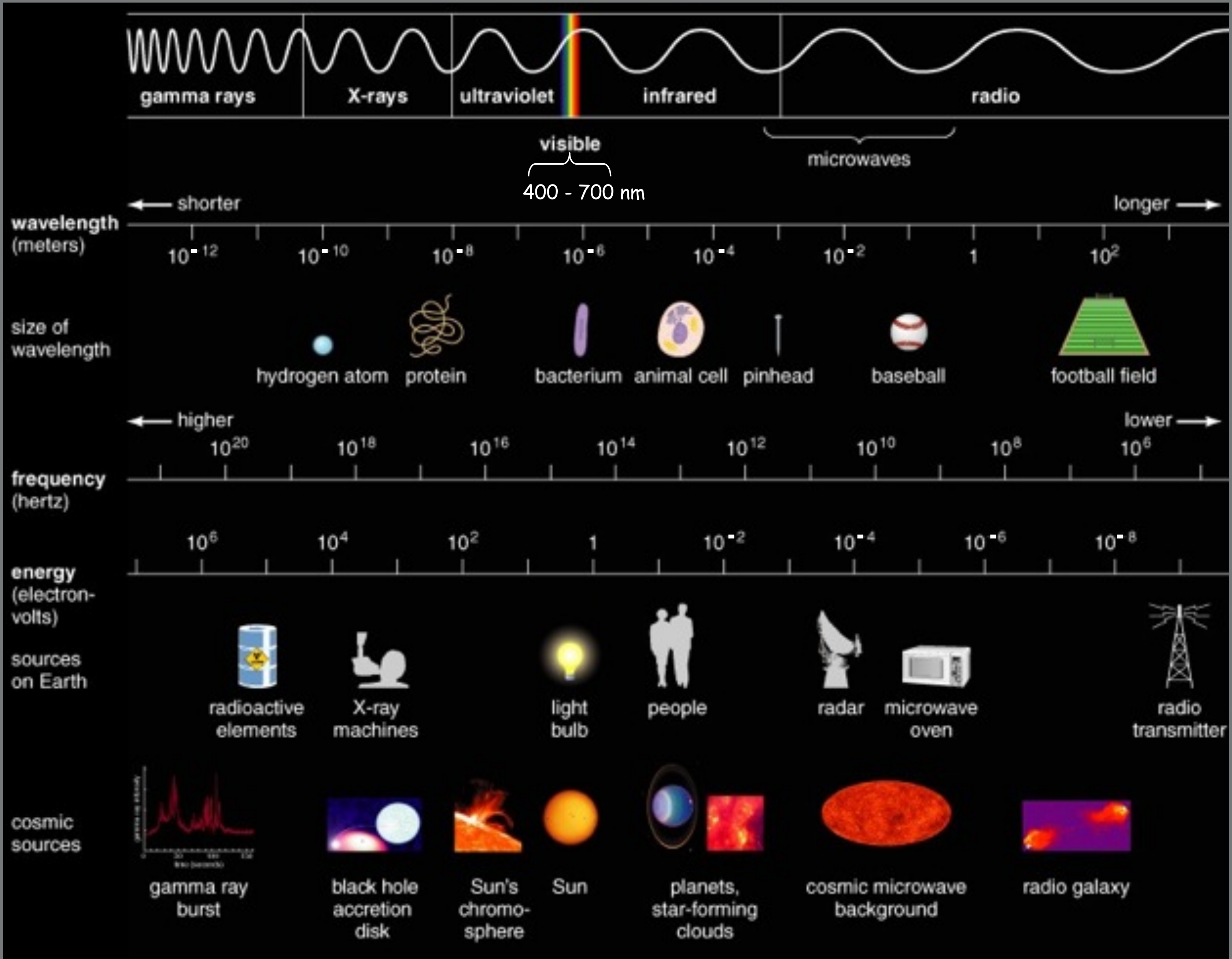
Reading Question

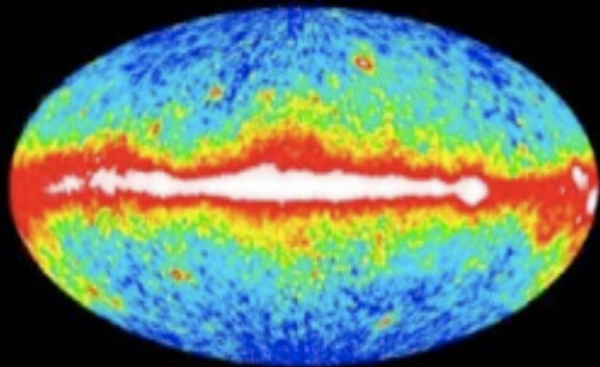
What is LIGHT?

A. Light is a wave, like sound only much faster.
B. Light is like little particles. Each one is a photon.
C. Light is the absence of dark.
D. A kind of energy we model with some of the properties of waves and some properties of particles.
E. Light is the sensation you feel when hit by energy, visible or invisible.

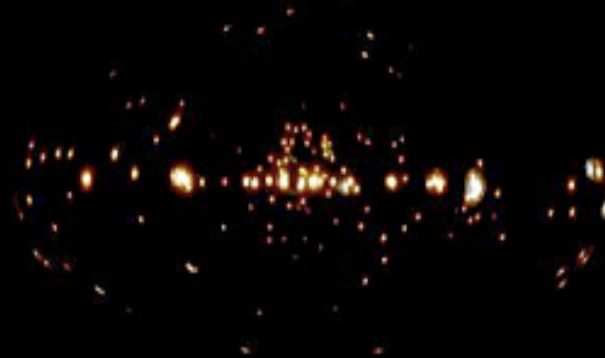
Light: The Cosmic Messenger

The Electromagnetic Spectrum

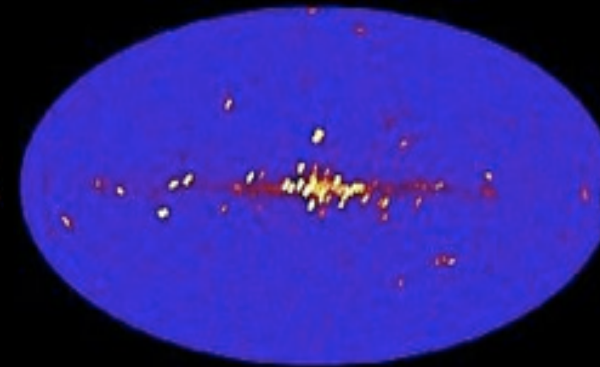




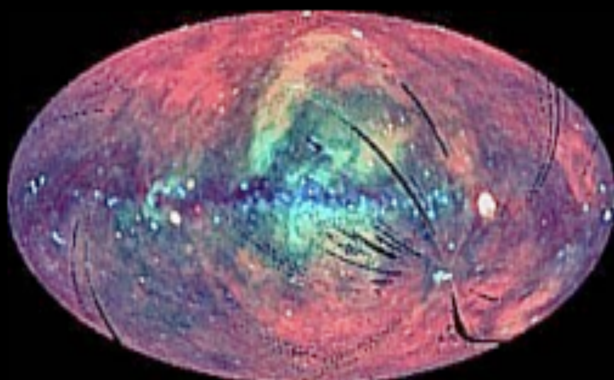
Gamma-Ray >100MeV (CGRO, NASA)



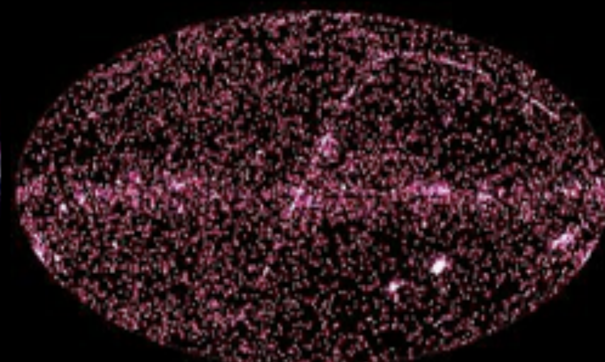
Gamma-Ray (N. Gehrels et.al. GSFC, EGRET, NASA)



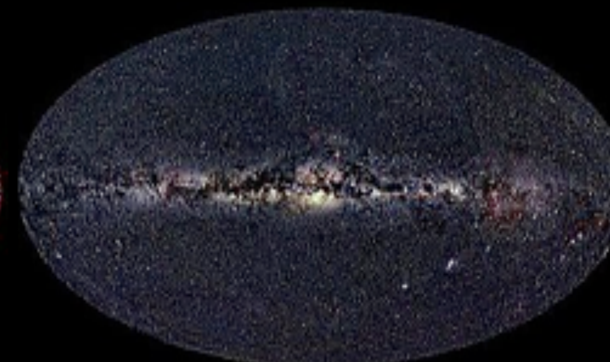
X-Ray 2-10keV (HEAO-1, NASA)



X-Ray 0.25, 0.75, 1.5 keV (S. Digel et. al. GSFC, ROSAT, NASA)

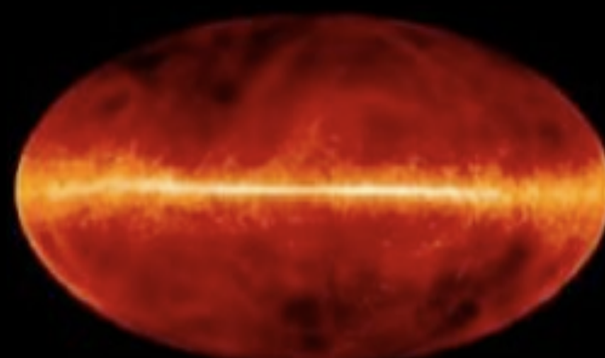


Ultraviolet (J. Bonnell et.al.(GSFC), NASA)

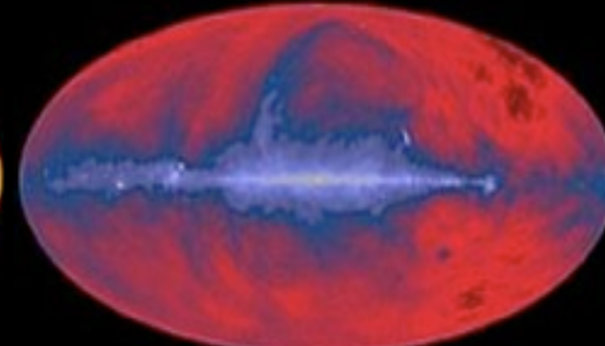


Visible (Axel Mellinger)

Infrared (DIRBE Team, COBE, NASA)



Radio 1420MHz (J. Dickey et.al. UMn. NRAO SkyView)

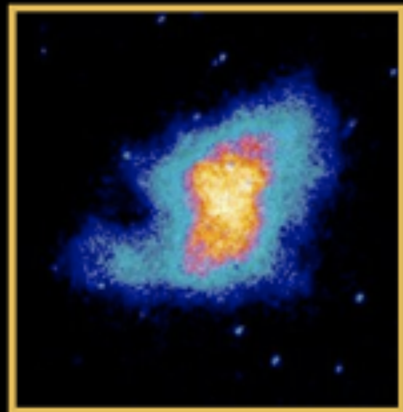


Radio 408MHz (C. Haslam et al., MPIfR, SkyView)

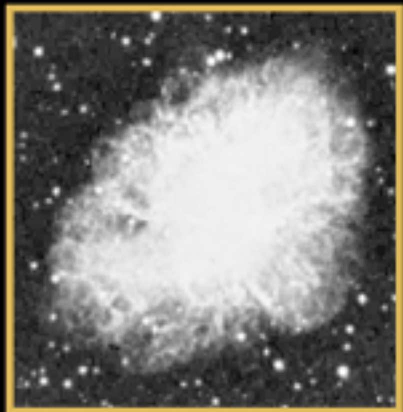
M1 – The Crab Nebula

Distance: 6300 light-years (1.9 kpc) Image Size = 6.5 x 6.5 arcmin Visual Magnitude = 8.4

X-Ray: Chandra



Ultraviolet: ASTRO-1

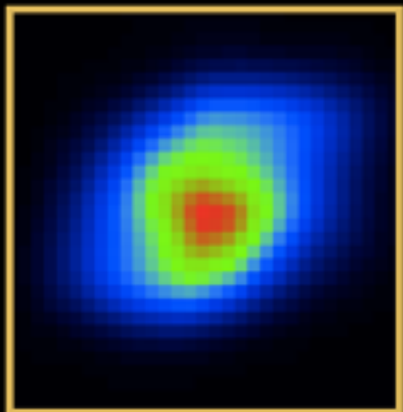


Visible: DSS

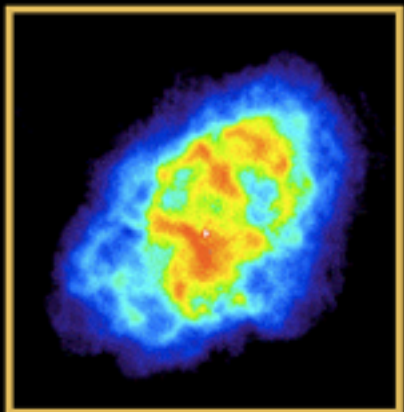
Visible: Color VLT

Near-Infrared: 2MASS

Mid-Infrared: Spitzer

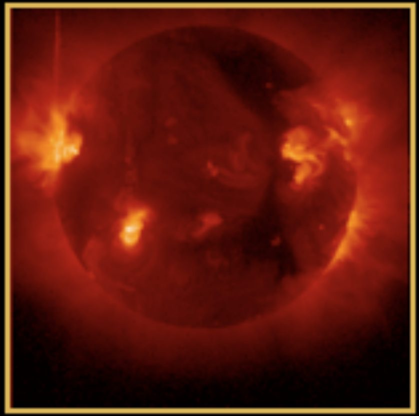


Far-Infrared: IRAS

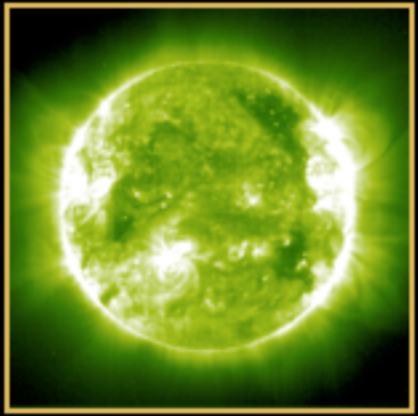


Radio: NRAO

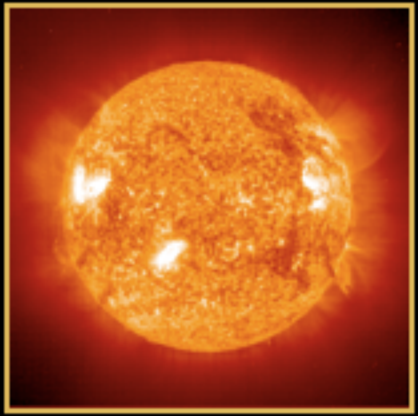
The Crab Nebula (Messier 1), located in the constellation of Taurus, is a supernova remnant (SNR), the result of a cataclysmic supernova explosion in the year 1054. This explosive death of a star was so bright that it could be seen in the daytime sky for 23 days, and was documented by astronomers throughout the Far East.



