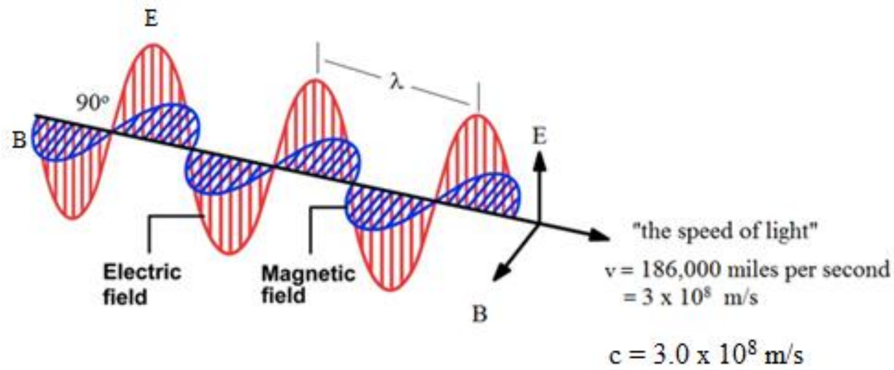
Physics 25 Chapter 24 Electromagnetic Waves

Dr. Joseph F. Alward



Electromagnetic (EM) waves are so-called because they have electric-field and magnetic-field components. The reader is familiar with magnetic fields; they were introduced in Chapter 21. Not discussed before, however, are electric fields. We will do this below.

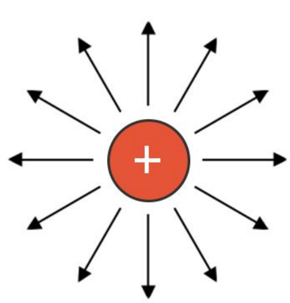
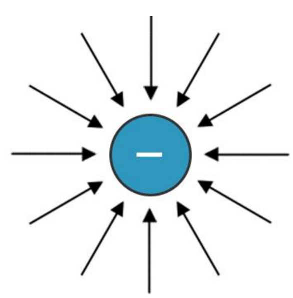
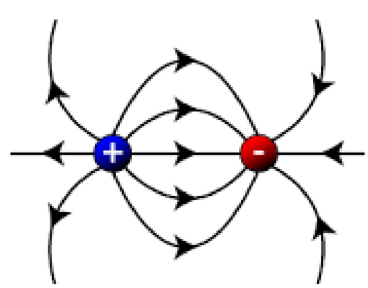
Electric Fields

Shown below are the electric fields of three different electric charge configurations.

The arrows show the directions along which positive charges would flow. The smaller is the spacing between adjacent lines, the stronger is the "electric field intensity," E.

The value of E at a point is the ratio of the electric force F acting on an imagined positive charge Q placed at the point, divided by the charge Q:

$E = F/Q$

Positive Charge	Negative Charge	Dipole
		

Let's now return to our discussion of EM waves.

One source of electromagnetic waves are oscillating electric charges, such as occur when radio waves are created by electrons oscillating in an antenna wire at the radio station. The frequency of the electromagnetic wave is the frequency of the oscillating charge producing the wave.

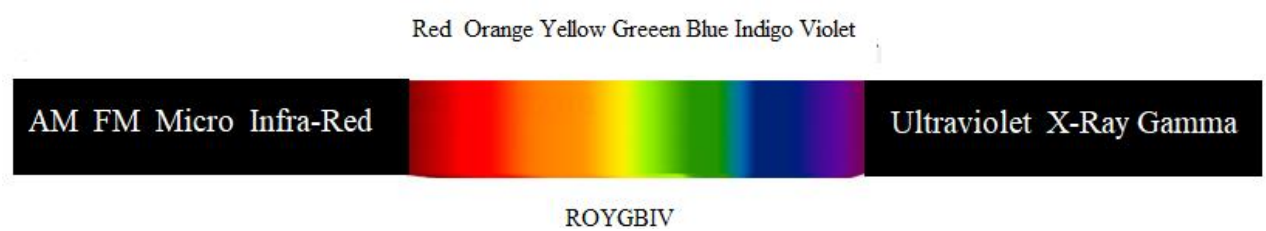
Another source of electromagnetic waves are heated atoms whose electrons are "excited up" into higher-lying orbits, which then emit electromagnetic waves as they return to their original states. This is the behavior responsible for burning embers in a firepit lowing "red hot," and later, "White hot." These electron excitation-de-excitation processes are described in Chapter 30.

