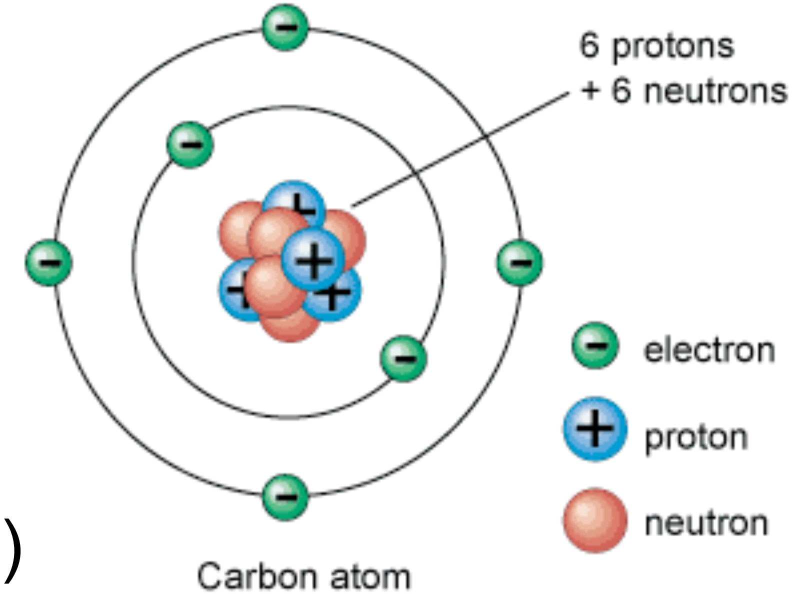
From Last Time

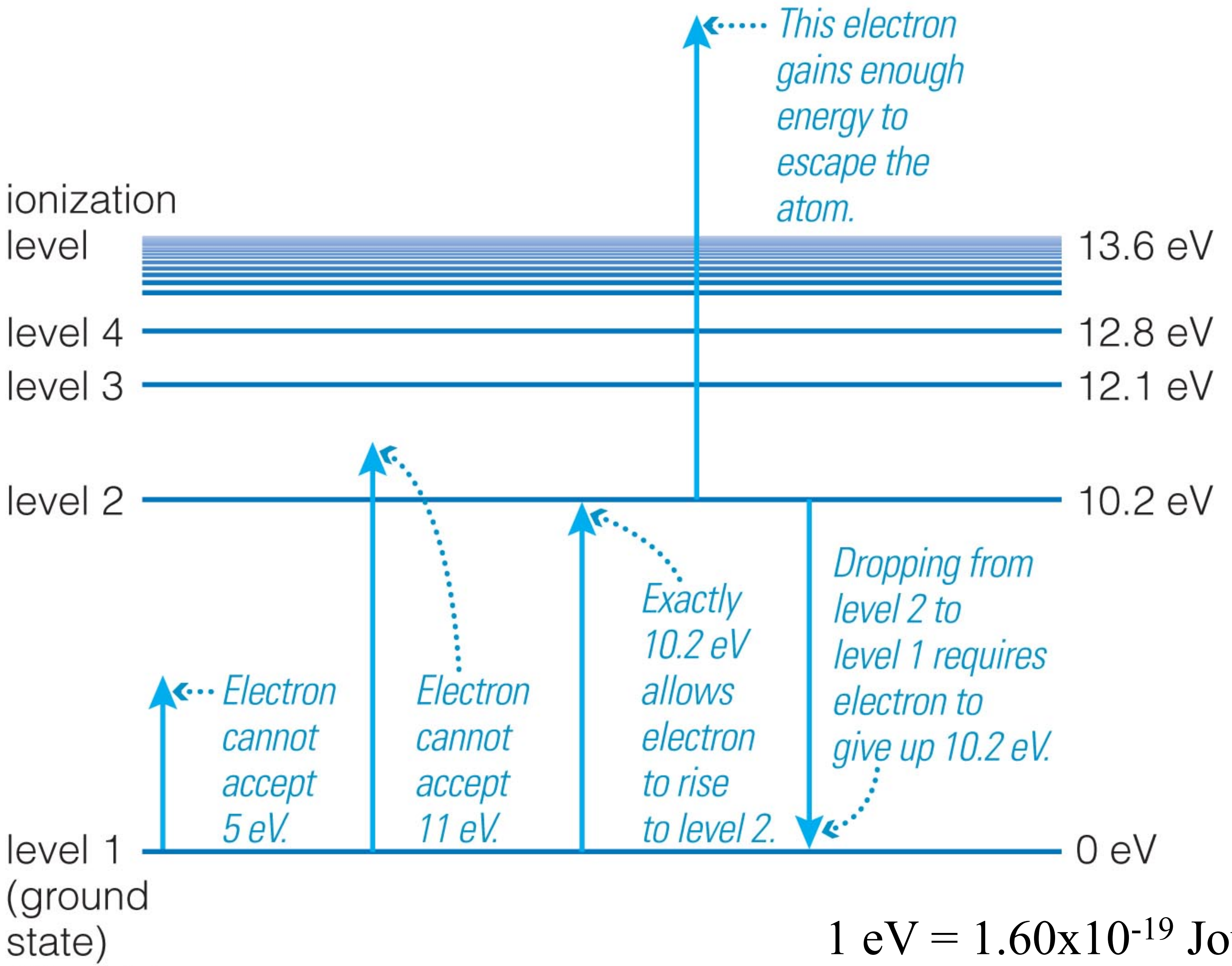
- **Light:** Absorption, Emission, Transmission, Reflection, and Scattering
- $c = \lambda \times f$
- $E = h \times f$
- "Light" (electromagnetic radiation) extends from gamma rays (high E, high f, small λ) to radio waves (small E, small f, large λ)

From Last Time



- Atoms are made up of:
  - Protons (+ charge, in nucleus)
  - Neutrons (no charge, in nucleus)
  - Electrons (- charge, orbits the nucleus)
- Molecules are made up of 2 or more atoms
  - O_2, H_2O, NH_3
- Temperature (mostly) and pressure dictate what phases are stable (solid, liquid, gas, plasma)

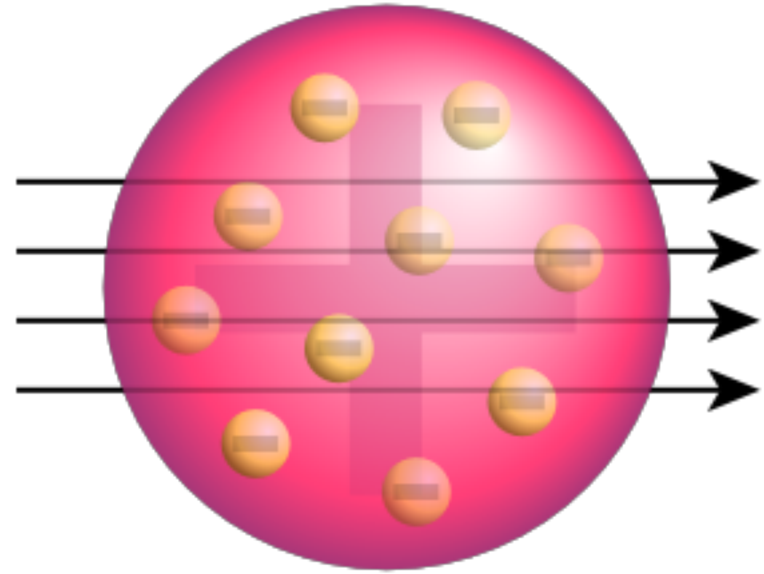
Energy Levels in the Hydrogen Atom



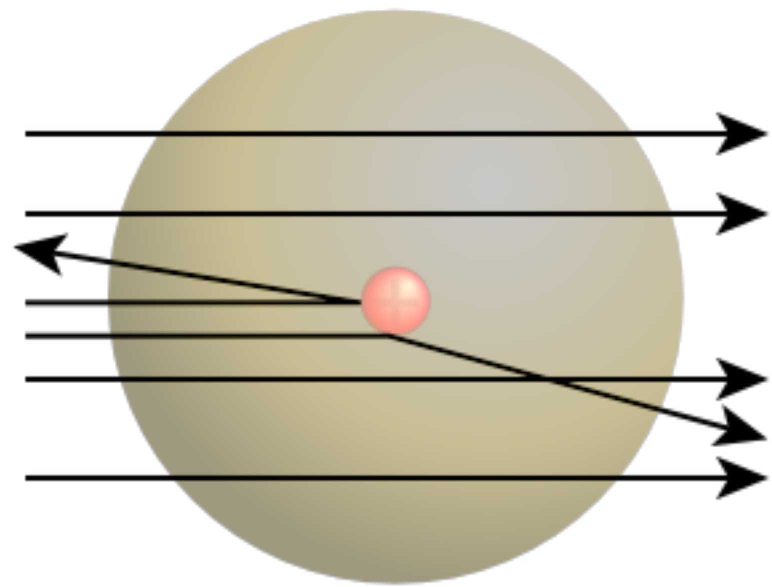
1 eV = 1.60×10^{-19} Joules

Models of the Atom, around 1910

- "Plum Pudding"
  - The prevailing view
  - An atom was a "pudding" of positive charge with electrons (negatively charges) embedding throughout



- Ernest Ruthorford realized that you could test this by bombarding a thin sheet of atoms with fast-moving positively charged particles



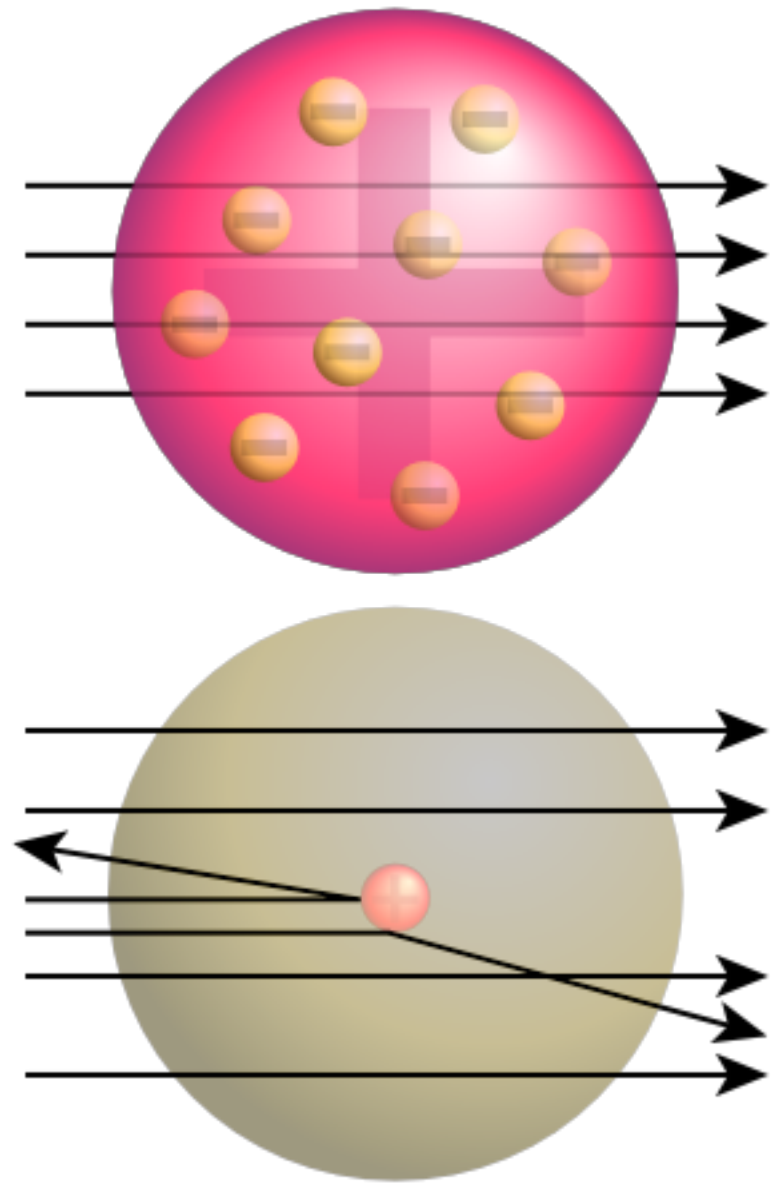
- If the particles pass right through, perhaps slowing down slightly, or being slightly deflected, the "Plum Pudding" model would be validated

- A tiny fraction bounced back

Models of the Atom, around 1910

It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you. On consideration, I realized that this scattering backward must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. It was then that I had the idea of an atom with a minute massive center, carrying a charge.

