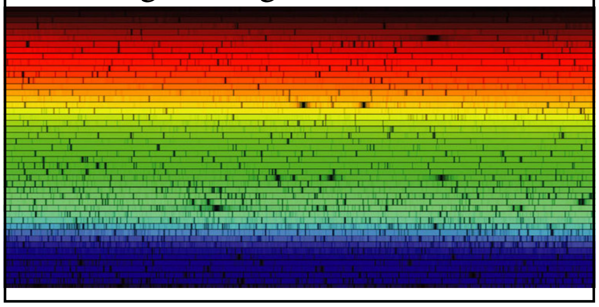
Chapter 5
Light and Matter:
Reading Messages from the Cosmos



Agenda

- Announce:
  - Light & Spectroscopy Tutorial Due by next test (counted as HW)
  - Thin Lens Lab on Thursday
- Projects
- Ch. 5—Light & Matter
- Elegant Universe

5.1 Light in Everyday Life

- 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 (power) in light in units of **watts:** 1 watt = 1 joule/s

What do you pay for?

- Watts
- Joules

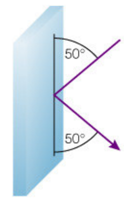
Colors of Light

- White light is made up of many different colors

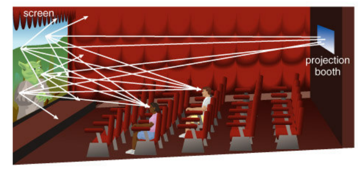
How do light and matter interact?

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

Reflection and Scattering

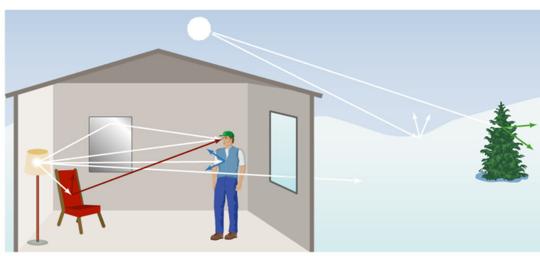


Mirror reflects light in a particular direction



Movie screen scatters light in all directions

Interactions of Light with Matter



Interactions between light and matter determine the appearance of everything around us

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.

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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 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.

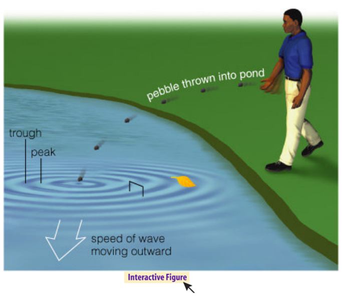
5.2 Properties of Light

- What is light?
- What is the electromagnetic spectrum?

What is light?

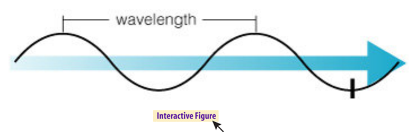
- Light can act either like a wave or like a particle
- Particles of light are called **photons**

Waves



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

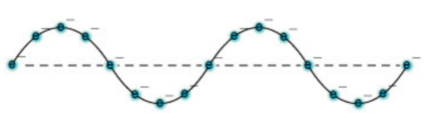
Properties of Waves



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

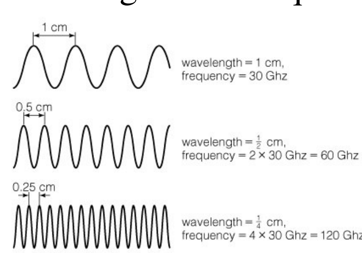
wave speed = wavelength x frequency

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 x frequency = speed of light = 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

