_R *or else disintegrates.* P_R *is stable in the dark.*

Absorption of ***red radiation*** *by* P_R *converts it into* P_{FR}.

Absorption of ***far red radiation*** *by* P_{FR} *converts it into* P_R.

In the dark, P_{FR} *spontaneously converts back to* P_R.

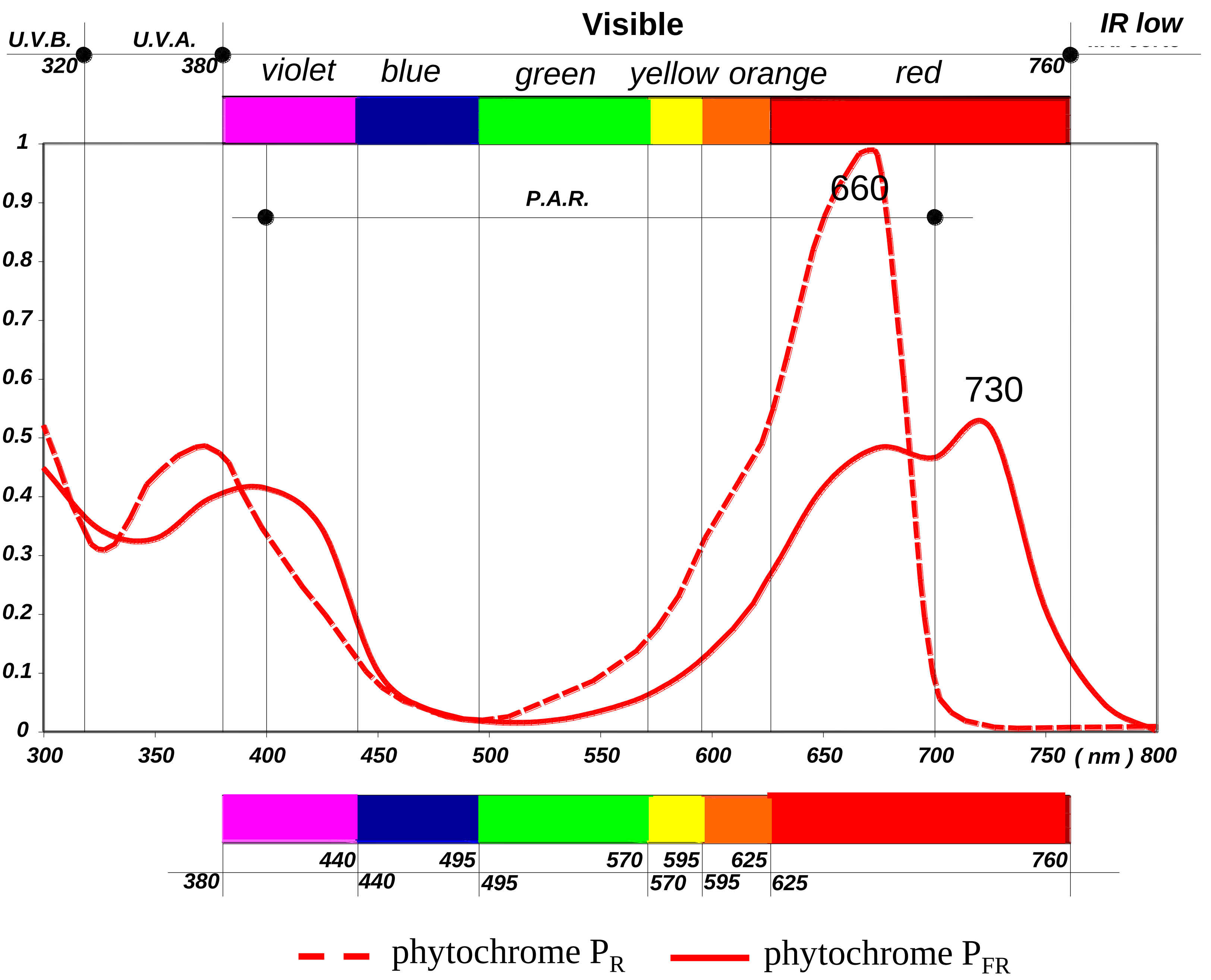




P_{FR} is the biologically active form, acting as the switch that turns on such plant responses as flowering or seed germination.

When the threshold concentration of P_{FR} is attained, the response is stimulated.

Phytochromes regulate different processes through the plant life cycle, including induction of seed germination, seedling deetiolation, flowering time, fruit quality, root elongation, tolerance to biotic and abiotic stressors.


Visible
U.V.B.
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IR low
320
380
760
violet
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yellow orange
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P.A.R.
660
730
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0.9
0.8
0.7
0.6
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650
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750
(nm) 800
440
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595
625
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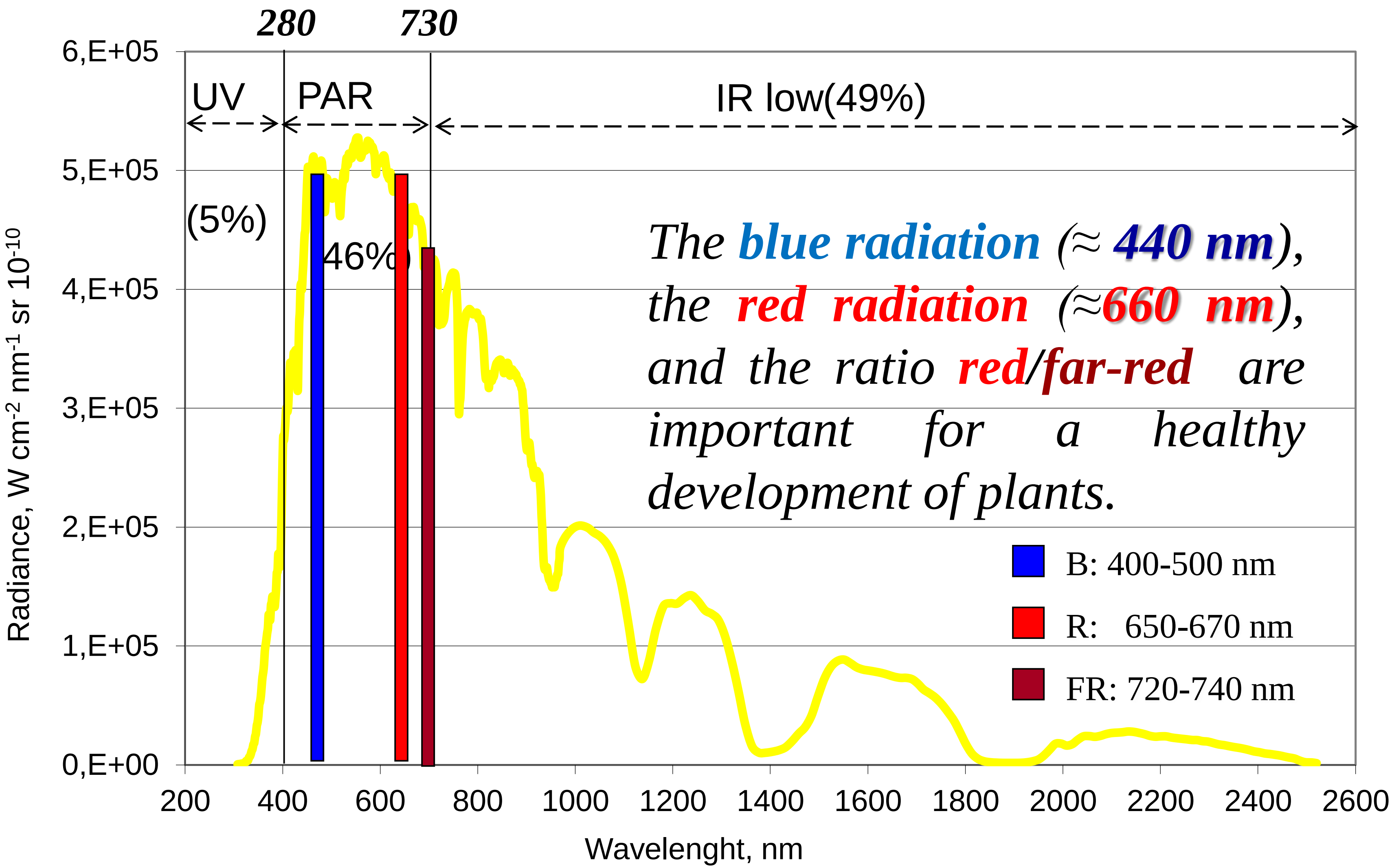
380
440
495
570
595
625
phytochrome P_R
phytochrome P_{FR}

Spectral distribution of incident solar radiation



*The **blue radiation** (≈ **440 nm**), the **red radiation** (≈**660 nm**), and the ratio **red**/**far-red** are important for a healthy development of plants.*

*The **blue radiation** (around 440 nm) is very important for the healthy development of plants.*

*A deficiency of **blue radiation** causes excessive growth of stems and determines the yellowing of leaves.*

*The internodes of plants will be reduced in length if radiation in the **blue wavelengths** is excessive.*

*The **ratio red / far-red** has its importance in the development of plant species.*

*A low level of **far-red** prevents the growth of the stems. Internodes will elongate if there is an excess of **far-red**.*

*Thus a balance between **blue** and **far-red** in the spectrum is required for some plants.*


< R/FR

PHOTOTROPISM

Plants have developed a number of strategies to capture the maximum amount of solar radiation through their leaves. Phototropism studies the influence of solar radiation on the curvature of the leaves, branches and roots of plants.

