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**: $1 \text{ watt} = 1 \text{ joule/s}$
Colors of Light

- White light is made up of many different colors
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
Wavelength and Frequency

wavelength \times frequency = \text{speed of light} = \text{constant}
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 \hspace{1em}, \hspace{1em} \( f = \) frequency

\( c = 3.00 \times 10^8 \text{ m/s} = \) speed of light

\[ E = h \times f = \text{photon energy} \]

\( h = 6.626 \times 10^{-34} \text{ joule} \times \text{s} = \text{photon energy} \)
Special Topic: Polarized Sunglasses

• **Polarization** describes the direction in which a light wave is vibrating
• Reflection can change the polarization of light
• Polarized sunglasses block light that reflects off of horizontal surfaces
What is the electromagnetic spectrum?
The Electromagnetic Spectrum

Frequency: $3.00 \times 10^{15}$ Hz
Wavelength: $1.00 \times 10^{-7}$ m
Speed: $3 \times 10^{8}$ m/s
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?
What is the structure of matter?

Atom

Electron Cloud

Nucleus

10^{-10} meter
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. \((^4\text{He}, ^3\text{He})\)
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
Phases of Water
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
Phases and Pressure

- Phase of a substance depends on both temperature and pressure
- Often more than one phase is present
How is energy stored in atoms?

- Electrons in atoms are restricted to particular energy levels

Excited States

Ground State

- Electrons in atoms are restricted to particular energy levels
Energy Level Transitions

- The only allowed changes in energy are those corresponding to a transition between energy levels.
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 amount 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?
What are the three basic types of spectra?

Continuous Spectrum

Emission Line Spectrum

Absorption Line Spectrum

Spectra of astrophysical objects are usually combinations of these three basic types.
The Sun
Toaster oven filament
Neon lamp
Spica (blue, O star)
Reflected sunlight from a green leaf

Visual spectrum

Plot of intensity vs. wavelength

Intensity (relative)

Wavelength (nm)
# Three Types of Spectra

## The Details of Spectra - Illustrating Kirchhoff's Laws

### Continuous Spectrum
- **Show**
- **Continuous Spectrum**
  - The spectrum shows a smooth, continuous rainbow of light.
  - A graph of the spectrum is also continuous, notice that intensity varies slightly at different wavelengths.
- **The light bulb produces light with a continuous spectrum**

### Emission Line Spectrum
- **Show**
- **Emission Line Spectrum**
  - We see bright emission lines at specific wavelengths (color), but no other light.
  - The graph shows an upward spike at the wavelength of each emission line.
- **The cloud also emits its own light, but only at specific wavelengths determined by its composition**

### Absorption Line Spectrum
- **Show**
- **Absorption Line Spectrum**
  - We see dark absorption lines where the cloud has absorbed lights of specific wavelengths (colors).
  - The graph shows a dip in intensity at the wavelength of each absorption line.
- **The cloud absorbs light at specific wavelengths determined by its composition**

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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
How does light tell us what things are made of?

Spectrum of the Sun
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

- Each type of atom has a unique spectral fingerprint
Sample 1

H - Hydrogen
He - Helium
Li - Lithium
C - Carbon
Na - Sodium
Ne - Neon

Wavelength (nm)
Chemical Fingerprints

- Observing the fingerprints in a spectrum tells us which kinds of atoms are present
Example: Solar Spectrum
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.
How does light tell us the temperatures of planets and stars?
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.
Wien's Law: The Cosmic Thermometer

![Graph showing the intensity of radiation versus wavelength, with a peak in the visible spectrum and a decrease towards ultraviolet and infrared. The graph includes a scale for temperature from 50 K to 10^5 K, with a calculated temperature of 9.91 x 10^2 K.]
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 is this object?

Reflected Sunlight:
Continuous spectrum of visible light is like the Sun’s except that some of the blue light has been absorbed - object must look red
What is this object?

Thermal Radiation:
Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K
What is this object?

Carbon Dioxide: Absorption lines are the fingerprint of CO$_2$ in the atmosphere
What is this object?

Ultraviolet Emission Lines:
Indicate a hot upper atmosphere
What is this object?

Mars!
What have we learned?

• What are the three basic type 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 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.

• 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.
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?
How does light tell us the speed of a distant object?

The Doppler Effect
The Doppler Effect
Explaining the Doppler Effect
Same for Light
Measuring the Shift

- We generally measure the Doppler Effect from shifts in the wavelengths of spectral lines
The amount of blue or red shift tells us an object's speed toward or away from us:

- **Spectrum of Stationary Hydrogen Gas (Laboratory)**
  - Wavelength (nm)
  - Range 2

- **Spectrum of Moving Cloud of Hydrogen Gas**
  - Wavelength (nm)

  Speed of Gas Cloud (relative to us):
  - Moving toward us: 3000 km/s
  - Moving away from us: 3000 km/s
  - Speed = 0 km/s
Doppler shift tells us ONLY about the part of an object’s motion toward or away from us:
Measuring Redshift
Measuring Redshift
Measuring Velocity

Spectrum of Stationary Hydrogen Gas (Laboratory)

- Rest wavelength: 400.0 nm

Spectrum of Moving Cloud of Hydrogen Gas

- Observed wavelength: 400.0 nm
- Wavelength shift: ---- nm
- Relative speed: ------ km/s
Measuring Velocity

Spectrum of Stationary Hydrogen Gas (Laboratory)

Rest wavelength: 400.0 nm

Spectrum of Cold Gas Cloud in front of Quasar

Observed wavelength: 400.0 nm

Wavelength shift: nm

Relative speed: km/s
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