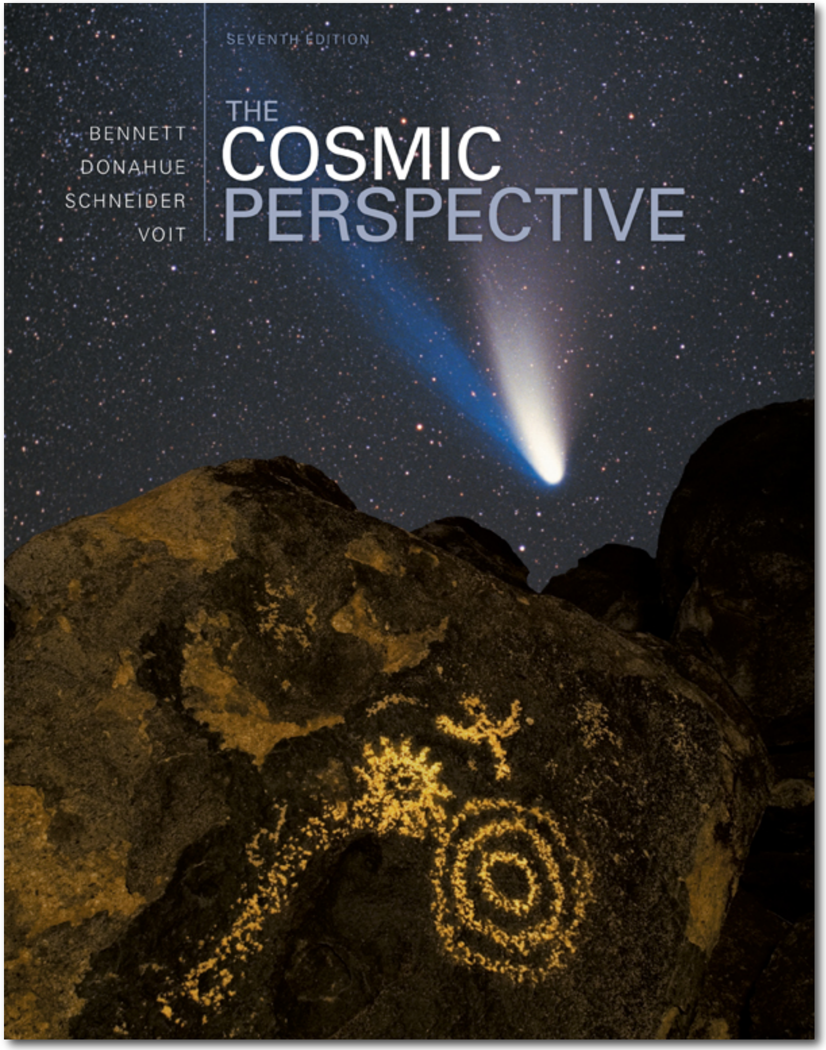
The Cosmic Perspective

Light and Matter: Reading Messages from the Cosmos



My Teaching website in located at:
http://chartasg.people.cofc.edu/chartas/Teaching.html

Lecture: Tuesday and Thursday

Location: ONLINE / RITA 387

Time: TR 10:50 am-12:05 pm

Instructor: Dr. George Chartas

Office: RITA 307

Office hours:TR 3:00 pm - 4:00 pm (email me to schedule an online meeting)

Phone: (843) 953-3609

Email: chartasg@cofc.edu

Required materials:

The textbook for the course is Bennett, J., Donahue, M., Schneider, N., and Voit, M., titled The Cosmic Perspective 9th Edition.

ASTRO-NEWS

Astro-News:

Each class will contain a segment called Astro-News. Every student will be expected to give a ~3-minute presentation during Astro-News (only one presentation per student over the entire course). The presentation may be in PowerPoint, keynote, or PDF. Astro-News will cover events that have been recently presented in a recognized astronomy media source.

Great sources of astronomy news include:

(a) the Science Section of the New York Times (see http://www.nytimes.com/pages/science/index.html),

(b) the NASA News Website (see http://www.nasa.gov/news/index.html),

(c) the Hubble Space Station News website (see http://hubblesite.org/newscenter/),

(d) the Sky and Telescope news site (see http://www.skyandtelescope.com/news), and

(e) the spaceweather website (see http://www.spaceweather.com/).

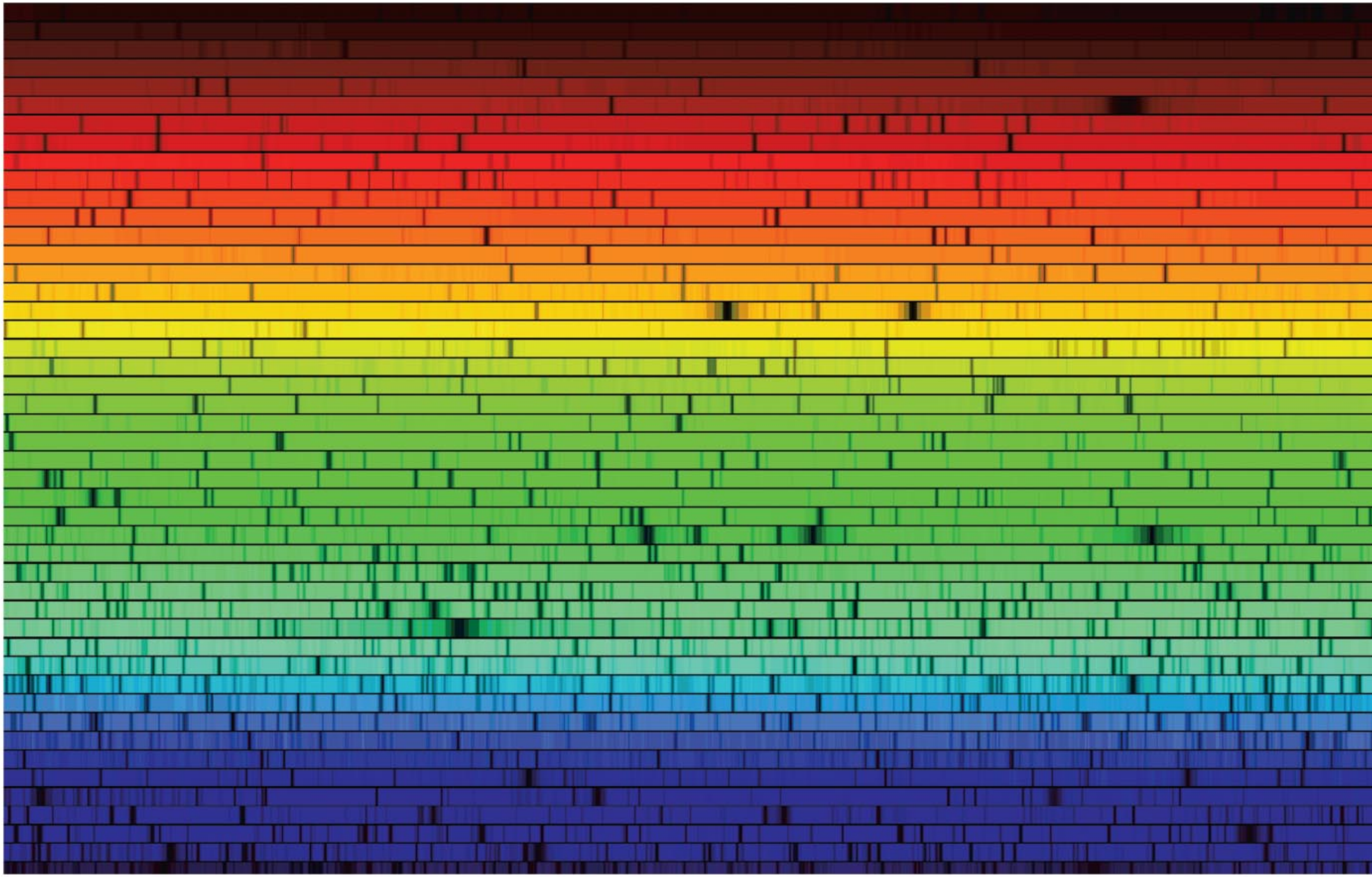
Midterm Exams Homework and Quizzes:
There will be 3 ONLINE midterm exams over the semester. Homework will be assigned after each chapter and I expect it to be submitted by the assigned due date listed on the schedule web site. Short quizzes will be given during lectures. The quizzes will be based on material already presented in lectures. There will be a final exam that will cover most of the material presented in the lectures.

Grades

Your final grade will be calculated as follows:

Homework + Quizzes	20%
Astro-News	10%
Midterms	40%
Final	30%

Light and Matter: Reading Messages from the Cosmos



5.1 Light in Everyday Life

- Our goals for learning:
  - **How do we experience light?**
  - **Speed of Light**
  - **How do light and matter interact?**

How do we experience light?

- The warmth of sunlight tells us that light must contain and transport something that has energy.
- The energy in light emitted by an object per unit time is defined as its luminosity
- units of luminosity are **watts:** 1 watt = 1 joule/s.

The Sun – Eight minutes ago

Distance from Sun = 1.5×10^8 km,
Speed of light $c = 3 \times 10^5$ km/s
Time for light to reach us = ?

The Sun – Eight minutes ago

Distance from Sun = 1.5×10^8 km

$c = 3 \times 10^5$ km/s

c = distance/time

→time=distance/c=1.5×10^8km/3×10^5 km/sec

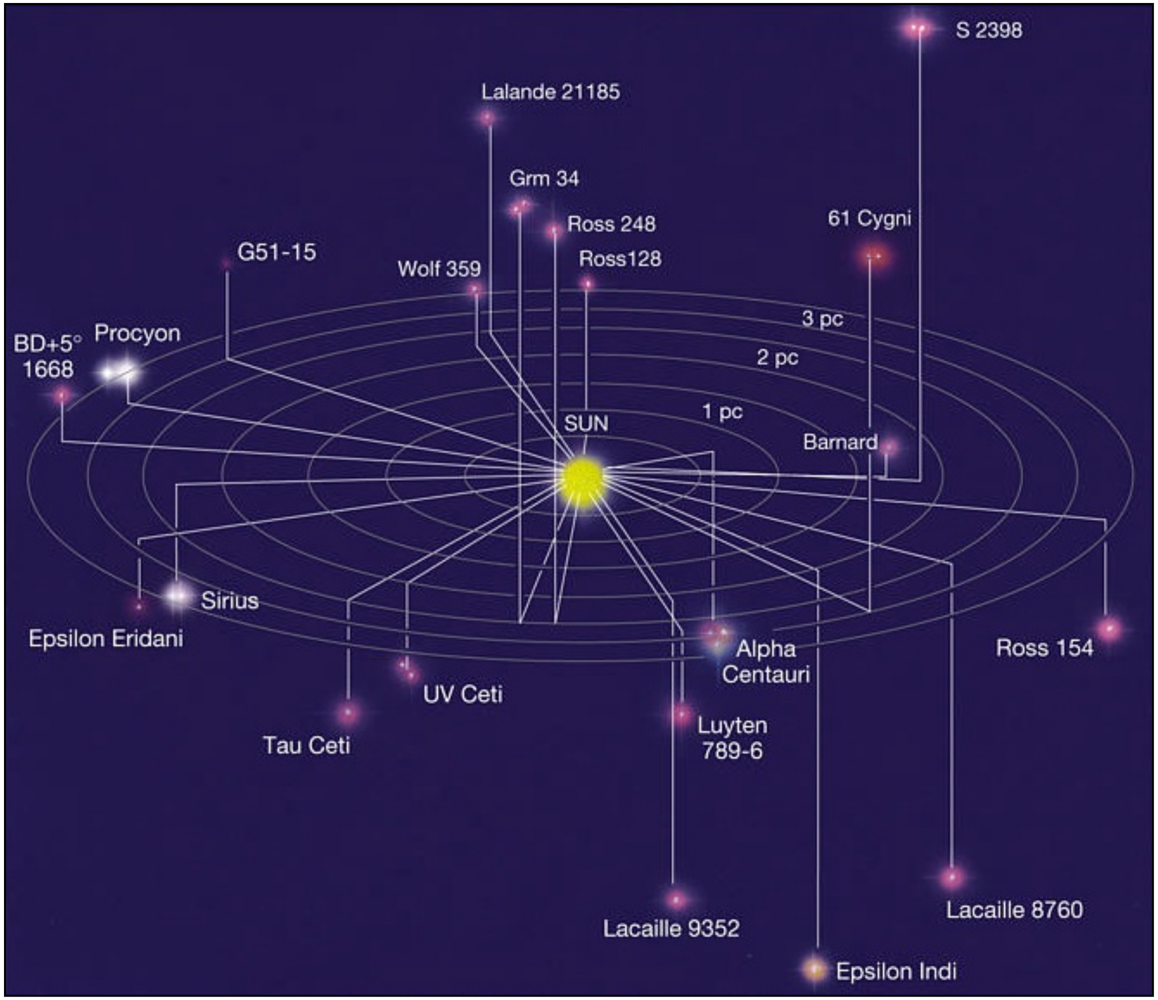
→time=500 sec

Light Year = ly : distance light travels in one year

1 ly = c × 1yr = 3×10^5 km/s × 1yr = 3×10^5 km/s × 3.1557×10^7s

1 ly = 9.46×10^{12} m

Nearest Stars – Few Years Ago

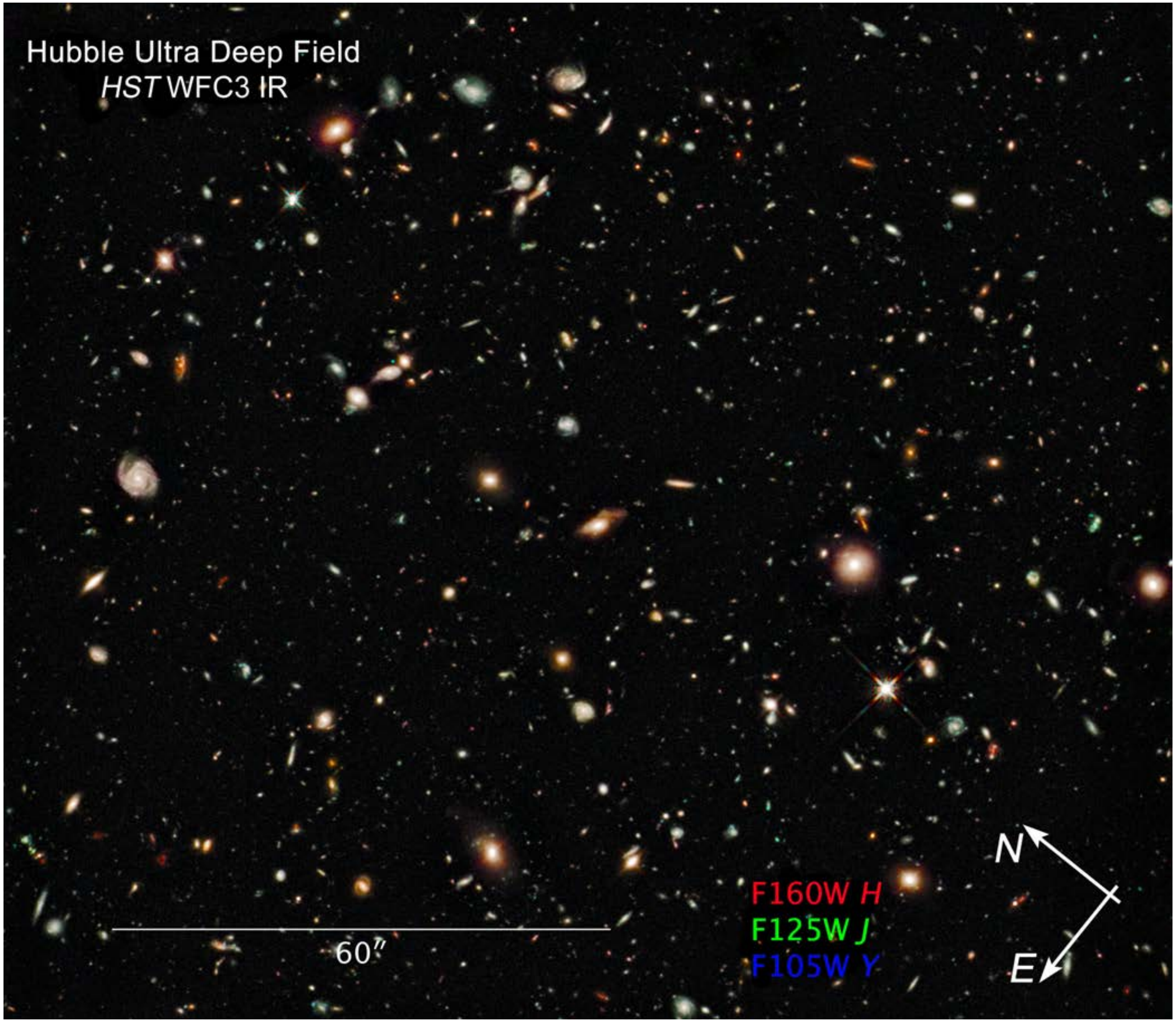


1 pc = 3.26 ly Kessel Run

Andromeda Galaxy (M31) – 2.5 Million Years Ago

disk radius of M31 ~ 110,000 ly
disk radius of Milky Way ~ 50,000 ly

Distant Galaxies – Billion of Years Ago

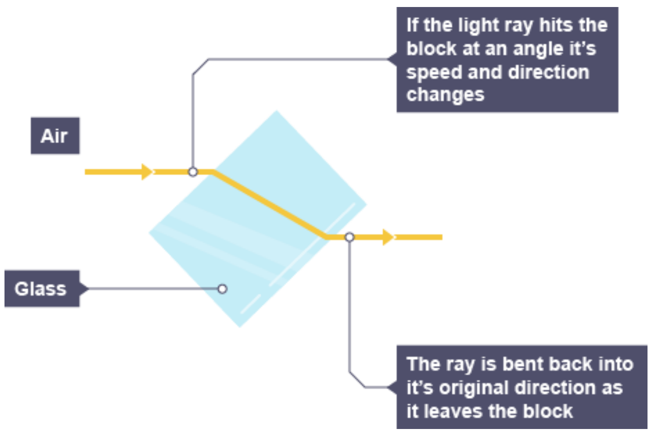


Measuring the Speed of Light

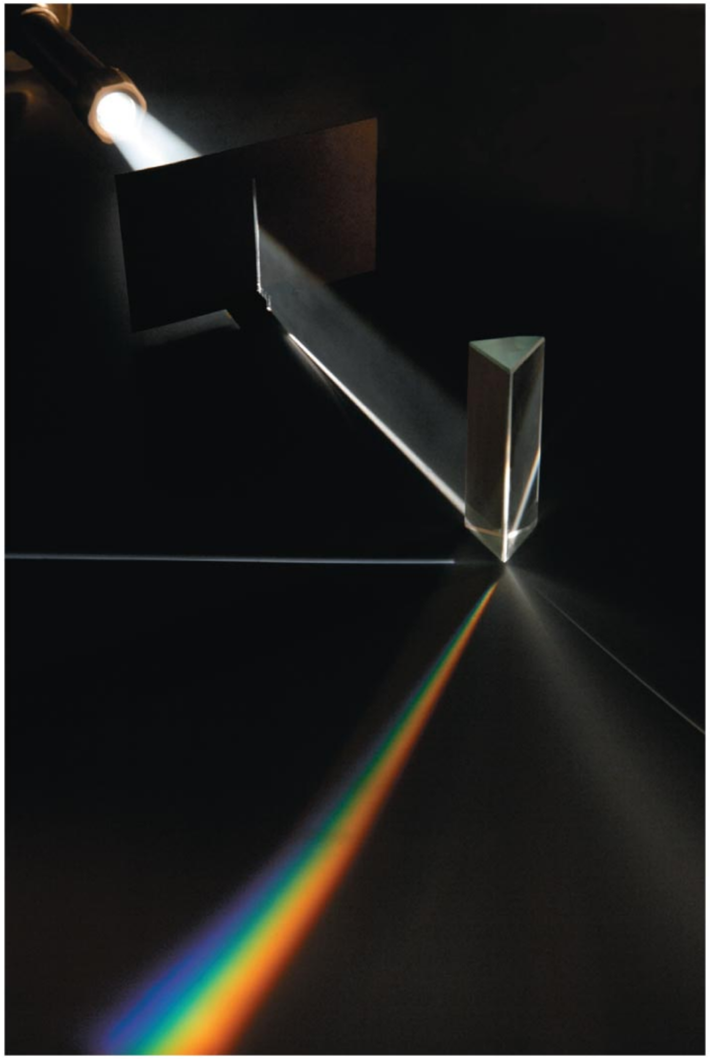
1. By 1975 the speed of light in vacuum was known to be 299,792,458 m/s with a relative measurement uncertainty of 4 parts per billion. **In 1983 the meter was redefined** in the International System of Units (SI) as the distance travelled by light in vacuum in 1⁄299,792,458 of a second.

2. The speed of light c_{medium} is less than c_{vacuum} when it travels through media like gases, liquids or solids: $n = c_{vacuum}/c_{medium} > 1$

n is called the **index of refraction**



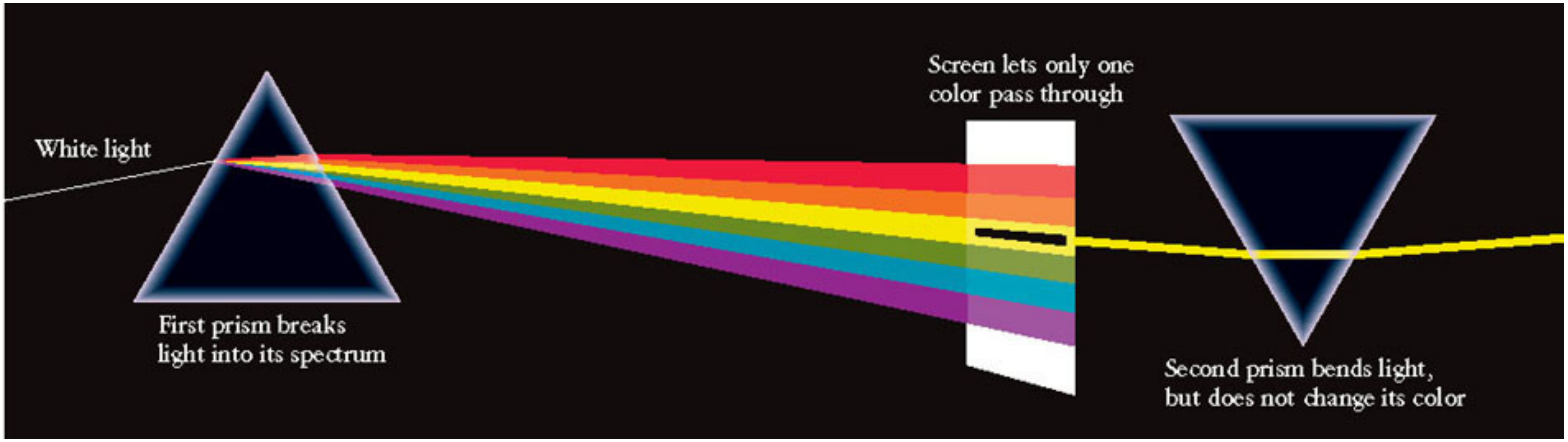
Colors of Light



- White light is made up of many different colors.

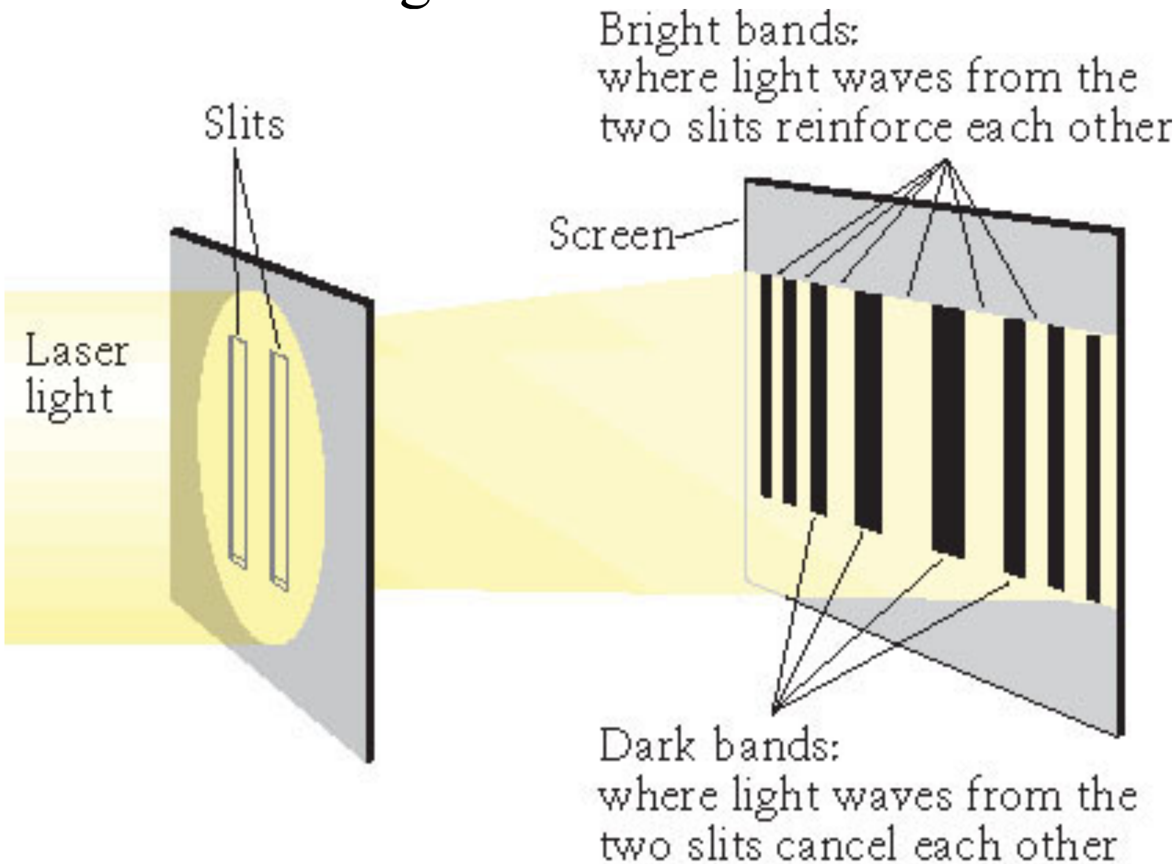
The Nature of Light

Newton's experiments showed that white light is a combination of all the colors that appear in its spectrum.



The Nature of Light

Huygens (proposed in 1678) and Young (demonstrated in 1801):
Wavelike nature of light.

