The Nature of Light and Matter  1
Light

ASTR 103

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The Nature of Light

Basic properties:

– Light travels in a straight line.
– Most surfaces reflect light.
  • Amount of reflection depends on the medium.
    – Glass 4%, water 2%, aluminum 87%, silver 98%
    • When light reflects, incident angle = reflected angle
– When light travels from one transparent medium to another:
  • small fraction of light reflects.
  • light that passes through changes its direction. (called refraction)
– When travelling from a less dense to a denser medium (e.g. air to water) light rays refract towards the normal,
  ⇒ angle of refraction is smaller than the angle of incidence.
Amount of bending (refraction) depends on many factors:

- **Angle of incidence**: larger the angle of incidence more the deviation from initial direction.

- **The medium**: some material refracts light more than other.
  - The refractive power (ie. amount of bending) of the medium is given by the refractive index. Higher the number more it refracts light.
  - Water 1.3, ordinary glass 1.5, air 1.0003, diamond 2.4

- **Color**:
  - Blue light is refracted (bent) more than red light.
  - It is called the dispersion of light
• White light is a mixture of a continuous spectrum of colors, from red to magenta.

• When a beam of white light passes through a glass prism, due to dispersion it is separated into different colors, forming a spectrum.
Formation of Mirages

- Cold air is denser than warm air and, therefore has a greater refractivity.
- On a sunny day air near the ground is warmer and less refractive than the air higher up.
- As light travels at a shallow angle along a boundary between air of different temperatures, the light rays bend towards the colder (upper) air and gets totally reflected.
Rainbows are formed by refraction, reflection and the dispersion of sunlight in raindrops.

Angle between incident and refracted light is largest and brightest around 42° for red and 40° for blue.

⇒ inner ring of the rainbow is blue and outer ring is red.

After two refractions and a reflection light exits the raindrop in slightly different directions depending on the color.
Secondary rainbow

- Light could reflect more than once inside the raindrop, producing higher order rainbows.

- When light reflects twice inside a water droplet, a secondary rainbow is formed. Due to extra reflection (only 2% of the light reflected)
  - secondary rainbow is fainter.

*Sunlight* ≈ 41°

*Secondary rainbow*

*Sunlight* ≈ 51°
Rainbows can form whenever there are water droplets (mist) in air, and sunlight. A rainbow can form a complete circle, but the horizon only allows us to see half of the rainbow circle. From a mountain top or an airplane more of the rainbow can be seen.

Is this real or fake?

https://www.reddit.com/r/earthporn/comments/2zz5cb/full_double_rainbow_from_my_backyard_in_redding
Nature of color was first revealed by Newton through a series of experiments. He was the first to understand colors of the rainbow. They were published in 1704 in the book *Opticks*.

(Shape of the rainbow was first explained by Rene Descartes in 1637, but he could not explain the color)
What is light?

• Newton proposed the corpuscular theory of light. That light is made up of little particles - called corpuscles.
  – A light source (lamp, light bulb) emits corpuscles.
  – They travel in straight lines in all direction from the source and bounce off (reflects) when they illuminate an object.
  – Corpuscular theory was able to explain many properties of light (reflection, refraction, color).

• In 1768 Christian Huygens proposed the wave theory of light.
  – According to the wave theory, light is a wave propagating from the light source.

According to Newton light is *corpuscles* emitted from the light source

According to Huygens light is a wave generated by the light source, like water ripples on a pond formed when a stone is dropped
Wave motion

- A wave is a disturbance propagating (moving) in a medium.
  Example: Waves on the surface of water

Waves along a rope

Stadium waves (medium is people)

credit: Dan Russell
Wave motion

- It appears like a ripple is moving:
  - but particles in the medium only do a local cyclic movement.
  - only the disturbance (wave) is moving.
- Waves carry energy in the form of a disturbance, but not the matter in the media.
- Variation causing the wave could be any property:
  - position of particles as in above examples
  - density, pressure
  - value of some field, like the magnetic or electric field as in the case of light, radio waves...
  - Epidemic, fashion,

Animations: [www.phy.olemiss.edu/~perera/animations/waves.html](http://www.phy.olemiss.edu/~perera/animations/waves.html)
• **Amplitude** \( (A) \): the magnitude of the wave at its peak.

• **Wavelength** \( (\lambda) \): the distance between two adjacent crests or troughs (or any two similar adjacent positions)

• **Period** \( (T) \): the time it takes for one complete wave to pass a given point (or time to complete one cycle)

• **Frequency** \( (f) \): number of complete waves passing a point in unit time: \( f = \frac{1}{T} \)
  - usually measured in Hertz (Hz: cycles per second).

• **Speed** \( (s) \): distance the wave travels in a unit time

Obviously, speed = wave length \( \times \) frequency

\[ s = \lambda f \]
Wave Theory of Light

In addition to basic properties, wave theory of light was able to explain phenomena that did not have an explanation in the corpuscular theory. Like diffraction, interference, polarization.

But waves in what?
- All known wave motion required a medium, (water waves, waves along a rope, sound waves in air...)
- But light can travel in the empty space (vacuum), so the medium cannot be ordinary material.

19th century physicists came up with various explanations, finally it was realized that light is a electromagnetic wave.
Thales (6th c BCE) noted that amber attracts feathers and other light materials when rubbed with fur - The first historical reference to static electricity.