$$\lambda \times f = c$$

λ = wavelength , f = frequency

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

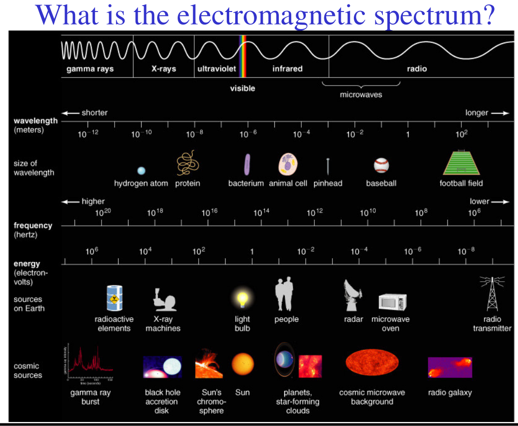
$E = h \times f$ = photon energy

$h = 6.626 \times 10^{-34}$ joule x s

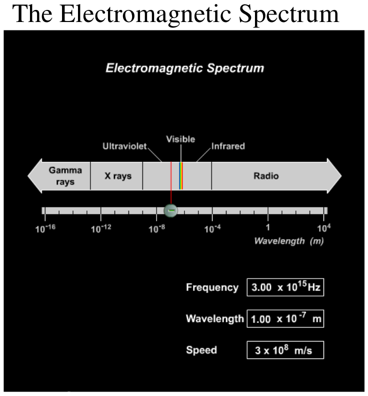
Special Topic: Polarized Sunglasses

- **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 horizontal surfaces

What is the electromagnetic spectrum?



The Electromagnetic Spectrum



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.

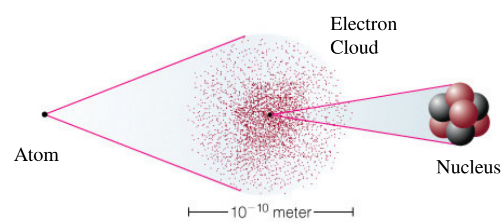
What have we learned?

- 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

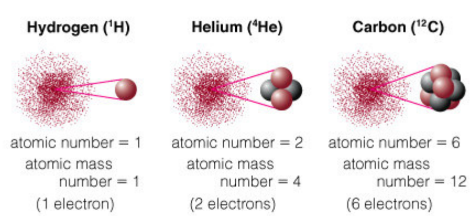
- What is the structure of matter?
- What are the phases of matter
- How is energy stored in atoms?

What is the structure of matter?



Atomic Terminology

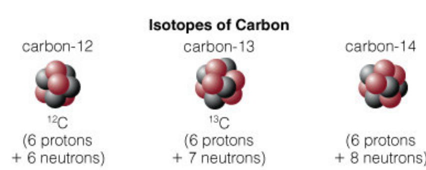
- Atomic Number = # of protons in nucleus
- Atomic Mass Number = # of protons + neutrons



- Molecules: consist of two or more atoms (H_2O, CO_2)

Atomic Terminology

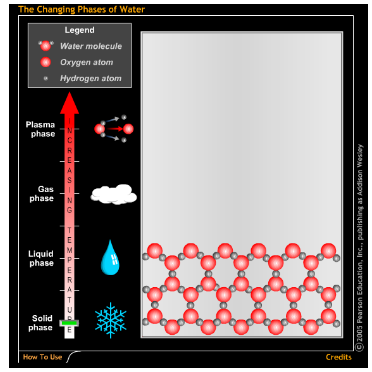
- Isotope: same # of protons but different # of neutrons. (^{4}He, ^{3}He)



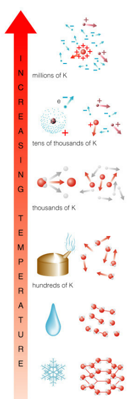
What are the phases of matter?

- Familiar phases:
  - Solid (ice)
  - Liquid (water)
  - Gas (water vapor)
- Phases of same material behave differently because of differences in chemical bonds

Phases of Water

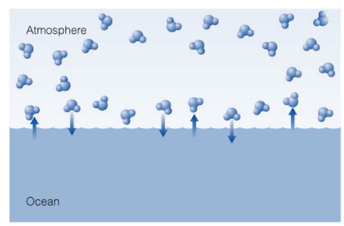


Phase Changes



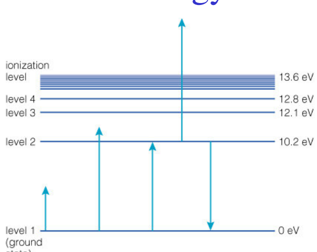
- **Ionization:** Stripping of electrons, changing atoms into plasma
- **Dissociation:** Breaking of molecules into atoms
- **Evaporation:** Breaking of flexible chemical bonds, changing liquid into solid
- **Melting:** Breaking of rigid chemical bonds, changing solid into liquid

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?

