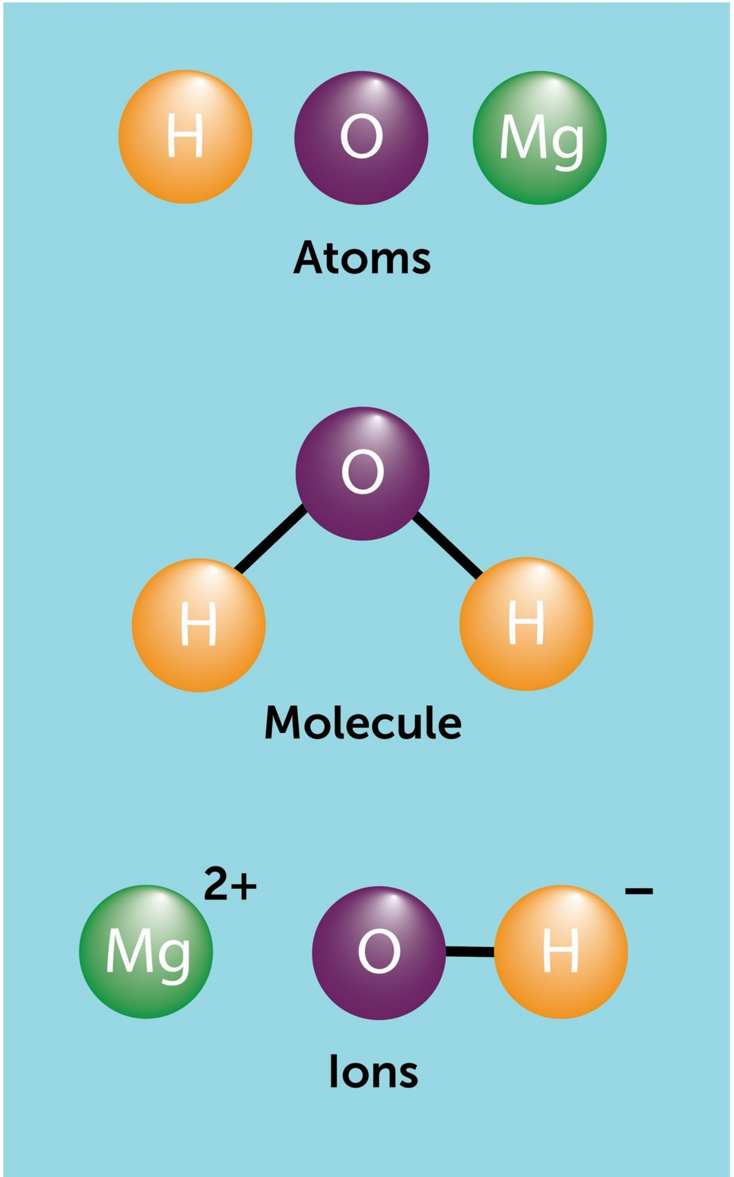
Chapter 5:
Light and Matter: Reading Messages from the Cosmos

5.3 Properties of Matter

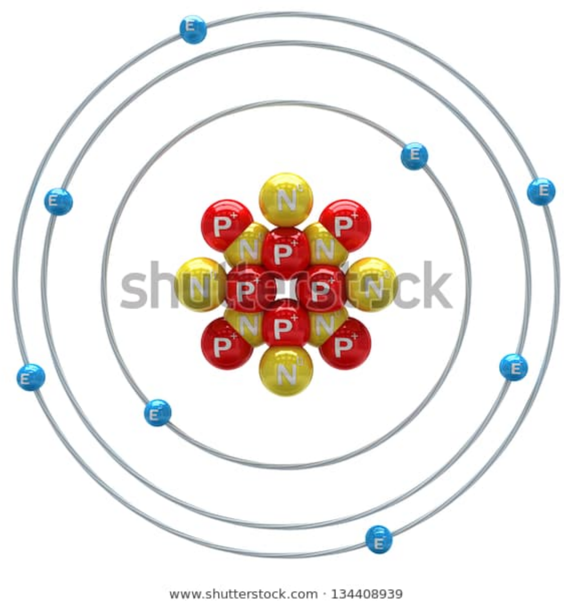
- Our goals for learning:
  - **What is the structure of matter?**
  - **What are the phases of matter**
  - **How is energy stored in atoms?**

Molecules, atoms, sub-atomic particles



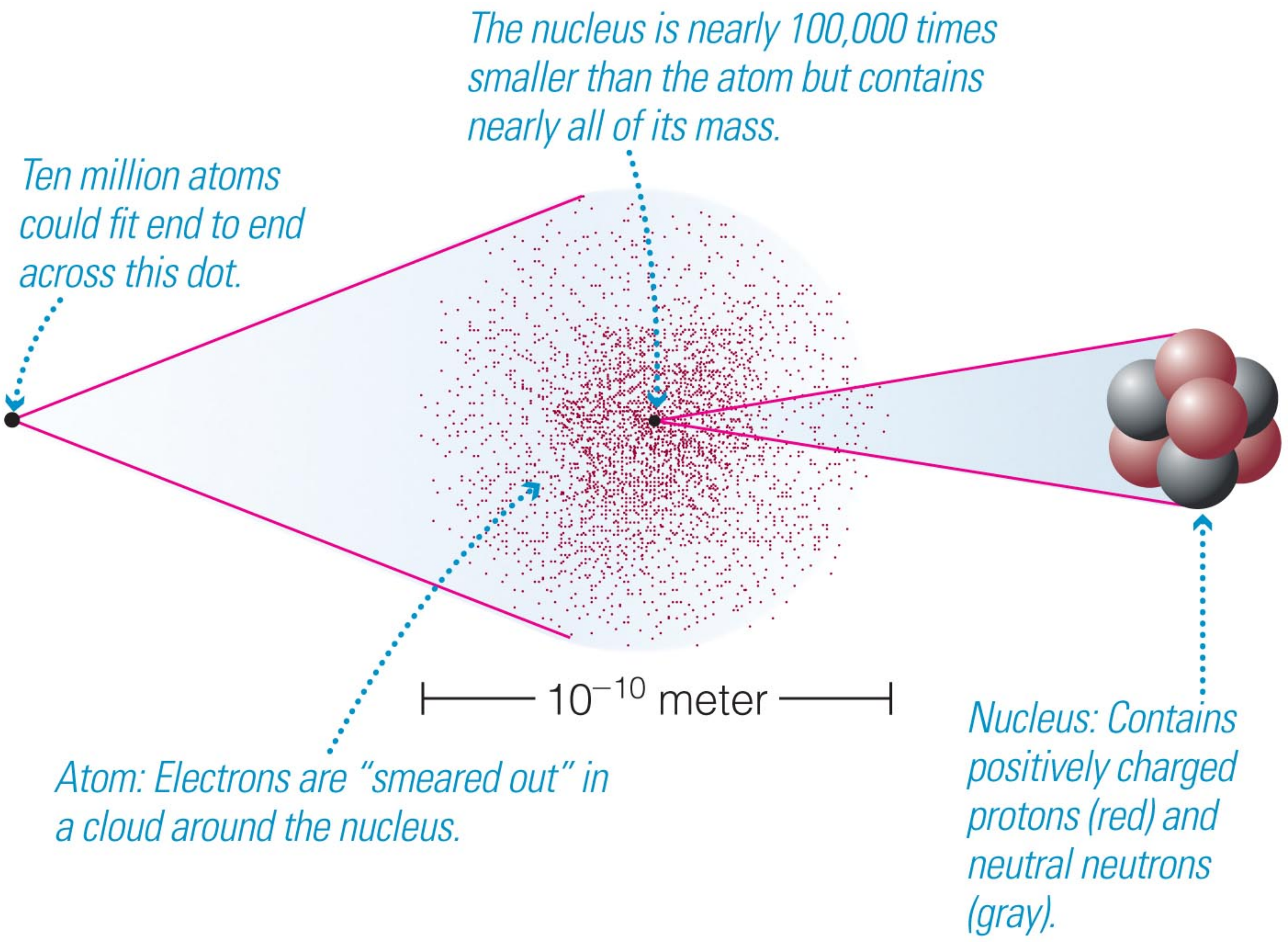
Source: Royal Society of Chemistry

Hydrogen atom



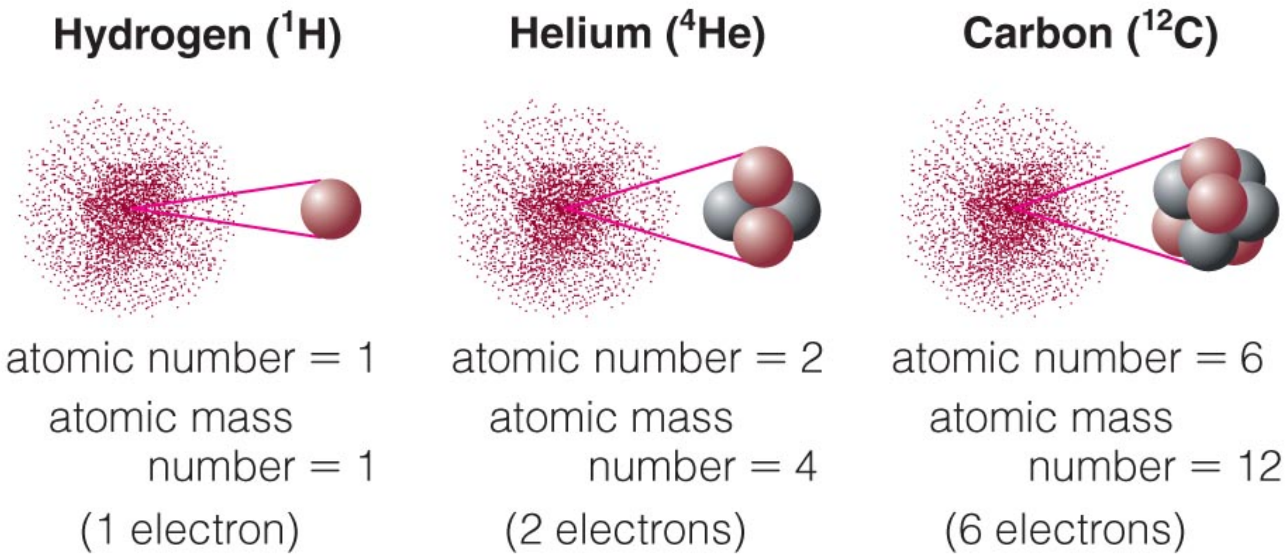
Oxygen atom

What is the structure of matter?



Atomic Terminology

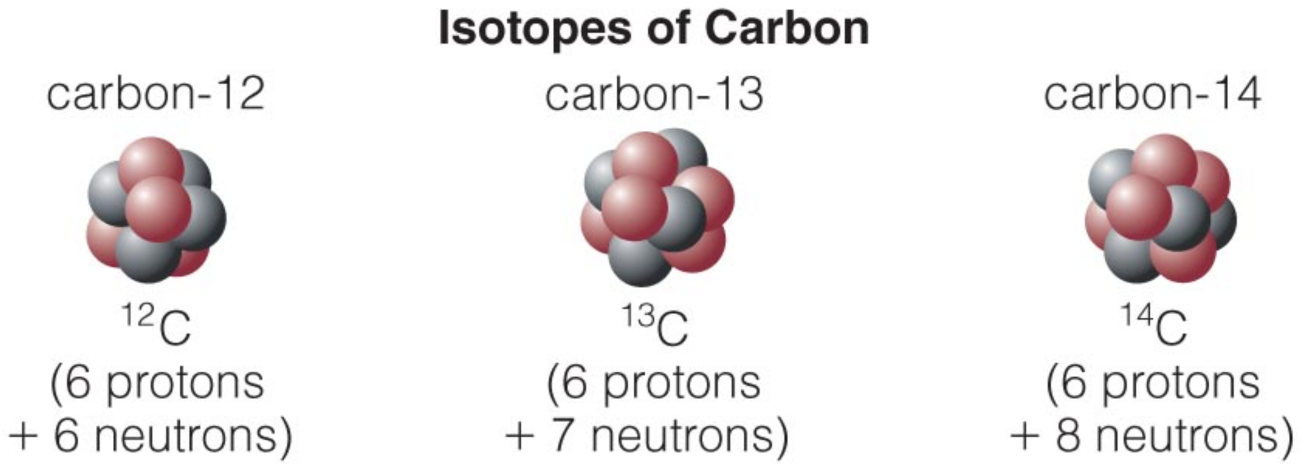
- Atomic number = # of protons in nucleus
- Atomic mass number = # of protons + neutrons



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

Atomic Terminology

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

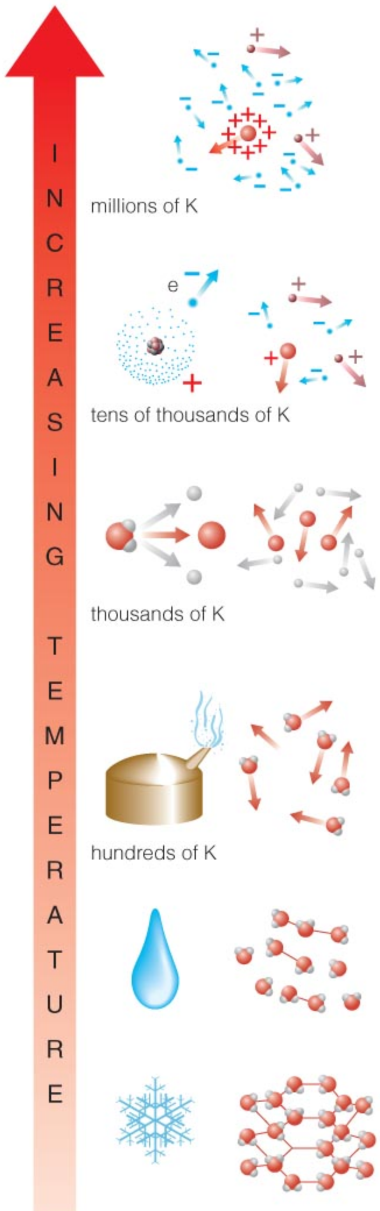


What are the phases of matter?

