Why can we see visible light?

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Abstract. Visible light only constitutes a very narrow part of the wide electromagnetic spectrum. This article outlines several reasons why the human eye can see only within this limited range. Solar emissions and low absorption in the atmosphere are determining causes, but not the only ones. The energy of chemical bonds, the optical properties of matter, black body emissions and the wave character of light cause further limitations, all of which have a remarkable congruence.

Since the end of the 19th century, we have known that visible light[1] forms part of electromagnetic radiation. The wave equation for both an electric and magnetic field could be deduced from the Maxwell equation, and the existence of electromagnetic waves was demonstrated experimentally by Heinrich Hertz in 1888.
The frequency scale of electromagnetic waves covers a tremendous 25 orders of magnitude, from radio waves to cosmic radiation. However, visible light covers only a very small part of the scale. The ratio of the frequencies of violet and red light is only about two. Upon considering this, a fundamental question arises: “Why is it that the human eye (and in fact any other animal eye) can discern only this range of electromagnetic radiation? Is it merely accidental, or are there any serious reasons for this?” In this article we aim to demonstrate that there is no chance for any other range of visible light but the existing one.

Solar Radiation

The answer to why visible light is what we can see may be very simply stated: these wavelengths are mostly emitted by the sun. In figure 1 we observe the spectrum of solar radiation. Its maximum value approximately corresponds with the middle of the visible spectrum, and one may assume that evolution could have created light sensors perfected for this range of electromagnetic radiation.

[1] In this article, visible light means the range of electromagnetic radiation having a wavelength from 390 nm to 750nm.

Why do we see the visible light?

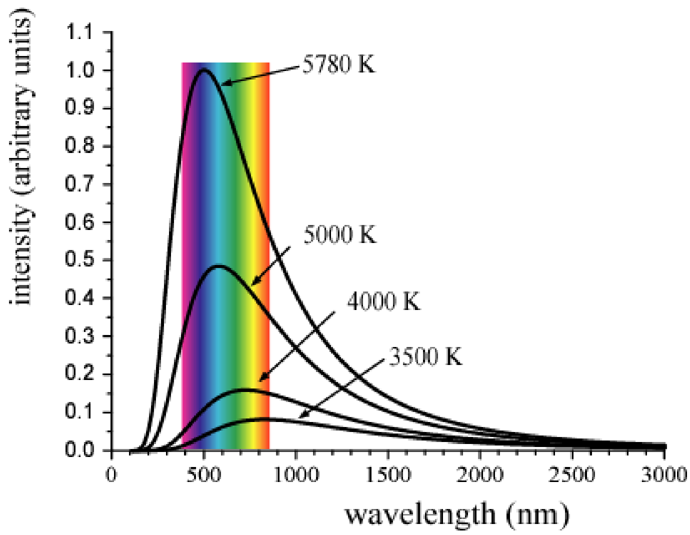

Figure 1: Spectral distribution of black body radiation for different temperatures including the surface temperature of the Sun, 5780K. The visible light range is denoted by the colored band.

Absorption in the Earth's atmosphere

Solar emissions in a particular section of the electromagnetic spectrum are not the only conditions that must be met to ensure a sufficient amount of light on the Earth's surface. The radiation has to go through the Earth's atmosphere, which means that the absorption of visible light must be low. Such is actually the case. The absorption coefficient of the atmosphere is depicted in figure. 2. One can see the "window" in the visible region and larger absorption in both ultraviolet and infrared.
The absorption of electromagnetic radiation in ranges close to visible light could be carried out through two different mechanisms.

1. Mechanical oscillations of molecules. This is true for the infrared region with wavelengths of about 10μm. The absorption by carbon dioxide at 4.26 μm and 15.00 μm would be an example.
2. Changes in the energy state of an electron, or some changes in chemical bonds. This happens in the visible and ultraviolet regions. For example, both creation and annihilation of ozone molecules are caused by the absorption of ultraviolet.

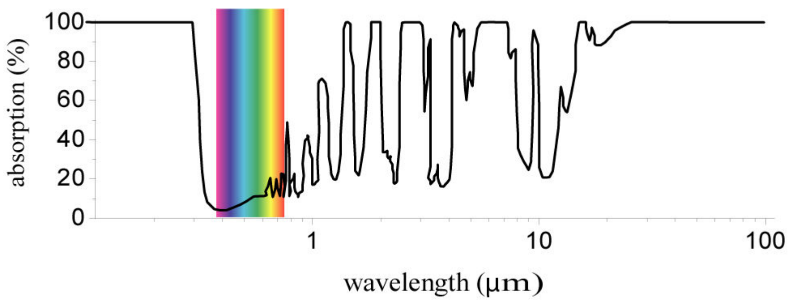

Figure. 2: Absorption of electromagnetic radiation in the Earth's atmosphere.

Why do we see the visible light?