Phototropism depends on auxins – plant growth hormones - that, strongly influenced by the radiation, exert their action causing the curvature of the stem to the illuminated areas.

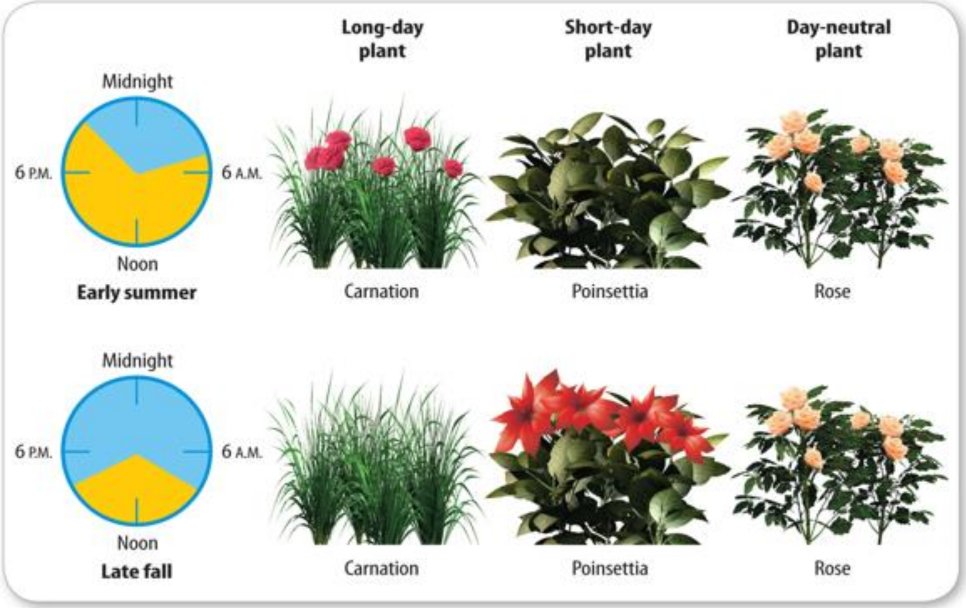
When solar radiation is shined on one side of a plant, the auxins move to the dark side of the plant. The hormones stimulate the cells on the dark side of the plant to elongate, while the cells on the radiation side of the plant remain the same.

This elongation on one side and staying the same on the other causes the plant to bend in the direction of the solar radiation. This bending allows more radiation to reach more cells on the plant that are responsible for conducting photosynthesis.

Photoperiodism

The term "photoperiodism" describes the plant's ability to response to changes in lengths of day and night.

Plant growth and development processes that are affected by photoperiod include flowering, vegetative growth, internode elongation, tuber, rhizome and bulb formation, sex expression, the formation of pigments such as anthocyanin, the number and size of root nodules, fruit set, leaf fall and dormancy.



Plants can be described in relation to their photoperiod responses as:

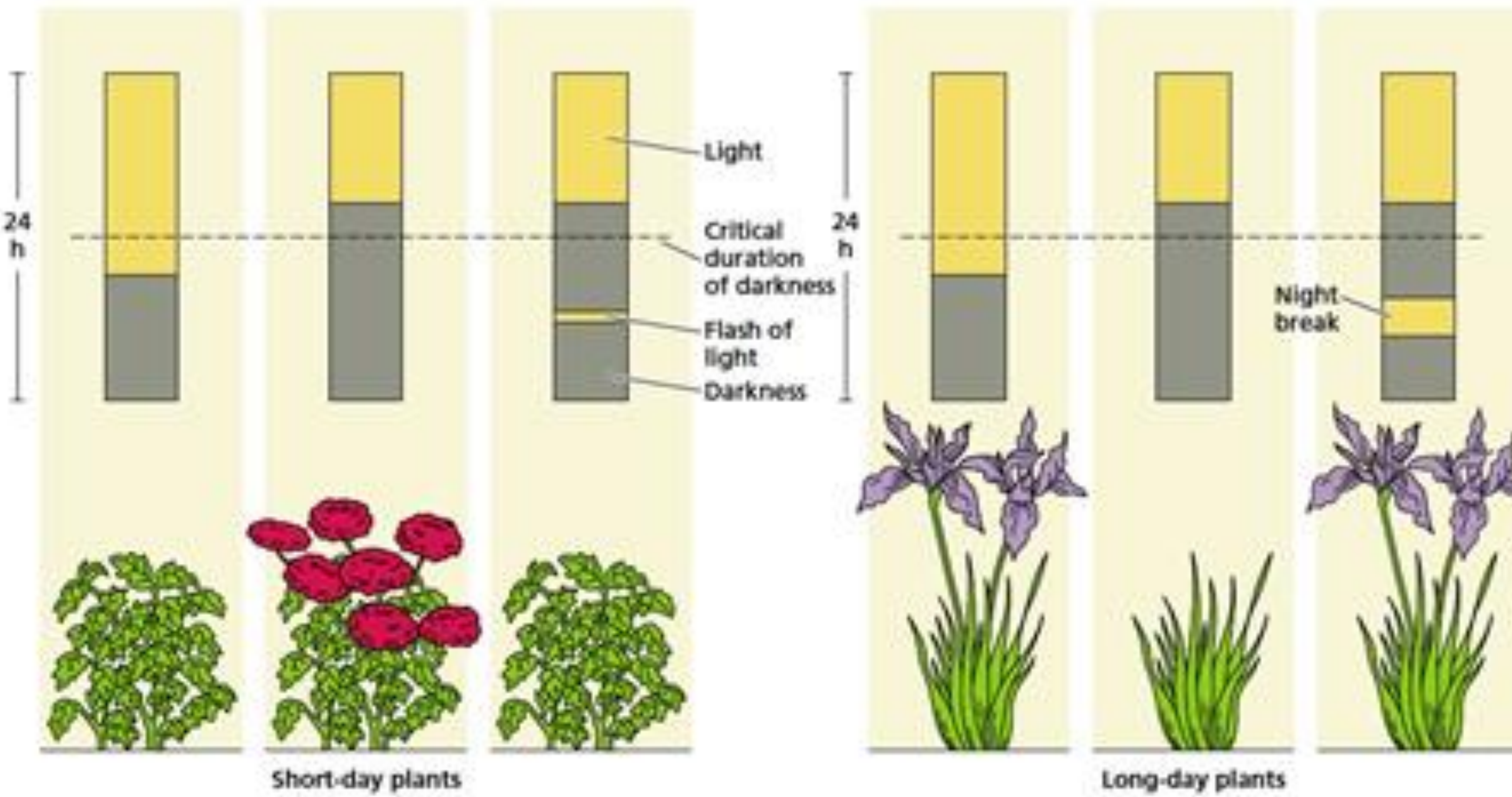
- ***Long-day plants:*** *summer flowering plants that have a critical period of radiation exposure longer than 12 -14h/d.*
  sugar beet (Beta vulgaris), raddish (Raphanus sativus), spinach (Spinacea oleracea), spring wheat (Triticum aestivum);

- ***Short-day Plants:*** *plants that flower in late summer and fall; they have a critical period of radiation exposure of less than about 12-14h/d .*
  chrysanthemum (Chrysanthemum sp.), poinsettia (Euphorbia pulcherrima), soybean (Glycine max);

- ***Day-neutral plants:*** *plants that flower in photoperiods of any length*
  sunflower (Helianthus annuus), common bean (Phaseolus vulgaris), garden pea (Pisum sativum), and corn (Zea mays);

- ***Intermediate-day plants:*** *plants that flower only in periods neither too long nor too short for the particular plant*

