Light and Matter: Reading Messages from the Cosmos
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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. (To get an idea of the magnitude of 1 joule: 1 calorie = 4200 joules. A person consumes and burns ~ 2000 calories per day = 8,400,000 joules. There are 24x60x60 = 86,400 seconds in a day. So a human burns ~ 8,400,000/86,400 = 97.2 joules/second ~ 100 Watt. So you use as much energy as a 100 Watt light bulb that is on continuously!)
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/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.

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Thought Question

Why is a rose red?

A. The rose absorbs red light.
B. The rose transmits red light.
C. The rose emits red light.
D. The rose reflects red light.
Thought Question

Why is a rose red?

A. The rose absorbs red light.
B. The rose transmits red light.
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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 do light and matter interact?
  – 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.

*Wavelength* is the distance from one peak to the next (or one trough to the next).

Leaf bobs up and down with the **frequency** of the waves.
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.

Wave speed = wavelength \times frequency
A light wave is a vibration of electric and magnetic fields.

- Electrons move when light passes by, showing that light carries a vibrating electric field.

- 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 x frequency = speed of light = constant

wavelength = 1 cm, frequency = 30 GHz

wavelength = 0.5 cm, frequency = 2 \times 30 \text{ GHz} = 60 \text{ GHz}

wavelength = 0.25 cm, frequency = 4 \times 30 \text{ GHz} = 120 \text{ GHz}
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

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

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

\( h = 6.626 \times 10^{-34} \) joule x s = Planck's constant
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

- **Wavelength (meters)**
  - Abbreviations: gamma rays, X rays, ultraviolet, infrared, radio
  - Scale: $10^{-12}$ to $10^2$

- **Frequency (hertz)**
  - Scale: $10^0$ to $10^{20}$

- **Energy (electron-volts)**
  - Scale: $10^{-8}$ to $10^6$

- **Sources on Earth**
  - radioactive elements
  - X-ray machines
  - light bulb
  - people
  - radar
  - microwave oven
  - radio transmitter

- **Cosmic Sources**
  - gamma ray burst
  - black hole accretion disk
  - Sun's chromosphere
  - Sun
  - planets, star-forming clouds
  - cosmic microwave background
  - radio galaxy
Thought Question

The higher the photon energy,

A. the longer its wavelength.
B. the shorter its wavelength.
C. energy is independent of wavelength.
Thought Question

The higher the photon energy,

A. the longer its wavelength.

B. the shorter its wavelength.

C. energy is independent of wavelength.
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?
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 (\(^4\text{He}, \text{\textsuperscript{3}He}\))

Isotopes of Carbon

- carbon-12 (\(^{12}\text{C}\), 6 protons + 6 neutrons)
- carbon-13 (\(^{13}\text{C}\), 6 protons + 7 neutrons)
- carbon-14 (\(^{14}\text{C}\), 6 protons + 8 neutrons)
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
• 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.
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 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 does light tell us the speed of a distant object?
What are the three basic types of spectra?

- Spectra of astrophysical objects are usually combinations of these three basic types.
What are the three basic types of spectra?

- The Sun
- Toaster oven filament
- Neon lamp
- Spica (blue, O star)
- Reflected sunlight from a green leaf

Visual spectrum

Plot of intensity vs. wavelength

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Three Types of Spectra

a. Continuous Spectrum

b. Emission Line Spectrum

c. Absorption Line Spectrum
The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption.
• 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?
Chemical Fingerprints

- Each type of atom has a unique set of energy levels.

- Each transition corresponds to a unique photon energy, frequency, and wavelength.

a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.
Chemical Fingerprints

- Downward transitions produce a unique pattern of emission lines.

The spectrum shows emission lines produced by downward transitions between higher levels and level 2 in hydrogen.
Chemical Fingerprints
Chemical Fingerprints

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

| 410.1 nm | 434.0 nm | 486.1 nm | 656.3 nm |

- This spectrum shows absorption lines produced by upward transitions between level 2 and higher levels in hydrogen.
Chemical Fingerprints

Production of Absorption Lines

White light from star

Star

Add Gas Cloud

Telescope

Spectrum

Intensity

Wavelength (nm)

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Chemical Fingerprints

- Each type of atom has a unique spectral fingerprint.
Chemical Fingerprints

- Observing the fingerprints in a spectrum tells us which kinds of atoms are present.
Chemical Fingerprints

**Example:** Solar Spectrum
• 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.
Thought Question

Which letter(s) label(s) absorption lines?
Thought Question

Which letter(s) label(s) absorption lines?
Thought Question

Which letter(s) label(s) the peak (greatest intensity) of infrared light?
Thought Question

Which letter(s) label(s) the peak (greatest intensity) of infrared light?
Thought Question

Which letter(s) label(s) emission lines?
Thought Question

Which letter(s) label(s) emission lines?
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.
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
Thought Question

Which is hottest?

A. a blue star
B. a red star
C. a planet that emits only infrared light
Thought Question

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A. a blue star
B. a red star
C. a planet that emits only infrared light
Thought Question

Why don't we glow in the dark?

A. People do not emit any kind of light.
B. People only emit light that is invisible to our eyes.
C. People are too small to emit enough light for us to see.
D. People do not contain enough radioactive material.
Thought Question

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Example: 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.
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K.
Carbon dioxide:
Absorption lines are the fingerprint of CO$_2$ in the atmosphere.
Ultraviolet emission lines: Indicate a hot upper atmosphere
What is this object?

Mars!
How does light tell us the speed of a distant object?
The Doppler Effect
The Doppler Effect

• Same for Light
Measuring the Shift

- We generally measure the Doppler effect from shifts in the wavelengths of spectral lines.
Measuring the Shift

The amount of blueshift or redshift tells us an object's speed toward or away from us.
Measuring the Shift

• Doppler shift tells us ONLY about the part of an object's motion toward or away from us:
Thought Question

I measure a line in the lab at 500.7 nm. The same line in a star has wavelength 502.8 nm. What can I say about this star?

A. It is moving away from me.
B. It is moving toward me.
C. It has unusually long spectral lines.
Thought Question

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Measuring the Shift

- Measuring Redshift
Measuring the Shift

- Measuring Redshift
Measuring the Shift

- 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

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Measuring the Shift

• Measuring Velocity
Rotation Rates

• 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?

• 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 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 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.