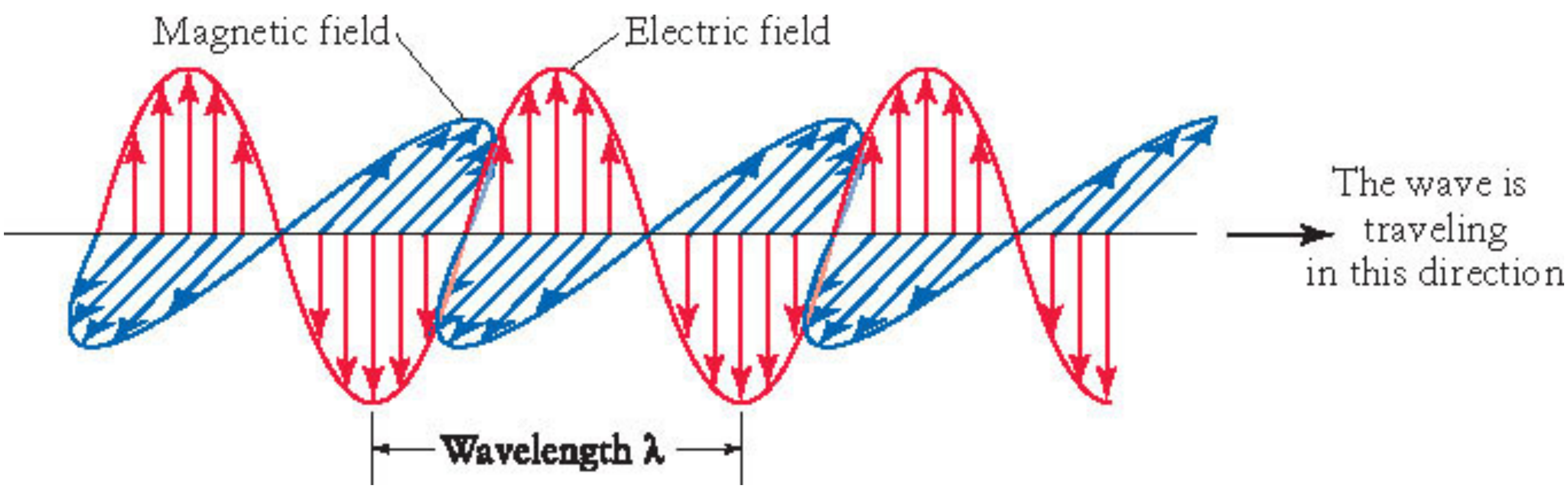


(a) An experiment with light

The Nature of Light

James Maxwell: light is electromagnetic radiation

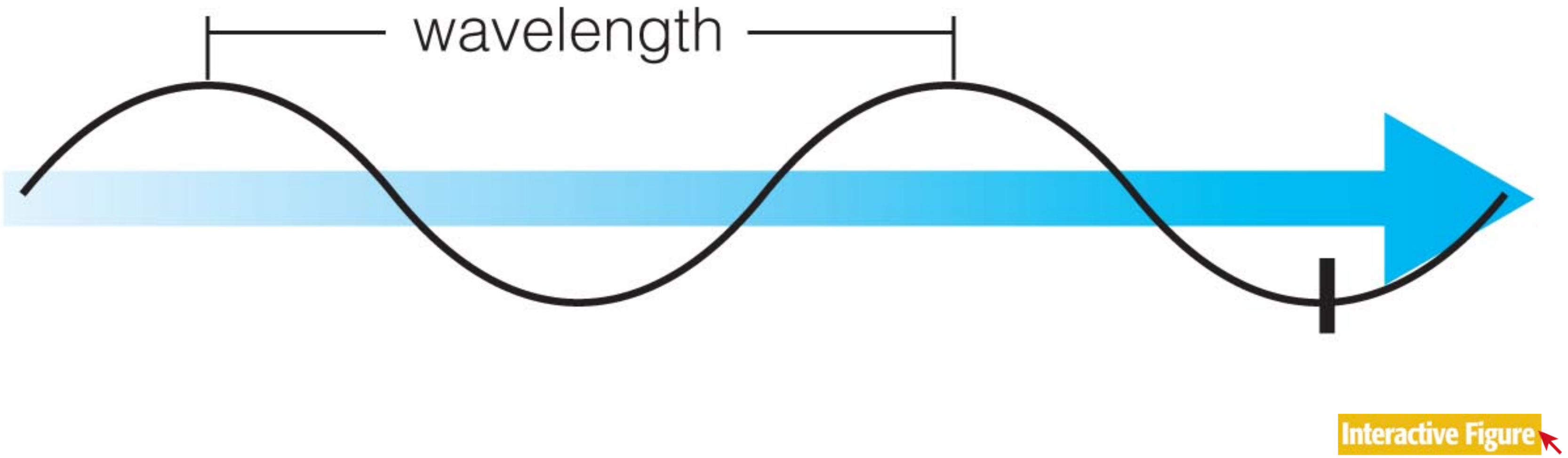
- Light is electromagnetic radiation that consists of oscillating electric and magnetic fields.
- Maxwell showed that electromagnetic waves travel through space at the speed of light.
- The distance between successive wave crests is called the wavelength of the light.



Nature of Light

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

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.

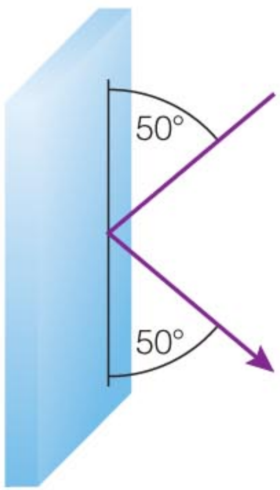
Wave speed = wavelength x frequency

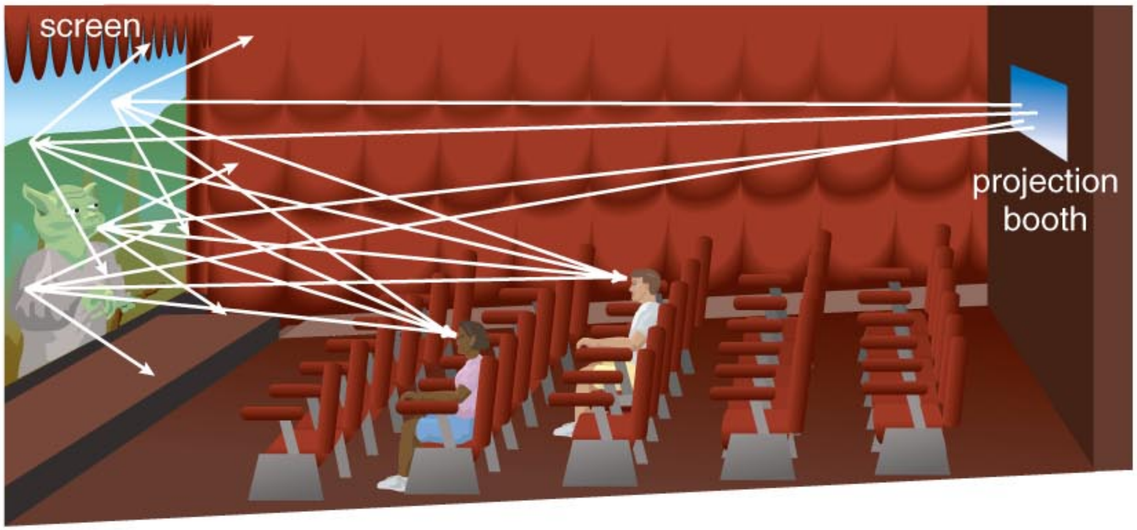
$$c = \lambda \nu$$

How do light and matter interact?

- Emission
- Absorption
- Transmission
  - Transparent objects transmit light.
  - Opaque objects block (absorb) light.
- Reflection/scattering

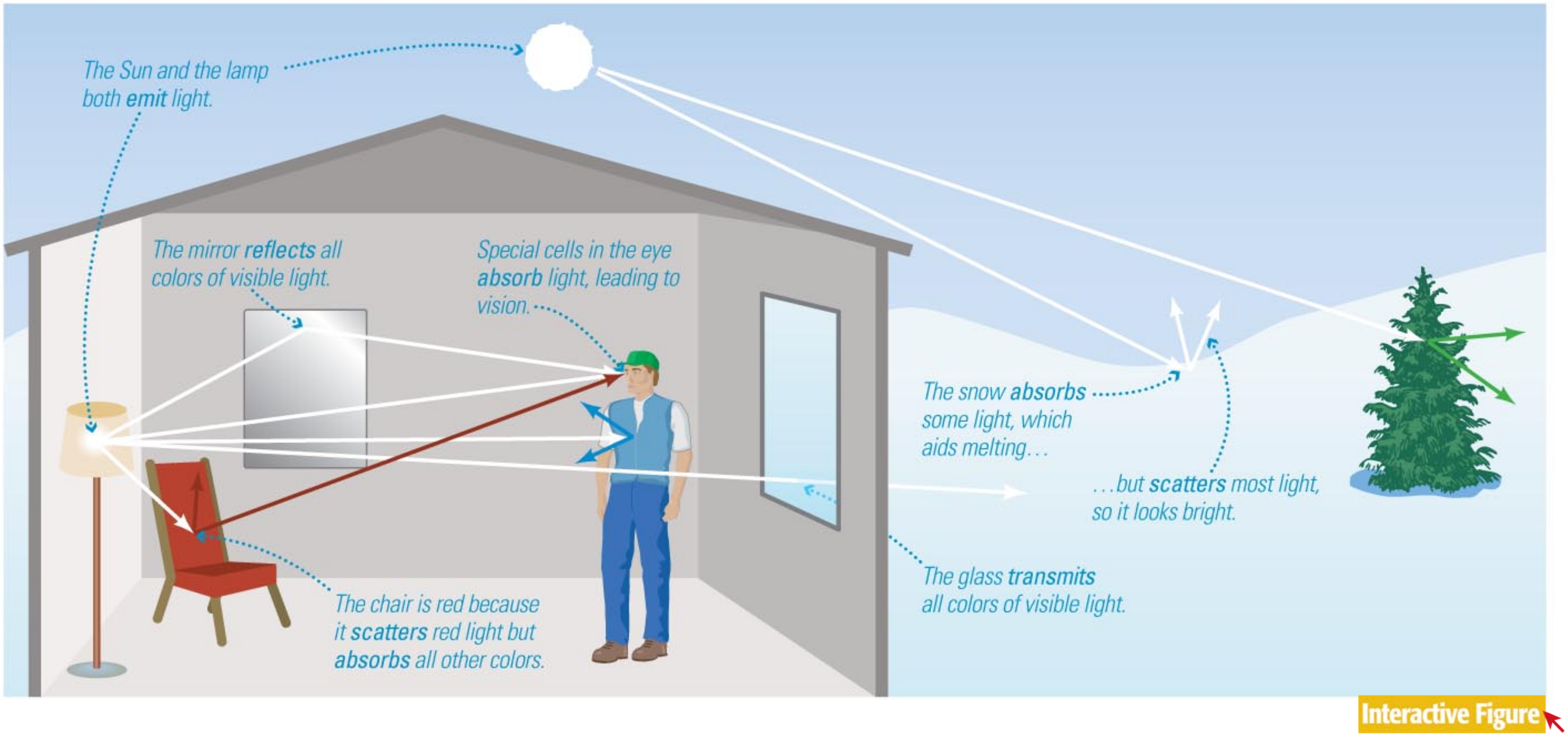
Reflection and Scattering





- 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.

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 scatters red light.

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 scatters red light.

What have we learned?

- **How do we experience light?**
  - Light contains and transports energy.
  - Light comes in many colors that combine to form white light.
- **Speed of light**
  - Light in vacuum travels at a speed of $c = 3 \times 10^5$ km/s
  - Looking at the stars we are looking into the past.
- **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.

Wavelength and Frequency

The frequency of a wave is just the number of crests that pass a given point per sec or the number of complete cycles that pass per sec.

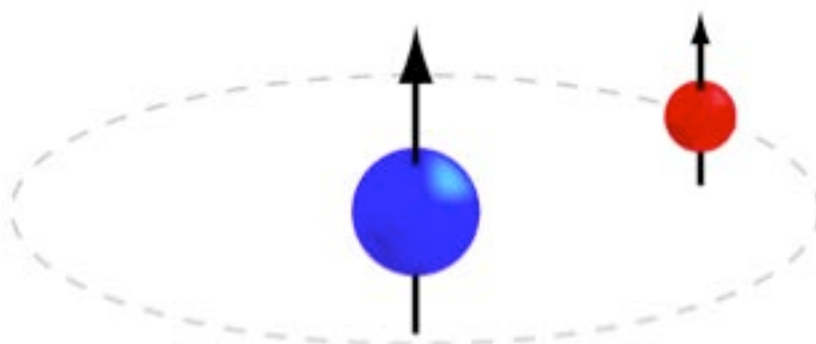
$c = \lambda / T_{crest} = \lambda\nu$

ν= frequency of an electromagnetic wave
c = speed of light = 3×10^8 m/s
λ= wavelength of the wave in meters

Unit of frequency 1 Hz = s^{-1}

AM radio: 535 kHz - 1605 kHz
FM radio: 88 MHz - 108 MHz

Wavelength and Frequency



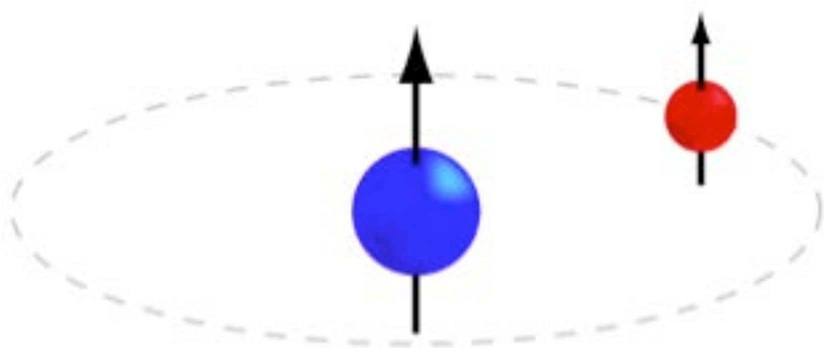
21-centimeter line

An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

Question:
Neutral Hydrogen emits radio waves with a wavelength of 21.1cm. What's the frequency, Kenneth?

Use $c = 3 \times 10^8$ m/s

Wavelength and Frequency



21-centimeter line

An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

Question:
Neutral Hydrogen emits radio waves with a wavelength of 21.1cm. What's the frequency, Kenneth?

Answer:

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^{10}\ \frac{\text{cm}}{\text{s}}}{21.1\ \text{cm}} = 1420\ \text{MHz}$$

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

The dual nature of light is evident in the formula that relates the energy of a photon to its wavelength :

$$E = h\nu = h\frac{c}{\lambda}$$

$$E = energy\ of\ photon\ (eV)$$

$$\nu = frequency\ of\ photon\ (s^{-1})$$

$$h = 4.135 \times 10^{-15}\ eV\ s \text{ (Planck's Constant)}$$

$$\text{c} = \text{speed of light} = 3 \times 10^{8}\ \text{m s}^{-1}$$

$$\lambda = \text{wavelength of the wave (m)}$$

Wavelength, Frequency, and Energy

The dual nature of light is evident in the formula that relates the energy of a photon to its wavelength :

$$E = h\nu = h\frac{c}{\lambda}$$

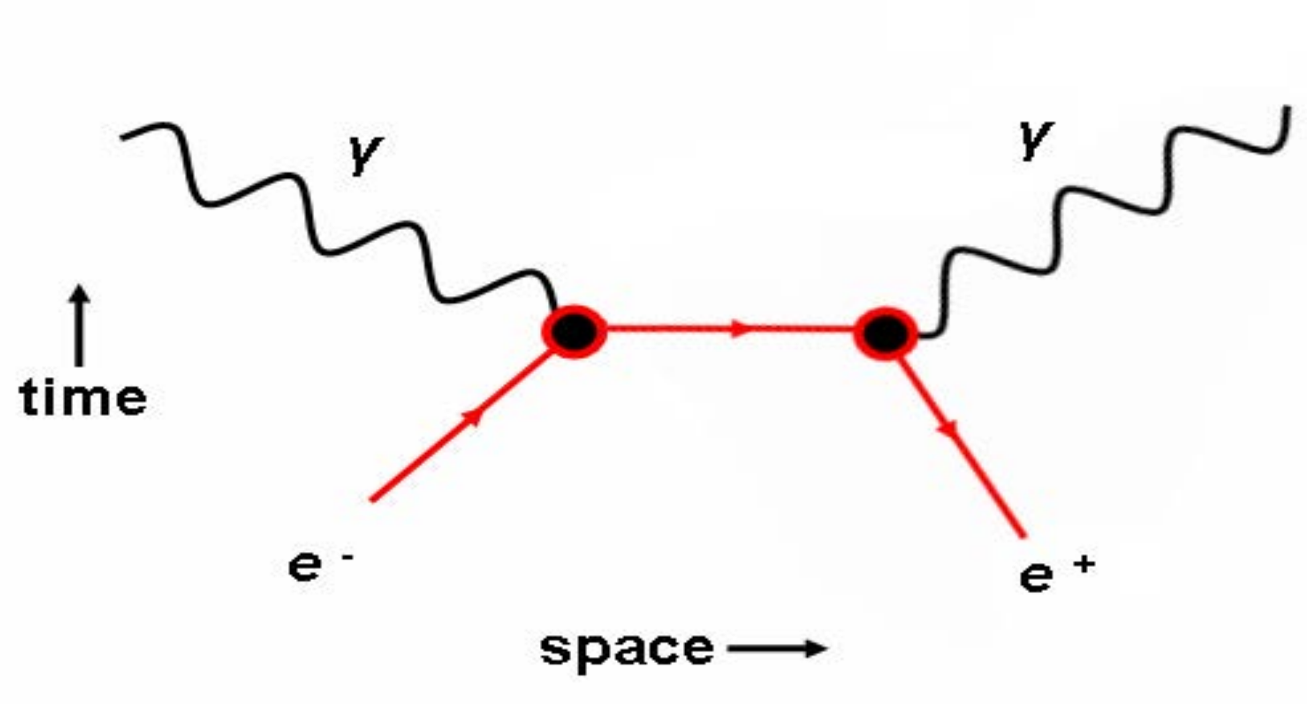
$$E = energy\ of\ photon\ (J)$$

$$\nu = frequency\ of\ photon\ (s^{-1})$$

$$h = 6.625 \times 10^{-34}\ J\ s\ \text{(Planck's Constant)}$$

Wavelength, Frequency, and Energy

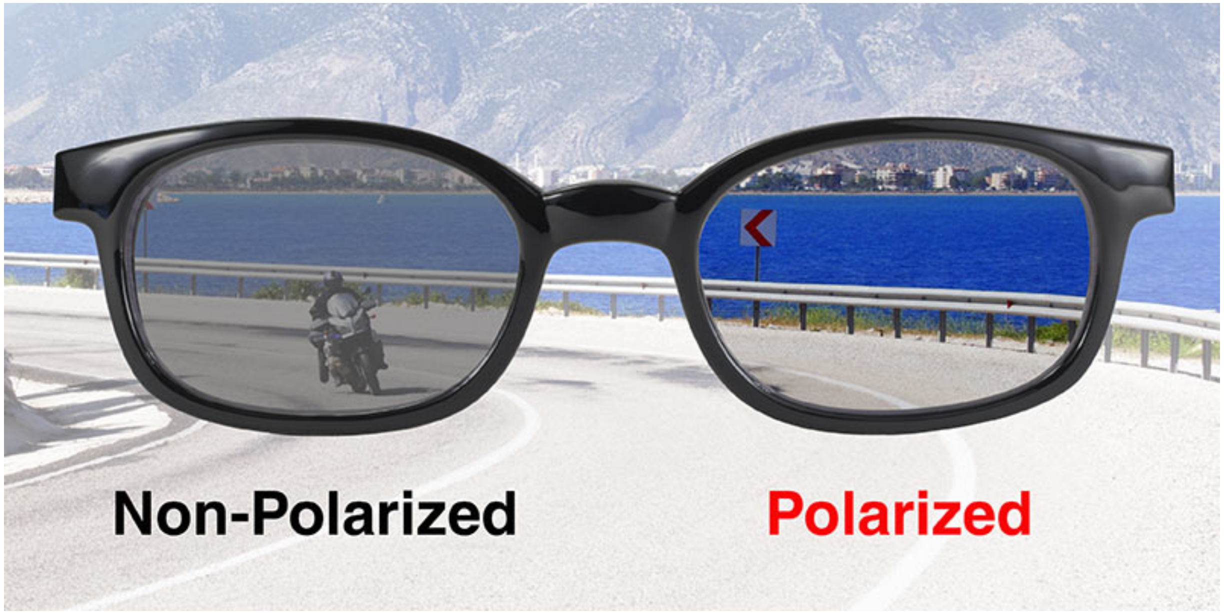
Electron-positron annihilation



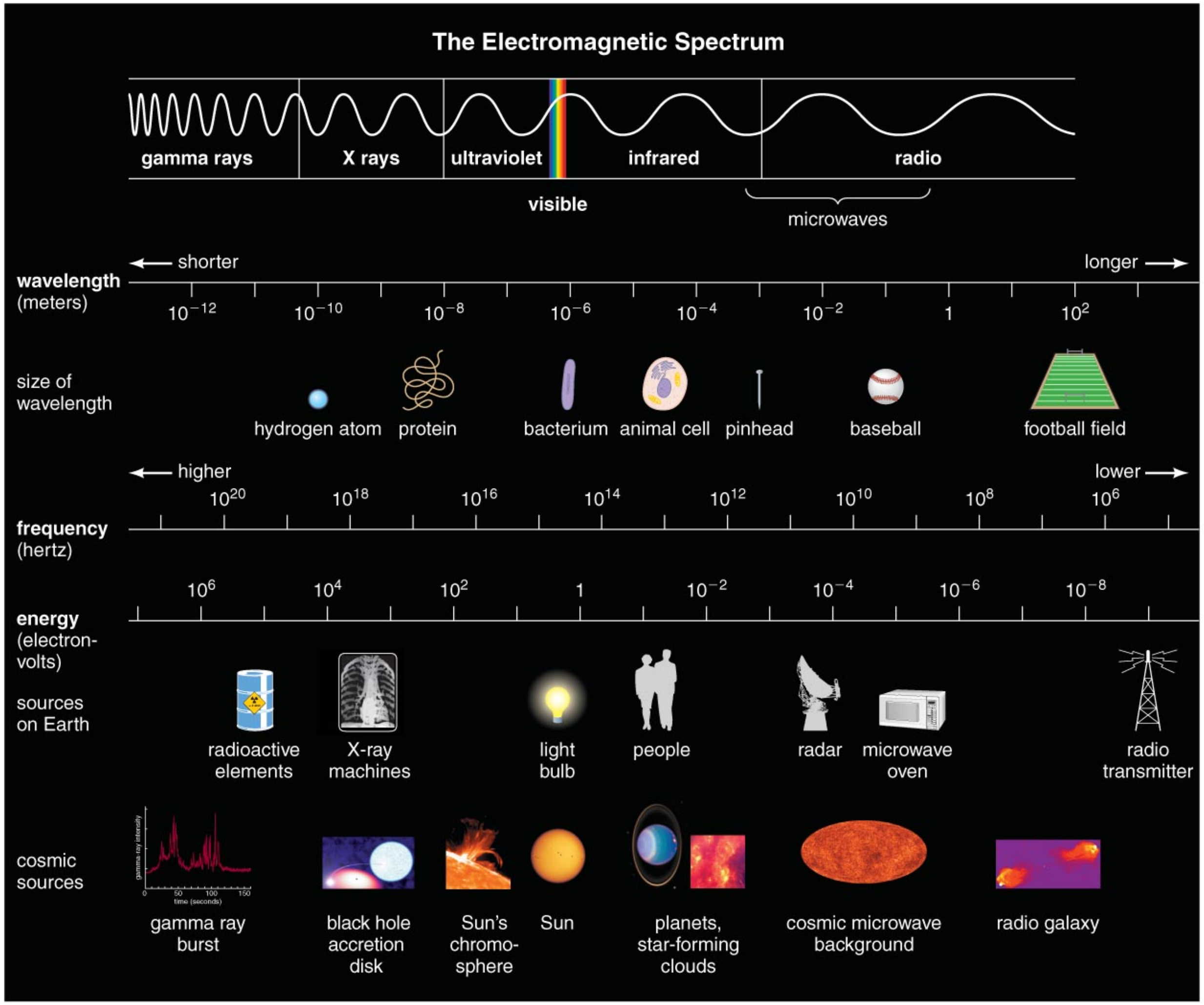
E_{photon}= 511keV, λ= ?

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.



The Electromagnetic Spectrum:
Entire range of wavelengths of light



Interactive Figure

Thought Question

The higher the photon energy, $E = h\nu = h\frac{c}{\lambda}$

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

Thought Question

The higher the photon energy, $E = h\nu = h\frac{c}{\lambda}$

A. the longer its wavelength.

B. the shorter its wavelength.

C. energy is independent of wavelength.

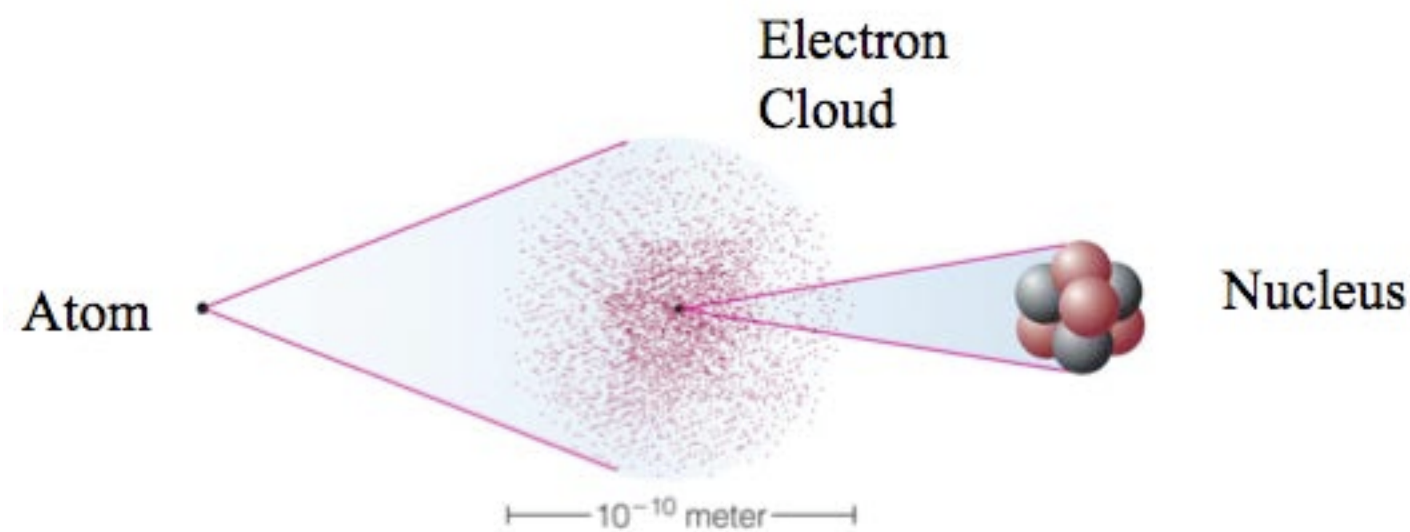
What have we learned?

- **What is light?**
  - Light can behave like either a wave or a particle.
  - A light wave is a vibration of electric and magnetic fields that travels at the speed of light.
  - 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

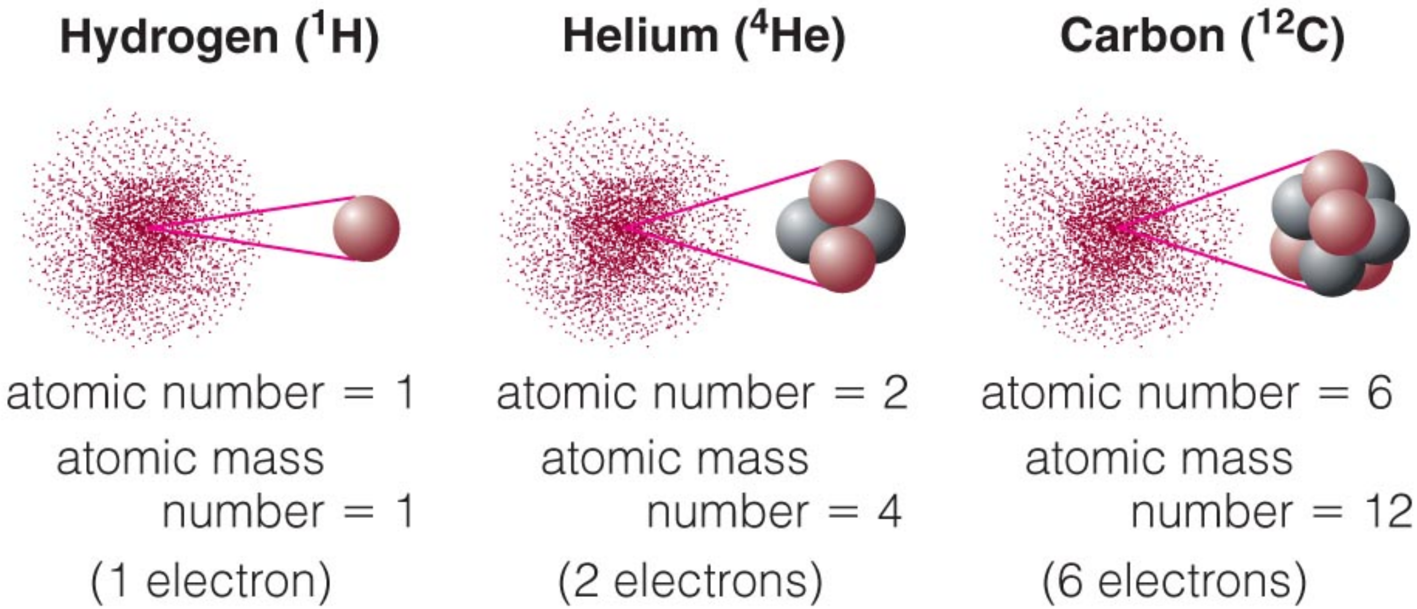
- Our goals for learning:
  - **What is the structure of matter?**
  - **What are the phases of matter**
  - **How is energy stored in atoms?**

What is the structure of matter?