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

* The fourth phase of matter: plasma

Phase Changes



Full ionization (plasma)

Partial ionization (plasma & neutral matter)

Breaking molecules (dissociation)

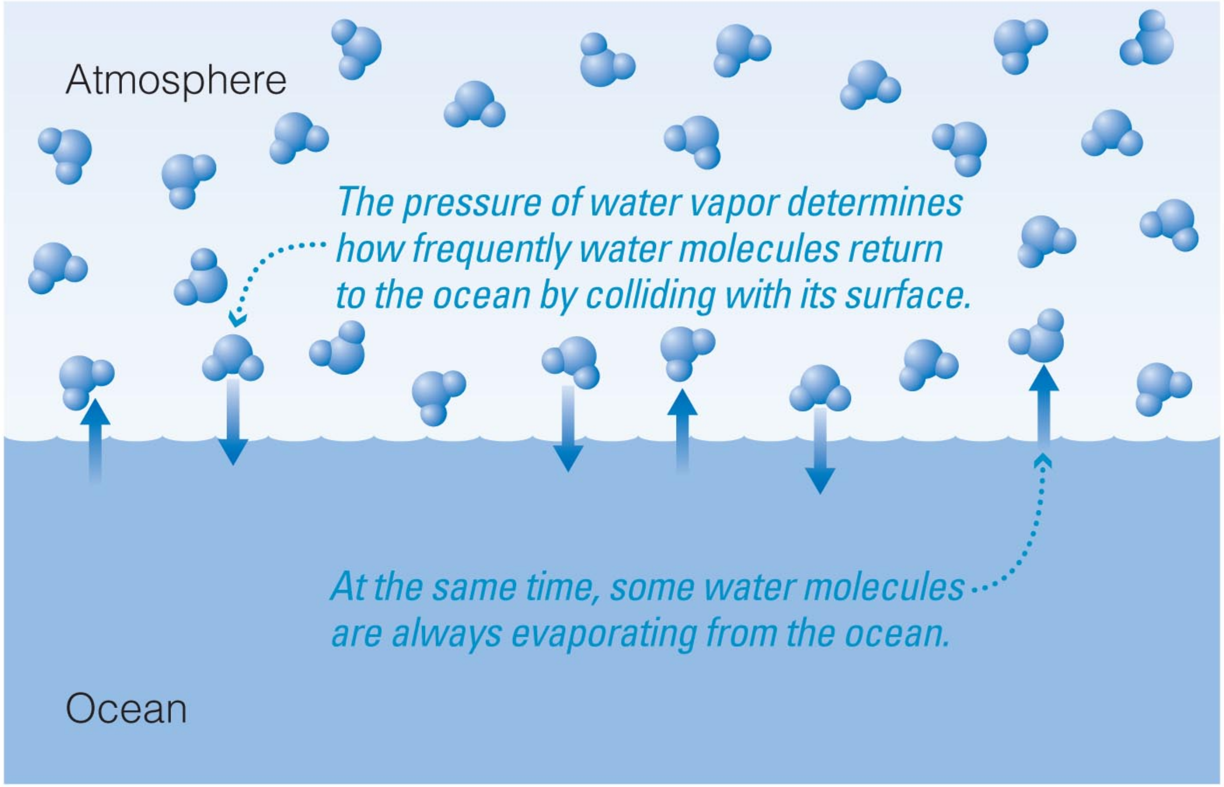
Breaking flexible Bonds (gas)

Flexible chemical bonds (fluid)

Rigid chemical bonds (solids)

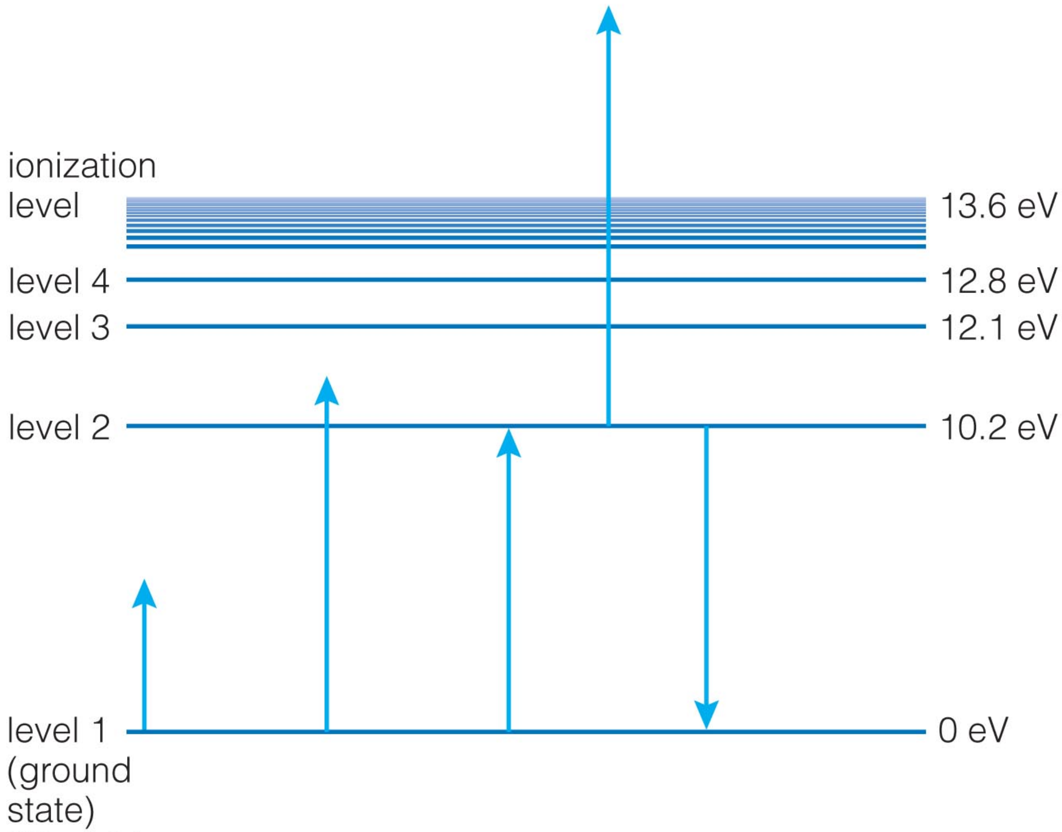
- **Ionization:** stripping of electrons, changing atoms into **plasma**
- **Dissociation:** breaking of molecules into atoms
- **Evaporation:** breaking of flexible chemical bonds, changing liquid into solid
- **Melting:** breaking of rigid chemical bonds, changing solid into liquid

Phases and Pressure



- Phase of a substance depends on both temperature and pressure.
- Often more than one phase is present.

How is energy stored in atoms?

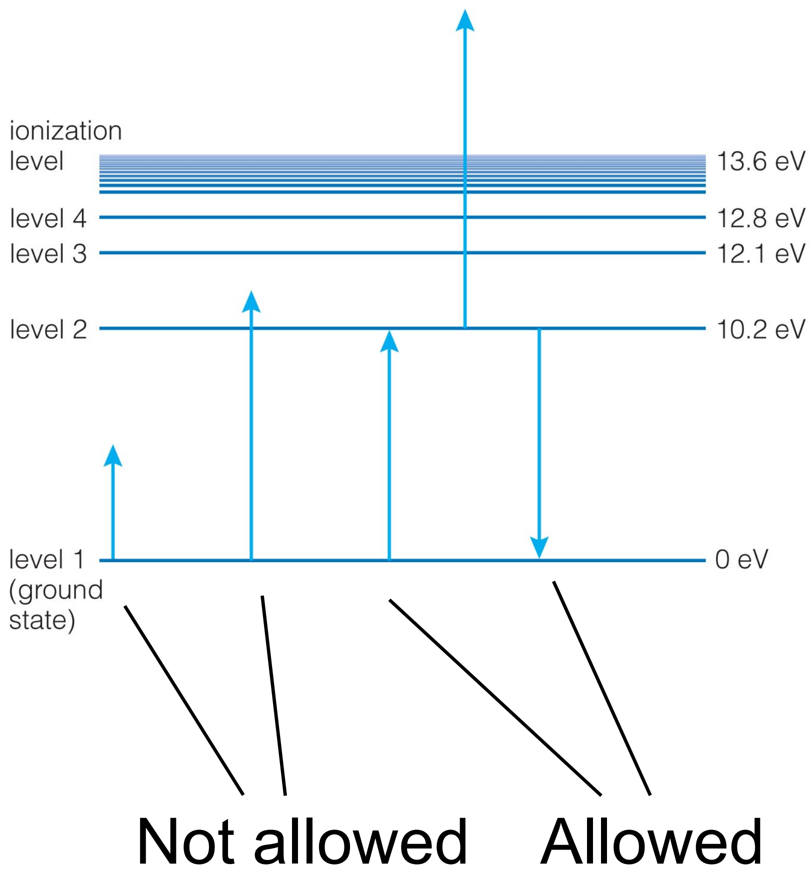


Excited states

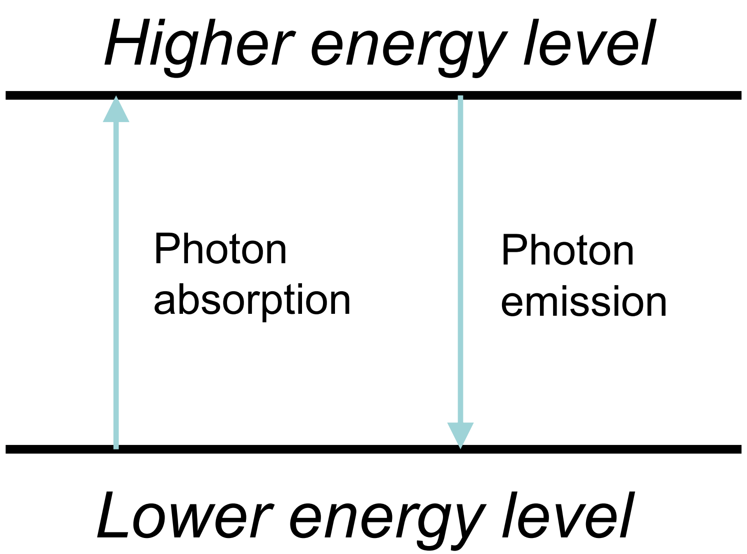
Ground state

- Electrons in atoms are restricted to particular energy levels.

Energy Level Transitions



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



What have we learned?

- **What is the structure of matter?**
  - Matter is made of atoms, which consist of a nucleus of protons and neutrons surrounded by a cloud of electrons.
- **What are the phases of matter?**
  - Adding heat to a substance changes its phase by breaking chemical bonds.
  - As temperature rises, a substance transforms from a solid to a liquid to a gas, then the molecules can dissociate into atoms.
  - Stripping of electrons from atoms (ionization) turns the substance into a plasma.

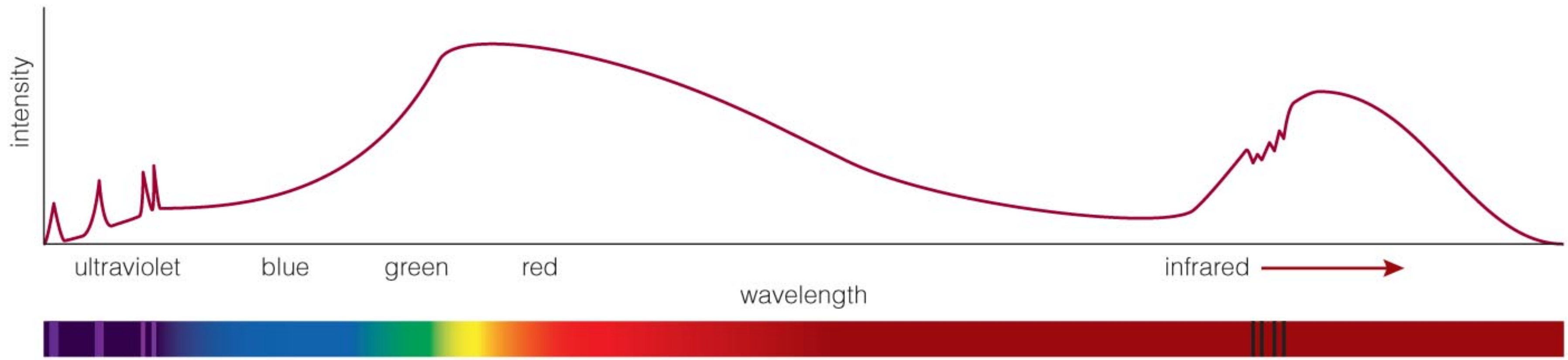
What have we learned?

