5. Light: The Cosmic Messenger

5.1 Light in Everyday Life

Our goals for learning:

- What is the difference between energy and power?
- What are the four ways in which light and matter can interact?

Power

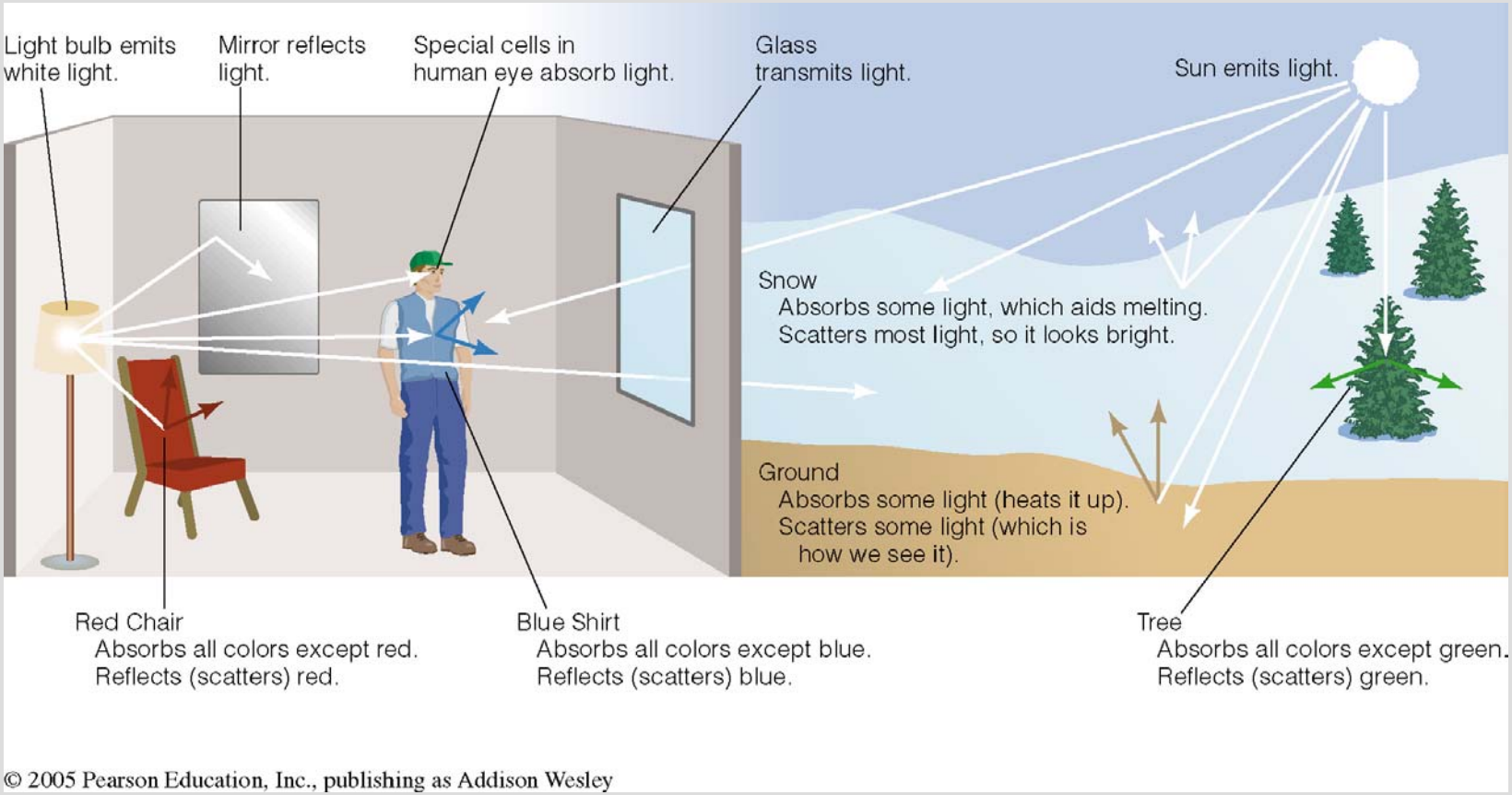
- **power**: the rate at which energy is used/emitted
- It is measured in units called **watts**.

  1 watt = 1 joule per second
- A 100 watt light bulb radiates 100 joules of energy every second.

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** – matter repels light in another direction

Interactions of light and matter



5.2 Properties of Light

Our goals for learning:

- In what way is light a wave?
- In what way is light made of particles?
- How are wavelength, frequency, and energy related for photons of light?

Light

A vibration in an electromagnetic field through which energy is transported.