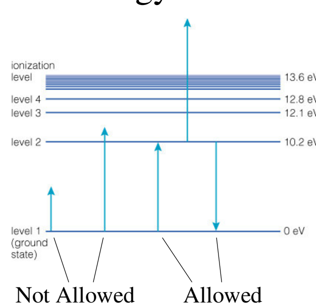


Excited States

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

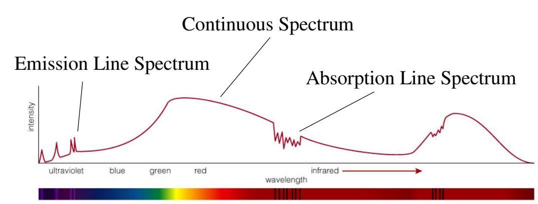
What have we learned?

- 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

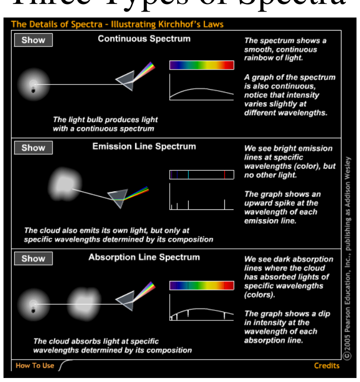
- What are the three basic types of spectra?
- How does light tell us what things are made of?
- How does light tell us the temperatures of planets and stars?
- How do we interpret an actual spectrum?

What are the three basic types of spectra?

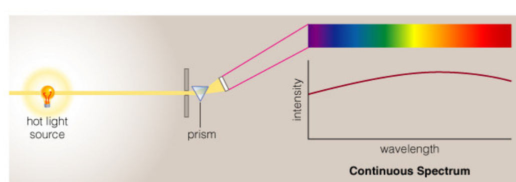


Spectra of astrophysical objects are usually combinations of these three basic types

Three Types of Spectra

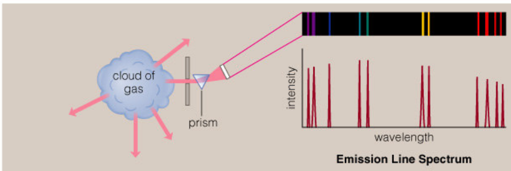


Continuous Spectrum



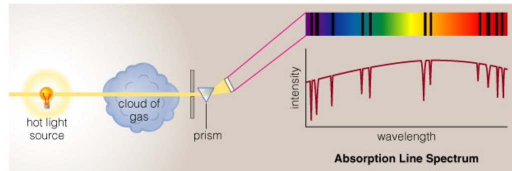
- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption

Emission Line Spectrum



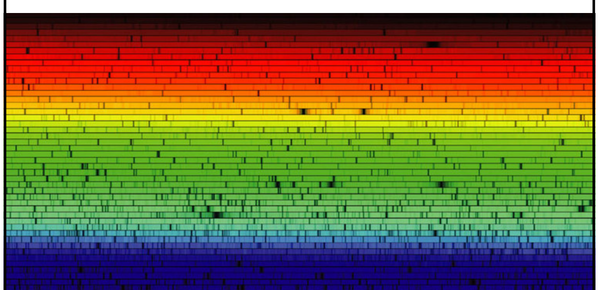
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines

Absorption Line Spectrum



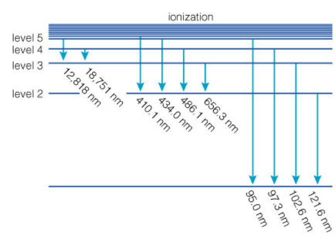
- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum

How does light tell us what things are made of?



Spectrum of the Sun

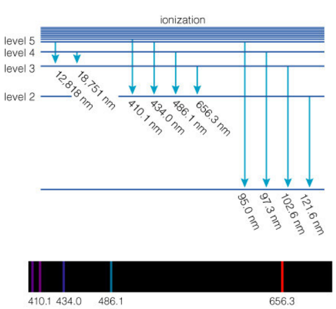
Chemical Fingerprints



Energy levels of Hydrogen

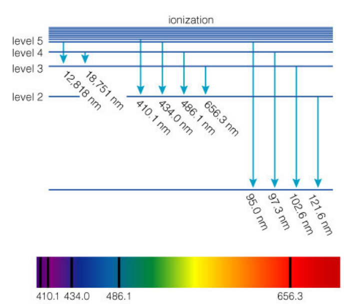
- Each type of atom has a unique set of energy levels
- Each transition corresponds to a unique photon energy, frequency, and wavelength