Electromagnetic Waves

As shown in the figure at the top of this Chapter, electromagnetic (EM) waves consist of traveling electric and magnetic disturbances; these disturbances are caused by vibrating electric charges oscillating at a certain frequency. The EM waves thus created have a frequency that is the same as the oscillation frequency of the electric charge.

At any point, the electric field vector is perpendicular to the magnetic field vector. These disturbances travel as waves through air vacuum, and through transparent materials with a speed that varies, depending on the medium—air, vacuum glass, and other transparent media. Through air or vacuum, the speed of electromagnetic waves is 3.0×10^8 m/s; this speed is called "the speed of light." In other substances, such as glasses, and water, the speed is less than this.

The Electromagnetic Spectrum



The smaller the wavelength, the more harmful EM radiation is to living things. X-rays and gamma rays have wavelengths short enough to disrupt chemical bonds, and even nuclei, which can lead to DNA mutations and cancer. If the intensity of gamma radiation is great enough--such as can occur near the detonation of an atomic bomb, or a hydrogen bomb--death to living organisms can come virtually immediately.

Visible Light

The table below shows the average wavelengths of the various bands of visible light, ROYGBIV. The "blue" end of the visible spectrum is the short-wavelength end, while the "red" end is the long end. Note: 1.0 nanometer (nm) = 1.0×10^{-9} m

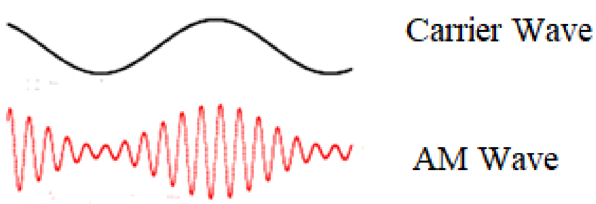
Color	λ (nm)
Red	650
Orange	590
Yellow	570
Green	510
Blue	475
Indigo	445
Violet	400

AM and FM Waves

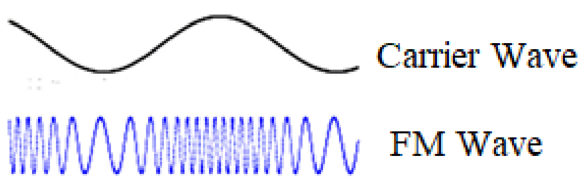
Varying pressure and frequency in sound information produced in the radio station is used to impress a kind of "code," or "pattern" on a so-called "carrier wave." The carrier wave is then said to have been changed, or "modulated."

The modulated electromagnetic wave is broadcast by an antenna at a radio station. A radio receives this modulated wave and possesses the necessary de-coding apparatus to extract from the wave the exact pattern of varying sound pressure and frequency present in the spoken words, or music, that was input into the microphones in the radio station.

AM ("amplitude-modulated") radio stations modulate the carrier wave by changing the wave "amplitude."



FM ("frequency-modulated") radio stations modulate the frequency.



Example A:	Example B:
DNA-destroying gamma radiation has wavelength comparable to the diameter of atomic nuclei: 1.0×10^{-15} m, and is thereby capable of transforming strands of DNA (mutating it). What is the frequency of gamma radiation that has this wavelength? $f = c/\lambda$ $f = 3.0 \times 10^{8}/1.0 \times 10^{-15}$ $= 3.0 \times 10^{23}$ Hz	What is the wavelength of an AM radio station's carrier wave whose broadcast frequency is 600 kilohertz? $\lambda = c/f$ $= 3.0 \times 10^{8} / 600 \times 10^{3}$ $= 500$ m AM radio wavelengths are about this many times longer than gamma waves wavelength: 500,000,000,000,000,000

The Doppler Effect for Light

v = *Relative* speed between source and observer
f_o = Observed frequency
f_s = Source frequency

$f_o = f_s (1 \pm v/c)$

The ratio v/c is often symbolized as β:

$$f_o = f_s (1 \pm \beta)$$

If the distance between source and observer is increasing, use the negative sign. In this case, the observed frequency will be lower than the source frequency, analogous to the lowered sound frequency that is heard by a listener listening to the siren of an ambulance racing away from the observer.

If the distance between source and observer is decreasing, as is the case when the light source is approaching the observer, use the positive sign. This situation, in which the observed frequency is higher than the broadcast frequency, is analogous to the heard frequency of sound from an ambulance approaching a stationary listener.

Example:

650 nm light from a galaxy is observed on Earth as 590 nm light. The wavelength is shifted toward the shorter end (blue end) of the visible spectrum, so it was "blue-shifted."