- **How is energy stored in atoms?**
  - The energies of electrons in atoms correspond to particular energy levels.
  - Atoms gain and lose energy only in amounts corresponding to particular changes in energy levels.

5.4 Learning from Light

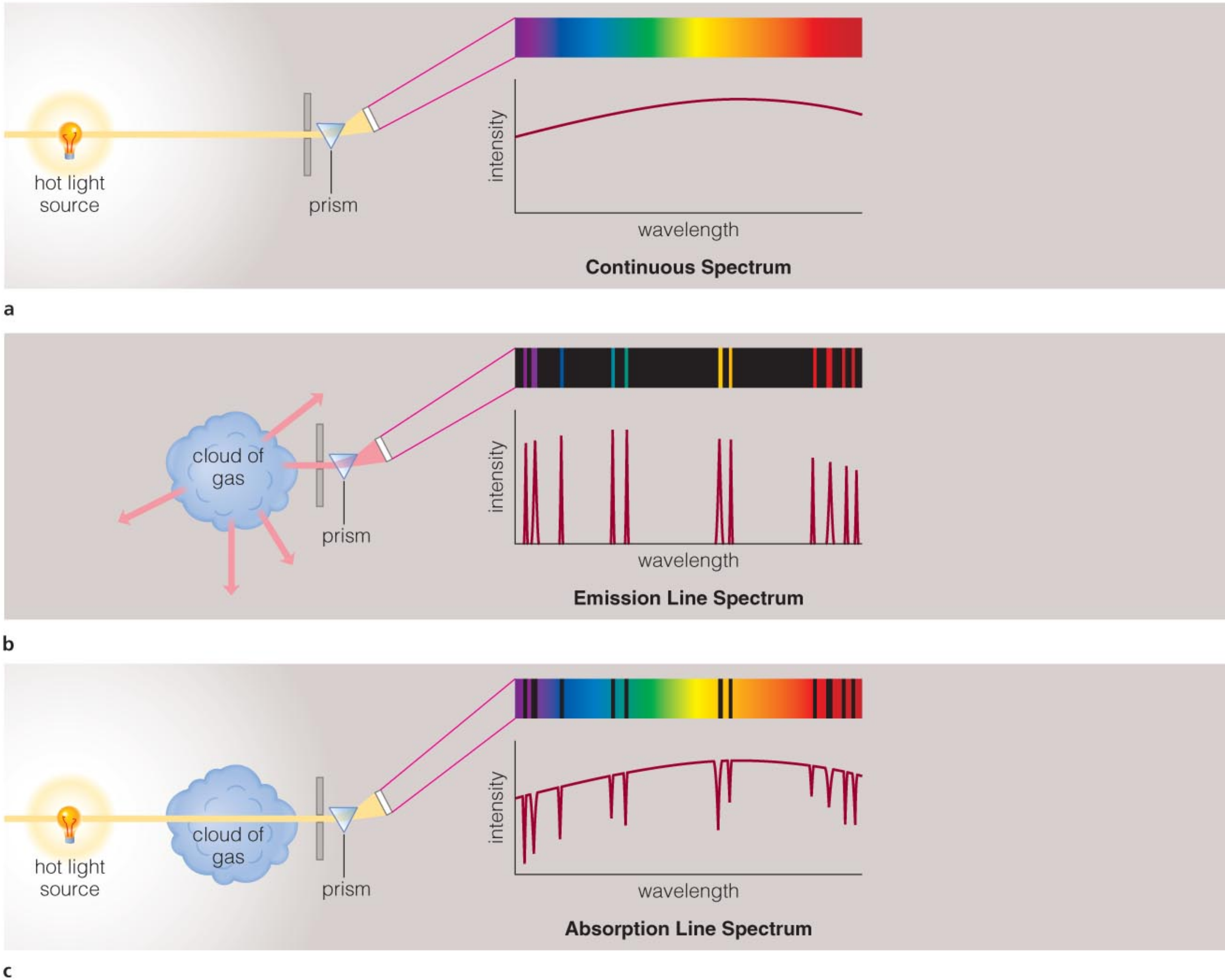
- Our goals for learning:
  - **What are the three basic types of spectra?**
  - **How does light tell us what things are made of?**
  - **How does light tell us the temperatures of planets and stars?**
  - **How does light tell us the speed of a distant object?**

What are the three basic types of spectra?

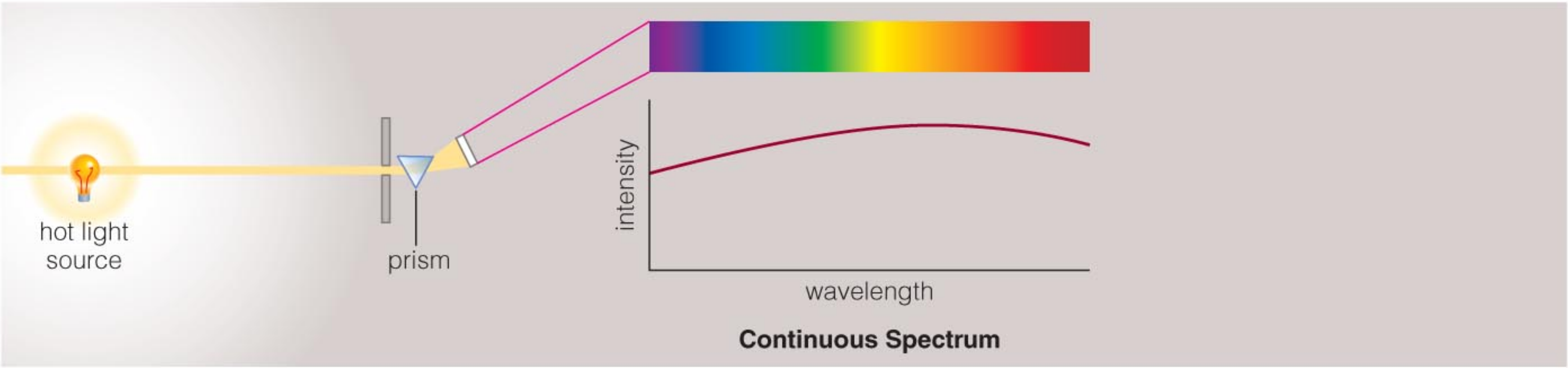


- Spectra of astrophysical objects are usually combinations of three basic types:

Three Types of Spectra

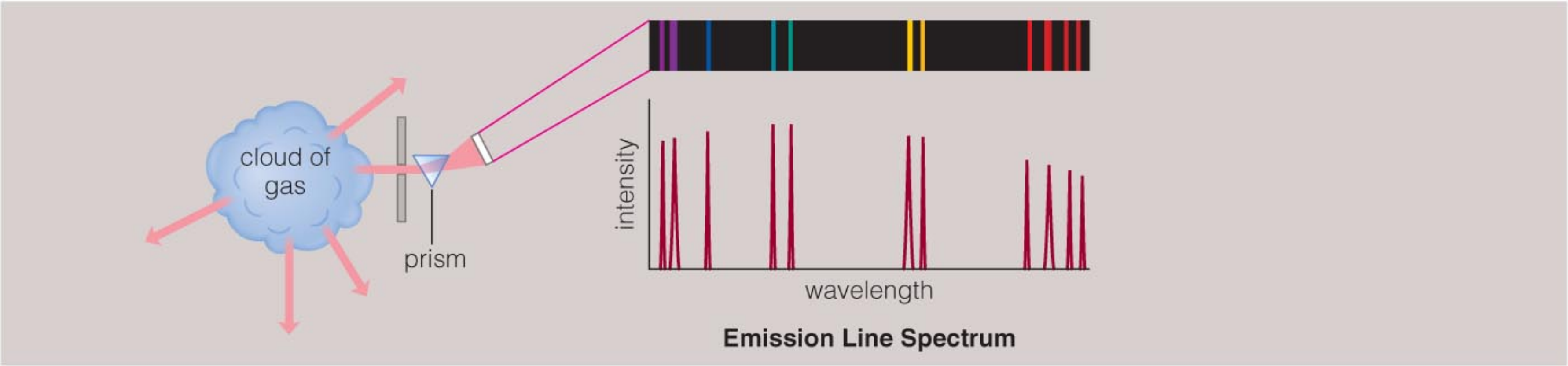


Continuous Spectrum



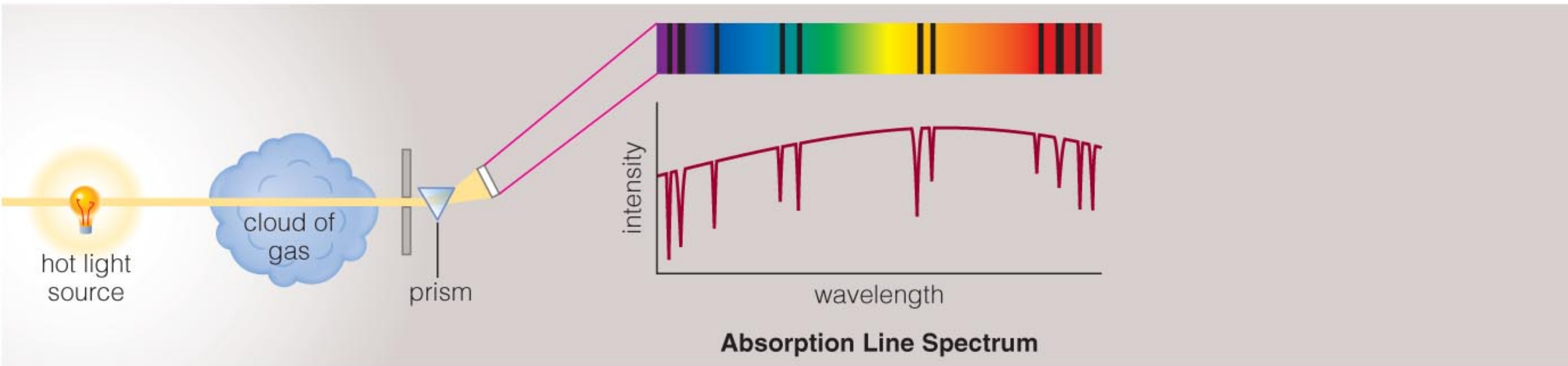
- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption.

Emission Line Spectrum



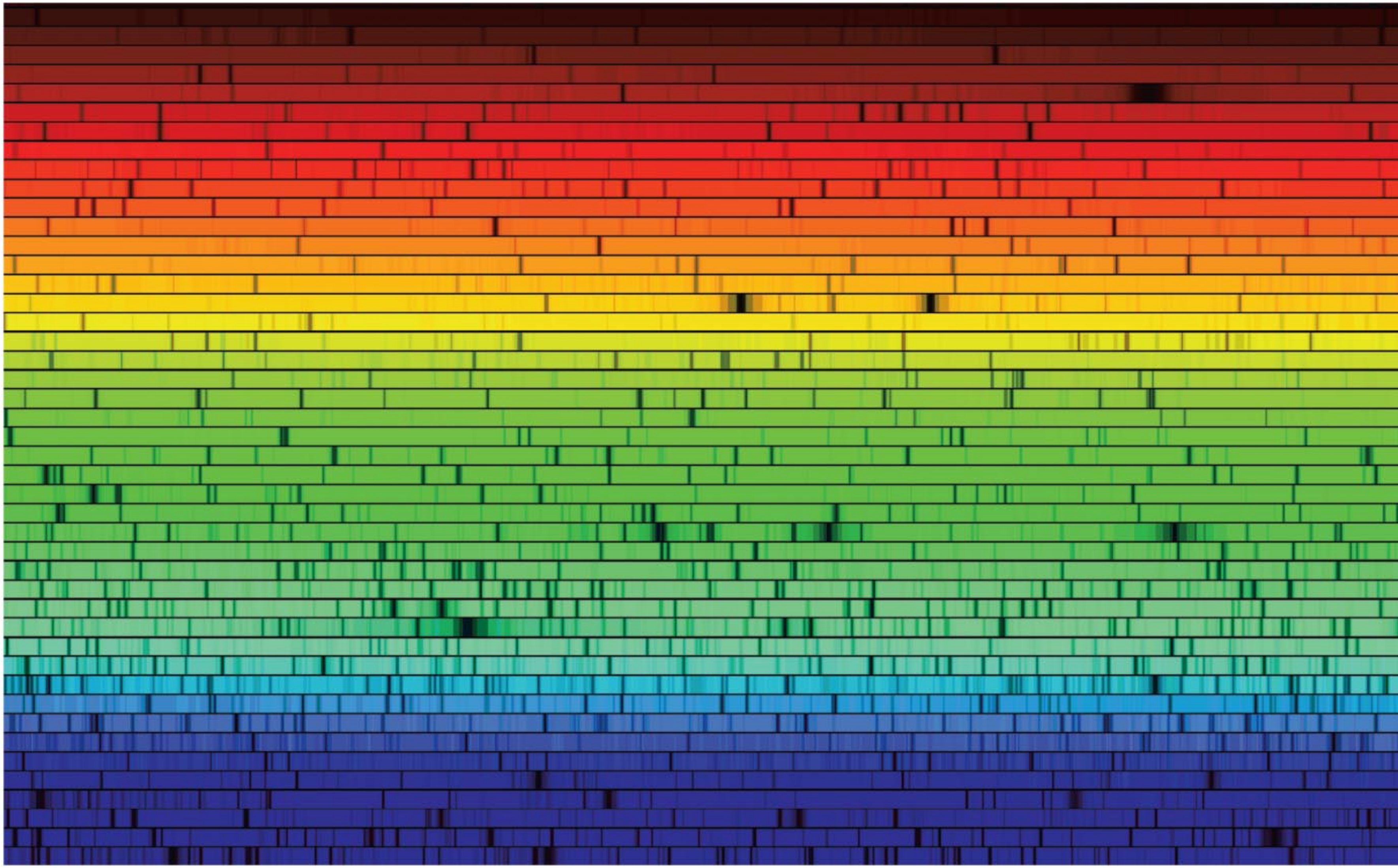
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines.