Chemical Fingerprints



- Downward transitions produce a unique pattern of emission lines

Chemical Fingerprints

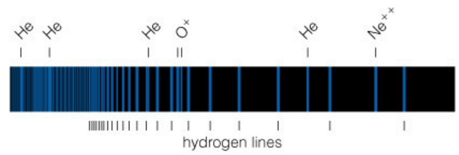


- Because those atoms can absorb photons with those same energies, upward transitions produce a pattern of absorption lines at the same wavelengths

Chemical Fingerprints

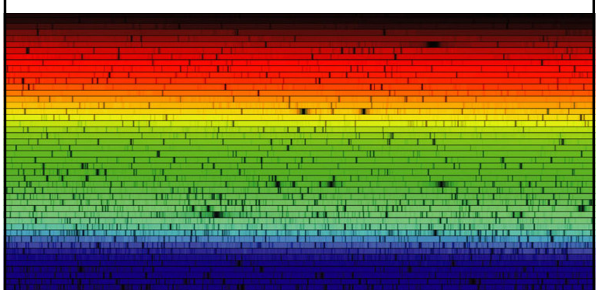
- Each type of atom has a unique spectral fingerprint

Chemical Fingerprints

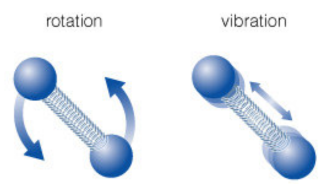


- Observing the fingerprints in a spectrum tells us which kinds of atoms are present

Example: Solar Spectrum



Energy Levels of Molecules



- Molecules have additional energy levels because they can vibrate and rotate

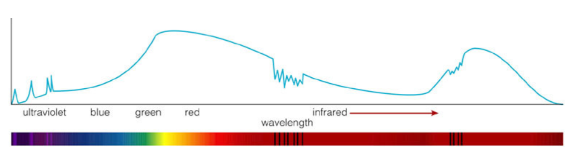
Energy Levels of Molecules

Spectrum of Molecular Hydrogen

- 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) labels absorption lines?



A B C D E

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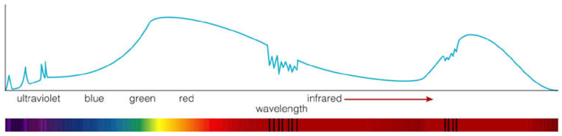
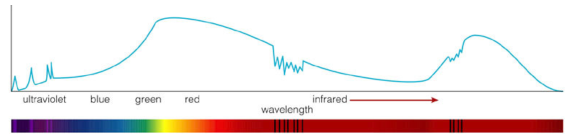


A B **C** **D** E

Thought Question

Which letter(s) labels the peak (greatest intensity) of infrared light?



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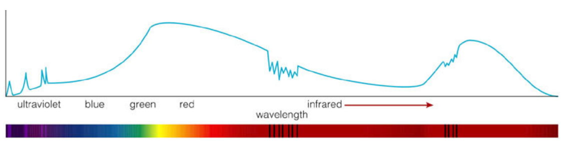
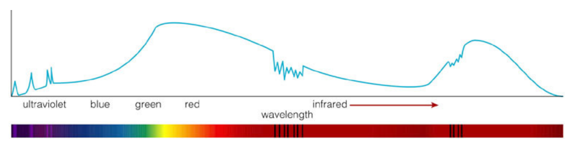


A B C D **E**

Thought Question

Which letter(s) labels emission lines?



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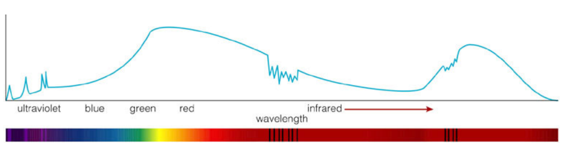
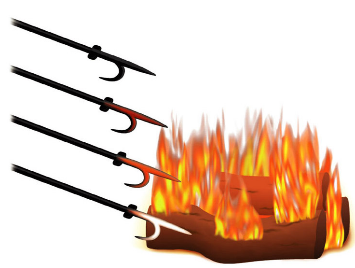


A B C D E

How does light tell us the temperatures of planets and stars?