X-Ray: Yohkoh

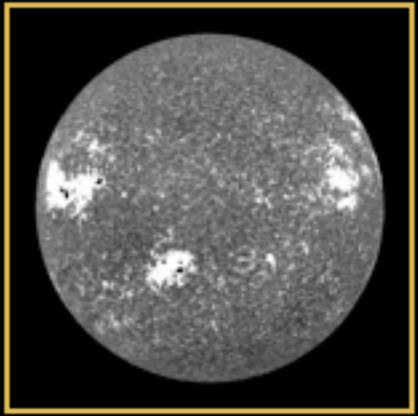


Ultraviolet: SOHO-EIT

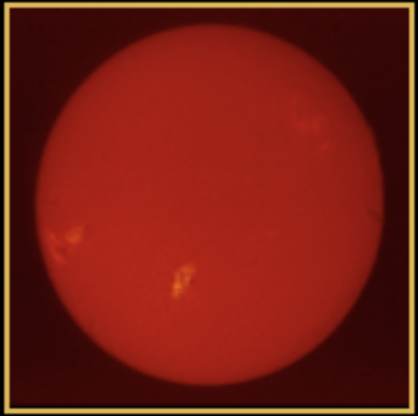


Extreme UV: SOHO-EIT

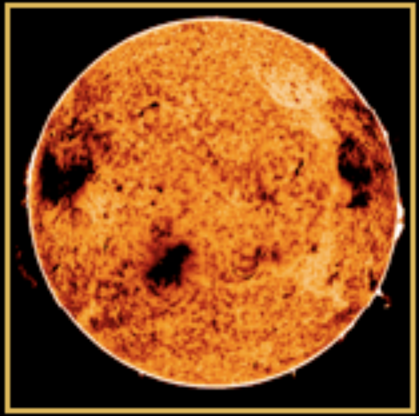
Visible: White Light BBSO



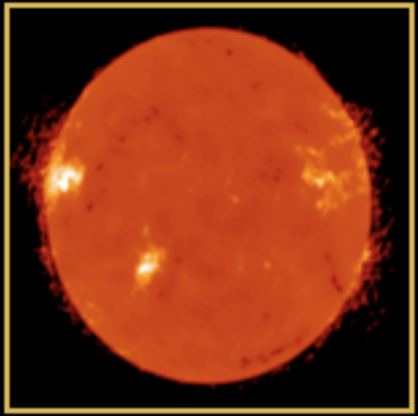
Visible: Calcium-K BBSO



Visible: H-alpha Learmonth



Infrared: NSO



Radio: NobeyamaObs

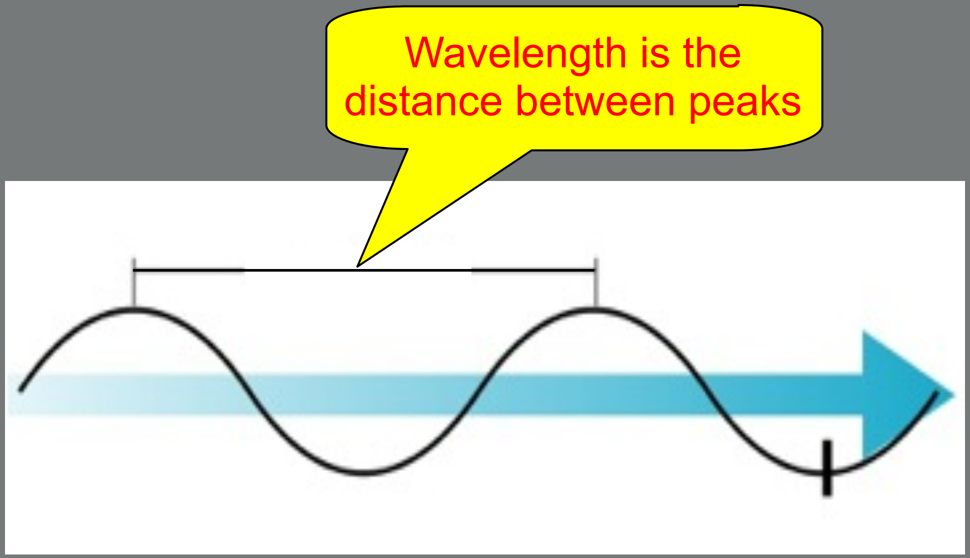
What is Light and what can it tell us?

- The Electromagnetic Spectrum
- Properties of Light
- Light and Matter
- Properties of Matter
- Three types of Spectra
- What we can learn
- The Doppler Shift
- Our Milky Way in different lights

Wave-Particle Duality of Light

- Light can behave like a wave
  - Frequency, wavelength, amplitude
- Light can also behave like a particle
  - Photons = little bundles (bullets) of energy

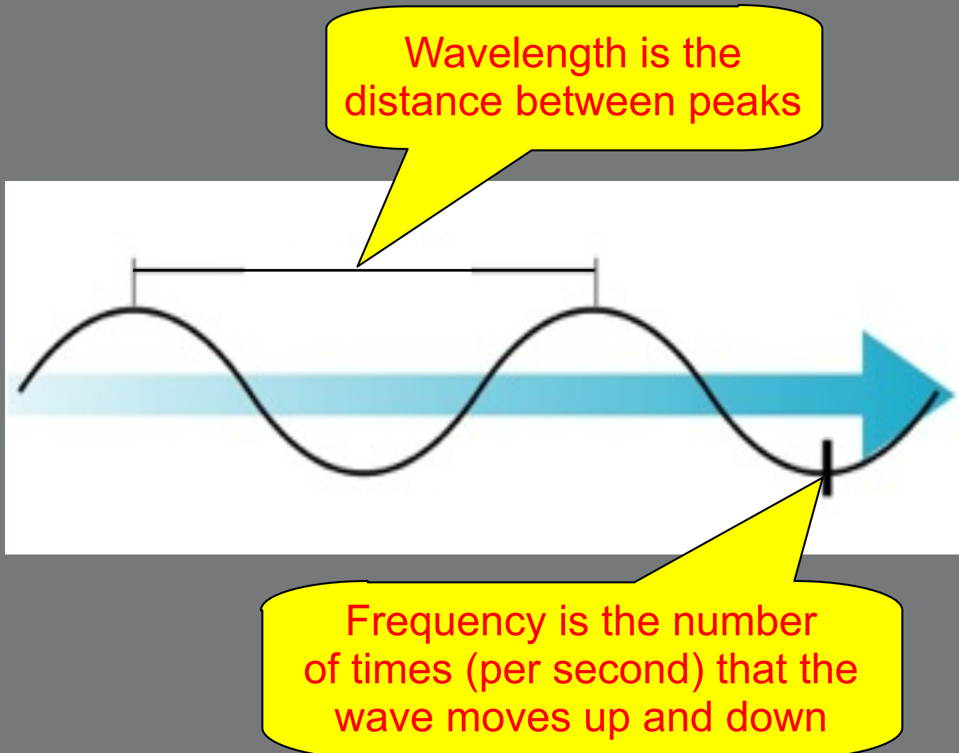
Light as a WAVE



<u>Wavelength</u> can be measured in any length unit. Ex: m, nm, Å (Angstroms)
Typically represented as λ (lambda)

For different types of light, this can be many meters or smaller than atoms

Light as a WAVE

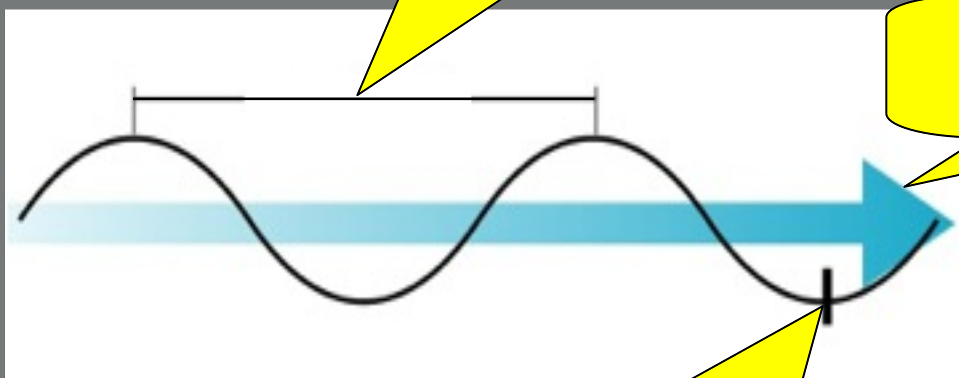


Frequency is measured in Hertz (cycles per second).

Represented as *f*

The higher the frequency, the more cycles pass per second

Light as a WAVE



<u>Speed</u> of light often represented by c.

c = 300,000 km/s

c = 3×10^{8} m/s

c = 671,000,000 mph

Thought Question

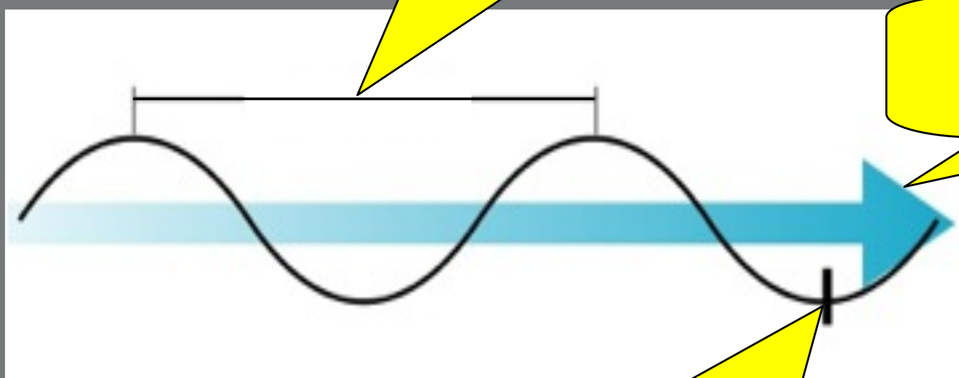
How are the wavelength and frequency of a light wave related?

A. If wavelength increases, so does frequency (direct relationship)
B. If wavelength increases, frequency decreases (inverse relationship)
C. It depends on the speed of the light wave
D. It depends on what type of light we are using (e.g. X-rays vs ultraviolet vs radio waves…)
E. They aren't related

Light as a WAVE

Wavelength is the distance between peaks

All light travels with a constant speed



Frequency is the number of times (per second) that the wave moves up and down

$$\lambda \times f = c$$

OR

$$f = c / \lambda$$

OR

$$\lambda = c / f$$

- The shorter the wavelength, the higher the frequency
  - Think of the train

Reading Question

What causes spectral lines?

A. Blackbody radiation.
B. Electron energy level transitions in an atom.
C. The Doppler shift of rapidly moving objects.
D. High frequency electromagnetic waves.
E. Protons and neutrons spinning in a charged atom.

Thought Question

How are the wavelength and frequency of a light wave related?

A. If wavelength increases, so does frequency (direct relationship)

B. If wavelength increases, frequency decreases (inverse relationship)

C. It depends on the speed of the light wave

D. It depends on what type of light we are using (e.g. X-rays vs ultraviolet vs radio waves…)

E. They aren't related

Light as a PARTICLE

- Light can also be modeled as a particle
  → "photon" (NOT proton!)

- A photon is a mass-less particle of electromagnetic radiation energy

<u>proportional</u> — Each photon has an energy *<u>proportional</u>* to its frequency

$$E = h \times f$$

Photon Energy = Planck's Constant × Frequency

Each photon has an energy proportional to its frequency

$$E \propto f$$
$$E \propto 1 / \lambda$$

Remember: $\propto$ means "is proportional to"

Higher Frequencies
or
Shorter Wavelengths → MORE ENERGY

UV or X-rays are more dangerous than visible or infrared light

Four Ways in Which Light can Interact with Matter

1. Emission
2. Absorption
3. Transmission
4. Reflection/Scattering

Four Ways in Which Light can Interact with Matter

1. **Emission** – matter releases energy as light
2. Absorption
3. Transmission
4. Reflection/Scattering

Four Ways in Which Light can Interact with Matter

1. **Emission** – matter releases energy as light
2. **Absorption** – matter takes energy from light
3. **Transmission**

4. **Reflection/Scattering**

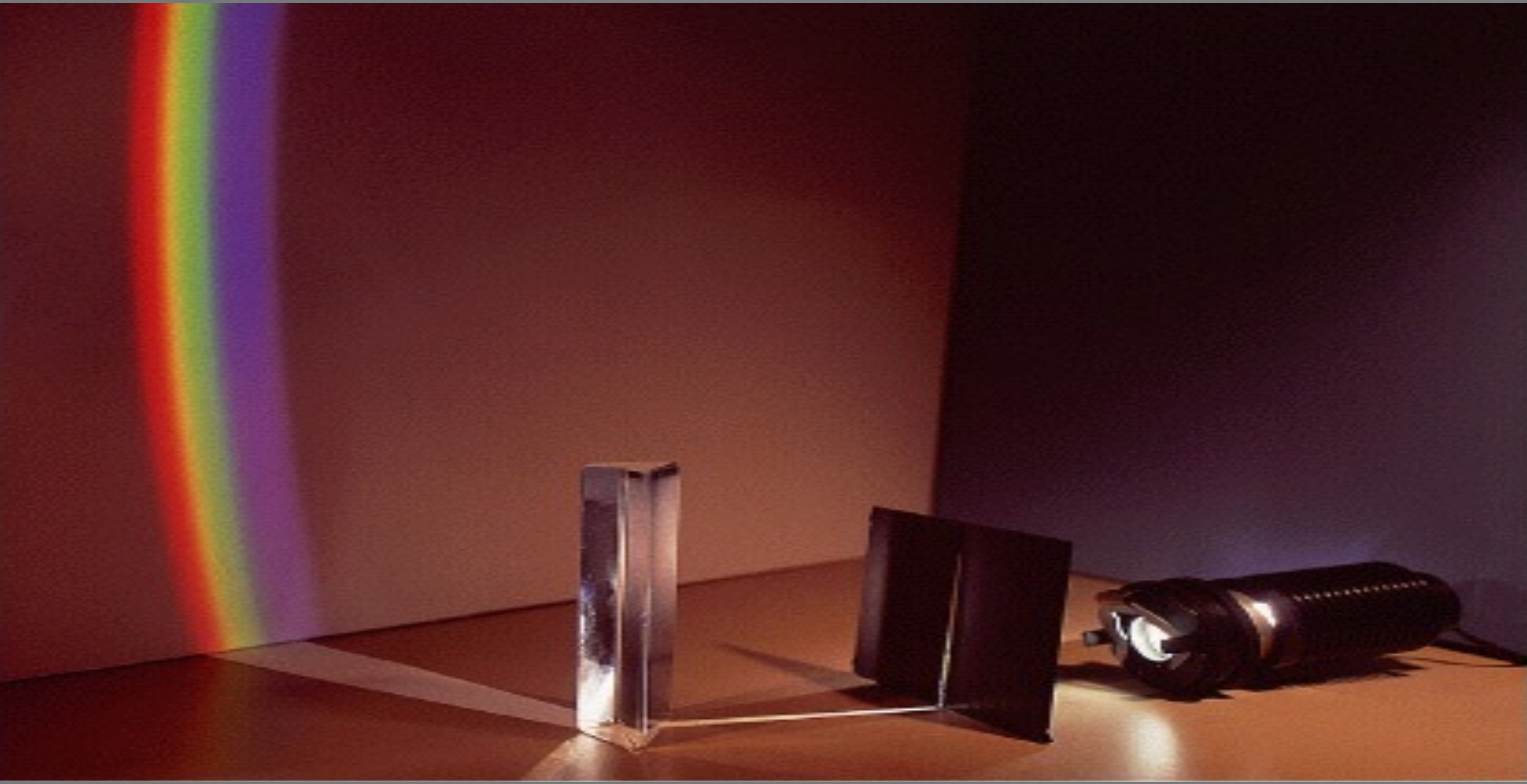
Four Ways in Which Light can Interact with Matter

1. **Emission** – matter releases energy as light
2. **Absorption** – matter takes energy from light
3. **Transmission** – matter allows light to pass through it
4. **Reflection/Scattering**

Four Ways in Which Light can Interact with Matter

1. **Emission** – matter releases energy as light
2. **Absorption** – matter takes energy from light
3. **Transmission** – matter allows light to pass through it
4. **Reflection/Scattering** – matter repels light in another direction

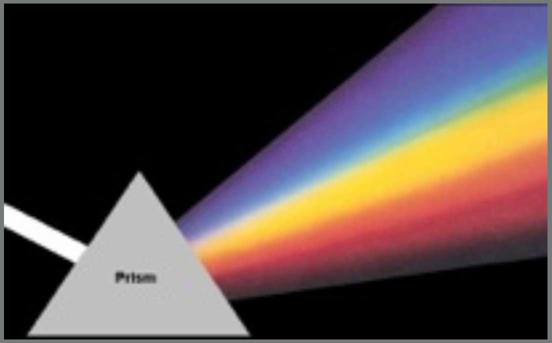
Colors of Light



- White light is made up of many different colors

Thought Question

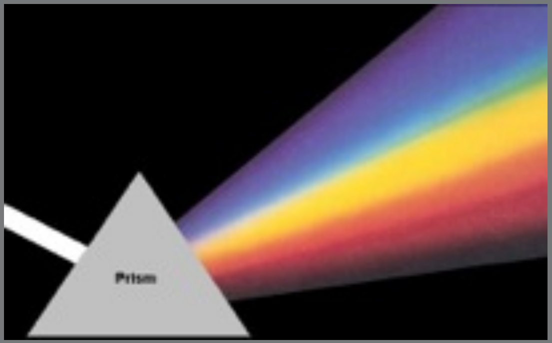
What will happen to the spectrum in the front of the room if I put a red filter into the beam?