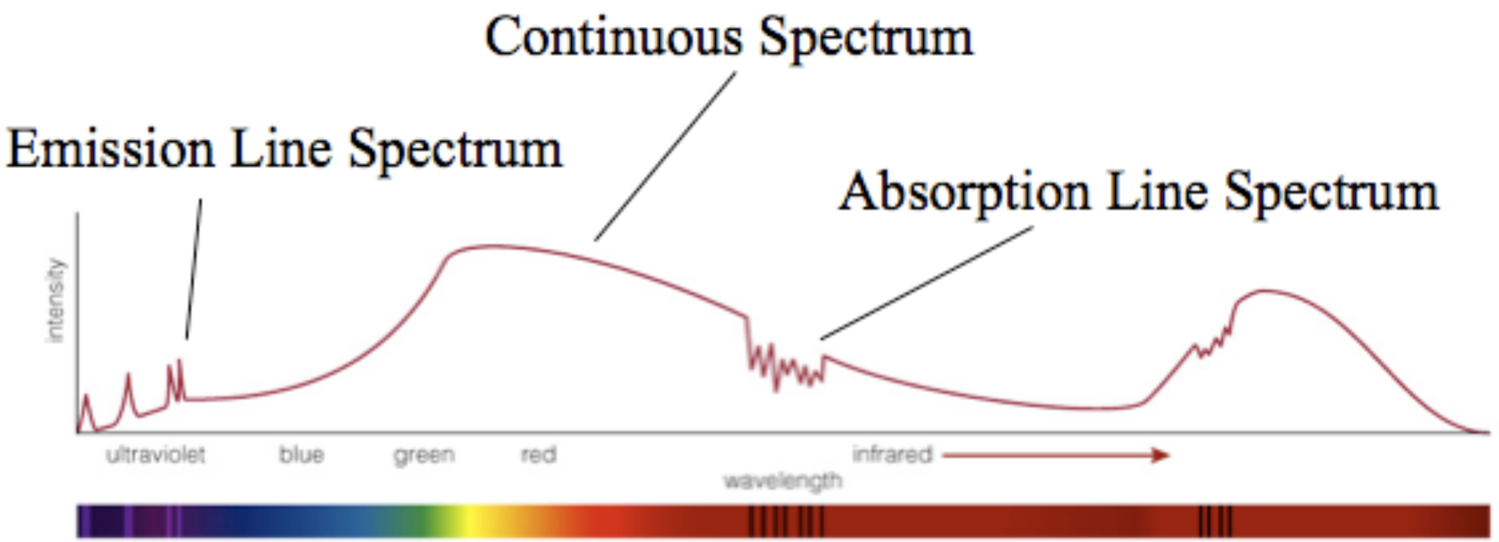
—Ernest Rutherford



5.4 Learning from Light

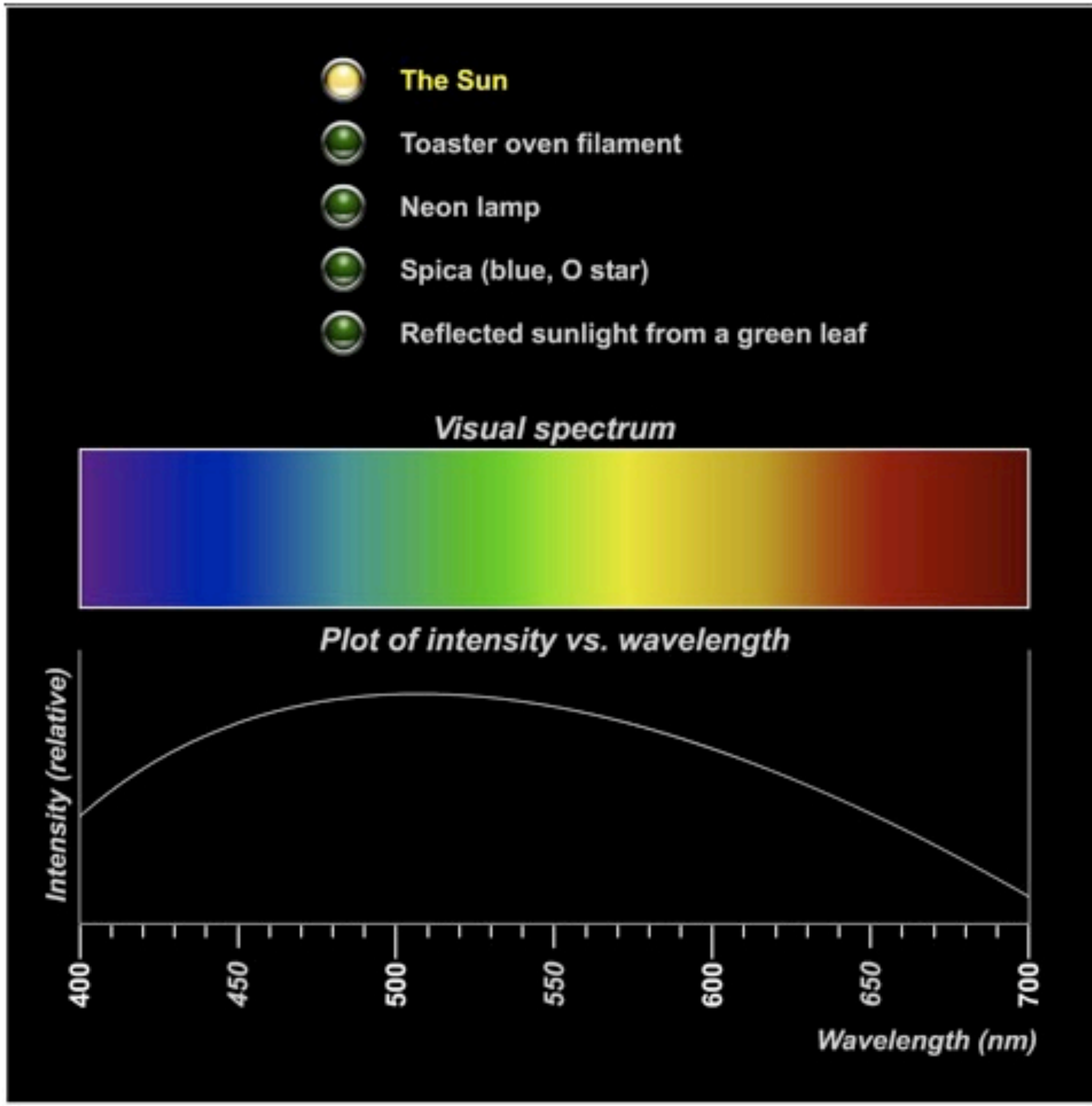
- Our goals for learning:
  - **What are the three basic types of spectra?**
  - **How does light tell us what things are made of?**
  - **How does light tell us the temperatures of planets and stars?**
  - **How does light tell us the speed of a distant object?**

What are the three basic types of spectra?

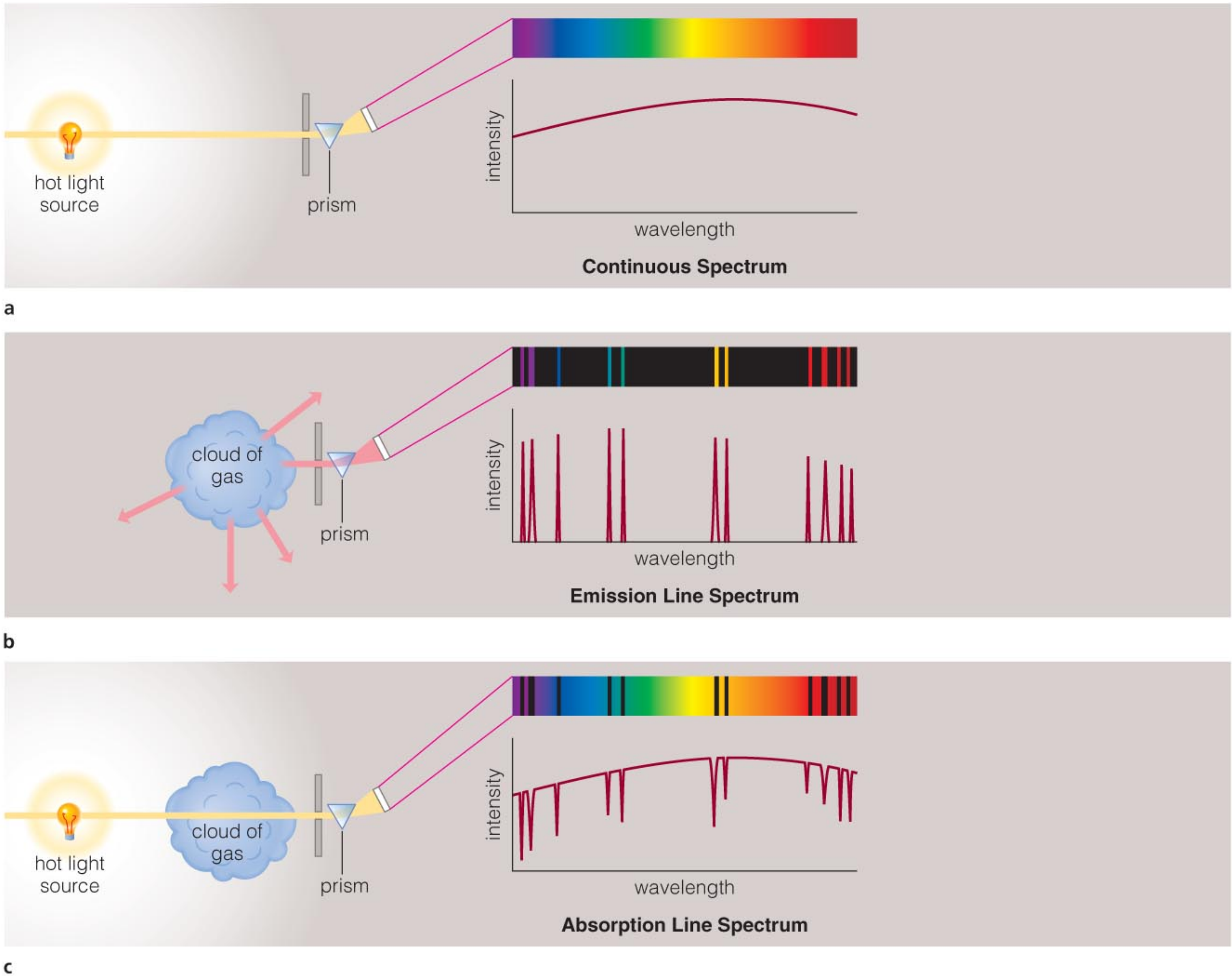


- Spectra of astrophysical objects are usually combinations of these three basic types.

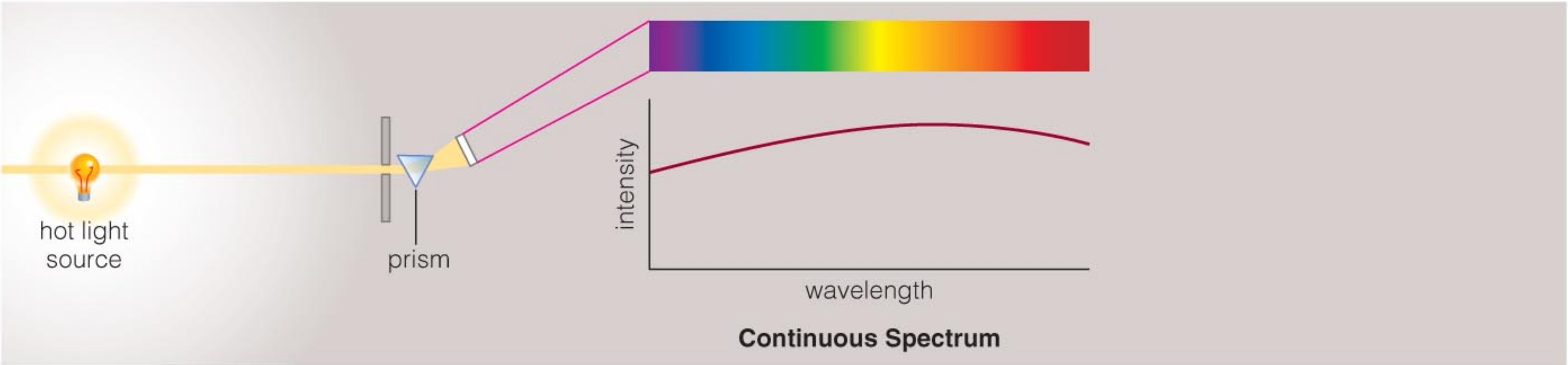
What are the three basic types of spectra?