Absorption Line Spectrum

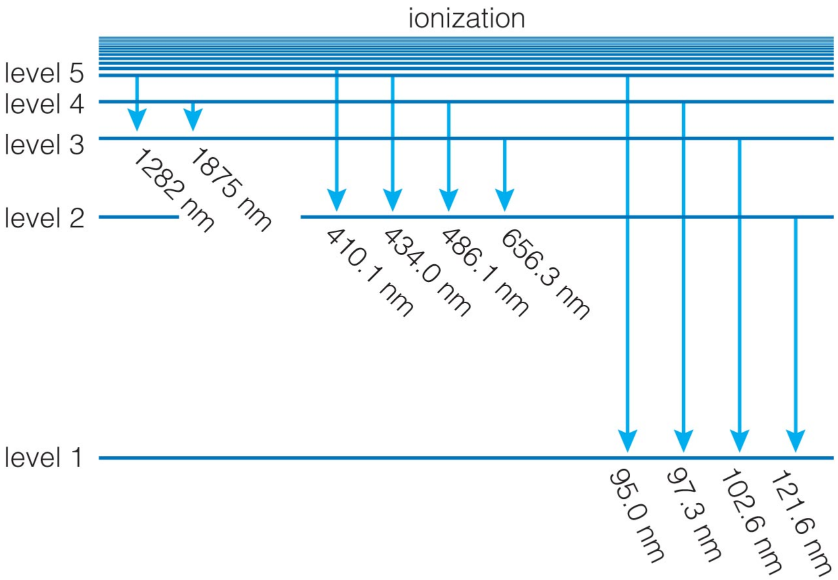


- A cloud of gas between us and a light bulb (or a star) can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.

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.

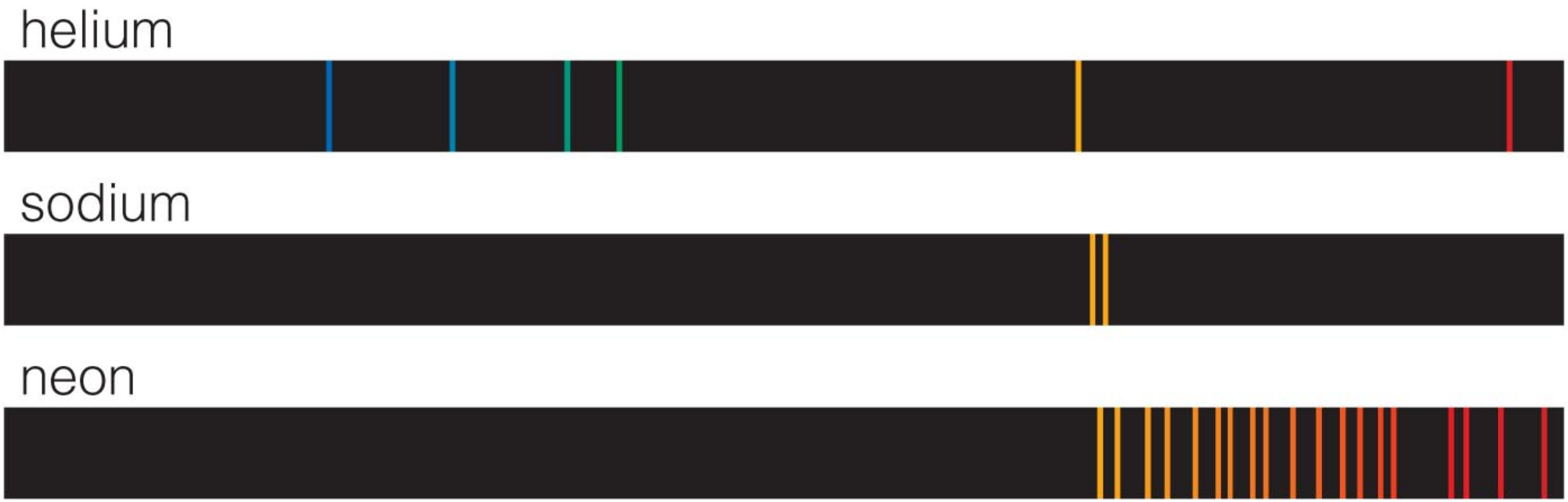
b This spectrum shows emission lines produced by downward transitions between higher levels and level 2 in hydrogen.

Chemical Fingerprints

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

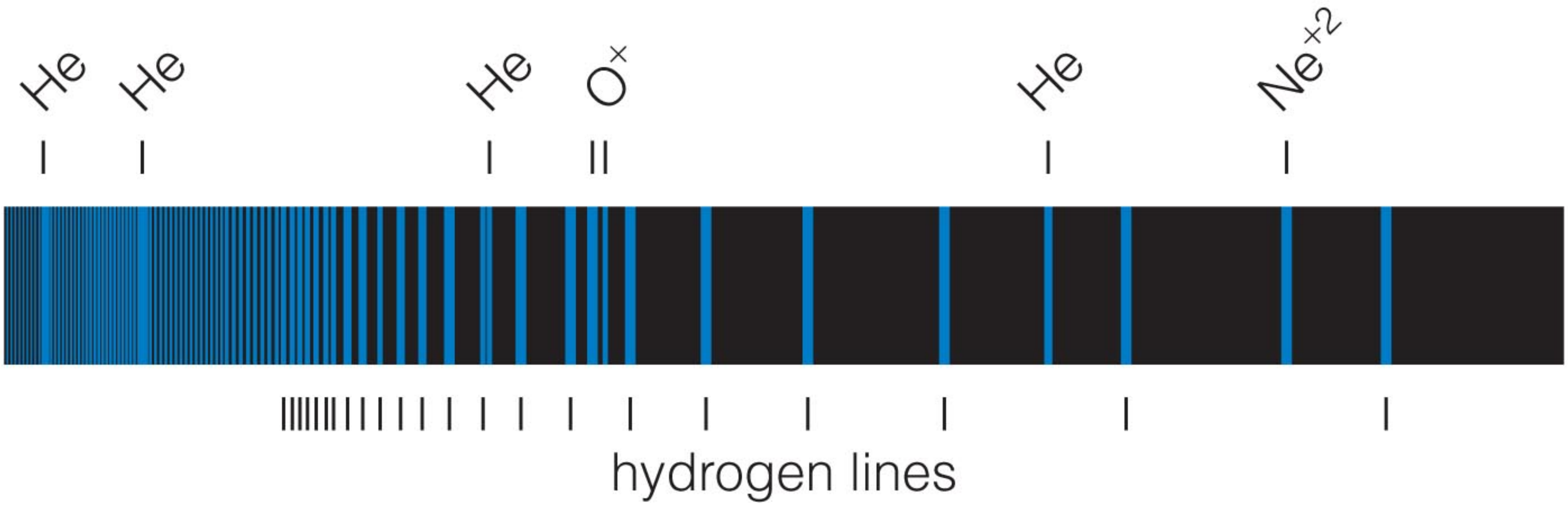
c This spectrum shows absorption lines produced by upward transitions between level 2 and higher levels in hydrogen.

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.

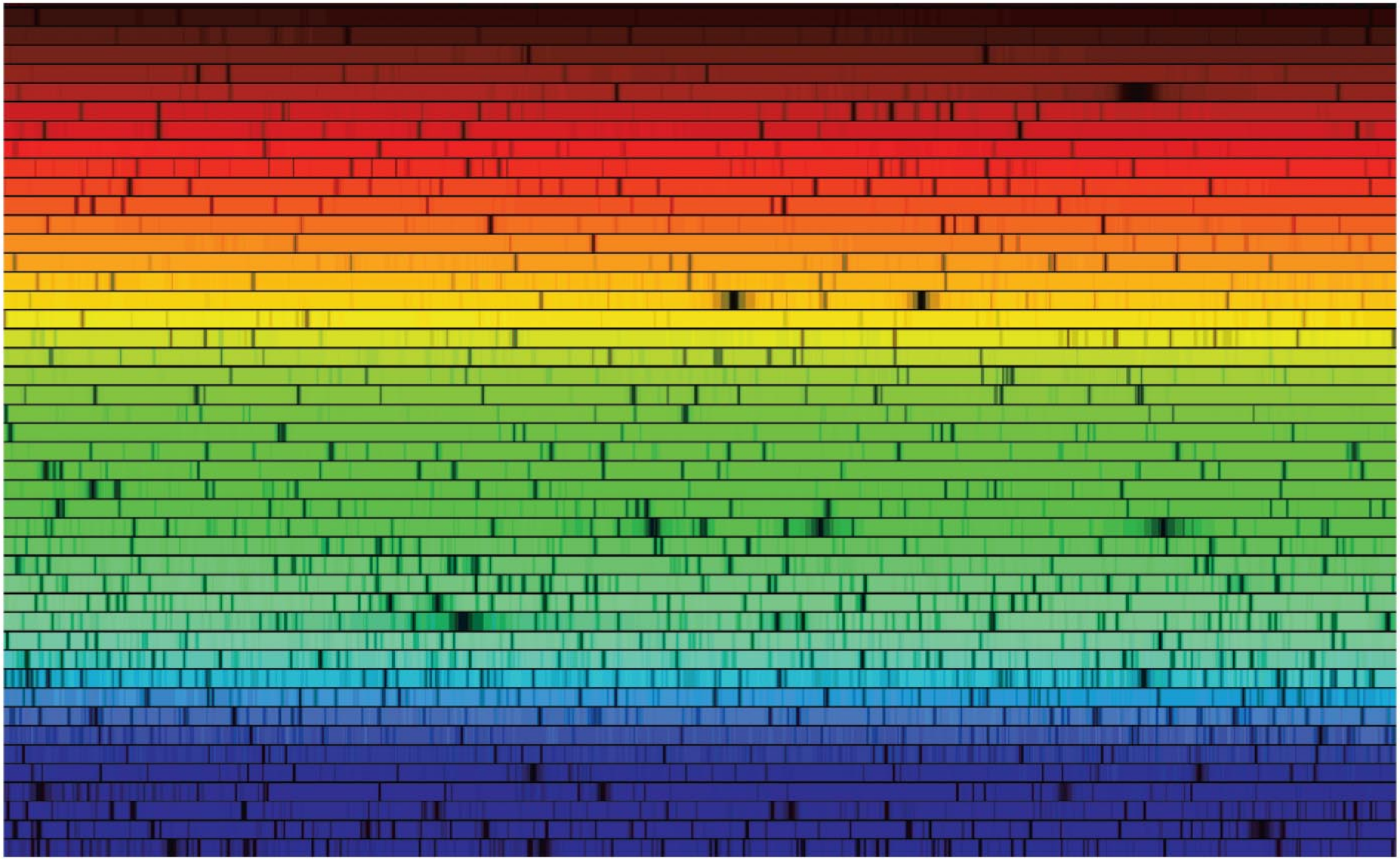
What does this remind you of?

