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REVIEW ARTICLE

The physics of light and sunlight

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Abstract

The physical properties of light, both natural and artificial, play a significant role in its interaction with humans. Although there is a yet-to-be-explained duality between light as waves and light as photons, we do understand many of the characteristics of light that affect living things. Here I review the general history of light and its properties, especially those that affect human health.

1. A brief history of light and sunlight

Light began when the universe did. The Big Bang that started the cosmos some 15 billion years ago was an intense explosion of light emitted at a temperature of billions of degrees. Some of that light energy was converted into matter according to the equation $E = mc^2$, and so light is responsible for matter as well. Table I shows other steps in the evolution of light and its effect on life, including the formation of our own sun [1, 2]. Today, we live in a world dominated by sunlight.

2. Understanding light

Since the earliest times humanity has recognized the importance of light, but there has been only a slow clarification of its nature, with the key question being whether light is wave-like or particle-like. The particle picture dominated after Isaac Newton sent white light through a glass prism and split the light into colors, which in 1704 he interpreted to mean light was particulate. But in 1801 the English scientist Thomas Young showed that two beams of light interfere with each other to produce a series of light and dark areas, which means light is wave-like. In 1873, James Clerk Maxwell showed that light is an electromagnetic wave, consisting of coupled electric and magnetic fields propagating at a speed $3x10^8$ m/sec. (See Table 2).

Further understanding came through quantum theory, initiated by the German physicist Max Planck in 1900. In 1905, Albert Einstein extended Planck's ideas to show that light is quantized, with each discrete unit (later called a photon) carrying energy $E = hf$ (h is Planck's constant, f is the fre-

Table 1. Main events in the history of light. Times are extremely approximate.

Time after Big Bang	Event
0 seconds	Light is born and begins to form elementary particles
3 minutes	Elementary particles form the first nucleus, deuterium
300,000 years	Cosmic background radiation begins: light fills the cosmos.
10 billion years	Our sun is born
11 billion years	Life arises on Earth, perhaps energized by sunlight
15 billion years (today)	Sunlight maintains and affects life on Earth

Table 2. Milestones in our understanding of light

Year	Person and idea
1704	Isaac Newton: light is a particle
1801	ThomasYoung: light is a wave
1873	James Clerk Maxwell: light is an electromagnetic wave
1900	Max Planck: energy quanta, $E = hf$
1905	Albert Einstein: light is a particle with energy $E = hf$
1948	Richard Feynman: QED theory; photons carry electromagnetic force

quency of the light). In 1948, Richard Feynman developed quantum electrodynamics (QED) to explain how photons carry electromagnetic force. But QED does not explain the fact that although light is indeed particle-like, it is also wave-like – a paradox that Nobel Laureate Feynman called "the *only* mystery," the enigma at the heart of quantum mechanics [3].

3. The basic properties of light

Despite the wave-particle paradox, both approaches are useful to systematize light and its effects. The wave picture focuses on wavelength and frequency, which obey the equation

$$c = f\lambda \qquad (1)$$

where c is the speed of light ($3x10^8$ m/s in vacuum), and λ is the wavelength. Wavelength is a convenient way to define different regions of electromagnetic radiation, from extremely large values for radio waves to sub-microscopic values for X-rays and gamma rays. Representative values, including the regions of visible and ultraviolet light, are given in Table 3.

In contrast, the photon picture emphasizes the energy of each photon through the relation $E = hf$, which can be put into the useful form:

$$E = \left(\frac{1{,}240\ nm}{\lambda}\right) eV \qquad (2)$$

When wavelength λ is inserted in units of nanometers (1 nm = $1x10^{-9}$ m), this relation gives photon energy E in electron volts (eV), where 1 eV is the energy needed to move an electron through an electrical potential difference of 1 volt.

Table 3. Wavelengths (in m and nm; 1 nm = 10^{-9} m) and photon energies (in eV and in kcal/mole; 1 eV/molecule = 23.1 kcal/mole) for regions of the electromagnetic spectrum, including radio, infrared, visible (750–400 nm), ultraviolet (UV), and X-ray. The UV region is subdivided into UV-A, 400–350 nm; UV-B, 350–280 nm; UV–C, 280–100 nm.

Type/color	Wavelength	*E* (eV)	*E* (kcal/mole)
FM radio	3 m	$4.1x10^{-7}$	$9.5x10^{-5}$
Infrared	1,000 nm	1.2	28
Visible: red	750 nm	1.6	37
Visible: green	550 nm	2.2	51
Visible: violet	400 nm	3.1	72
Ultraviolet	400–100 nm	3.1–12.4	72 – 286
X-ray	1 nm	1,240	28,600

Table 3 shows photon energies in units of eV and also of kcal/mole, as a guide to how light affects living systems. As light interacts with such a system, each photon imparts energy to one or more constituent molecules. If the energy is great enough to break molecular bonds, the result is a serious and potentially adverse change in biomolecular structure and activity. As can be found in standard references, bond strengths within biomolecules generally lie in the range 3–10 eV or 70–230 kcal/mole, corresponding to photon wavelengths of 400–100 nm. Thus radio, infrared, and red photons are unlikely to cause disruption (see Eq. 2 and Table 3). But ultraviolet (UV) photons carry energies sufficient to cause damage. X-ray photons are especially harmful, carrying enough energy to disrupt large numbers of molecular bonds.

