The Nature of Light
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 the light was traveling. 

\[ d = rt \] again gave \( c \)
Light is electromagnetic radiation and is characterized by its wavelength ($\lambda$)
Wavelength and Frequency

Frequency and wavelength of an electromagnetic wave

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

- \( v \) = frequency of an electromagnetic wave (in Hz)
- \( c \) = speed of light = \( 3 \times 10^8 \) m/s
- \( \lambda \) = wavelength of the wave (in meters)
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.
Because of its electric and magnetic properties, light is also called electromagnetic radiation.

- Visible light falls in the 400 to 700 nm range.
- Stars, galaxies and other objects emit light in all wavelengths.
Three Temperature Scales

- **Kelvin**
  - Sun’s core temperature: $15.5 \times 10^6$ K
  - Boiling point of water: 373 K
  - Freezing point of water: 0 K
  - Absolute zero: 0 K

- **Celsius**
  - Sun’s surface temperature: 5800 °C
  - Boiling point of water: 100 °C
  - Freezing point of water: 0 °C
  - Absolute zero: -273 °C

- **Fahrenheit**
  - Sun’s core temperature: 27.9 $\times 10^6$ °F
  - Boiling point of water: 9981 °F
  - Freezing point of water: 32 °F
  - Absolute zero: -460 °F
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

\[ \lambda_{\text{max}} = \frac{0.0029 \text{ K m}}{T} \]

\( \lambda_{\text{max}} \) = 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:

\[ E = \sigma T^4 \]
At a distance of 1 AU from the Sun, this square meter of area receives 1370 watts of light power from the Sun.
• 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

(a) CONTINUOUS SPECTRUM
(blackbody emits light at all wavelengths)

(b) ABSORPTION LINE SPECTRUM
(atomic spectrum of cooler gas; atoms absorb certain specific wavelengths, producing dark lines in the spectrum)

(c) EMISSION LINE SPECTRUM
(atomic spectrum of cooler gas; atoms re-emite absorbed light energy at 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
Kirchoff’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
Kirchoff’s Third Spectral Law

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

– or digitally like this
Astronomers’ Observations

Absorption spectrum of the Sun

Emission spectrum of iron (in the laboratory on Earth)

For each emission line of iron, there is a corresponding absorption line in the solar spectrum; hence there must be iron in the Sun’s atmosphere.
The atmosphere scatters blue light more effectively than red light — hence mostly blue light reaches your eye when you look at the sky.

(a) Why the sky looks blue
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.

(b) Why the setting Sun looks red
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
Nucleus has protons (shown in red) and neutrons (shown in blue)
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.
(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up to the $n = 3$ orbit

(b) Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon
Lyman series (ultraviolet) of spectral lines: produced by electron transitions between the $n = 1$ orbit and higher orbits ($n = 2, 3, 4, \ldots$)

Balmer series (visible and ultraviolet) of spectral lines: produced by electron transitions between the $n = 2$ orbit and higher orbits ($n = 3, 4, 5, \ldots$)

Paschen series (infrared) of spectral lines: produced by electron transitions between the $n = 3$ orbit and higher orbits ($n = 4, 5, 6, \ldots$)
Bohr’s formula for hydrogen wavelengths

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

N = number of inner orbit

n = number of outer orbit

R = Rydberg constant (1.097 \times 10^7 m^{-1})

\( \lambda \) = wavelength of emitted or absorbed photon
Balmer Lines in Star Spectrum

Shorter wavelength

H40  H30  H20  H15
The wavelength of a spectral line is affected by the relative motion between the source and the observer.

Wave crest 1: emitted when light source was at $S_1$

Wave crest 2: emitted when light source was at $S_2$

Wave crests 3 and 4: emitted when light source was at $S_3$ and $S_4$, respectively

This observer sees blueshift

This observer sees redshift
Doppler Shifts

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

$$\frac{\Delta \lambda}{\lambda_o} = \frac{v}{c}$$

- $\Delta \lambda = \text{wavelength shift}$
- $\lambda_o = \text{wavelength if source is not moving}$
- $v = \text{velocity of source}$
- $c = \text{speed of light}$
Key Words

- absolute zero
- absorption line spectrum
- atom
- atomic number
- Balmer line
- Balmer series
- blackbody
- blackbody curve
- blackbody radiation
- blueshift
- Bohr orbits
- continuous spectrum
- degrees Celsius
- degrees Fahrenheit
- Doppler effect
- electromagnetic radiation
- electromagnetic spectrum
- electromagnetism
- electron
- electron volt
- element
- emission line spectrum
- energy flux
- energy level
- energy-level diagram
- excited state
- Frequency
- gamma rays
- ground state
- infrared radiation
- ionization
- isotope
- joule
- kelvin
- Kirchhoff’s laws
- light scattering
- *luminosity
- Lyman series
- microwaves
- nanometer
- neutron
- nucleus
- Paschen series
- periodic table
- photoelectric effect
- photon
- Planck’s law
- proton
- quantum mechanics
- radial velocity
- radio waves
- redshift
- *solar constant
- spectral analysis
- spectral line
- spectroscopy
- spectrum (plural spectra)
- Stefan-Boltzmann law
- ultraviolet radiation
- visible light
- watt
- wavelength
- wavelength of maximum emission
- Wien’s law
- X rays