Three Types of Spectra

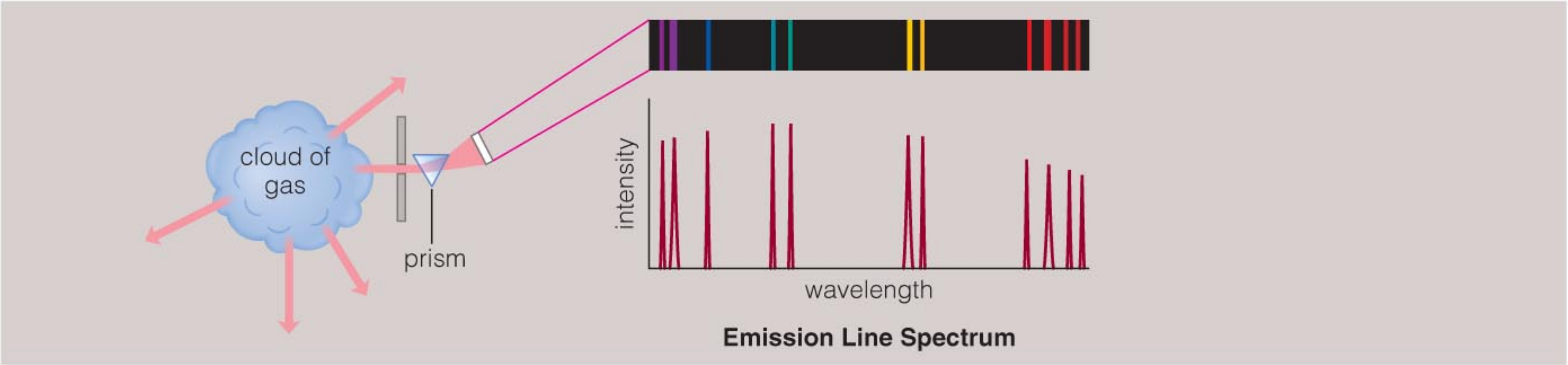


Continuous Spectrum



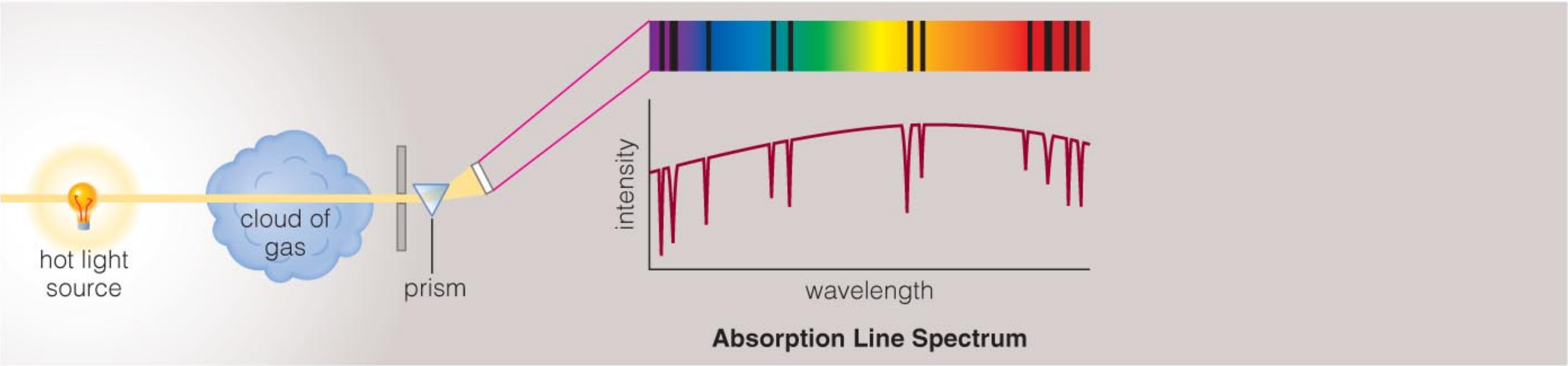
- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption.

Emission Line Spectrum



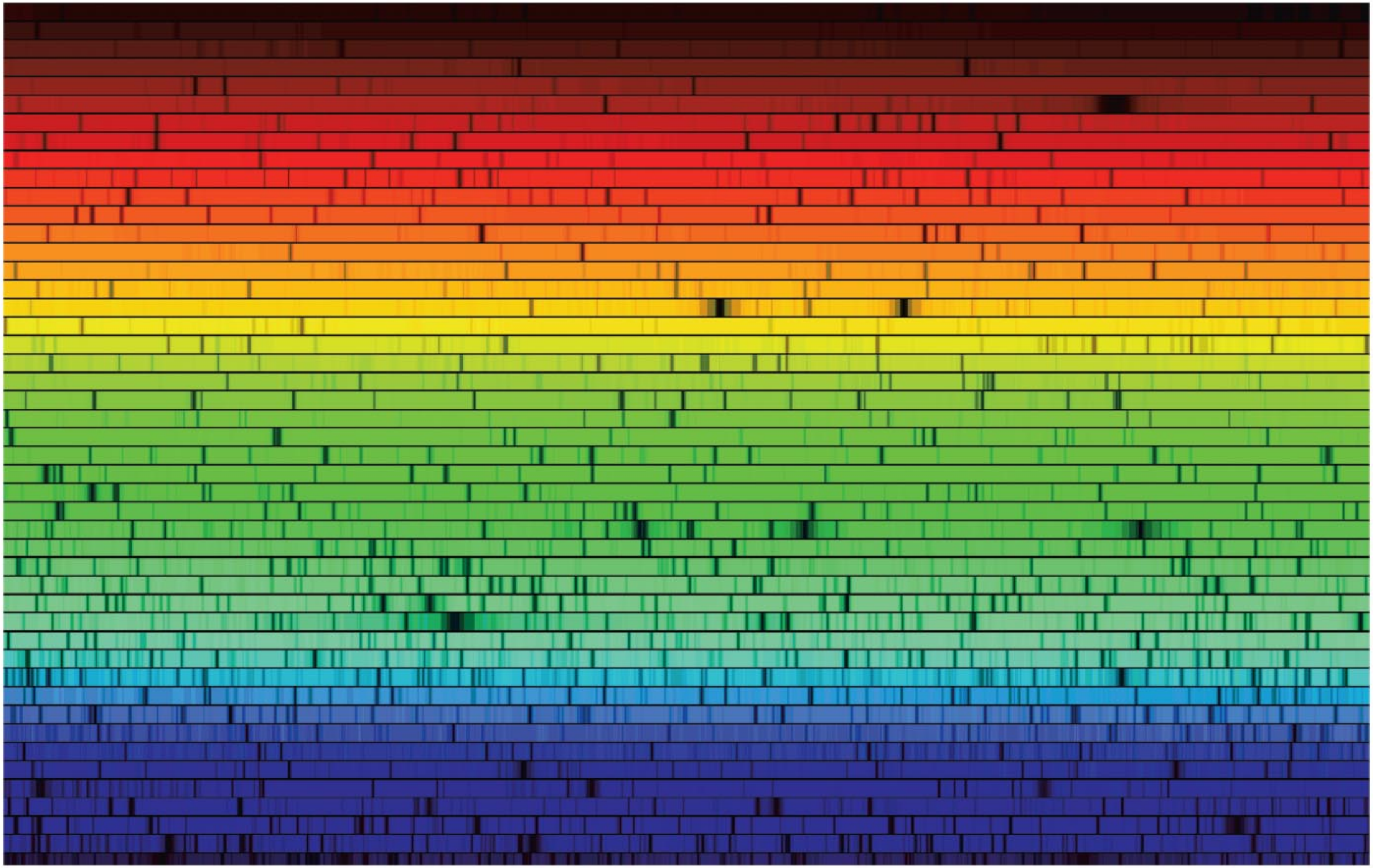
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines.

Absorption Line Spectrum

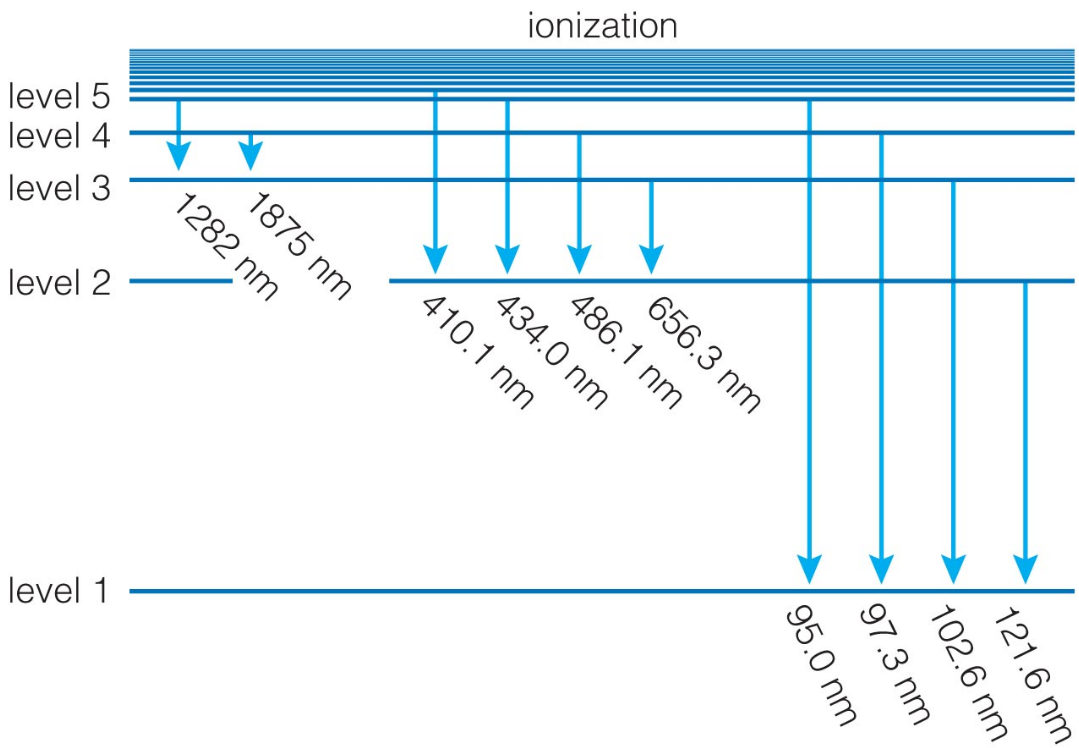


- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.

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 a unique photon 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

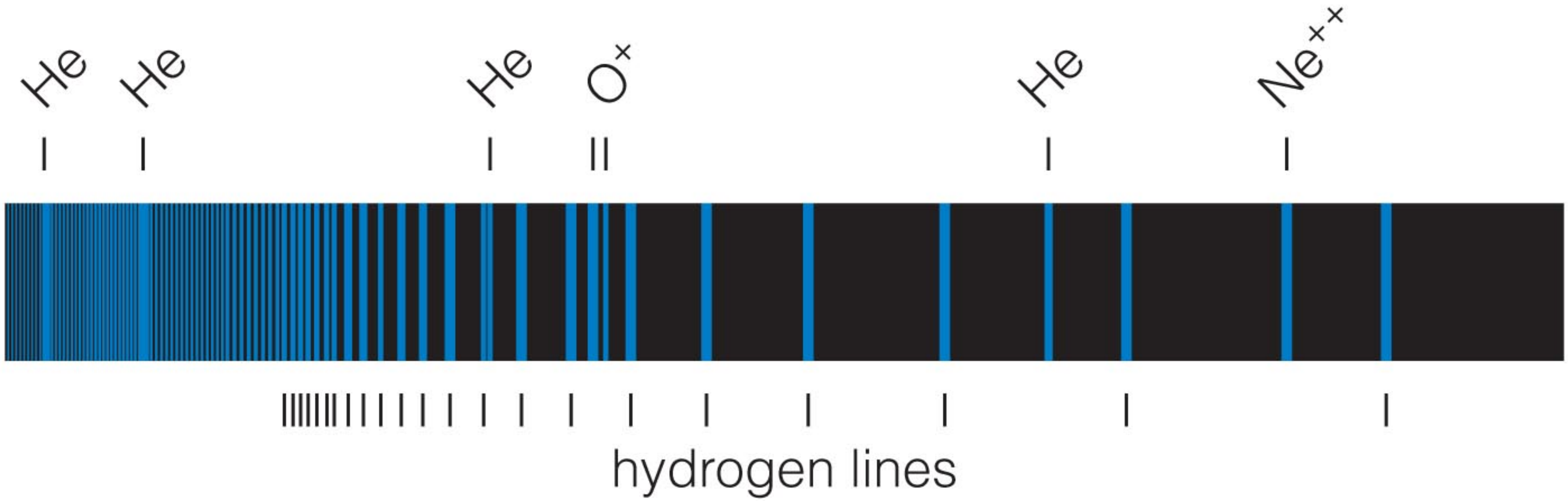
- Because those atoms can absorb photons with those same energies, upward transitions produce a pattern of absorption lines at the same wavelengths.

c This spectrum shows absorption lines produced by upward transitions between level 2 and higher levels in hydrogen.

Chemical Fingerprints

- Each type of atom has a unique spectral fingerprint.

