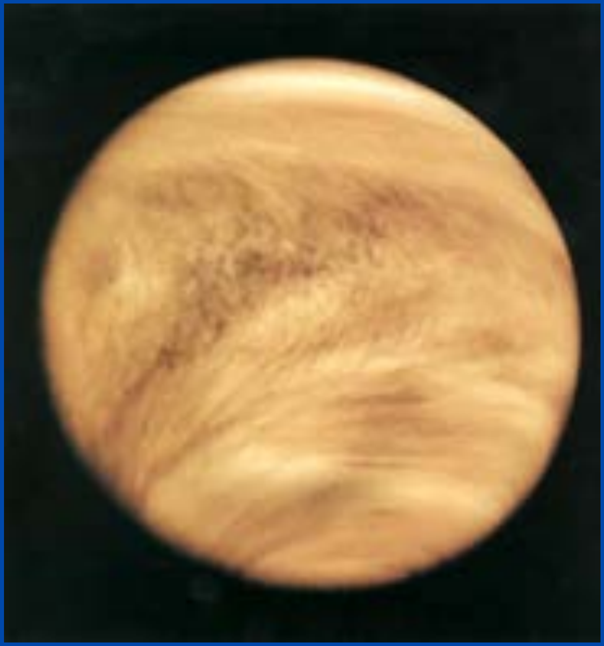
Lecture 5
Part 1: The Scientific Method
Part 2: Light and Matter



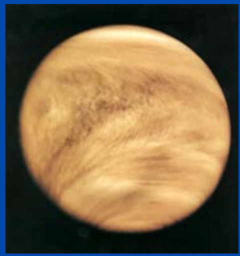
Venus clouds in ultraviolet light

Claire Max

April 17, 2014

Astro 18: Planets and Planetary Systems

UC Santa Cruz



Outline of this lecture

- The Scientific Method
- Properties of light
- Properties of matter
- Interaction of light with matter

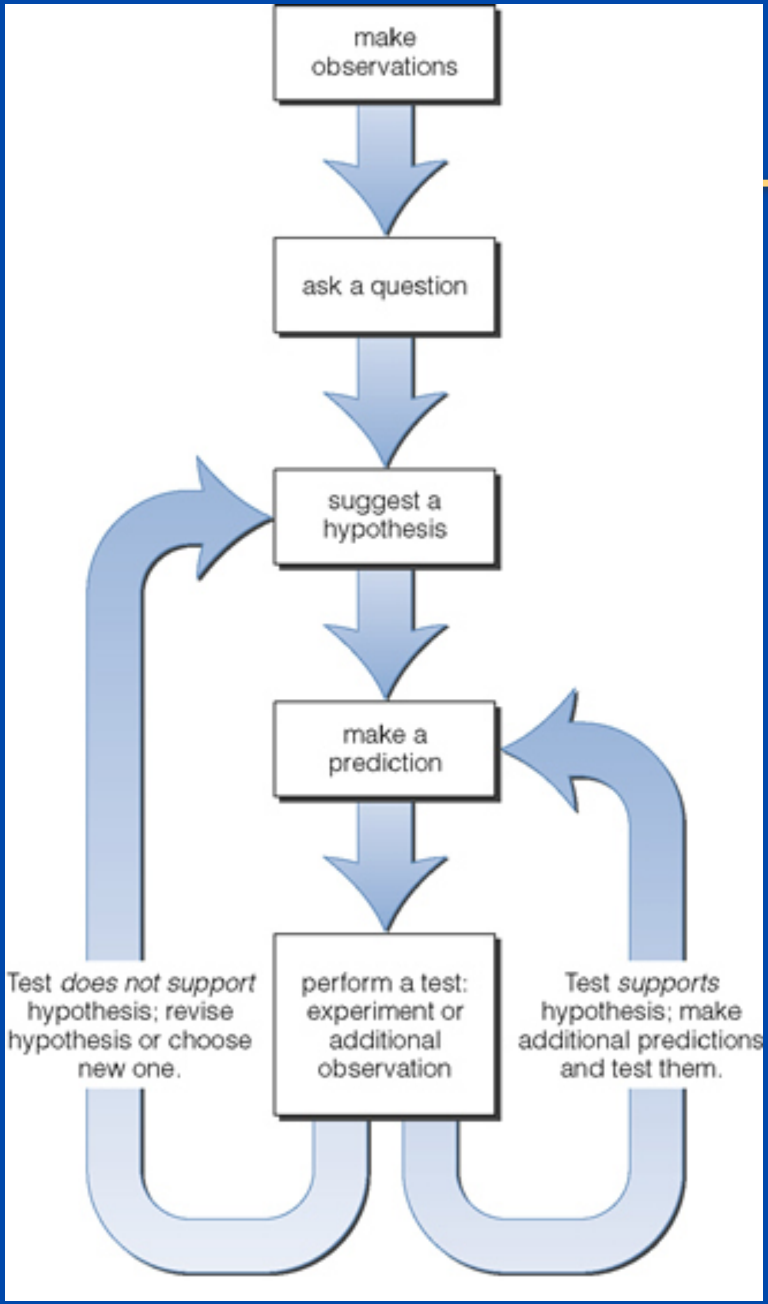
Please remind me to take a break at 12:45 pm!