(a) What is the frequency of the 650 nm light emitted by the source?

$$f_s = c/\lambda_s$$
$$= (3.0 \times 10^{8})/(650 \times 10^{-9})$$
$$= 4.62 \times 10^{14} \text{ Hz}$$

(b) What is the frequency of the 590 nm light seen by the observer?

$$f_o = c/\lambda_o$$
$$= (3.0 \times 10^{8})/(590 \times 10^{-9})$$
$$= 5.08 \times 10^{14} \text{ Hz}$$

(c) What is the relative speed v between source and observer?

$$5.08 = 4.62\ (1 \pm v/c)$$

We must choose the positive sign, else the right side could not be made to equal 5.08.

$$5.08 = 4.62\ (1 + v/c)$$
$$v/c = 0.10$$
$$v = 3.0 \times 10^{7} \text{ m/s}$$

(d) Is the galaxy moving toward Earth, or away from Earth?

The observed frequency is greater than the emitted frequency, so, by analogy to the increase in frequency of an ambulance siren, the galaxy--like the ambulance--is moving toward the Earth observer.

Light Intensity: Spherically Symmetric Light Sources

The units of light intensity are "watts per square meter" (W/m^2).

The intensity varies with the distance r from the source, and depends on the output power P of the source. The intensity at a distance r from a spherically symmetric light source is given by the equation below.

$$I = P/4\pi r^2$$

The quantity $4\pi r^2$ is the area of the surface of an imaginary sphere of radius r, at the center of which is the light source.

Light Intensity

The table below shows the dependence of intensity (I) on the distance (r) from a light bulb, whose output power is P = 60 W.

For example, 0.10 meter from the source:

$$I = 60/4\pi\,(0.01\ \text{m})^2$$
$$= 480\ \text{W/m}^2\ \text{(approximately)}$$

r (m)	I (watts/m^2)
0.10	480.0
0.20	120.0
0.50	19.2
1.00	4.8
2.00	1.2

Note the "inverse square" dependency of intensity on distance. For example, doubling the distance from 0.10 m to 0.20 m quarters (reduces to one-fourth) the intensity from 480 to 120 W/m^2.

Another example: Doubling the distance from 1.00 to 2.00 m quarters the intensity from 4.8 to 1.2 W/m^2.

Example:

How far from a 50-watt, spherically-symmetric light source would an observer detect a light intensity of 0.05 W/m^2?

$$I = P/4\pi r^2$$
$$4\pi r^2 I = P$$
$$4\pi r^2 (0.05) = 50$$
$$r = 8.92 \text{ m}$$

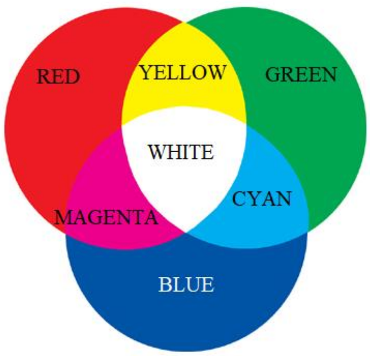
Mixing Colors of Light

Humans have “trichromatic” color vision, meaning that the color sensors (cones) in the retina respond more efficiently to the three colors, red, green, and blue (RGB) light, than to other colors. These three colors are called “the primary colors.” Mixtures of any two of the primary colors of light result in colors that are called “the secondary colors”: magenta, yellow, cyan.

Mixtures in various intensities of R, G, and B, produce various color sensations when they land on the retina. Below are the colors produced when *equal* intensities of the primary colors are mixed together. Keep in mind: we are mixing *light waves*, not paint. (Mixing paint comes later in this chapter.)

Table of Colors

R	Red
G	Green
B	Blue
R + G	Yellow (Y)
R + B	Magenta (M)
G + B	Cyan (C)
R + G + B	White (W)
K	Black



The “color” black is the total absence of visible light.

Example A:

What intensity of red light must be added to 70 watts/m^2 of cyan light to create white light, and what will be the intensity of the light created?

70 C = 35 G + 35 B

Add 35 R:

35 R + 35 G + 35 B = 105 W

105 W/m^2 of white light is created.

Example B:

Green light of intensity 40 watts/m^2 is mixed with magenta light whose intensity is 60 watts/m^2. What is the resulting intensity and color?