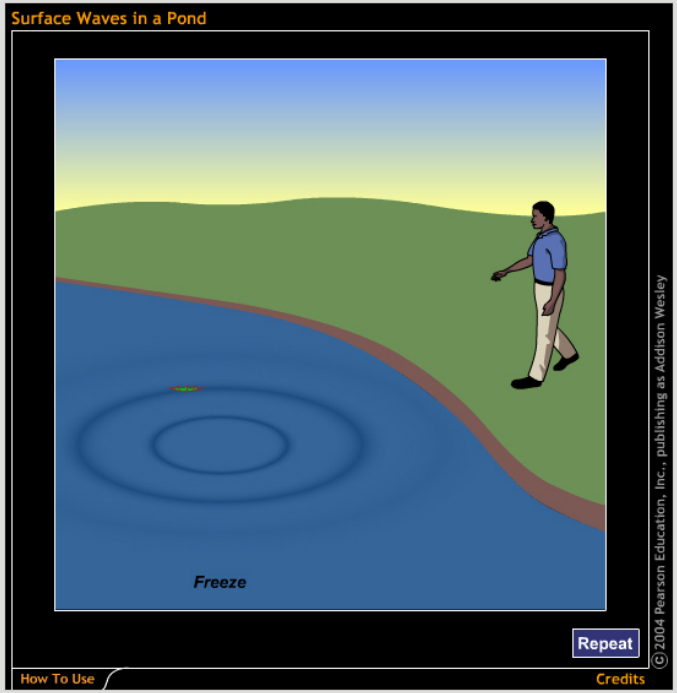
Dual Natures

Light as a wave $f\lambda = c$

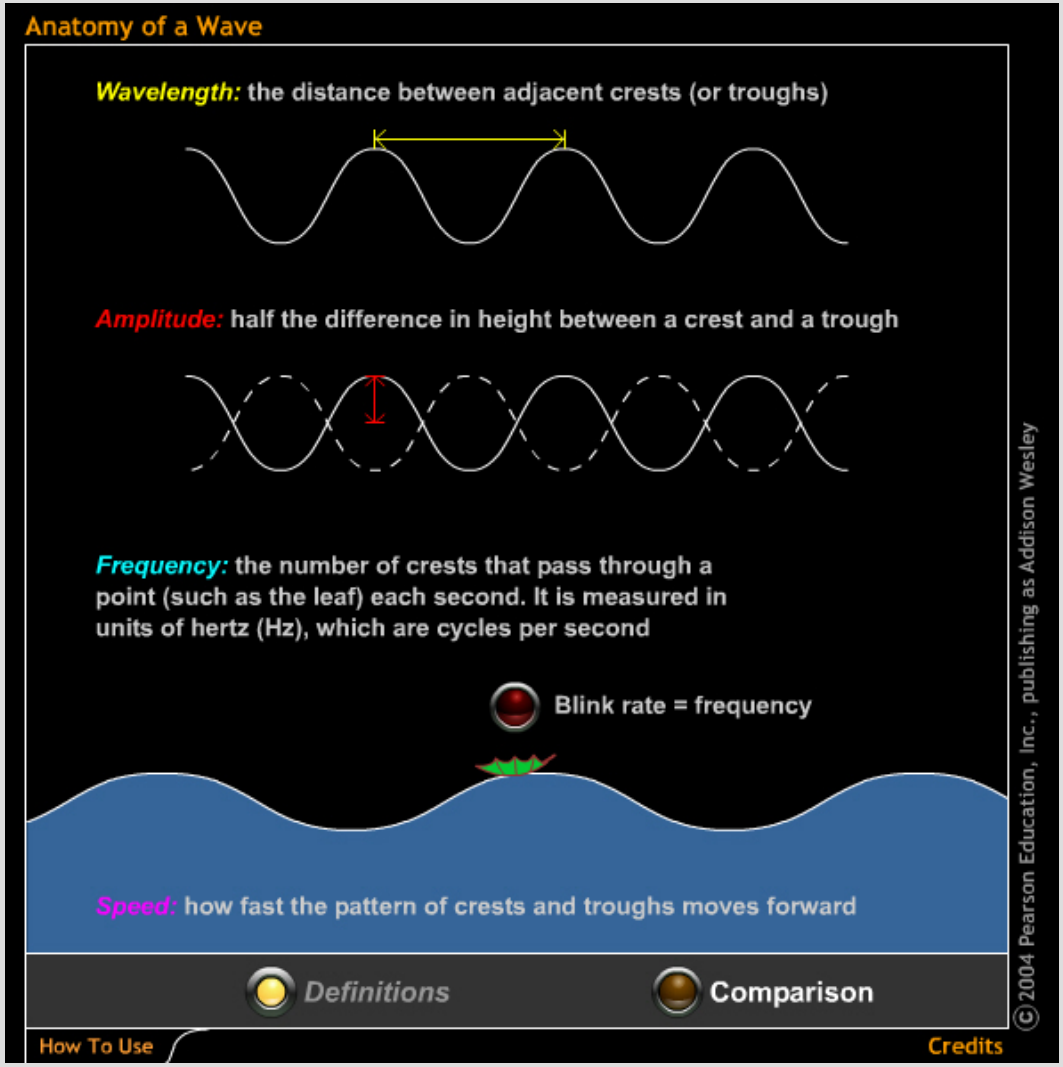
Light as a particle $E = hf$ photon

Light as a Wave

A *wave* is a pattern which is revealed by its interaction with particles.

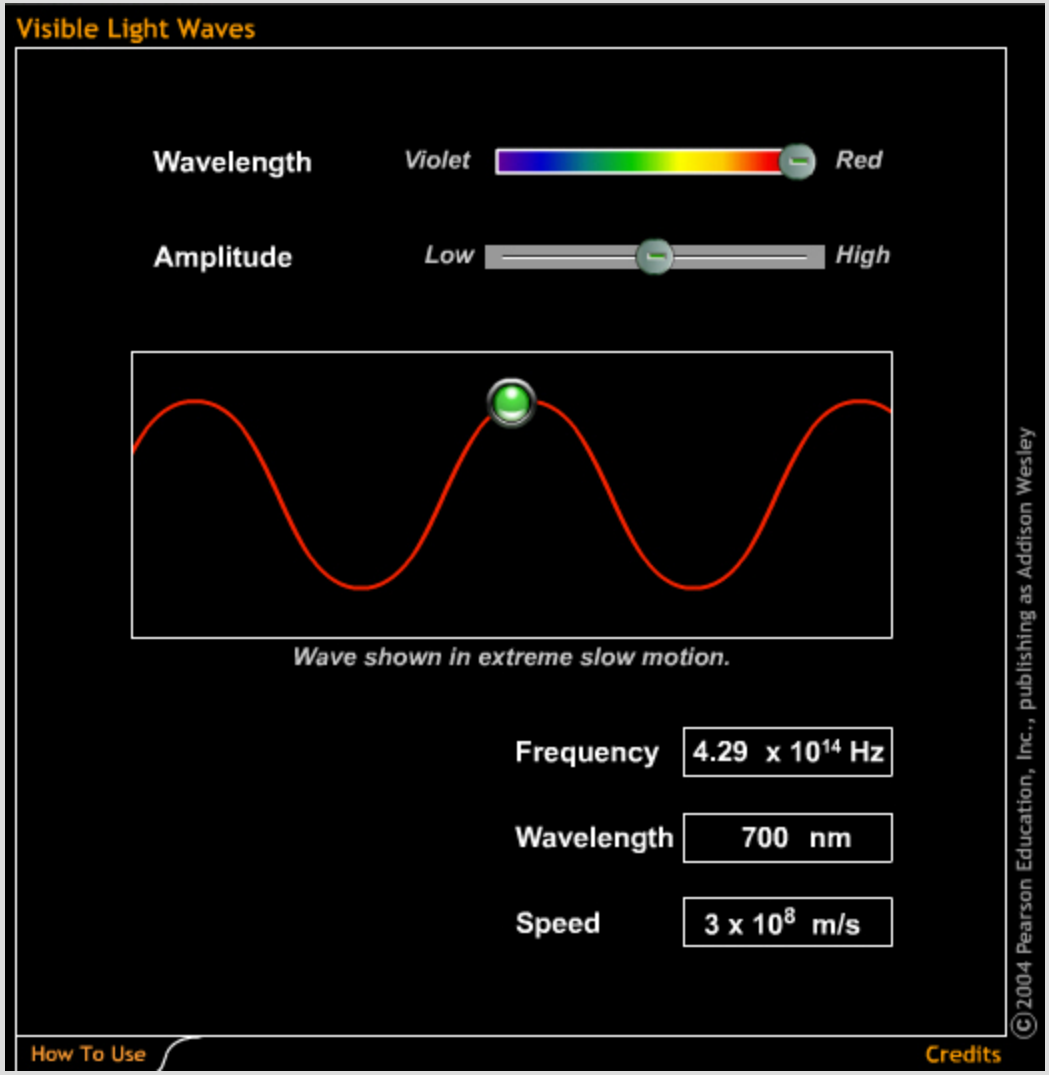


Properties of a Wave



Light as a Wave

- For a wave, its speed: $s = f\lambda$
- But the speed of light is a constant, c.
- For light: $f\lambda = c$
- The higher f is, the smaller λ is, and vice versa.
- Our eyes recognize f (or λ) as *color*!

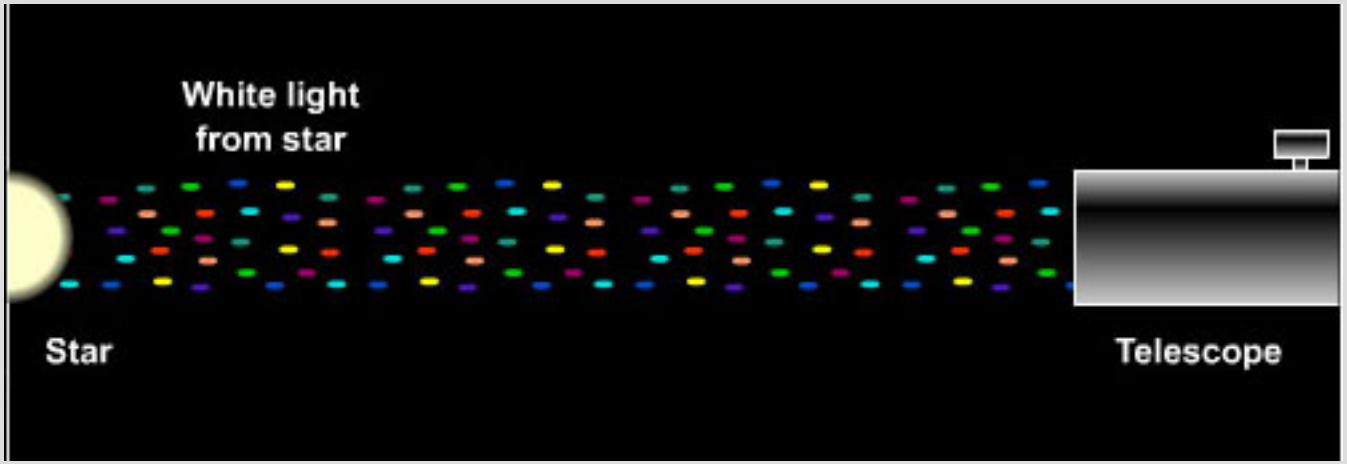


Light as a Particle

- Light can also be treated as *photons* – packets of energy.
- The energy carried by each photon depends on its frequency (color)

  $E = hf = hc / \lambda$ ["h" is called Planck's Constant]

- Bluer light carries more energy per photon.

