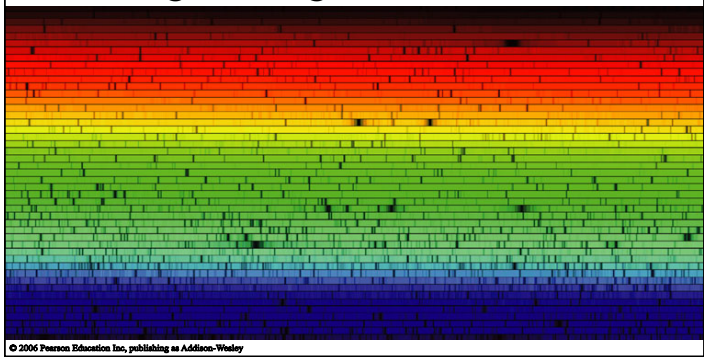
Chapter 5
Light and Matter:
Reading Messages from the Cosmos



How do we experience light?

- The warmth of sunlight tells us that light is a form of energy
- We can measure the amount of energy emitted by a source in units of **watts:** Power = energy/time (1 watt = 1 joule/s)
- We can measure the flux received in watts/meter^2
- How are flux and power related?

$$\text{Flux} = \frac{\text{Power}}{\text{surface area}} = \frac{E/t}{4\pi d^2} \quad (\text{watt/meter}^2)$$

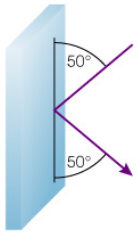
Colors of Light

- White light is made up of many different colors

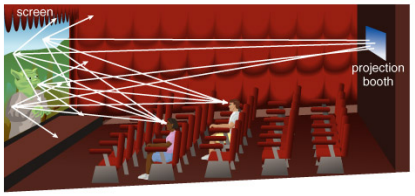
How do light and matter interact?

- Emission
- Absorption
- Transmission
- Reflection or Scattering

Reflection and Scattering

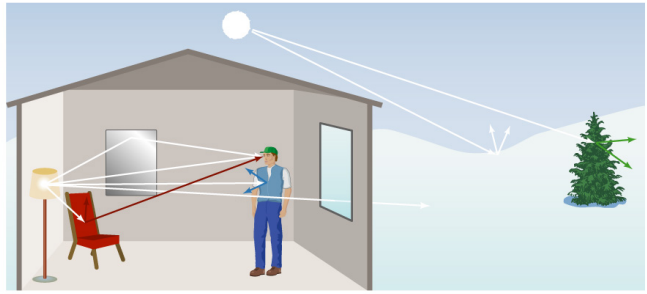


Mirror reflects light in a particular direction



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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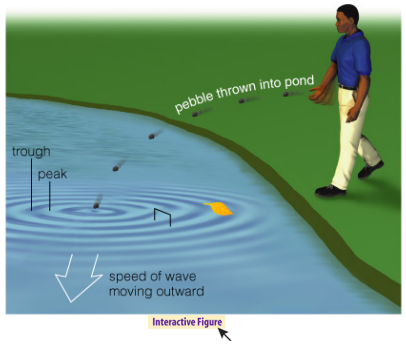
What is light?

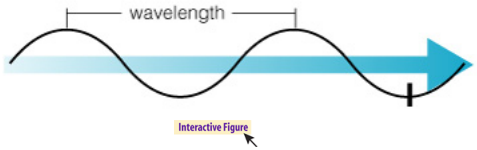
- Light can act either like a wave or like a particle
- Particles of light are called **photons**

Waves



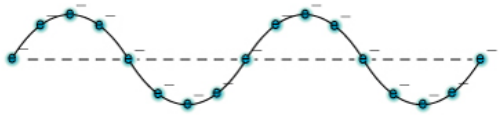
- A **wave** is a pattern of motion that can carry energy without carrying matter along with it