7 25272 73070 6

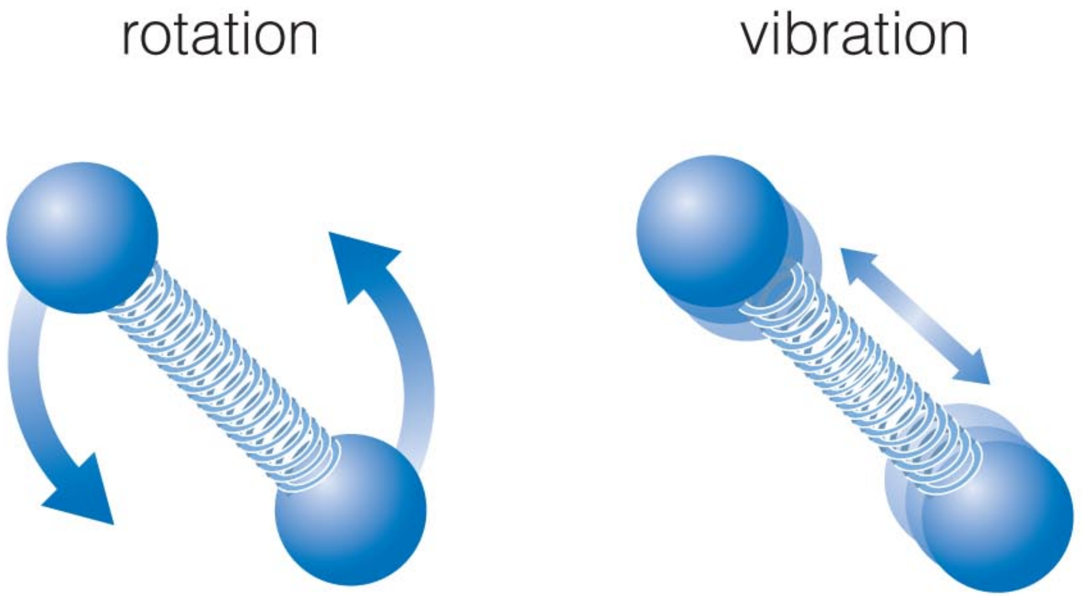
- **A bar code!** This is as unique a ‘fingerprint’ as the spectrum of a certain atom, or combinations thereof

Chemical Fingerprints

Example: Solar Spectrum



Energy Levels of Molecules



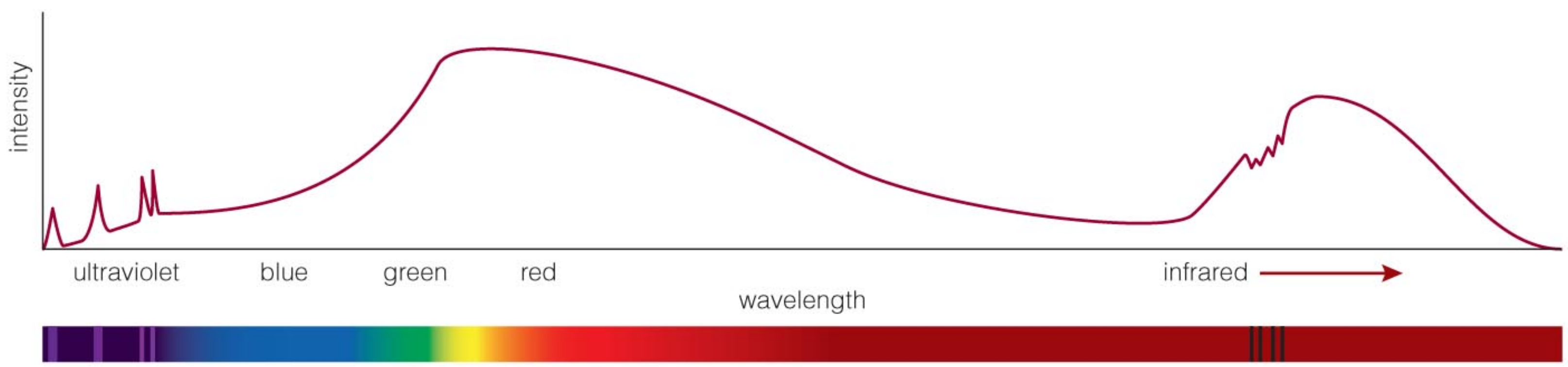
- Molecules have additional energy levels because they can vibrate and rotate.

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?



A B C D E

Thought Question

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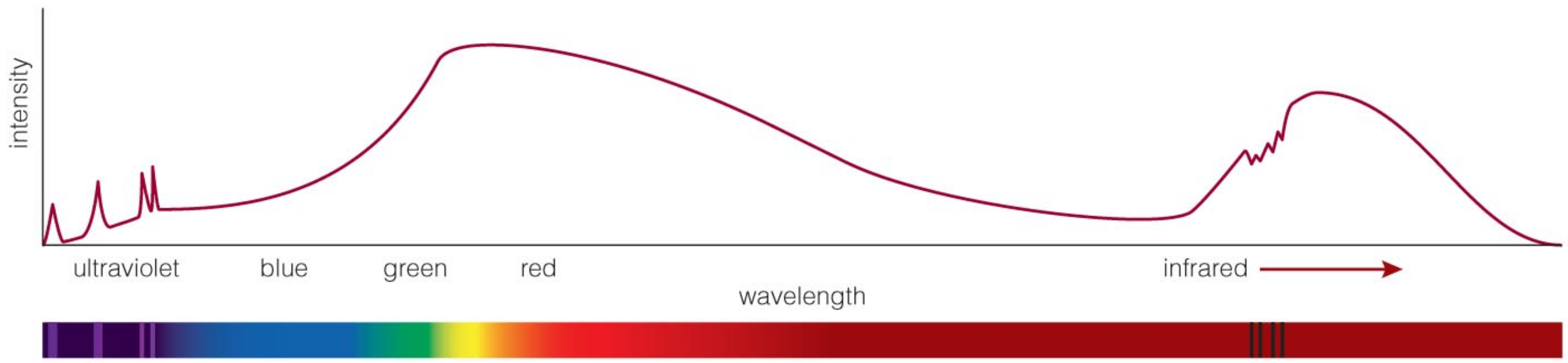
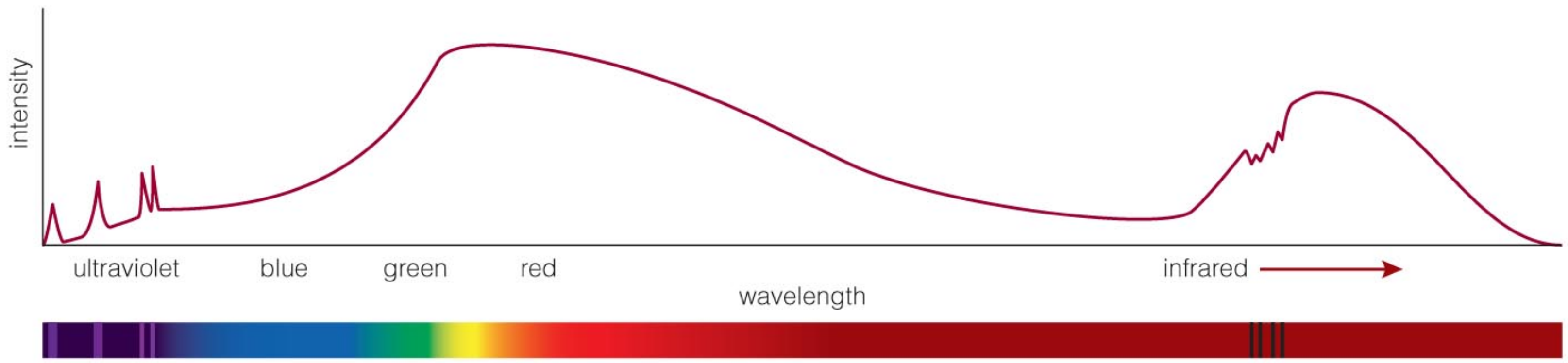


A B **C** **D** E

Thought Question

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



A B C D E

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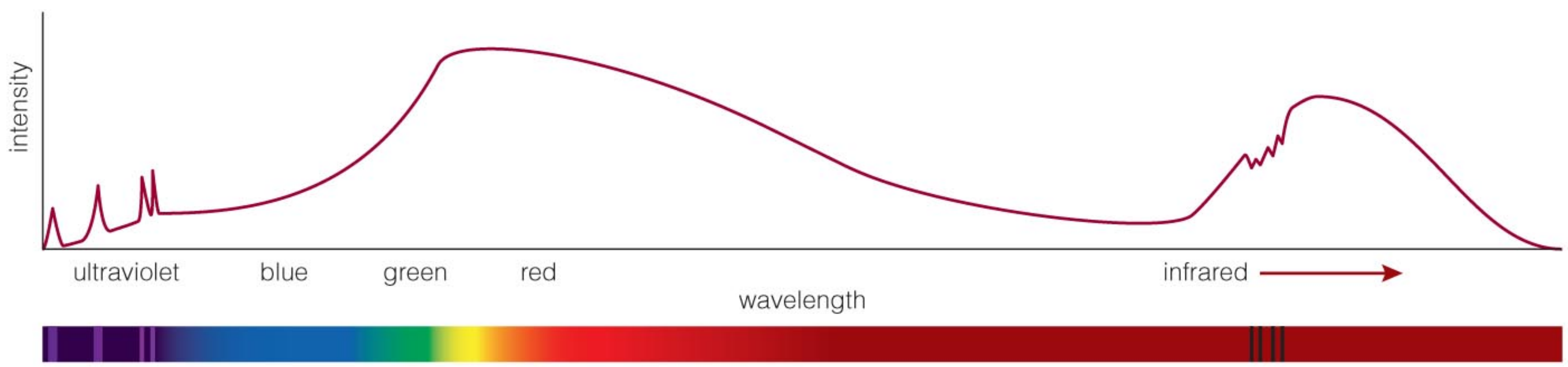
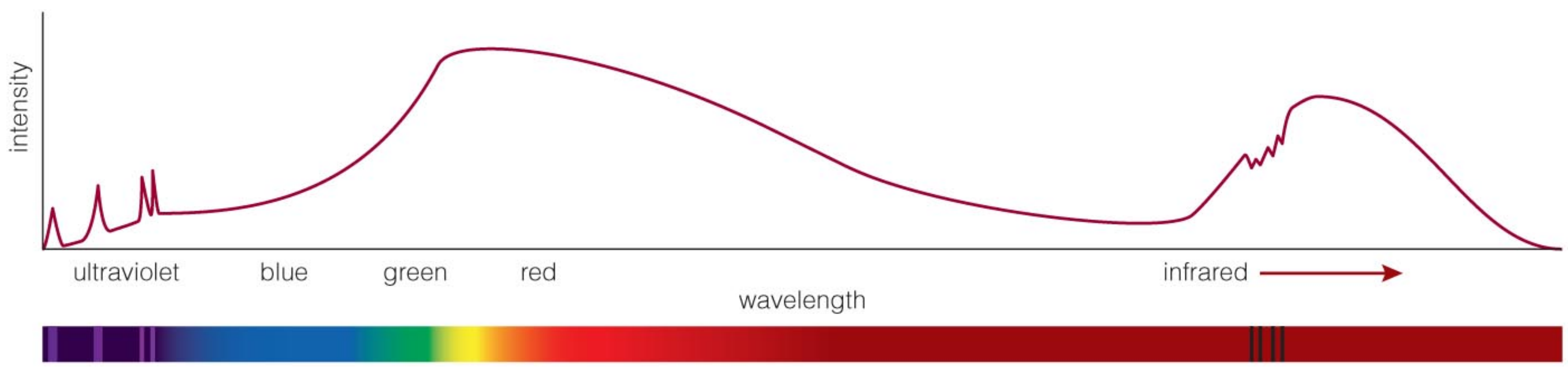


A B C D **E**

Thought Question

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



A B C D E

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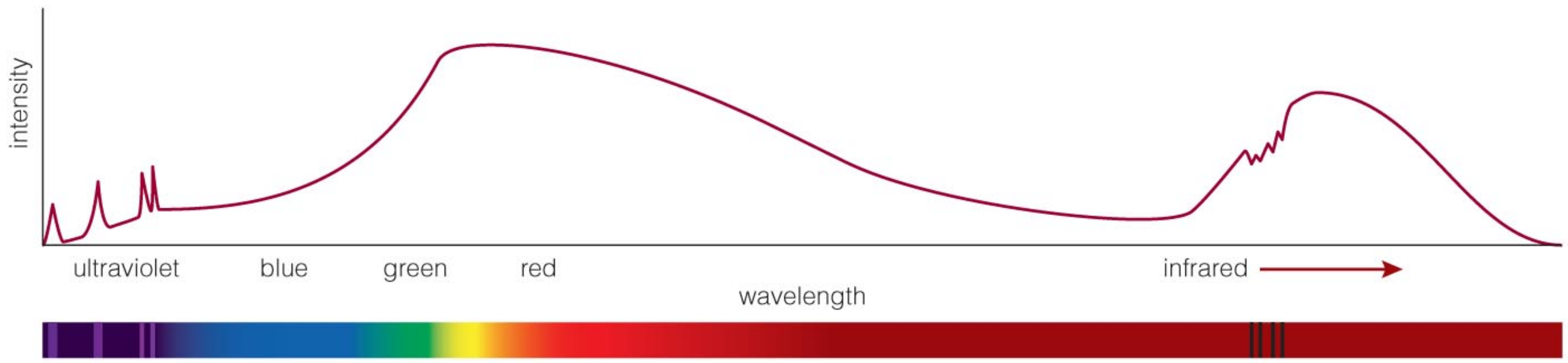
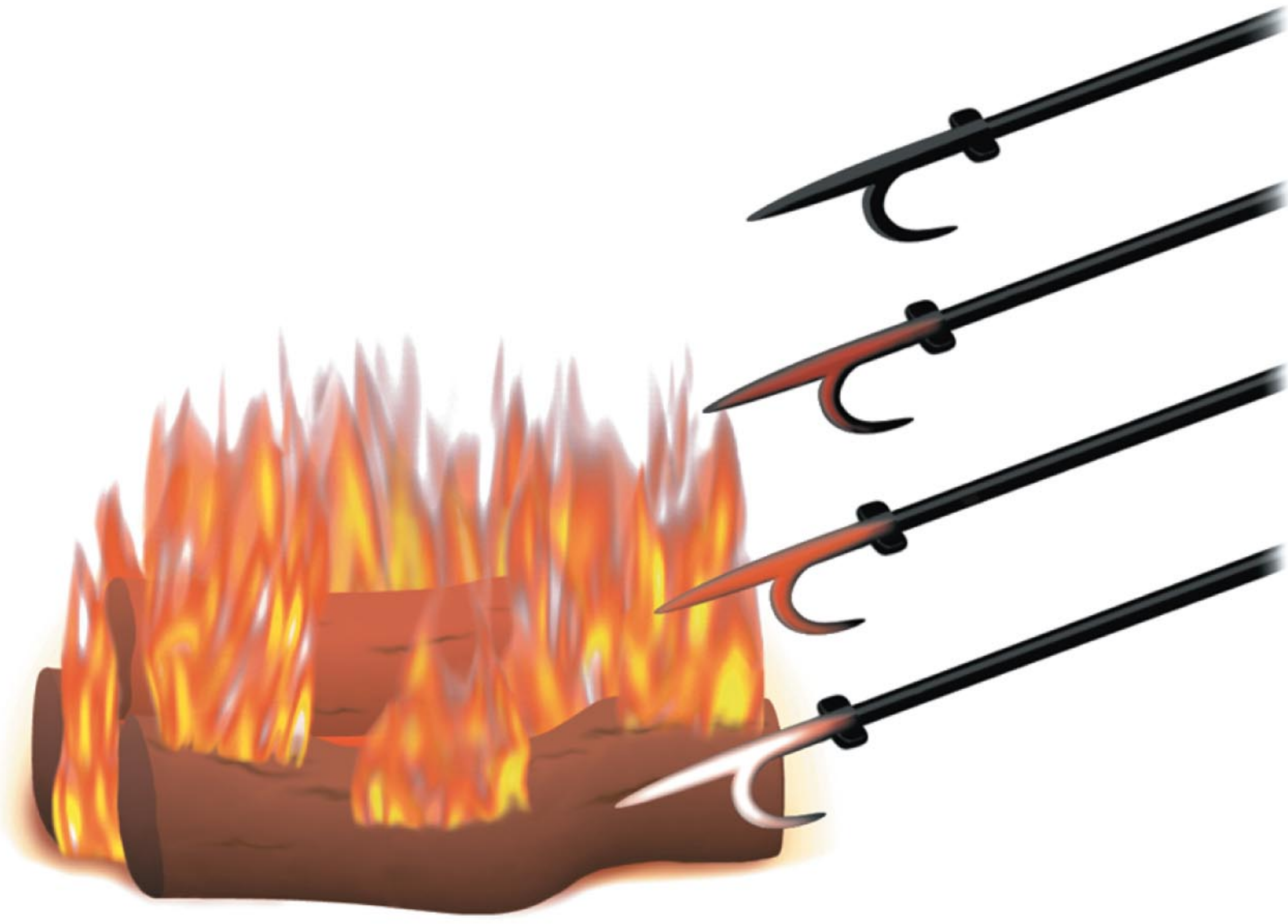