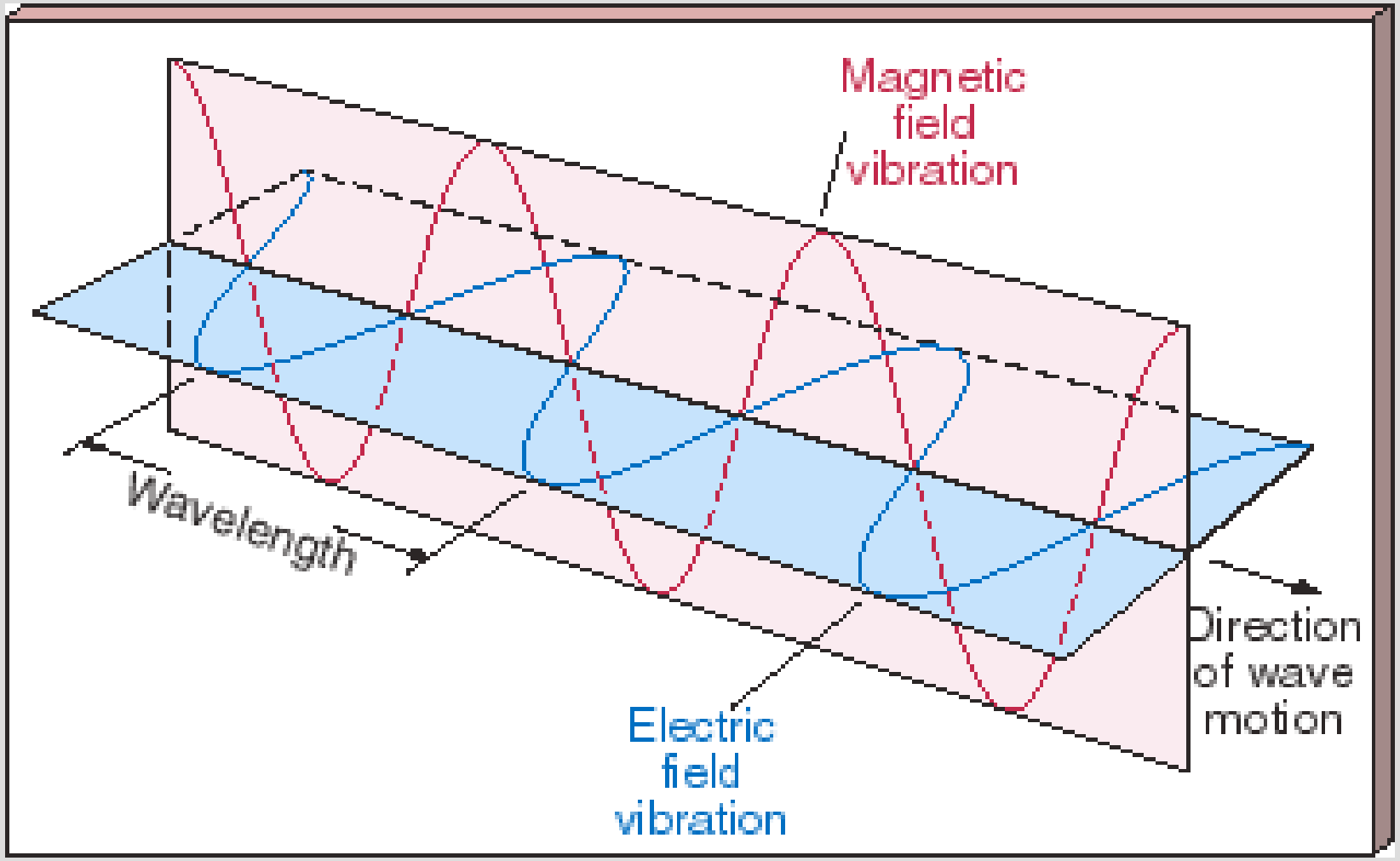


5.3 The Many Forms of Light

Our goals for learning:

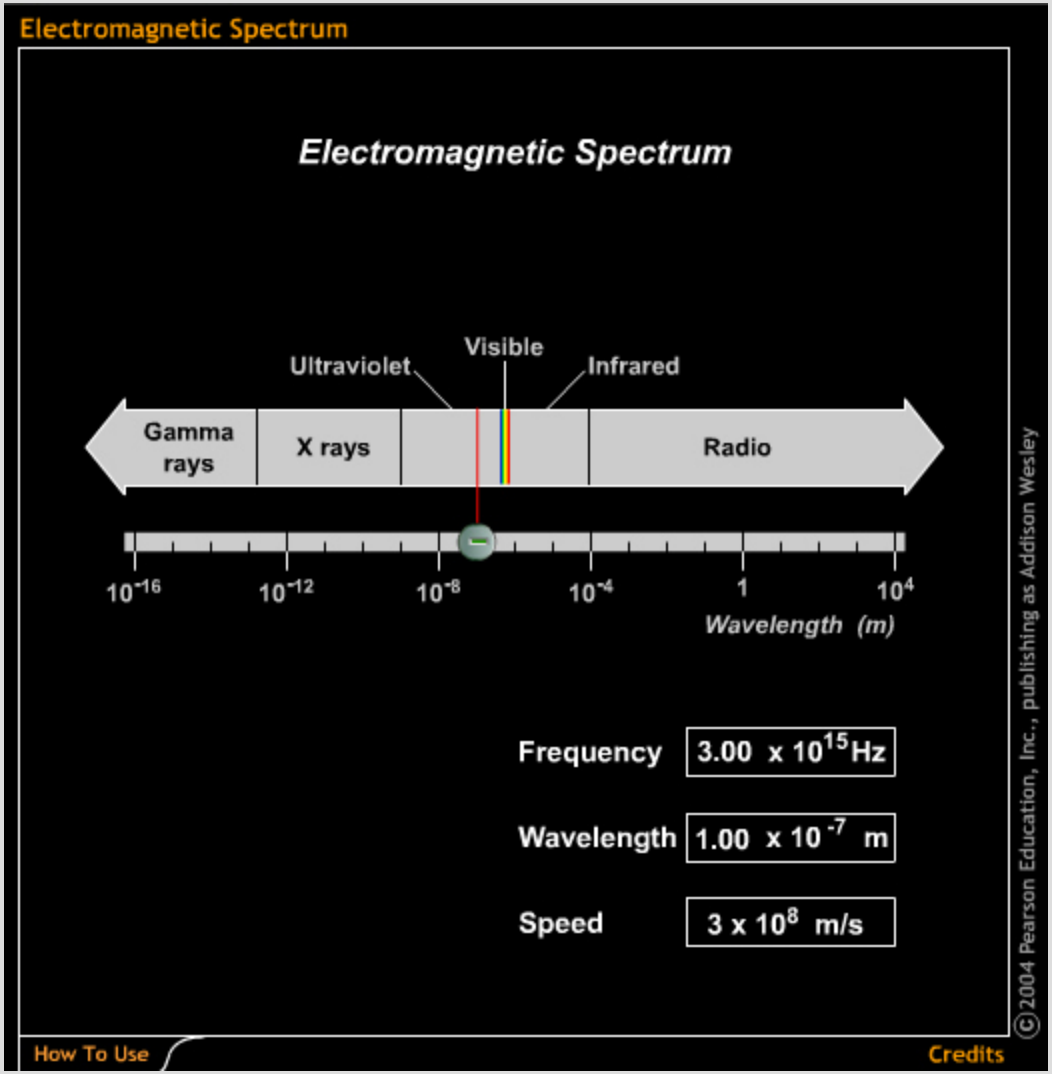
- List the various forms of light that make up the electromagnetic spectrum.

Electromagnetic Waves



The Electromagnetic Spectrum

Most wavelengths of light can not be seen by the human eye.



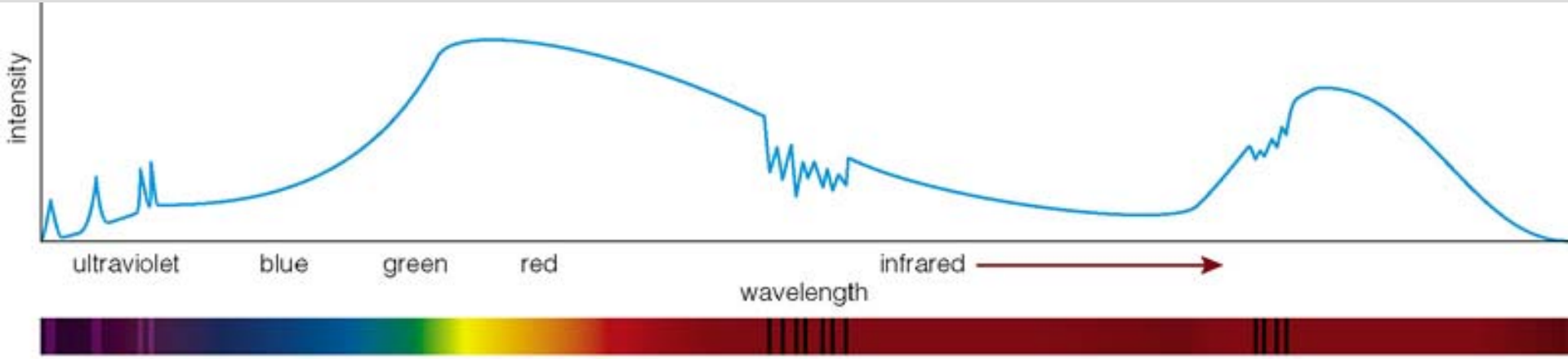
5.4 Light and Matter

Our goals for learning:

- How can we use emission or absorption lines to determine the composition of a distant object?
- Are there any material objects that don't give off any light?
- What are the two rules of thermal radiation?