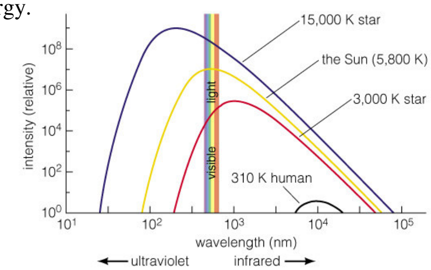


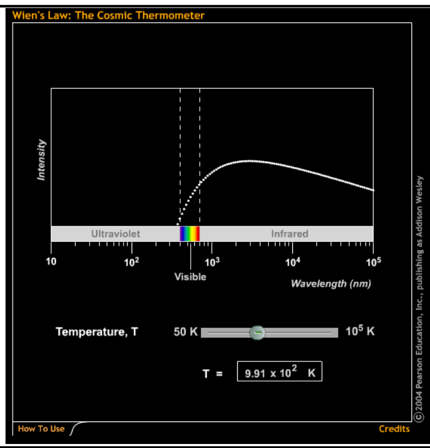
Thermal Radiation

- 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.





Thought Question
Which is hotter?

a) A blue star.
b) A red star.
c) A planet that emits only infrared light.

Thought Question
Which is hotter?

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
Why don't we glow in the dark?

a) People do not emit any kind of light.
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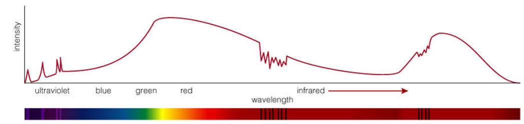
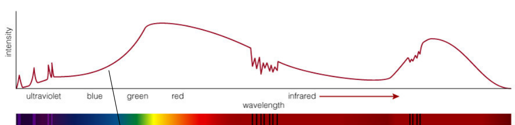
How do we interpret an actual spectrum?



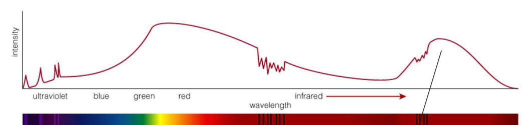
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What is this object?



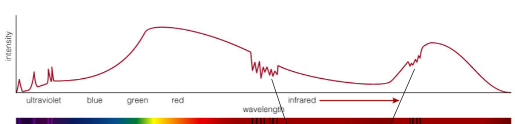
Reflected Sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed - object must look red

What is this object?



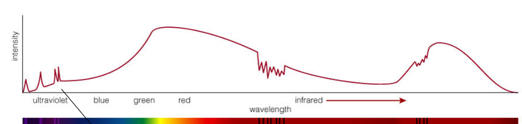
Thermal Radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K

What is this object?



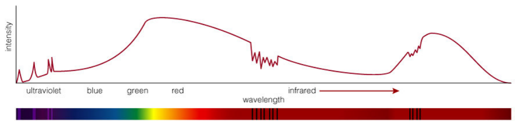
Carbon Dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere

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.

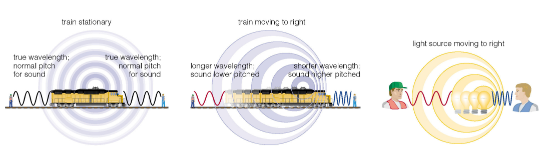
What have we learned?

- 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

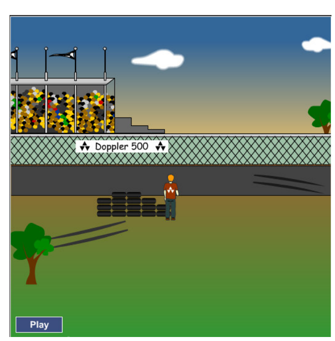
- Our goals for learning
- How does light tell us the speed of a distant object?
- How does light tell us the rotation rate of an object?