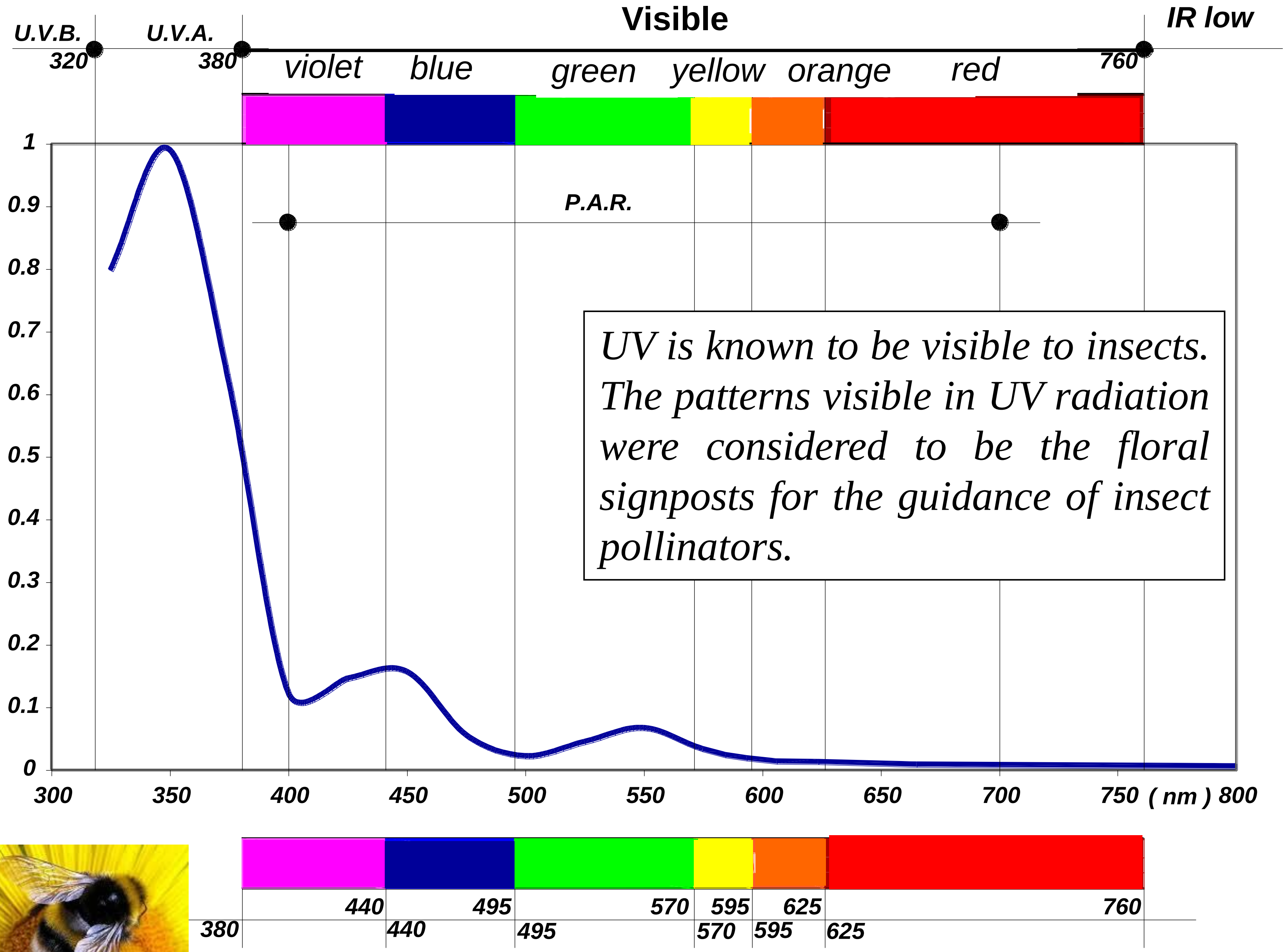
Photoperiodic regulation of flowering.



The short-day plants bloom when the length of the night is greater than a critical period of darkness. The interruption of the night period with a flash of radiation (night interruption) prevents flowering.

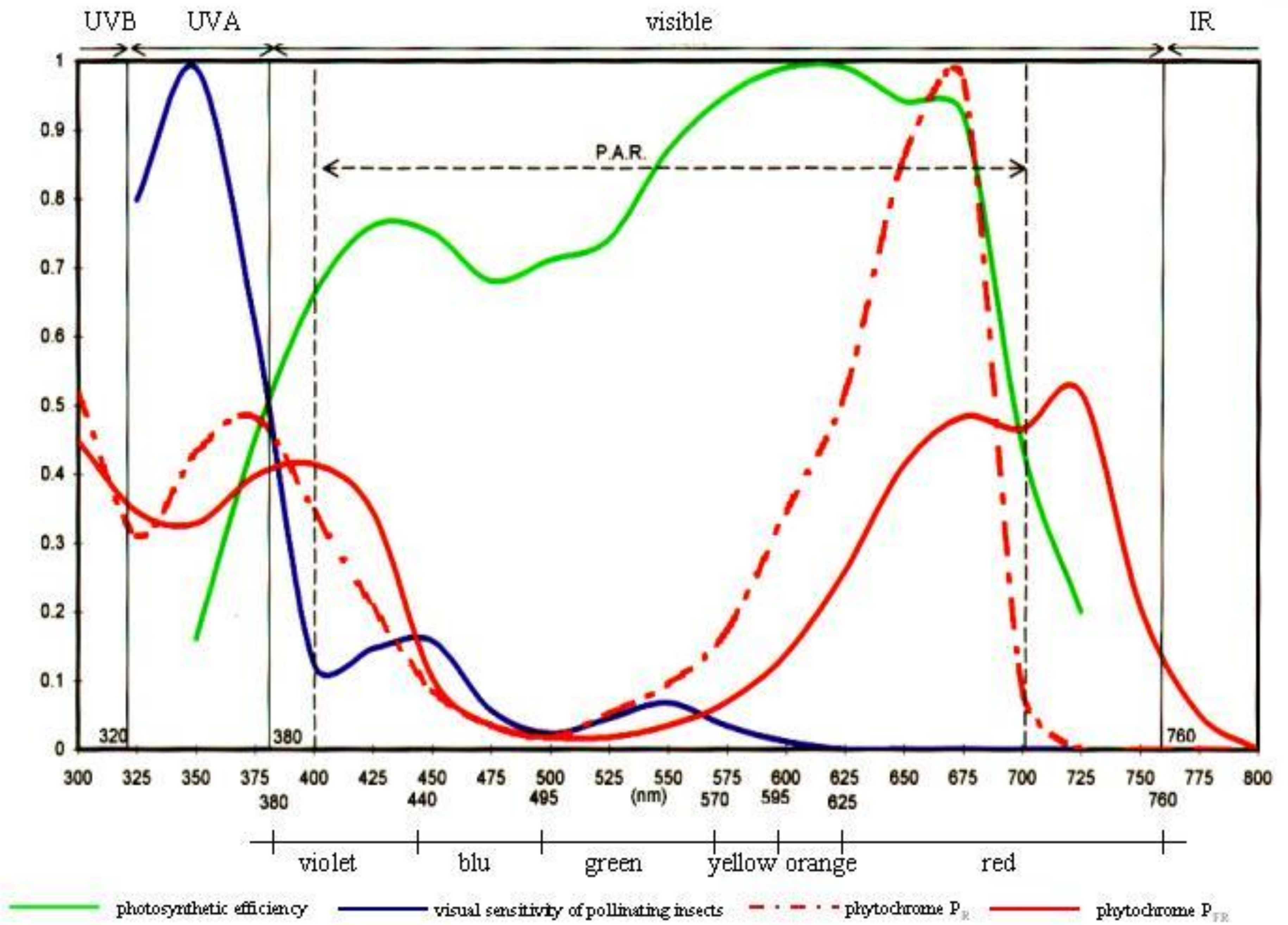
The long-day plants bloom when the duration of the night period is more short of a particular critical period. In some long-day plants the shortening of the night period with a flash of radiation induces flowering.

UV and pollinating insects



UV is known to be visible to insects. The patterns visible in UV radiation were considered to be the floral signposts for the guidance of insect pollinators.

Visual sensitivity of pollinating insects



UVB
UVA
visible
IR
P.A.R.
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
320
380
760
300 325 350 375 400 425 450 475 500 525 550 575 600 625 650 675 700 725 750 775 800
380 440 495 (nm) 570 595 625 760
violet
blu
green
yellow
orange
red
photosynthetic efficiency
visual sensitivity of pollinating insects
phytochrome P_R
phytochrome P_{FR}