Light as Information Bearer

We can separate light into its different wavelengths (spectrum).

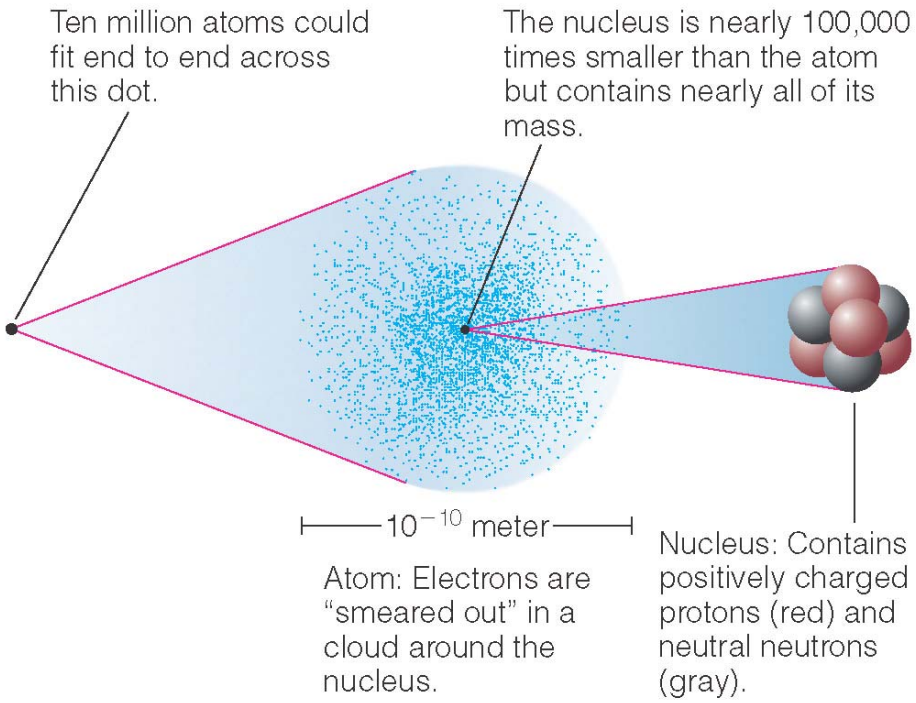


By studying the spectrum of an object, we can learn its:

1. Composition
2. Temperature
3. Velocity

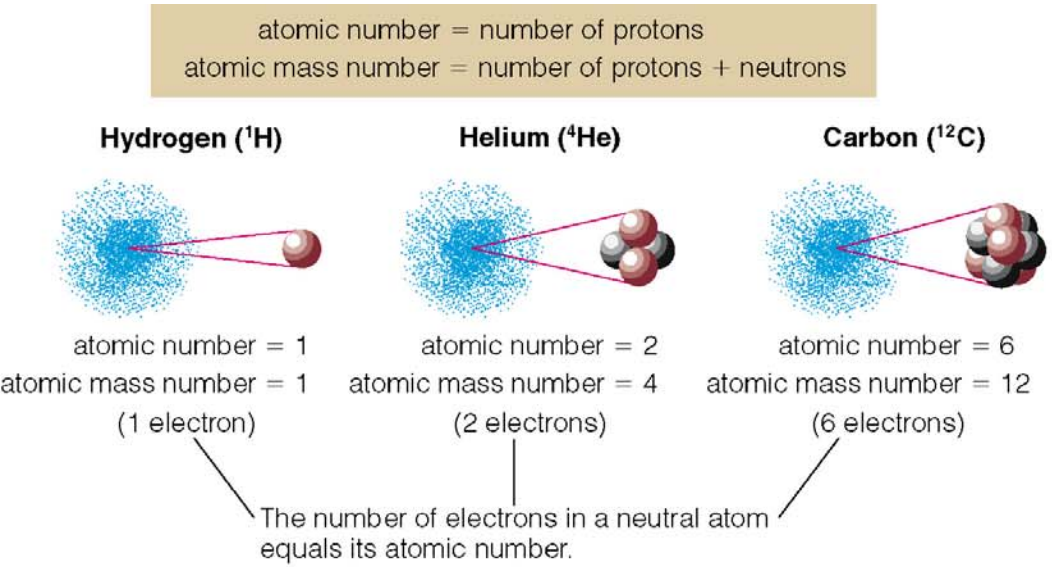
What is matter?

Atomic structure:



Atomic Terminology

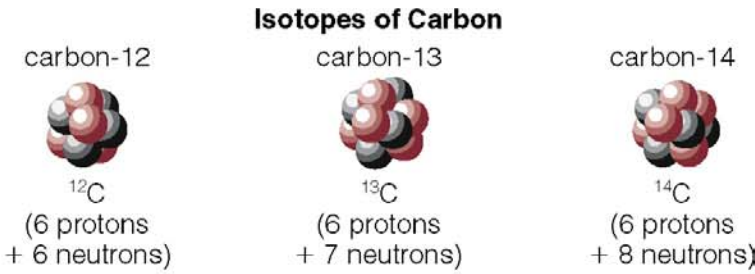
- Atomic Number = # of protons in nucleus
- Atomic Mass Number = # of protons + neutrons



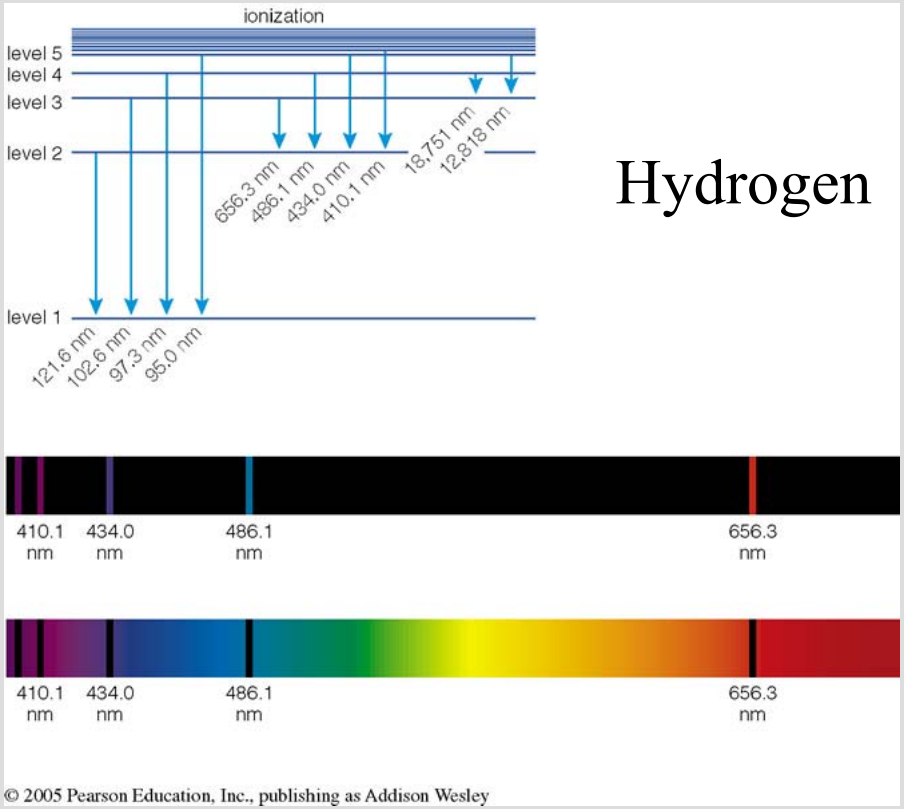
Atomic Terminology

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

Different isotopes of a given element contain the same number of protons but different numbers of neutrons.