A. Blue gets through, the other colors disappear
B. Red gets through, the other colors disappear
C. All the colors turn red
D. Red stays red, but the rest turn white
E. It depends on which side of the grating I put the red filter

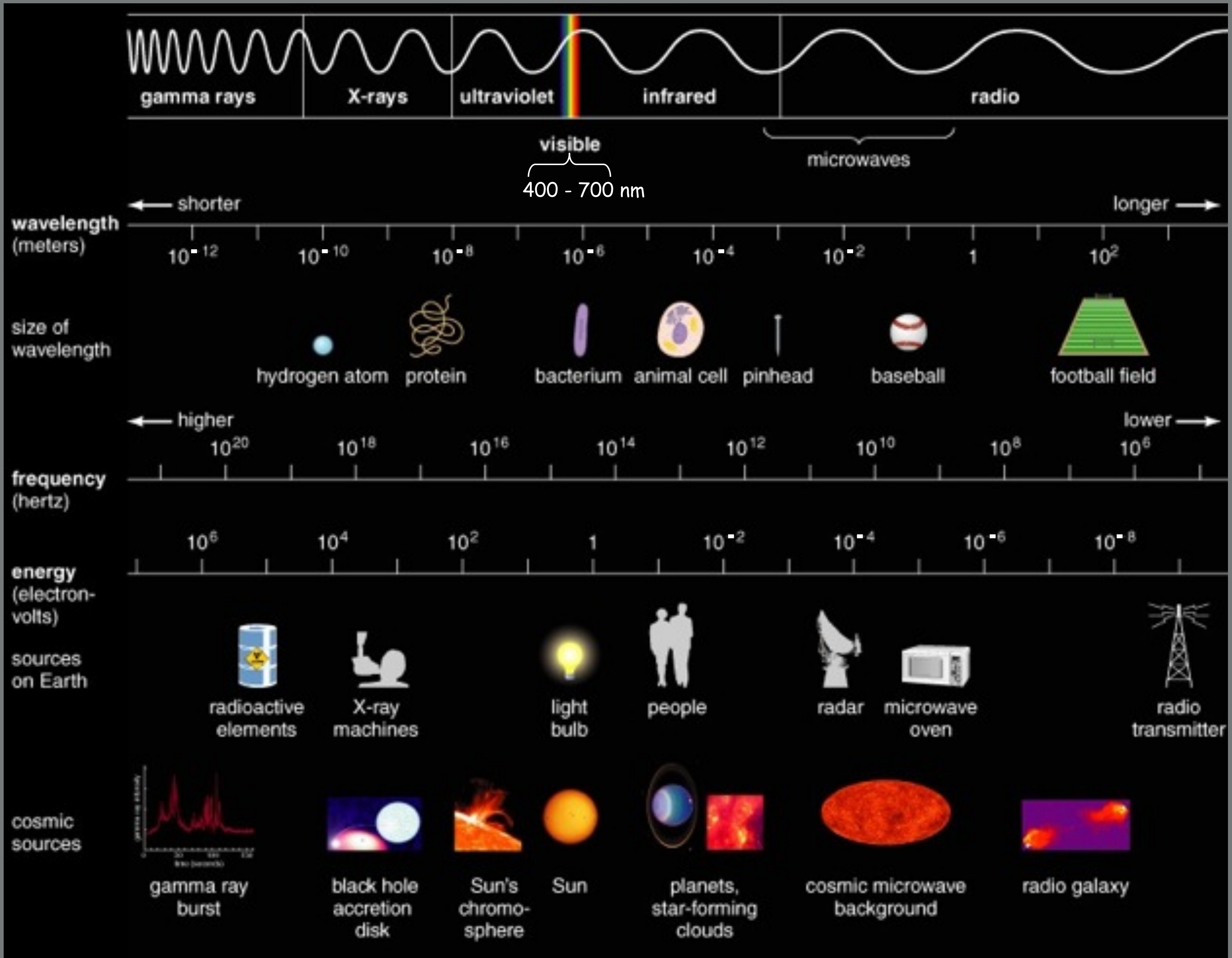
Thought Question

What color would a pure blue object look if pure red light is shined on it?



A. Red
B. Blue
C. Purple
D. White
E. Black

The Electromagnetic Spectrum



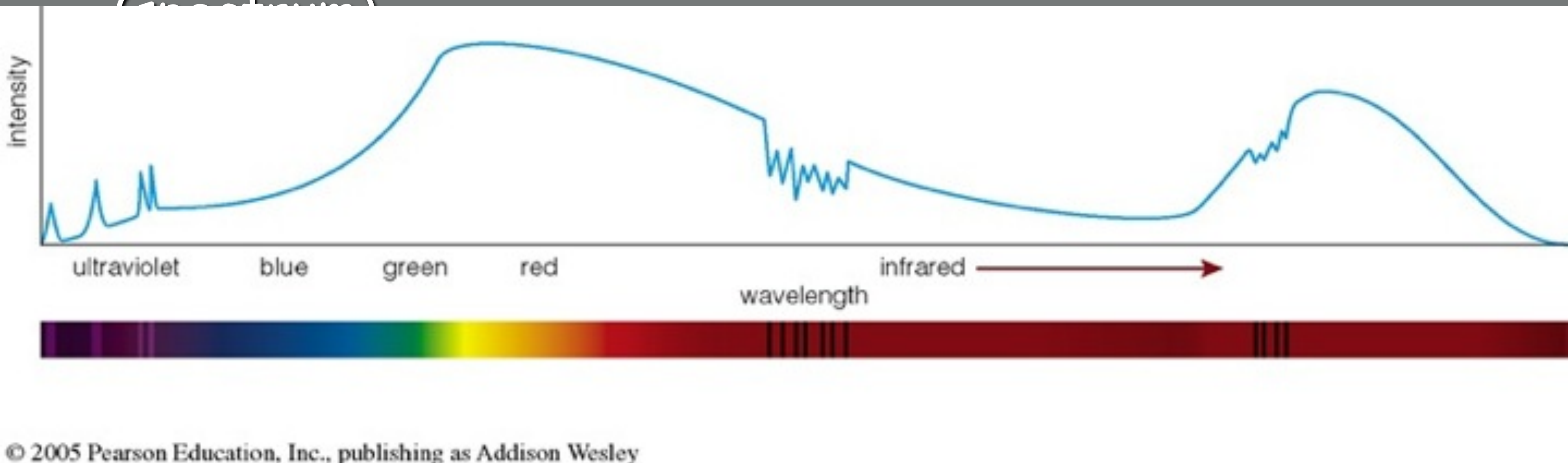
Thought Question

When compared to RED light, Blue light is:

A. Longer wavelength
B. Lower Frequency
C. Higher energy photons
D. Faster photons
E. None of the above

Light as Information Bearer

We can separate light into its different wavelengths (spectrum)



By studying the spectrum of an object, we can learn its:

- Composition
- Temperature
- Velocity

First, a quick review of atoms

Most matter is made of

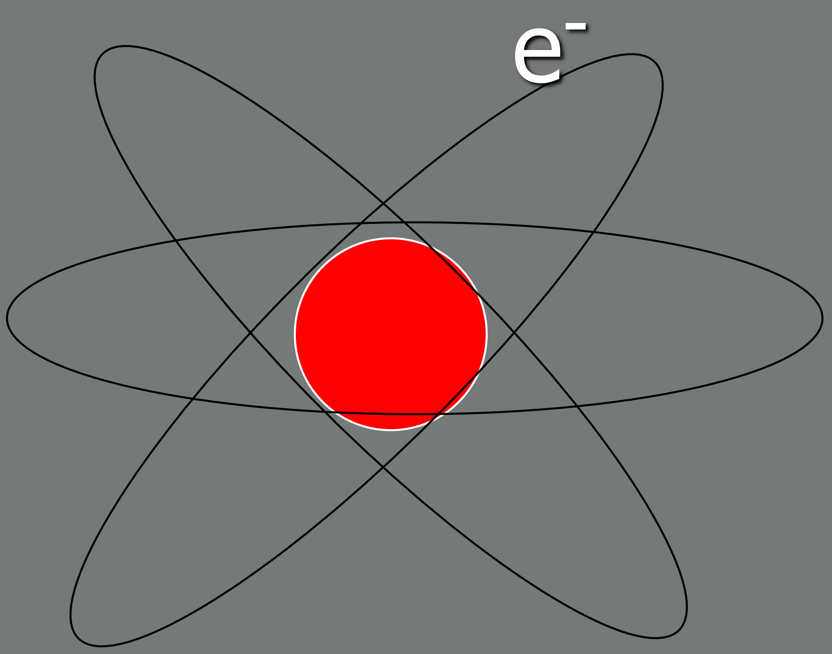
- Electrons
- Protons
- Neutrons
- Protons determine element
- Neutrons+Protons held together in nucleus by strong force
- Generally N_protons=N_Electrons

Phases of Matter

Solid	Liquid	Gas	Plasma
Example	Example	Example	Example
Ice	Water	Steam	Ionized Gas
H_2O	H_2O	H_2O	$H_2 \rightarrow H^+ + H^+ + 2e^-$
Cold	Warm	Hot	Hotter
$T<0°C$	$0<T<100°C$	$T>100°C$	$T>100,000°C$ I>10 electron Volts!
			
Molecules Fixed in Lattice	Molecules Free to Move	Molecules Free to Move, Large Spacing	Ions and Electrons Move Independently, Large Spacing

Electron Energy Levels in Atoms

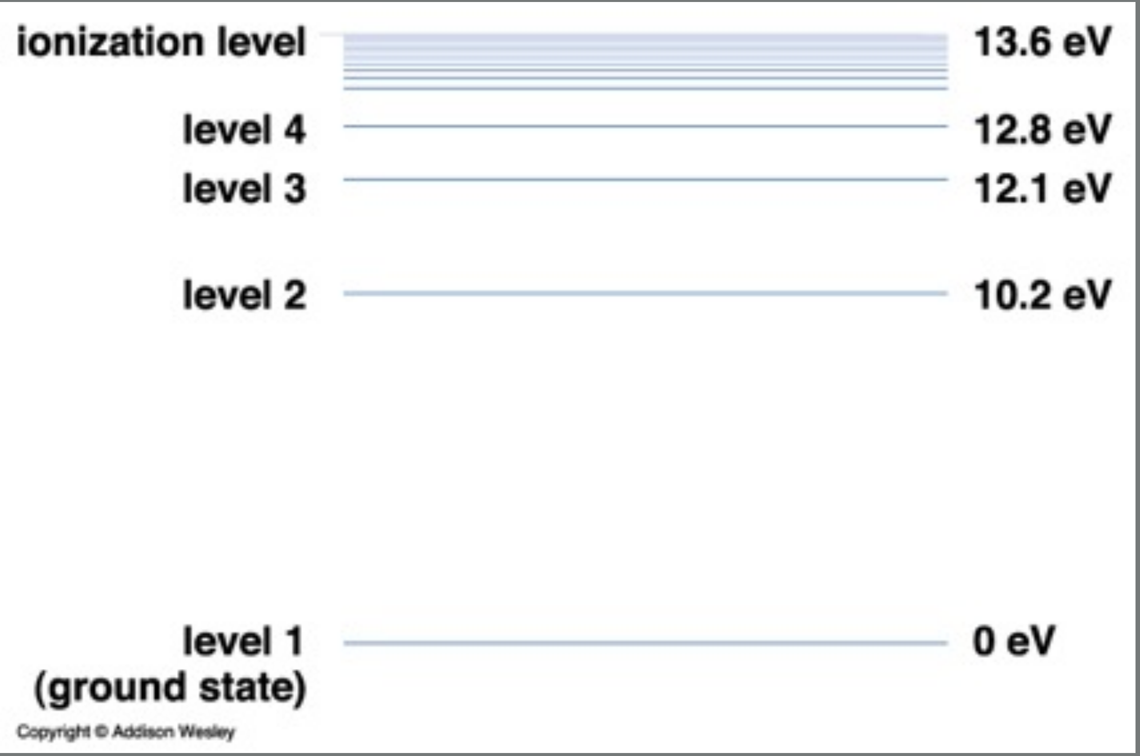
- Atoms are made up of protons(+), neutrons (0) and electrons(-)
- Electrons move in different energy states around the nucleus
- Some electrons in a given atom have more energy than others.



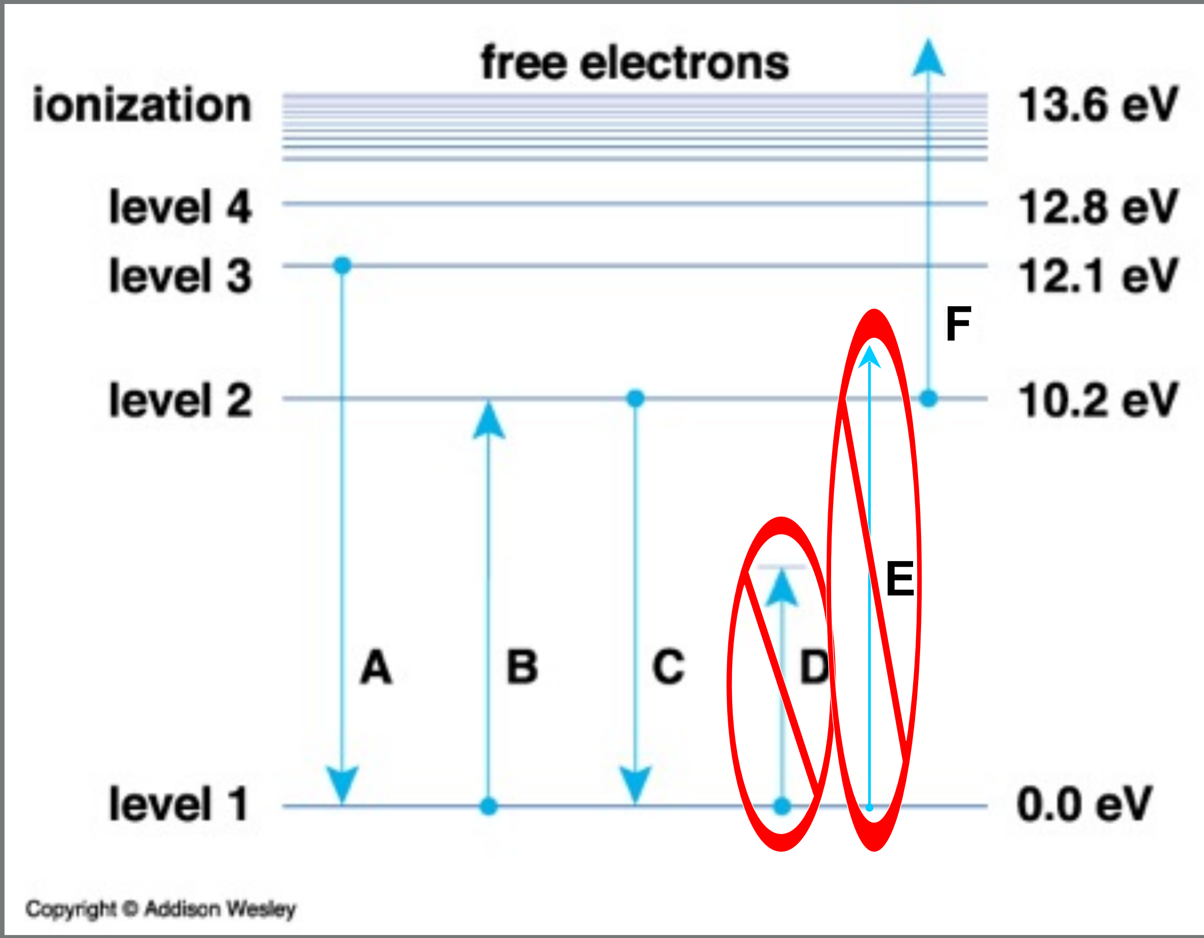
These energy states are "quantized"– there are only certain energies that the electrons are allowed to have. This is quantum physics.