The Scientific Method

- What is a scientific theory?
- How can we distinguish science from non-science?

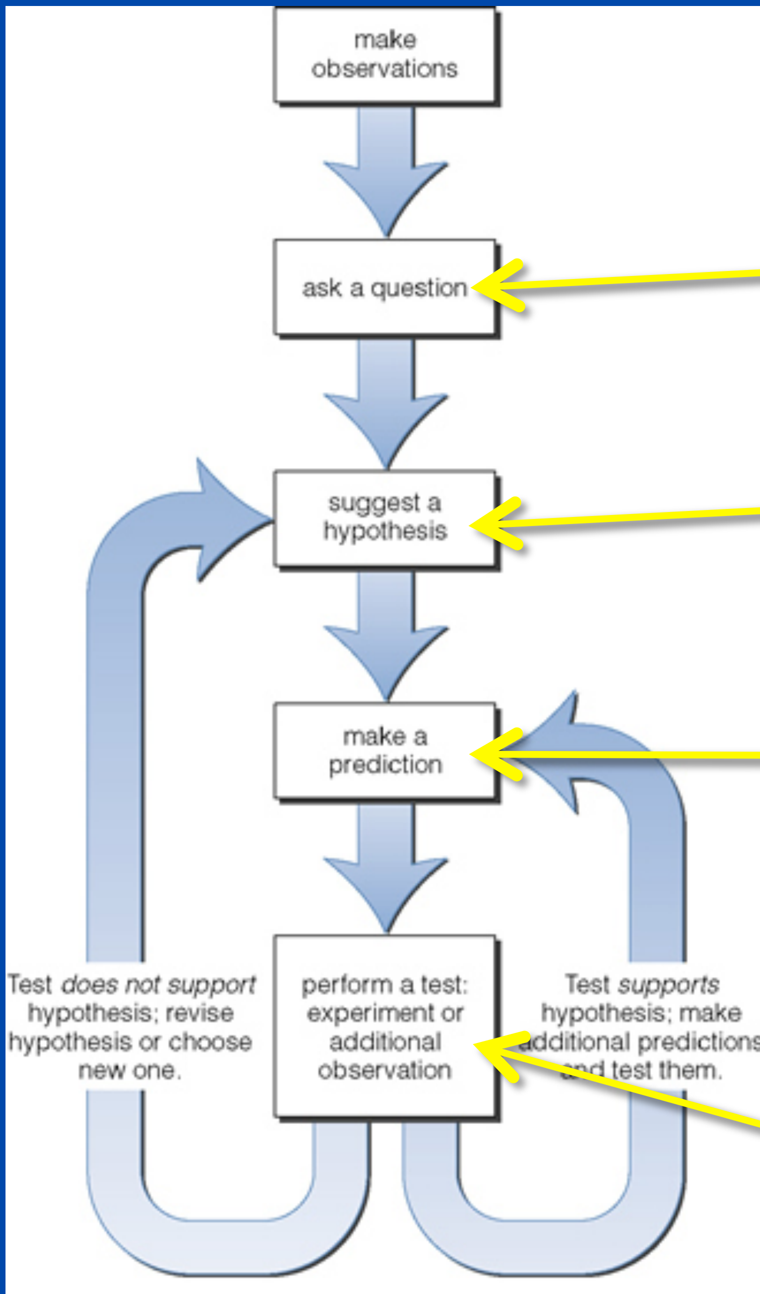
What is a scientific theory?