Properties of Waves



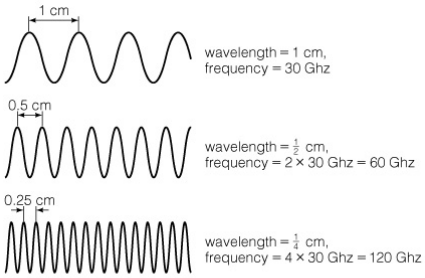
- **Wavelength** is the distance between two wave peaks
- **Frequency** is the number of times per second that a wave vibrates up and down

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



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

$\lambda\nu = c$

Or $\lambda = c / \nu$

λ= wavelength, ν= frequency

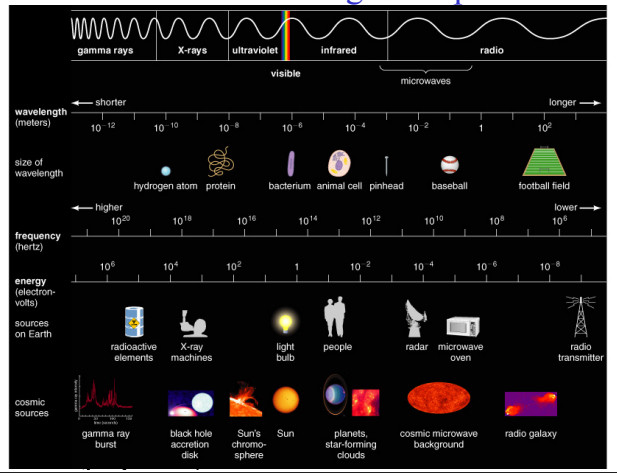
$c = 3.00 \times 10^8$ m/s = 300,000 km/s

= speed of light

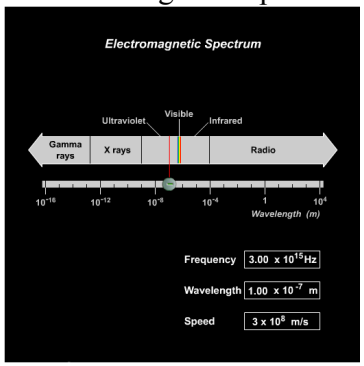
$E = h \times \nu$= photon energy

Or $E = hc / \lambda$

What is the electromagnetic spectrum?



The Electromagnetic Spectrum



Visible light: 4000 Å - 7000 Å (blue to red)
(Å = Angstrom, 1Å = 10^{-10} meters = 10 nm)

Thought Question
The higher the photon energy…

a) the longer its wavelength.
b) the shorter its wavelength.
c) energy is independent of wavelength.

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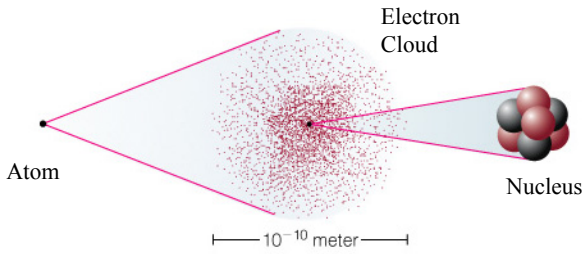
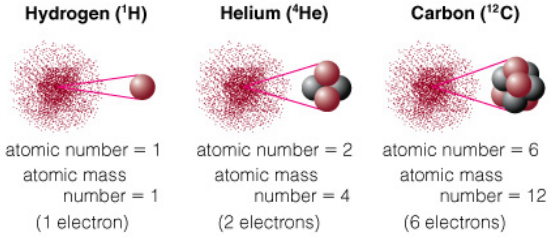
What is the structure of matter?



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)

Isotopes of Carbon

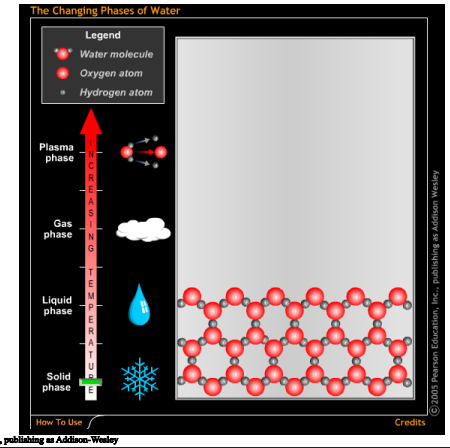
How many protons and how many neutrons does ^{14}C have?