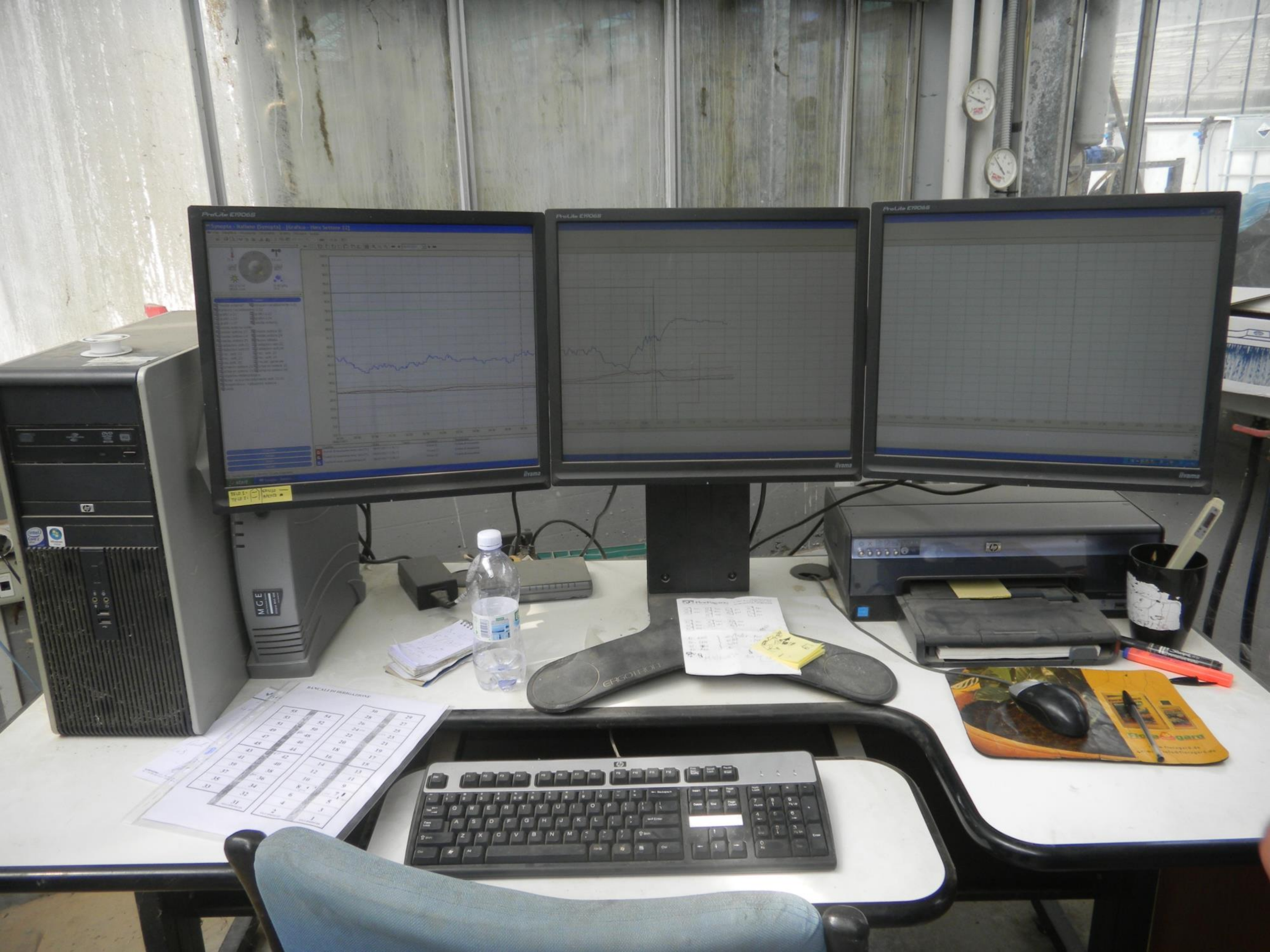
		EFFECTS OF RADIATION		
	Wavelength [nm]	***Photosynthesis***	***Photomorphogenesis***	***Thermal effect***
UV	***280-320***	***Insignificant***	***Negligible***	***Insignificant***
PAR	***400-700***	***Significative***	***Significative***	***Significative***
IR short	***750-2500***	***Insignificant***	***Significative***	***Significative***
LWIR	***2500-25000***	***Insignificant***	***Insignificant***	***Significative***

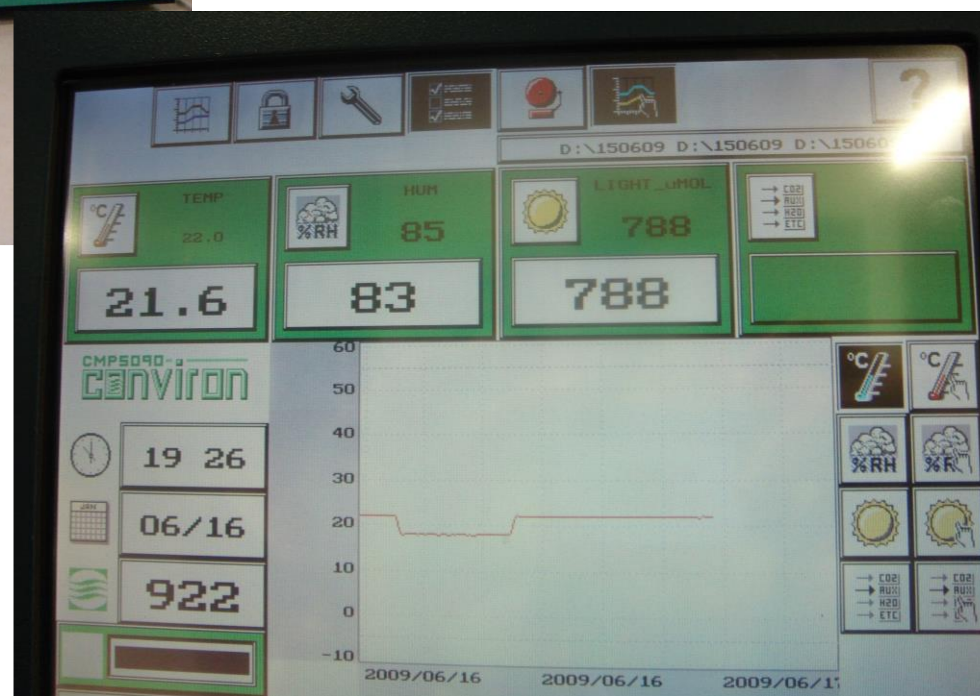
Low irradiance levels *on most plants lead to:*

- ➢ *smaller leaves with a greater length-to-width ratio;*
- ➢ *elongation of internodes;*
- ➢ *reduced concentration of chlorophyll;*
- ➢ *less dry weight at particular stages of maturity.*

***High irradiance levels** on most plants lead to:*

- *stimulation of auxiliary branch growth*
- *proliferation of growing points*
- *possible photodestruction of chlorophyll*
- *stress symptoms attributed to spectral radiation excesses*
- *significant heating of leaves, desiccation and eventual necrosis*


ProLite E1906S
iiyama
MGE


D:\150609 D:\150609 D:\15060
TEMP
22.0
21.6
HUM
85
83
LIGHT_uMOL
788
788
CO2
AUX
H2O
ETC
CMP5090
conviron
19 26
06/16
922
2009/06/16
2009/06/16

RADIATION MEASUREMENTS

*The **radiometric measurements** measure radiant energy associated with a radiation. Radiometry is the science of the measurement of electromagnetic radiation in any portion of the spectrum. The units of measurement are: W, Wm^{-2}, $Wm^{-2}nm^{-1}sr^{-1}$, kLy (1kLy = 1kcal/cm^2 =41860 kJ/m^2).*

*The **photometric measurements** represent the brightness of the radiation to the human eye. Photometry concerns the quantification of radiation sources and lighting conditions in numbers directly related to the perception of the human eye. Photometry is the science of measuring radiant energy such as light according to the sensitivity of the human eye. Photometric quantities are restricted to the visible range from 380 to 780 nm. The units of measurement are: lumen [lm], candle [cd] (1 cd = 1 lm sr^{-1}), lux (1 lux = 1 lm m^{-2}).*

Radiometry includes the entire radiation spectrum, while photometry is limited to the visible spectrum as defined by the response of the human eye.

The photometric measurement depends on how the source appears to the human eye. This means that the variation of eye response with wavelength, and the spectrum of the radiation, determines the photometric value. Invisible sources have no luminance, so a very intense ultraviolet or infrared source registers no reading on a photometer.

The conversion of radiometric quantities in photometric quantities, and vice versa, is not simple and immediate, because the radiation can affect a wide range of wavelengths while the brightness can be defined only from 380 to 760 nm.

Approximately, a conversion factor for the solar radiation in the PAR: 1 lux ~ 236 Wm^{-2}

Corresponding radiometric and photometric quantitites. The radiometric quantities, on the left, are shown with their usual symbols and SI units of measure. When integrated spectrally using $V(\lambda)$ weighting, one obtains the photometric counterpart, on the right

Radiometric quantity	Symbol	Unit	Unit	Symbol	Photometric quantity
Radiant energy	Q	J	lm s	Q_v	Luminous energy
Radiant flux (power)	P, Φ	W	lm	Φ_v	Luminous flux
Irradiance	E	W/m^2	$lm/m^2=lx$	E_v	Illuminance
Radiance	L	$W/(m^2\ sr)$	$lm/(m^2\ sr)$	L_v	Luminance
Radiant intensity	I	W/sr	lm/sr=cd	I_v	Luminous intensity

The table provides a listing of photometric quantities and their radiometric counterparts. Every quantity in the photometric system has an analogous quantity in the radiometric system.

Some examples of parallel quantities include:

- *Luminance (photometric) and radiance (radiometric)*
- *Luminous flux (photometric) and radiant flux (radiometric)*
- *Luminous intensity (photometric) and radiant intensity (radiometric)*

Concerning greenhouse cultivation, ***solar radiation may be measured in terms of its intensity (lux) or in terms of the number of photons reaching a surface (photon flux density).***

The metric unit of visible light intensity is the lumen and the term ***lux refers to the number of lumens per square metre of surface area****. A footcandle is roughly equivalent to 10 lux.*

In horticulture we are more interested in the number of photons reaching a surface. Photons are basically packets of energy which make up a stream of radiation. The number of photons trapped by a leaf determines the level of photosynthesis and therefore the amount of plant growth.