Interaction of Light with Matter

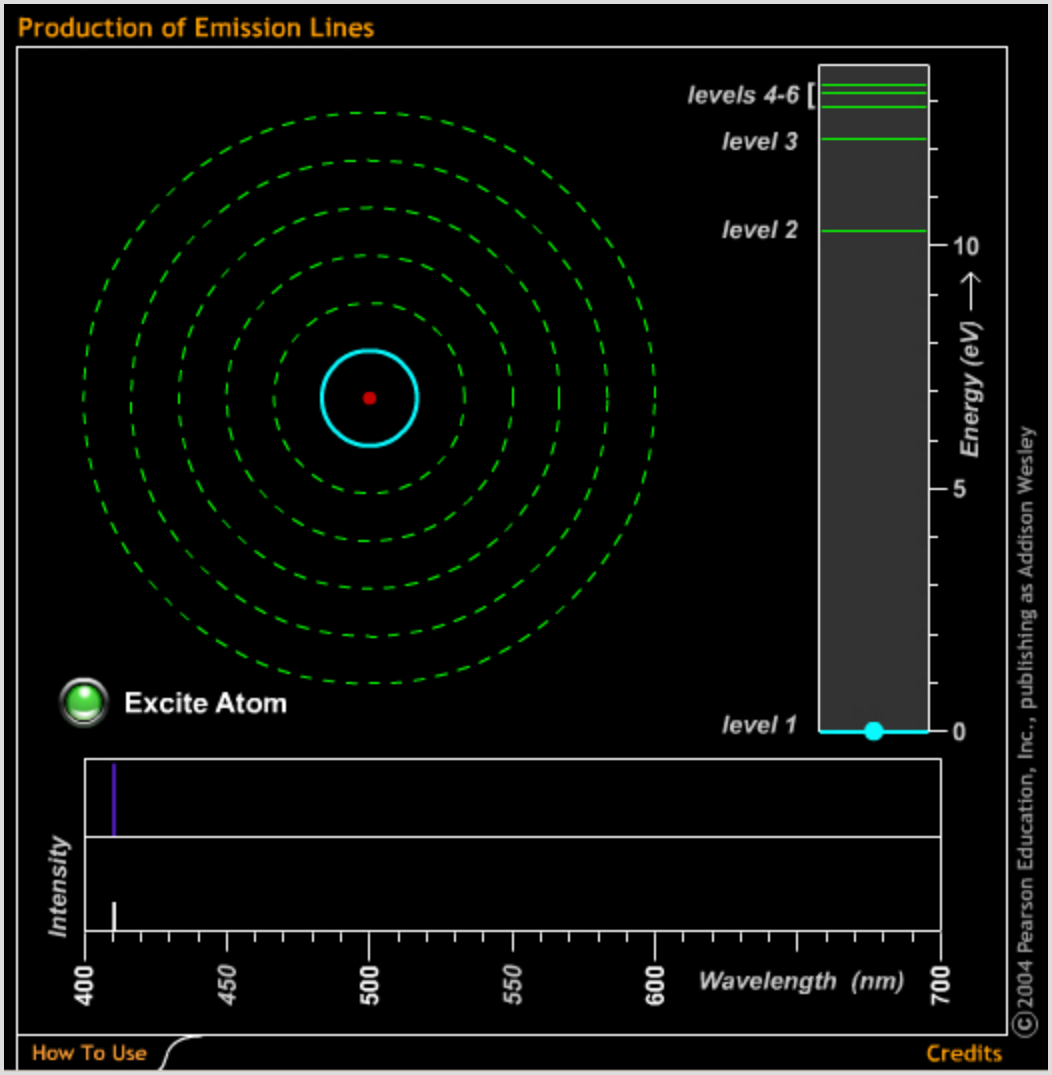


Hydrogen

- Remember that each electron is only allowed to have certain energies in an atom.
- Electrons can absorb light and gain energy or emit light when they lose energy.

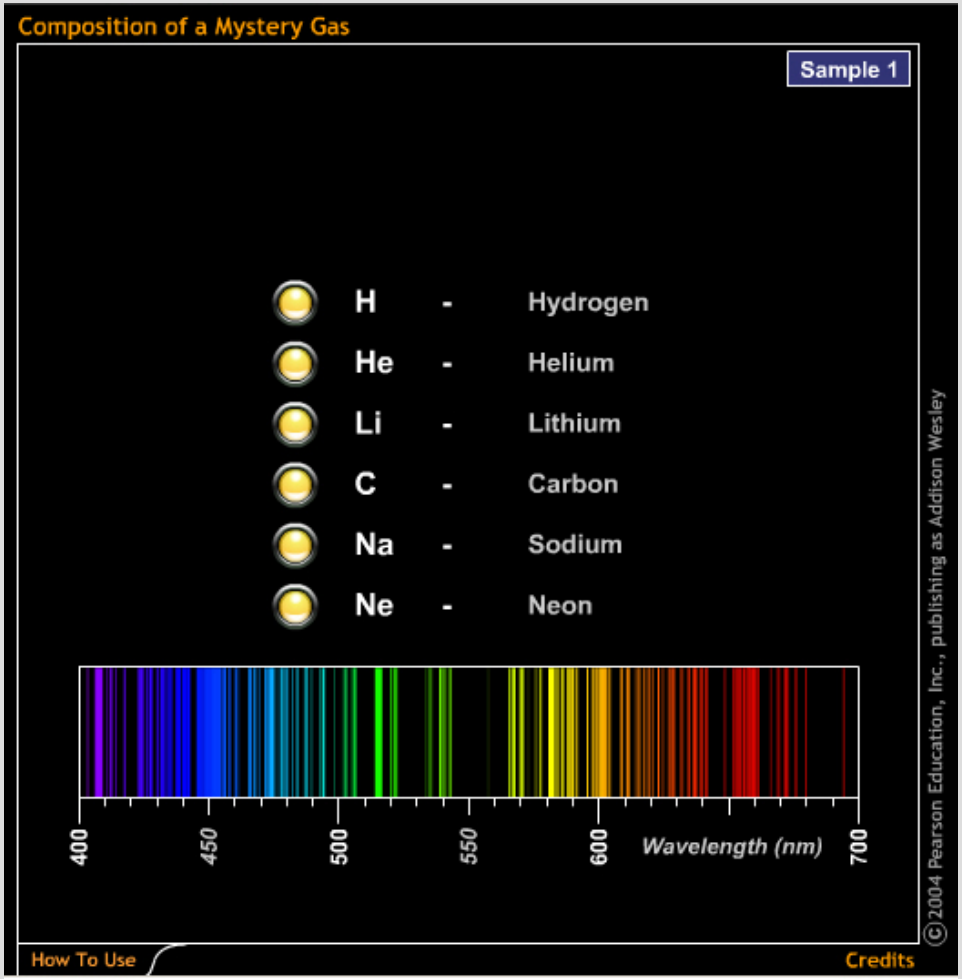
- It is easiest to think of light as a photon when discussing its interaction with matter.
- Only photons whose energies (colors) match the "jump" in electron energy levels can be emitted or absorbed.