Example of electron energy levels in a hydrogen atom

- Lower level is lower energy. (think of stairs)
- Units: electronvolt (eV) TINY!
  - 1 Calorie = 3 x 10^{22}eV



- Electrons can move between levels if they are given or lose the exact amount of energy corresponding to the difference in the energy levels.
- If an electron gets enough energy, the electron will fly free

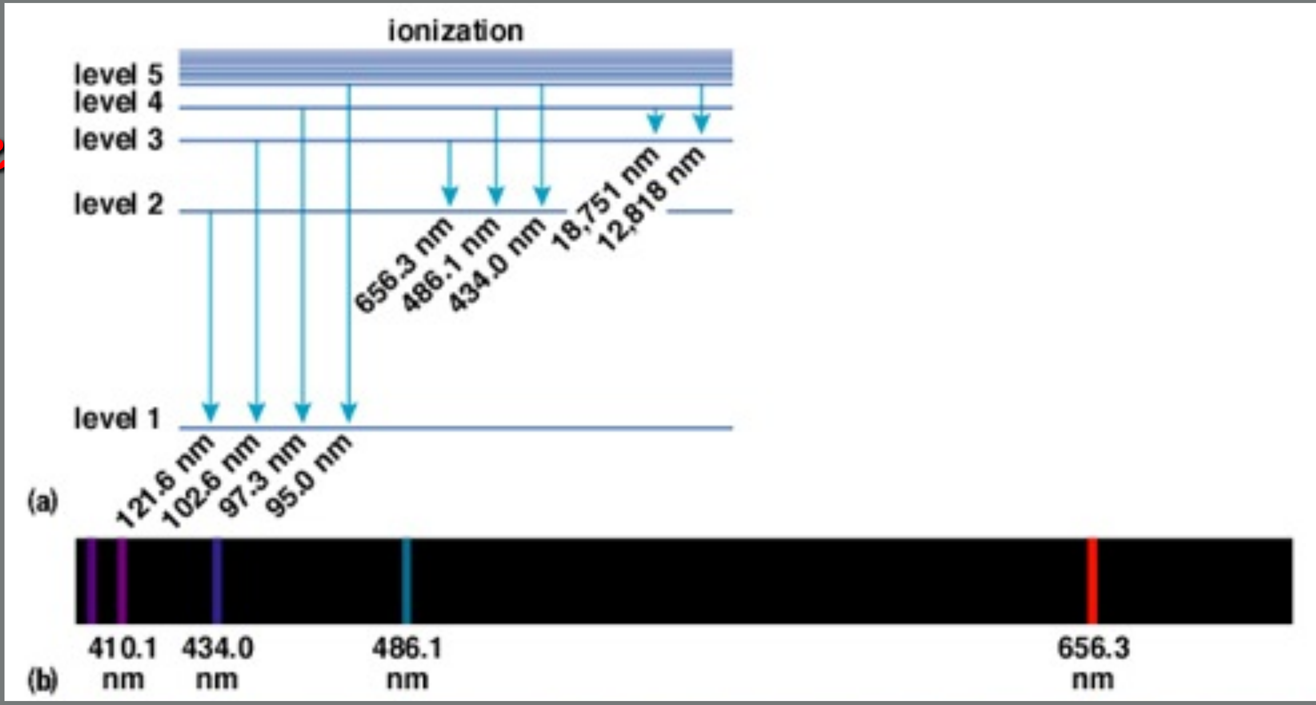


Example: Energy jumps A & C result in the electron *losing energy*, B & F *require energy*, and D & E *are not possible*. F ionizes the atom with an energy gain of ≥3.4 eV

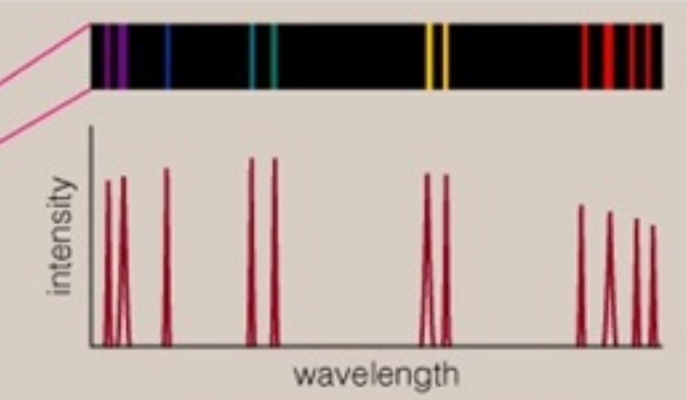
When an electron drops down a level, it releases energy. Where does that energy go?

PHOTONS!

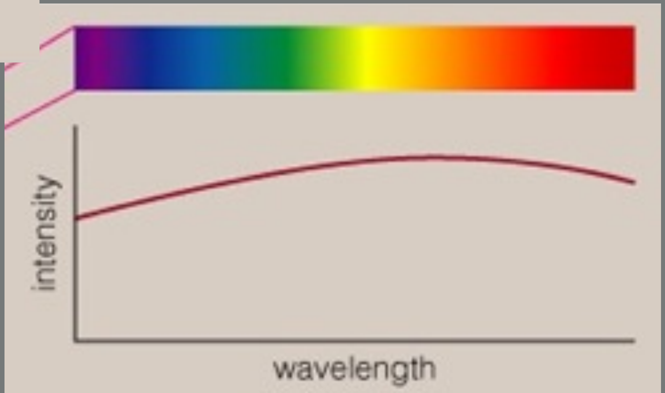
- The energy change between levels is equal to the energy of the photon.
- Larger energy jumps will be SHORTER wavelength photons



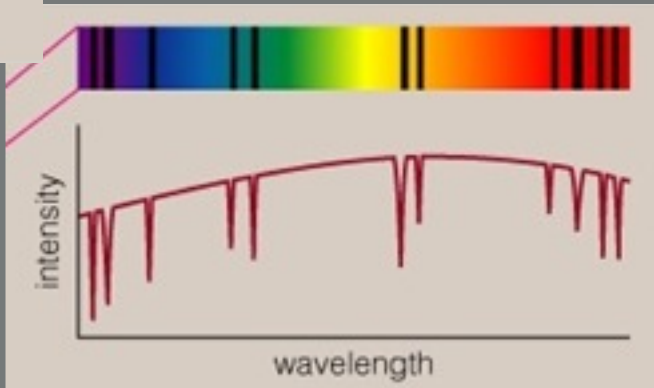
Three types of spectra



Emission Line Spectrum



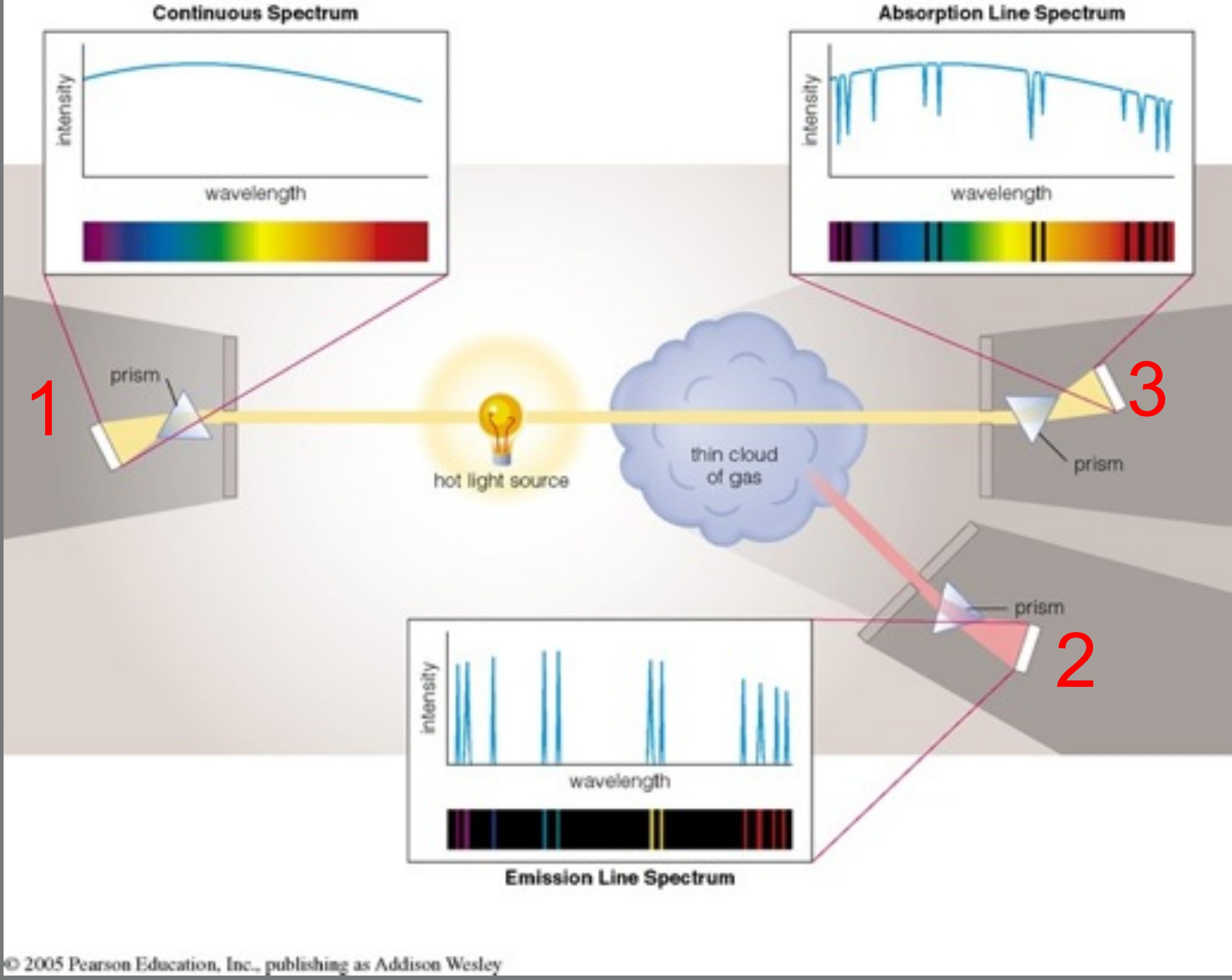
Continuous Spectrum



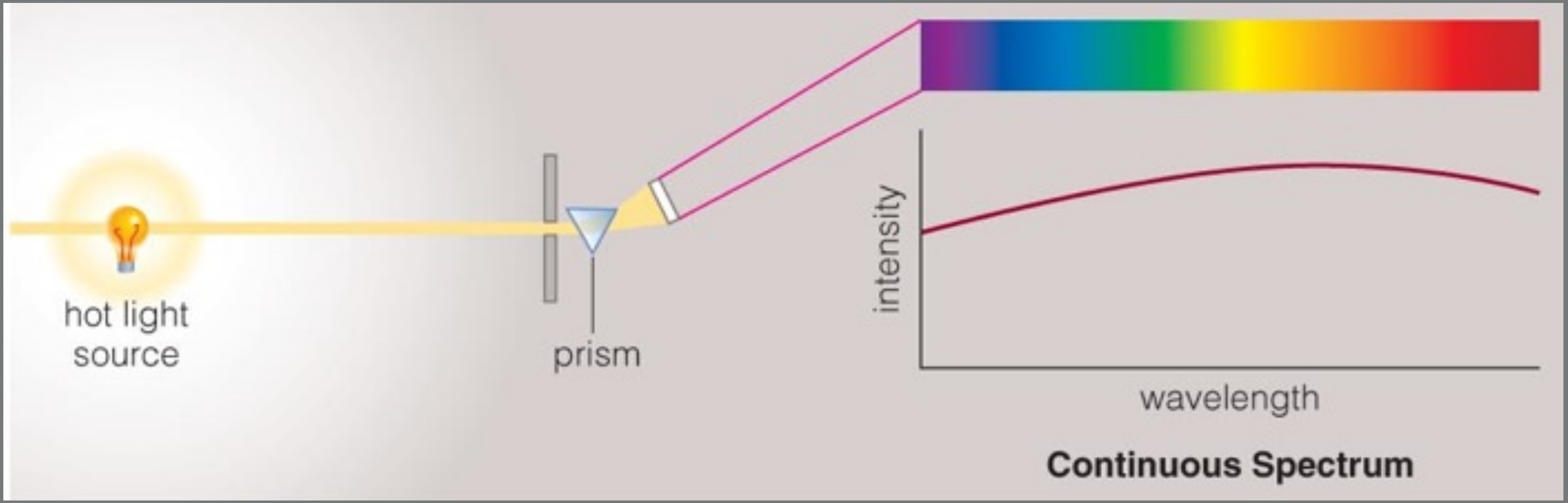
Absorption Line Spectrum

Kirchhoff's Laws

1) Hot solid, liquid, or dense gas
2) Thin, hot gas (compared to background)
3) Continuous spectrum viewed through a cooler gas (compared to background)