Photon flux density is measured as mol $m^{-2}s^{-1}$ *or moles per square metre per second. For convenience, since a mol is a very large number, photon density is usually measured in micromoles per square metre per second (μ mol).*

Radiant Flux (Φ) *is the amount of radiant energy emitted, transmitted, or received per unit time that is in wavelengths from 0.01 to 1000 μm and includes the regions of the electromagnetic spectrum commonly referred to as Ultra Violet (UV), Visible, and Infra Red (IR).*

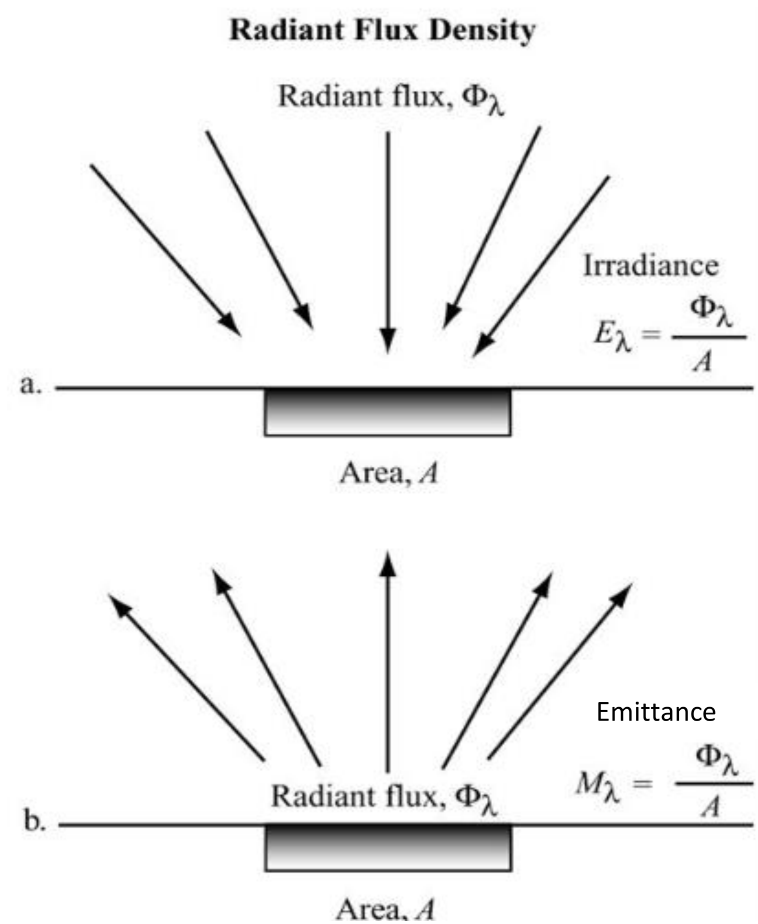
The flux is measured in units of Joules per second (J/s), or Watts (W).

A radiant flux of 1 W means that a source produces 1 Joule every second.

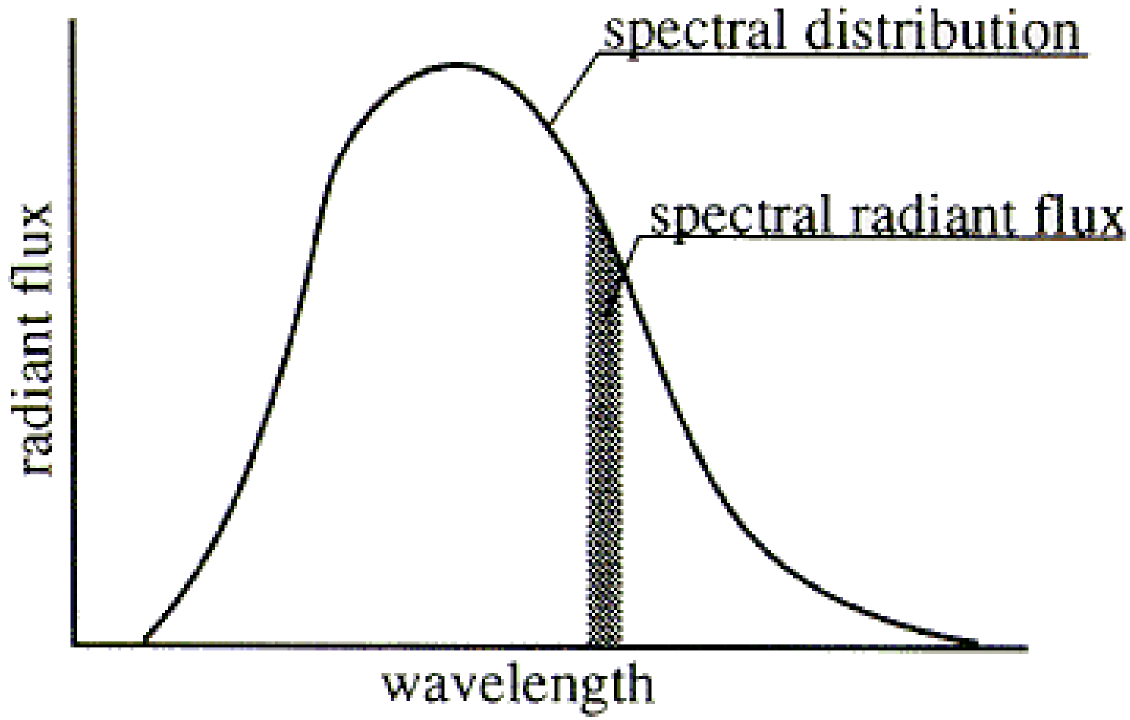
If we integrate radiant flux over time we obtain the total Energy (Q) output by the source.

*The **radiant flux density** is the amount of radiant flux crossing a unit of area, and is measured in W m^{-2}.*

- ***Irradiance** is radiant flux density incident on a surface from all directions above the surface (Wm^{-2}) e.g. Solar radiation arriving at surface*
- ***Emittance** (radiance or radiant exitance) (Wm^{-2}) is radiant flux density emitted by a surface into all directions above the surface*



Spectral radiant flux density *(W $m^{-2}\mu m^{-1}$): radiant flux density per unit of wavelength interval.*



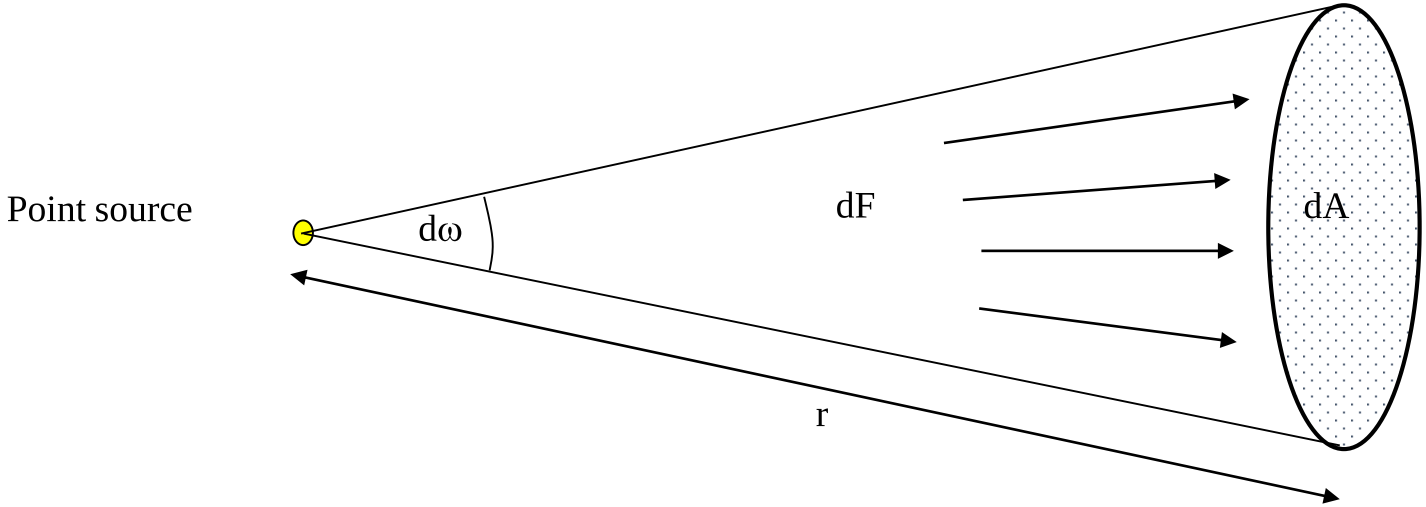
Radiant intensity (I)*: the radiant energy that is emitted by a source per unit time per unit solid angle in a given direction; it is measured in units of watts per steradian (Wsr^{-1}). This is a directional quantity.*