- Ion: same # of protons but different # of electrons. (He^0, He^+, He^{+2})

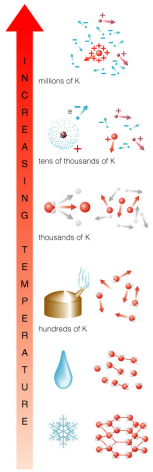
What are the phases of matter?

- Phases:
  - Solid (ice)
  - Liquid (water)
  - Molecular Gas (water vapor)
  - Atomic Gas (H, O atoms)
  - Plasma (ionized H, O, etc.)
- Phases of same material behave differently because of differences in chemical bonds

Phases of Water

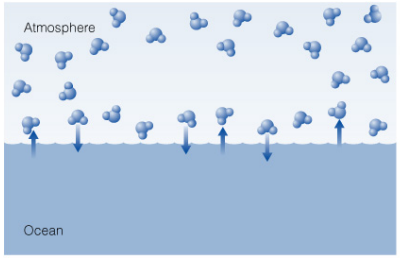


Phase Changes



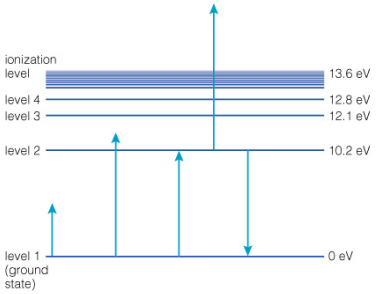
- **Ionization:** Stripping of electrons, changing atoms into plasma
- **Dissociation:** Breaking of molecules into atoms
- **Evaporation:** Breaking of flexible chemical bonds, changing liquid into gas
- **Melting:** Breaking of rigid chemical bonds, changing solid into liquid

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

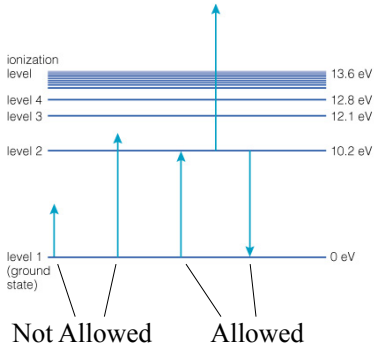
Ground State

- Electrons in atoms are restricted to particular energy levels

Electron orbitals

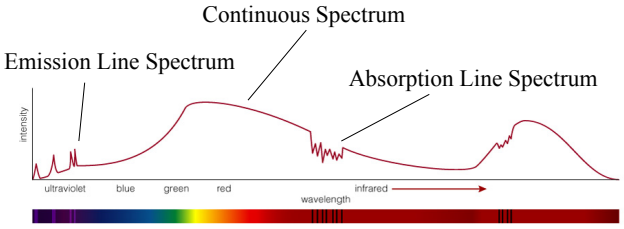
- Rules of quantum mechanics:
  1) Only certain orbits are allowed
  2) Limit to number of electrons in an orbit
     1^{st} (lowest) orbit - 2 electrons
     2^{nd} orbit - 8 electrons
  3) Electron prefer the lowest energy levels

Energy Level Transitions (H)

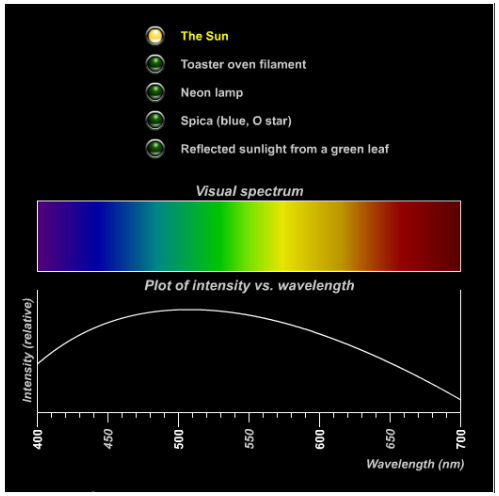


- The only allowed changes in energy are those corresponding to a transition between energy levels