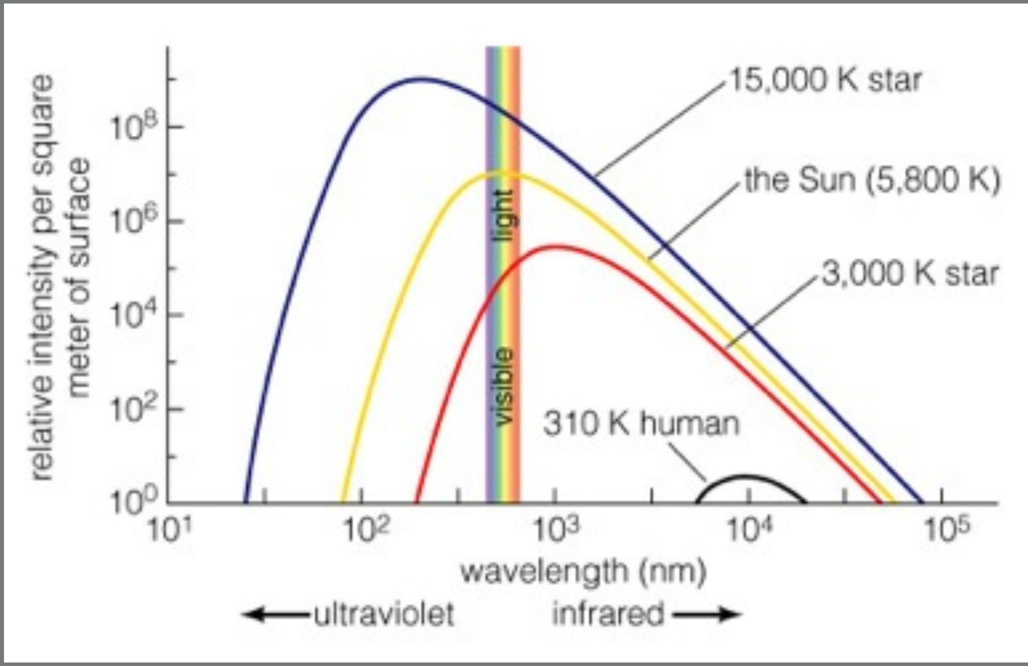
Continuous Spectrum

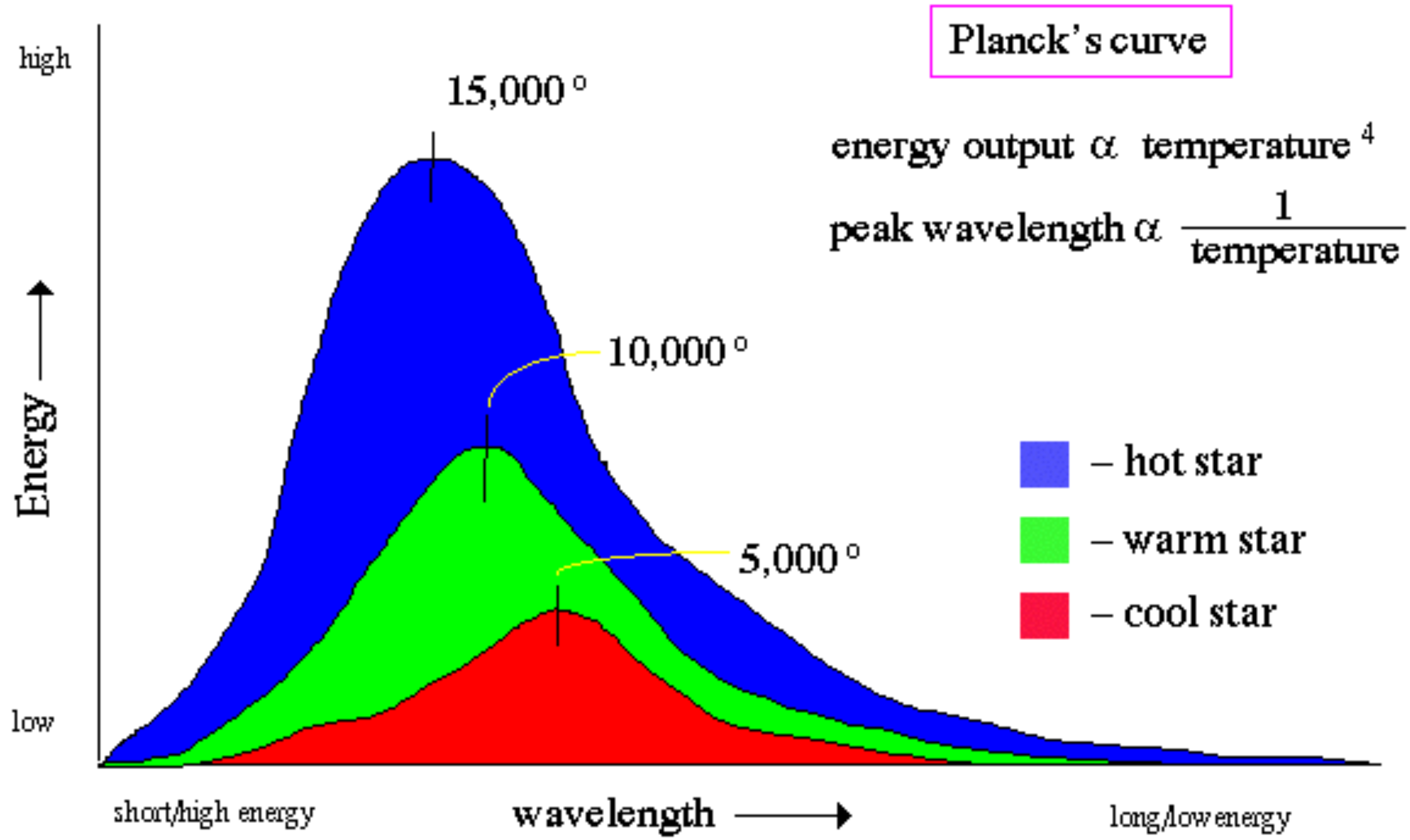


- Hot solids (or dense liquid): Emit a continuous rainbow of light
  - Thermal Radiation (or Blackbody Radiation)

Colors of Hot, Solid Objects

- Hotter objects peak at bluer wavelengths (photons with a shorter wavelength, higher frequency, and higher average energy.)
  - Wien's Law
    - $\lambda_{max} \propto 1 / T$
    - $=2,900,000$ nm/T
    - $=.29$ cm/T

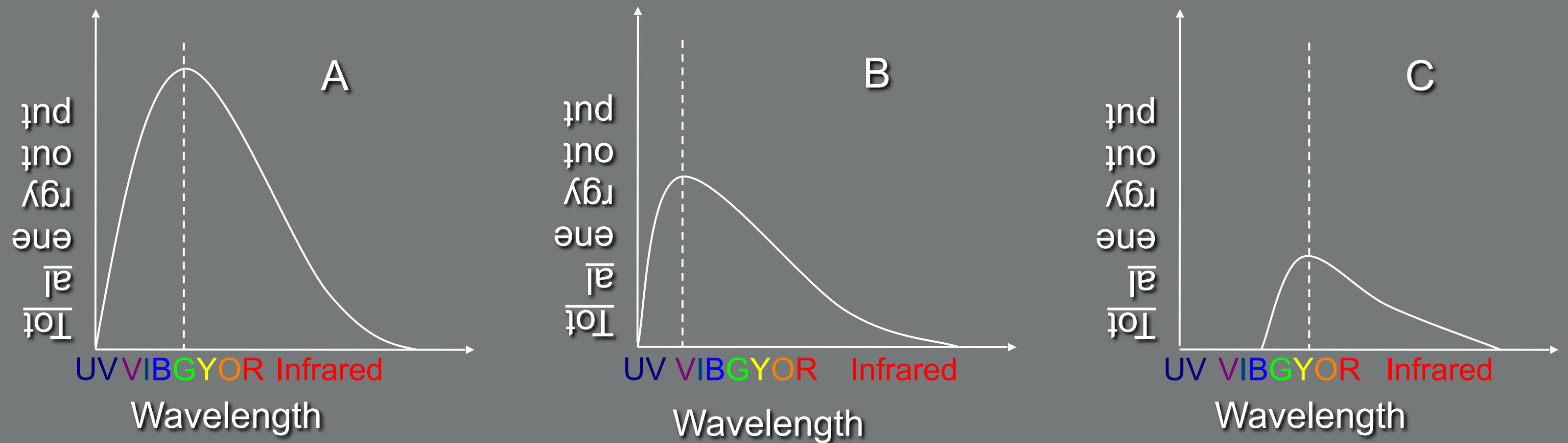




Planck's curve
15,000 °
energy output α temperature 4
peak wavelength α 1 / temperature
10,000 °
5,000 °
– hot star
– warm star
– cool star
high
low
Energy
short/high energy
wavelength
long/low energy

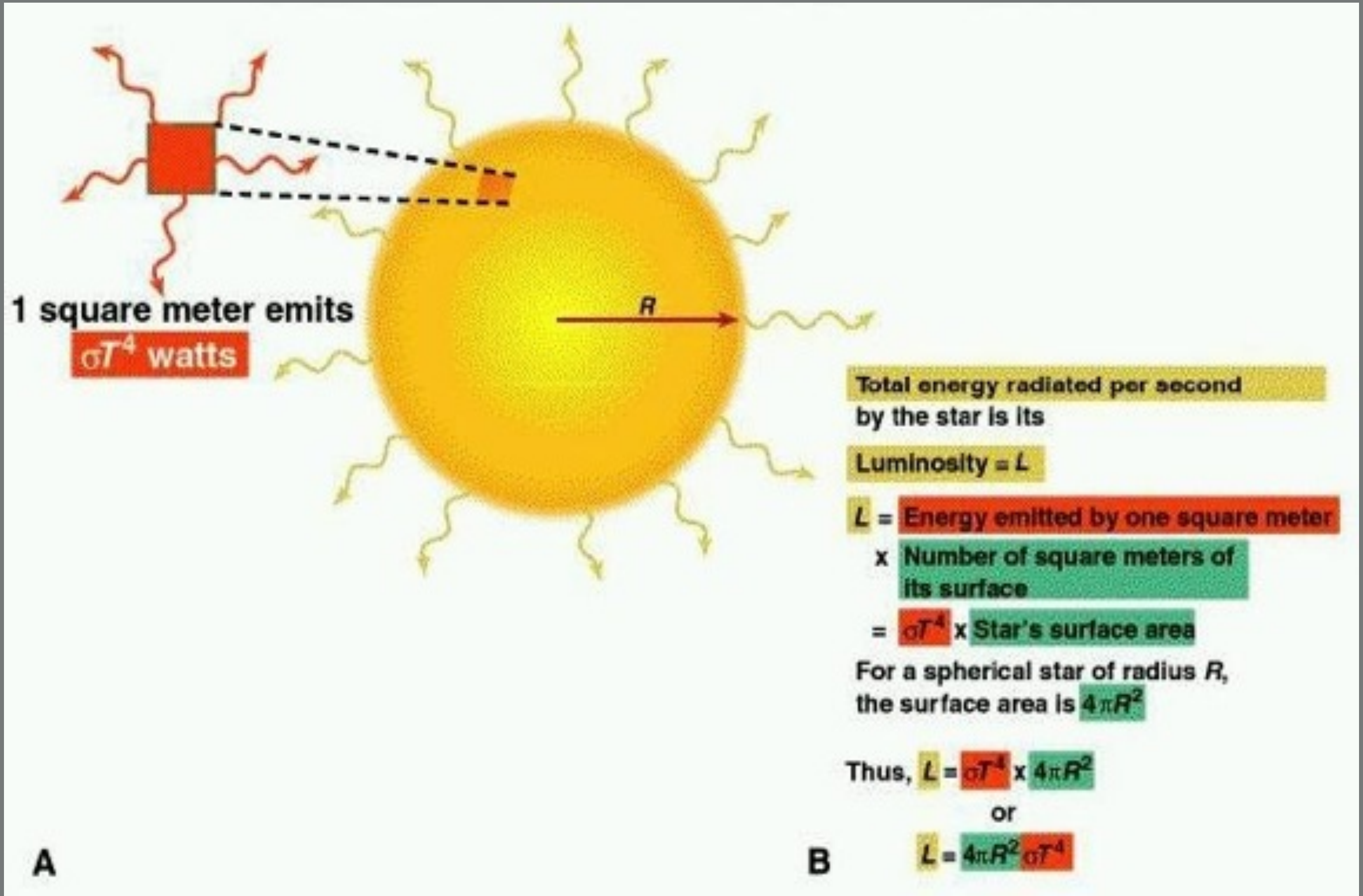
Thought Question

The three spectral curves shown in the graphs below illustrate the *total* energy output (over the whole surface) versus wavelength for three unknown objects. Which of the objects has the highest temperature?



Stefan Boltzmann Law

- Power (energy s^{-1}) $\propto AT^4$
- $A = 4\pi r^2$



What color are hot objects?

- Classic example: red hot pokers:

As temperature increases:

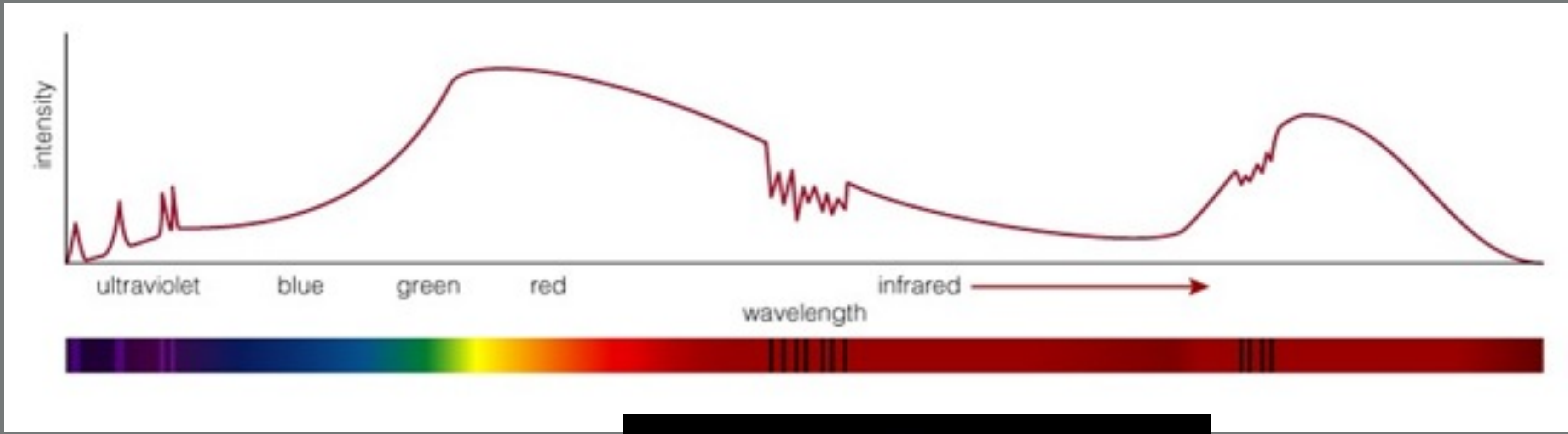
IR→ red → blue/white

Some Blackbody Temperatures			
Region	**Wavelength (centimeters)**	**Energy (eV)**	**Blackbody Temperature (K)**
Radio	> 10	$< 10^{-5}$	< 0.03
Microwave	10 - 0.01	10^{-5} - 0.01	0.03 - 30
Infrared	0.01 - 7×10^{-5}	0.01 - 2	30 - 4100
Visible	7×10^{-5} - 4×10^{-5}	2 - 3	4100 - 7300
Ultraviolet	4×10^{-5} - 10^{-7}	3 - 10^{3}	7300 - 3×10^{6}
X-Rays	10^{-7} - 10^{-9}	10^{3} - 10^{5}	3×10^{6} - 3×10^{8}
Gamma Rays	$< 10^{-9}$	$> 10^{5}$	$> 3 \times 10^{8}$

Humans in the Infrared

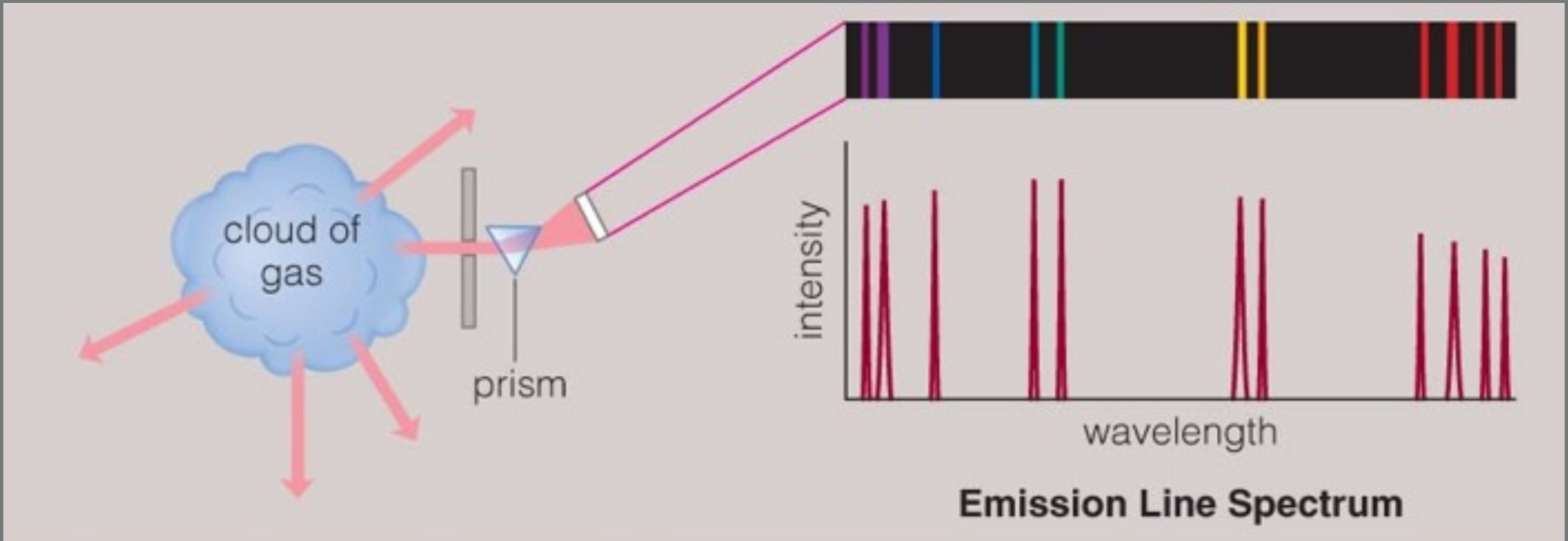
(false color)

What is this object?



Mars!