Atomic Terminology

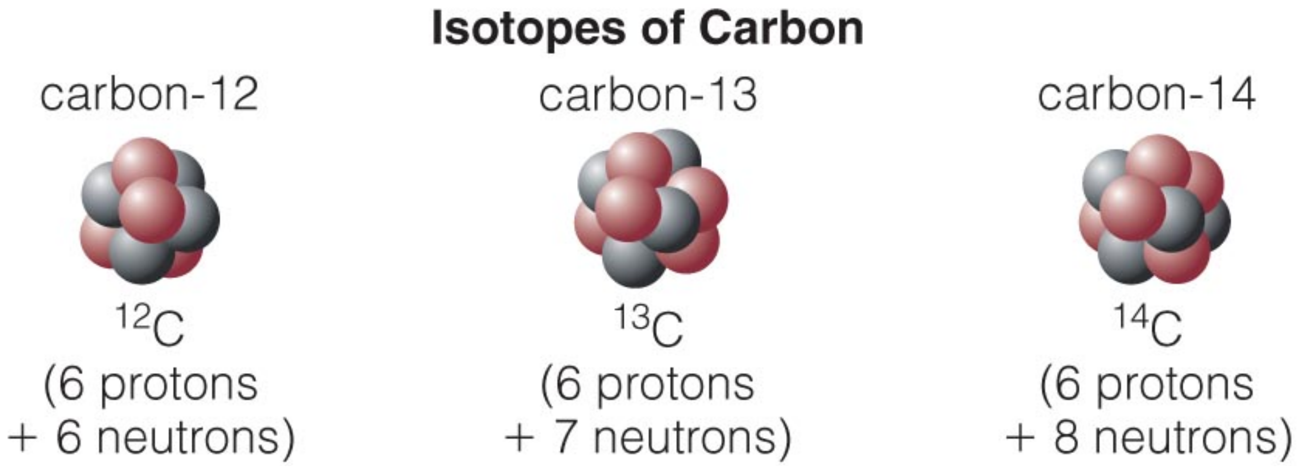
- Atomic number = # of protons in nucleus
- Atomic mass number = # of protons + neutrons



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

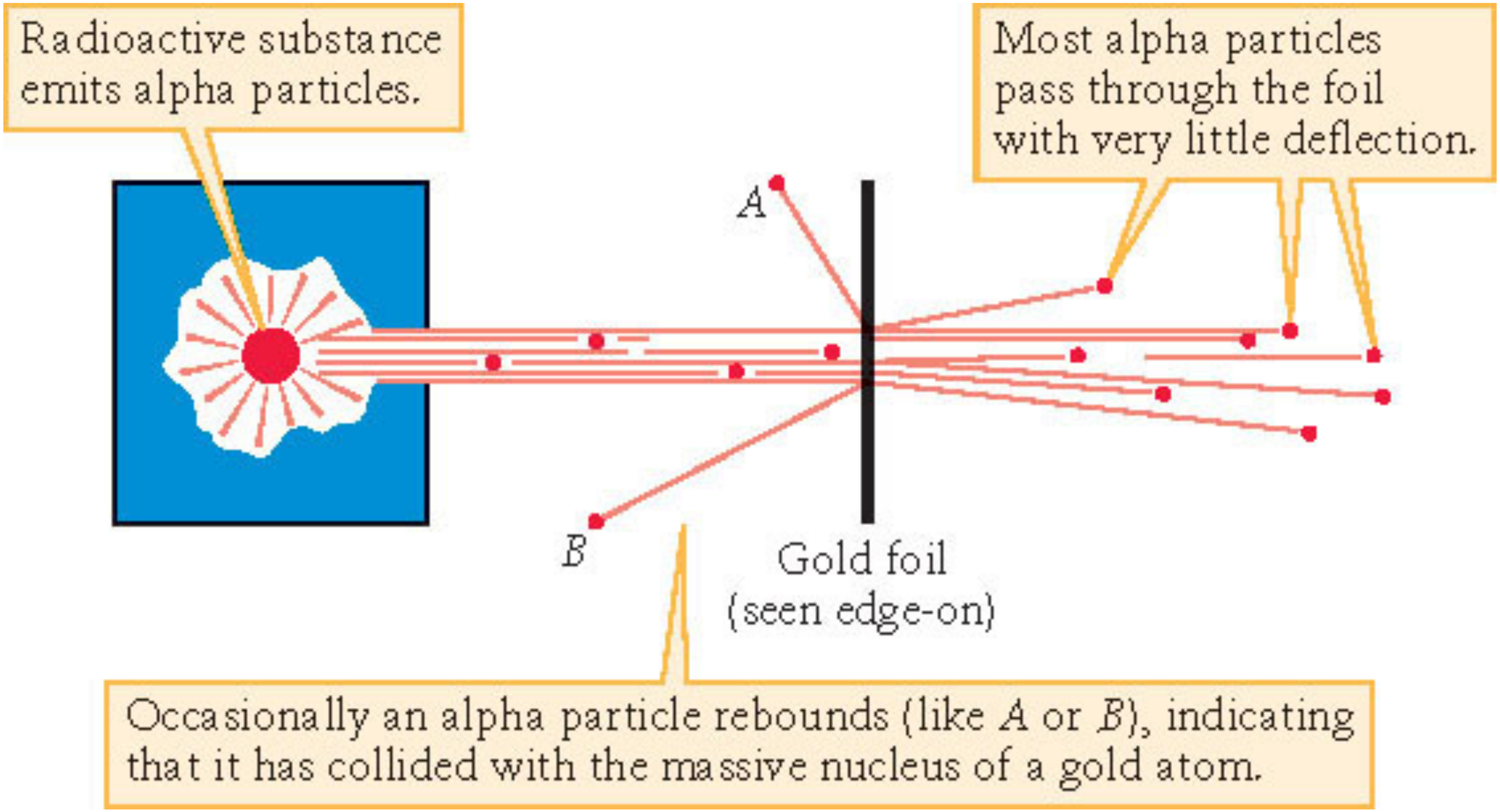
Atomic Terminology

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



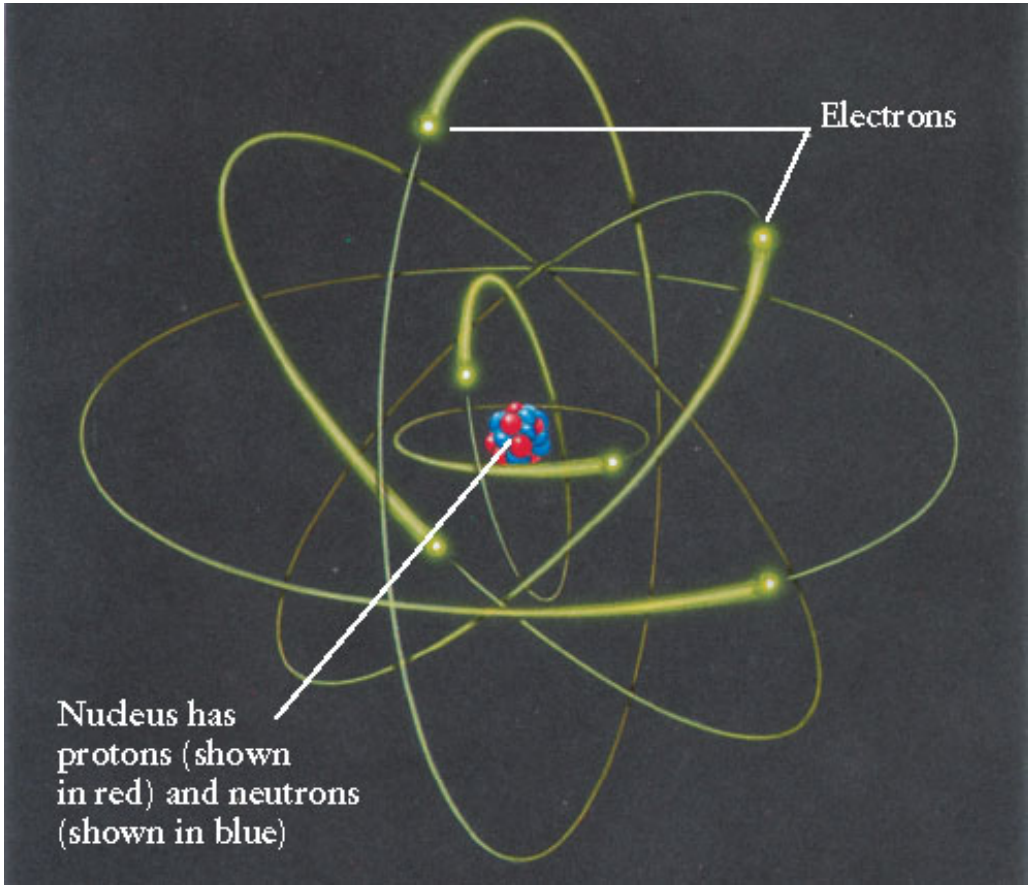
How is energy stored in atoms?

Rutherford's Experiment



How is energy stored in atoms?

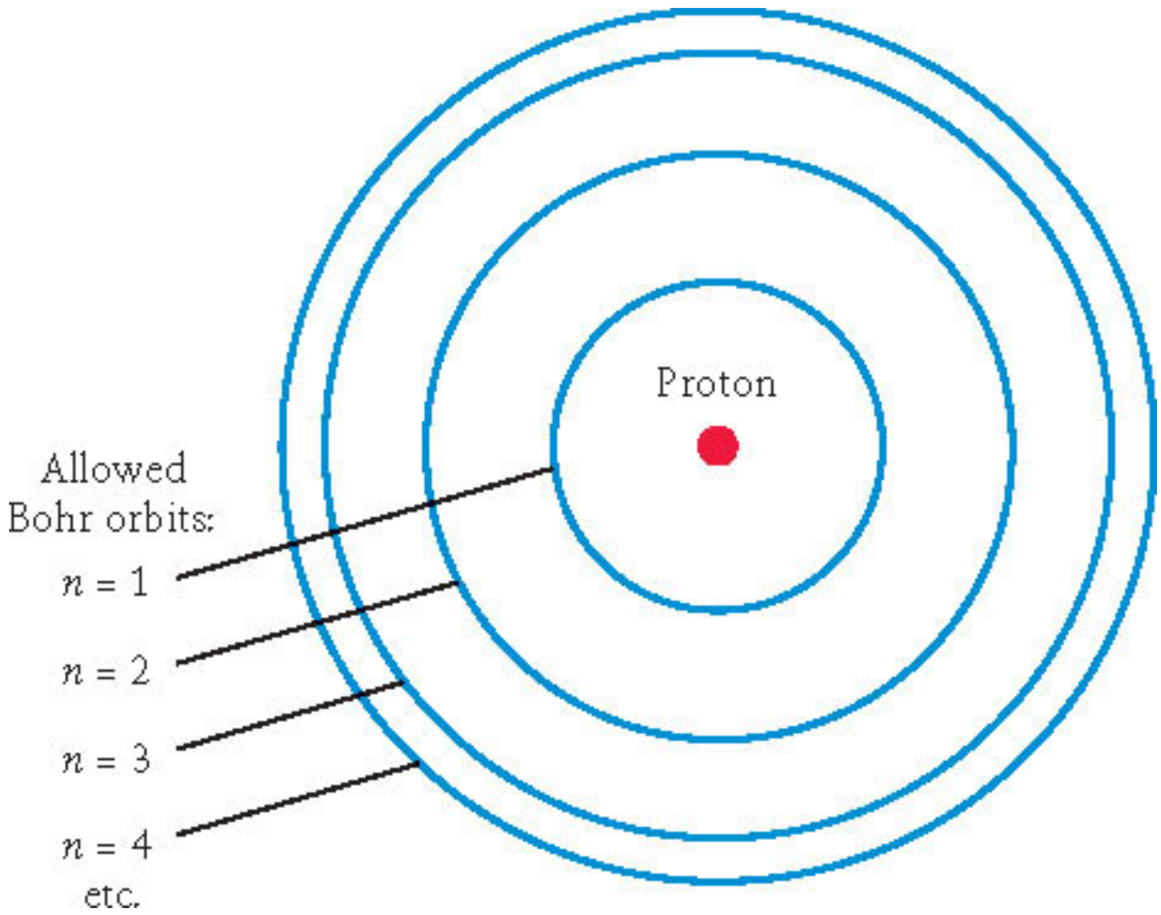
Rutherford's Model of the Atom



The number of protons in the nucleus of an atom determines the element that the atom represents.

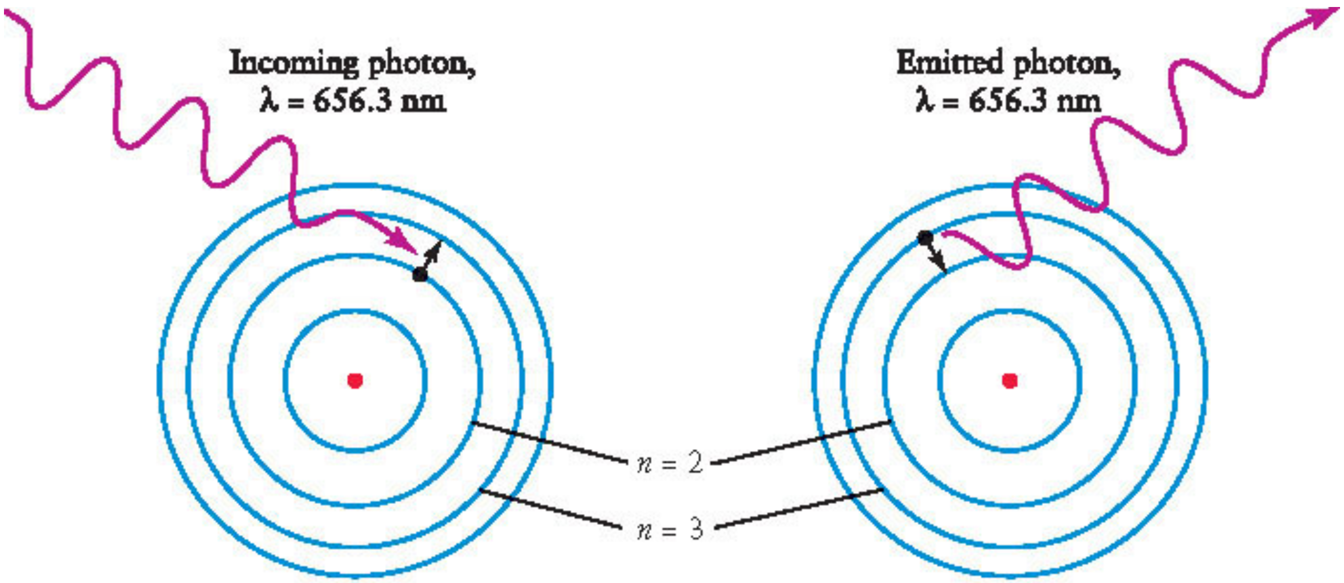
How is energy stored in atoms?

Niels Bohr's Model for the Atom



How is energy stored in atoms?

Niels Bohr's Model for the Atom



(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the n = 2 orbit up the n = 3 orbit

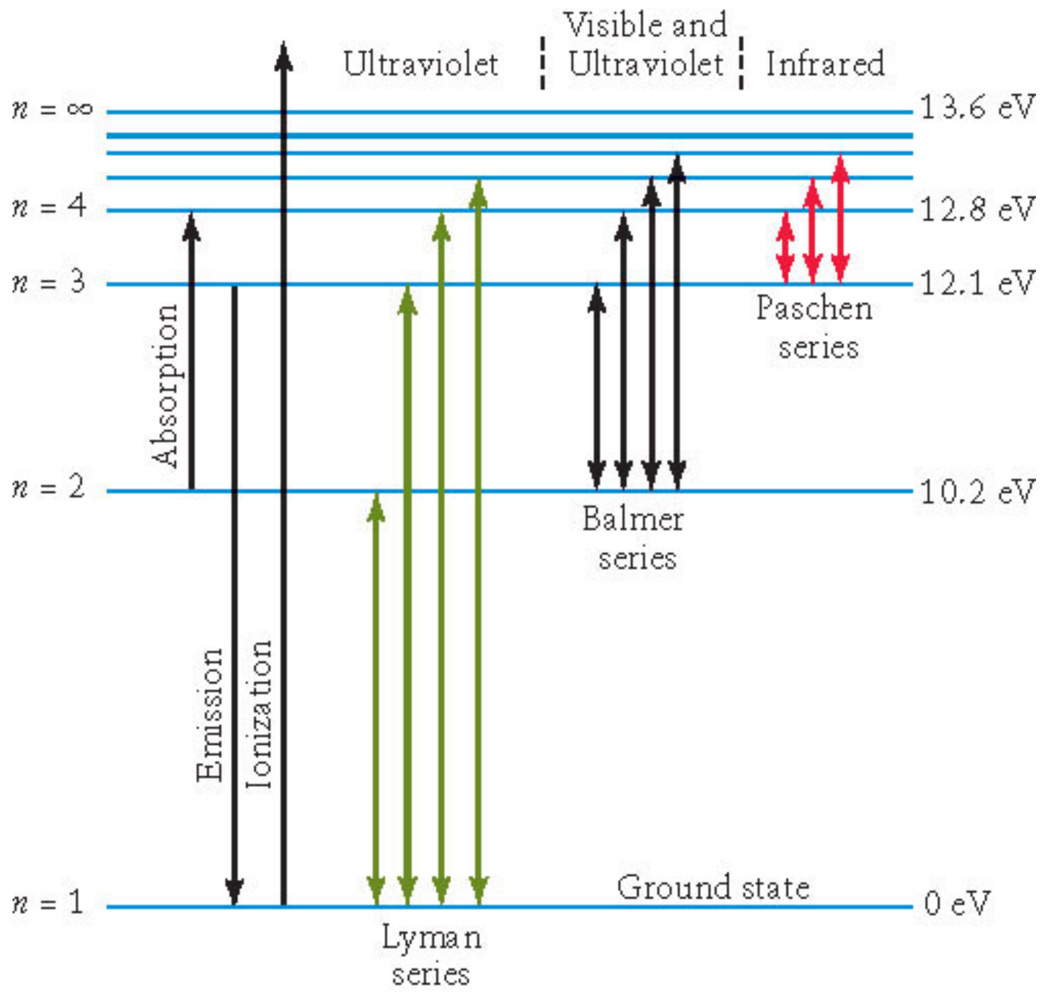
(b) Electron falls from the n = 3 orbit to the n = 2 orbit; energy lost by atom goes into emitting a 656.3-nm photon

$$\frac{1}{\lambda} = R\left(\frac{1}{n_{in}^{2}} - \frac{1}{n_{out}^{2}}\right)$$

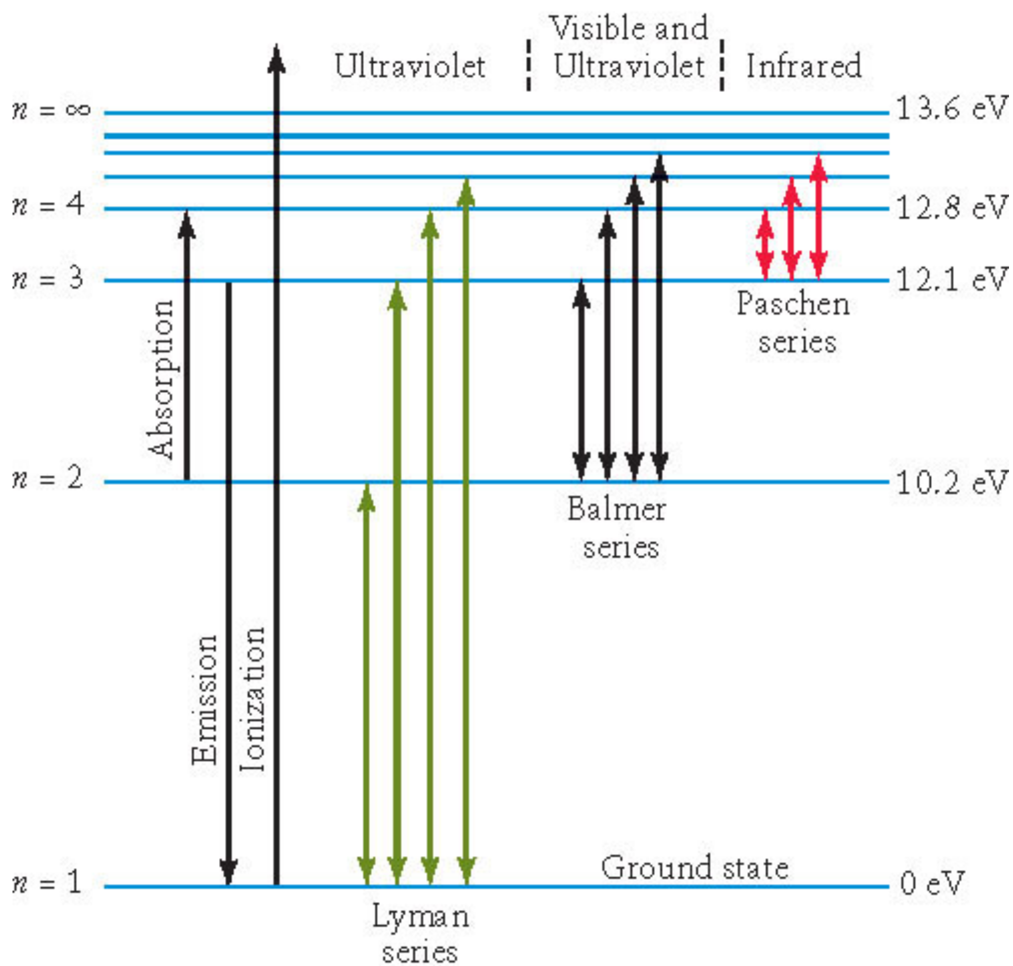
R is the Rydberg constant

$R = 1.097 \times 10^{7}\,\mathrm{m}^{-1}$

Niels Bohr's Model for the Hydrogen Atom



Niel Bohr's Model of the Hydrogen Atom



1. H_δ Wavelength ?

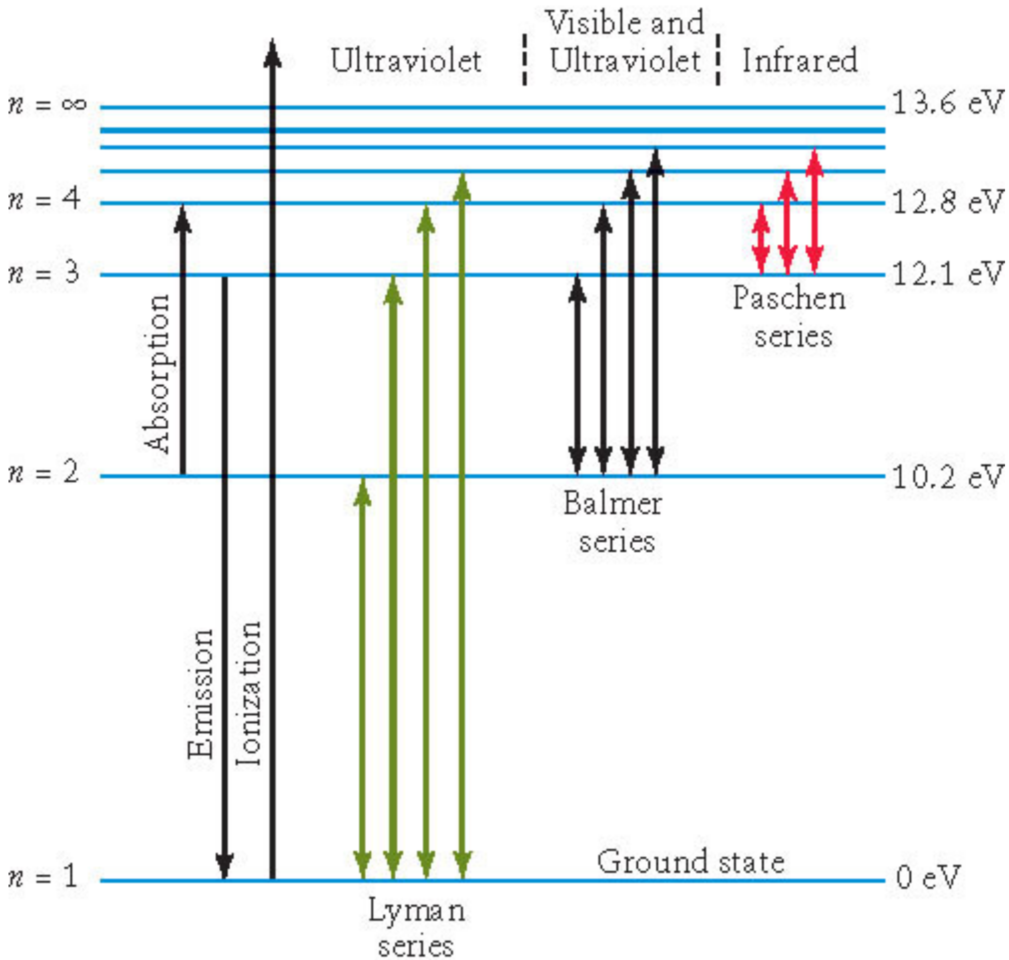
(hint R = 1.097 x $10^7 m^{-1}$)

2. What lines in the Balmer series fall in the UV ?

3. What are the energy ranges for the Lyman, Balmer and Paschen Series?

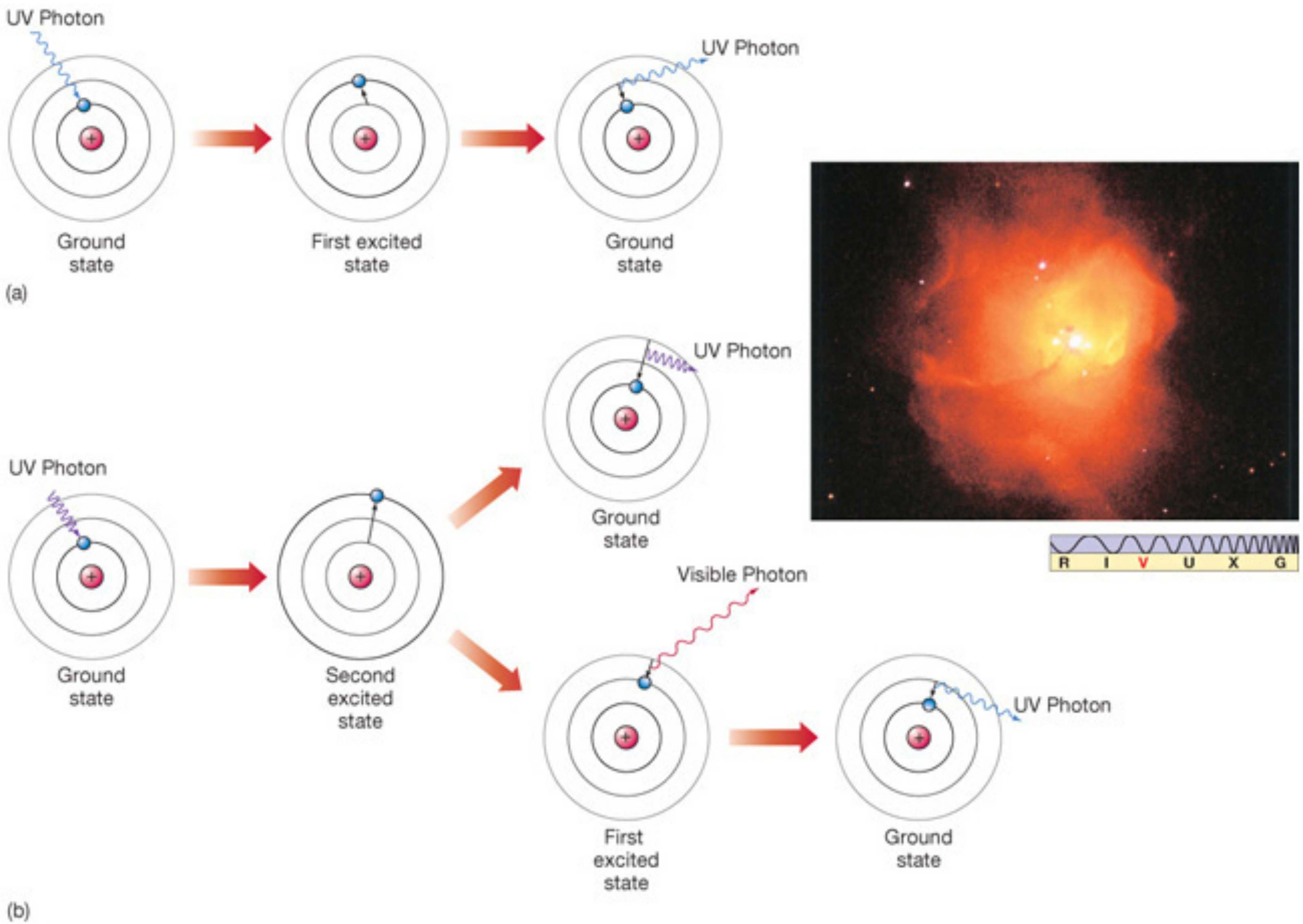
$$\frac{1}{\lambda} = R\left(\frac{1}{n_{in}^{\,2}} - \frac{1}{n_{out}^{\,2}}\right)$$

De-excitation



1. A Hydrogen atom in the ground state absorbs a L_β photon. What photon might that atom emit when de-excited?

Atomic De-excitation and Excitation



Hot stars within the Orion nebula emit high energy ultraviolet photons that are absorbed by the surrounding gas to heat it up to high temperatures.