Emission of Light

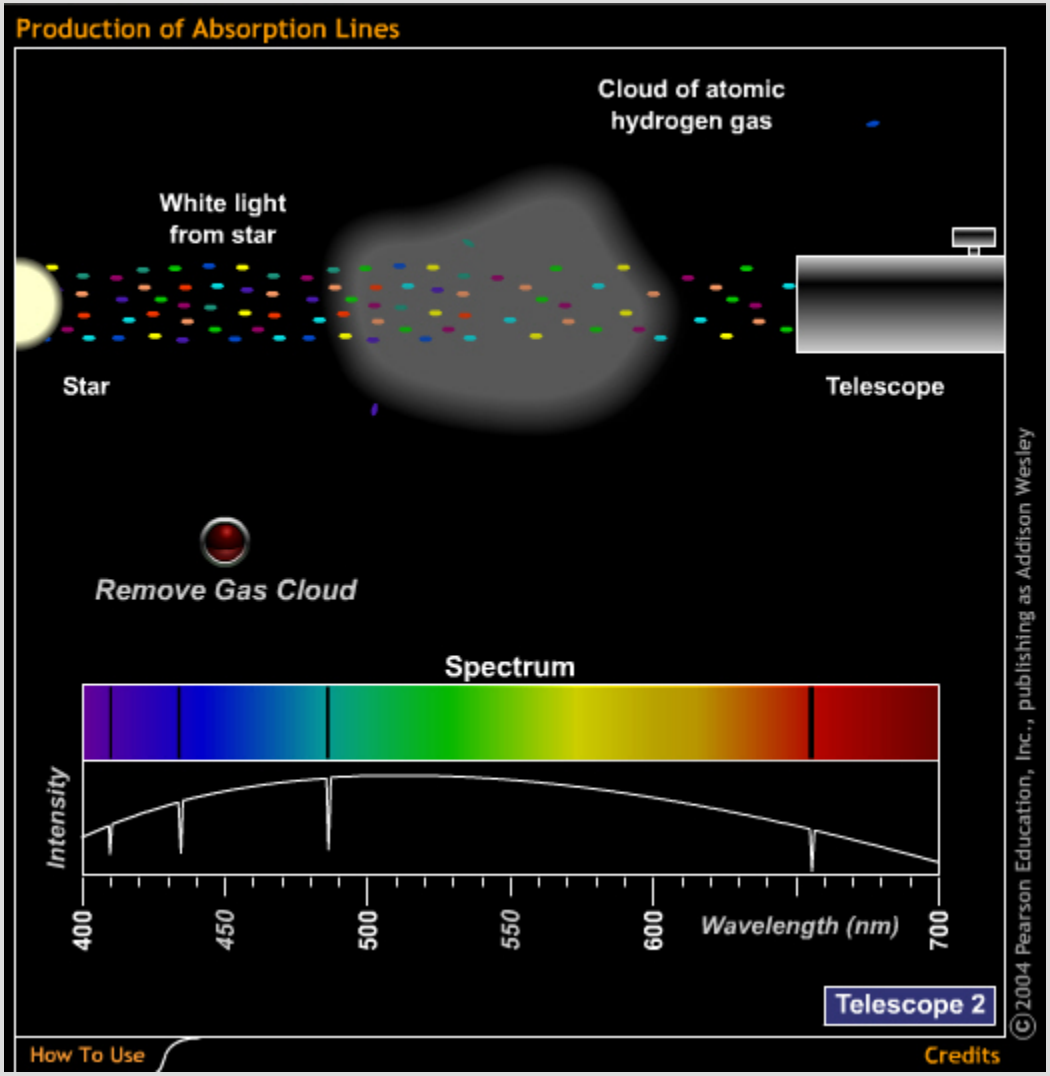


Emission Spectra

- The atoms of each element have their own distinctive set of electron energy levels.
- Each element emits its own pattern of colors, like fingerprints.
- If it is a hot gas, we see only these colors, called an **emission line spectrum**.

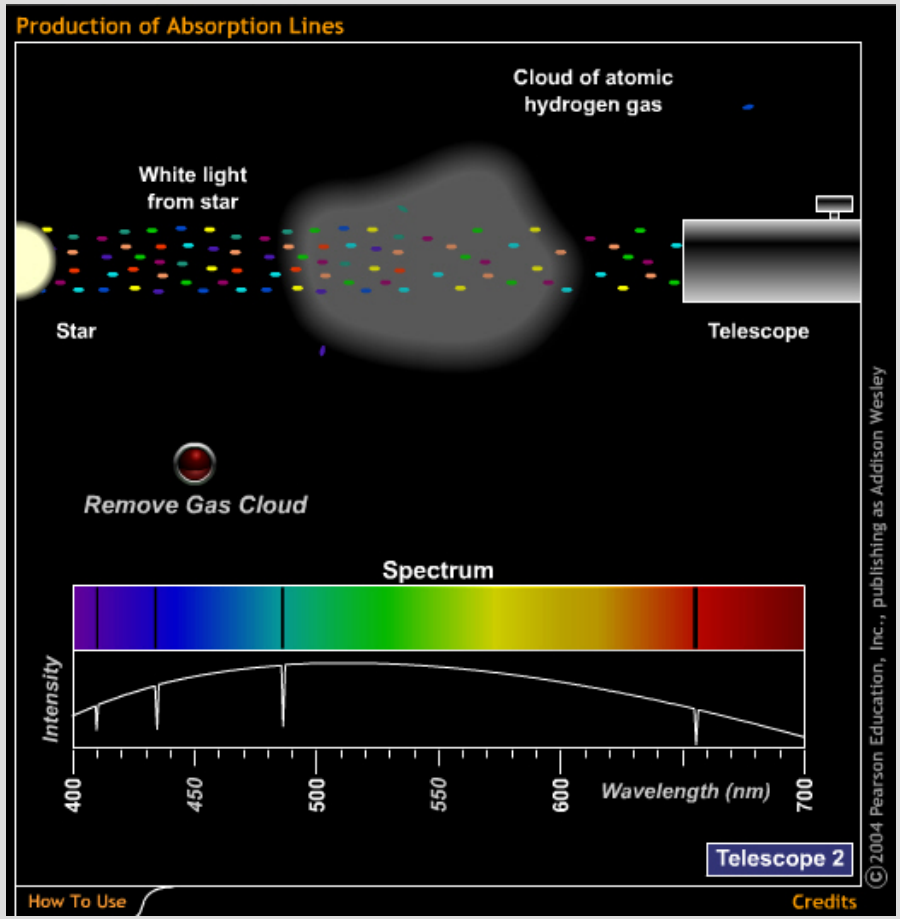


Absorption of Light



Absorption Spectra

- If light shines through a gas, each element will absorb those photons whose colors match their electron energy levels.
- The resulting **absorption line spectrum** has all colors minus those that were absorbed.

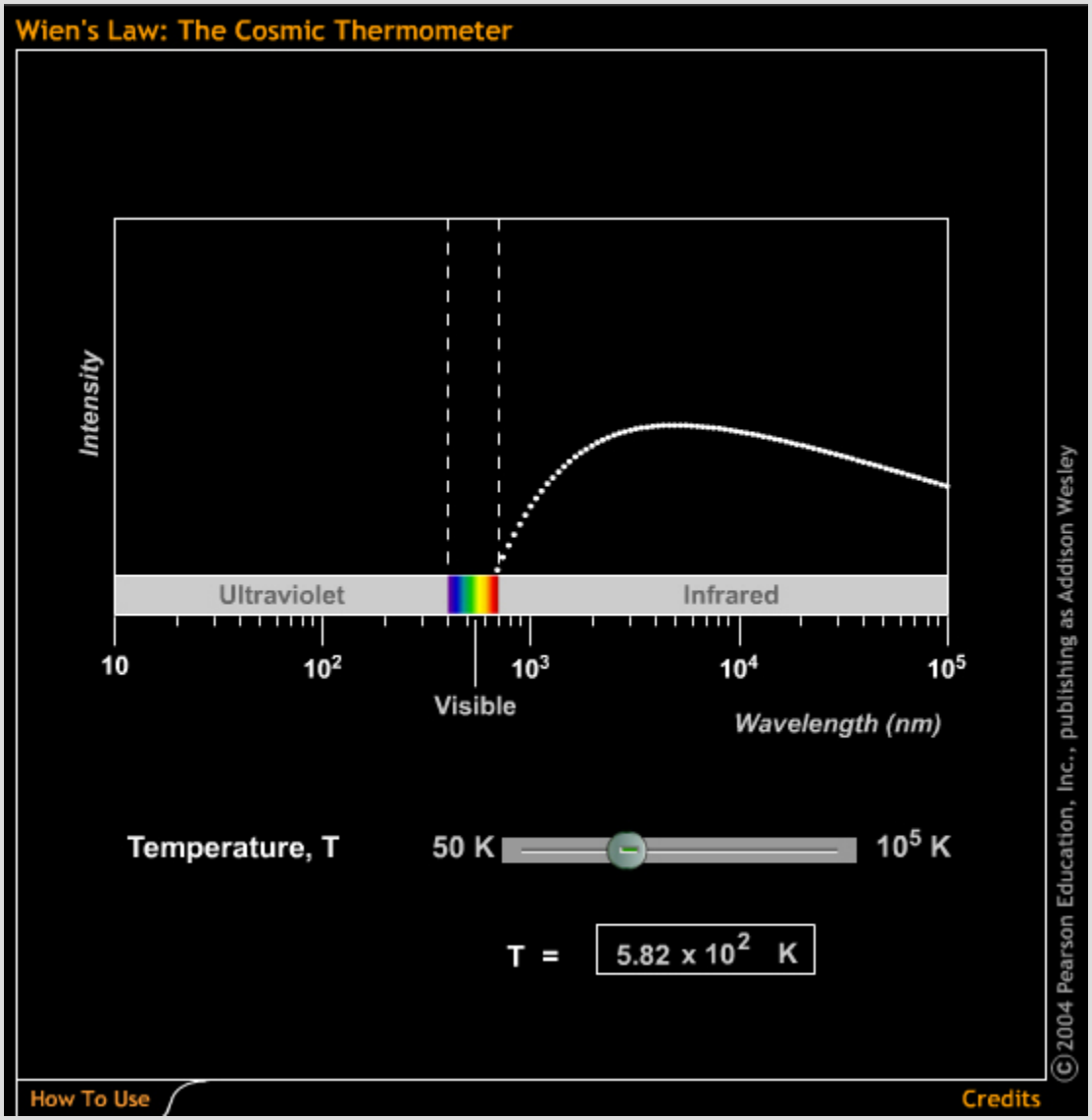


- We can determine which elements are present in an object by identifying emission & absorption lines.