Emission Spectra

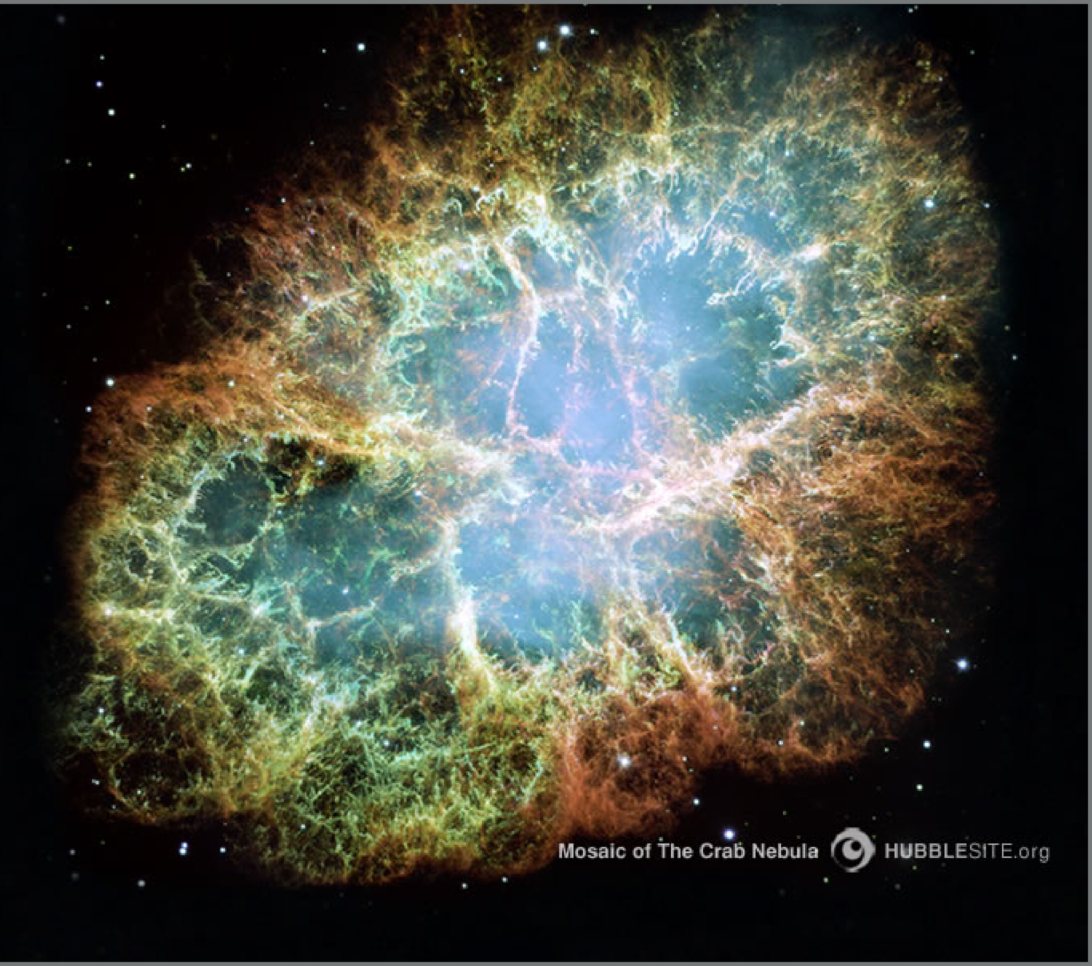


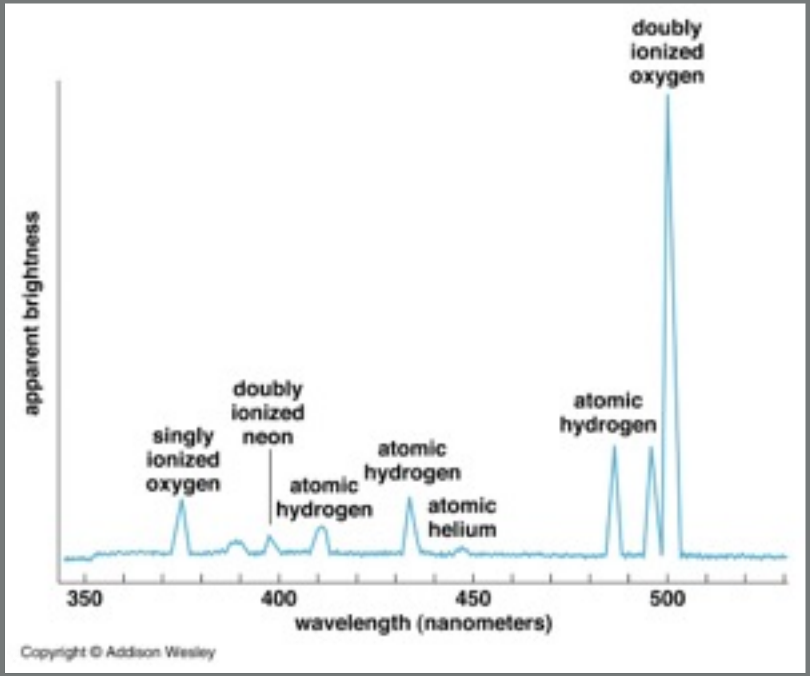
- Emission for thin, hot gas: Gas glows in specific colors.
  - Colors represent electrons "falling down" energy levels
  - This is a FINGERPRINT of the elements in the gas.

Thought Question

Why does it need to be a HOT gas to give off an emission spectrum?

A. Hot gases glow brighter than cold gases
B. The electrons need to be in high energy levels
C. Hot gases give off higher energy photons
D. Cold photons don't have enough energy to make it here to Earth
E. Hot things glow, cool things don't.

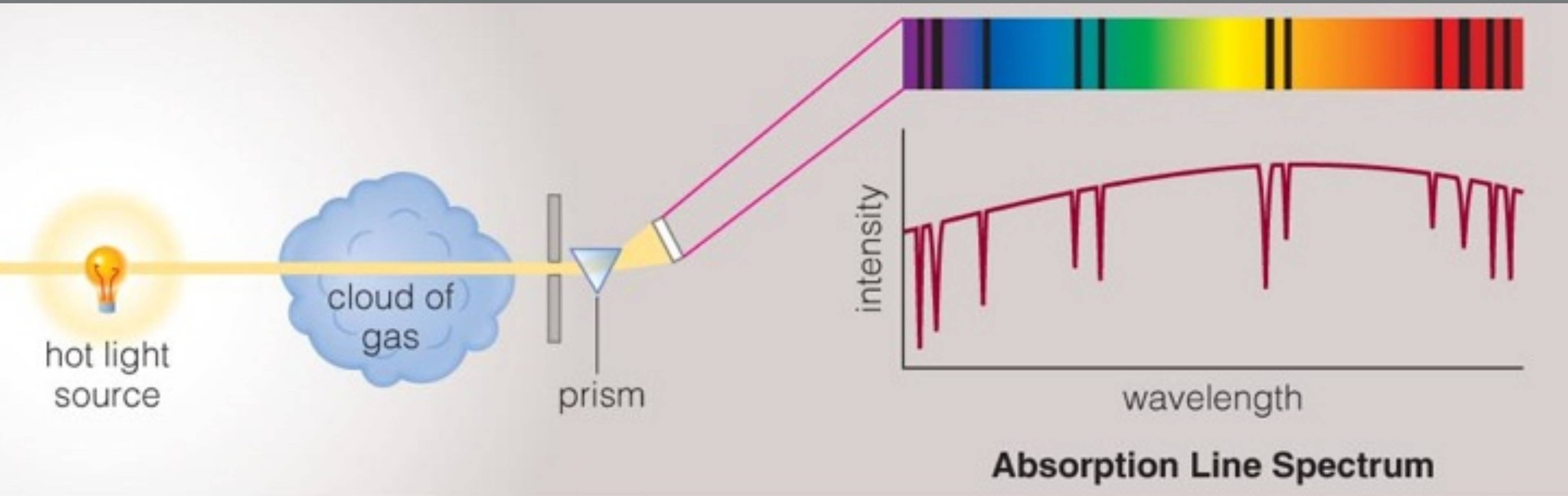




Spectrum shows bright emission lines from various elements

The Crab nebula: remains of an exploded star (supernova)

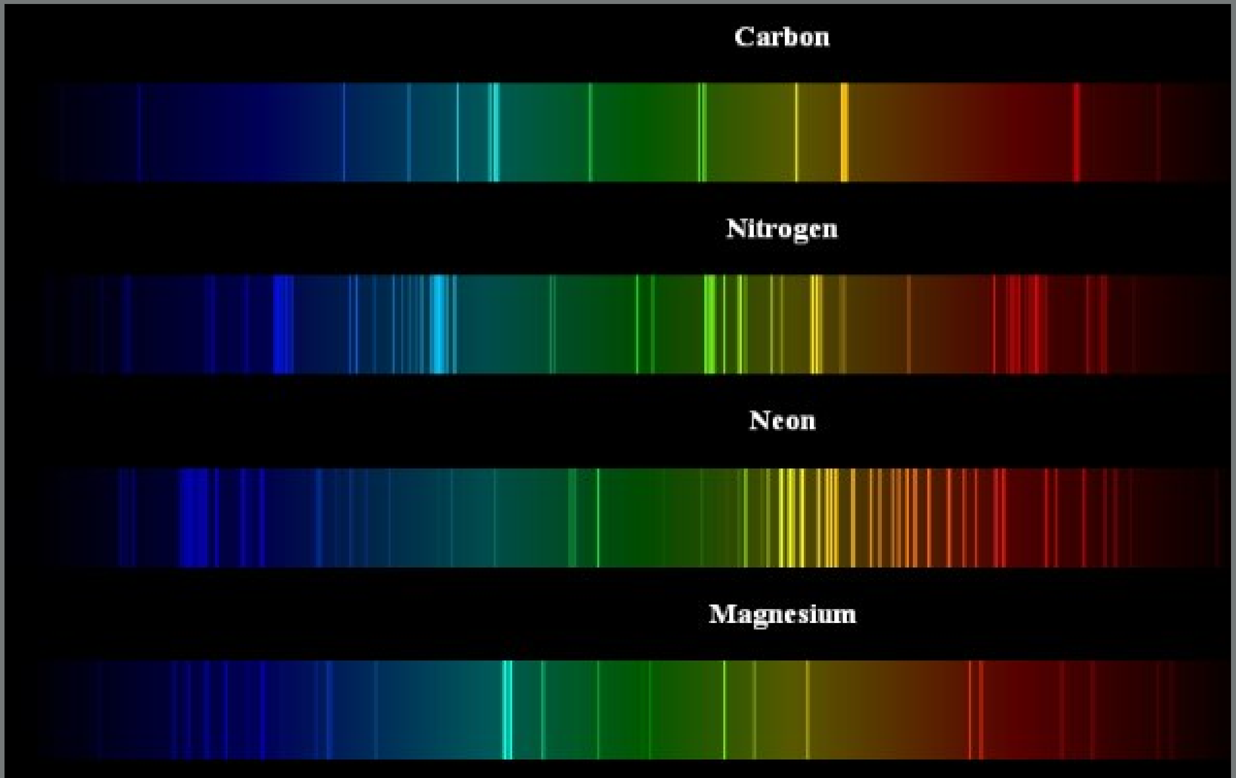
Absorption Spectrum



- Hot object viewed through COOL gas: Dark lines on top of a rainbow
  - Gas can only absorb photons OF THE RIGHT ENERGIES to move electrons to excited states

Each atom has a different set of energy levels

- Just like no two people have the same fingerprints, no two elements have the same emission spectrum

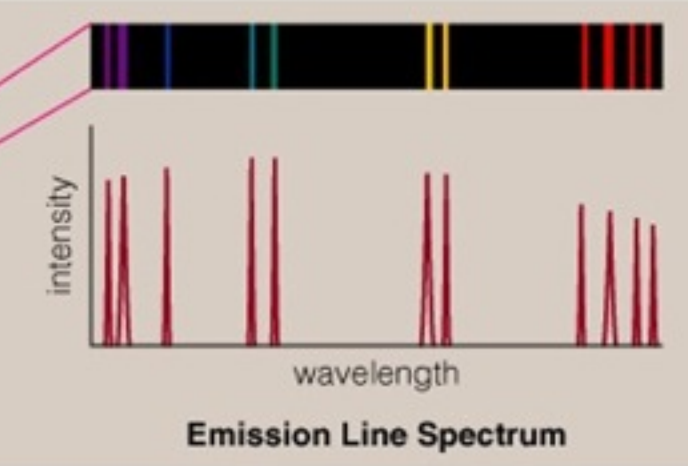


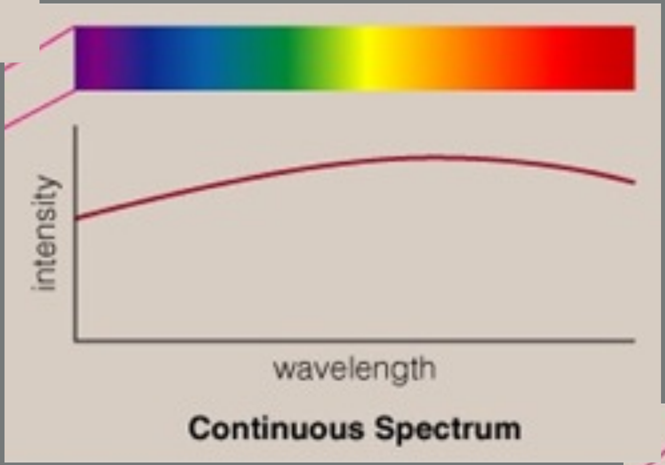
Thought Question

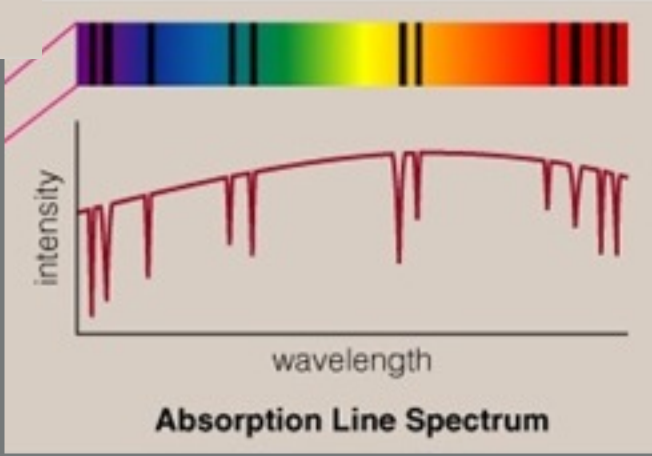
Why don't we see those atoms re-emit the same photon when they de-excite?

A. The atom will re-emit the photon at different wavelengths.
B. The gas hasn't been heated up enough to emit photons.
C. The electron will stay at the higher energy level forever.
D. Once the photon has been absorbed, it is lost and converted to heat.
E. When the atom re-emits the photon it may not be emitted towards us.