- The word "theory" has a somewhat different meaning in science than in everyday life.
- A *scientific theory* must:
  - — Explain a wide variety of observations with a few simple principles
  - — Be supported by a large, compelling body of evidence
  - — Must not have failed crucial tests of its validity
  - — Must be amenable to modification if new data require this
- Newton's laws of gravitation are a good example
  - They explain a wide body of observations, have lots of evidence, but under some (very unusual) circumstances they require modification
  - Near black holes and neutron stars, gravity is so strong that Einstein's theory of General Relativity applies, instead of Newton's laws



Ideal scientific method

- **Based on proposing and testing hypotheses**
- **Hypothesis = educated guess**
- **Testing is crucial**



More realistically:

What are some questions I can actually answer?

Can take many tries to pose a sensible one

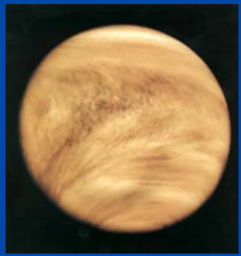
In astronomy, frequently a "post-diction"

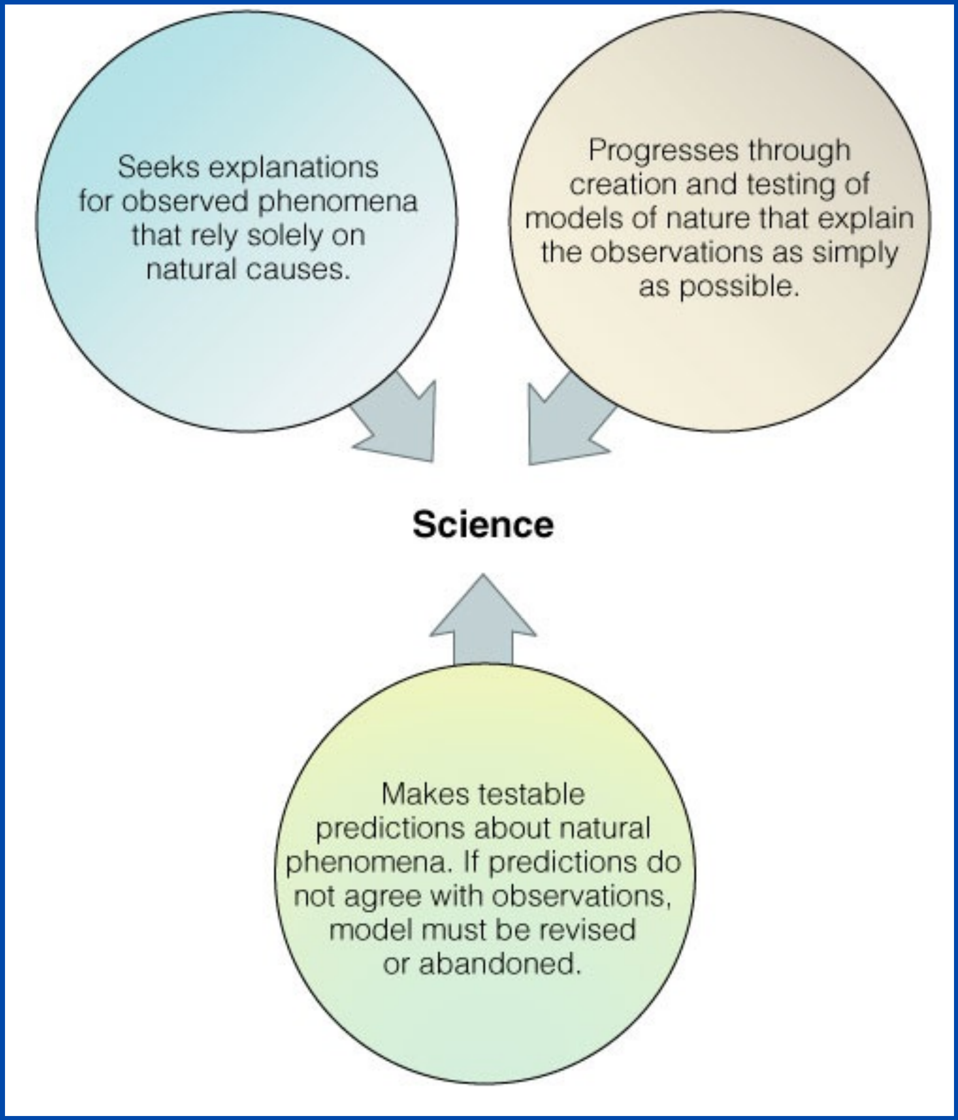
Test results can be ambiguous

But science doesn't always proceed in this idealized way!