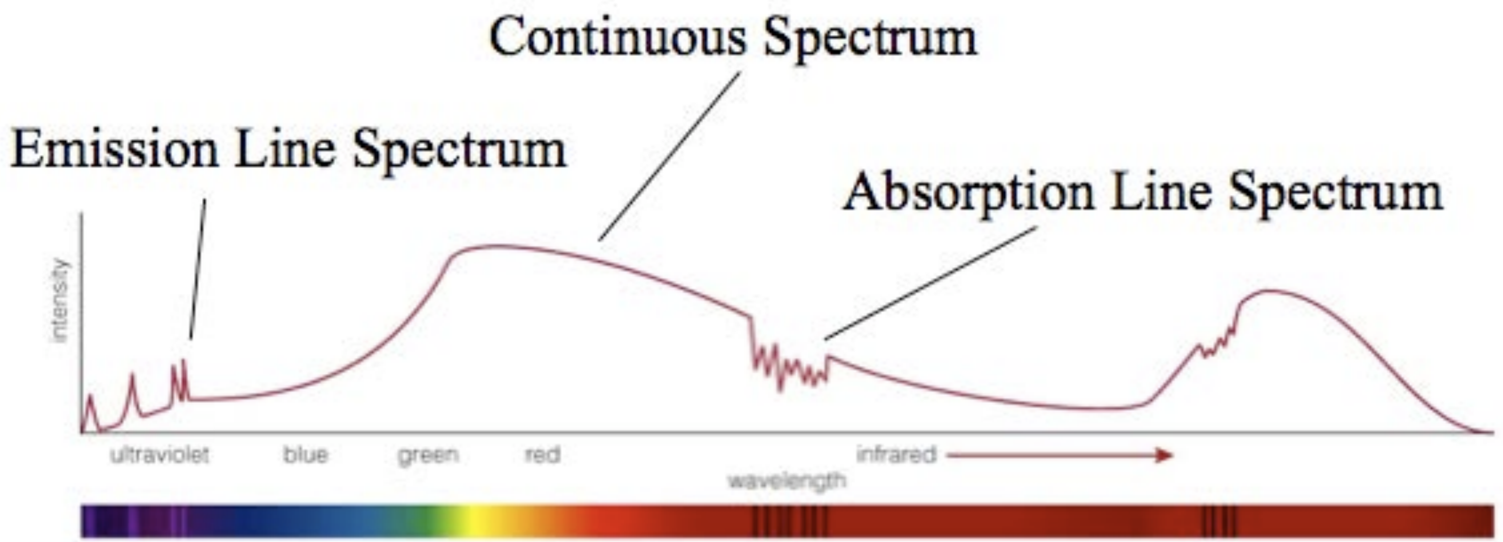
What is remarkable is that the emission spectrum produced by heated hydrogen gas on Earth contains the same 656 nm red line as the one found in the spectrum of the Orion Nebula located 1,340 light years away.

Orion Nebula (observed with the CofC 24 in)

5.4 Learning from Light

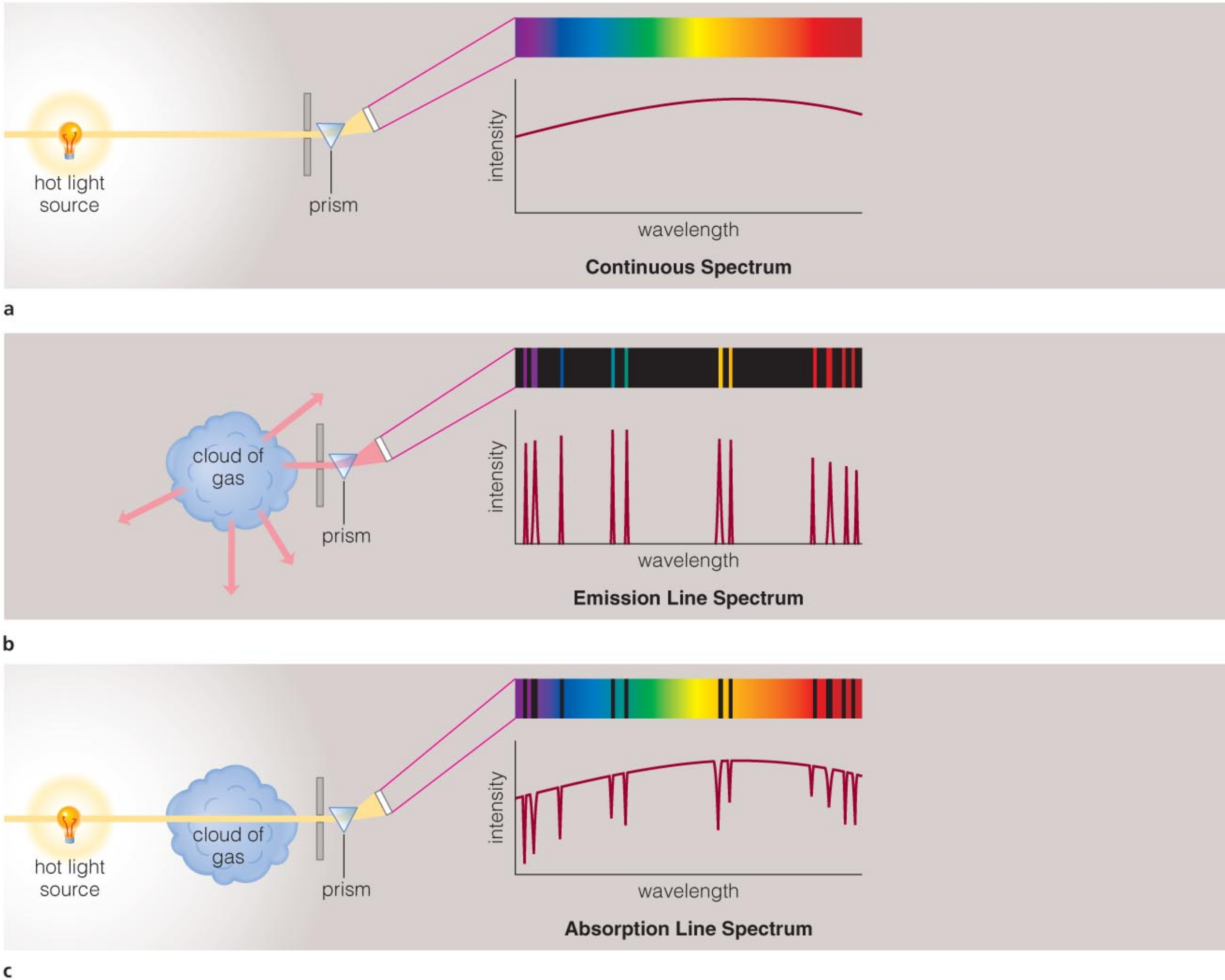
- Our goals for learning:
  - **What are the three basic types of spectra?**
  - **How does light tell us what things are made of?**
  - **How does light tell us the temperatures of planets and stars?**
  - **How does light tell us the speed of a distant object?**

What are the three basic types of spectra?

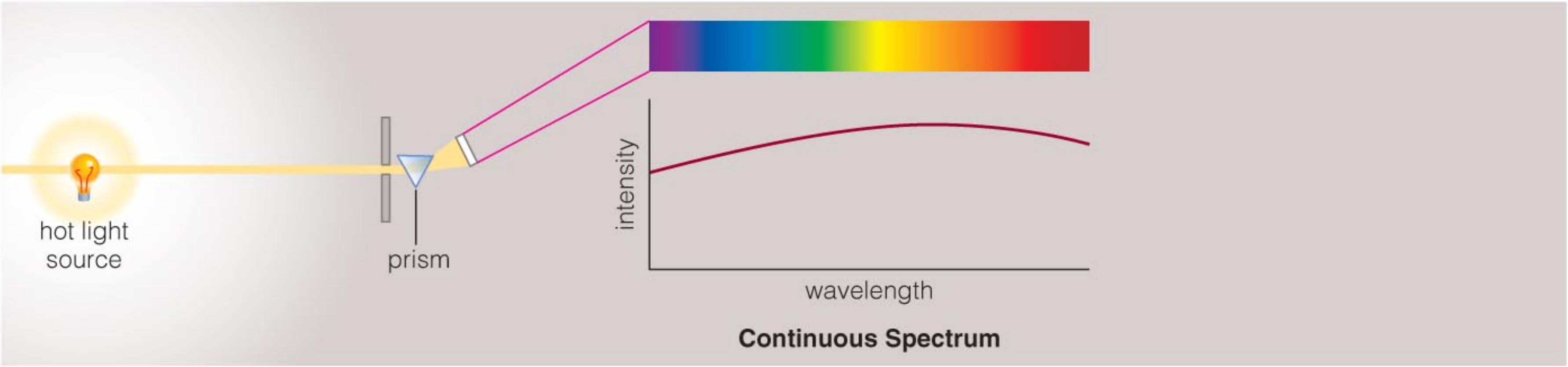


- Spectra of astrophysical objects are usually combinations of these three basic types.

Three Types of Spectra

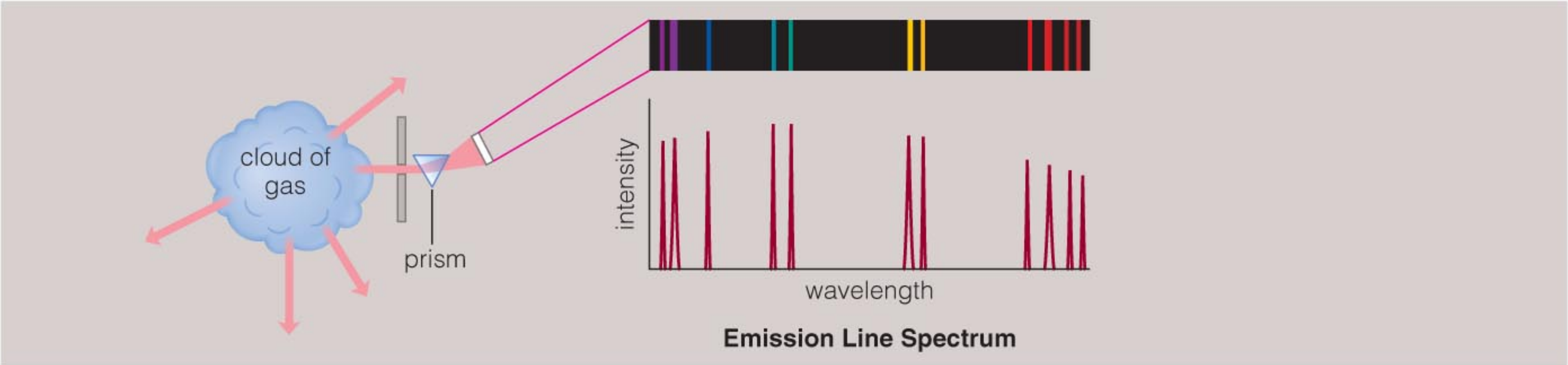


Continuous Spectrum



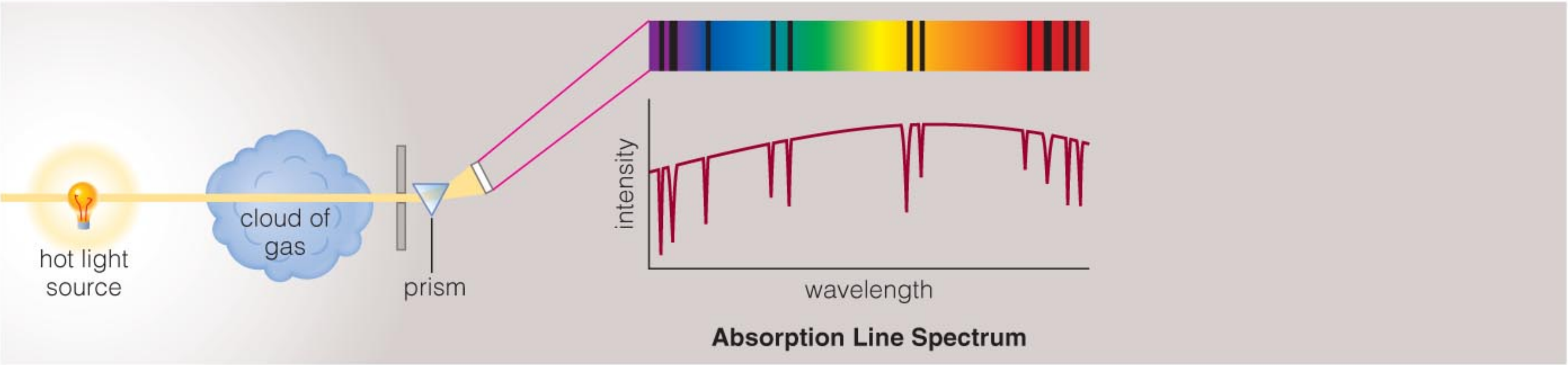
- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption.

Emission Line Spectrum



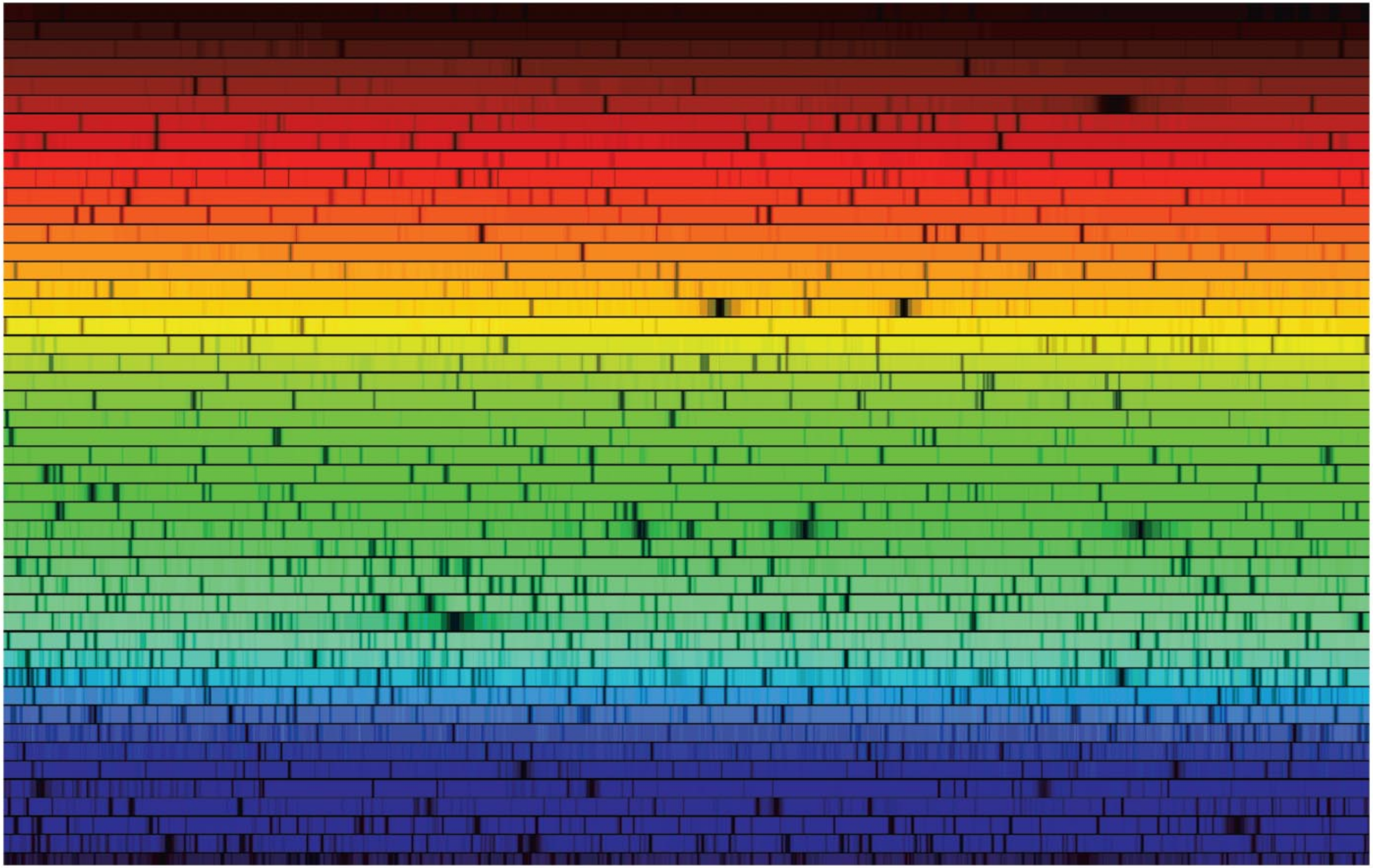
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines.

Absorption Line Spectrum

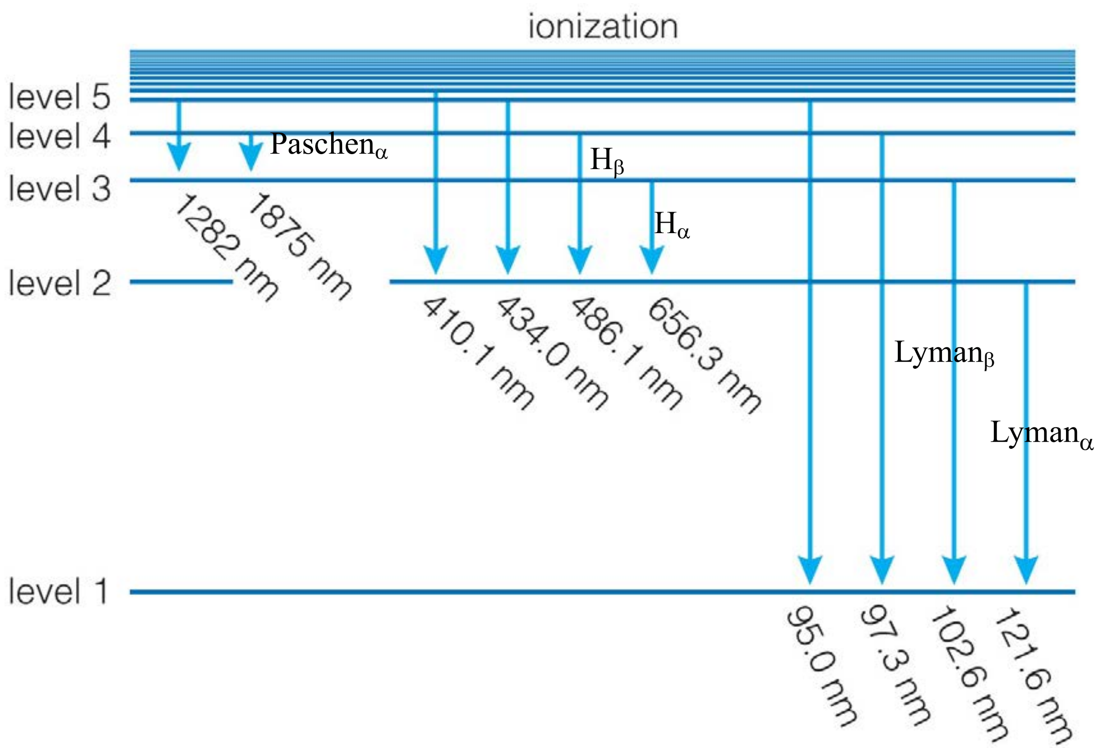


- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.

How does light tell us what things are made of?



Chemical Fingerprints



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

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

Chemical Fingerprints

- **Downward transitions produce** a unique pattern of **emission lines**.

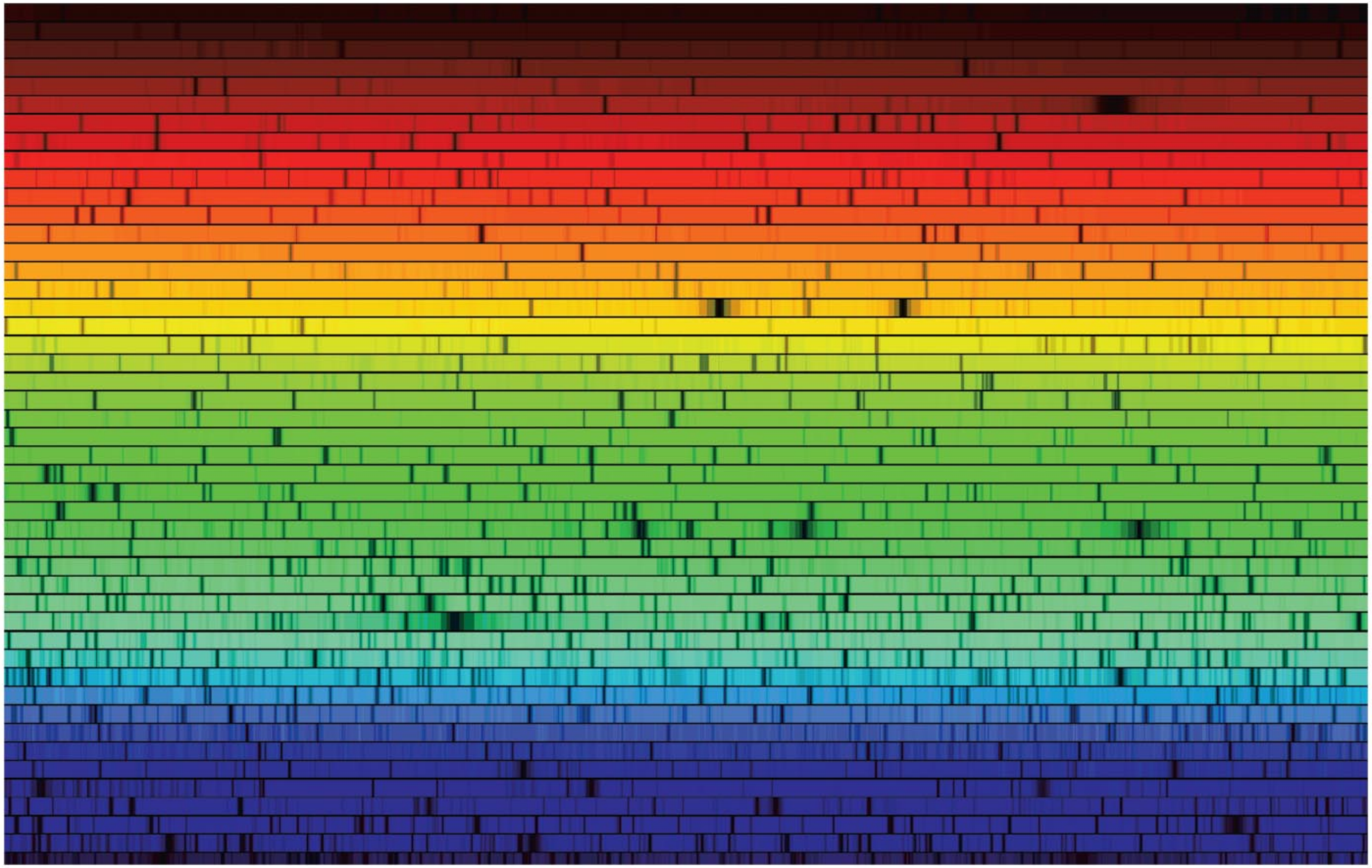
b This spectrum shows emission lines produced by downward transitions between higher levels and level 2 in hydrogen.

Chemical Fingerprints

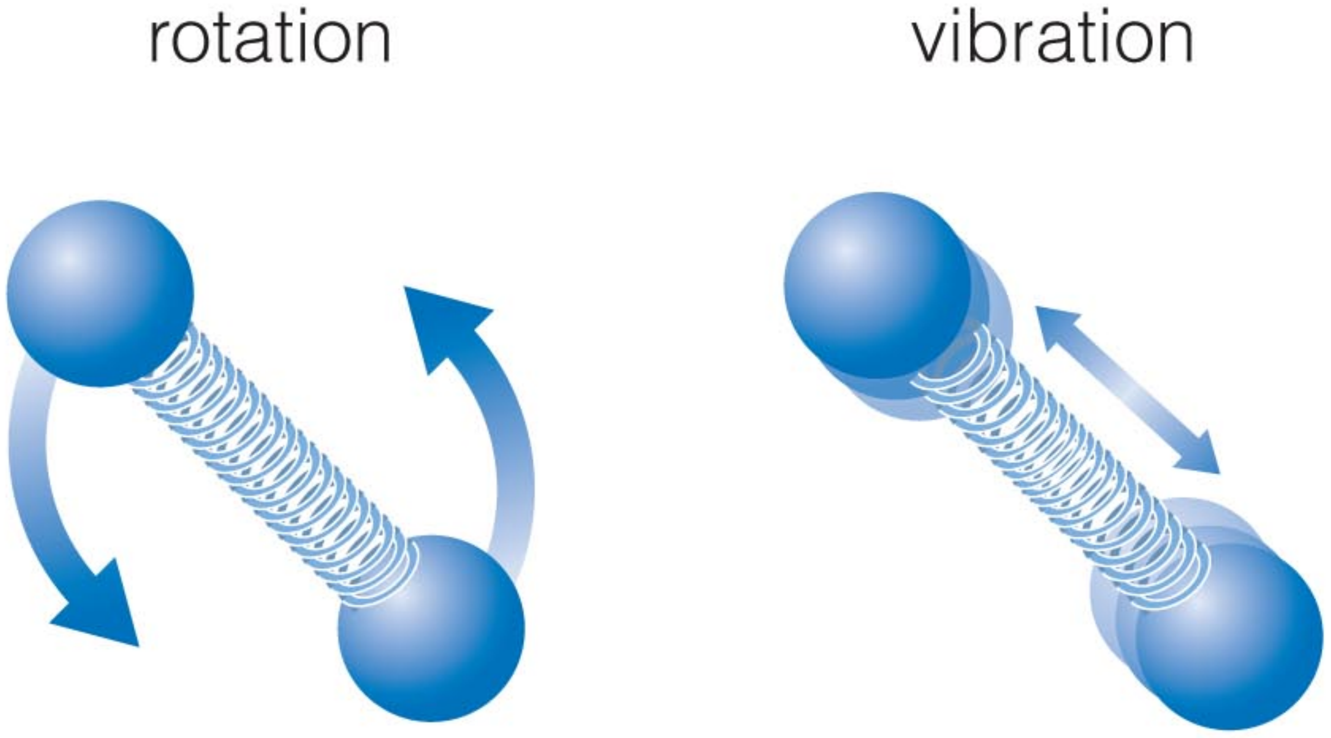
- Each type of atom has a unique spectral fingerprint.