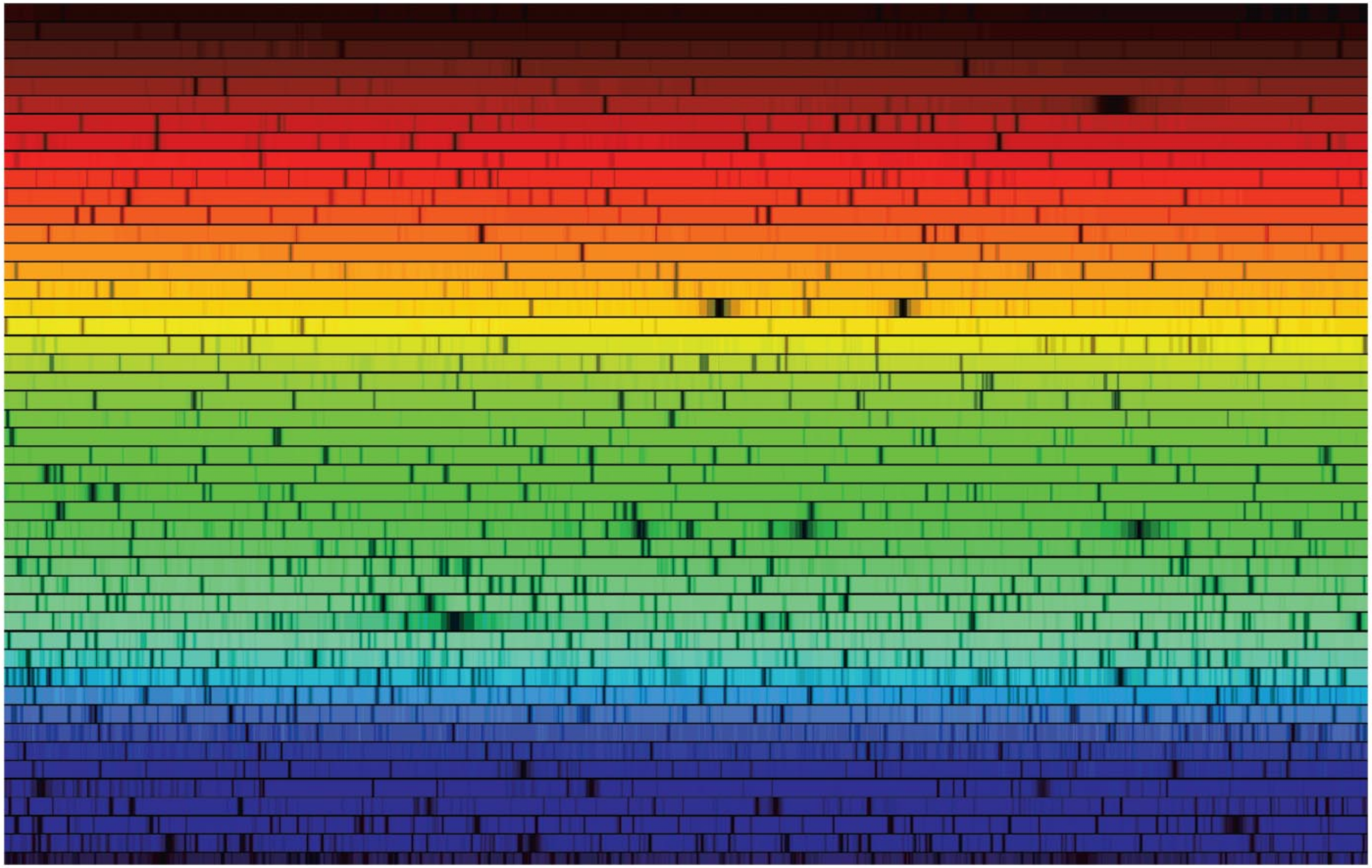
Chemical Fingerprints



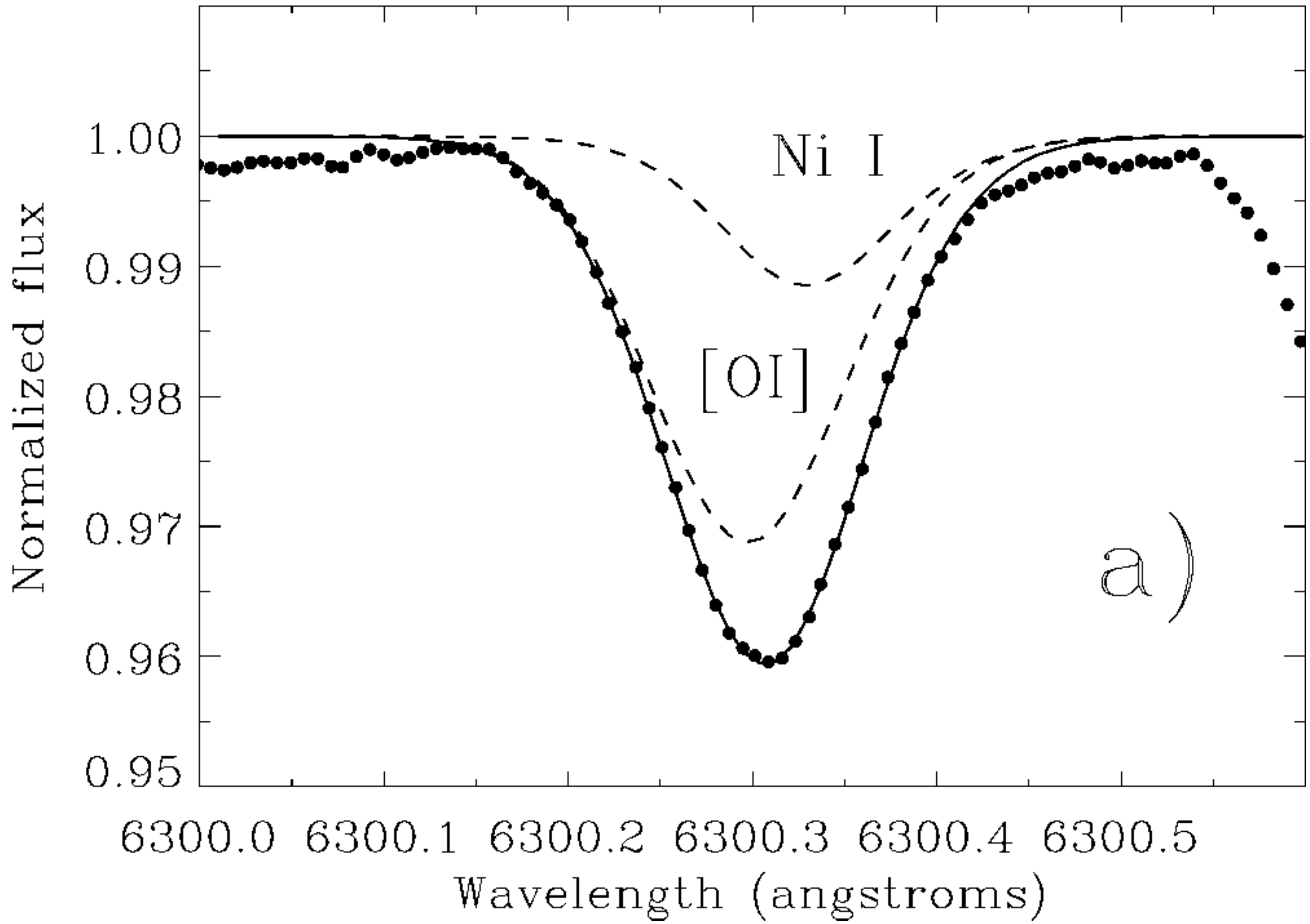
- Observing the fingerprints in a spectrum tells us which kinds of atoms are present.

Chemical Fingerprints

Example: Solar Spectrum



Oxygen in the Sun, 2001



For decades people overestimated the abundance of oxygen in the Sun by 30%, because the absorption line they used was actually a blend of an oxygen line and a nickel line. Whoops!

When an electron in an atom jumps from a high-energy level to a lower-energy one, what happens?

- a photon of light is emitted
- a photon of light is absorbed
- the atom's temperature changes
- the atom changes color
- none of the above

When an electron in an atom jumps from a high-energy orbital to a lower-energy one, what happens?

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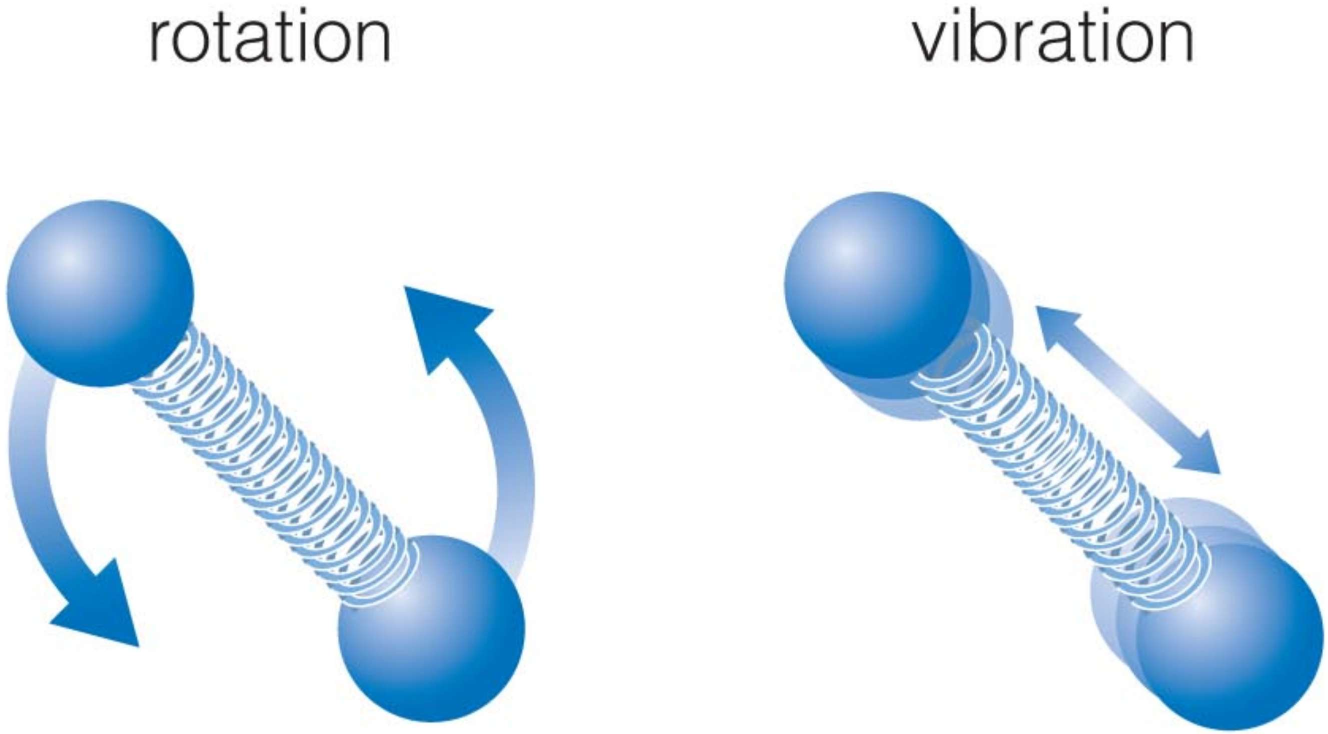
Energy Levels of Molecules



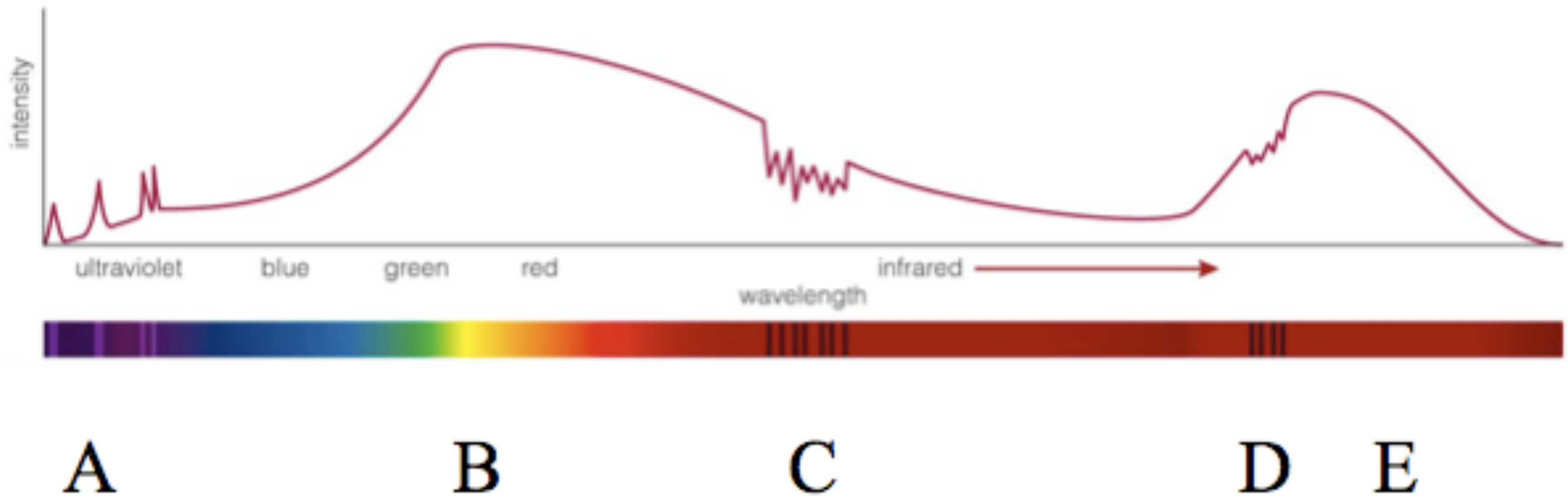
- Molecules have additional energy levels because they can vibrate and rotate.