Rules for Emission by Opaque Objects

1. Hotter objects emit more total radiation per unit surface area.
   - Stephan-Boltzmann Law
   - $E = \sigma T^4$
2. Hotter objects emit *bluer* photons (with a higher average energy.)
   - Wien Law
   - $\lambda_{max} = 2.9 \times 10^6 / T(K)$ [nm]

Thermal Radiation



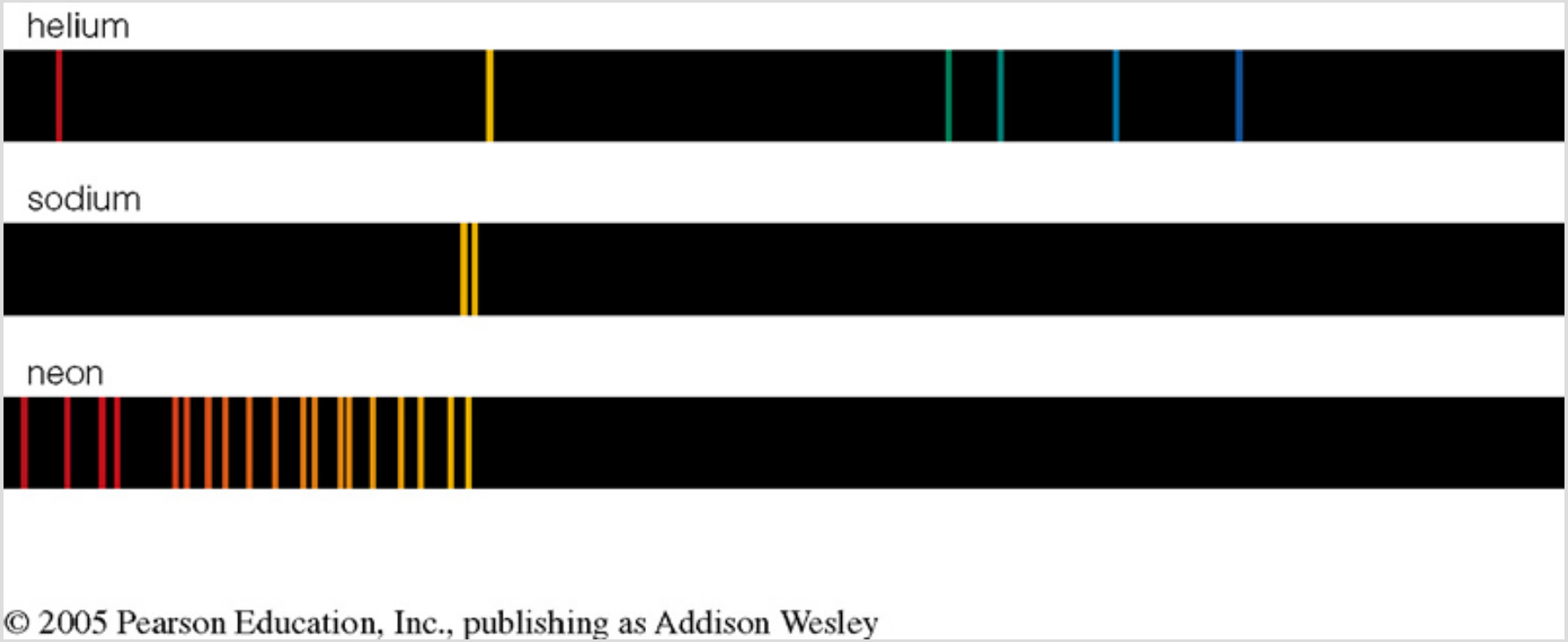
Kirchhoff's Laws

1 A hot, dense glowing object (solid or gas) emits a continuous spectrum.

Kirchhoff's Laws

2 A hot, low density gas emits light of only certain wavelengths --

⇨ an emission line spectrum.

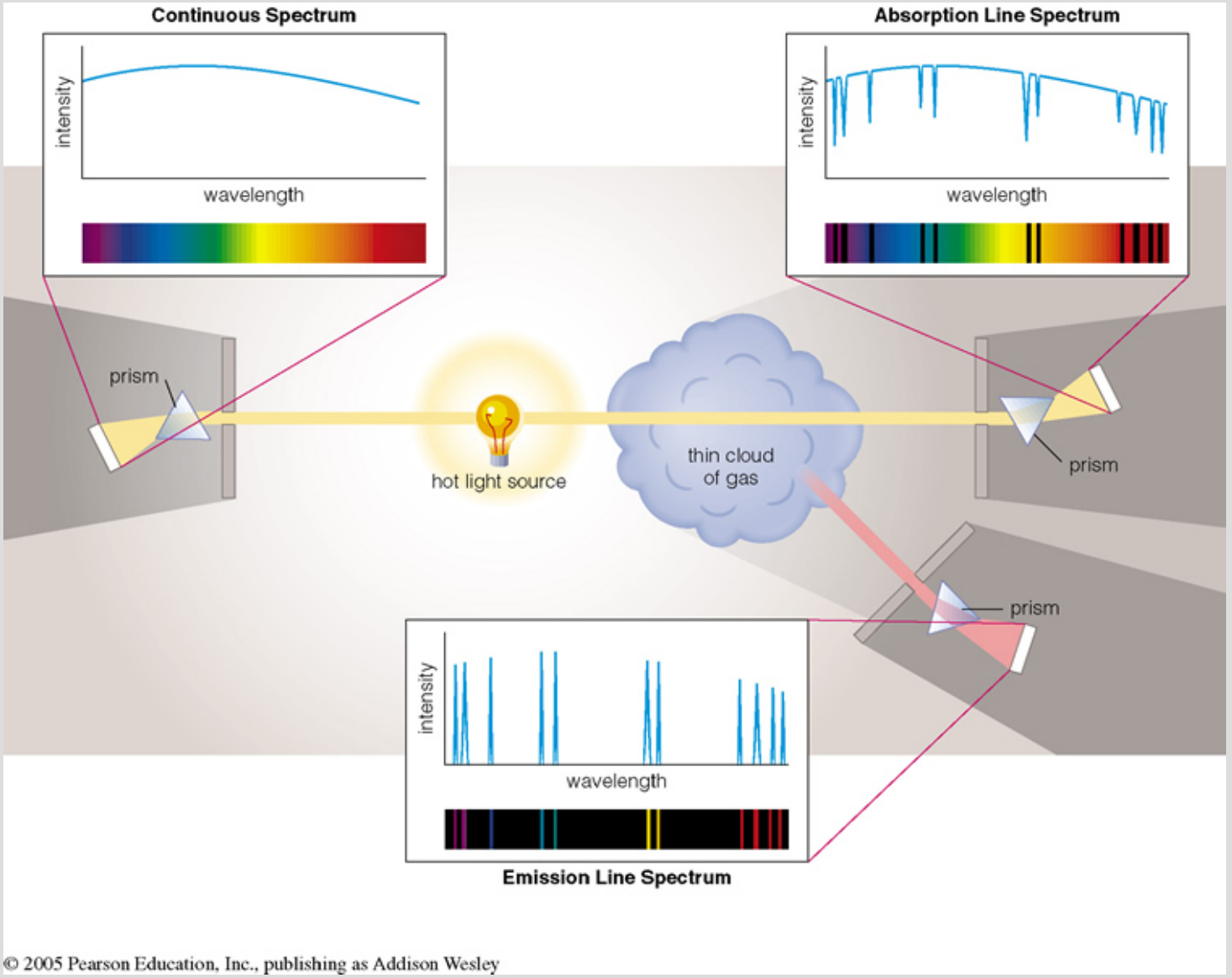


Kirchhoff's Laws

3 When light having a continuous spectrum passes through a cool gas, dark lines appear in the continuous spectrum --

⇨ an absorption line spectrum.

Kirchhoff's Laws



5.5 The Doppler Shift

Our goals for learning:

- What is a Doppler shift?
- What do we learn from a redshift or blueshift?
- How does a star's rotation affect its spectral lines?