- (origin of the word electricity is from "ilektron" the Greek name for amber)

He also observed that lodestone attract iron, the magnetism.

Knowledge about electricity and magnetism was developed as two separate phenomena until the later half of the 19th century

In 1865, James Clerk Maxwell showed that electricity and magnetism are related, two aspects of the same entity, which he named electromagnetism.

- He found that "electromagnetic waves" can exist and they travel at the same speed as light.

- Thus he realized that light was nothing but electromagnetic waves traveling in space.
Light as an Electromagnetic Wave

In an EM wave, strengths of electric and magnetic fields are changing in a cyclic manner, propagating like a wave.

- Intensity of light depends on the amplitude of the wave.
- Its frequency determines the color
  - red light frequency $4.6 \times 10^{14}$ Hz, blue light frequency $6.7 \times 10^{14}$ Hz
  - using $s = \lambda f$ (slide 15) ⇒ $\lambda = \frac{s}{f}$ (s = speed of light $3 \times 10^8$ m/s)

- wave length of red light: $\sim 650$ nm, wave length of blue light: $\sim 450$ nm

(nm nanometer, 1 nm = $1 \times 10^{-9}$ m. thickness of paper $\sim 60,000$ nm)
Radio waves

- Since frequency can be anything, can there be EM waves with other frequencies?
  - Maxwell believed there should be
    - He predicted the existence of low frequency EM waves $10^4$-$10^6$ Hz.
    - They (radio waves) were discovered by Heinrich Hertz in 1887.
      - Radio waves are produced by oscillating electric currents (charges)
      - which generates oscillating electric and magnetic fields and propagates away.

Just like falling water droplet create water waves, oscillating electric currents produce radio waves.
Electromagnetic Spectrum

- Visible light is only a small portion of a wider spectrum of waves known as Electromagnetic radiation, all travelling at the speed of light in empty space (vacuum).
- Total spectrum spans from very low frequency radio waves to extremely high frequency gamma rays (γ-rays).
- Different frequency ranges have different names:
  - Radio, microwave, infrared, visible, ultraviolet, x-ray, γ-ray ...

Infra-red, can feel as heat

visible light

ultra violet, causes sunburn
Infra-red radiation scatters less

- Amount of light scatters depend on the relative size of the wave length of the light and size scattering particles.
- If the wave length is larger than the size of the scattering particles it scatter less.
- That is the reason why red light scatters less than blue light in the atmosphere.
  - Wavelength of red light is larger in comparison to molecules and dust particles in the atmosphere so scatters less.
- Infra-red radiation has wavelengths even longer than the red light, so it won’t scatter by even larger particles in the atmosphere, like tiny water droplets in fog/mist.
- IR can be used to see through mist, fog or dust.
Infrared imaging used in astronomy to see through dust clouds

Barnard 68 dark nebula (dust cloud)

Galactic center

Pinwheel galaxy M101

- Infrared imaging used in astronomy to see through dust clouds
Atmospheric absorption of EM radiation

- All types of electromagnetic radiation is produced by various kinds of celestial objects.
- However, atmosphere is transparent only for two wavelength regions, in the optical region and in radio wave region.
- To see with other types of EM radiation, instruments have to be placed above the Earth's radiation absorbing atmosphere, in satellites, airplanes, or high altitude balloons.

Atmospheric opacity to different wavelengths of the Electromagnetic Spectrum

Optical window

Radio window

Chandra: X-ray
Spitzer: IR
SOFIA: IR
Plank: microwave
The Modern view of light
According to the current understanding, light exhibits both particle and wave properties.

(subject of Quantum Physics, an area of modern physics)

• Both particle theory and wave theory are correct. Each describes a different aspect of light.
  – When regarded as a wave it is described as an electromagnetic wave characterized by its frequency (or the wavelength) and the amplitude.
  – Also light can be considered as made of particles, called photons.
    • In that context light is a collection of photons, each having a specific energy depending on the frequency (color) of light.
      – energy of a photon: \( E = hf \), \( h \) a constant (Planks constant), \( f \) frequency.

• color \( \Rightarrow \) frequency \( \Rightarrow \) energy of the photon
• Intensity \( \Rightarrow \) number of photons \quad \text{higher intensity} \Rightarrow \text{more photons}
Review Questions

• What is refraction? Which color of light refracts the most?
• Why is the secondary rainbow fainter than the primary?
• What is the order of colors in a rainbow?
• Is it possible to touch a rainbow?
• Why do rainbows appear in the morning or late afternoon, but not around noon?
• What is meant by the wavelength of a wave?
• What is frequency? How is the period of a wave related to its frequency?
• How are frequency, wavelength and velocity related to one another?
• Why was the wave theory of light accepted over corpuscular theory in the 19th century?
• Why does infrared light able to penetrate fog and dust?
• Why does infrared light able penetrate cosmic dust clouds better than visible light?
• What is the speed of radio waves?
• Why does it take some time to hear the thunder after lightning?
• What is the modern view of the nature of light?
• Why do X-ray telescopes are placed in satellites orbiting the Earth, not on the ground?
• What are the observational evidence that light can travel in a vacuum?
• What is 92.1 in the Rebel radio 92.1 FM?