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?



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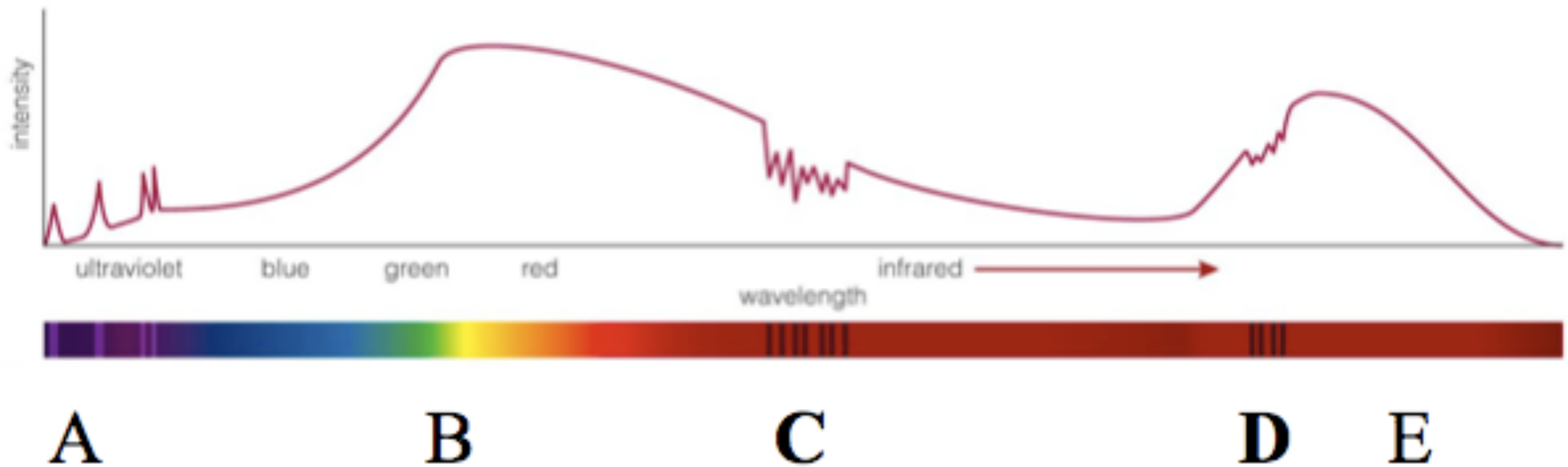
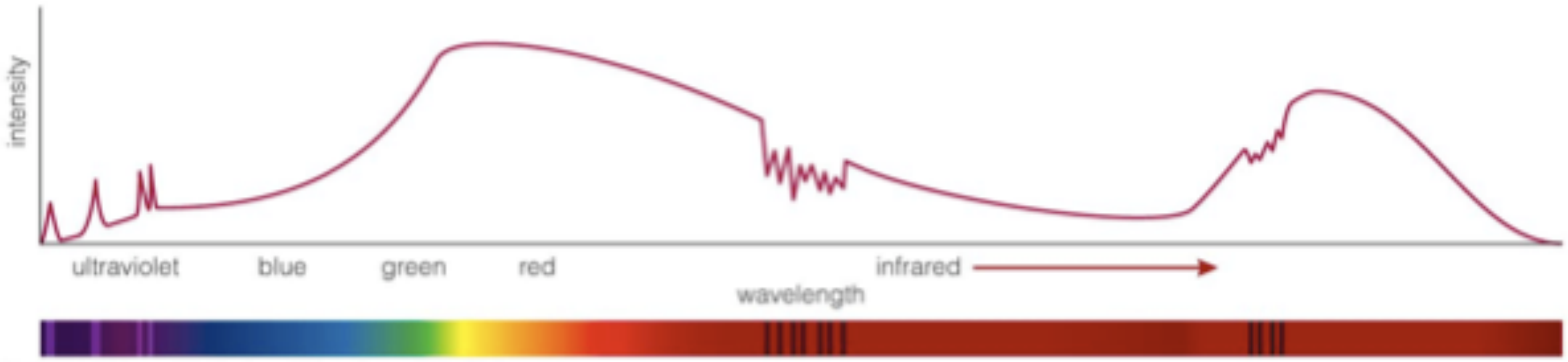


Thought Question

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



A B C D E

Thought Question

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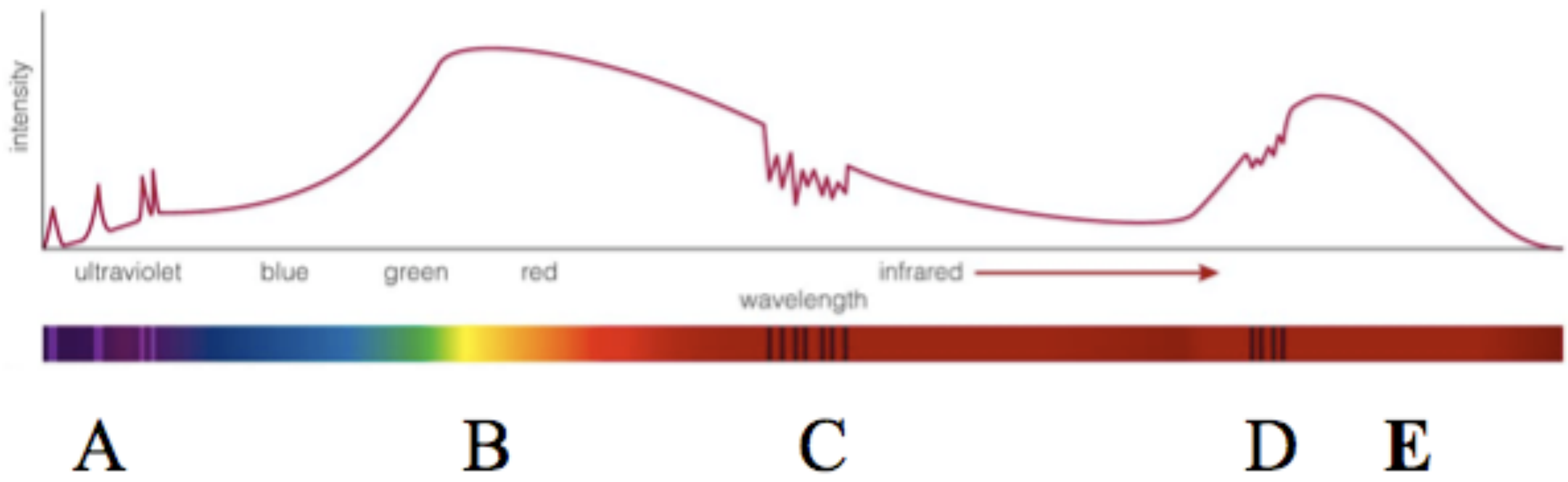
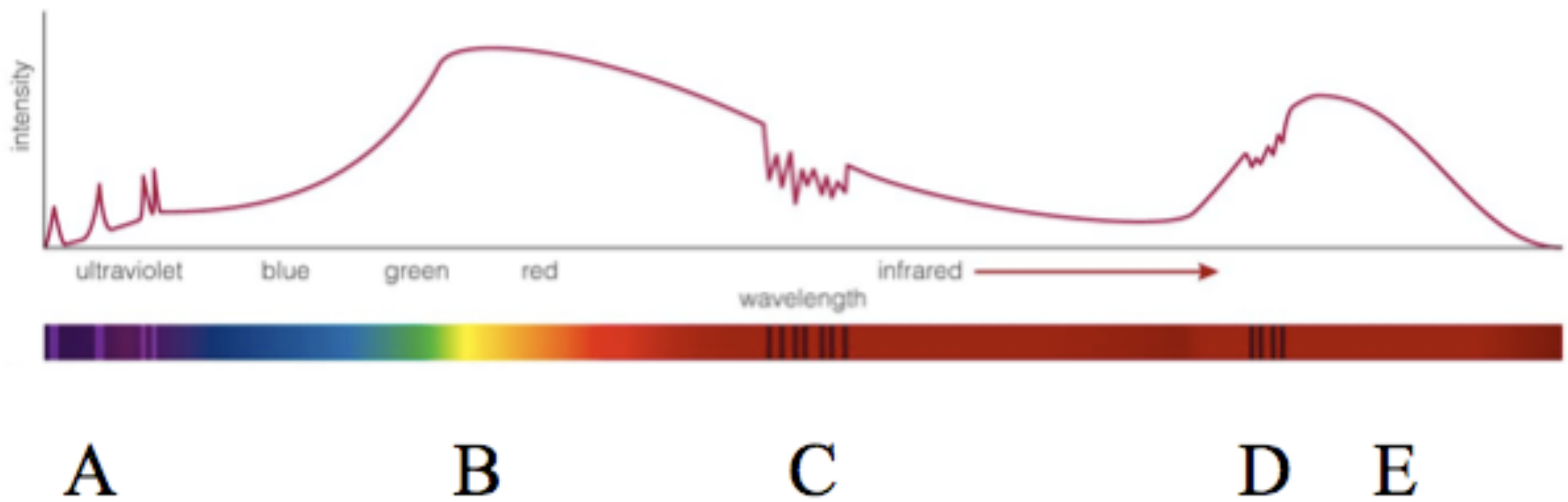