It is interesting to note that absorption at both extremes of visible light is connected with two serious environmental problems. Absorption by ozone molecules protects the biosphere from ultraviolet radiation, and the potential destruction of the ozone layer could represent a grave threat for life on Earth. On the other side of the electromagnetic spectrum, the absorption of infrared radiation by CO_2 molecules can boost the greenhouse effect, leading to serious global climate changes.

We might conceivably conclude our argument at this point, since the reason for the establishment of the visible light range is clear: this radiation has its highest intensity at the surface of our planet. No other points seem necessary. Yet surprisingly, there are still other arguments which may be presented.

Two reasons why we cannot see in the far ultraviolet region

A) Photon detection is impossible

The whole human body is based on chemical bonds, and physiological processes are based on chemical reactions. The same is true for the detection of light at the retina of the eye, where photon energy is absorbed by rhodopsin that changes its geometrical isomerism from trans to cis. The photon must be absorbed as a whole, which means that there must be the possibility to change the energy level of a molecule by the same amount as photon energy does. Moreover this change must be reversible, since the same retina detects light throughout human life. The most effective way to do this is to exploit reversible changes in chemical bonds. This means that the energy of a visible photon must be in the same range as the energy of chemical bonds. This is actually the case. The energy of chemical bonds varies from 0.01eV (van der Waals) to 5eV (covalent), while visible light consists of photons with energies from 1.6eV (red light) up to 3.4eV (violet light).

A photon with significantly higher energy cannot be absorbed by a chemically controlled reversible mechanism, and its absorption leads to large-scale unpredictable destruction. It is well known that ultraviolet or even x-ray radiation is detrimental to human and animal tissues. There is a good example demonstrating how much work is done by our body to heal damage to our skin from exposure to common solar radiation. There exists a rare genetic disease called *xeroderma pigmentosum* that causes the total lack of the mechanism which corrects damage due to ultraviolet radiation. People affected by this disease cannot be exposed to sunlight, even when scattered and coming through an ordinary glass window. They are called “moon children”, because they may only venture outside at night to avoid any risk. As this cannot be maintained at all times, they often die of cancer at a very young age. Thus the human body is somehow sensitive to ultraviolet radiation, though not in a way useful for light detection and vision.

B) The eye lens cannot create an optical image on the retina.

The human eye is an optical system in which a converging lens and a spherical shaped cornea create an optical image on the retina. Rays of light are deviated by refraction and to do this, optical material with a refractive index significantly larger than 1.0 must be available. The refractive index of the human eye lens is about 1.4 in the visible spectrum, but for higher energies the refractive index for practically all materials converges to one. One example – quartz glass – is illustrated in figure 3. The dispersion relation is unique for any individual material but a general trend – convergence towards one for short wavelengths – is valid for any material.

This is why after reaching the diffraction limit of optical microscopy, resolution could not be improved by using ultraviolet or even x-ray radiation. At the same time, this is the reason why a hypothetical ultraviolet eye could never exist.

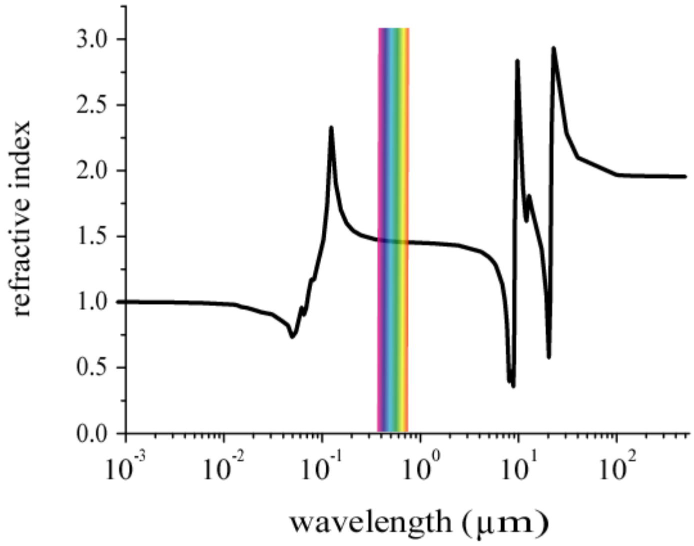

Figure. 3: Refractive index of quartz glass. It is worth mentioning that for visible light (color band) the index of refraction is almost constant, which leads to the slight chromatic aberration of a quartz lens.

Two reasons why we cannot see in the far infrared region

A) The human body itself emits infrared light

Not only the sun or a light bulb, but any body with a temperature above absolute zero emits electromagnetic radiation. For temperatures below 500˚C, the radiation is almost entirely within the infrared region. The human body, with its temperature of about 40˚C, emits infrared electromagnetic radiation with a maximum intensity at a wavelength of 10µm, as seen in figure 4. This makes effective and sensitive infrared vision impossible. The detected radiation signal would be overshadowed by the inner radiation of the human body, eye and retina itself.