A B C D E

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

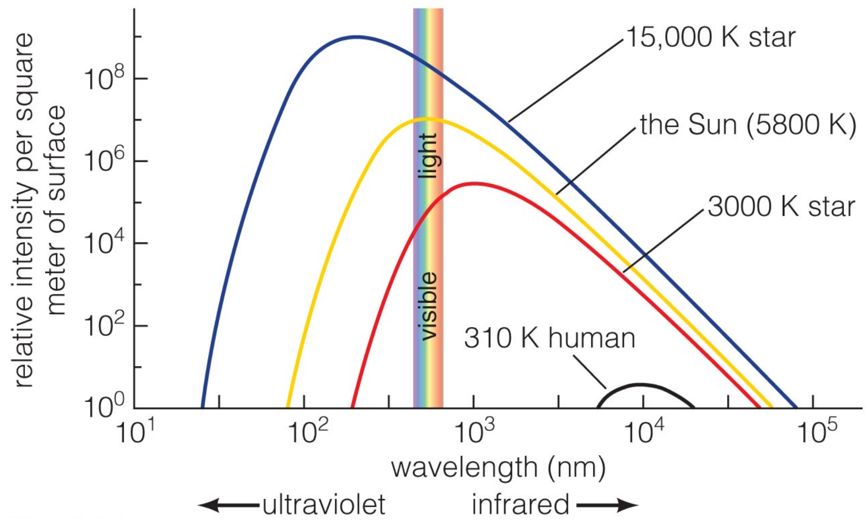


Thermal Radiation

- Nearly all large or dense objects emit thermal radiation, including stars, planets, you.
- An object's thermal radiation spectrum depends on only one property: its **temperature.**

Properties of Thermal Radiation

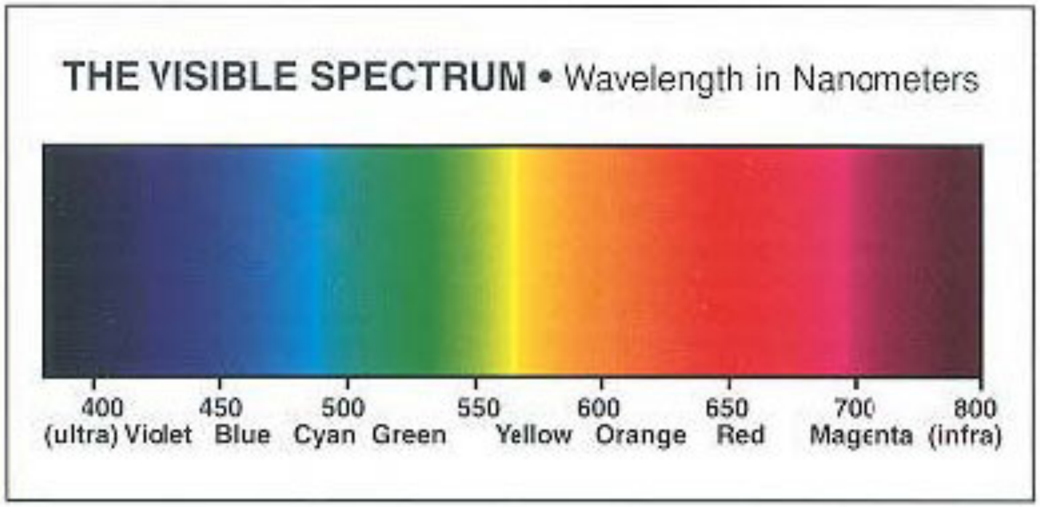
1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.



Thought Question

Which is hottest?

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



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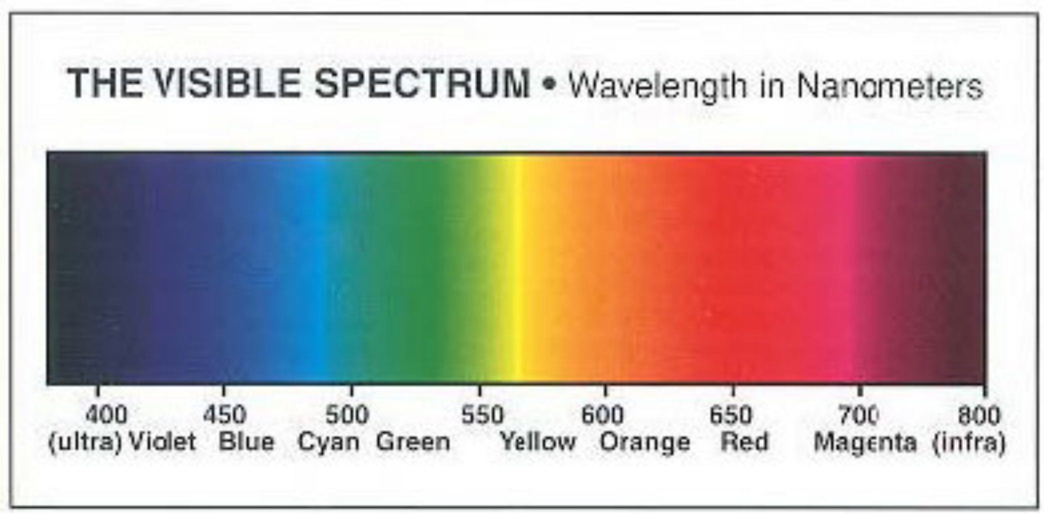
C. a planet that emits only infrared light

Blue color → lower wavelength = higher frequency = higher energy / temperature



Thought Question

Why don't we glow in the dark?

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

Thought Question

Why don't we glow in the dark?

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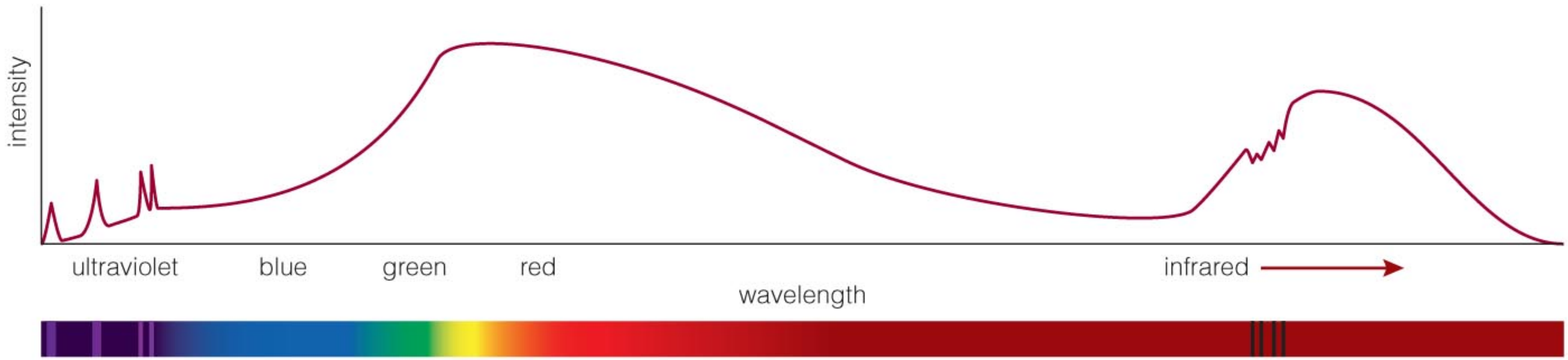
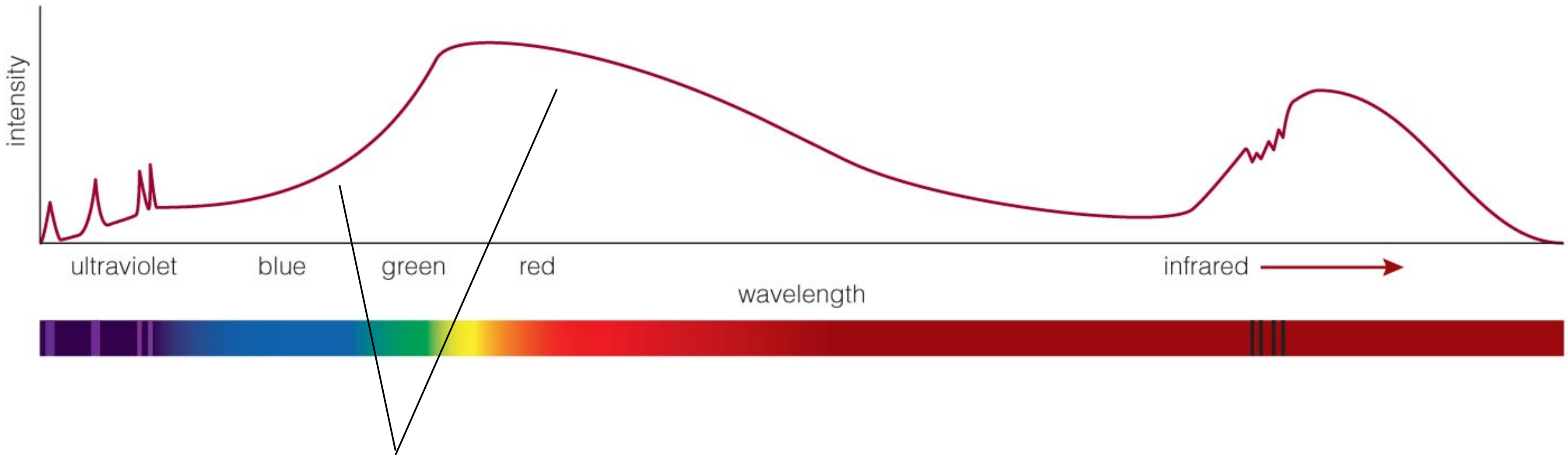
B. People only emit light that is invisible to our eyes (infrared).
C. People are too small to emit enough light for us to see.
D. People do not contain enough radioactive material.

Example: How do we interpret an actual spectrum?



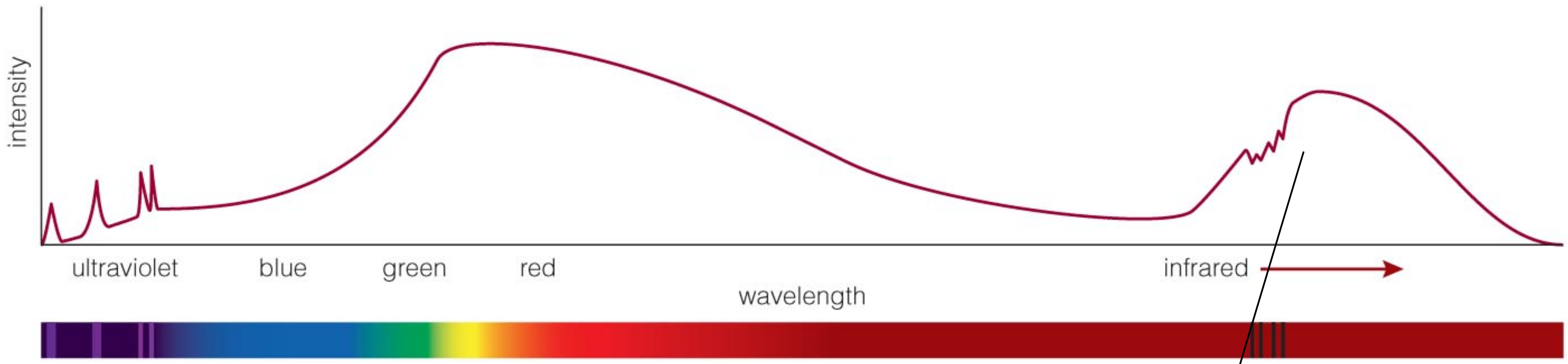
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What is this object?