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

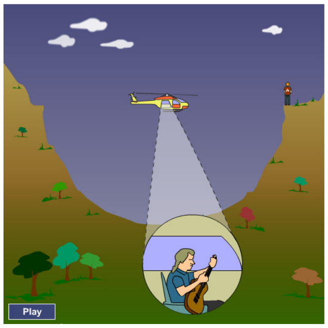


The Doppler Effect

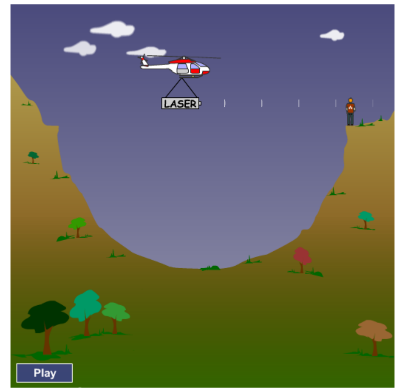
The Doppler Effect



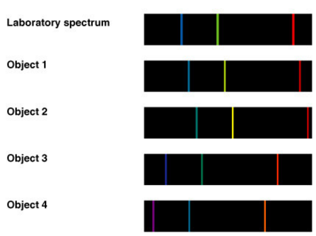
Explaining the Doppler Effect



Same for Light



Measuring the Shift



Stationary

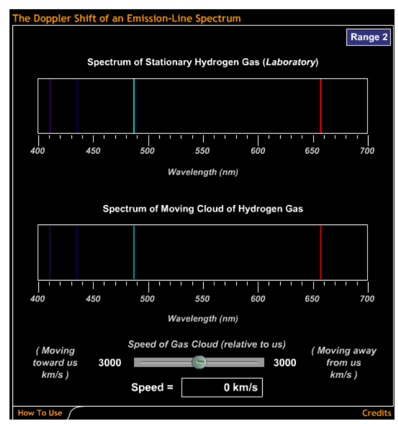
Moving Away

Away Faster

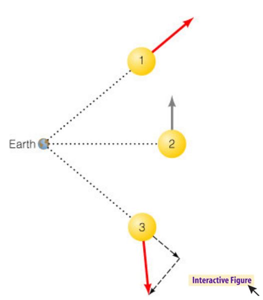
Moving Toward

Toward Faster

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



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.

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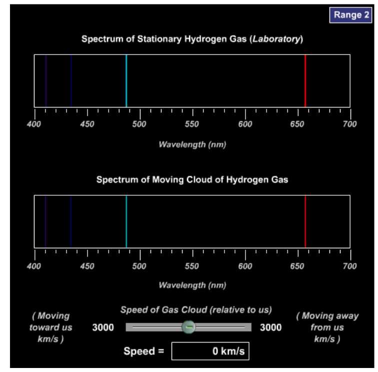
Measuring Redshift



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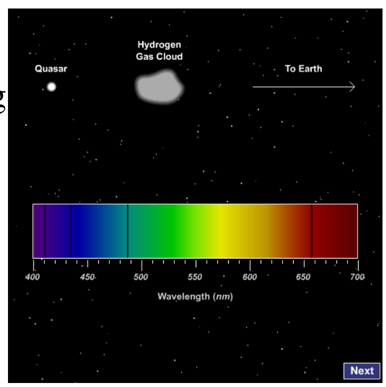
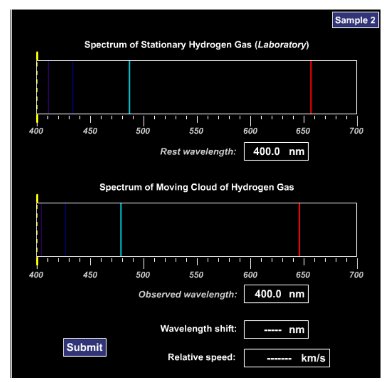
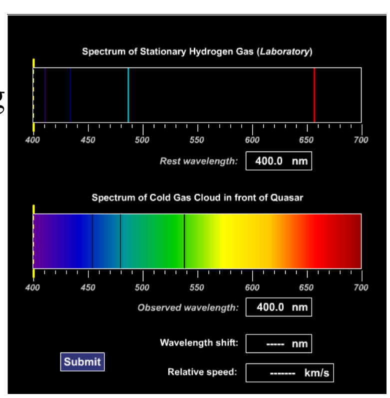


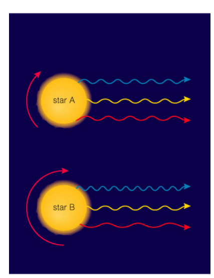
Measuring Velocity



Measuring Velocity

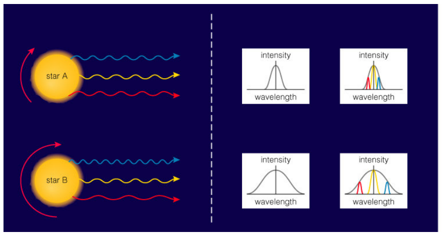


How does light tell us the rotation rate of an object?



- 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