It is very interesting to note that infrared vision actually exists in wildlife. Some species of snakes such as rattlesnakes or pythons have a special organ along with the normal eye that is capable of “seeing” infrared light. These organs are said to be more sensitive than any other infrared detector made by man. They are able to detect radiation up to a wavelength of 10µm, which is the region where warm-blooded animals emit. The principle behind their functioning is as yet not fully known. The quality of infrared vision cannot be compared to that of normal eyes however, as we can deduce from the fact that the snake has retained its “visible” eyes together with the infrared one. Eyes for infrared vision are more similar to insect eyes than to the human ones. There are more individual detectors, each of which are able to detect radiation coming from a limited visual angle. In this way, the snake can get approximate information about the sources of infrared light in the vicinity of its head, for instance a small warm-blooded animal. It is able to distinguish a living body from a dead one at a distance of 5 to 10cm. One can see that the capabilities of these eyes are in fact very limited.

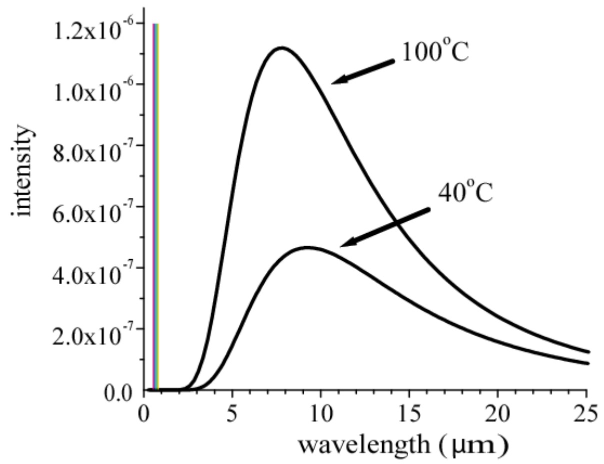

Figure 4: Black body radiation at low temperatures. The visible light range is the narrow colored strip just on the left. The scale at the y-axis is normalized to scale in figure 1.

B) Visual acuity is limited by diffraction

Light has wave characteristics, and as any other wave diffracts when its wave edge is somehow restricted, for instance by passing through a circular hole or a narrow slit. Before entering the eye, light must go through the pupil where diffraction occurs. When a plane wave hits the eye upon diffraction at the pupil, it becomes divergent and the lens is not able to convert the light beam into a single point in focus, as in figure 5. Instead of focusing into a point, light illuminates a small spot with a diameter of d approximately rendered by

$$d \cong 1.22\frac{\lambda f}{D},$$

where λ is the wavelength, f focal length and D diameter of the pupil. By applying normal values, one obtains a spot diameter d of about 5μm. This is the size of the image of an individual star, for instance. Visual acuity is thus inversely proportional to wavelength. With a longer wavelength we would have a lower capacity for vision.
The diffraction of light is a major limitation, especially for the small compound eyes of insects. There was no evolutionary driving force to construct a lens eye for insects. If the compound eye had the same size as a human one, its resolution would be much worse. But if the eye must be sub-millimeter in dimension, a compound eye is much better for vision, having other advantages, notably an extremely large visual angle.

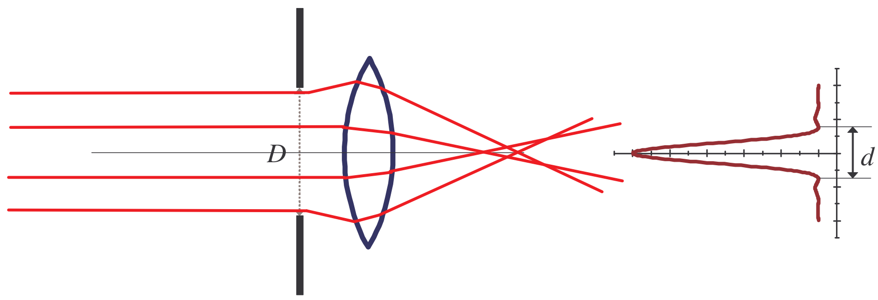

Figure 5: Light diffraction at the pupil of the eye (left) and intensity distribution at the retina (right) when a plane wave hits the eye.

Conclusion

We may summarize the above-mentioned facts in these brief statements:

1. Solar radiation is most intense in the visible range.
2. The Earth's atmosphere is effectively transparent in the same spectral range.
3. The energy of chemical bonds is comparable with the energy levels of visible photons, thus visible light can be detected by chemical changes.
4. In the visible range, the refractive index of matter is sufficiently different from unity and therefore the optical system of an effective eye lens may be formed.
5. The human body emits electromagnetic radiation that is far in scale from visible light and does not overexpose the eye itself.
6. Due to the small wavelengths, diffraction of light at the eye's pupil is weak and does not disturb the sharp image on the retina.

All these requirements must be met simultaneously. In fact they are not fully independent. Chemical bonds cannot have the same energy as photons of human body thermal radiation, because stable macromolecules could never exist in such conditions. Nonetheless we observe the remarkable congruence of several different physical states, allowing us to see with fine resolution and sensitivity, and to enjoy the beautiful world around us.