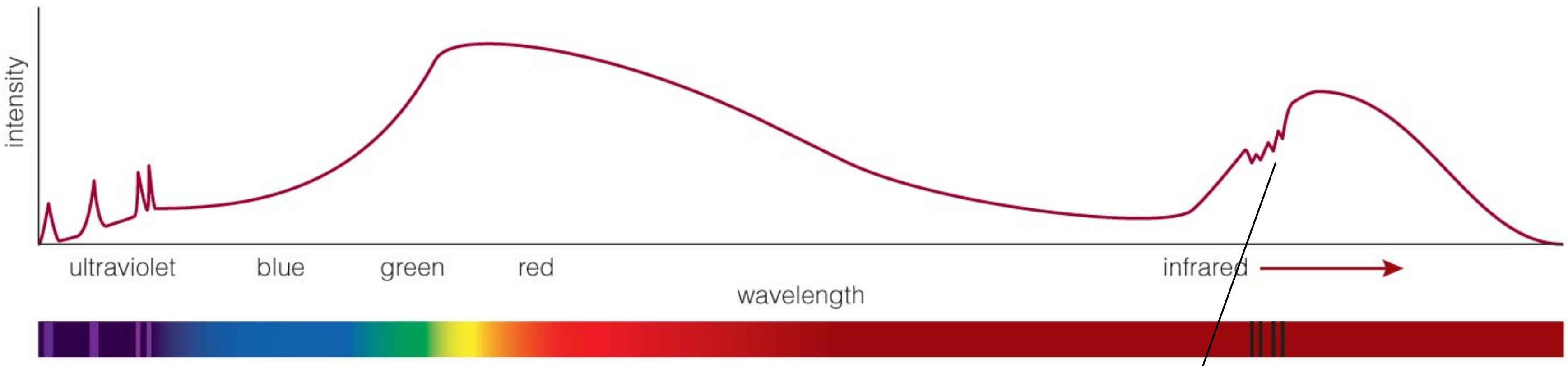
Reflected sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed—object must look reddish.

What is this object?



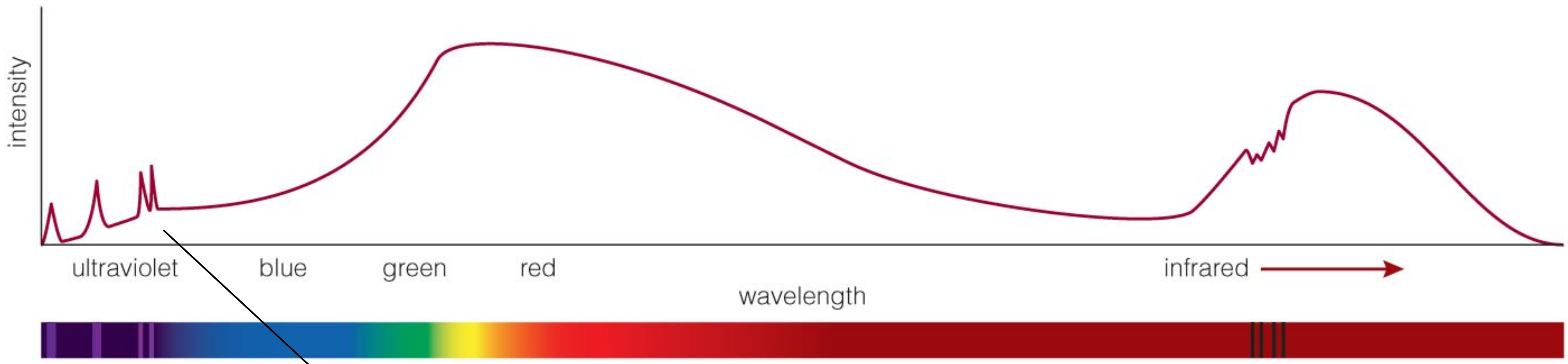
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K / - 48° C / -55° F

What is this object?



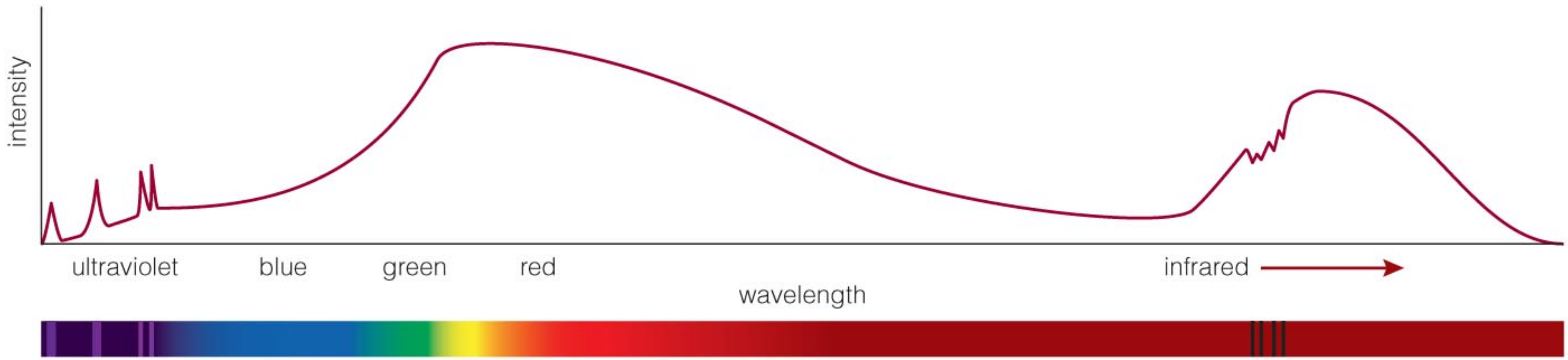
Carbon dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere.

What is this object?



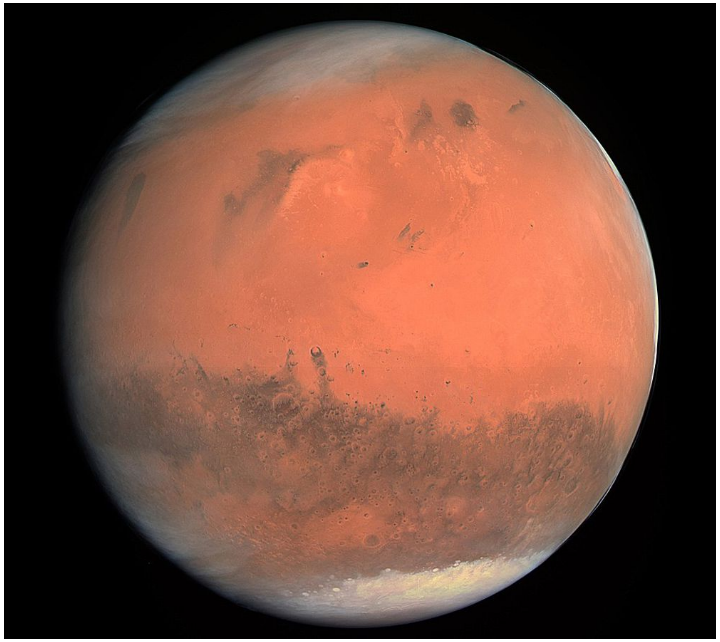
Ultraviolet emission lines: Indicate a hot upper atmosphere

What is this object?

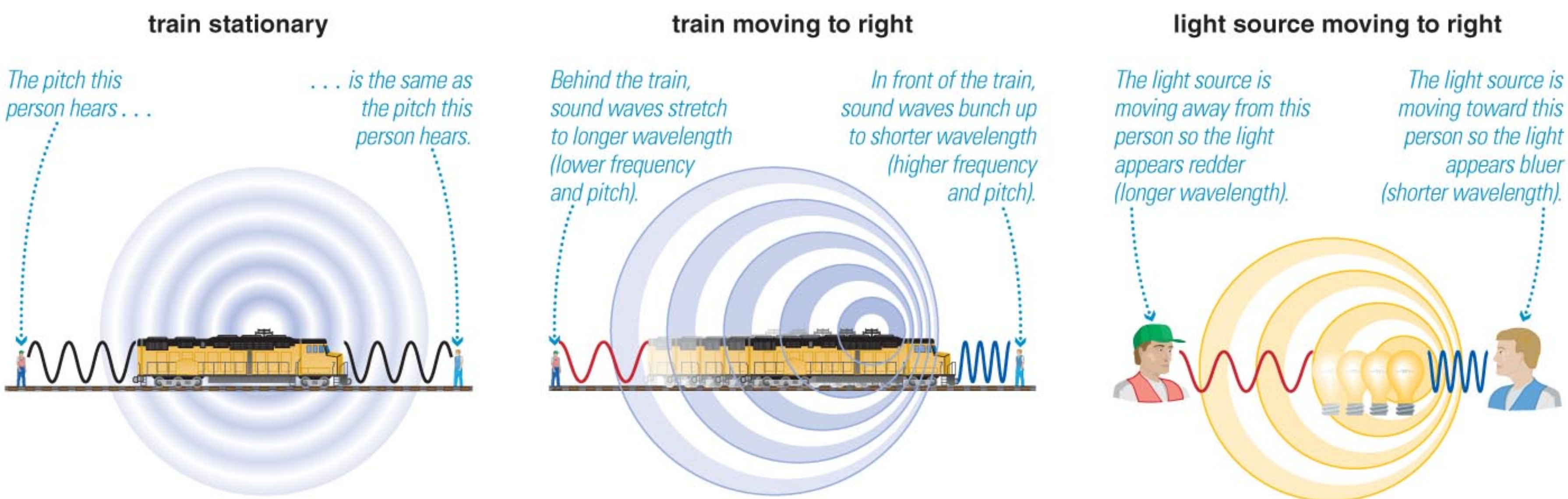


Mars!

The red planet!



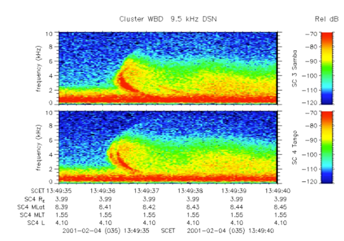
How does light tell us the speed of a distant object?



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

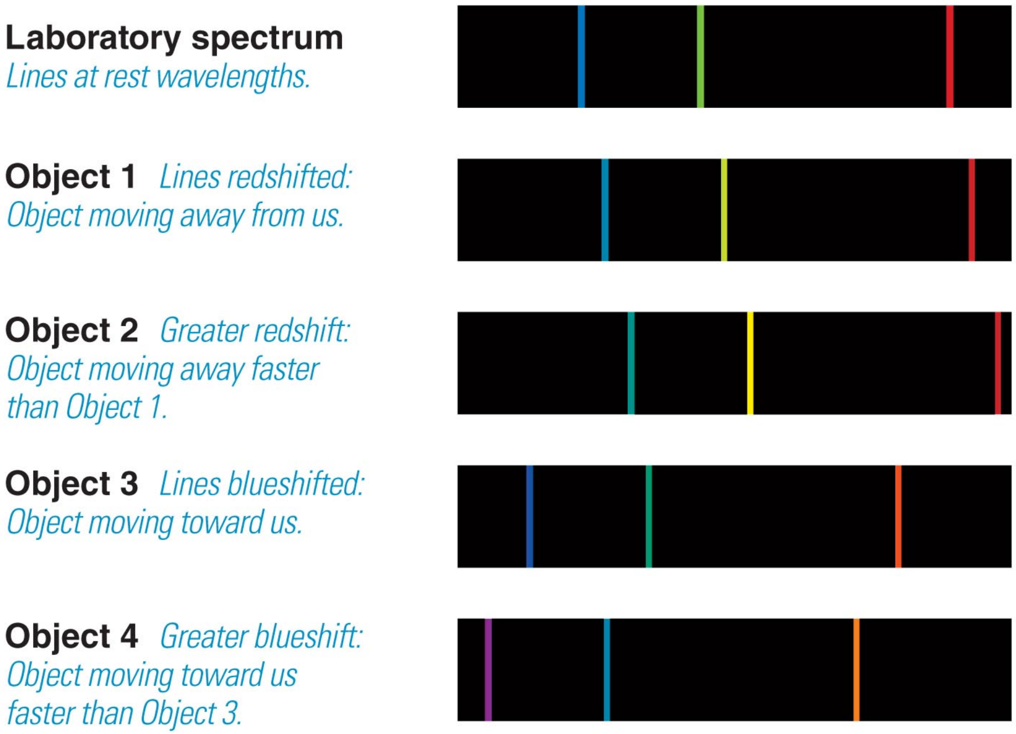
b For a moving train, the sound you hear depends on whether the train is moving toward you or away from you.