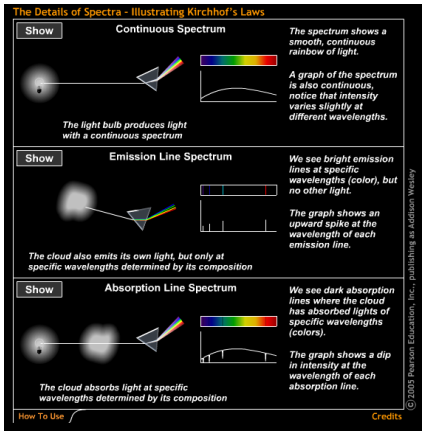
What are the three basic types of spectra?



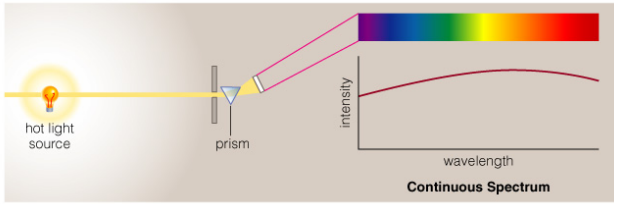
Spectra of astrophysical objects are usually combinations of these three basic types



Three Types of Spectra

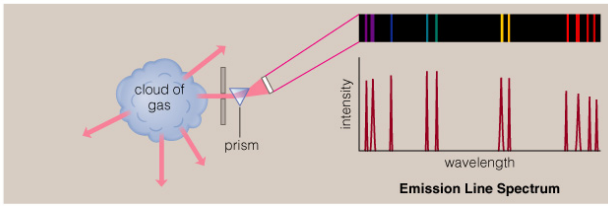


Continuous Spectrum



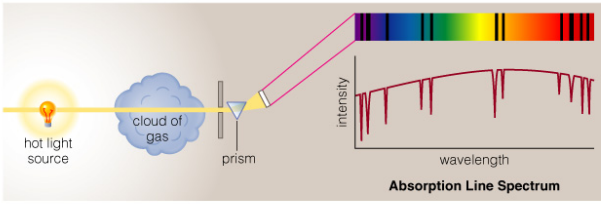
- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption

Emission Line Spectrum



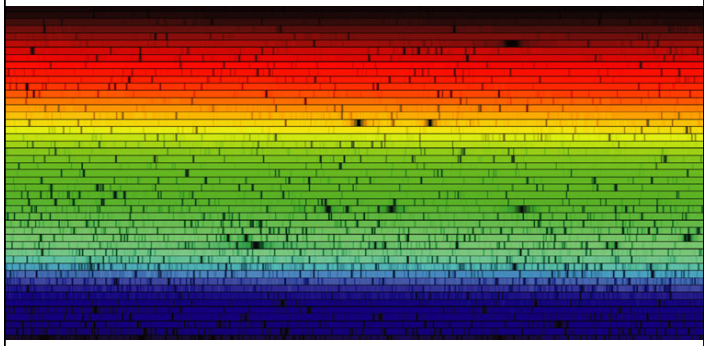
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines

Absorption Line Spectrum



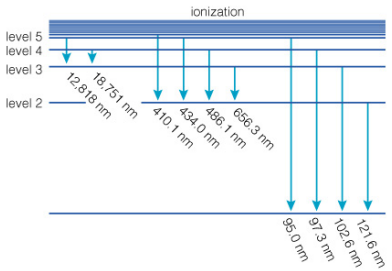
- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum

How does light tell us what things are made of?