Consider flux dF emitted from point source into solid angle $d\omega$, where dF and $d\omega$ are very small

***Intensity** (I) is defined as flux per unit solid angle :*

$$I = dF/d\omega \, (Wsr^{-1})$$

Solid angle : $d\omega = dA/r^2$ *(steradians, sr)*



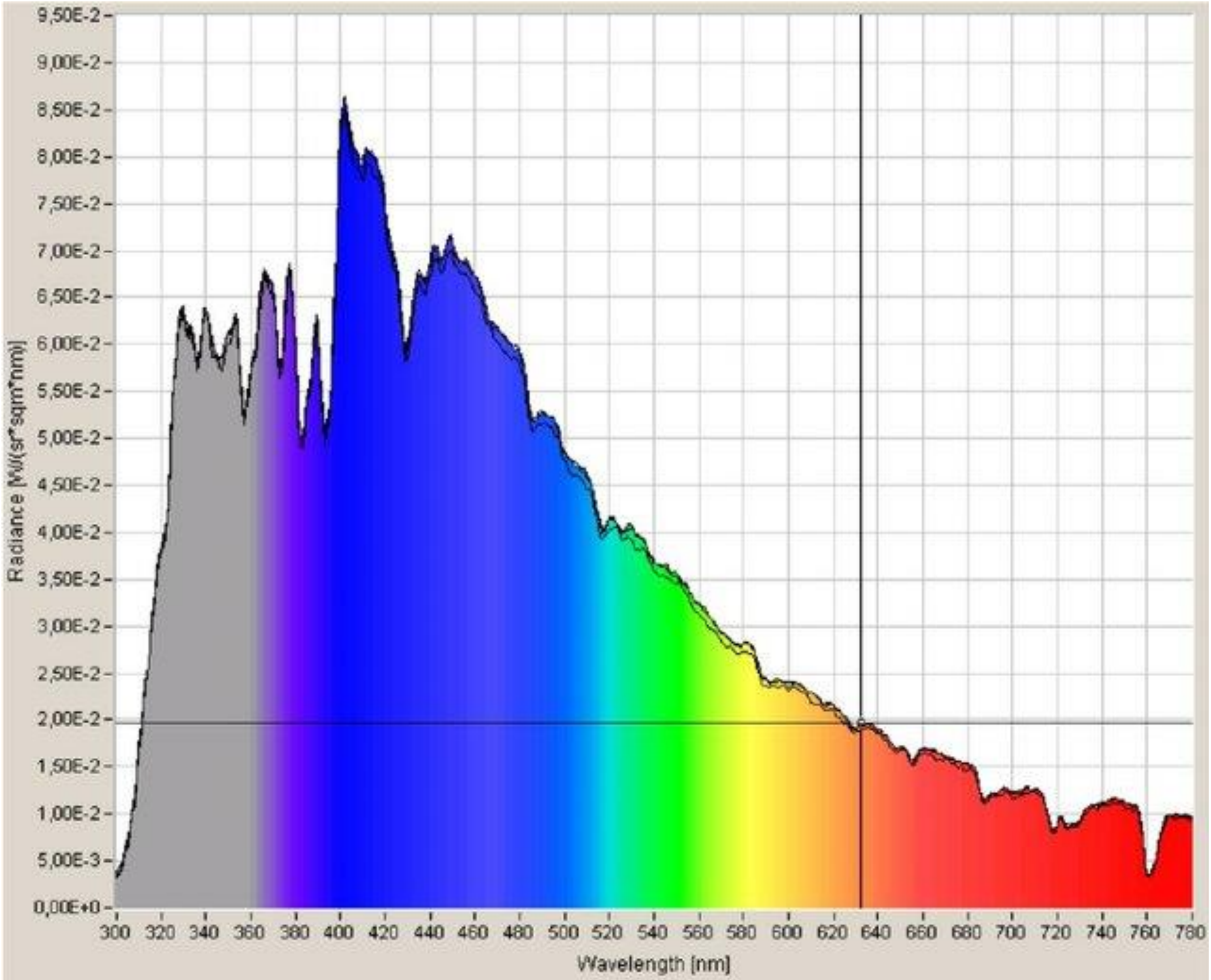
Radiance (L_λ) *is the radiant flux emitted, reflected, transmitted or received by a surface, per unit solid angle leaving an extended source in a given direction per unit projected source area in that direction. It is a directional quantity.*

It is measured in watts per meter squared per steradian ($Wm^{-2}sr^{-1}$)

It is necessary to extend the concept of radiance so that it not only covers the distribution of radiant power with respect to position and direction, but also with respect to wavelength.

Spectral radiance *is the spectral distribution of radiance. It is a directional quantity. It is measured in: $W \cdot sr^{-1} \cdot m^{-2} \cdot Hz^{-1}$*

Spectral radiance, like radiance, is defined at a point on a surface in the direction of a ray trough that point.



Spectral radiance distribution of the solar radiation.

It is characterized by high values in the low wavelengths and low values in the long wavelengths

Spectral Radiance, Spectral Irradiance, and Spectral Radiant Flux are terms that characterize radiation within a certain wavelength band (UV, VIS and/or IR).

It is also common to consider those values for unit wavelength (per nm) in the spectrum.

Spectral radiance is a key measure when selecting a source for an application. In general, most radiation sources exhibit variations in spectral radiance across their spectrum of emission.

… in brief...

Radiant flux *(W): the amount of radiant energy emitted, transmitted, or received per unit time.*

Radiant flux density *(Wm^{-2}): radiant flux per unit area*

Irradiance *(Wm^{-2}): radiant flux density incident on a surface*

Radiant spectral flux density *($W\ m^{-2}\mu m^{-1}$): radiant flux density per unit of wavelength interval.*

Radiant intensity *(Wsr^{-1}): flux emanating from a surface per unit solid angle.*

Radiance *($Wm^{-2}sr^{-1}$): radiant flux density emanating from a surface per unit solid angle*

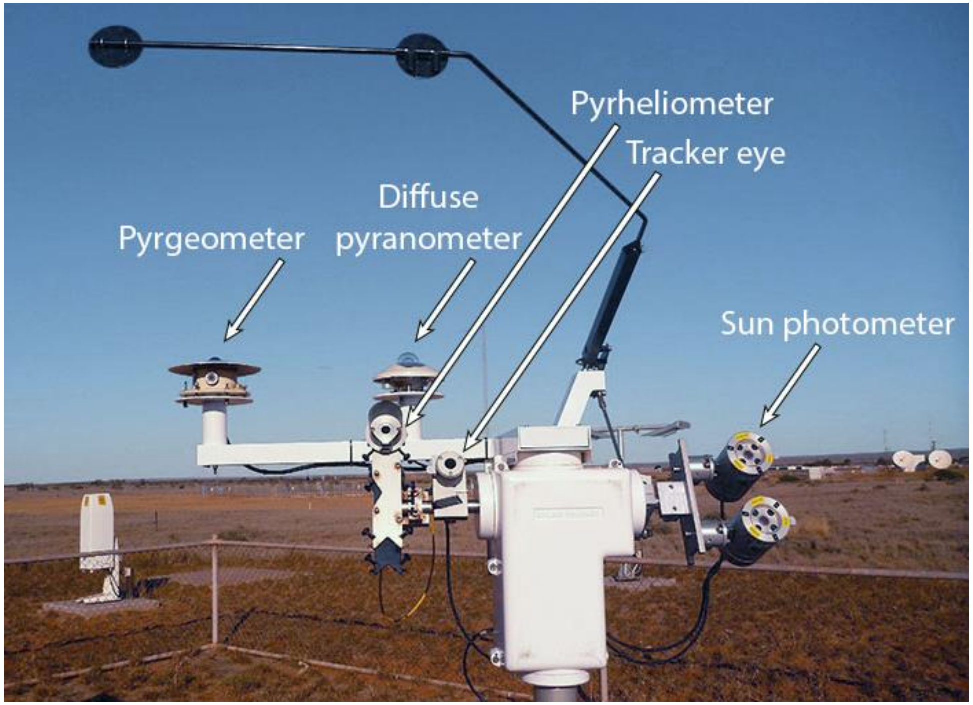
Spectral radiance *($Wm^{-2}sr^{-1}\mu m^{-1}$): radiance per unit wavelength interval.*

Radiant emittance *(Wm^{-2}): radiant flux density emitted by a surface.*

Solar radiation sensors

The solar radiation sensors can be:

- *Pyranometers*
- *Pyrgeometers*
- *Net radiometers*
- *Quantum sensors*
- *Albedometers*
- *Pyrheliometers*



The solar radiation sensors measure various aspects of the energy imparted by the sun on the Earth's surface.

A leveling fixture fitted with a bubble level may be required to accurately install solar radiation sensors.

Pyranometer

Pyranometer is an instrument for measuring the solar irradiance.

The thermopile sensor construction ***measures the solar energy that is received from the total solar spectrum and the whole hemisphere*** *(180 degrees field of view). The output is expressed in Watts per meter square.*

Pyranometer can be used under all weather conditions and it is easy to use. The pyranometer is designed for continuous indoor and outdoor use.