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



'Whistler' plasma waves in Earth's magnetosphere

Measuring the Shift



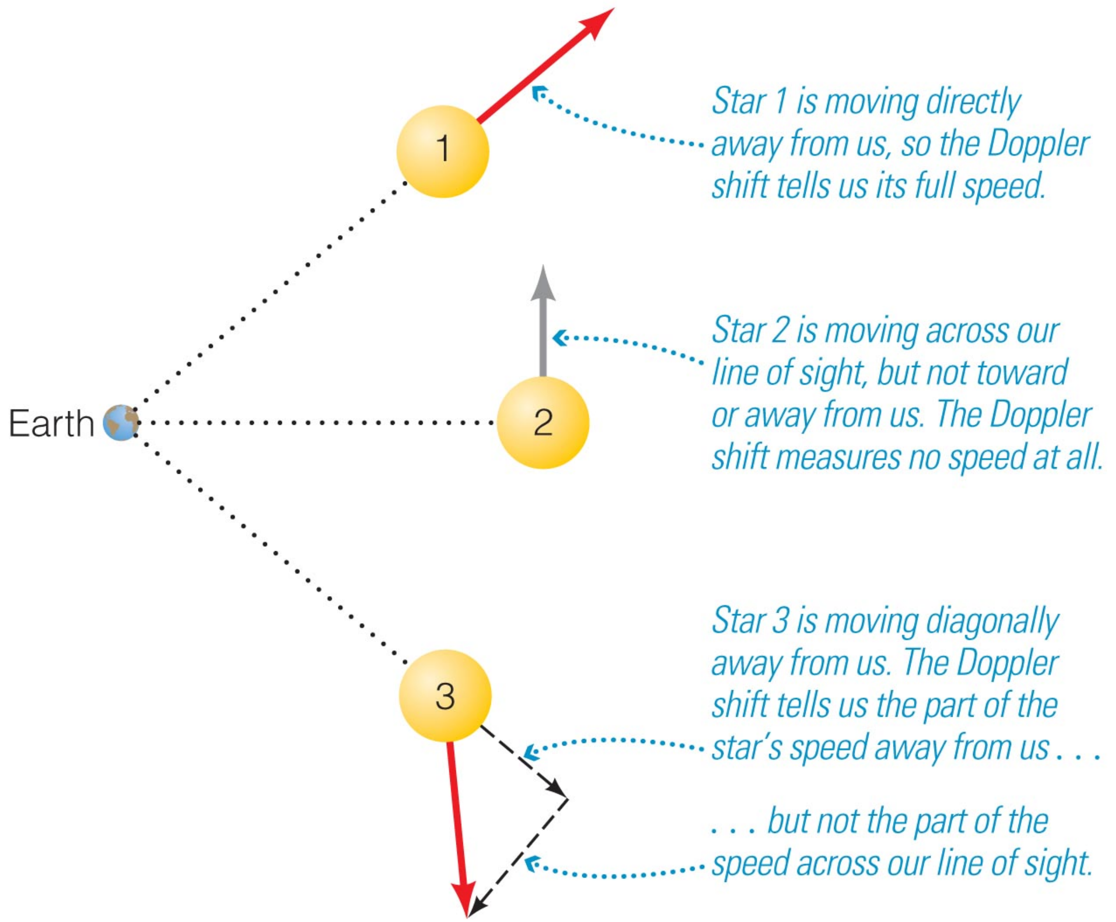
- We generally measure the Doppler effect from shifts in the wavelengths of spectral lines.

Measuring the Shift

- The amount of blueshift or redshift tells us an object's speed toward or away from us.

Measuring the Shift

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



Thought Question

I measure a line in the lab at 500.7 nm. The same line in a star has wavelength 502.8 nm. What can I say about this star?

A. It is moving away from me.
B. It is moving toward me.
C. It has unusually long spectral lines.

Thought Question

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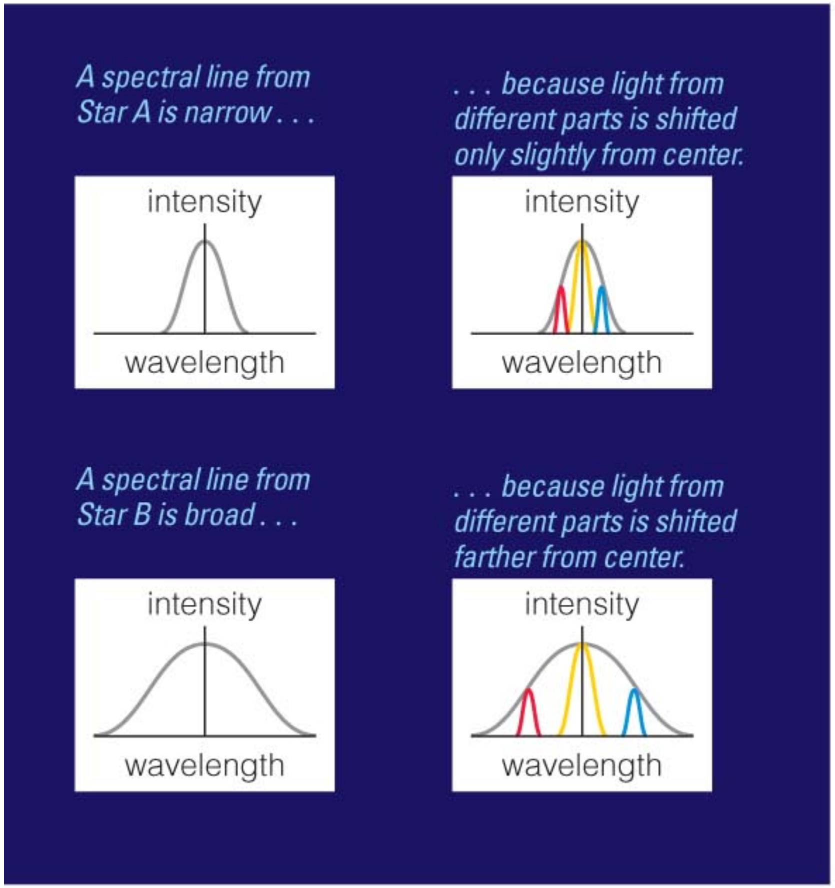
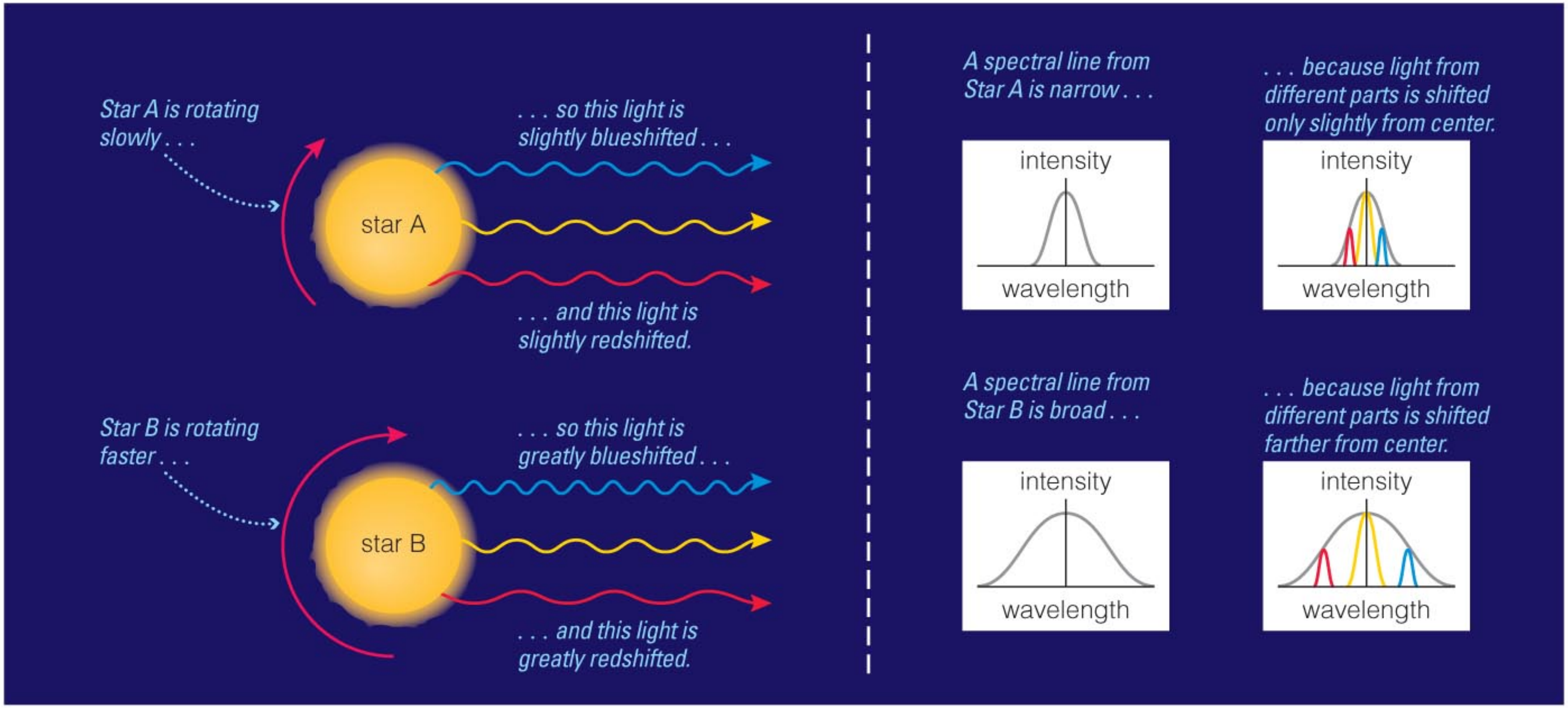
Rotation Rates



- 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.

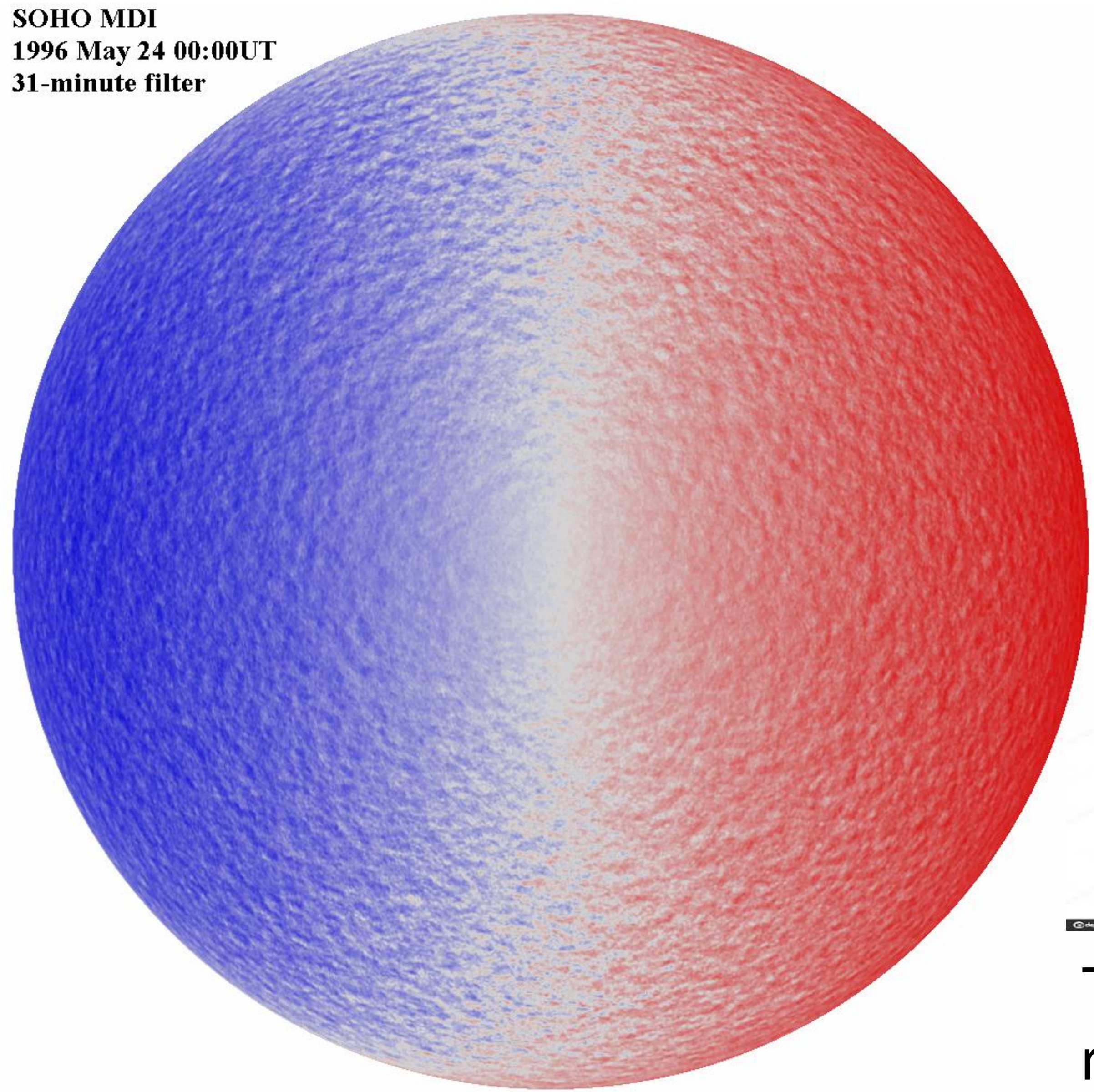
What have we learned?

- **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.

For objects closer to us, like the Sun



Credit: NASA / MSFC

The Sun is rotating, as we know!