4. Sunlight and its effects on humans

Since light can cause undesirable as well as beneficial results, it is essential to consider the role of sunlight in human health. Our sun is only a medium-sized star, but it produces energy at a rate we can hardly comprehend. As an extremely hot body with a surface temperature of nearly 6,000 degrees Kelvin, the sun radiates 62 megawatts from each square meter of its surface. That power is diminished when the light reaches the Earth, but is still considerable: 1.4 kilowatts/m^2 at the outer surface of our atmosphere (this quantity is called the solar constant). Moreover, as a so-called "black body" radiator, the sun's light covers the entire electromagnetic spectrum, from radio waves to visible light to the UV and X-ray ranges [4].

As illustrated in Table 3, the short-wavelength portion of this spectrum is potentially dangerous for humans. But far less short-wavelength light reaches the Earth's surface than the sun produces, because the gasses in our atmosphere – especially ozone, O_3 – selectively absorb UV and shorter wavelengths. Nevertheless, some UV does impinge on the Earth, and there is extensive evidence correlating the rate of skin cancer in human populations with UV exposure.

The level of solar UV depends on many short- and long-term factors: the state of the ozone layer; local atmospheric conditions such as smog; global atmospheric conditions, for instance due to volcanic activity; location on the Earth's surface; time of year, season, and day; and solar activity, which changes the light from the sun on short-term scales, and on an 11-year cycle. The complexity of these interactions can be seen by examining maps of the distribution of sunlight over the United States and Europe, which are far more intricate than a simple dependence on latitude [5, 6]. This complexity needs to be carefully considered in any studies of correlations between solar UV and human illness.

5. Artificial light and its effects on humans

Artificial light can also produce direct biological damage if it includes excessive UV radiation. There is a more subtle possibility as well, namely, that at least in the industrialized nations, people may now be exposed to sufficient artificial light at night to suppress or distort ordinary circadian rhythms. One important outcome is to inhibit the production of melatonin, normally generated by the pineal gland in the hours of darkness. Since melatonin plays a role in protecting DNA from damage and has other physiological functions, the prevalence of artificial light may lead to serious consequences for such diseases as breast cancer [7], and other undesirable outcomes.

One possible complication in studying light-at-night effects is the variety of artificial sources now available for indoor and outdoor illumination: incandescent, tungsten-halogen, fluorescent, mercury-vapor, sodium vapor, light-emitting diode, and more. Each has its own intensity and spectral distribution of light. Incandescent bulbs, for instance, produce relatively less blue light than the sun, whereas fluorescent and mercury-vapor lamps are rich in blue-violet-UV light. Thus there is no single type of "light at night." It depends on the specific type of artificial illumination, and generally differs substantially from daylight.

Whether this is a serious factor in light-at-night effects depends on understanding the mechanism in the eye that controls melatonin. Recent research suggests that newly-discovered photoreceptors residing in the ganglion cell layer of the retina are central in this regulation [8]. Full knowledge of the photoresponse of these sensors is important for scientific understanding of human responses to light. Combined with analysis of the relevant properties of artificial illumination, it would also provide the basis for clinical understanding and treatment of light-at-night effects.

6. Conclusions

The wave-particle duality of light continues to baffle us, but the physical properties of light that may adversely affect human health can be clearly stated. The photon theory shows why short-wavelength light is likely to be more damaging to humans than other types of light; of course, this general conclusion omits other factors such as selective absorption of light by tissues and organs, and the role of internal repair mechanisms.

Even after penetrating the Earth's atmosphere, sunlight carries enough UV energy to cause biological damage, as in skin cancer. The amount and spectral distribution of UV in sunlight depends on a multiplicity of factors, which should enter into further studies of possible links between duration of exposure to sunlight and harmful changes in endocrine function.

Though exposure to UV light from artificial light sources may cause direct biological damage, a potentially far more widespread issue is the pervasiveness of light at night and its effects on melatonin. This complex problem requires a variety of scientific and clinical approaches; among them, a clear understanding of the spectral response of the eye that sets circadian rhythms and determines melatonin production, coupled with a clear understanding of typical intensities and wavelengths of artificial light that we encounter at night.

REFERENCES

1 Perkowitz S. Empire of Light. Washington (DC): Joseph Henry Press; 1998. p. 1–15.
2 Steven Weinberg. The First Three Minutes. New York: Basic Books; 1988.
3 Perkowitz S. Empire of Light. Washington (DC): Joseph Henry Press; 1998. p. 87.
4 U. S. National Research Council. Solar Influences on Global Change. Washington (DC): National Academy Press; 1994.
5 U. S. Department of Energy. http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/; http://www.homepower.com/solmap.gif.
6 Palz W, Grief J, editors. European Solar Radiation Atlas. Heidelberg: Springer-Verlag; 1996.
7 Stevens RG, Rea MS. Light in the built environment: potential role of circadian disruption in endocrine disruption and breast cancer. Cancer Causes Control 2001;**12**:279–287.
8 Provencio I, Rodriguez IR, Jiang G, Hayes WP, Moreira EF, Rollag MD. A novel human opsin in the inner retina. J Neurosci 2000; **20**:600–605.