Chemical Fingerprints

Example: Solar Spectrum



Energy Levels of Molecules



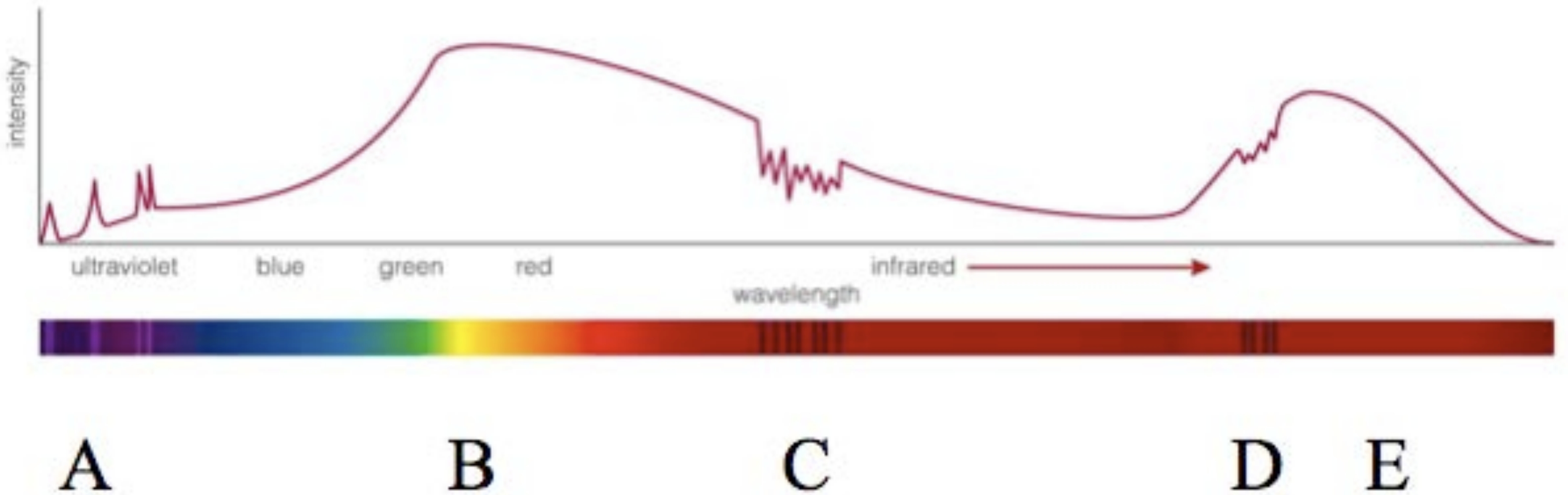
- Molecules have additional energy levels because they can vibrate and rotate.

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.

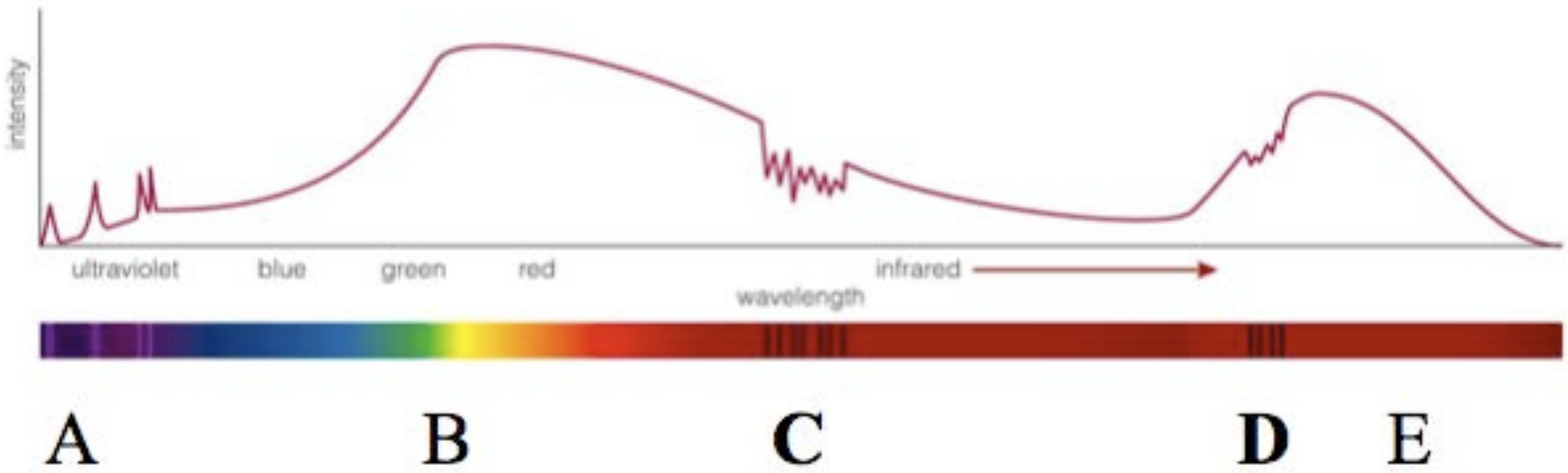
Thought Question

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



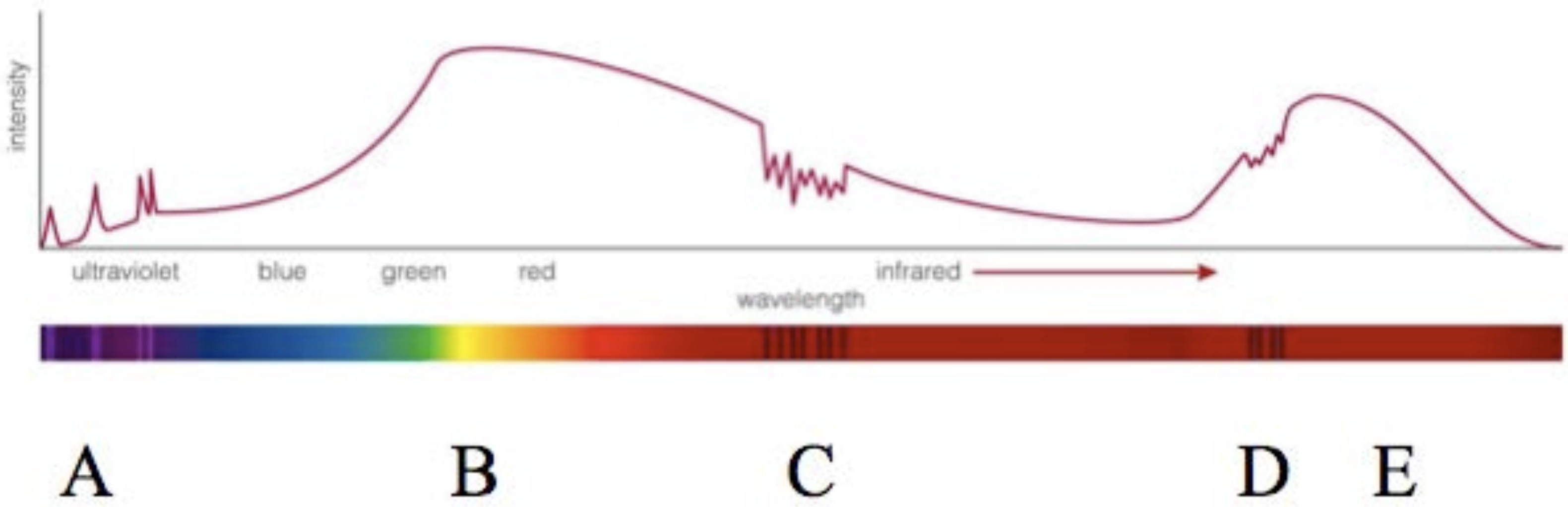
Thought Question

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



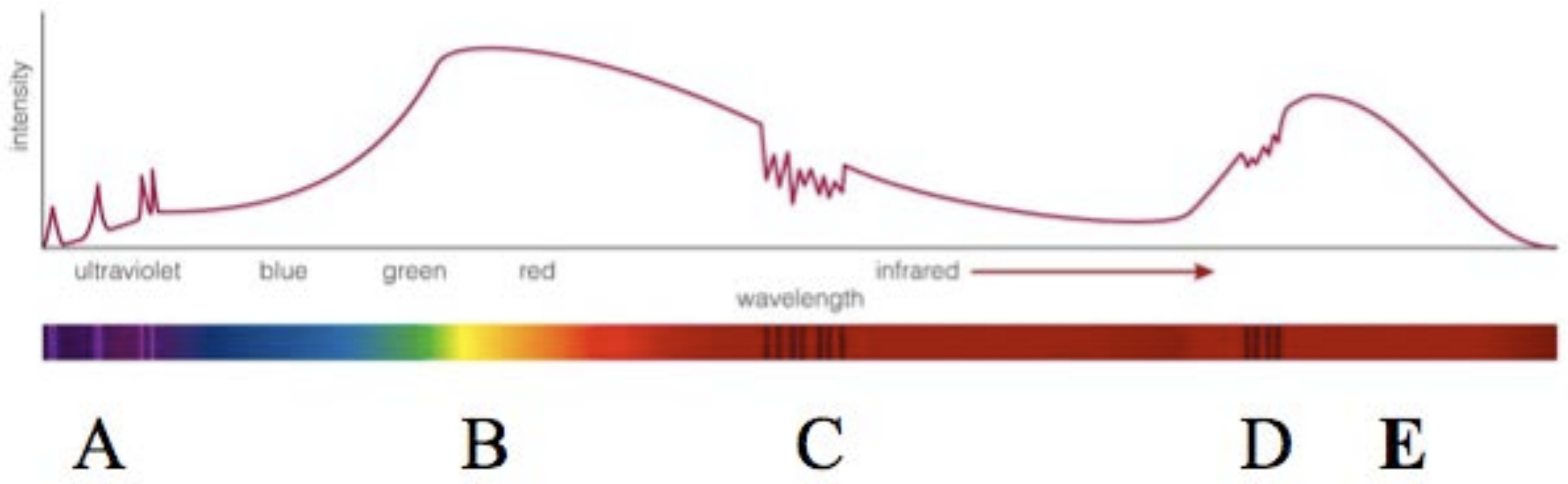
Thought Question

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



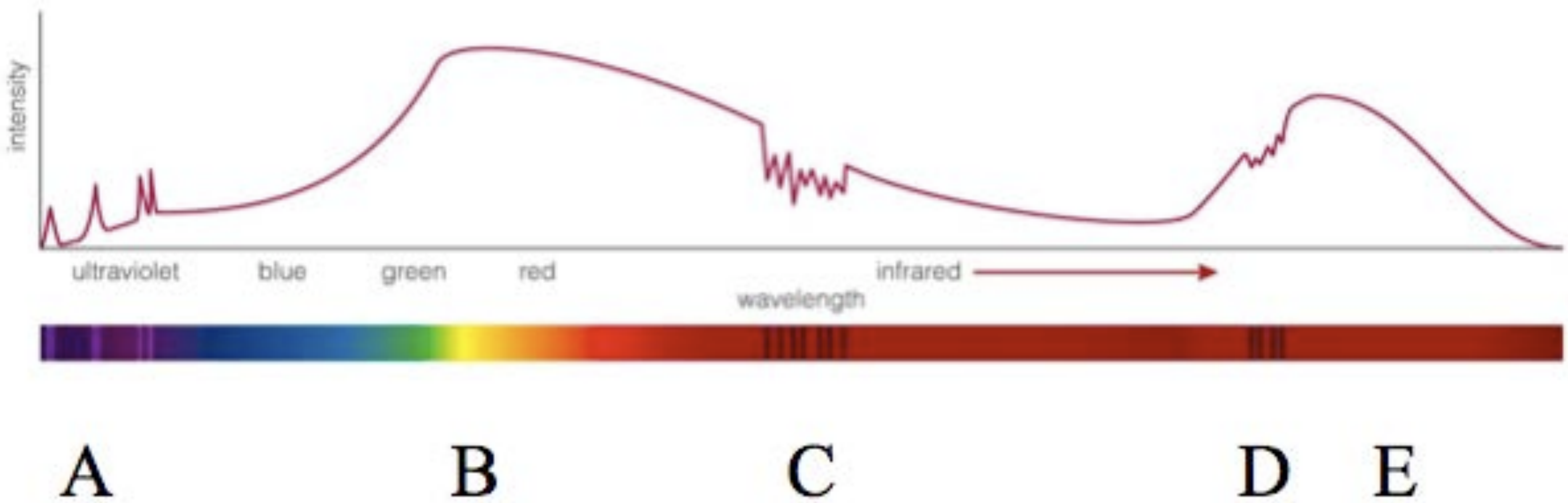
Thought Question

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



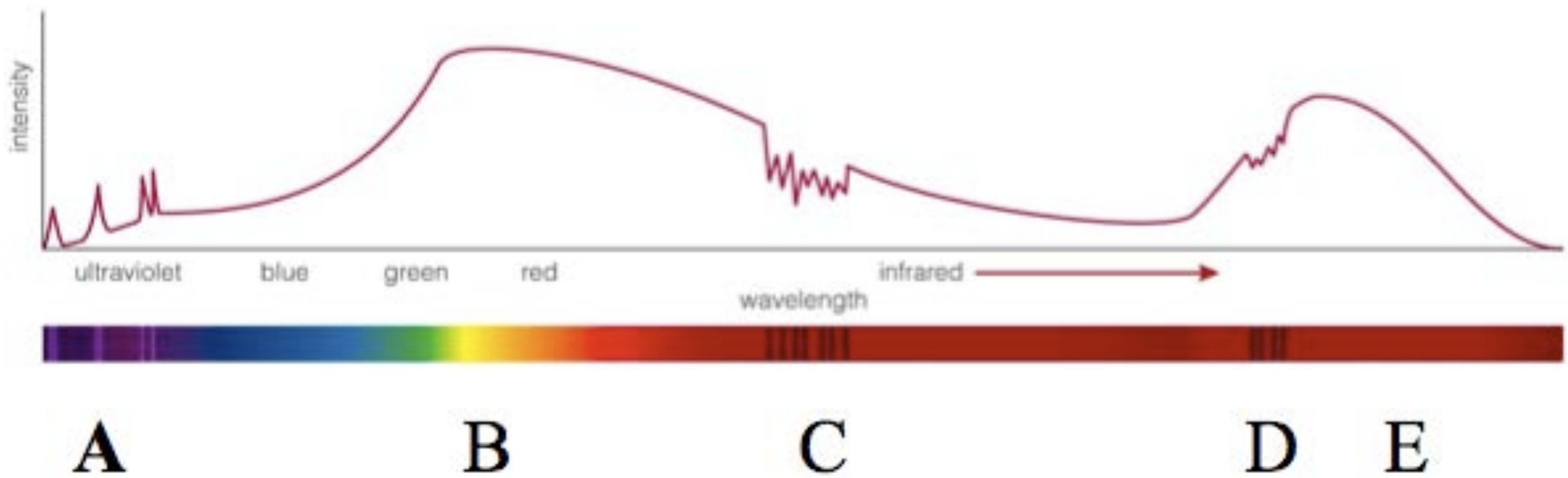
Thought Question

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

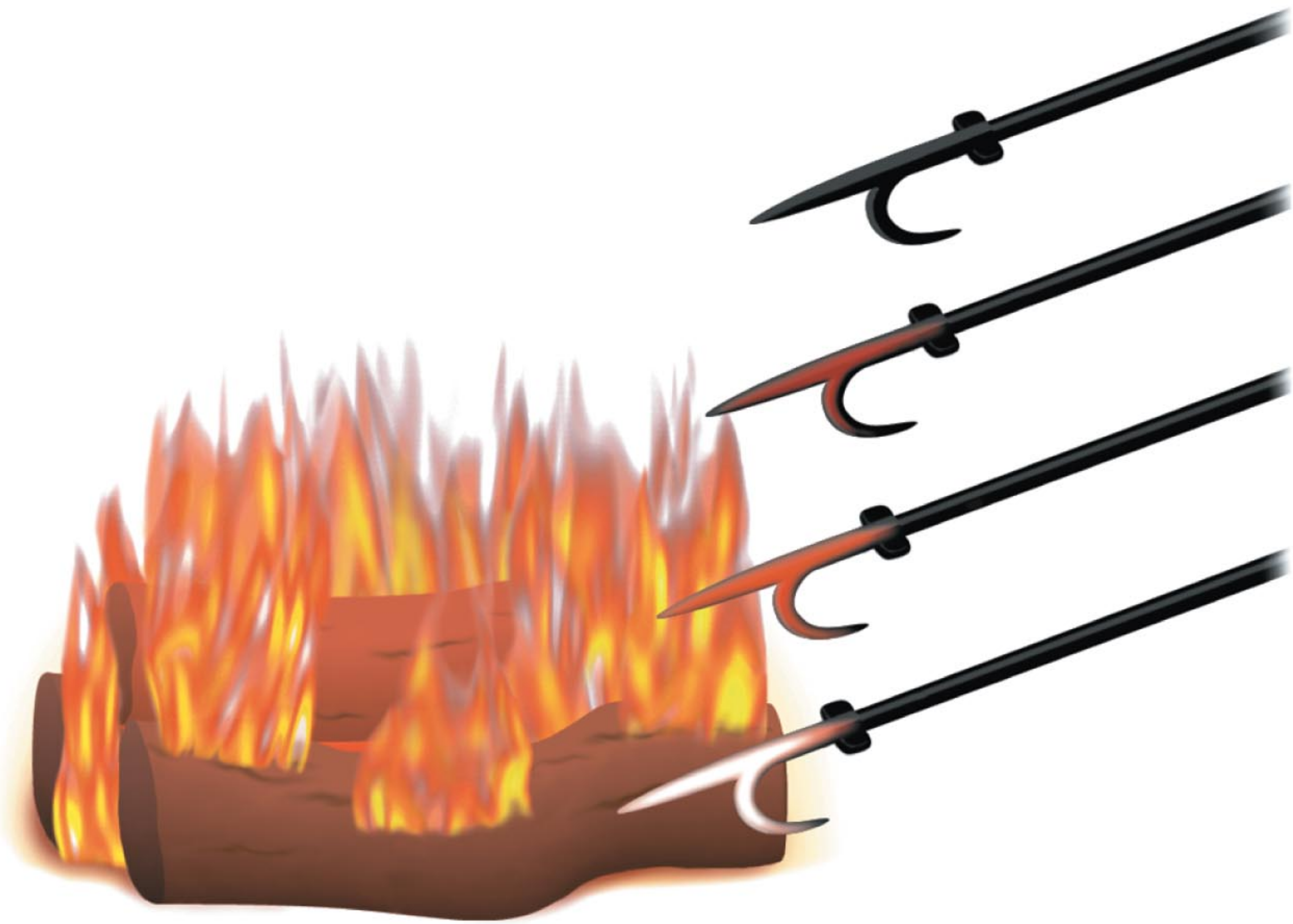


Thought Question

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



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



Thermal Radiation

Thermal radiation is electromagnetic radiation emitted from an object's surface and is related to its **temperature**.

Thermal radiation is generated when **kinetic energy** from the movement of charged particles within atoms **is converted into electromagnetic radiation**.

Examples of objects that emit thermal radiation:
The solid filament of a light bulb emits white light that is a mixture of light of many wavelengths.

The sun and stars, even though are gaseous, emit light that is very similar to that emitted by a very hot solid.

Kinetic Energy

The kinetic energy of an object of mass m and velocity v is:

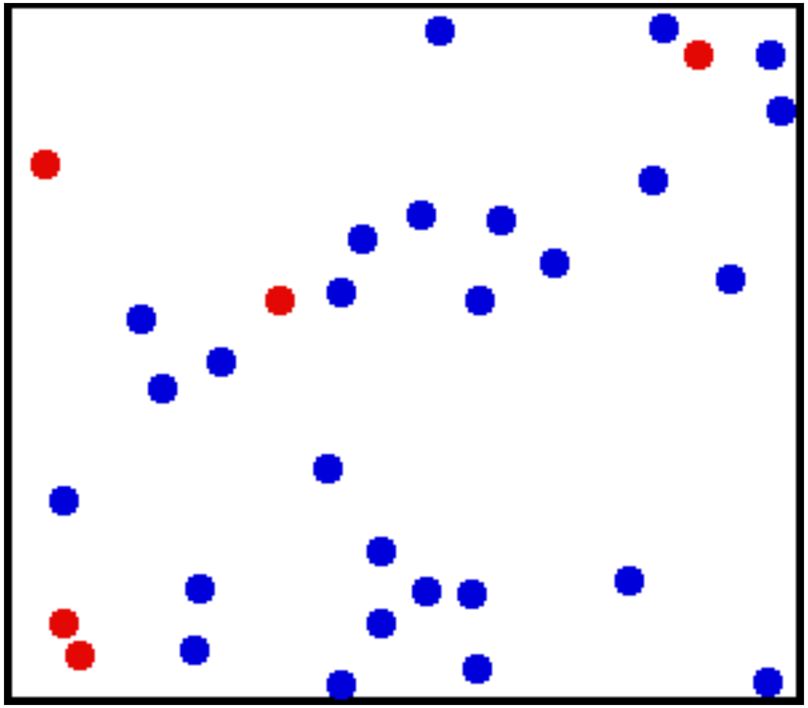
$$E_k = \frac{1}{2}mv^2$$

If m is expressed in kg and v in m/s, the kinetic energy is expressed in Joules (J).

Temperature of a Gas

The temperature of a gas is a direct measure of the average amount of kinetic energy per atom or molecule. The average kinetic energy of a gas atom or molecule is:

$$E_k = \frac{3}{2}kT$$



E_k = average kinetic energy of a gas atom or molecule in joules (J)

$k = 1.38 \times 10^{-23}$ J/K (Boltzmann constant)

T = temperature of gas, in kelvins

Average Speed of a Gas Molecule or Atom

The average speed v (m/s) of a gas molecule or atom is:

$$\frac{1}{2}\mathrm{mv}^2 = \frac{3}{2}k\mathrm{T} \Rightarrow \mathrm{v} = \sqrt{\frac{3k\mathrm{T}}{\mathrm{m}}}$$

$k = 1.38 \times 20^{-23}$ J/K (Boltzmann constant)

T = temperature of gas, in kelvins

m = mass of atom or molecule in kg

The average speed of the oxygen molecules that you breathe at a room temperature of 20° C is about 0.478 km/s.

Absolute Temperature Scale

The SI unit for temperature (T) is the kelvin. The Kelvin scale is a thermodynamic (absolute) temperature scale where absolute zero, the theoretical absence of all thermal energy, is zero kelvin (0 K).

$$T(K) = T(^\circ C) + 273.15^\circ$$

For example the average surface temperatures of Mercury and Mars are about 700 K and 300 K, respectively.

The temperatures in the upper atmospheres of Jupiter and Neptune are about 125 K and 55 K, respectively.