It is ideal for measuring available energy for use in solar energy applications, plant growth, thermal convection and evapotranspiration.

.

It uses a photodiode detector, which creates a voltage output that is proportional to the incoming radiation.

Also due to the unique design of the diffuser, its sensitivity is proportional to the cosine of the angle of incidence of the incoming radiation, allowing for accurate and consistent measurements.

It can be directly connected to voltmeter or data logger.

Direct readout in Watts per square meter (W/m²) can be derived from the measured voltage divided by the calibration coefficient.

Pygeometers

Pyrgeometers measures near-surface infra-red radiation spectrum in the wavelength spectrum approximately from 4.5 µm to 100 µm.

Pyrgeometers are used to measure "downward and upward longwave irradiance". Longwave radiation is the part of radiation that is not emitted by the sun.

Pyrgeometers are suitable for day-and-night longwave irradiance measurements in meteorological applications.

Long-wave radiations are emitted by all objects existing on the Earth. However, the main purpose of a pyrgeometer is to perform meteorological observation of atmospheric radiation and the net radiation from between the earth and the atmosphere.

A screw-in mounting rod and bracket are available for easy installation to a mast or wall. The small size and sealed construction make this instrument the ideal choice for horticulture and agriculture.

The pyrgeometer is operated based on the principle that radiant energy is converted into heat energy, which can be measured by a thermopile.

Pyrgeometers have a silicon window with a solar blind filter coating on the inside to block all short-wave solar radiation.

An internal temperature sensor is fitted to enable calculation of the downward long wave radiation.

Net Radiometer

Net Radiometer measures net radiation which is the balance between incoming and outgoing radiation under outdoor conditions.

The double-sided detector has black conical absorbers with an anti-stick weather resistant protective coating. The vertical stick prevents birds from affecting the output signal.

It is easy to use. It is based on a thermopile sensor. The voltage is proportional to the net radiation. It can be directly connected to voltmeter or data logger with an mV input.

The net radiometer consists of a pyranometer and pyrgeometer pair that faces upward and a complementary pair that faces downward. The pyranometer pair measures the short-wave radiation and the pyrgeometer pair measures long-wave radiation.

Net radiometers are sensors for measuring net radiation, i.e. the balance between the incoming sun and sky radiation and the ground-reflected short-wave and ground-emitted long-wave radiation.

All 4 sensors are integrated directly into the instrument body, instead of separate modules mounted onto the housing. But are each calibrated individually for optimal accuracy.

Quantum sensor

Quantum sensor measures Photosynthetically Active Radiation (PAR).

The Photosynthetically Active Radiation (PAR) can be measured in energy units (watts m^{-2}*) or as Photosynthetic Photon Flux Density (PPFD), which has units of quanta (photons) per unit time per unit surface area.*

The units most commonly used are micromoles of quanta per second per square meter ($\mu mol\ s^{-1}\ m^{-2}$*).*

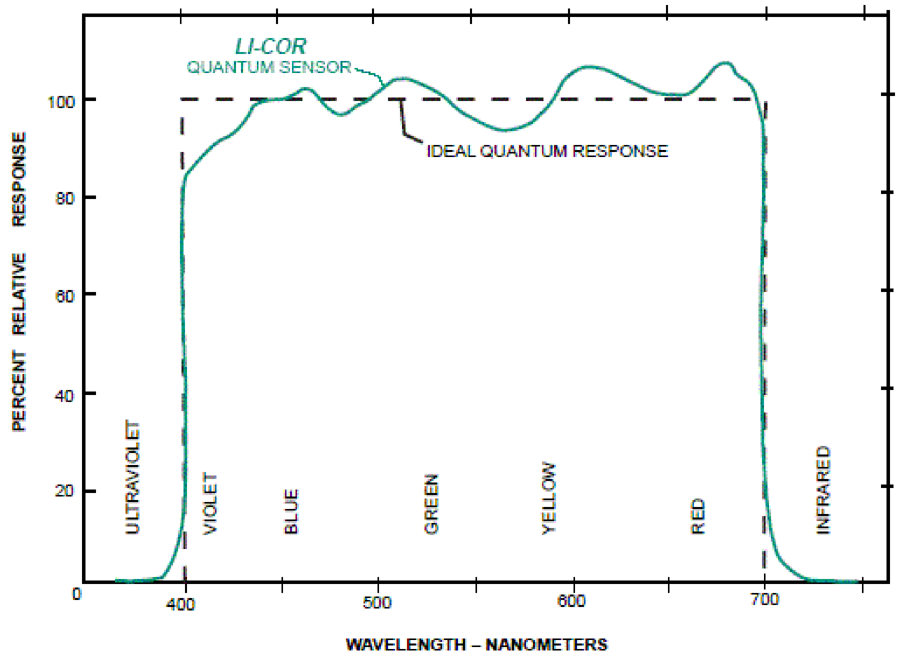
Quantum sensor measures photosynthetic photon flux density (PPFD, in μmol of photons m^{-2} s^{-1}), which is the number of photons in the 400 to 700 nm waveband incident per unit time on a unit surface.

It uses a silicon photovoltaic detector mounted in a cosine-corrected head. A shunt resistor in the sensor's cable converts the signal from microamps to millivolts, allowing these sensors to be measured directly by a datalogger.

It provides accurate measurements—in the open, in greenhouses, under plant canopies, or in growth chambers—for most broad-spectrum radiation sources, including natural sunlight, artificial, or mixed sources.

Quantum meter with Handheld Meter

Spectral sensitivity of a quantum sensor



Albedometers

Albedometers are instruments that measure global and reflected solar radiation, and the solar albedo.

An albedometer is composed of two pyranometers with thermopile sensors; the upfacing one measuring global solar radiation, the downfacing one measuring reflected solar radiation.

Albedo, also called solar reflectance, is defined as the ratio of the reflected radiation to the global radiation.

The solar albedo depends on the directional distribution of incoming radiation and on surface properties at ground level.

This results in a scale from 0 (no reflection) to 1 (total reflection).

Albedos of typical surfaces:

0,04 for asphalt

0,15 for green grass

0,5 for dry sand

0,9 for fresh snow.

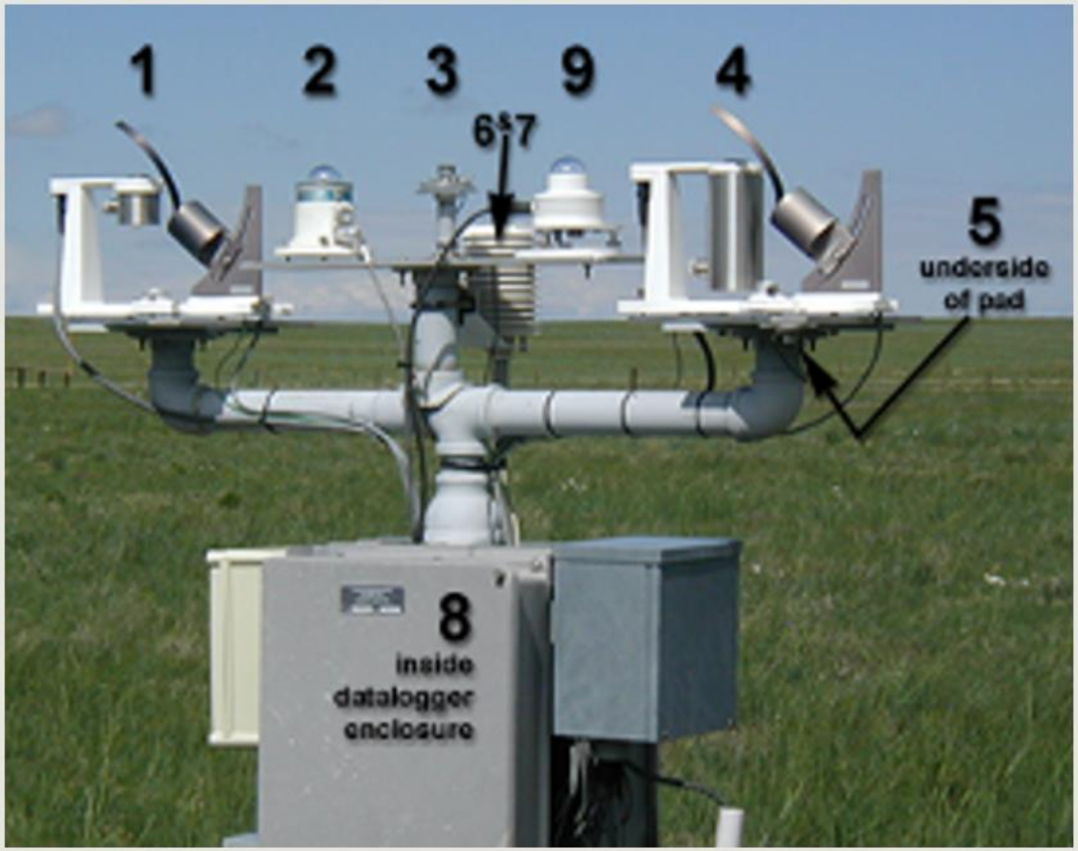
Pyrheliometer

A pyrheliometer is an instrument designed specifically to measure the direct beam solar irradiance with a field of view limited to 5°, also known as direct normal incidence.