Solution:
60 M = 30 R + 30 B

Add 40 G:

30 R+ 30 B + (30 G +10 G) = 90 W + 10 G
= 100 watts/m^2

Nine parts white, only one part green:
Color: “pale” green, or light green.

Example C:

60 W/m^2 of magenta light is mixed with 60 W/m^2 of yellow light.

(a) What intensity of what color must be added to create white light?

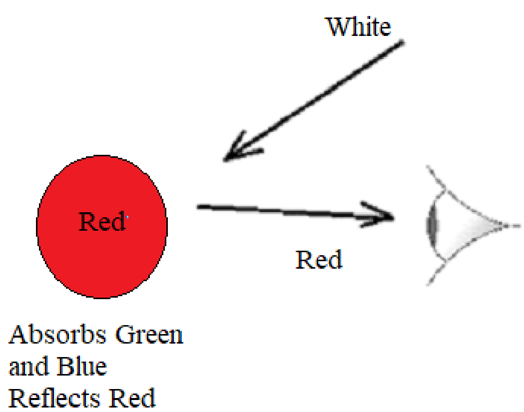
Answer: 60 W/m^2 Cyan light.

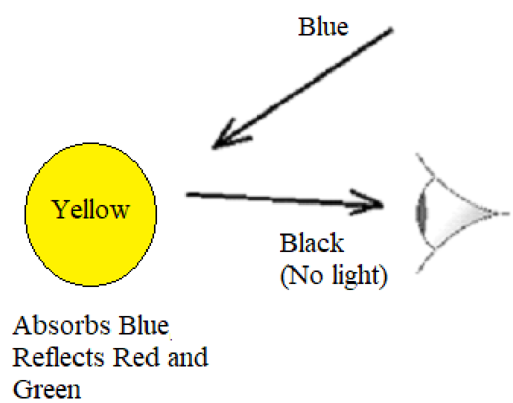
(b) What is the intensity of the resulting white light?

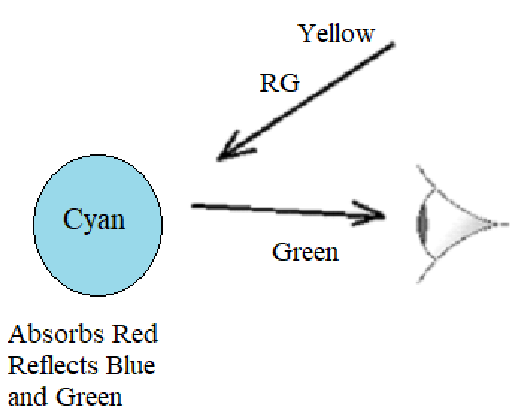
180 W/m^2

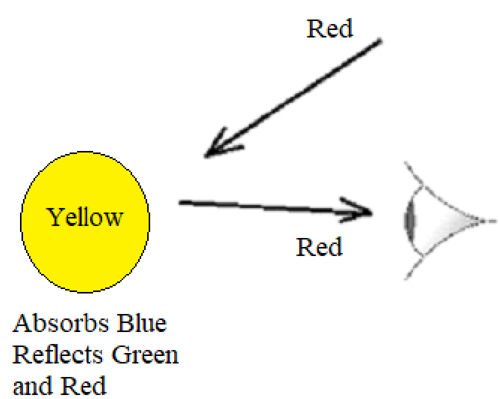
Colors of Objects

Objects are red (in white light) because the chemical composition of the surface of the object is such that green and blue light shining on them are absorbed; only the red portion of any light shining on a red object is not absorbed; it is instead reflected to the eye of the observer.