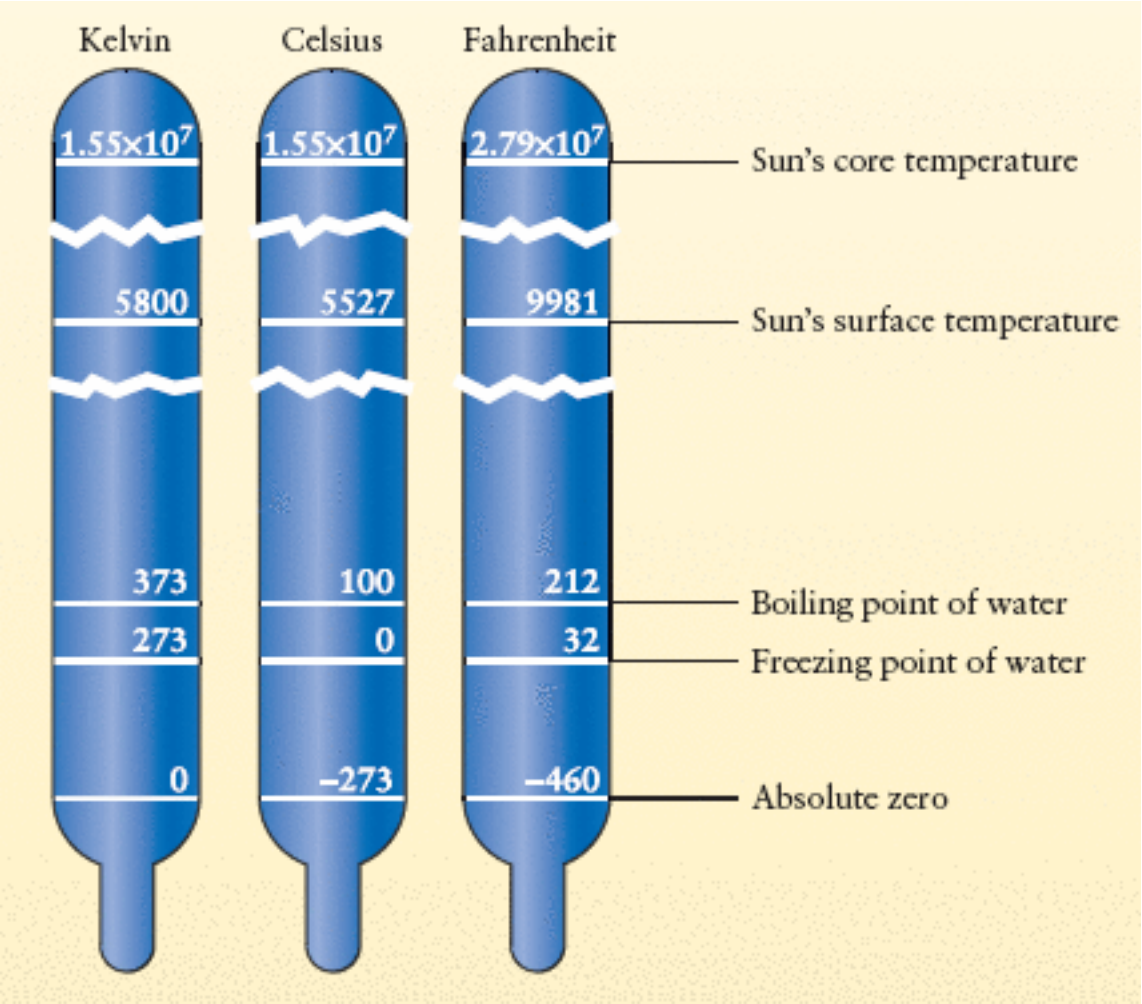
$$T_C = \frac{5}{9}(T_F - 32)$$

$$T_K = T_C + 273.15^\circ$$

T_C temperature in degrees Celsius

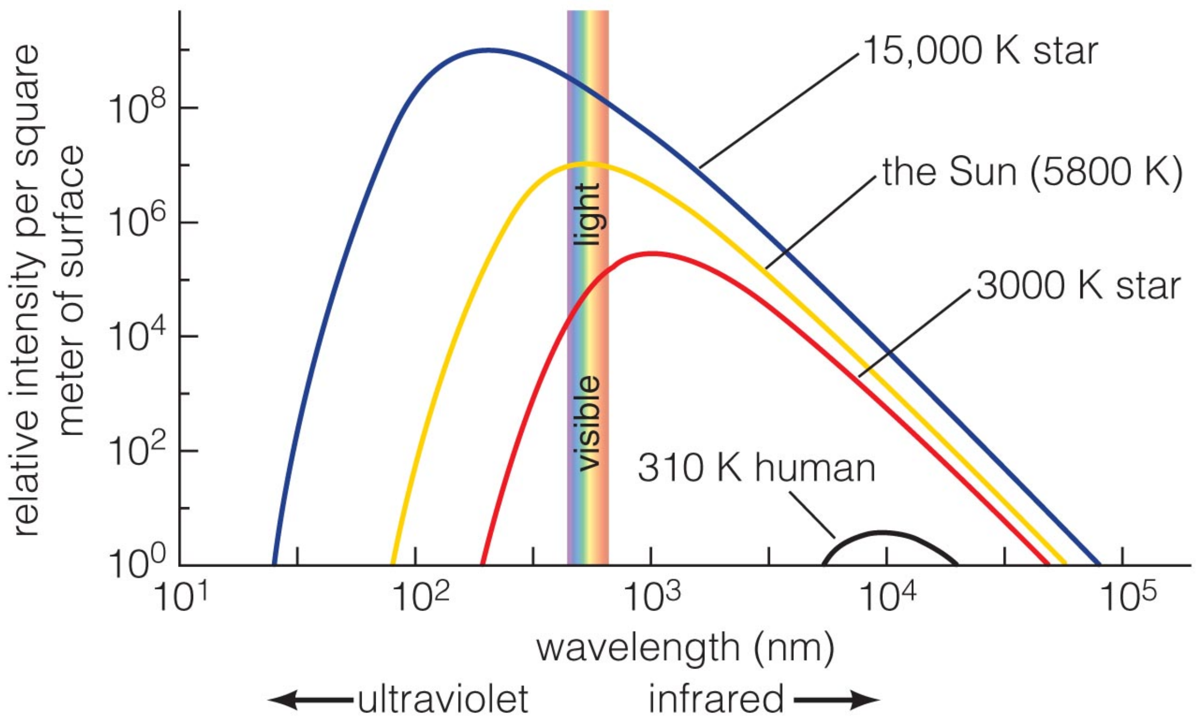
T_F temperature in degrees Fahrenheit

T_K temperature in kelvin



Properties of Thermal Radiation

1. Hotter objects emit more light at all frequencies per unit area (Stefan-Boltzmann Law).
2. Hotter objects emit photons with a higher average energy (the peak wavelength decreases). (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

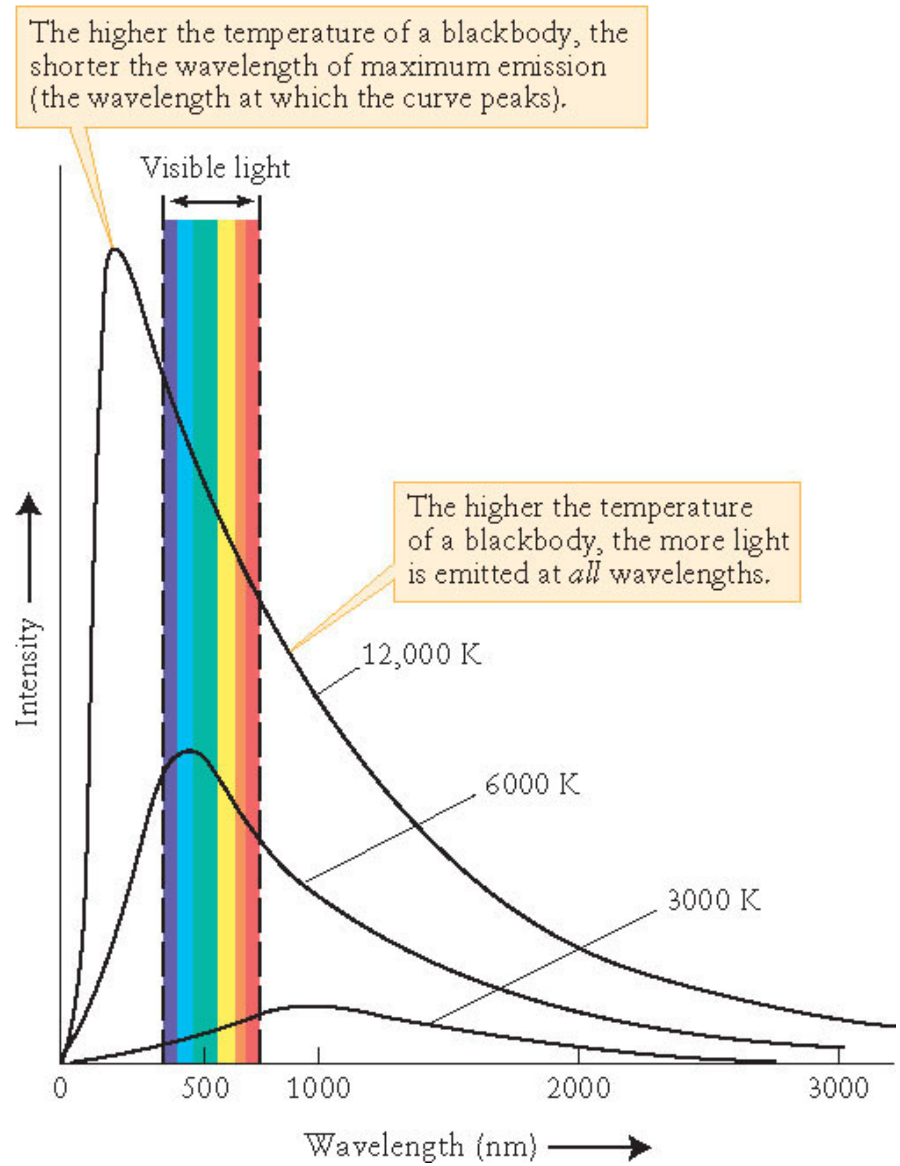
Which is hottest?

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

Intensity *vs*. Wavelength: Spectra

This figure shows the intensity of light emitted by a solid as a function of wavelength for three different temperatures of the emitting solid.

Notice that the dominant wavelength decreases with increasing temperature.

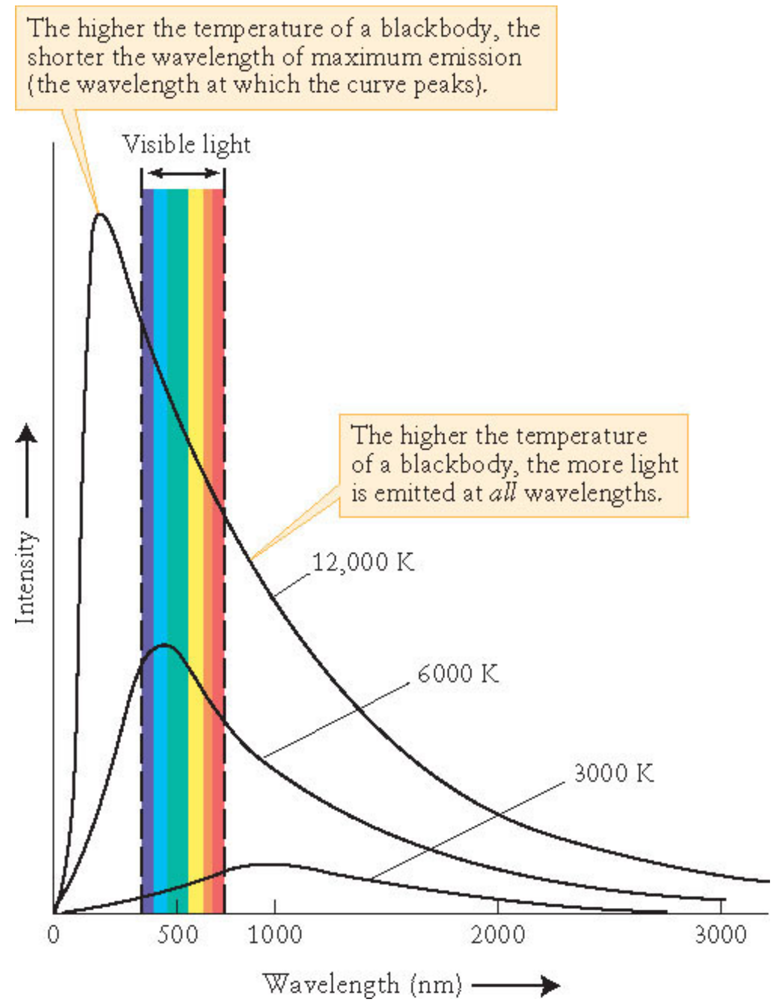


Temperatures of Stars

An ideal **blackbody absorbs** all the radiation that falls on it.

The spectra of stars are often approximated with blackbody spectra.

Property of blackbody spectra:
The higher an objects temperature the more intensely the object emits radiation and the shorter wavelength it emits more strongly.

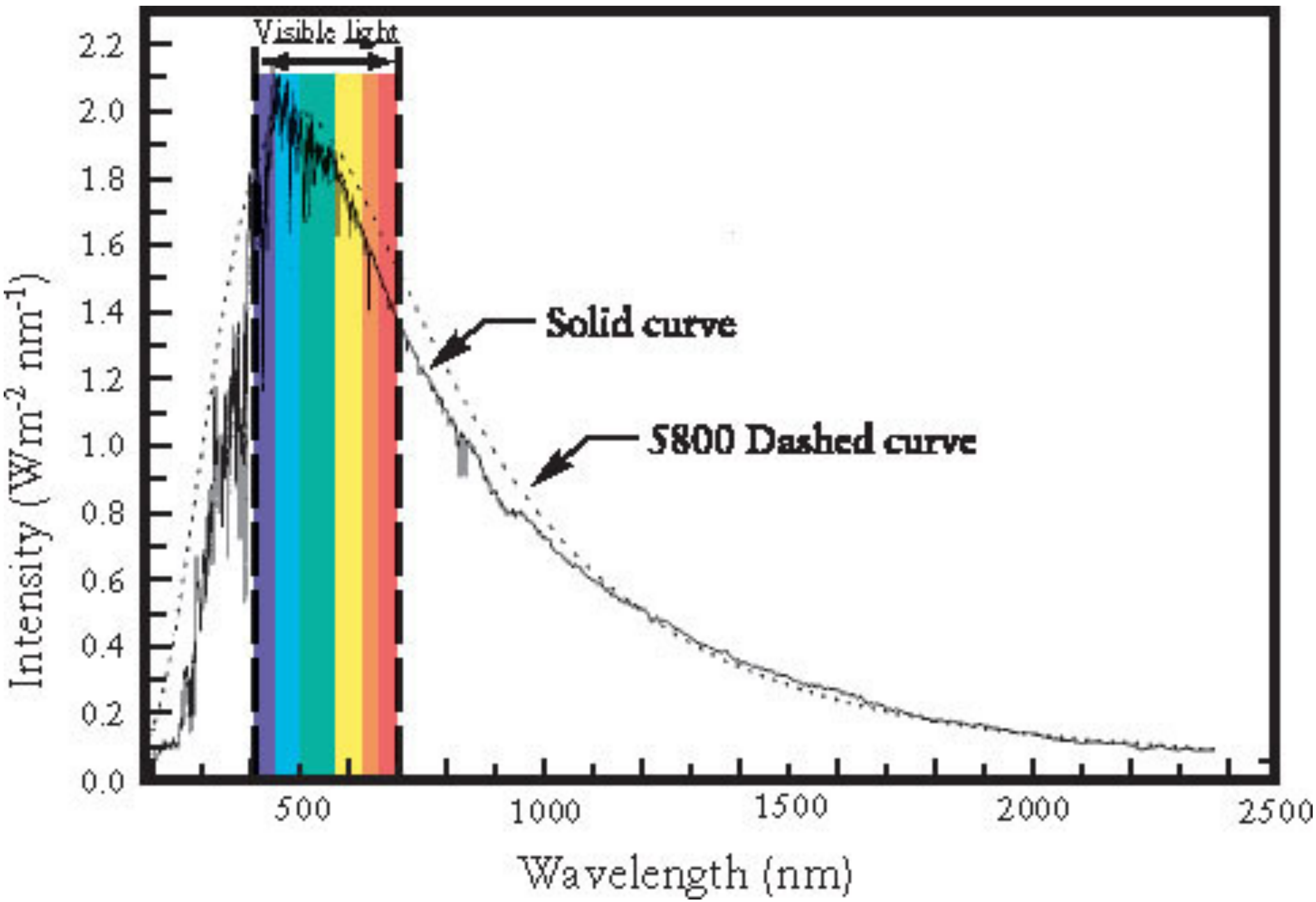


Temperatures of Stars

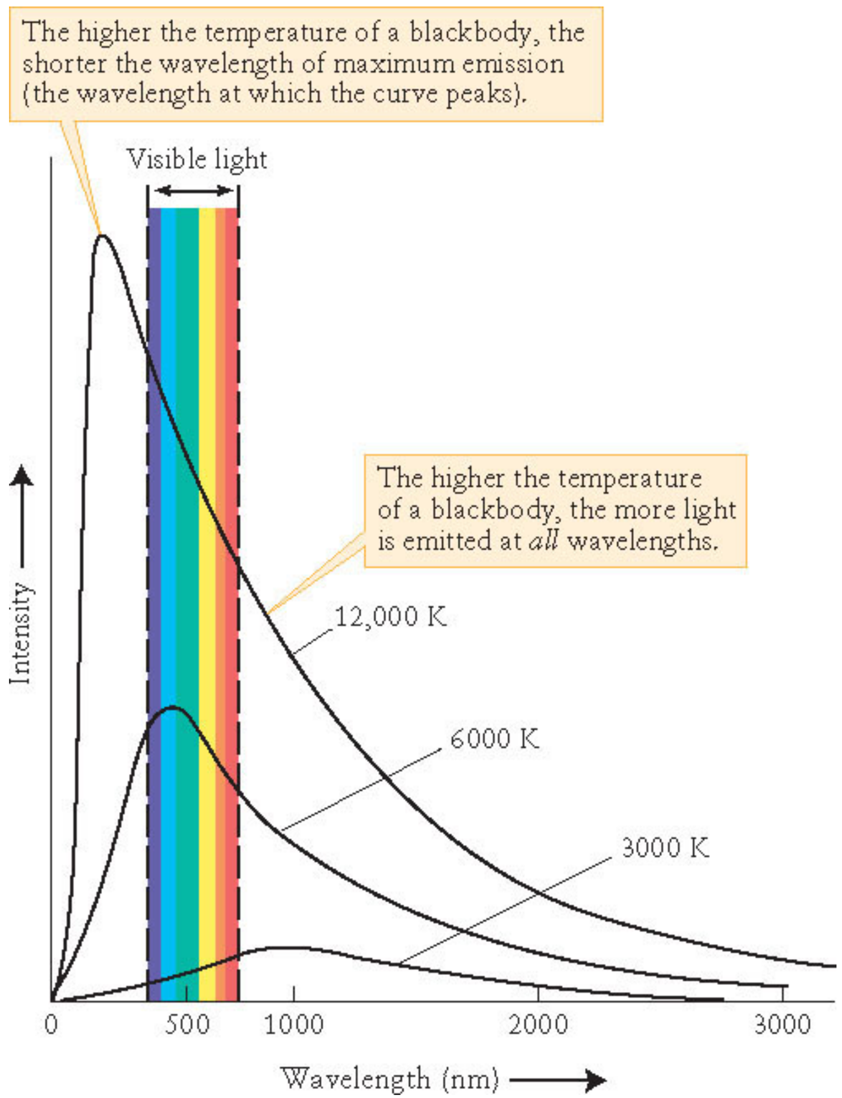
Example: The star Bellatrix in Orion that looks blue has a higher temperature than the red star Betelgeuse.


DIMMING GIANT
STAR BETELGEUSE
WILL IT EXPLODE?
SPACE.com

The Sun's Spectrum



Blackbody Radiation: Wien's Law



Wien's Law

$$\lambda_{max}(m) = \frac{0.0029\,K\,m}{T(K)}$$

λ_{max} = wavelength of maximum emission in meters

T = temperature of object in kelvins

Wien's Law: Sun

The maximum intensity of sunlight is at a wavelength of roughly 500 nm = 5.0×10^{-7} m. Use this information to determine the surface temperature of the Sun.

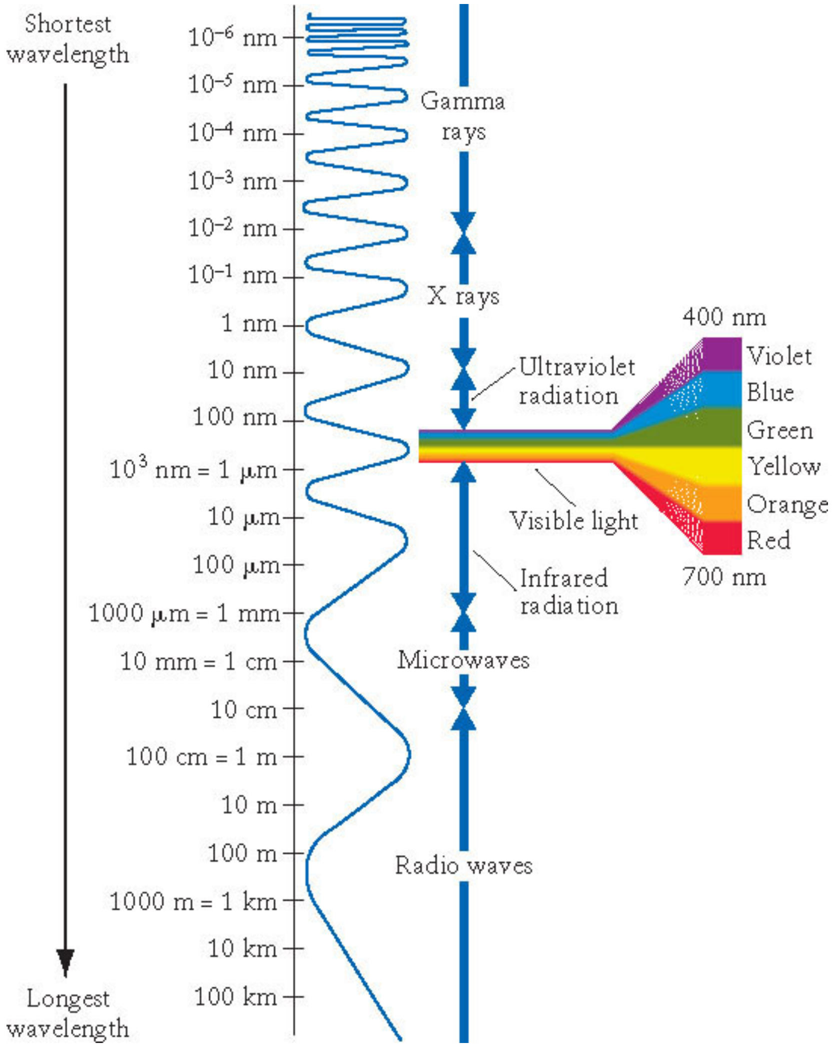
Wien's Law: Sun

The maximum intensity of sunlight is at a wavelength of roughly 500 nm = 5.0×10^{-7} m. Use this information to determine the surface temperature of the Sun.

Sun: $\lambda = 0.0029$ Km / T(K)

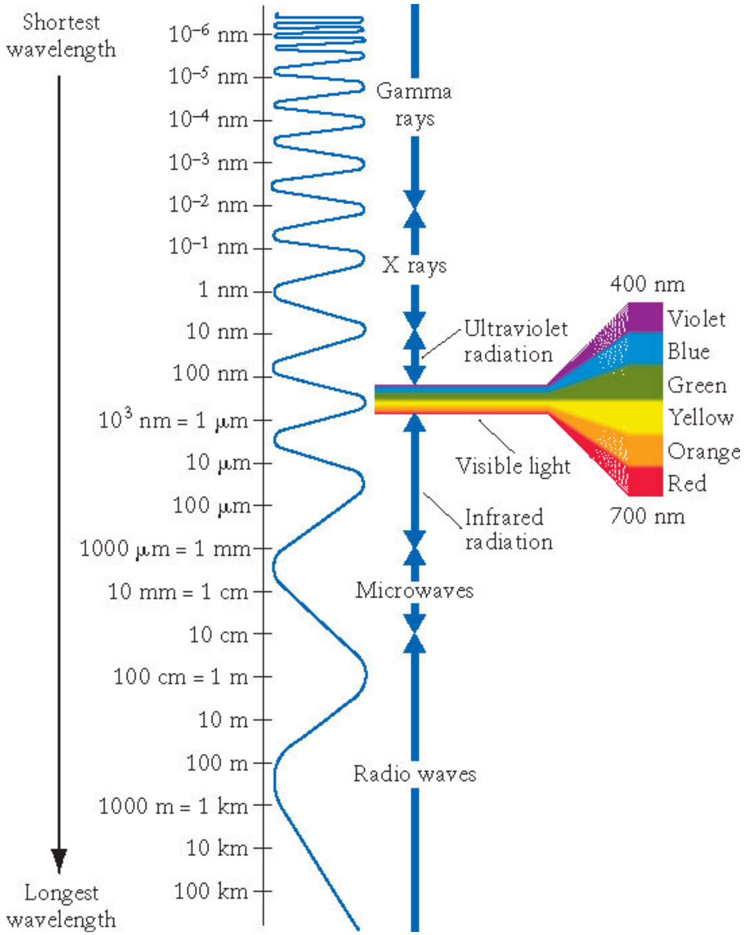
--> $T_{sun} = 0.0029$ K m / 5×10^{-7} m = 5800 K

Wien's Law: Sirius



Sirius, the brightest star in the night sky, has a surface temperature of about 10,000 K. Find the wavelength at which Sirius emits most intensely.

Wien's Law: Sirius



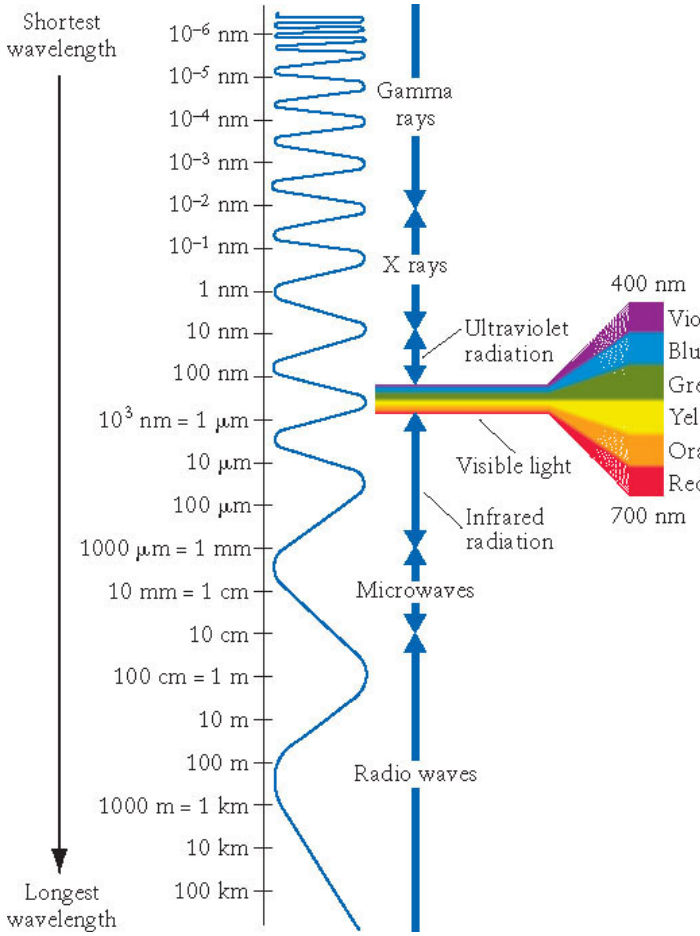
Sirius, the brightest star in the night sky, has a surface temperature of about 10,000 K. Find the wavelength at which Sirius emits most intensely.

