The Nature of Light

Chapter Five

Guiding Questions
1. How fast does light travel? How can this speed be measured?
2. Why do we think light is a wave? What kind of wave is it?
3. How is the light from an ordinary light bulb different from the light emitted by a neon sign?
4. How can astronomers measure the temperatures of the Sun and stars?
5. What is a photon? How does an understanding of photons help explain why ultraviolet light causes sunburns?
6. How can astronomers tell what distant celestial objects are made of?
7. What are atoms made of?
8. How does the structure of atoms explain what kind of light those atoms can emit or absorb?
9. How can we tell if a star is approaching us or receding from us?

Determining the Speed of Light

• Galileo tried unsuccessfully to determine the speed of light using an assistant with a lantern on a distant hilltop

Light travels through empty space at a speed of 300,000 km/s

• In 1676, Danish astronomer Olaus Rømer discovered that the exact time of eclipses of Jupiter’s moons depended on the distance of Jupiter to Earth
  • This happens because it takes varying times for light to travel the varying distance between Earth and Jupiter
  • Using \( d=rt \) with a known distance and a measured time gave the speed (rate) of the light

• In 1850 Fizeau and Foucault also experimented with light by bouncing it off a rotating mirror and measuring time
  • The light returned to its source at a slightly different position because the mirror has moved during the time light was traveling
  • \( d=rt \) again gave \( c \)

Light is electromagnetic radiation and is characterized by its wavelength (\( \lambda \)).

- White light
  - Spectrum falls on screen
  - Prism breaks light into its spectrum
  - Screen lets only one color pass through
  - First prism breaks light into its spectrum
  - Second prism bends light, but does not change its color
Wavelength and Frequency

Frequency and wavelength of an electromagnetic wave

\[ \nu = \frac{c}{\lambda} \]

\( \nu \) = frequency of an electromagnetic wave (in Hz)
\( c \) = speed of light = \( 3 \times 10^8 \) m/s
\( \lambda \) = wavelength of the wave (in meters)

The Nature of Light

- In the 1860s, the Scottish mathematician and physicist James Clerk Maxwell succeeded in describing all the basic properties of electricity and magnetism in four equations.
- This mathematical achievement demonstrated that electric and magnetic forces are really two aspects of the same phenomenon, which we now call electromagnetism.

Three Temperature Scales

An opaque object emits electromagnetic radiation according to its temperature.

A person in infrared-color-coded image -red is hottest
Wien’s law and the Stefan-Boltzmann law are useful tools for analyzing glowing objects like stars.

- A blackbody is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths.
- Stars closely approximate the behavior of blackbodies, as do other hot, dense objects.
- The intensities of radiation emitted at various wavelengths by a blackbody at a given temperature are shown by a blackbody curve.

**Wien’s Law**

\[ \lambda_{\text{max}} = \frac{2897 \text{ nm}}{T} \]

\( \lambda_{\text{max}} \) = wavelength of maximum emission of the object (in meters)
\( T \) = temperature of the object (in kelvins)

Wien’s law states that the dominant wavelength at which a blackbody emits electromagnetic radiation is inversely proportional to the Kelvin temperature of the object.

**Stefan-Boltzmann Law**

- The Stefan-Boltzmann law states that a blackbody radiates electromagnetic waves with a total energy flux \( E \) directly proportional to the fourth power of the Kelvin temperature \( T \) of the object:

\[ E = \sigma T^4 \]

Light has properties of both waves and particles:

- Newton thought light was in the form of little packets of energy called photons and subsequent experiments with blackbody radiation indicate it has particle-like properties.
- Young’s Double-Slit Experiment indicated light behaved as a wave.
- Light has a dual personality: it behaves as a stream of particle-like photons, but each photon has wavelike properties.
**Light, Photons and Planck**

- Planck's law relates the energy of a photon to its frequency or wavelength:
  \[ E = \frac{hc}{\lambda} \]
  - \( E \) = energy of a photon
  - \( h \) = Planck's constant
  - \( c \) = speed of light
  - \( \lambda \) = wavelength of light

- The value of the constant \( h \) in this equation, called Planck's constant, has been shown in laboratory experiments to be:
  \[ h = 6.625 \times 10^{-34} \text{ J s} \]

**Prelude to the Bohr Model of the Atom**

- **The Photoelectric Effect**
  - experiment explained by Einstein, but performed by others
  - What caused this strange result?
  - This is what Einstein won the Nobel Prize for

**Chemists' Observations**

1. Add a chemical substance to a flame
2. Send light from the flame through a narrow slit, then through a prism
3. Bright lines in the spectrum show that the substance emits light at specific wavelengths only

**Each chemical element produces its own unique set of spectral lines**

**Kirchhoff's Laws**

- **Absorption Line Spectrum**
  - when in gas cloud, absorbs light of certain specific wavelengths, producing dark lines in spectrum
- **Emission Line Spectrum**
  - when in gas cloud, emits absorbed light energy of the same wavelengths at which they absorbed it
Kirchhoff’s First Spectral Law

- Any hot body produces a continuous spectrum.
  - If it’s hot enough it looks something like this.
  - Digitally like this.

Kirchhoff’s Second Spectral Law

- Any gas to which energy is applied, either as heat or a high voltage, will produce an emission line spectrum like this.
  - Or digitally like this.

Kirchhoff’s Third Spectral Law

- Any gas placed between a continuous spectrum source and the observer will produce an absorption line spectrum like this.
  - Or digitally like this.

Astronomers’ Observations

- The atmosphere scatters blue light more effectively than red light—hence mostly blue light reaches your eye when you look at the sky.
- The atmosphere scatters blue light more effectively than red light—hence mostly red light reaches your eye when you look through a thick slice of atmosphere at the setting Sun.
An atom consists of a small, dense nucleus surrounded by electrons

- An atom has a small dense nucleus composed of protons and neutrons
- Rutherford’s experiments with alpha particles shot at gold foil helped determine the structure

**Periodic Table of the Elements**

- The number of protons in an atom’s nucleus is the atomic number for that particular element
- The same element may have different numbers of neutrons in its nucleus
- These slightly different kinds of the same elements are called isotopes

Spectral lines are produced when an electron jumps from one energy level to another within an atom

- The nucleus of an atom is surrounded by electrons that occupy only certain orbits or energy levels
- When an electron jumps from one energy level to another, it emits or absorbs a photon of appropriate energy (and hence of a specific wavelength).
- The spectral lines of a particular element correspond to the various electron transitions between energy levels in atoms of that element.
- Bohr’s model of the atom correctly predicts the wavelengths of hydrogen’s spectral lines.
Bohr’s formula for hydrogen wavelengths

\[
\frac{1}{\lambda} = R \times \left[ \frac{1}{N^2} - \frac{1}{n^2} \right]
\]

- \( N \) = number of inner orbit
- \( n \) = number of outer orbit
- \( R \) = Rydberg constant (1.097 x 10\(^7\) m\(^{-1}\))
- \( \lambda \) = wavelength of emitted or absorbed photon

Doppler Shifts

- **Red Shift**: The object is moving away from the observer
- **Blue Shift**: The object is moving towards the observer

\[
\frac{\Delta \lambda}{\lambda_0} = \frac{v}{c}
\]

- \( \Delta \lambda \) = wavelength shift
- \( \lambda_0 \) = wavelength if source is not moving
- \( v \) = velocity of source
- \( c \) = speed of light