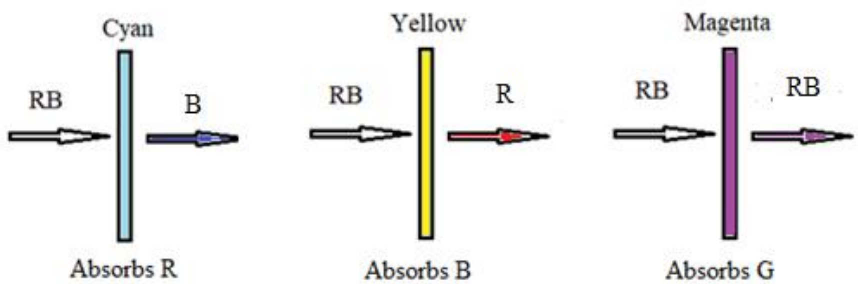


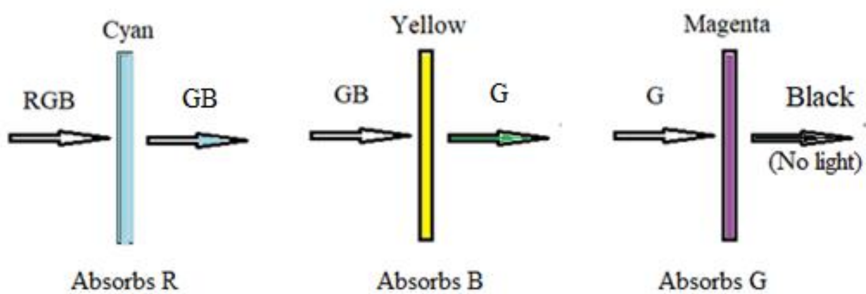


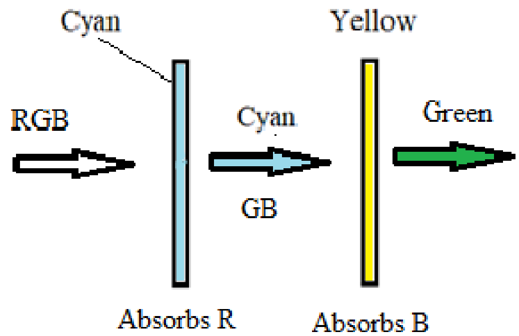
Filters

Filters are transparent media that allow certain colors to pass through, while absorbing or reflecting away other colors. For example, only blue and green light is transmitted through a cyan filter, while red is absorbed. In the examples below, the incident and transmitted colors are indicated.

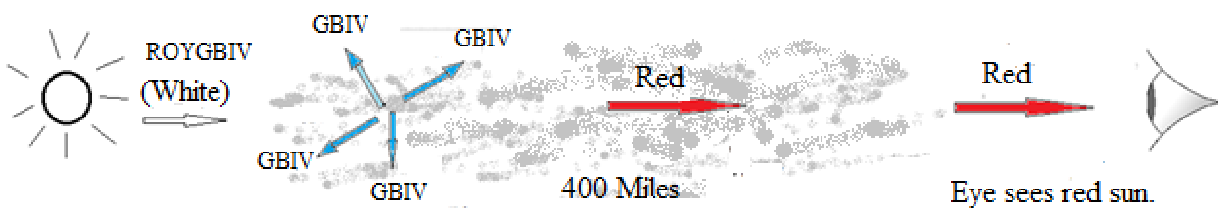
Under each filter below, the colors absorbed are indicated. Subtract those colors from the incident ones, and what's left is what's transmitted.





<u>Example</u>: A cyan filter is placed side-by-side with a yellow filter, and white light is incident on the pair. What color is transmitted through the pair?	 Together, the two filters absorb red and blue, allowing what's left--green--to pass through: RGB – R – B = G

Why are Sunsets and Sunrises Red?



Blue Light Scattering Accounts for Red Sunsets and Sunrises

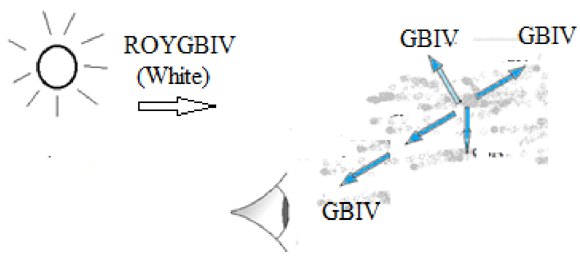
Oxygen and nitrogen molecules in the atmosphere absorb the green, blue, indigo, and violet (GBIV) light from of the incident white light from the sun, then radiate that light in every direction—right, left, forward, backward, upward, and downward.

This “filtering out” of the GBIV light is called “scattering.” The red, orange, yellow (ROY) light portion of the white light is also scattered, but in negligibly small amounts compared to blue light. The vast majority of the ROY portion of the incident white light goes straight through the atmospheric “filter” un-scattered.

At dawn, and again at sunset, light from the sun, peeking over the horizon, will travel through about 400-miles of atmosphere. At the end of its journey, having had most of its GBIV wavelengths scattered away by the 400-mile-thick atmosphere filter, the light arriving at the observer will be almost entirely a mixture of red, orange, and yellow (ROY)

Why is the Sky Blue?

Sunlight passes over the shoulder of the observer in the diagram below.

