Lecture 7: Light Waves

- Isaac Newton (1643-1727) was born in the year Galileo died
- He discovered the Law of Gravitation in 1665
- He developed the Laws of Mechanics that govern all motions
- In order to solve the resulting mathematical problem to determine the motions of real objects, he invented calculus in 1665
- Newton's laws explain the elliptical orbits deduced by Kepler!

Newton's Laws of Motion (1666)

- First Law: "Every body continues in a state of rest or uniform motion unless acted on by an outside force"

Newton's First Law of Motion
Newton's Laws of Motion (1666)

- Second Law: "When a force $F$ is applied to a mass $M$, the resulting acceleration $A$ is related to $F$ by"

$$ A = \frac{F}{M} \quad \text{or} \quad F = M \times A $$

- $A$ is directly proportional to $F$ (for fixed $M$)
- $A$ is inversely proportional to $M$ (for fixed $F$)

Newton's Law of Gravitation (1687)

- Universal Gravitation: "Every particle in the universe attracts every other particle with a force that is directly proportional to the product of the two masses and inversely proportional to the square of the distance between them"

$$ F = \frac{G M_1 M_2}{R^2} $$

- Here, $G$ is the universal gravitational constant, $M_1$ and $M_2$ are the two masses, and $R$ is the distance between them
Gravitational Acceleration

- If $M$ is the mass of the Earth and $m$ is the mass of another object at a distance $R$, then the force between them is given by
  \[ F = \frac{GMm}{R^2} \]

- The acceleration $A$ is given by the equation of motion
  \[ F = mA \]

- Combining relations yields for the acceleration
  \[ A = \frac{GM}{R^2} \]
  note that $A$ is independent of $m$

$A = 9.8 \text{ m/sec}^2 \text{ at Earth’s surface}$
Newton’s Laws

- Newton’s three laws of motion combined with his law of universal gravitation form the basis for the study of mechanics.
- These laws can be used together to derive all of Kepler’s laws from basic physical principles!
- This yields a deeper, more satisfying explanation for the patterns of motion of the planets.
- Questions remained: where does gravity come from?
- This was answered by Albert Einstein in 1915.
- Gravity is really due to the curvature of space-time...

Triumph of Scientific Method

- Science is a human endeavor, subject to the whims of culture, personality, religion, etc.
- The Scientific Method always guides us towards an objective description of our world.
- Sometimes it takes hundreds of years to make progress!!

Chapter 3: Radiation

- In order to understand the universe, we must be able to decode the information contained in the light we receive from celestial sources.
- The light takes time to reach us:
  - Moon: t=1 second
  - Sun: t=8 minutes
  - Jupiter: t=40 minutes
  - Stars: t=years
  - Galaxies: t=10^6 years
  - Beginning of universe: t=10^{10} years
- Hence telescopes are “time machines”
Radiation

• In one second, light travels a distance of 300,000 km or 186,000 miles.
• One light-year is the distance light travels in one year, or $5.9 \times 10^{12}$ miles ($9.5 \times 10^{12}$ km).
• The Andromeda Galaxy is about $2,000,000 = 2 \times 10^6$ light-years from Earth!

Radiation

• The information contained in the light we receive is unaffected by distance.
• The information remains intact so long as the light doesn’t run into something along the way.
• Since the Earth is not “special” (according to the Copernican hypothesis), we hypothesize that the physical laws we observe on Earth operate in the same way everywhere.

Radiation

• Even from such an enormous distance, the light from the Andromeda galaxy tells us about the stars there...
• The color of the light is related to the temperature of the stars emitting it.
Radiation

- As an object gets hotter, its color goes from red \(\rightarrow\) yellow \(\rightarrow\) blue \(\rightarrow\) white.
- As an object gets hotter, the radiation it emits becomes brighter.

Color and Temperature

Visible light is part of the electromagnetic radiation spectrum.
Why electromagnetic? Because the radiation contains oscillating electric and magnetic fields.

Wave Nature of Radiation
Electromagnetic Radiation

It's interesting to compare light waves with water waves. If you drop a pebble in a pond, it produces rippling waves...

We can measure the height of the water at a fixed location as a function of time:
Radiation
- Similarly, if you flash a strobe light, electromagnetic waves start to propagate...