Spectrum of the Sun

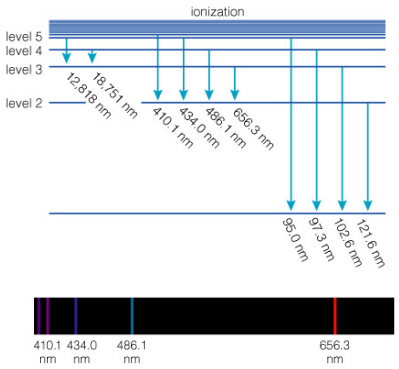
Chemical Fingerprints



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

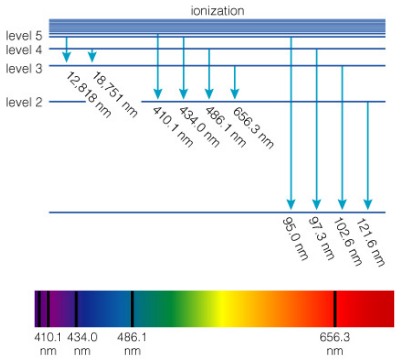
Chemical Fingerprints



- Downward transitions produce a unique pattern of emission lines

(Hydrogen spectrum)

Chemical Fingerprints

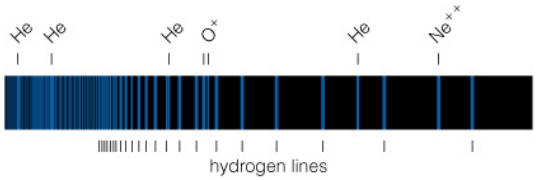


- Because those atoms can absorb photons with those same energies, upward transitions produce a pattern of absorption lines at the same wavelengths

Chemical Fingerprints

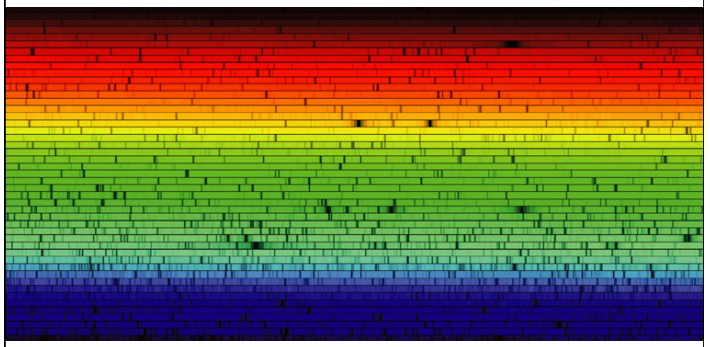
- Each type of atom has a unique spectral fingerprint

Chemical Fingerprints



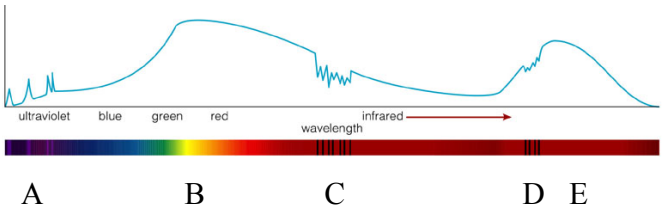
- Observing the fingerprints in a spectrum tells us which kinds of atoms are present

Example: Solar Spectrum



Thought Question

Which letter(s) labels absorption lines?



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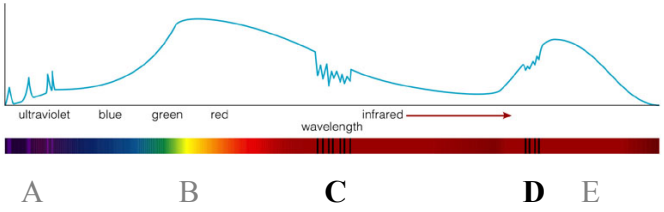
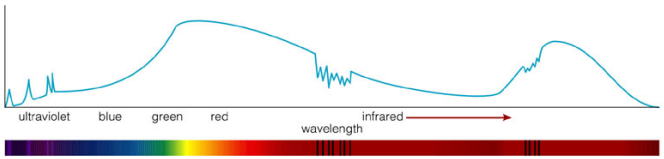


