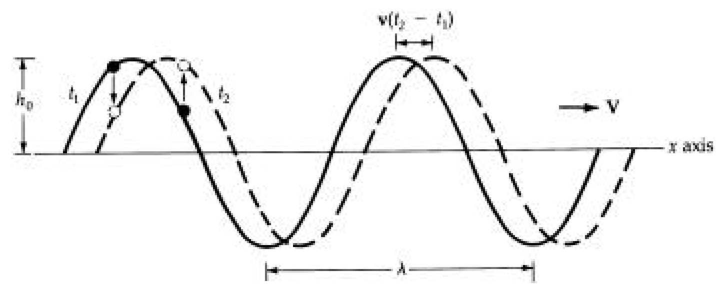
Electromagnetic Radiation

Wave - a traveling disturbance, e.g., displacement of water surface (water waves), string (waves on a string), or position of air molecules (sound waves).

$$h = h_0 \sin\left[(2p\ /\ l\ )(x - vt)\right]$$



Moving in the +*x* direction.

<u>Transverse</u> or <u>longitudinal</u>.

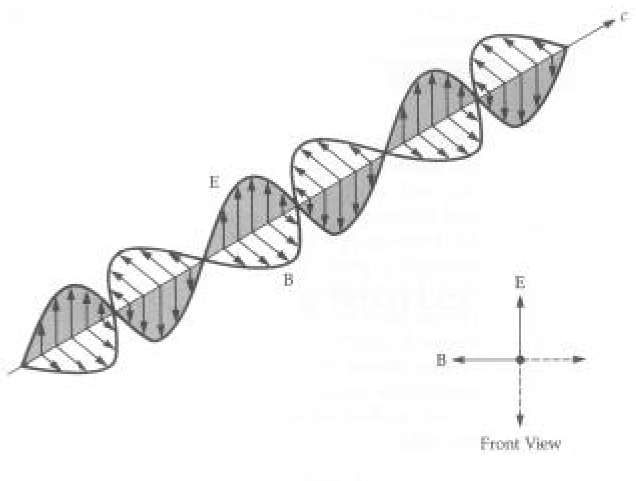
h_0 = amplitude; λ = wavelength; v = speed.

P = period = time for one up-down oscillation at a fixed point = time for wave to move forward one wavelength = λ/v.

Therefore, $v = \lambda\ \nu$, where $\nu = 1/P$ = frequency.

Electromagnetic Waves

Maxwell (1865): A disturbance in local electric field **E** => disturbance in local magnetic field **B** => disturbance in **E**, etc. Leads to a propagating disturbance (a wave) in a vacuum.



speed of light, $c = 3 \times 10^8$ m/s; $c = \lambda\nu$.

A transverse wave, i.e., disturbance(s) perpendicular to propagation direction.

Source? An oscillating electric charge or current.

Electromagnetic Waves

Consider a wave traveling in the *z*-direction.

$$E_x = E_{x1}\sin(kz - wt - d_1),$$

$$E_y = E_{y1}\sin(kz - wt - d_2),$$

where $k = 2p / l, w = 2pn, d$ = phase.

Unpolarized light: **E** direction changes randomly; E_x, E_y not correlated; $\delta_1 - \delta_2$ fluctuates randomly.

Plane-polarized light: **E** in fixed direction; $\delta_1 - \delta_2 = 0$.

Elliptically polarized light: **E** direction changes in a regular way, i.e., **E** vector rotates but changes in magnitude. $\delta_1 - \delta_2$ =constant.

Circularly polarized: **E** of fixed magnitude, rotates in a circular path. $E_{x1} = E_{y1}$, $\delta_1 - \delta_2 = \pi/2$.

The Electromagnetic Spectrum

Visible light: λ = 390 nm (violet) to λ = 720 nm (far red).

TYPES OF ELECTROMAGETIC RADIATION

λ	ν or $h\nu$	Type of EM radiation
10^{-5} A	1240 MeV	
10^{-4} A		Gamma rays
10^{-3} A	12.4 MeV	
10^{-2} A		
10^{-1} A		X-rays
1 A = 10^{-8} cm	12.4 keV	
1 nm		
10 nm	124 eV	Ultraviolet
100 nm		
1000 nm = 1μm	1.24 eV	Visible
10 μm		
100 μm	0.012 eV	Infrared
1000 μm		
10 mm = 1 cm	30,000 MHz	Radar
10 cm		UHF
100 cm = 1 m	300 MHz	FM
10 m		Short wave
100 m	3 MHz	
1000 m = 1 km	300 kHz	Broadcast
10 km		Long Wave
100 km	3 kHz	
1000 km		

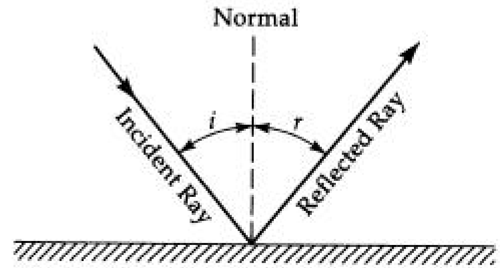
V B G Y O R

Open Window	eV = electron volt
	Hz = hertz = cycles per second
Partial Window	M (mega) = 10^6
	k (kilo) = 10^3
	A = angstrom
Opaque	μm = micrometer
	nm = nanometer

Full atmospheric transmission only in visible and some radio wavelengths.