- The electric and magnetic fields measured at point A look like this:

Light versus Water
- When you drop a rock in the pond, the waves are oscillations of the water height.
- They propagate only to the edge of the pond.
- Electromagnetic waves are oscillations of the EM field that are carried with the radiation.
- The oscillating E field produces an oscillating M field, and vice-versa! The waves are self-propagating!
- Hence, no "background fluid" is required. This is kind of weird...

Radiation
- The wavelength $\lambda$ is the distance between two peaks:

- The frequency $f$ is the number of peaks passing a fixed location per second:
• The time between passage of successive peaks at a fixed location is called the period of the wave:

\[ \text{period} = \frac{\lambda}{c} \] (seconds)

• The frequency \( f \) is related to the period by:

\[ f = \frac{1}{\text{period}} \] (cycles per second: Hz)

speed of light (universal constant)

• Combining these relations gives:

\[ f = \frac{c}{\lambda} \quad \text{or} \quad \lambda \times f = c \]

• The different colors of light correspond to different wavelengths

• Blue light has a shorter wavelength than red light
• The quantization of radiation energy was deduced by Albert Einstein in order to explain the photoelectric effect:

  - For red light, no electrons are ejected from the metal plate
  - For blue light, slow electrons are ejected
  - For ultraviolet (UV) light, fast electrons are ejected

• The observations raised an interesting question: If radiation energy is deposited continuously, then why don’t we see very slow electrons leaving the plate when we shine red light?
• The answer is that energy must be deposited in discrete amounts that increase in proportion to the frequency of the radiation

\[ E = h \times f \]

• The electrons in the plate absorb energy from a single photon
• The energy of a photon of red light is too small to kick an electron out of the metal plate
• Einstein won the Nobel Prize for this work in 1921
Radiation

- We measure the wavelength of visible light using Angstroms, with 1 Angstrom = 10^-8 cm
- Blue light has a wavelength of about 4,000 Angstroms
- Red light has a wavelength of about 7,000 Angstroms
- The energy in radiation is quantized (divided) into small units of energy called photons
- The minimum energy is contained in one photon, with energy
  \[ E = h \times f \]
  where \( h \) is Planck’s constant

- Each photon has energy
  \[ E = h \times f \]
- The energy \( E \) is related to the wavelength \( \lambda \) by
  \[ E = \frac{h \times c}{\lambda} \]
  since \( f = \frac{c}{\lambda} \)
- Hence, the energy decreases with increasing wavelength
- Therefore,
  - blue light has a higher energy than red light
  - blue light has a higher frequency than red light
  - blue light has a smaller wavelength than red light

Doppler Effect

- The observed wavelength of radiation depends on the speed of the source relative to the observer
- This is called the “Doppler Effect”
- A stationary observer see the rest wavelength (color) of the light
Doppler Effect

- An observer moving away (receding) from the source sees “stretched-out” light (longer wavelength; REDSHIFT)
  - A receding observer sees a longer wavelength, lower frequency, and lower energy, since
    \[ f = \frac{c}{\lambda} \quad \text{and} \quad E = hf \]

Doppler Effect

- An observer moving towards (approaching) the source sees “compressed” light (shorter wavelength; BLUESHIFT)
  - An approaching observer sees a shorter wavelength, higher frequency, and higher energy, since
    \[ f = \frac{c}{\lambda} \quad \text{and} \quad E = hf \]
Doppler Effect

- The emitted (rest frame) and observed wavelengths are related by

\[ \lambda_{\text{observed}} = \lambda_{\text{emitted}} \left(1 + \frac{v}{c}\right) \]

- Where \( v \) is the relative velocity of the observer and the source, and \( c \) is the speed of light.
- The observed wavelength is smaller than the emitted wavelength if \( v \) is negative (approaching observer).
- The observed wavelength is larger than the emitted wavelength if \( v \) is positive (receding observer).
- If we know both wavelengths, we can measure the relative speed \( v \).

Radiation Spectrum

- The radiation spectrum is the curve of brightness as a function of frequency (or wavelength).

- Brightness (intensity) is the amount of energy radiated by photons at the selected frequency (or wavelength).
Radiation Spectrum

- Different objects can be brighter at different frequencies (or wavelengths)

- The shape of the radiation spectrum is usually related to the temperature of the object

Black-Body Radiation

- The spectrum emitted from a body by virtue of its temperature is called black-body radiation or Planck radiation
Radiation Spectrum

- Visible radiation corresponds to temperatures in the range 4,000 K (red hot) to 7,000 K (blue hot)

- For the Planck curve, the wavelength of peak brightness determines its color