Thought Question

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



A B C D E

Thought Question

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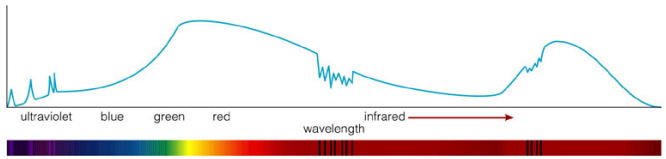
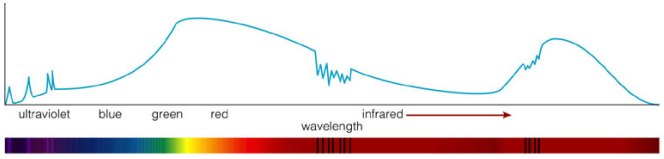


A B C D **E**

Thought Question

Which letter(s) labels emission lines?



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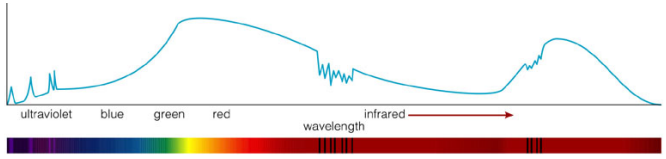
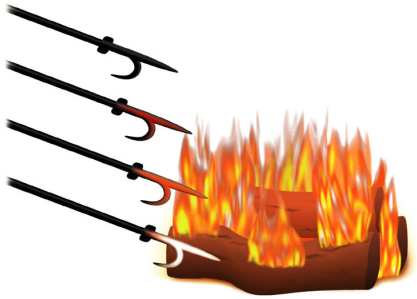


A B C D E

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

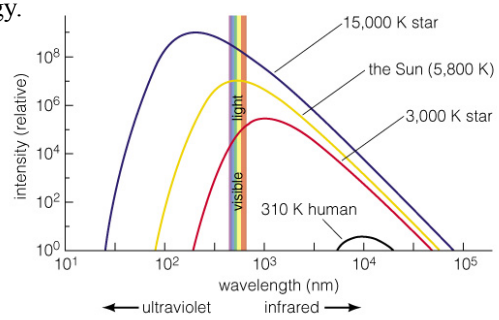


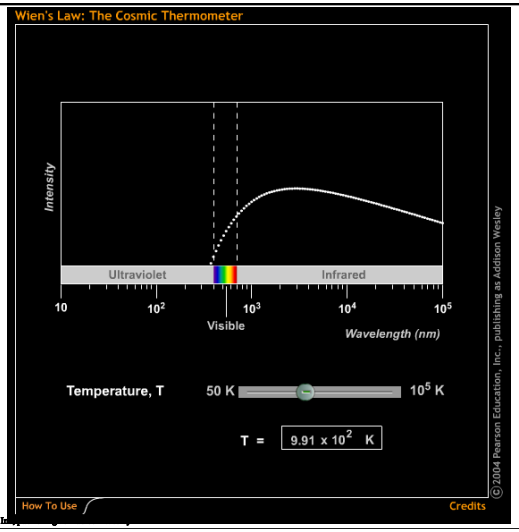
Thermal Radiation

- 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.

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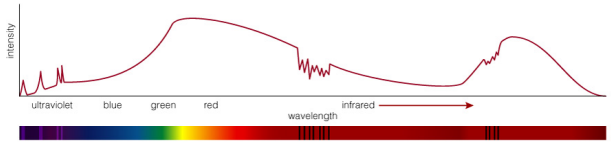
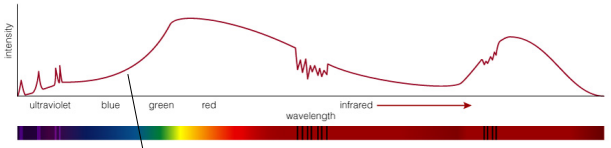
How do we interpret an actual spectrum?



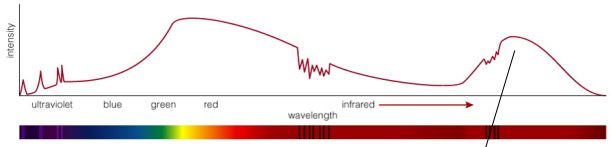
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What is this object?