Reflection

Use the concept of a ray: a line along the propagation direction of wave crests. Law of reflection: incident angle *i* of ray equals reflected angle *r*.

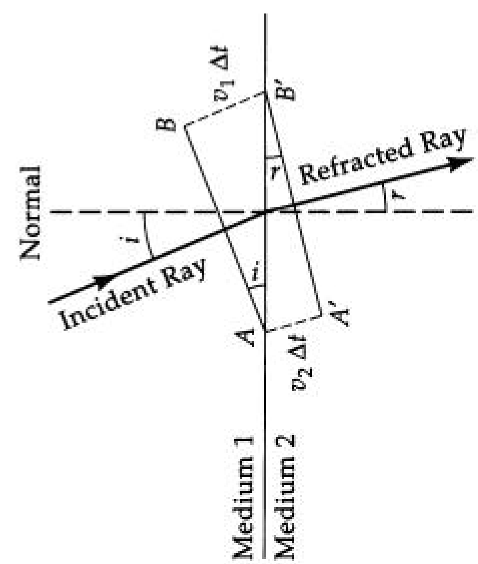


Refraction

Speed of light decreases when passing through a material medium. Speed equals $v = c/n$, where n = index of refraction. n = 1.003 for air, 1.3 for water, about 1.5 for glass.

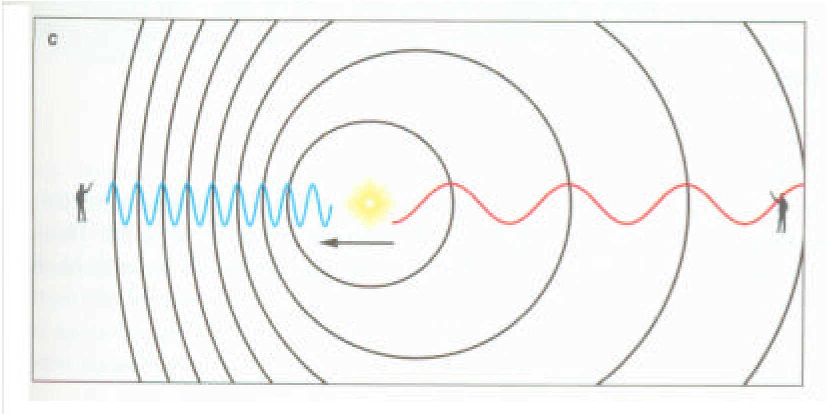
Light always takes the path of least time. Leads to refraction of wave front when changing media.

$$n_1 \sin i = n_2 \sin r.$$



Telescopes utilize reflection and refraction. In general, $n = n(\lambda)$, which leads to <u>dispersion</u>. Astronomers utilize this for <u>spectroscopy</u>.

The Doppler Effect



Let t be the time between successive crests.

$$l = (c + v)t = c(1 + v/c)/n_0 = l_0(1 + v/c),$$

$$n = c/l = n_0/(1 + v/c).$$

Note that $v > 0$ if source and observer moving apart, $v < 0$ if moving towards one another.

When v approaches c, need to use relativistic formulas:

$$l = l_0\left[(1 + v/c)/(1 - v/c)\right]^{1/2},$$

$$n = n_0\left[(1 - v/c)/(1 + v/c)\right]^{1/2}.$$

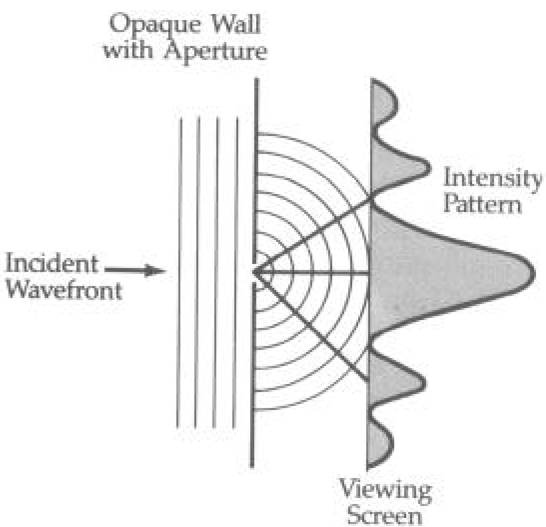
Note convergence to non-relativistic formula for $v << c$.

Diffraction and Interference

Electromagnetic radiation has wavelike properties.

We measure the intensity of light $I \propto |E|^2$.