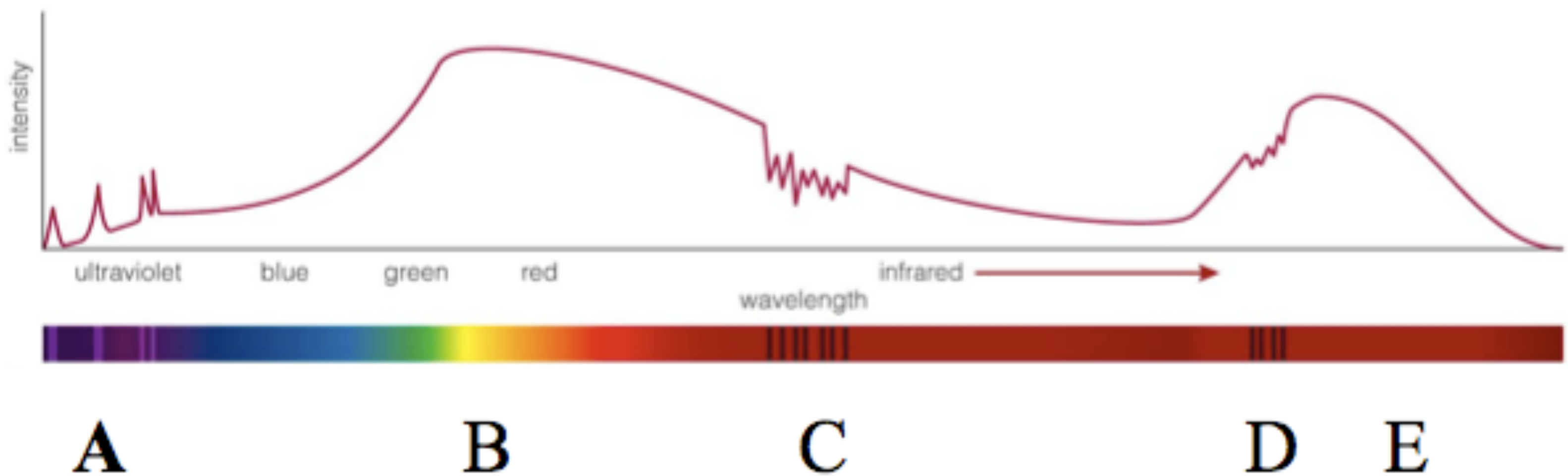
Thought Question

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

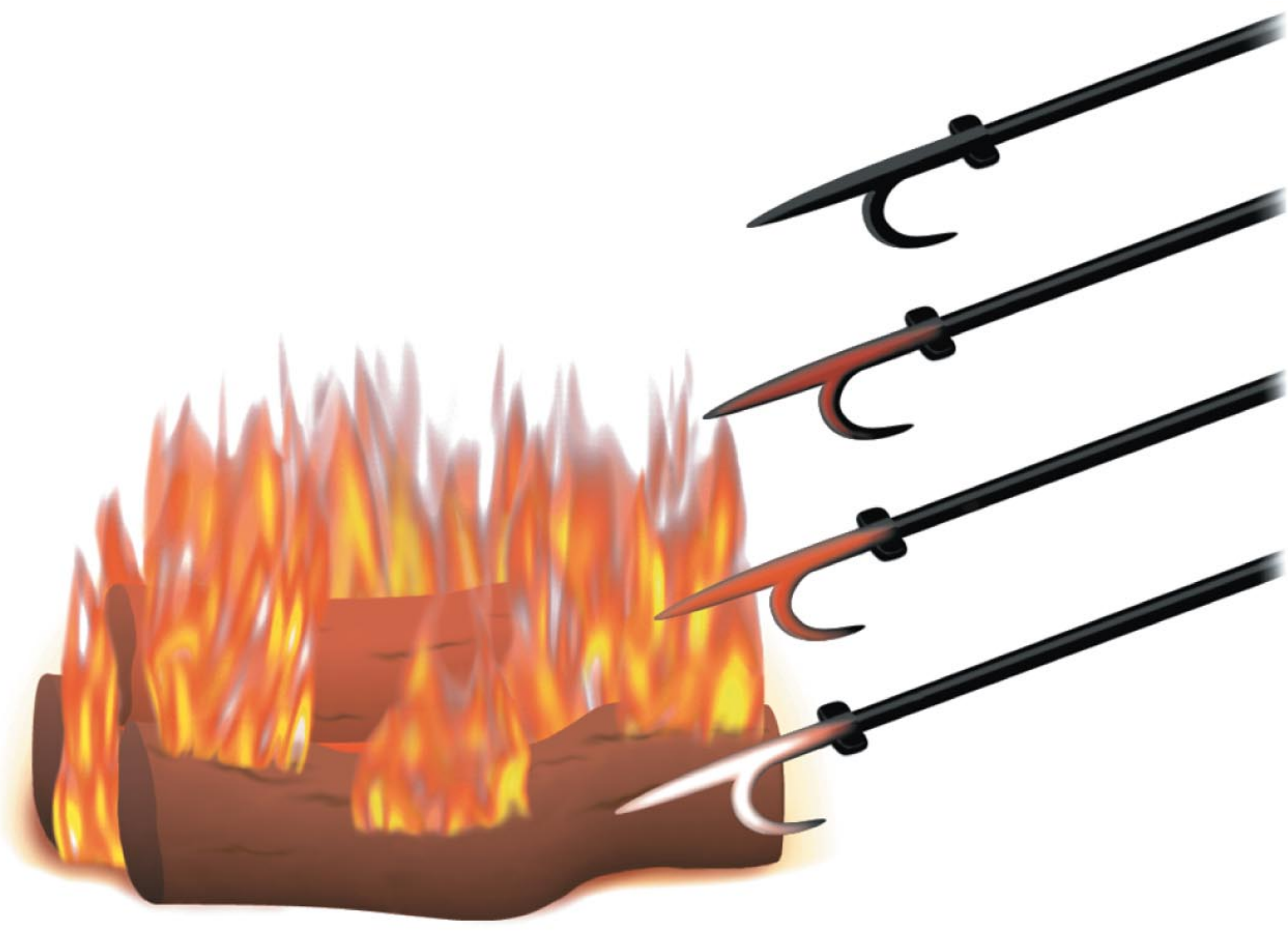


Thought Question

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



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



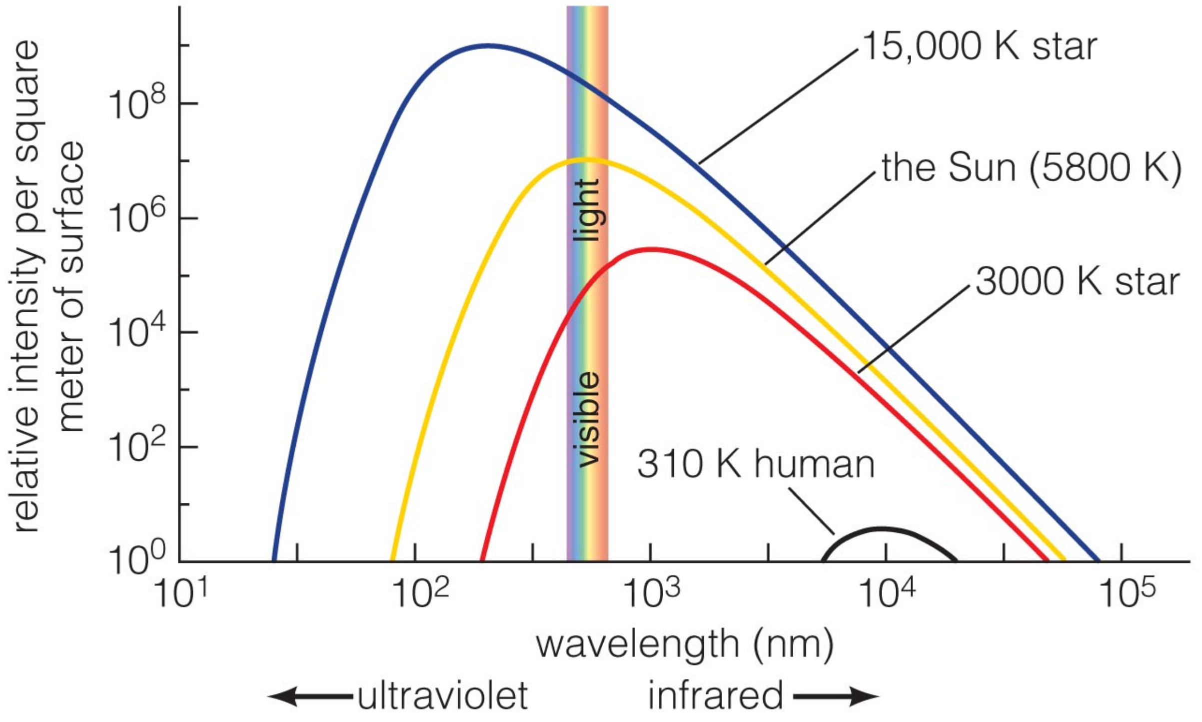
Thermal Radiation

- 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

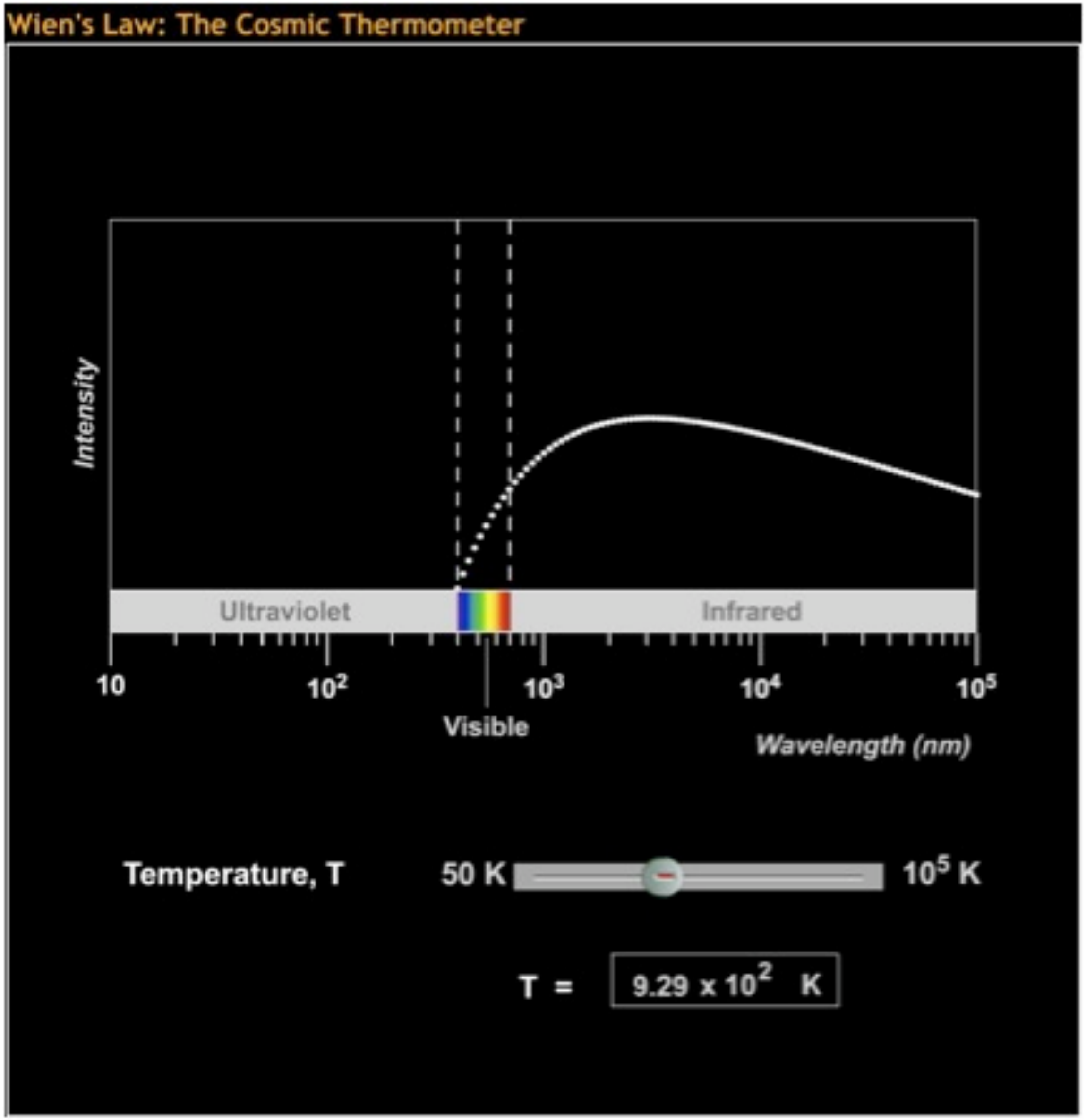
1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.



Two Laws for Thermal Radiation

- **Stefan-Boltzman law**
  - Emitted power (watt/m^2), $E = \sigma T^4$
  - $\sigma = 5.67 \times 10^{-8}$ watt/m^2/K^4
  - Amount of energy emitted is a very strong function of temperature
- **Wien's law**
  - λ_{max} = peak wavelength = 2,900,000/T nm
    - T is in Kelvin
    - At T increases, λ_{max} goes to shorter wavelengths

Wien's Law



Wien's Law: The Cosmic Thermometer
Intensity
Ultraviolet
Infrared
10
10²
10³
10⁴
10⁵
Visible
Wavelength (nm)
Temperature, T
50 K
10⁵ K
T =
9.29 x 10² K

Clicker: What happens to thermal radiation (a continuous spectrum) if you make the source hotter?

- It produces more energy at all wavelengths.
- The *peak* of the spectrum shifts redward.
- The *peak* of the spectrum shifts blueward.
- A and B
- A and C

Clicker: What happens to thermal radiation (a continuous spectrum) if you make the source hotter?

- It produces more energy at all wavelengths.
- The *peak* of the spectrum shifts redward.
- The *peak* of the spectrum shifts blueward.
- A and B
- ***A and C***

Thought Question

Why don't we glow in the dark?

A. People do not emit any kind of light.
B. People only emit detectable amounts of light at wavelengths that are invisible to our eyes.
C. People are too small to emit enough light for us to see.
D. People do not contain enough radioactive material.

Thought Question

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A. People do not emit any kind of light.

B. People only emit detectable amounts of light at wavelengths that are invisible to our eyes.

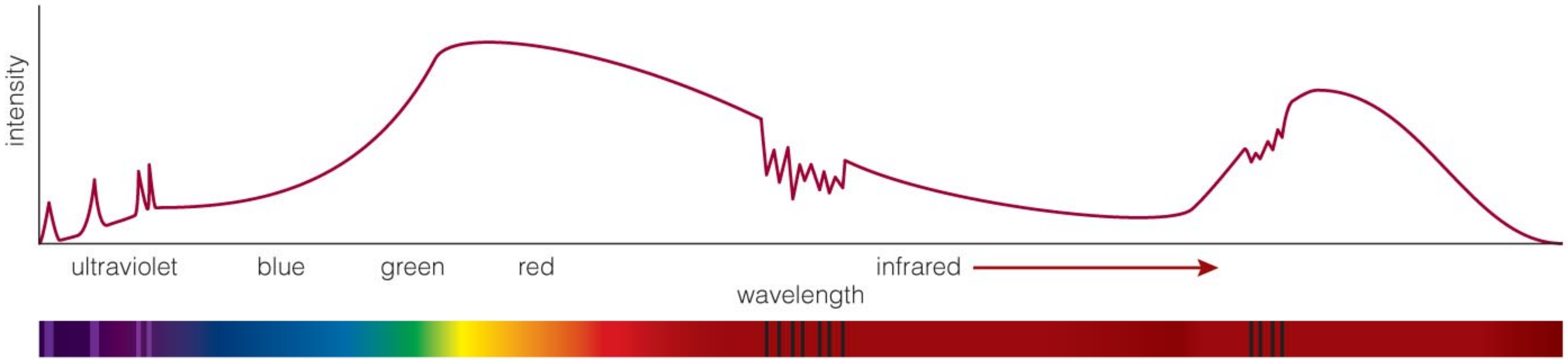
C. People are too small to emit enough light for us to see.