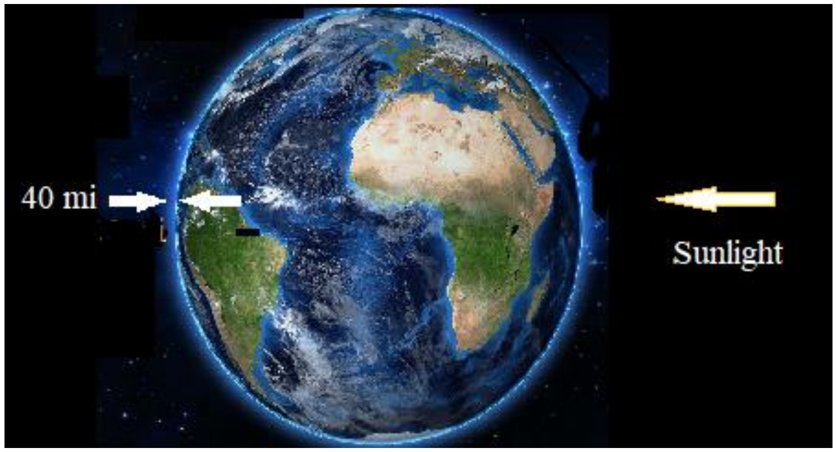


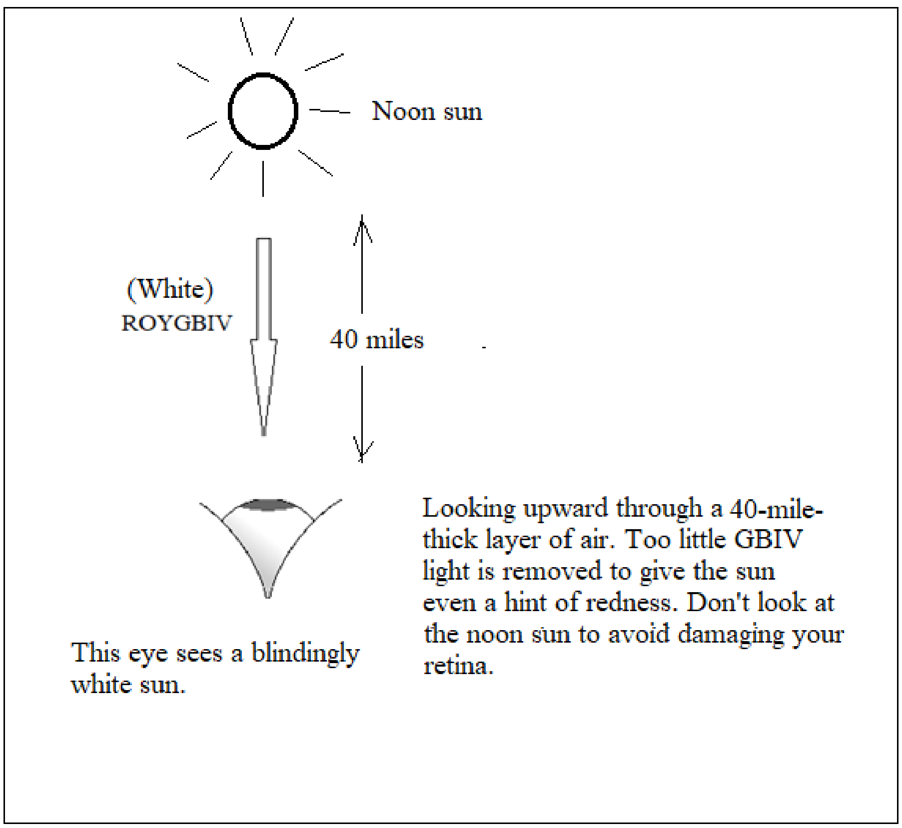
With her back to the sun, this
observer sees blue scattered
light, i.e., she sees blue sky.

Red-orange-yellow (ROY) light (not shown) goes straight through, while a significant amount of the blue GBIV end of the visible spectrum is scattered in all directions, including back toward the eye of the observer, who thereby sees bluish sky.

The red portion of the light is not relevant, and not shown.

The Noon Sun


40 mi
Sunlight


Noon sun
(White)
ROYGBIV
40 miles
Looking upward through a 40-mile-thick layer of air. Too little GBIV light is removed to give the sun even a hint of redness. Don't look at the noon sun to avoid damaging your retina.
This eye sees a blindingly white sun.

Mixing Paints

Magenta paint absorbs green, while cyan paint absorbs red. A mixture of both absorbs green and red from white light that's incident on it, and reflects blue.