This is achieved by the shape of the collimation tube, with precision apertures, and the detector design. The front aperture is fitted with a quartz window to protect the instrument and to act as a filter that passes solar radiation between 200 nm and 4000 nm in wavelength.

It is used with a solar tracking system to keep the instruments aimed at the sun.

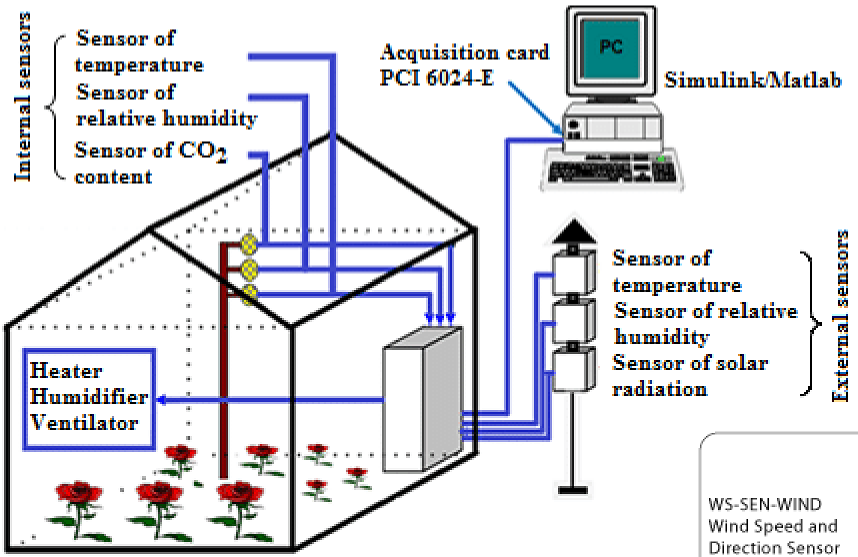
Monitoring Network Instrumentation

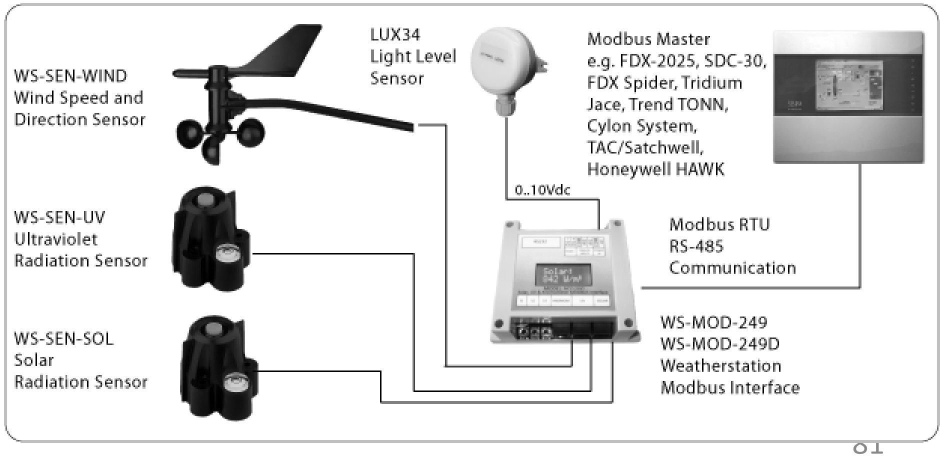


Detailed Instrument Information

4	Ultraviolet Multifilter Rotating Shadowband Radiometer
3	Photosynthetically Active Radiation Sensor
2	Broadband UVB-1 Pyranometer
1	Visible Multifilter Rotating Shadowband Radiometer
6 & 7	Air Temperature and Relative Humidity Sensor
8	Barometric Pressure Sensor
5	Downward Looking Photometer
9	UV-A biometer


apogee
INSTRUMENTS


Internal sensors
Sensor of temperature
Sensor of relative humidity
Sensor of CO_2 content
Acquisition card PCI 6024-E
PC
Simulink/Matlab
Sensor of temperature
Sensor of relative humidity
Sensor of solar radiation
External sensors
Heater
Humidifier
Ventilator


WS-SEN-WIND
Wind Speed and
Direction Sensor
LUX34
Light Level
Sensor
Modbus Master
e.g. FDX-2025, SDC-30,
FDX Spider, Tridium
Jace, Trend TONN,
Cylon System,
TAC/Satchwell,
Honeywell HAWK
0..10Vdc
WS-SEN-UV
Ultraviolet
Radiation Sensor
Modbus RTU
RS-485
Communication
WS-SEN-SOL
Solar
Radiation Sensor
WS-MOD-249
WS-MOD-249D
Weatherstation
Modbus Interface


grow

The amount of solar radiation entering a greenhouse is influenced by the:

- *orientation of the structure*
- *materials used in construction and covers*
- *shape of the roof.*

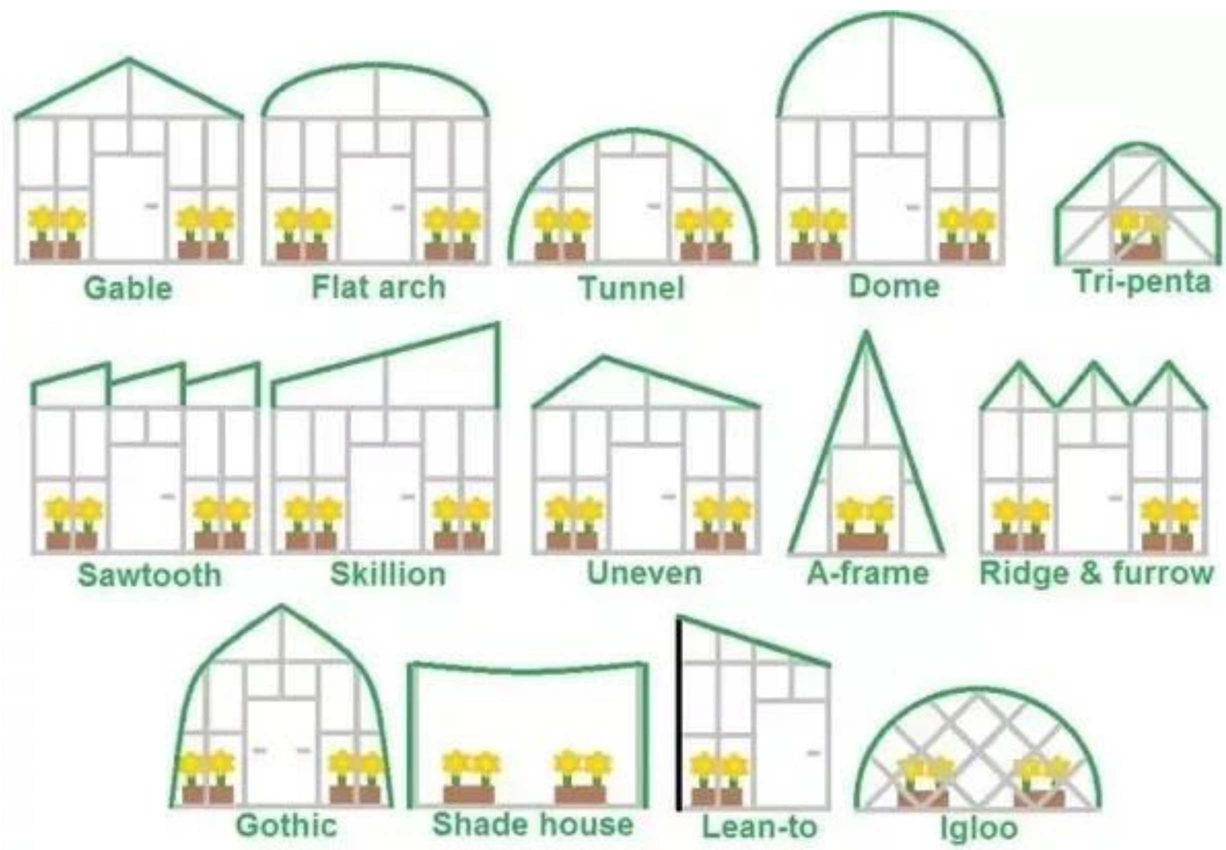
The greenhouse should be positioned north-south to provide more uniform solar radiation and reduce the shading effect of the support structure. The support structure must also be minimised to avoid shading.

Metals make good structural material because of their strength which means narrower trusses and purlins can be used. A typical greenhouse frame can reduce solar radiation transmission by more than 10%.

The type of covering material will also influence the level of solar radiation in the greenhouse.

Finally the shape of the roof will impact on how much solar radiation enters the greenhouse.

For example, a flat roof will limit the amount of solar radiation while a curved roof provides the greatest annual solar radiation transmission.



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