D. People do not contain enough radioactive material.

Thermal Infrared

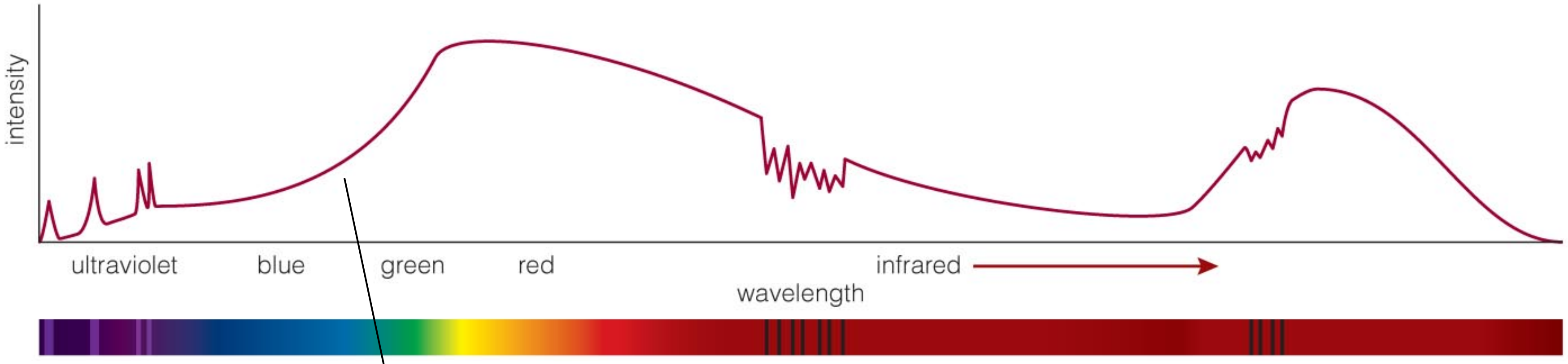
People emit light, but we do essentially all of it at wavelengths longer than our eyes can see

Example: How do we interpret an actual spectrum?



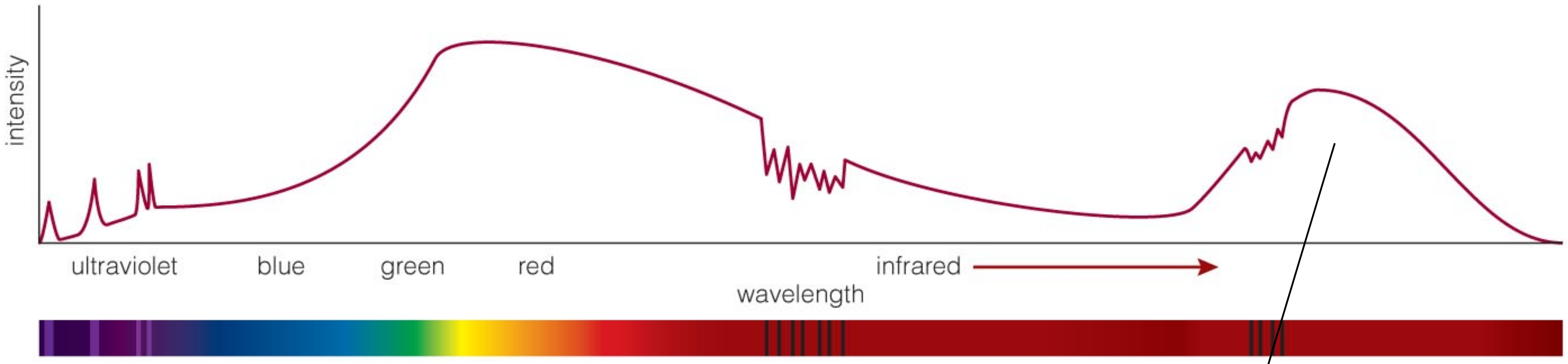
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What is this object?



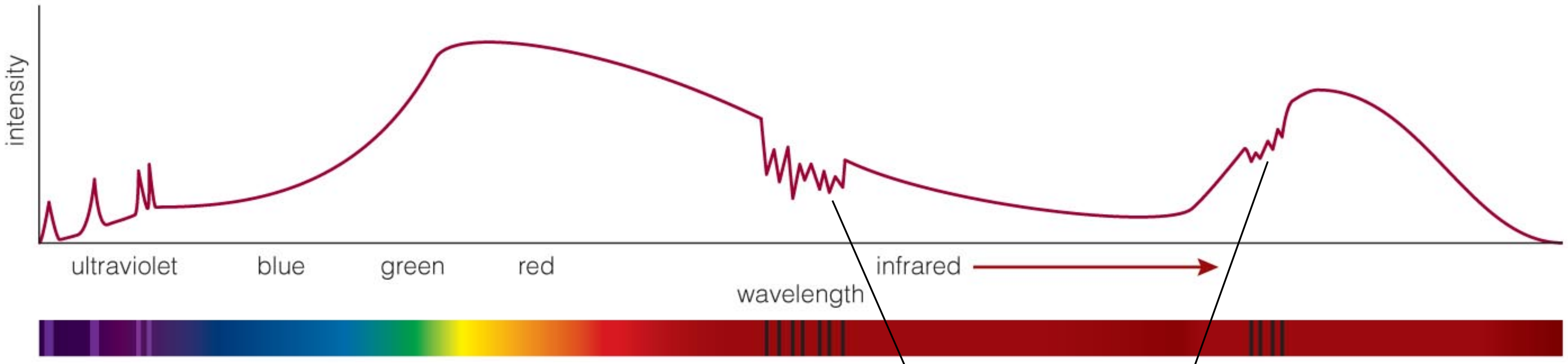
Reflected sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed—object must look red.

What is this object?



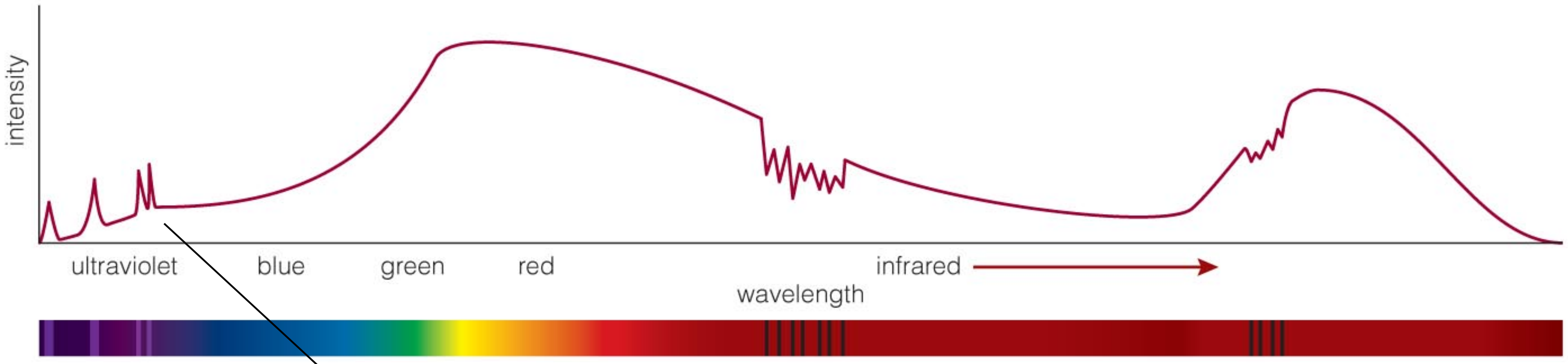
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K.

What is this object?



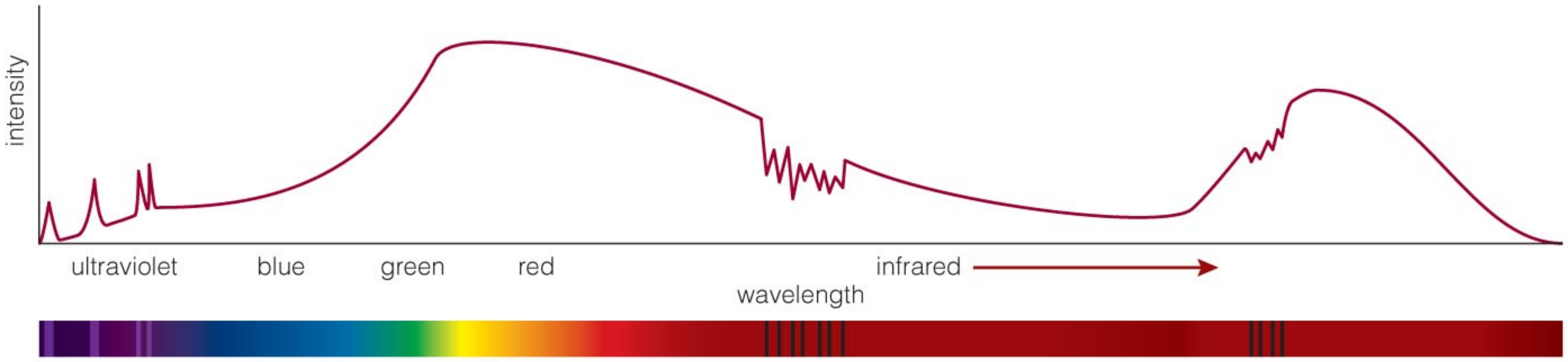
Carbon dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere.

What is this object?



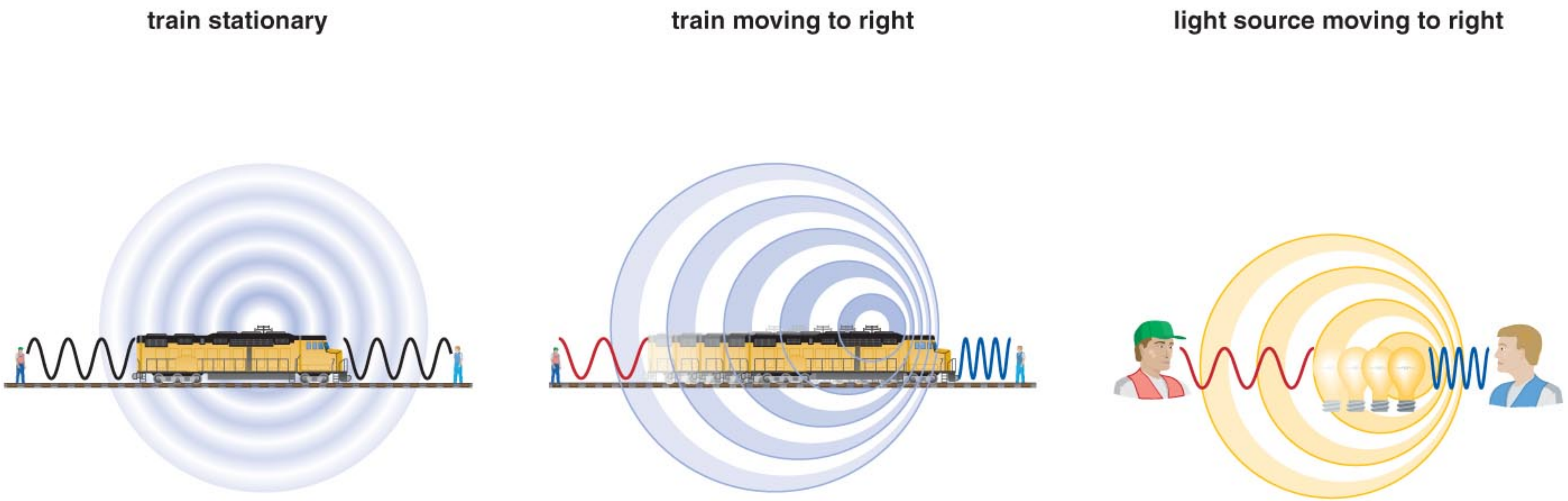
Ultraviolet emission lines: Indicate a hot upper atmosphere

What is this object?



Mars!