The Doppler Effect

1. Light emitted from an object moving towards you will have its wavelength shortened.

BLUESHIFT

2. Light emitted from an object moving away from you will have its wavelength lengthened.

REDSHIFT

3. Light emitted from an object moving perpendicular to your line-of-sight will not change its wavelength.

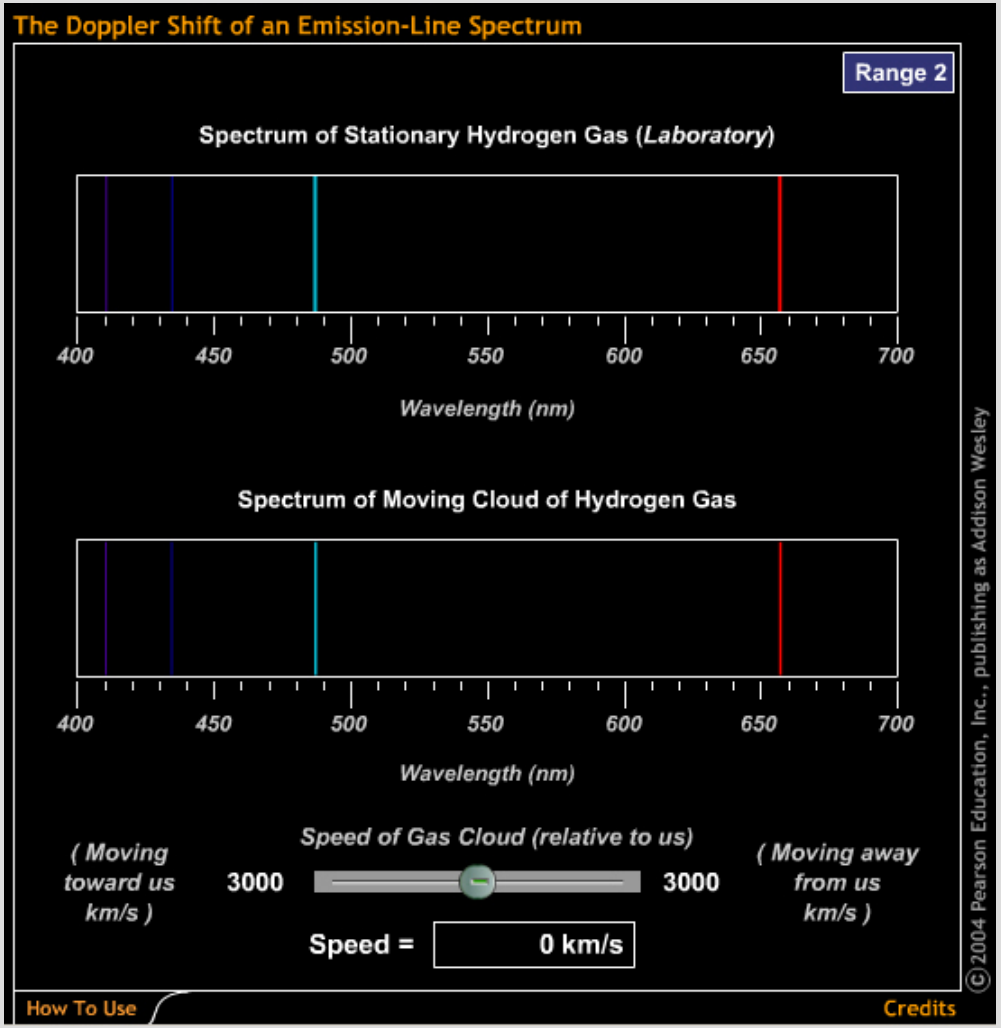
The Doppler Effect

The Doppler Effect

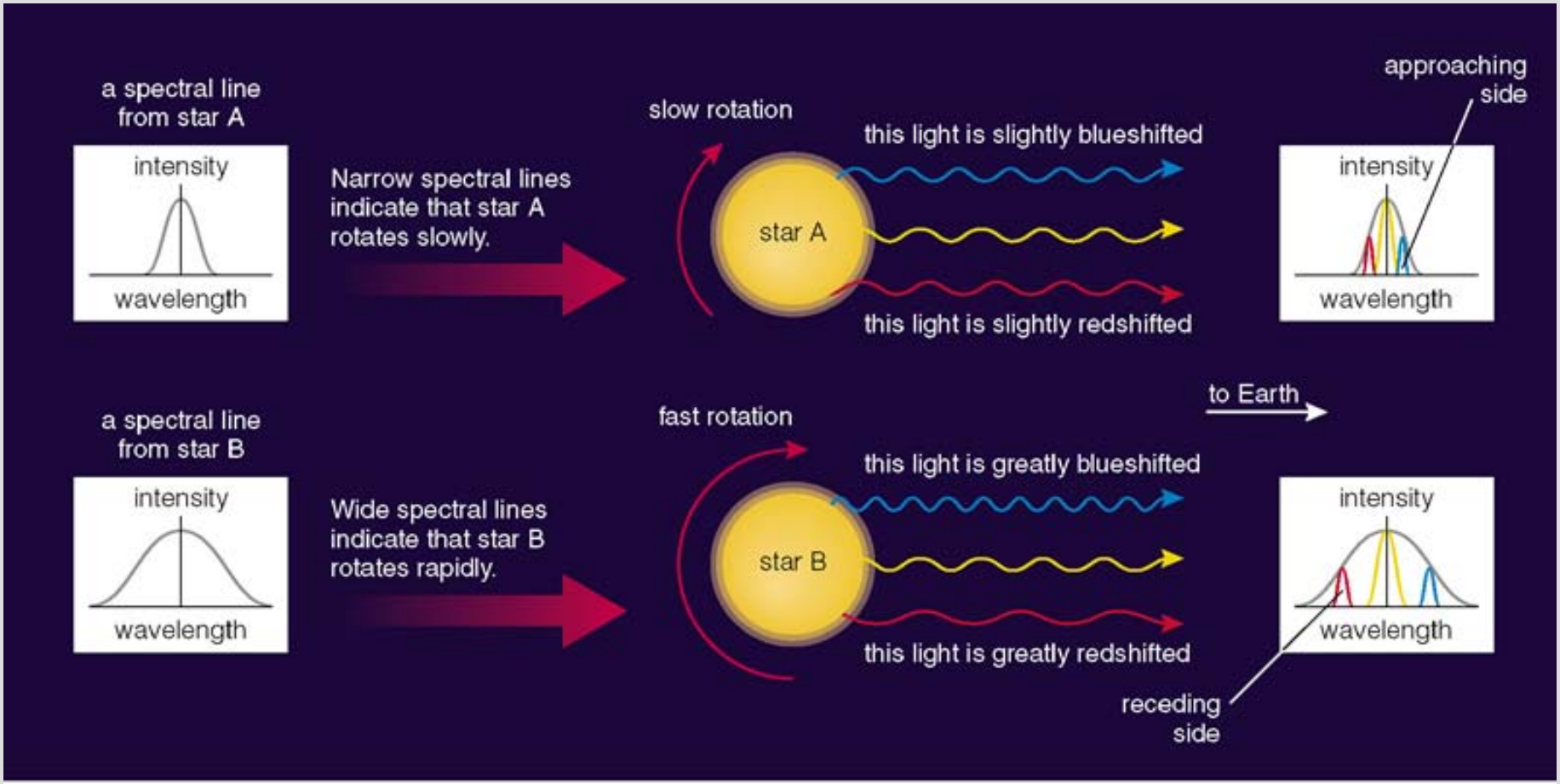
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Measuring Radial Velocity

- We can measure the Doppler shift of emission or absorption lines in the spectrum of an astronomical object.
- We can then calculate the velocity of the object in the direction either towards or away from Earth. (**radial velocity**)



Measuring Rotational Velocity



What have we learned?

- What is the difference between energy and power?
  - Power is the rate at which energy is used. The standard unit of power is 1 watt = 1 joule/s.
- What are the four ways in which light and matter can interact?
  - Matter can emit, absorb, transmit, or reflect light.
- In what way is light a wave?
  - Light is an electromagnetic wave – a wave of vibrating electric & magnetic fields – characterized by a wavelength and a frequency and traveling at the speed of light.

What have we learned?

- In what way is light made of particles?
  - Light comes in individual photons, each with a specific energy that depends on its frequency.
- How are wavelength, frequency, and energy related for photons of light?
  - Frequency increases when wavelength decreases, and vice versa. Energy is proportional to frequency.
- List the various forms of light that make up the electromagnetic spectrum.
  - In order of increasing frequency (energy), the forms of light are: radio, infrared, visible light, ultraviolet, X-rays, and gamma-rays.

What have we learned?

- How can we use emission or absorption lines to determine the composition of a distant object?
  - Emission or absorption lines occur only at specific wavelengths corresponding to particular energy level transitions in atoms or molecules. Each chemical element has a unique spectral signature consisting of a particular set of emission or absorption lines.
- Are there any material objects that don't give off any light?
  - No. All objects radiate light by virtue of their temperatures. This light is called thermal radiation.

What have we learned?

- What are the two rules of thermal radiation?
  - (1) Hotter objects emit more total radiation per unit area. (2) Hotter objects emit photons with a higher average energy.
- What is a Doppler shift?
  - It is a shift in the wavelength of an object's light caused by its motion toward or away from us.

What have we learned?

- What do we learn from a redshift or blueshift?
  - It tells us how fast the object is moving away from us (redshift) or toward us (blueshift). The Doppler shift does not tell us about motion across our line of sight.
- How does a star's rotation affect its spectral lines?
  - Because of Doppler shifts, faster rotating stars have broader spectral lines.