Chapter 5
Light and Matter:
Reading Messages from the Cosmos

5.1 Light in Everyday Life

Our goals for learning:
• How do we experience light?
• How do light and matter interact?

How do we experience light?
• The warmth of sunlight tells us that light is a form of energy
• We can measure the flow of energy in light in units of **watts**: 1 watt = 1 joule/s
How do light and matter interact?

- Emission
- Absorption
- Transmission
  - Transparent objects transmit light
  - Opaque objects block (absorb) light
- Reflection or Scattering

Reflection and Scattering

Mirror reflects light in a particular direction
Movie screen scatters light in all directions

Interactions of Light with Matter

Interactions between light and matter determine the appearance of everything around us
What have we learned?

• How do we experience light?
  – Light is a form of energy
  – Light comes in many colors that combine to form white light.
• How does light interact with matter?
  – Matter can emit light, absorb light, transmit light, and reflect (or scatter) light.
  – Interactions between light and matter determine the appearance of everything we see.

5.2 Properties of Light

Our goals for learning:
• What is light?
• What is the electromagnetic spectrum?

What is light?

• Light can act either like a wave or like a particle

• Particles of light are called photons
Waves

- A wave is a pattern of motion that can carry energy without carrying matter along with it.

Properties of Waves

- **Wavelength** is the distance between two wave peaks.
- **Frequency** is the number of times per second that a wave vibrates up and down.

\[
\text{wave speed} = \text{wavelength} \times \text{frequency}
\]

Light: Electromagnetic Waves

- A light wave is a vibration of electric and magnetic fields.
- Light interacts with charged particles through these electric and magnetic fields.
Particles of Light

- Particles of light are called photons
- Each photon has a wavelength and a frequency
- The energy of a photon depends on its frequency

Wavelength, Frequency, and Energy

\[ \lambda \times f = c \]

\( \lambda \) = wavelength, \( f \) = frequency
\( c = 3.00 \times 10^8 \text{ m/s} = \text{speed of light} \)

\[ E = h \times f = \text{photon energy} \]
\( h = 6.626 \times 10^{-34} \text{ joule} \times \text{s} = \text{photon energy} \)

What have we learned?

- What is light?
  - Light can behave like either a wave or a particle
  - A light wave is a vibration of electric and magnetic fields
  - Light waves have a wavelength and a frequency
  - Photons are particles of light.
- What is the electromagnetic spectrum?
  - Human eyes cannot see most forms of light.
  - The entire range of wavelengths of light is known as the electromagnetic spectrum.
5.3 Properties of Matter

Our goals for learning:
• What is the structure of matter?
• What are the phases of matter
• How is energy stored in atoms?

Atomic Terminology

• Atomic Number = # of protons in nucleus
• Atomic Mass Number = # of protons + neutrons

• Molecules: consist of two or more atoms (H₂O, CO₂)

Atomic Terminology

• Isotope: same # of protons but different # of neutrons. (⁴He, ³He)
What are the phases of matter?

- Familiar phases:
  - Solid (ice)
  - Liquid (water)
  - Gas (water vapor)

- Phases of same material behave differently because of differences in chemical bonds

Phase Changes

- **Ionization**: Stripping of electrons, changing atoms into plasma
- **Dissociation**: Breaking of molecules into atoms
- **Evaporation**: Breaking of flexible chemical bonds, changing liquid into solid
- **Melting**: Breaking of rigid chemical bonds, changing solid into liquid

How is energy stored in atoms?

Excited States

- Electrons in atoms are restricted to particular energy levels

Ground State
Energy Level Transitions

- The only allowed changes in energy are those corresponding to a transition between energy levels.

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What have we learned?

- What is the structure of matter?
  - Matter is made of atoms, which consist of a nucleus of protons and neutrons surrounded by a cloud of electrons.
- What are the phases of matter?
  - Adding heat to a substance changes its phase by breaking chemical bonds.
  - As temperature rises, a substance transforms from a solid to a liquid to a gas, then the molecules can dissociate into atoms.
  - Stripping of electrons from atoms (ionization) turns the substance into a plasma.

What have we learned?

- How is energy stored in atoms?
  - The energies of electrons in atoms correspond to particular energy levels.
  - Atoms gain and lose energy only in amounts corresponding to particular changes in energy levels.
5.4 Learning from Light

Our goals for learning:

- What are the three basic types of spectra?
- How does light tell us what things are made of?
- How does light tell us the temperatures of planets and stars?
- How do we interpret an actual spectrum?

Continuous Spectrum

- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption.

Emission Line Spectrum

- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines.
Absorption Line Spectrum

- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.

Chemical Fingerprints

- Each type of atom has a unique set of energy levels.
- Each transition corresponds to a unique photon energy, frequency, and wavelength.

Energy levels of Hydrogen

Chemical Fingerprints

- Downward transitions produce a unique pattern of emission lines.
Chemical Fingerprints

• Because those atoms can absorb photons with those same energies, upward transitions produce a pattern of absorption lines at the same wavelengths.

Chemical Fingerprints

• Observing the fingerprints in a spectrum tells us which kinds of atoms are present.

Energy Levels of Molecules

• Molecules have additional energy levels because they can vibrate and rotate.
Energy Levels of Molecules

- The large numbers of vibrational and rotational energy levels can make the spectra of molecules very complicated
- Many of these molecular transitions are in the infrared part of the spectrum

Thermal Radiation

- Nearly all large or dense objects emit thermal radiation, including stars, planets, you…
- An object’s thermal radiation spectrum depends on only one property: its temperature

Properties of Thermal Radiation

1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.
How do we interpret an actual spectrum?

• By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What have we learned?

• What are the three basic types of spectra?
  – Continuous spectrum, emission line spectrum, absorption line spectrum
• How does light tell us what things are made of?
  – Each atom has a unique fingerprint.
  – We can determine which atoms something is made of by looking for their fingerprints in the spectrum.

What have we learned?

• How do we interpret an actual spectrum?
  – By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

• How does light tell us the temperatures of planets and stars?
  – Nearly all large or dense objects emit a continuous spectrum that depends on temperature.
  – The spectrum of that thermal radiation tells us the object’s temperature.
5.5 The Doppler Effect

Our goals for learning:

• How does light tell us the speed of a distant object?
• How does light tell us the rotation rate of an object?

Measuring the Shift

Stationary
Moving Away
Away Faster
Moving Toward
Toward Faster

• We generally measure the Doppler Effect from shifts in the wavelengths of spectral lines

How does light tell us the rotation rate of an object?

• Different Doppler shifts from different sides of a rotating object spread out its spectral lines
Spectrum of a Rotating Object

• Spectral lines are wider when an object rotates faster

What have we learned?

• How does light tell us the speed of a distant object?
  – The Doppler effect tells us how fast an object is moving toward or away from us.
    • Blueshift: objects moving toward us
    • Redshift: objects moving away from us

• How does light tell us the rotation rate of an object?
  – The width of an object’s spectral lines can tell us how fast it is rotating