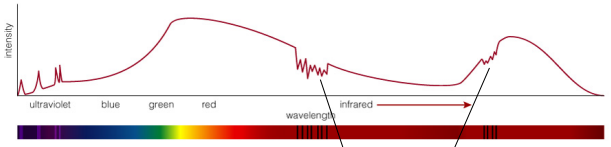
Reflected Sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed - object must look red

What is this object?



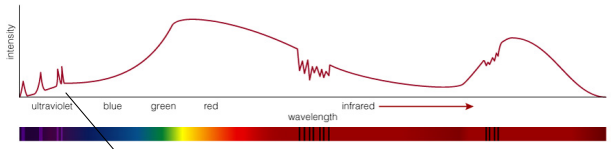
Thermal Radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K

What is this object?



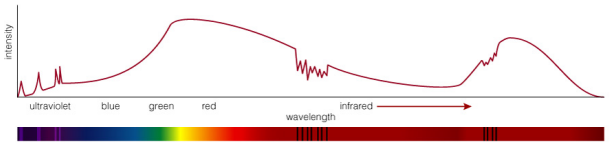
Carbon Dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere

What is this object?



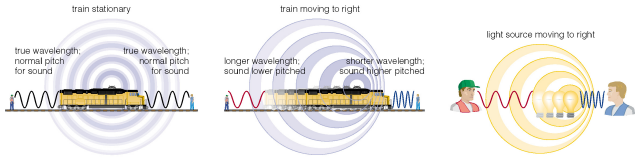
Ultraviolet Emission Lines:
Indicate a hot upper
atmosphere

What is this object?



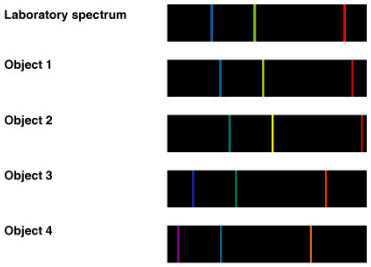
Mars!

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



The Doppler Effect

Measuring the Shift



Stationary

Moving Away
("redshifted")

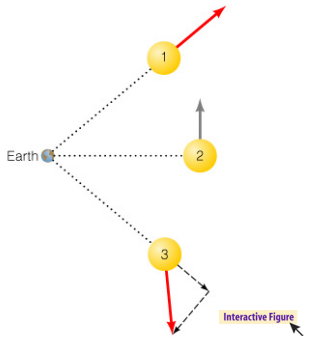
Away Faster

Moving Toward
("blueshifted")

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:



Doppler Formula

$$\frac{\Delta\lambda}{\lambda_{lab}} = \frac{v}{c}$$

Ex) An emission line has a laboratory wavelength of 6000 Å but is observed in a star's spectrum at a wavelength of 6001 Å. What is the star's velocity (relative to us)?

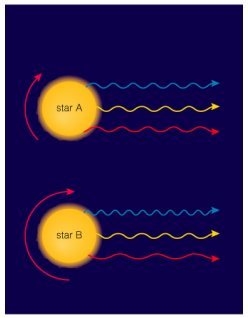
$$v = \frac{\Delta\lambda}{\lambda_{lab}} c = \frac{\lambda - \lambda_{lab}}{\lambda_{lab}} c = \frac{6001 - 6000}{6000} 300,000 \text{ km/sec}$$

$= 50$ km/sec

Is the star approaching or receding from us?

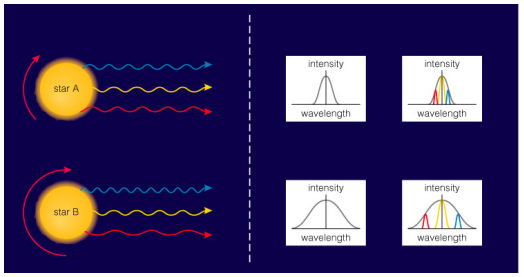
Receding – line is "redshifted" (towards longer wavelengths)

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