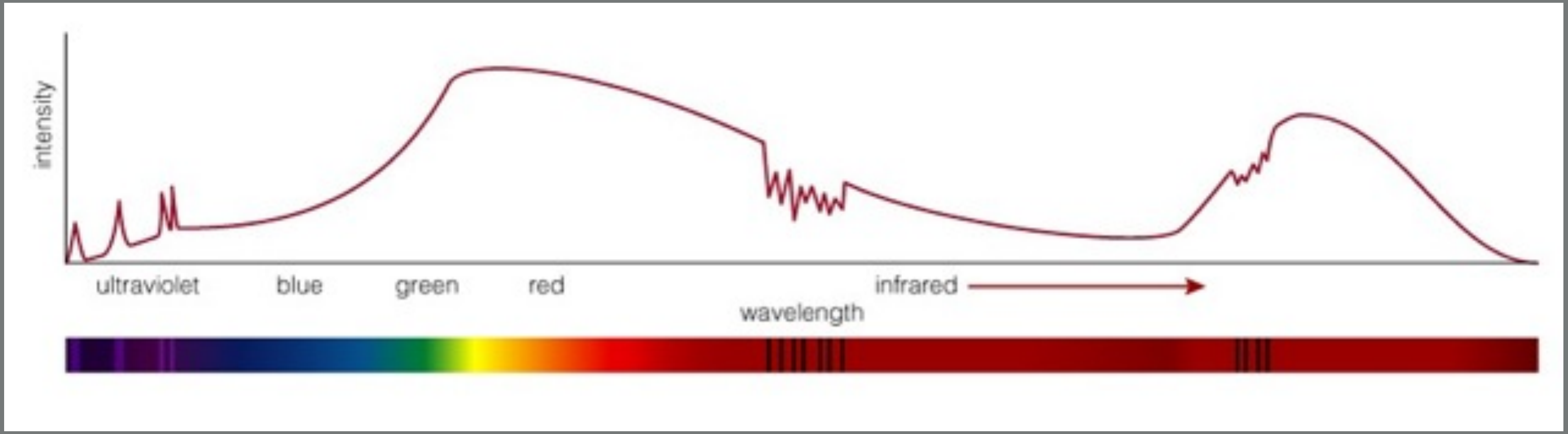
Three types of spectra





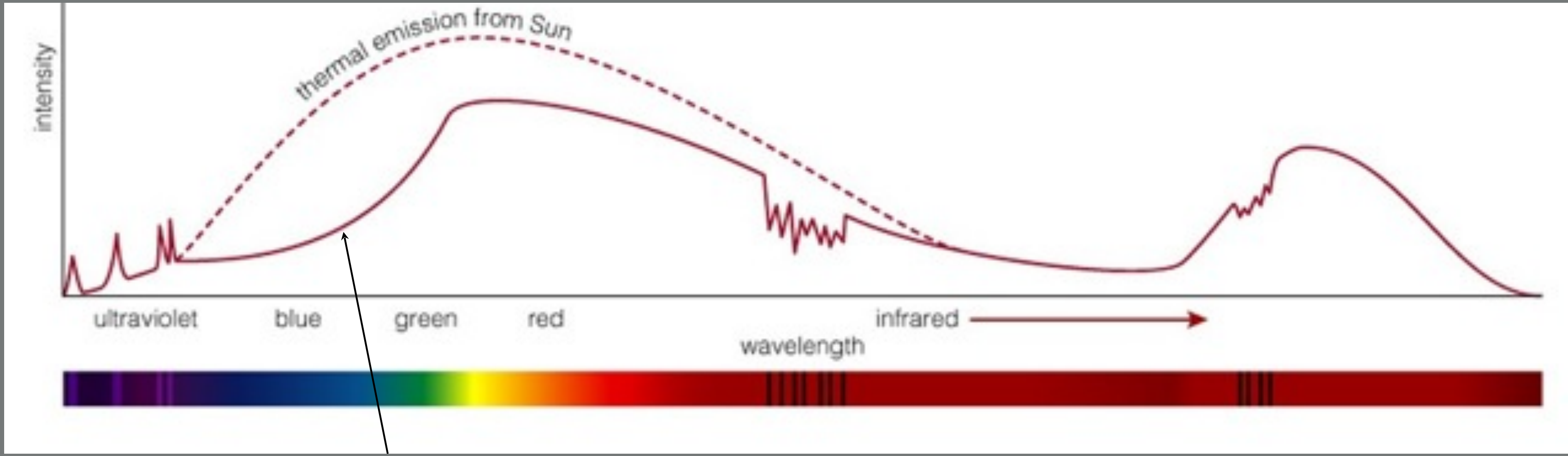


What can a spectrum tell us?



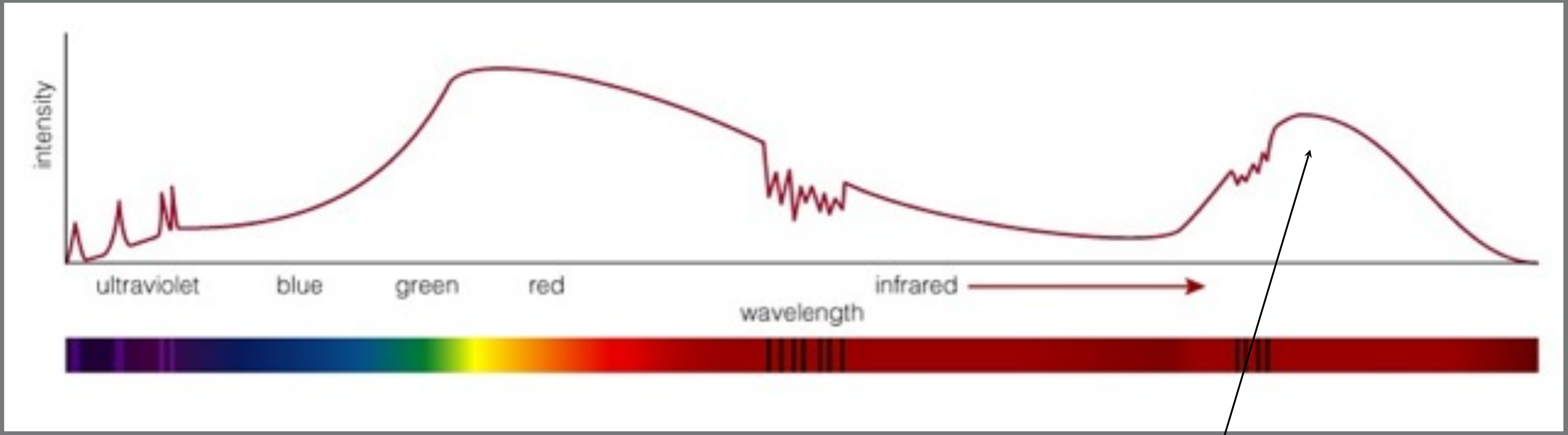
- Let's use its spectral information to determine what this object is.

What is this object?



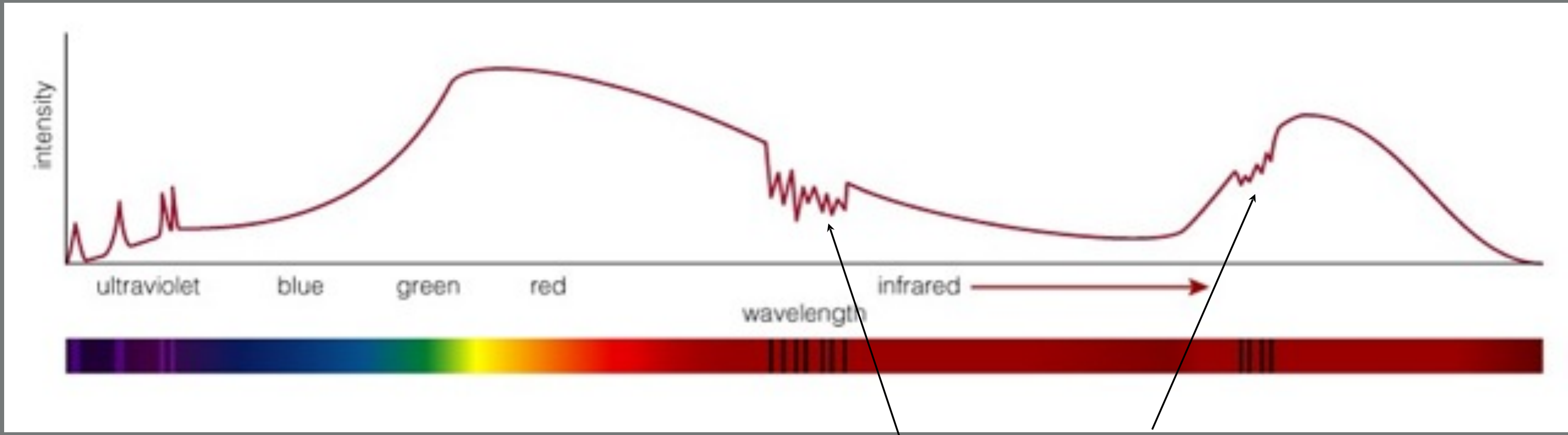
Continuous Spectrum: Spectrum of visible light is like the Sun's except that some of the blue light has been absorbed

What is this object?



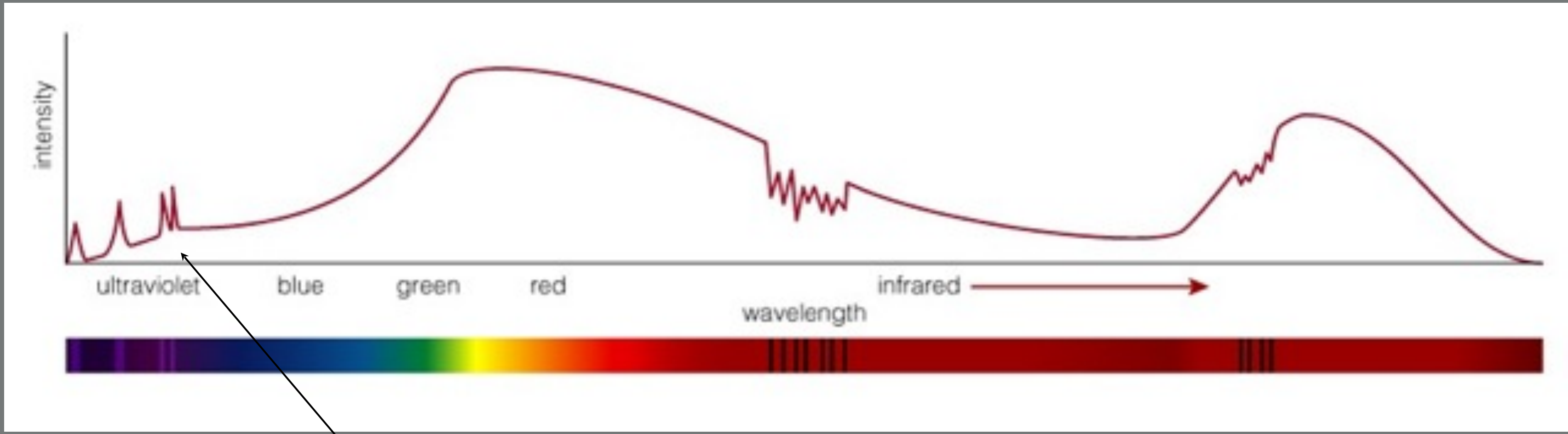
Continuous Spectrum:
Must be a solid object with peak emission at a wavelength corresponding to a temperature of 225 K

What is this object?



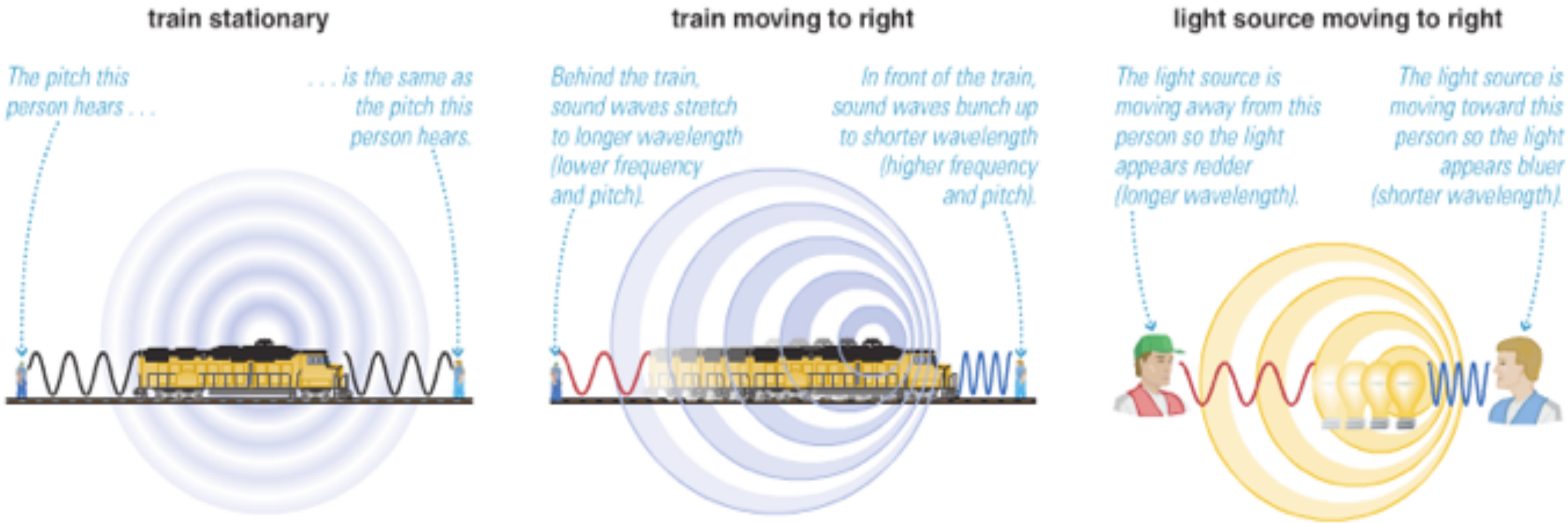
Infrared Absorption Lines: Absorption lines are the fingerprint of CO_2 gas

What is this object?



Ultraviolet Emission Lines: Indicate object is surrounded by a hot upper layer of gas

Doppler Shift



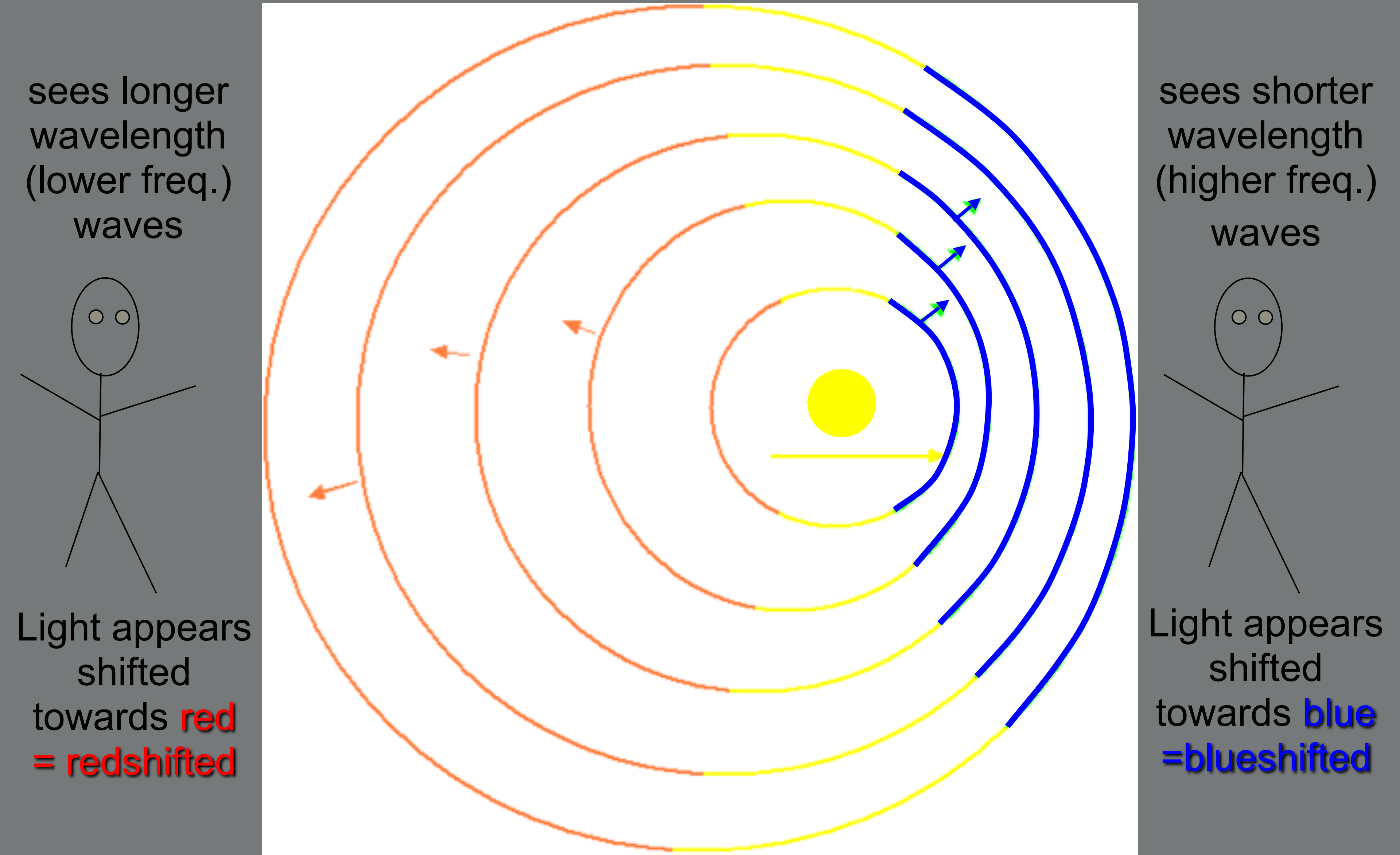
a The whistle sounds the same no matter where we stand near a stationary train.

b For a moving train, the sound you hear depends on whether the train is moving toward you or away from you.

c We get the same basic effect from a moving light source (although the shifts are usually too small to notice with our eyes).