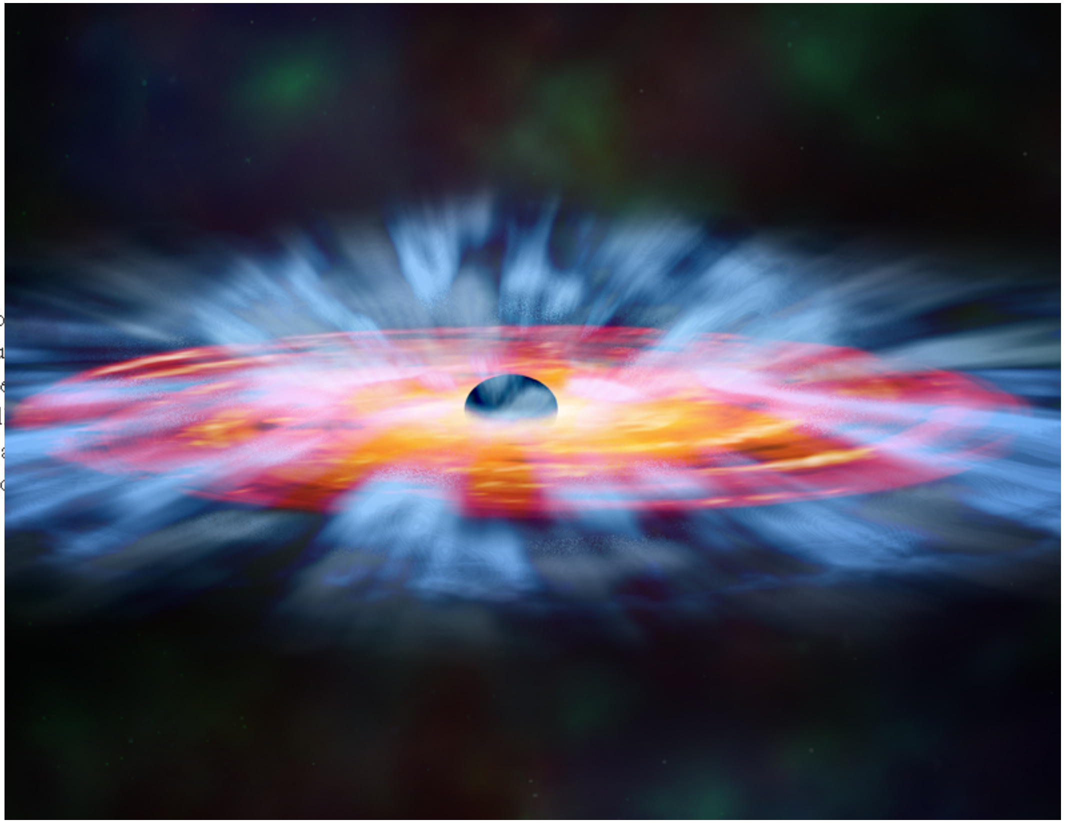
Sirius: $\lambda = 0.0029/T \rightarrow$

$\lambda = 0.0029$ K m / 10,000 K $\rightarrow$

$\lambda = 2.9 \times 10^{-7}$ m = 290 nm (UV band)

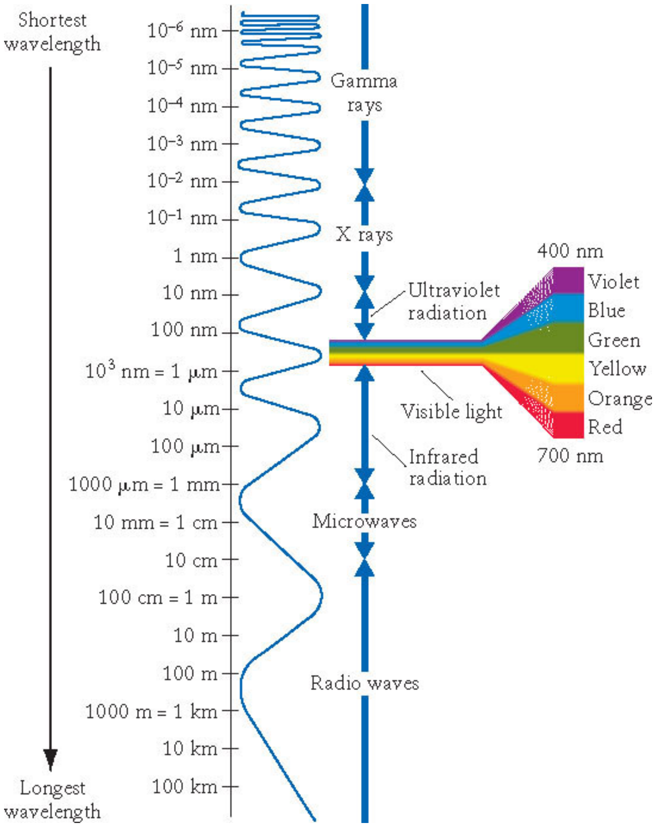
Wien's Law: Black Hole Accretion Disk

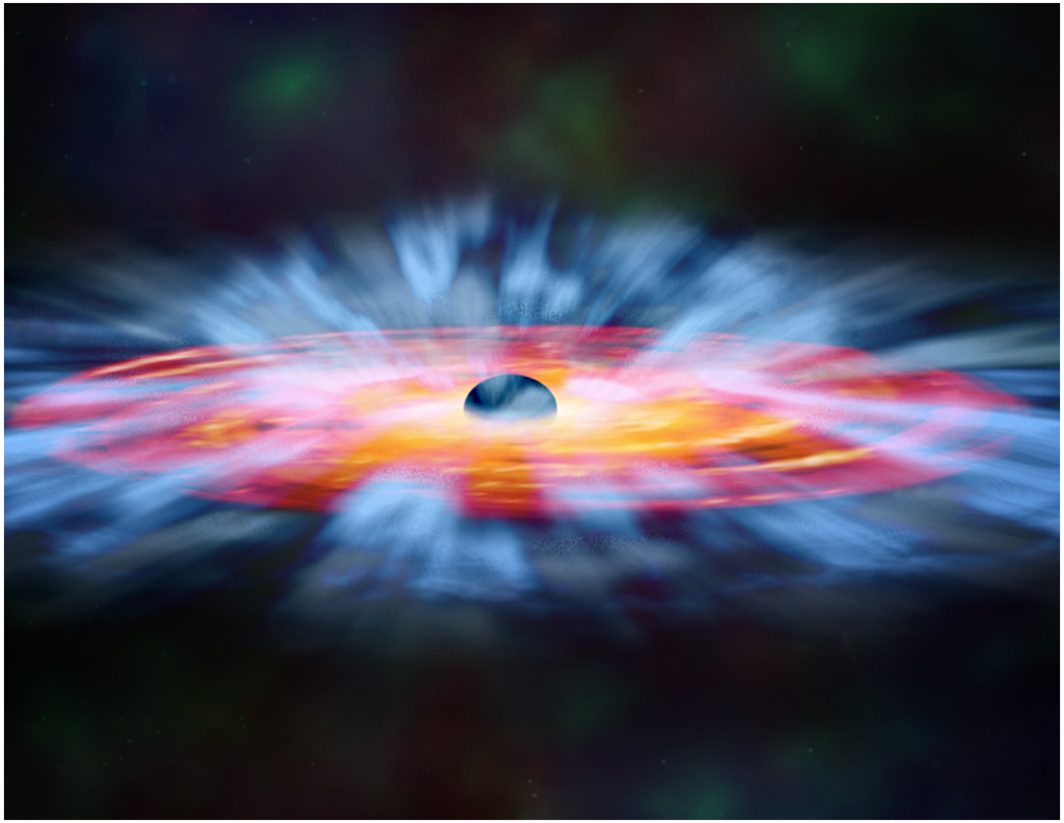




$T_{disk} \sim 10^6 K$, $\lambda = ?$

Wien's Law: Black Hole Accretion Disk





T_{disk}~10^6K, λ= ?

Black Hole: $\lambda = 0.0029/T = 0.0029$ K m / 1 × 10^6 K →

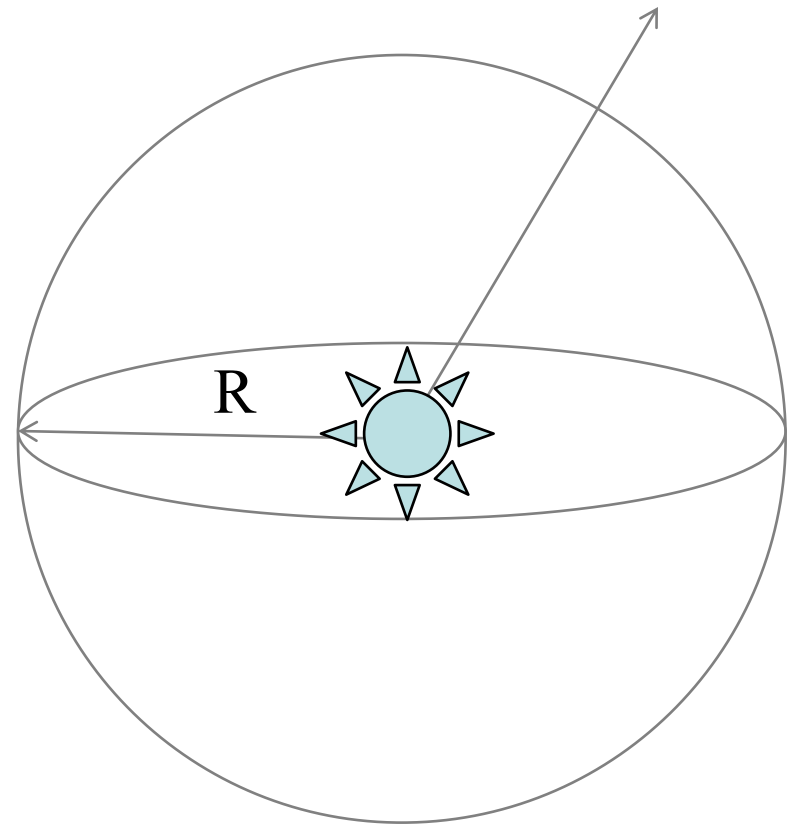
$\lambda = 2.9\ 10^{-9}$ m = 2.9 nm (X-ray band)

Flux Energy Density and Luminosity

Flux Energy Density $= F = \dfrac{E}{At}$ (J m^{-2} s^{-1})

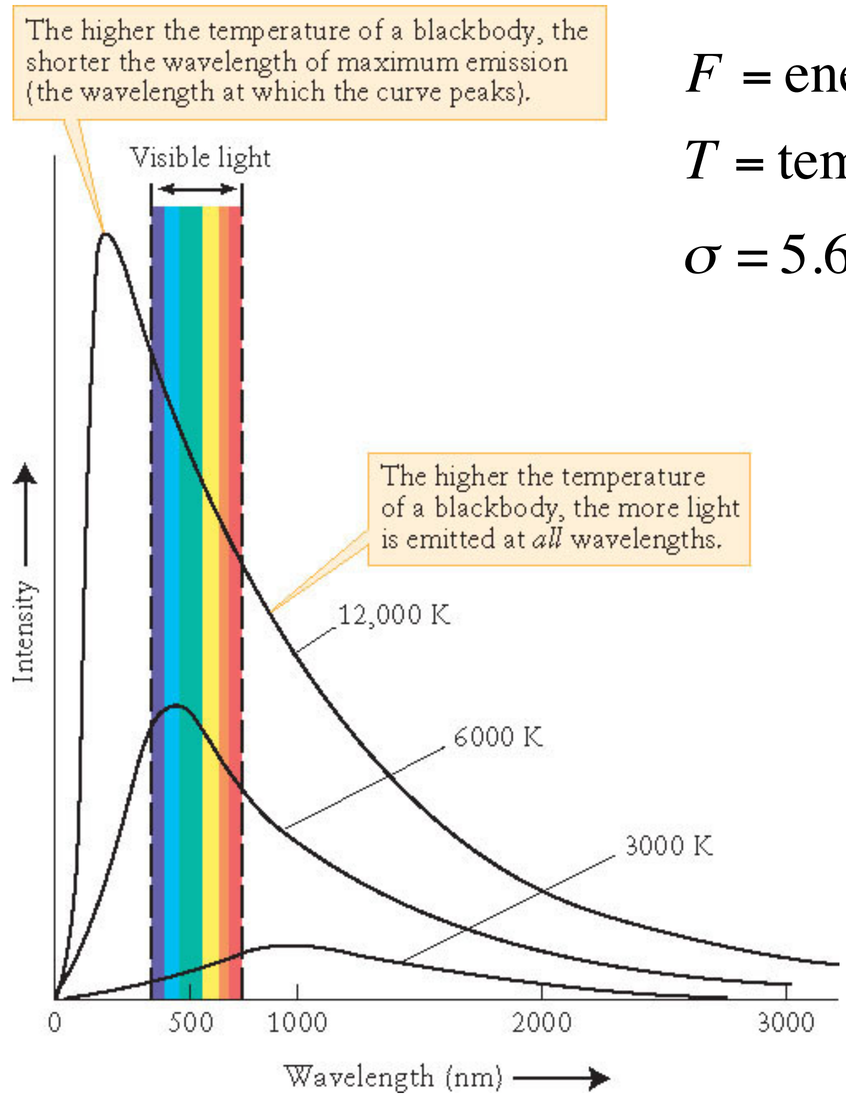
Luminosity $= L = \dfrac{E}{t}$ (J s^{-1})

E = energy crossing an area A within a time t



Since the area of a sphere is $4\pi R^2$, as one moves away from the source the flux will decrease by $1/R^2$

Blackbody Radiation: Stefan-Boltzmann Law

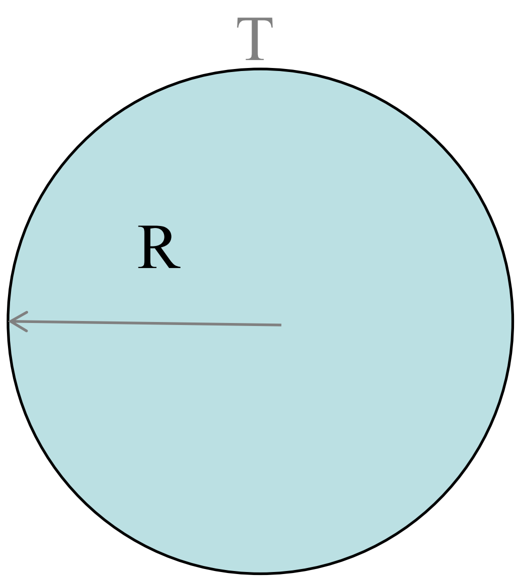


$$F = \sigma T^4$$

F = energy flux at the surface of a star, ($W\ m^{-2}$)

T = temperature of object, (kelvin)

$\sigma = 5.67 \times 10^{-8} W\ m^{-2} K^{-4}$



Stefan-Boltzmann's Law: Sirius vs. Sun

How does the energy flux from Sirius compare to the Sun's energy flux?

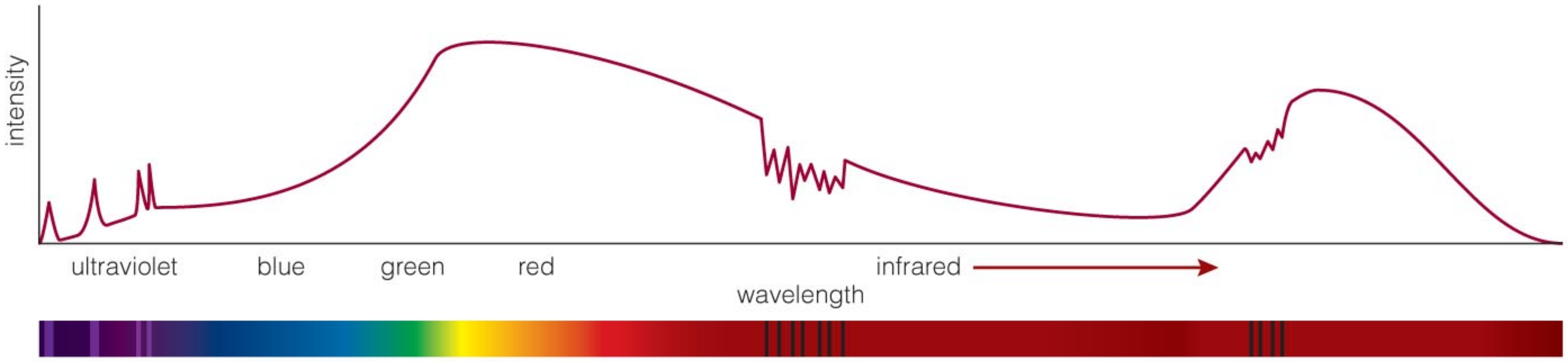
$T_{sirius} = 10{,}000$ K, $T_{sun} = 5{,}800$ K

Stefan-Boltzmann's Law: Sirius vs. Sun

How does the energy flux from Sirius compare to the Sun's energy flux?

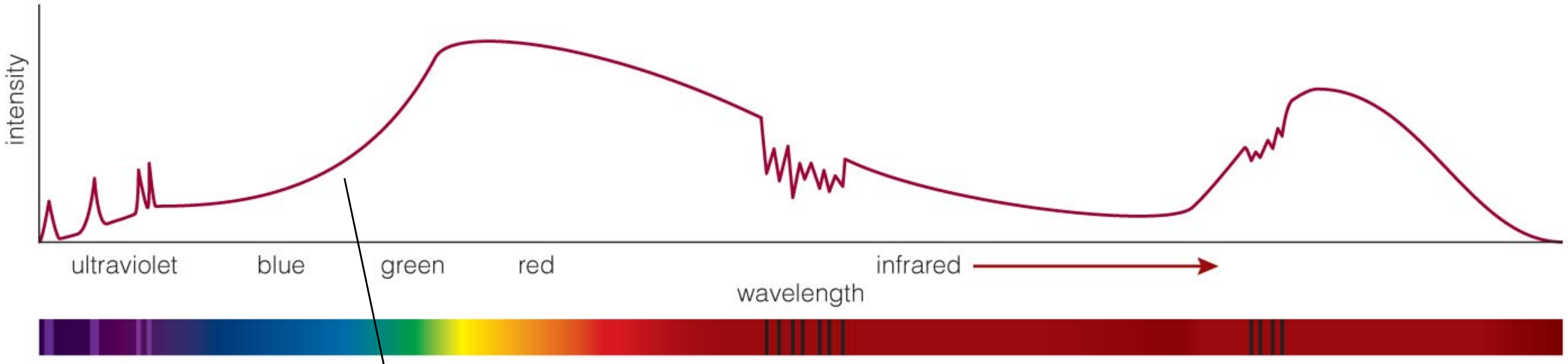
$F_{sirius}/F_{sun} = \sigma T^4_{sirius}/\sigma T^4_{sun} = (10{,}000\ K/5800\ K)^4 = 8.84$

Example: How do we interpret an actual spectrum?



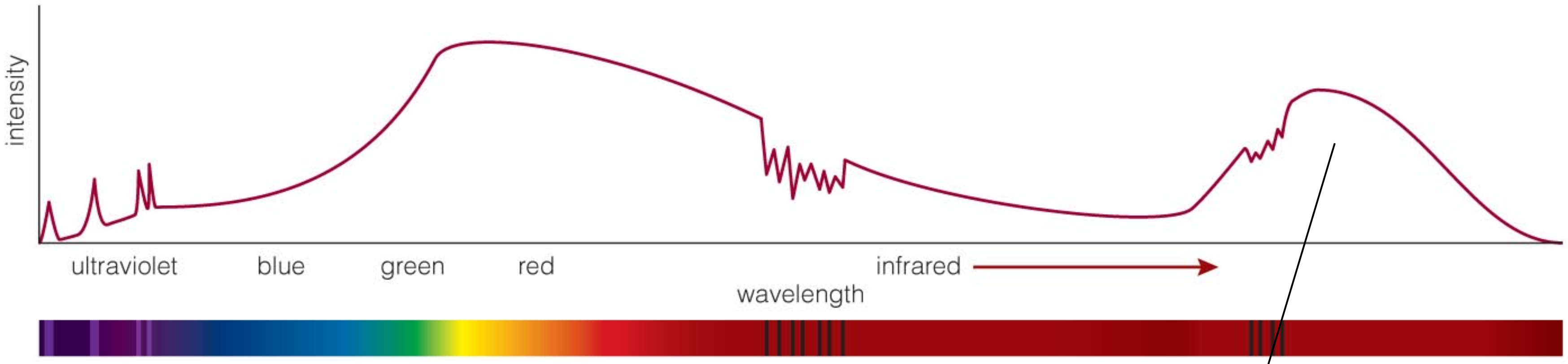
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What is this object?



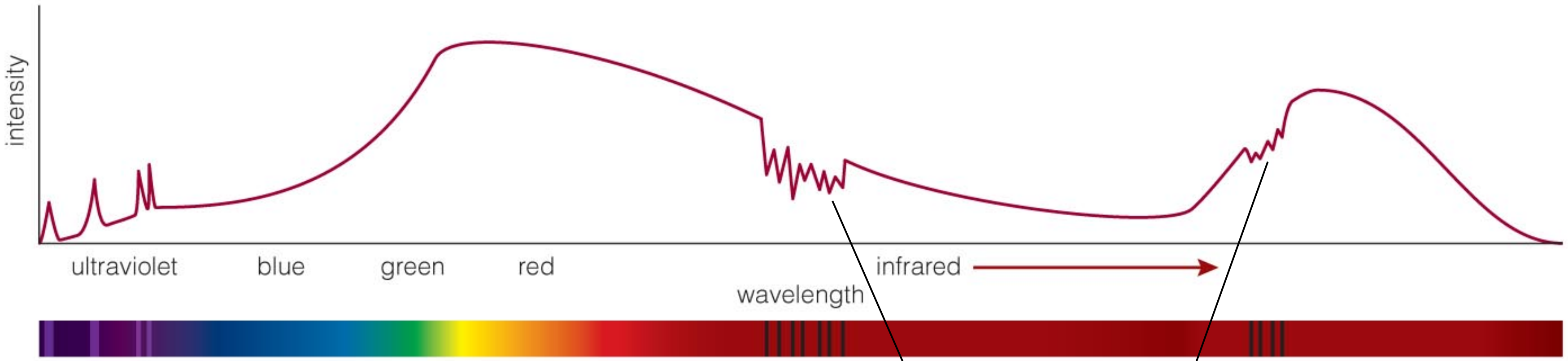
Reflected sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed—object must look red.

What is this object?



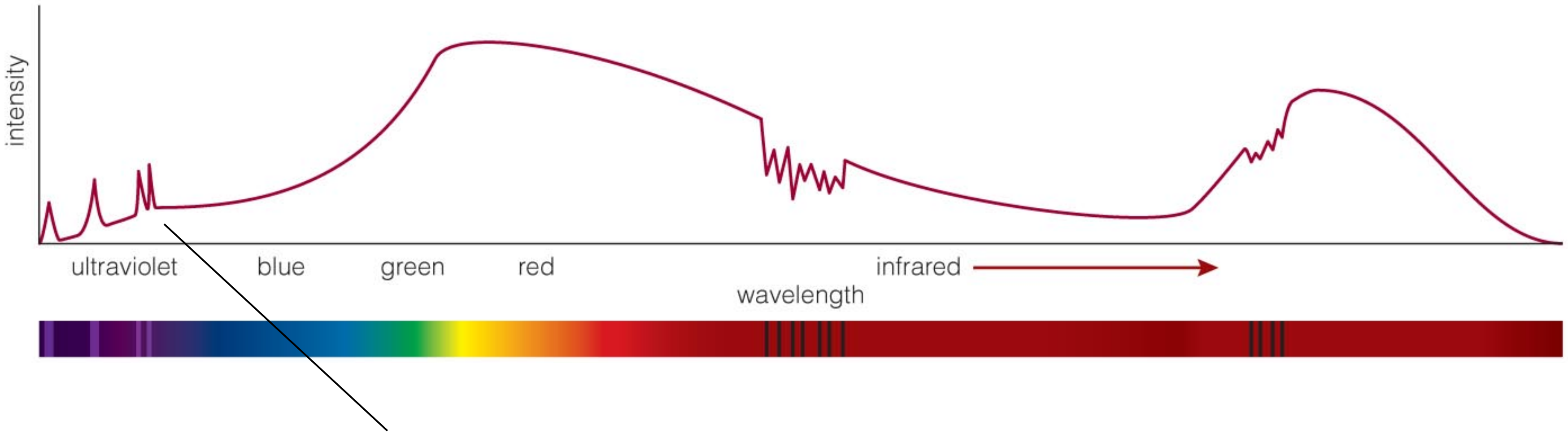
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K.

What is this object?



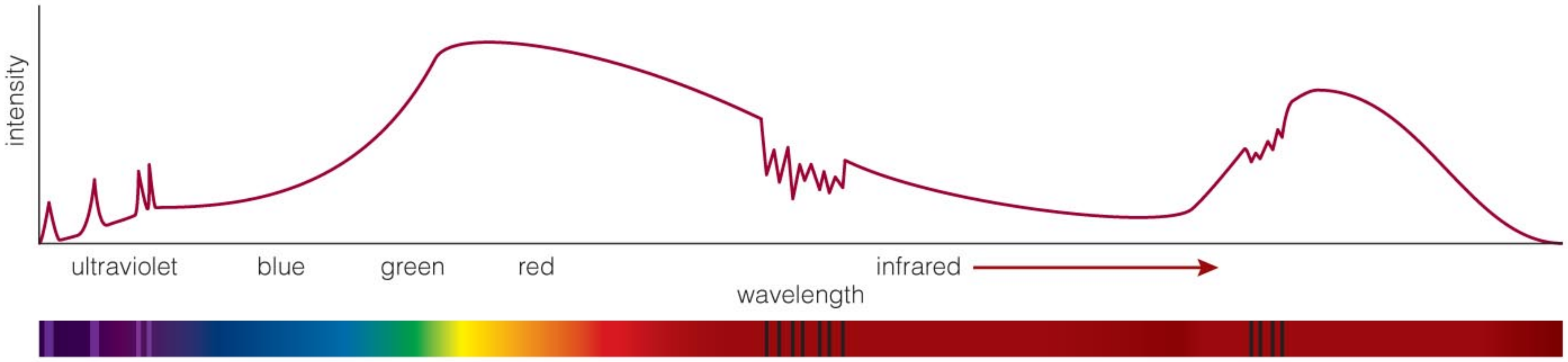
Carbon dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere.

What is this object?



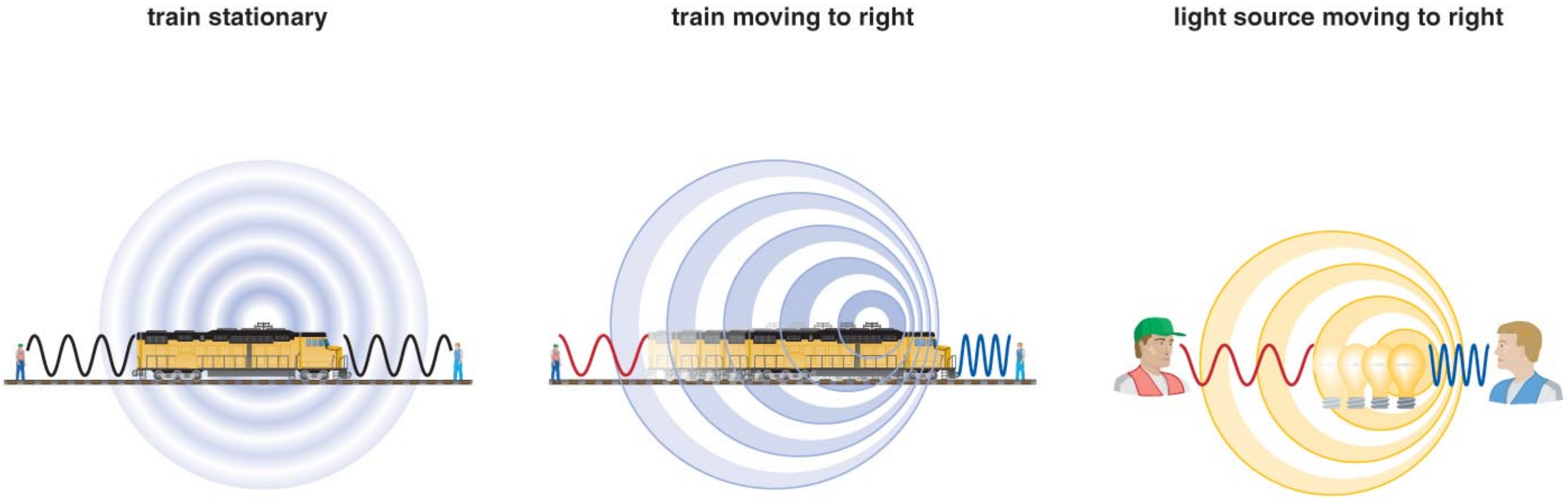
Ultraviolet emission lines: Indicate a hot upper atmosphere

What is this object?

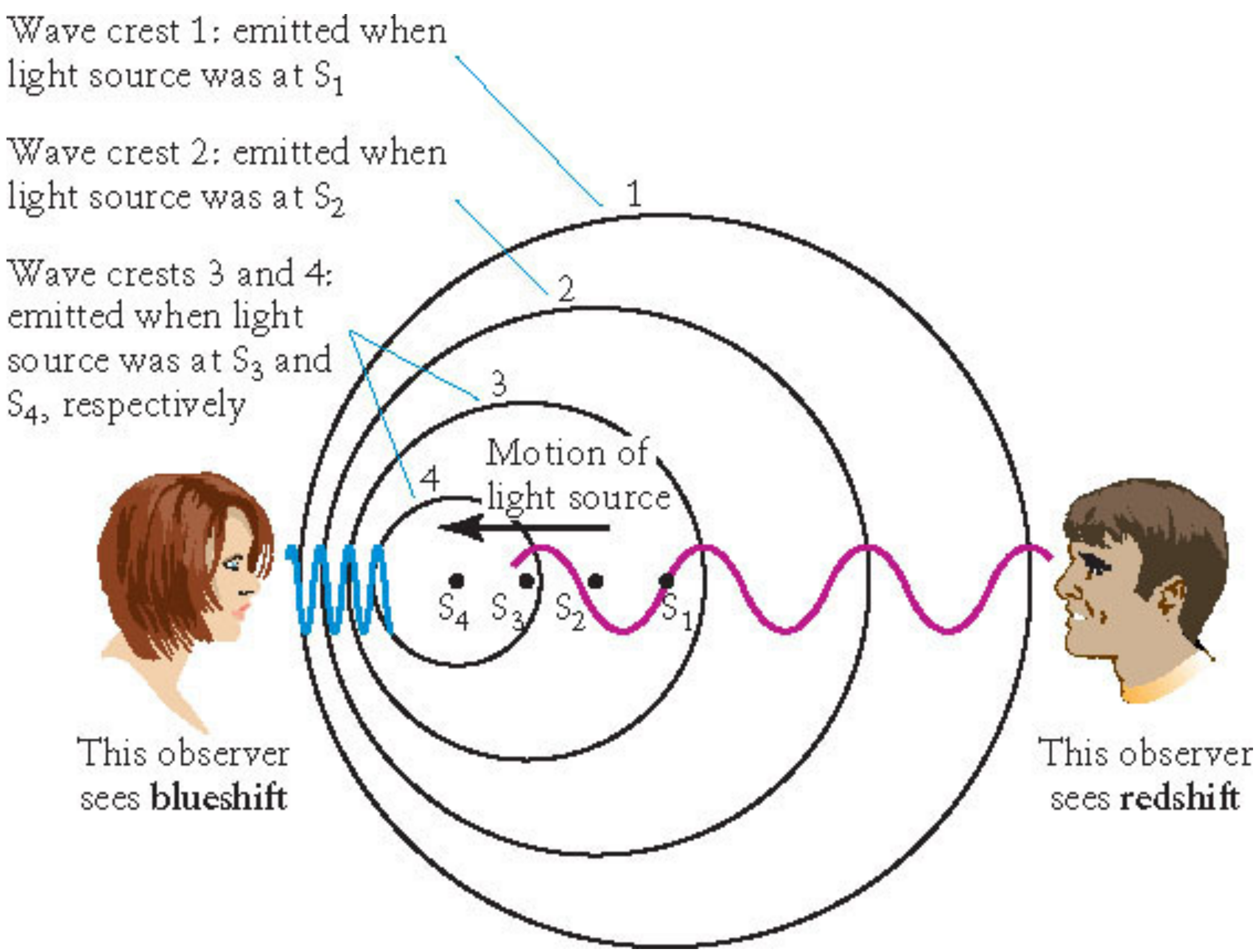


Mars!