Diffraction - single aperture



(A)

Electric field $E = E_1 \sin(kz - wt - d)$

Path lengths of waves from different parts of aperture vary. Therefore, waves from two parts of the aperture converging to a single point on the screen yield net field

$$E = E_0 \sin a + E_0 \sin(a + b)$$

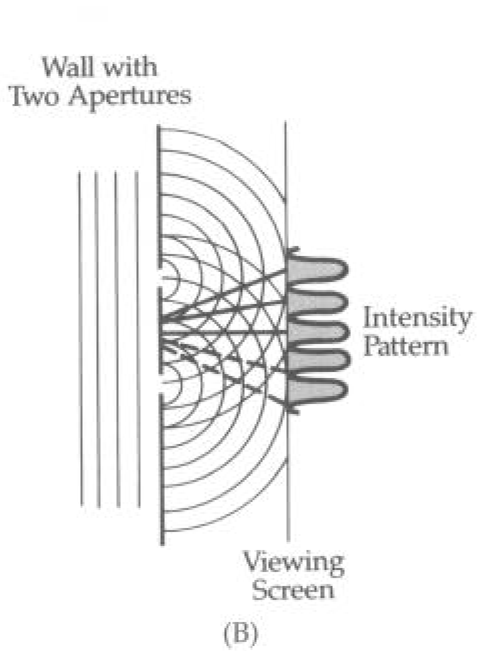
$\Rightarrow I \propto E_0^2 \left[\sin^2 a + \sin^2 b + 2 \sin a \sin(a + b)\right]$. Last term can be < 0.

$I = 0$ when $q \cong \dfrac{l}{d}$, where d is the diameter of the aperture.

Diffraction is critical for astronomy. Light from a point source is spread over an angle $q \cong \frac{l}{d}$, where *d* is the telescope diameter.

This angle is the resolution limit for a telescope, barring atmospheric turbulence, which limits optical “seeing” to 0.3”-1”.

Interference - multiple apertures



Multiple apertures lead to multiple peaks of width $q \cong \frac{l}{a}$, where *a* is the slit separation.

Since *a* >> *d* in principle, can achieve much higher resolution with multiple receivers => <u>interferometry</u>.

Interferometry

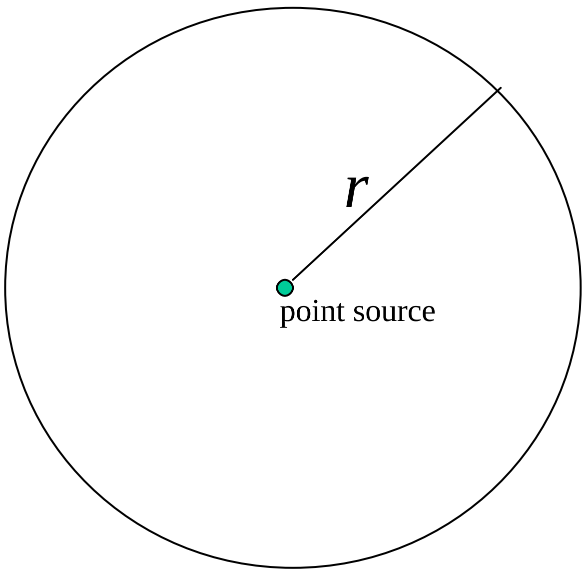
Two views of the Very Large Array (VLA) interferometer at Socorro New Mexico.

Combined signals from multiple dishes with wide separation yields extremely high resolution, even at (long) radio wavelengths.

Inverse Square Law for Flux of Radiation

A point source of electromagnetic radiation (EMR) emits uniformly in all directions.

Let L be the rate of emission of EMR at all ν (or λ). Units are J/s = W. L is equivalent to the power of the source.



Amount of energy per unit area per unit time received at distance r is the flux

$$F = \frac{L}{4\pi r^2}.$$

Distant objects appear fainter by factor $1/r^2$.

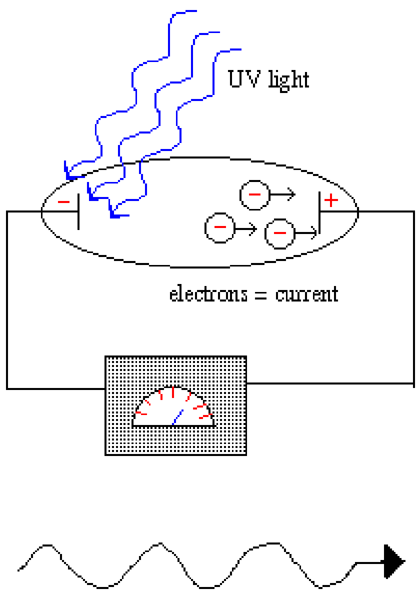
The Quantum Nature of Light

Light has particle-like properties as well!

Picture an EM wave of frequency ν as consisting of many quanta of energy $E = hn$, where h = 6.626 x 10^{-34} J s is Planck’s constant.

This model arises from successful theories of blackbody radiation (Planck – 1900) and the photoelectric effect (Einstein – 1905).

Photoelectric Effect



photon = wave particle of light

Electron current measured only when ν exceeds a critical value. This is not consistent with classical wave picture, but can be explained if lights consists of <u>photons</u> of energy $E = hn$.