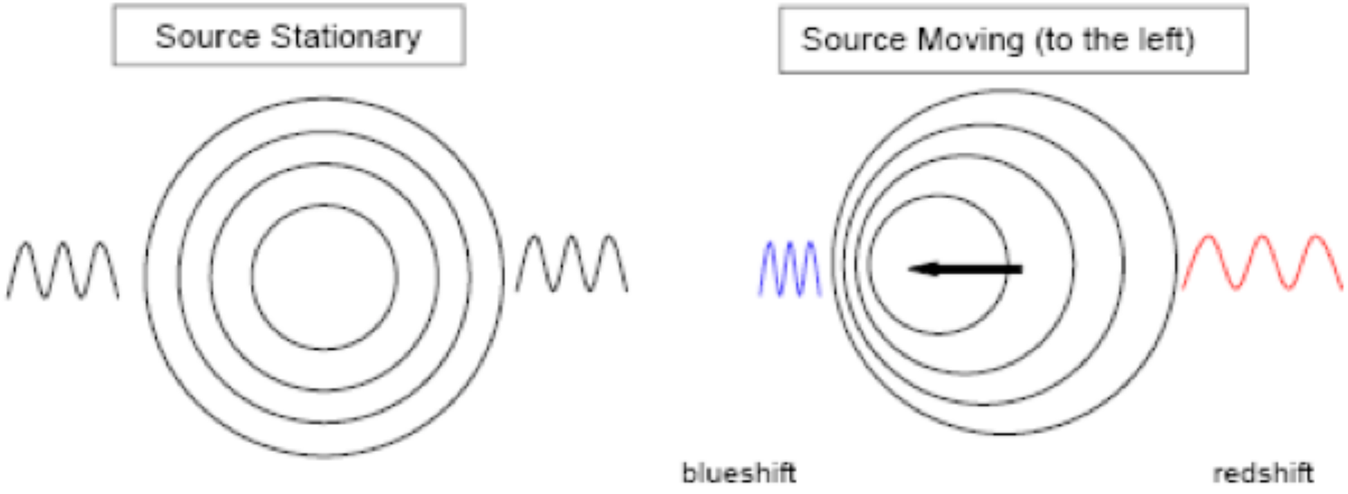
How does light tell us the speed of a distant object?



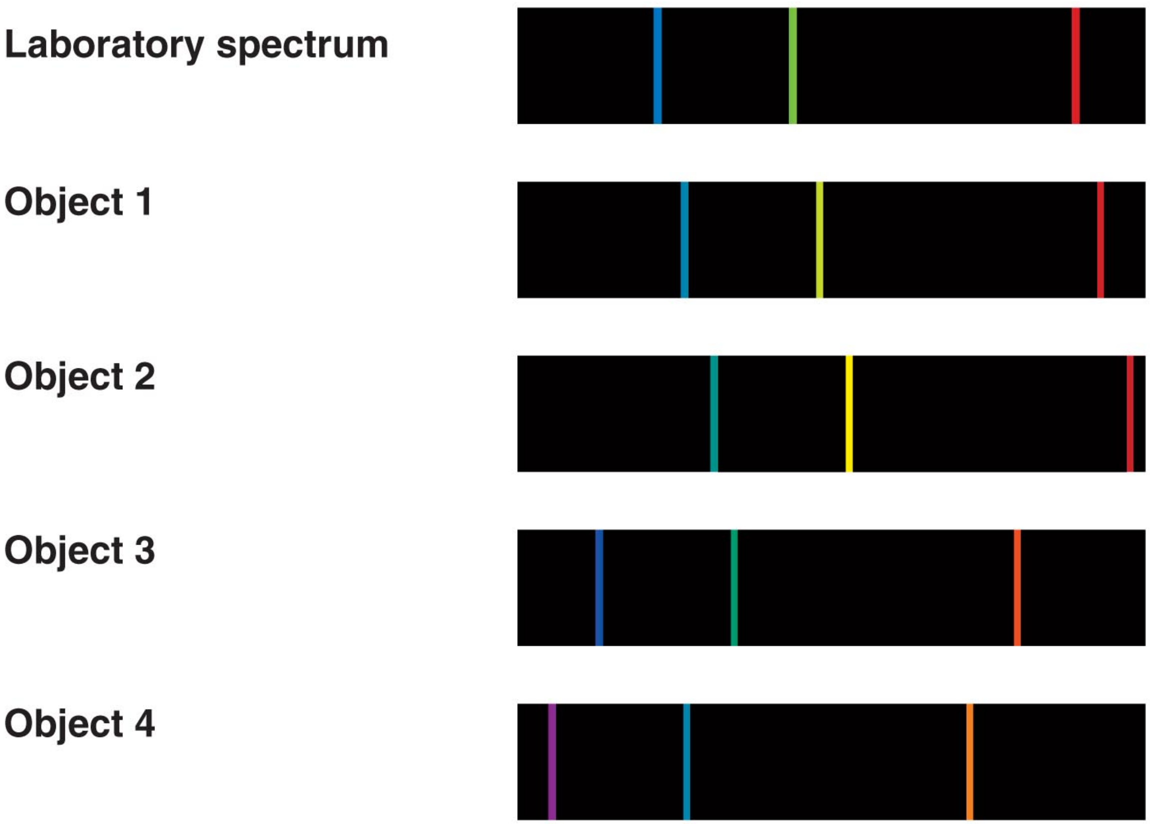
The Doppler Effect

- Same for Light as it is for Sound
  - Sound from a source coming towards you: sound waves hit you more often per second
    - Higher frequency, shorter wavelength (Higher pitch)
    - If moving away from you, lower frequency and lower pitch
  - Light waves from a source coming towards you: light waves hit you more often per second
    - Higher frequency, shorter wavelength, (bluer light)
    - If moving away from you, lower frequency and redder light

The Doppler Effect



Measuring the Shift



Stationary

Moving away

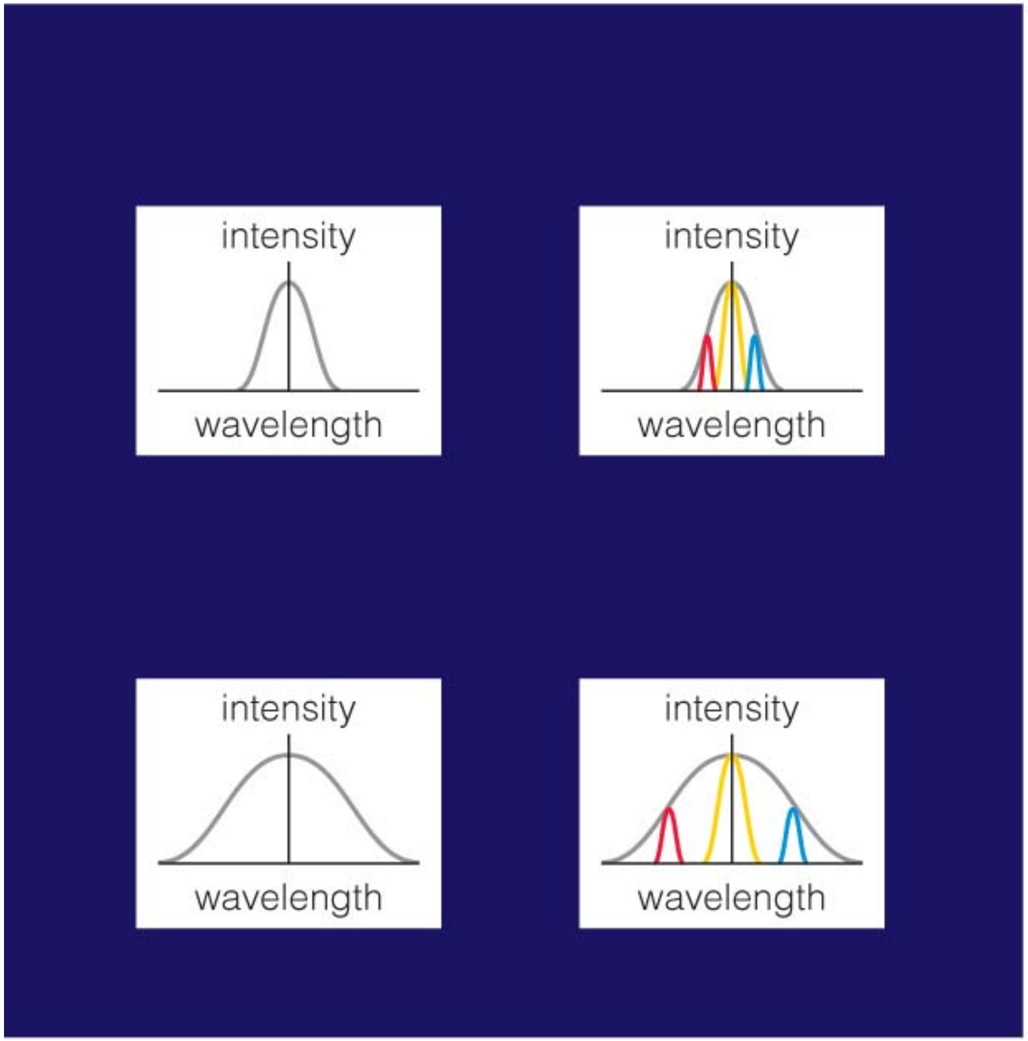
Away faster

Moving toward

Toward faster

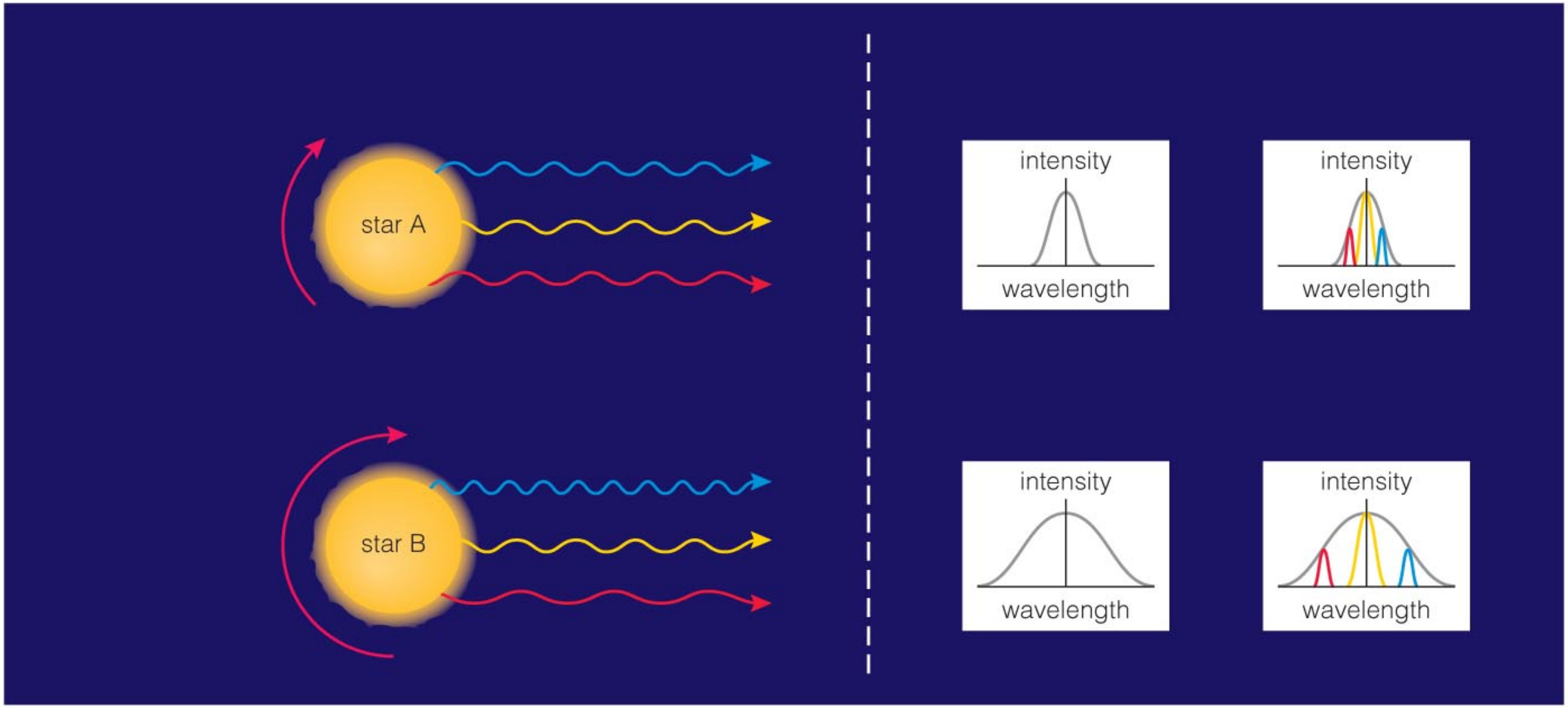
- We generally measure the Doppler effect from shifts in the wavelengths of spectral lines.

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.

What have we learned?

- **What are the three basic type of spectra?**
  - Continuous spectrum, emission line spectrum, absorption line spectrum
- **How does light tell us what things are made of?**
  - Each atom has a unique fingerprint.
  - We can determine which atoms something is made of by looking for their fingerprints in the spectrum.

What have we learned?

- **How does light tell us the temperatures of planets and stars?**
  - Nearly all large or dense objects emit a continuous spectrum that depends on temperature.
  - The spectrum of that thermal radiation tells us the object's temperature.
- **How does light tell us the speed of a distant object?**
  - The Doppler effect tells us how fast an object is moving toward or away from us.