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

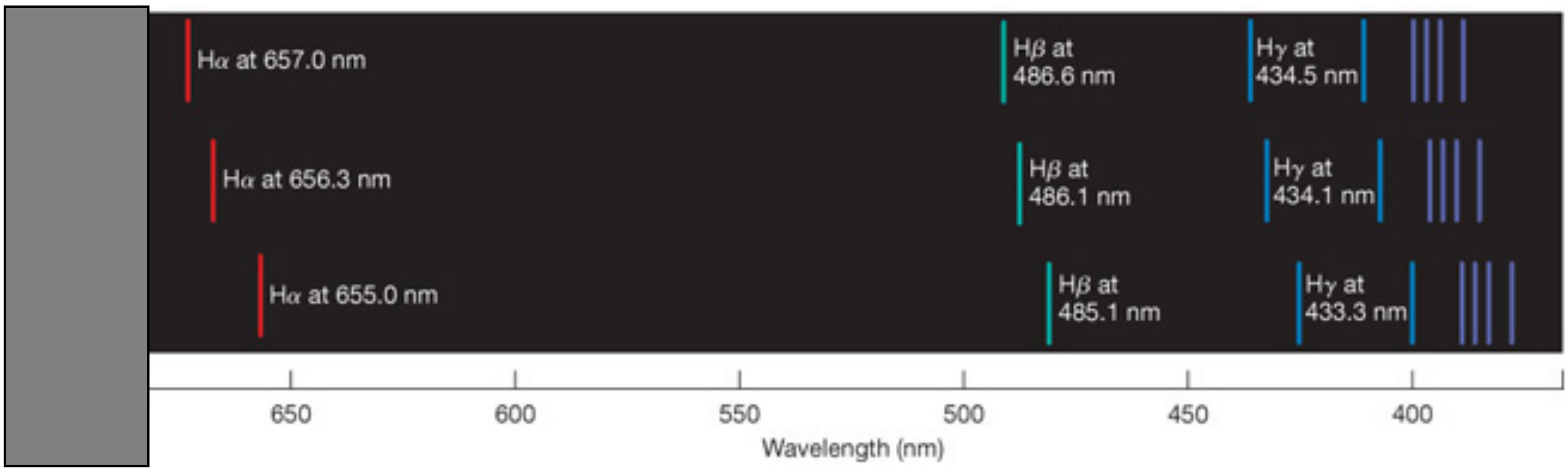


Doppler Effect



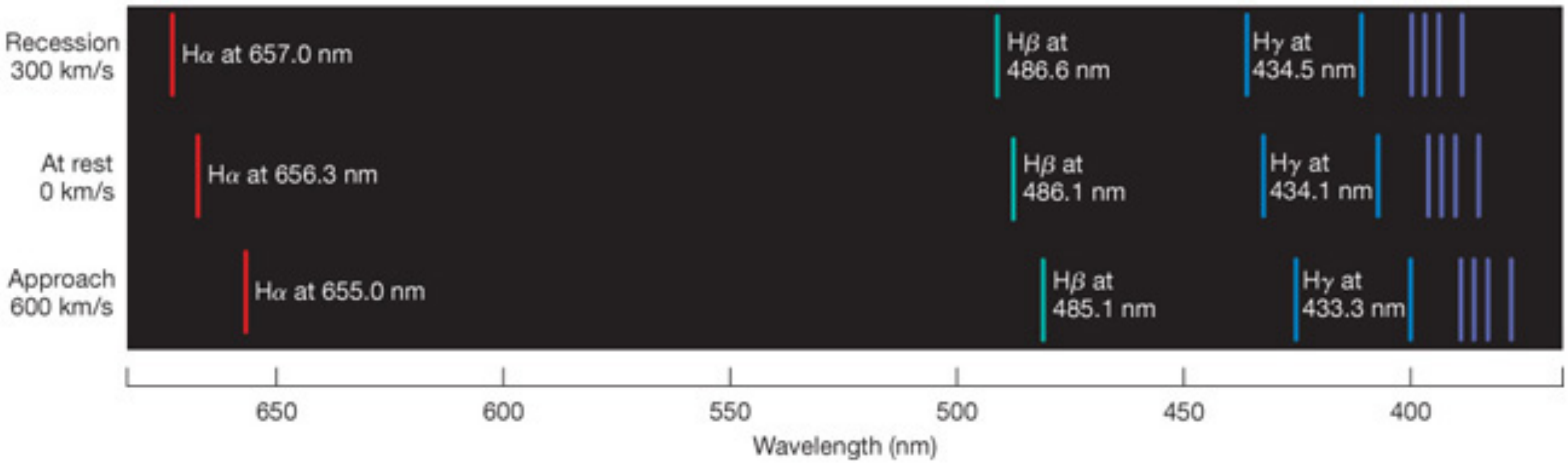
$$\frac{\lambda_{Observed} - \lambda_{Emitted}}{\lambda_{Emitted}} = \frac{\Delta\lambda}{\lambda_{Emitted}} = \frac{v_r}{c}$$

Doppler Shift



H_α (Rest Wavelength) = 656.3nm

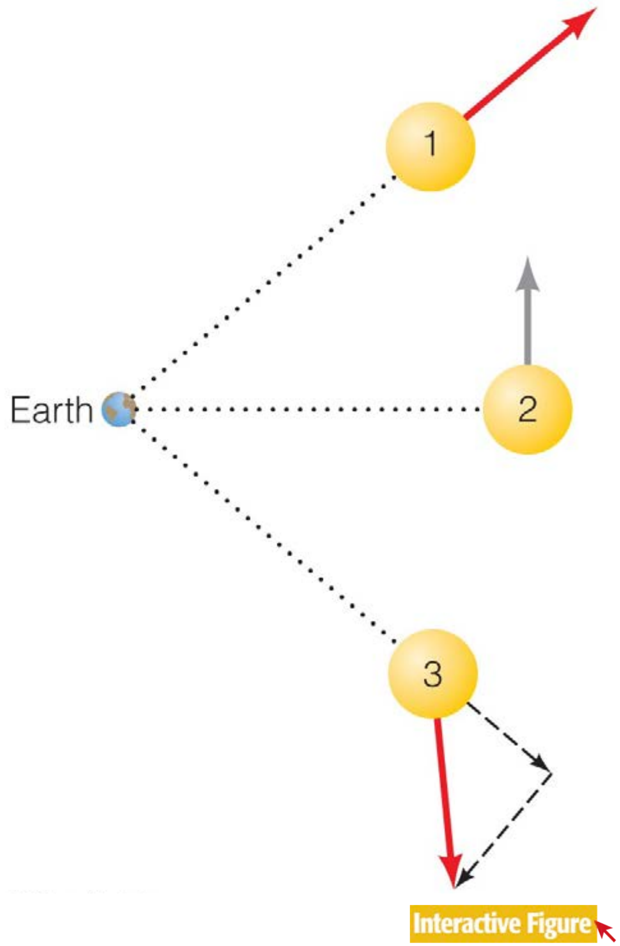
Doppler Shift



H_{α} (Rest Wavelength) = 656.3nm

Measuring the Shift

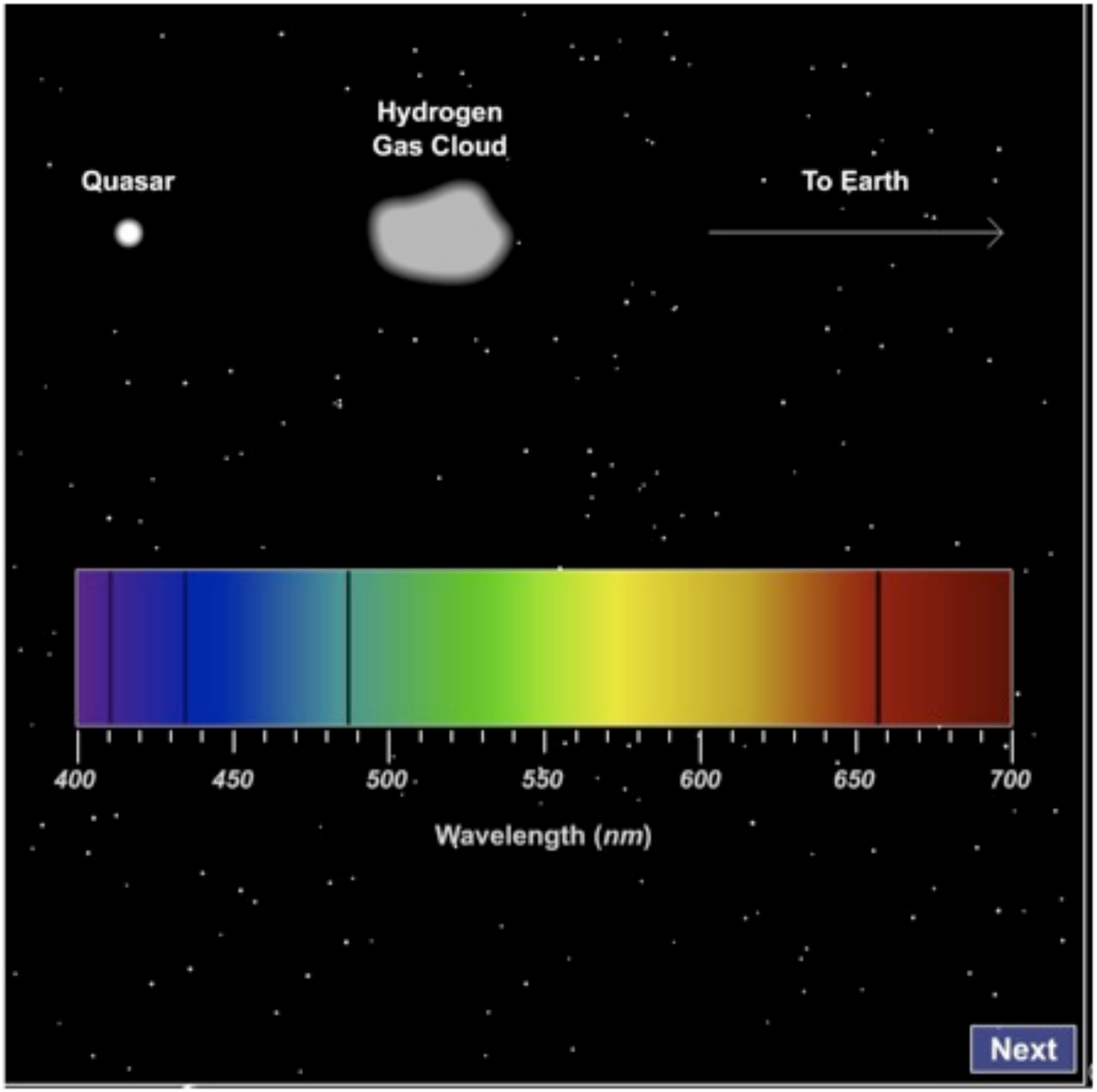
- Doppler shift tells us ONLY about the part of an object's motion toward or away from us:



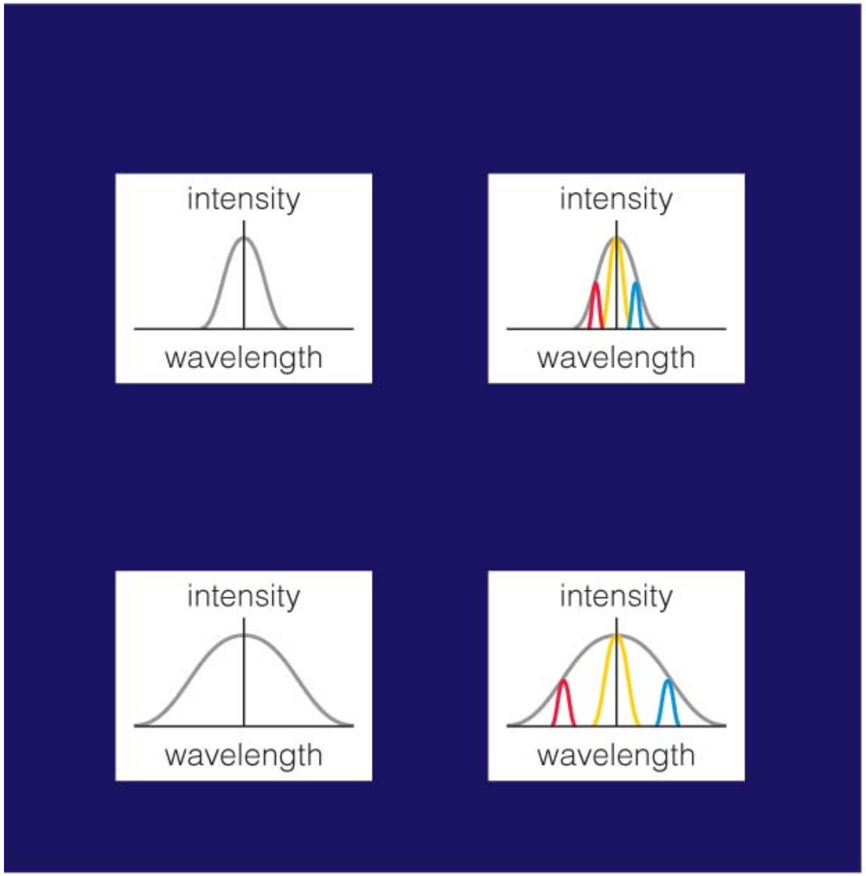
Measuring the Shift

- Measuring Cosmological Redshift z

$$\frac{\lambda_{Observed} - \lambda_{Emitted}}{\lambda_{Emitted}} = z$$

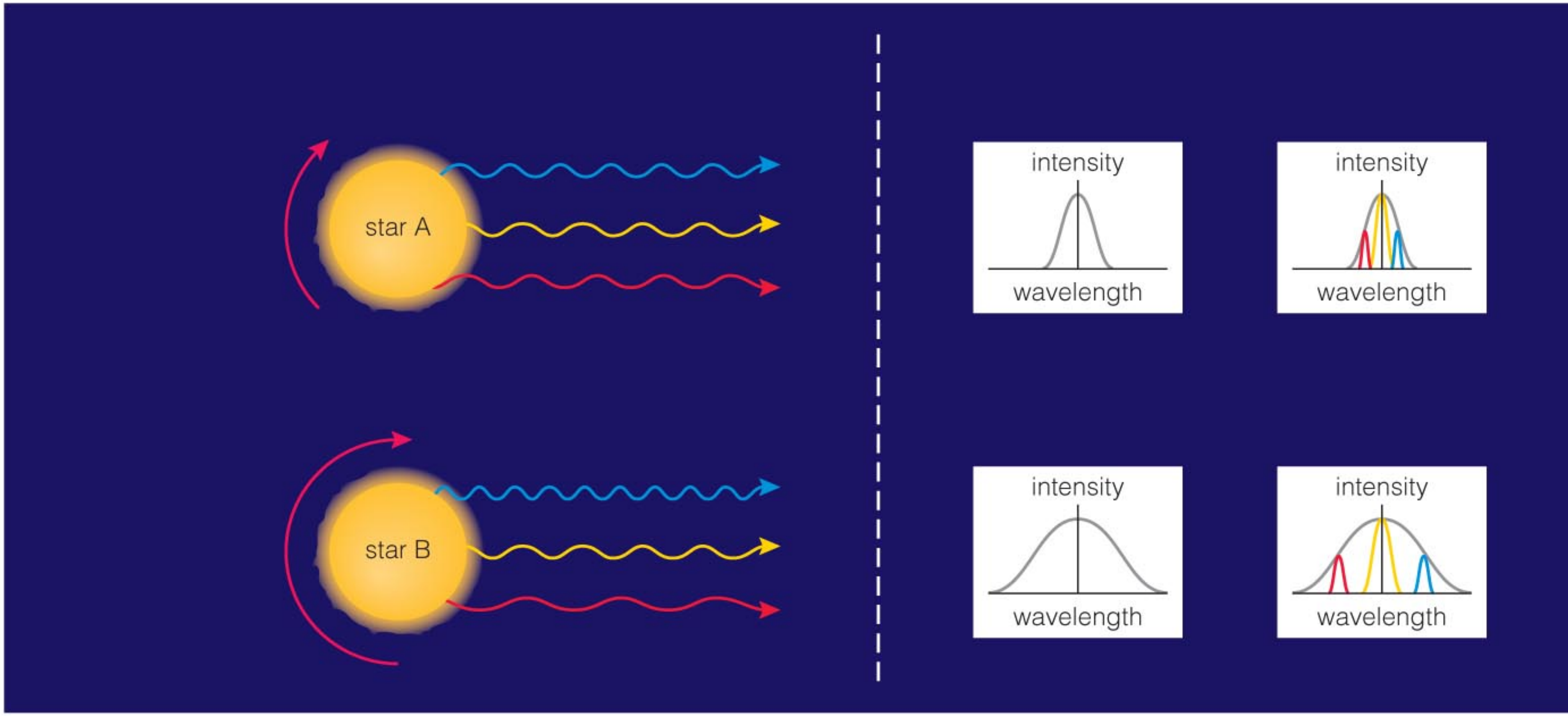


Rotation Rates



- Different Doppler shifts from different sides of a rotating object spread out its spectral lines.

Spectrum of a Rotating Object

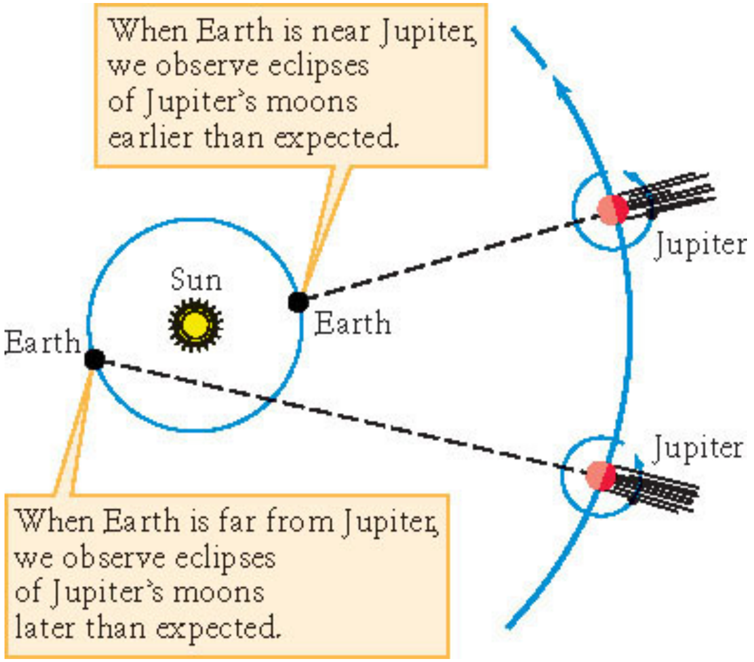


- Spectral lines are wider when an object rotates faster.

Measuring the Speed of Light

1. Galileo
→ concluded that the speed of light was too fast for him to measure.

2. Olaus Romer
→ By recording the time of eclipses of Io Romer noticed that they occurred several minutes later when the earth was far from Jupiter and earlier when closer to Jupiter.



Measuring the Speed of Light

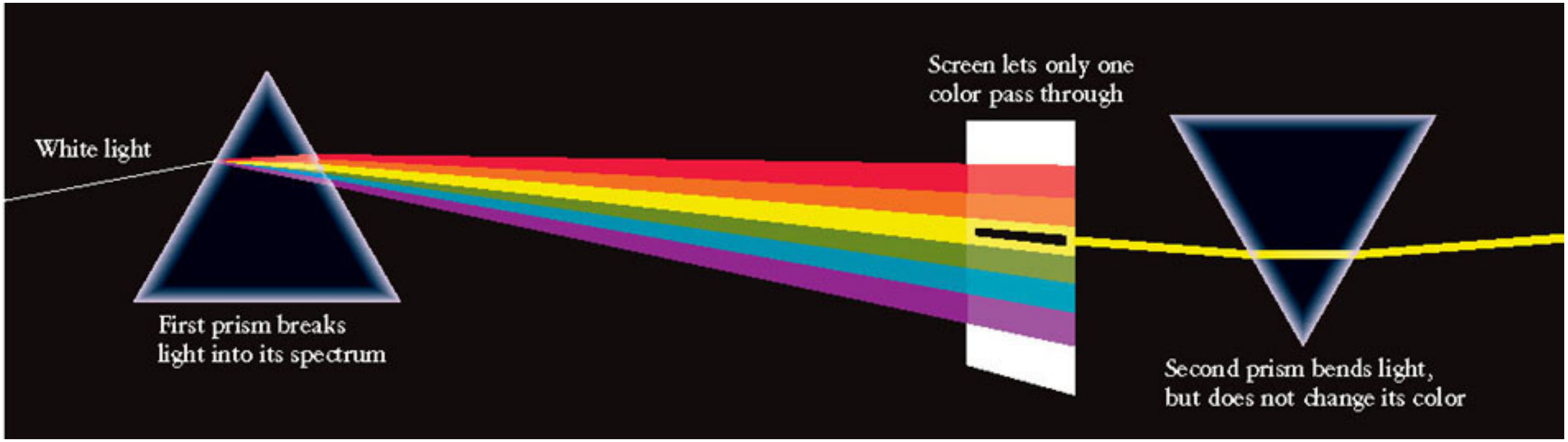
3. By 1975 the speed of light was known to be 299,792,458 m/s with a relative measurement uncertainty of 4 parts per billion. **In 1983 the meter was redefined** in the International System of Units (SI) as the distance travelled by light in vacuum in 1⁄299,792,458 of a second.

4. The speed of light c_{medium} is less than c when it travels through media like gases, liquids or solids: $n = c_{vacuum}/c_{medium} > 1$

n is called the **index of refraction**

The Nature of Light

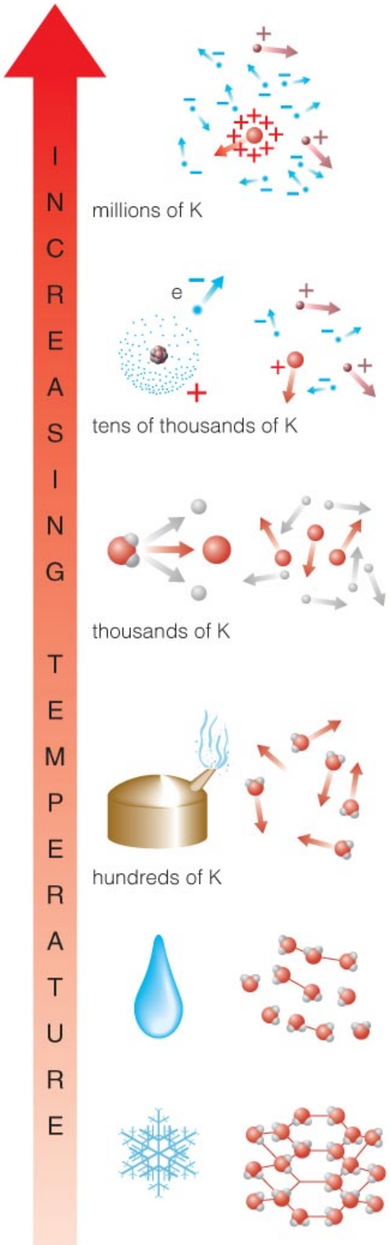
A second prism bends the light but does not change the color thus indicating that it actually separates the white light into the colors its made up of. Newton suggested that light is composed of particles too small to detect individually.



What are the phases of matter?

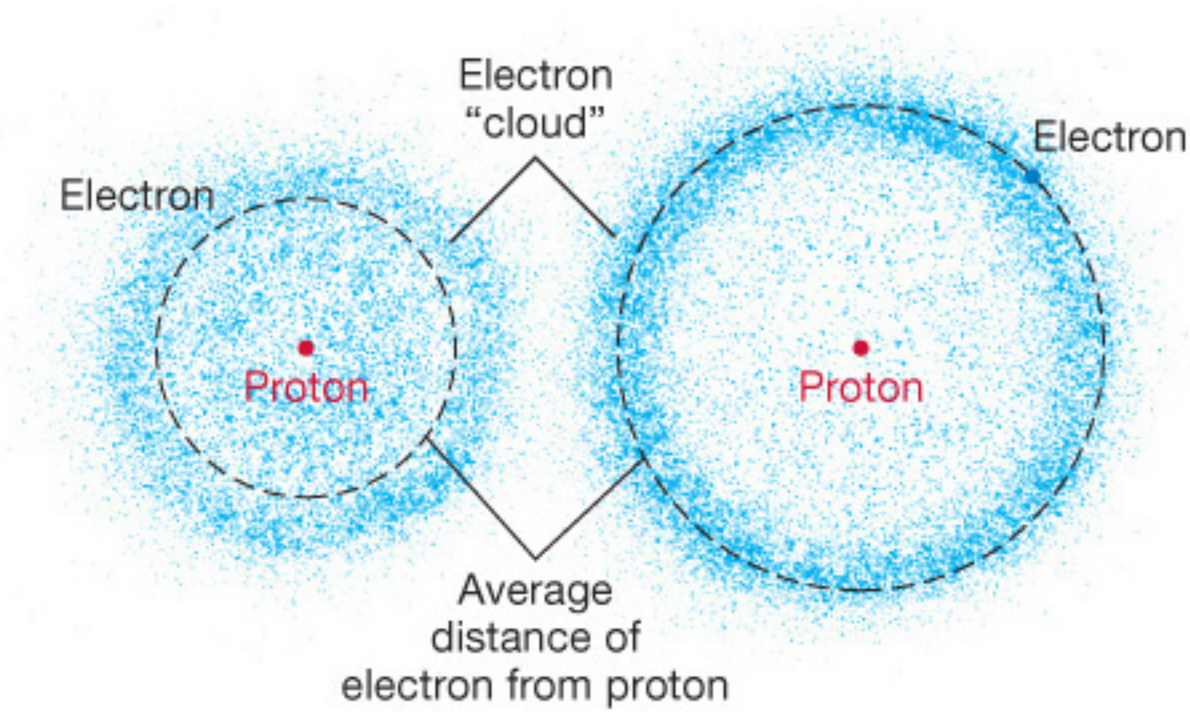
- Familiar phases:
  - Solid (ice)
  - Liquid (water)
  - Gas (water vapor)
- Phases of same material behave differently because of differences in chemical bonds.

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 gas
- **Melting:** breaking of rigid chemical bonds, changing solid into liquid

Modern Model for the Atom



(a) Ground state (b) Excited state