Doppler Shift

sees longer wavelength (lower freq.) waves



sees shorter wavelength (higher freq.) waves

Light appears shifted towards red = redshifted

Light appears shifted towards blue =blueshifted

Think of the freeway at night!

- The red lights are going away from you
- The blue/white lights are coming towards you

$\Delta\lambda/\lambda = v/c$

Figure 5.23 Interactive Figure Spectral lines provide the crucial reference points for measuring Doppler shifts.

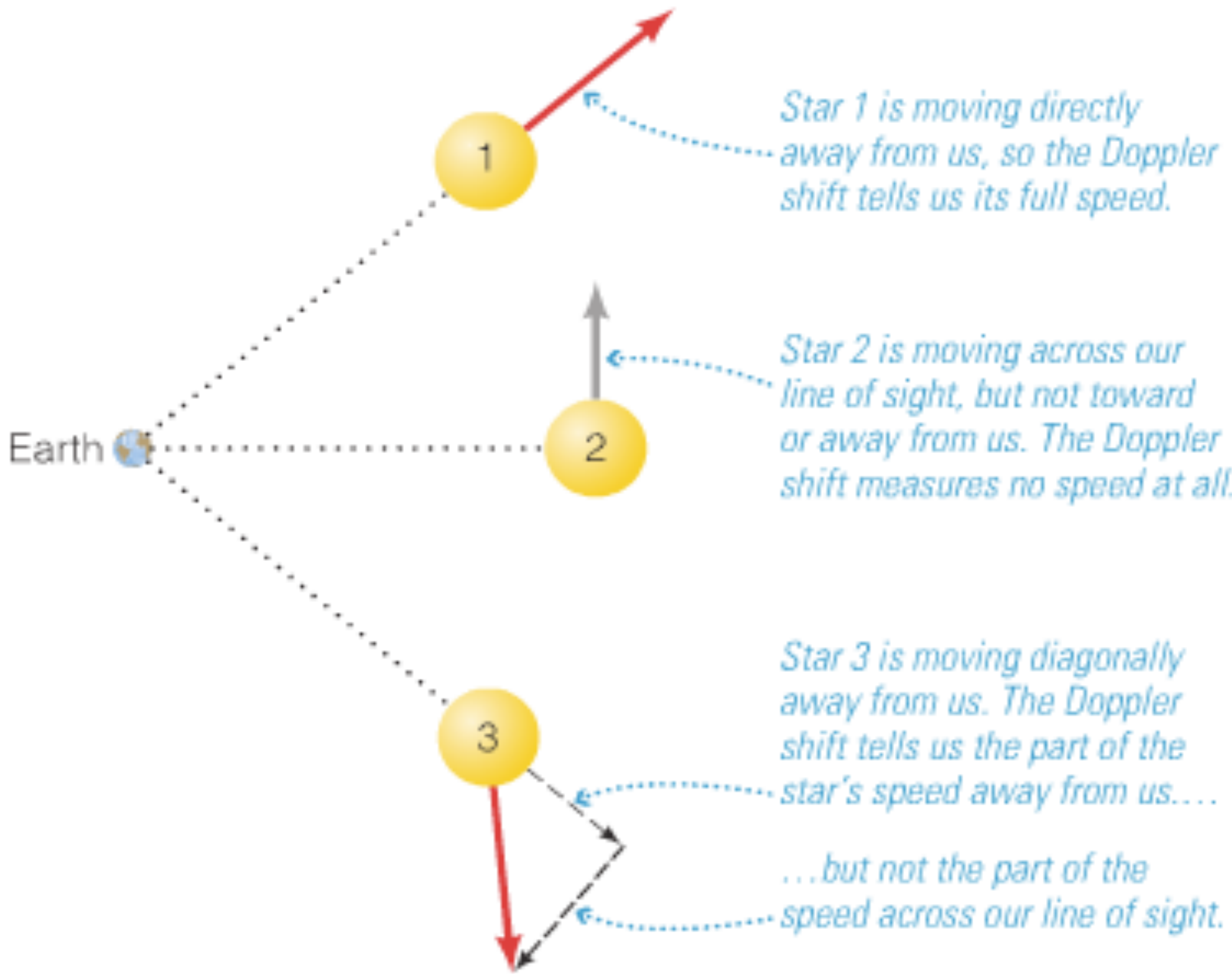
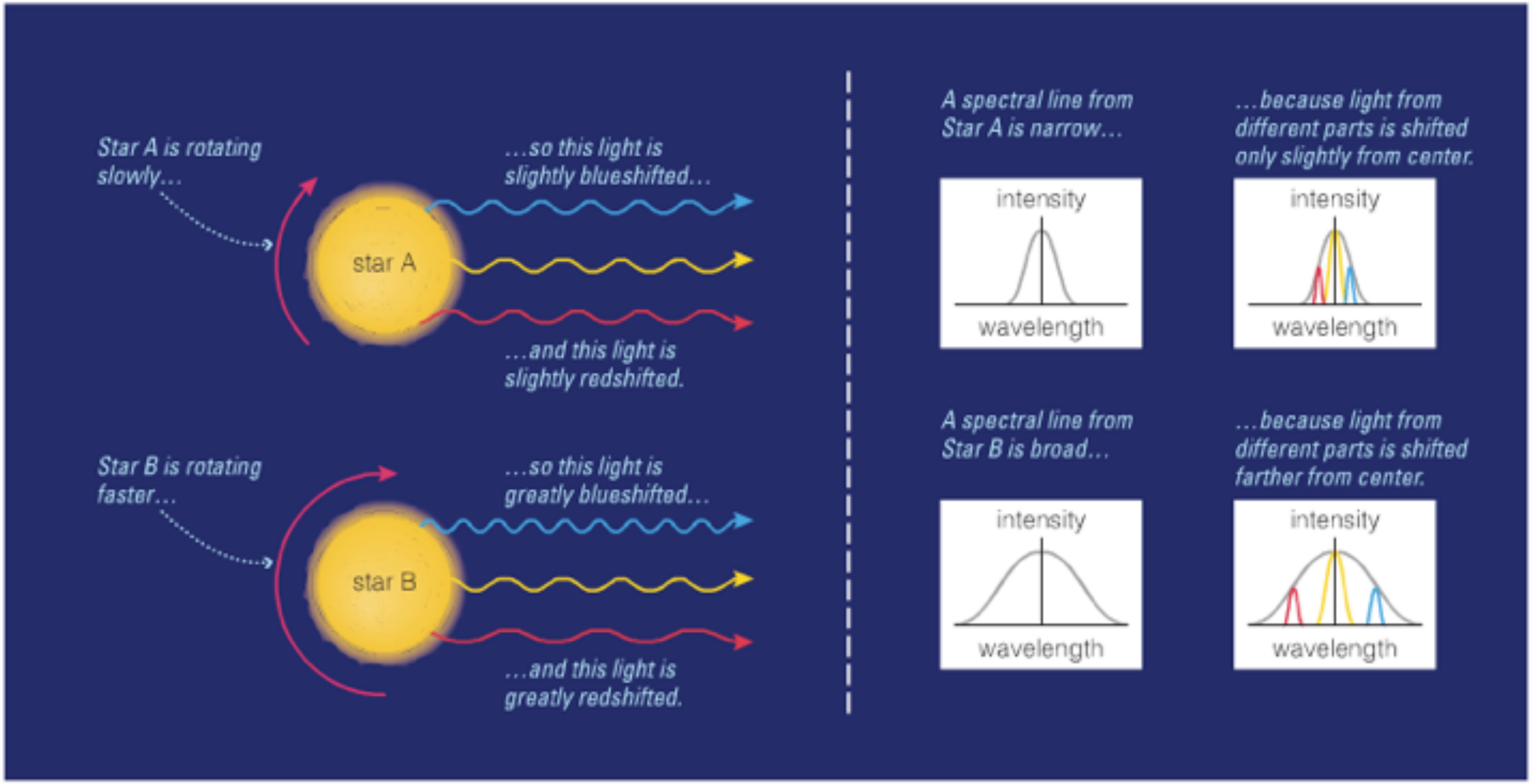
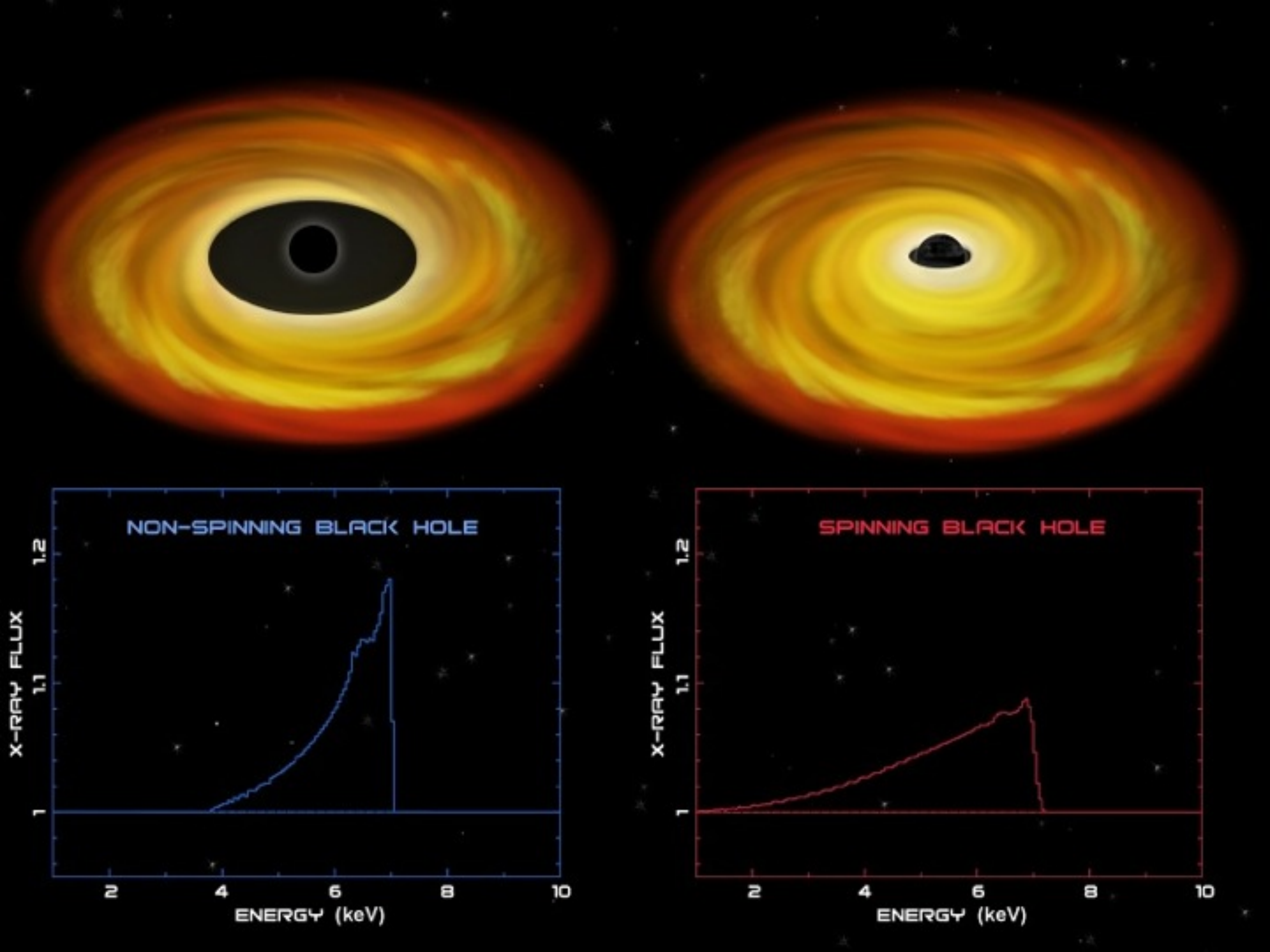


Figure 5.24 Interactive figure The Doppler shift tells us only the portion of an object's speed that is directed toward or away from us. It does not give us any information about how fast an object is moving across our line of sight.

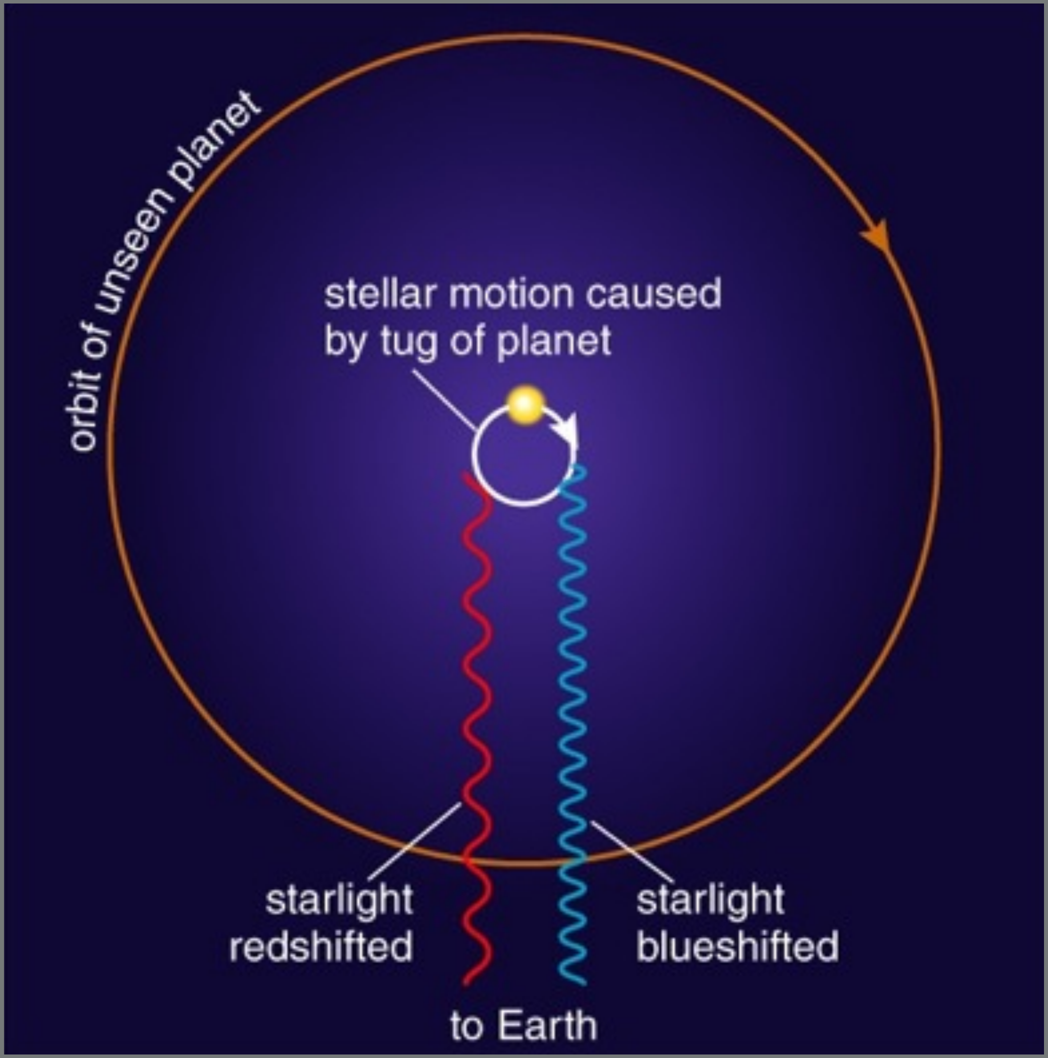
Rotation?



Star A is rotating slowly...
star A
...so this light is slightly blueshifted...
...and this light is slightly redshifted.
Star B is rotating faster...
star B
...so this light is greatly blueshifted...
...and this light is greatly redshifted.
A spectral line from Star A is narrow...
intensity
wavelength
...because light from different parts is shifted only slightly from center.
intensity
wavelength
A spectral line from Star B is broad...
intensity
wavelength
...because light from different parts is shifted farther from center.
intensity
wavelength


NON-SPINNING BLACK HOLE
X-RAY FLUX
ENERGY (keV)
SPINNING BLACK HOLE
X-RAY FLUX
ENERGY (keV)

Doppler Technique



- Measuring a star's Doppler shift can tell us its motion toward and away from us
- Current techniques can measure motions as small as 1 m/s (walking speed!)