- Sometimes we start by "just looking" and then coming up with possible explanations.
- Sometimes we follow our intuition rather than a particular line of hard evidence.
- There are frequently several blind alleys that don't work out, before a successful theory is developed and tested.
- But in the end, a theory must be tested against experiment

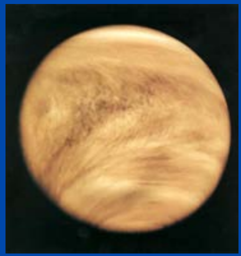
Hallmarks of science





- **Useful criteria to decide whether an argument is scientific or not**

Hallmarks of Science: #1



- In ancient times, actions of the gods were invoked as explanations for things that were hard to understand
- But modern science seeks explanations for observed phenomena that rely solely on natural causes
- Other kinds of explanations don't come under the heading "science", but rather are different kinds of discussions

Hallmarks of Science: #2

- Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.

- Example: By early 1600s, there were several competing models of planetary motion (Ptolemy, Copernicus, Kepler, …) Kepler's gained acceptance because it worked the best when compared with the latest data.

Hallmarks of Science: #3

- A scientific model should make testable predictions about natural phenomena.
- If subsequent tests don't agree with the predictions, a scientist would be willing (even eager) to revise or even abandon his/her model.
- If someone, in the face of data that contradict his/her model, isn't willing to revise or abandon it, they are not using the scientific method.

Issues for Planetary Science

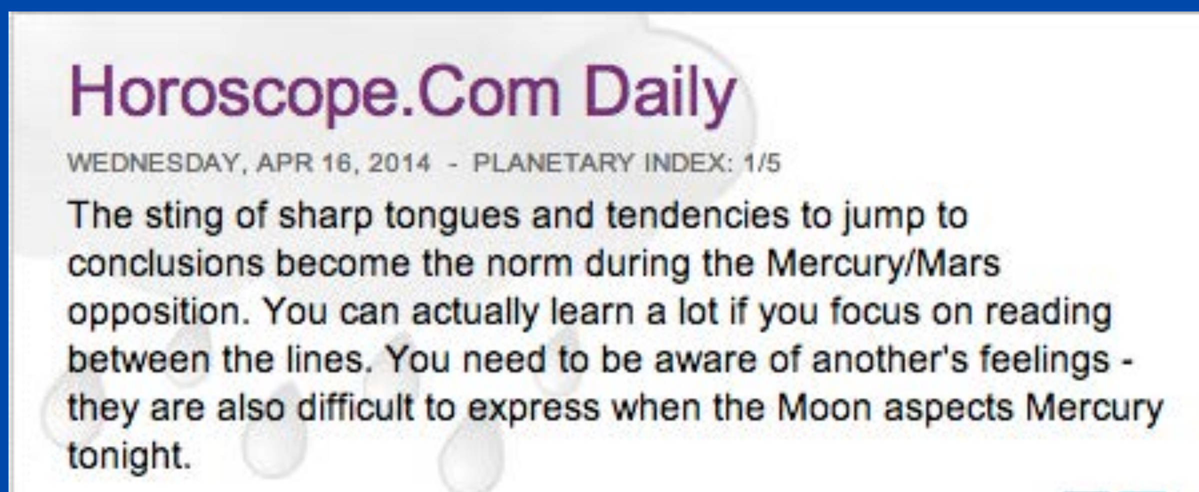
- Planets and their moons are hugely varied
- For example: We aren't advanced enough to have an *a priori* theory that would predict what a newly discovered moon of Jupiter or Saturn should be like
- "Retrodiction" or "postdiction" rather than "prediction"
  - Try to understand new observations using general principles based on previous body of data

What about astrology?

- How is astrology different from astronomy?
- Is astrology a scientific theory?
- Does astrology have scientific validity?

Astrology asks a different type of question than astronomy

- **Astronomy is a science focused on learning about how stars, planets, and other celestial objects work.**
- **Astrology is a search for hidden influences <u>on human lives</u> based on the positions of planets and stars in the sky.**



Horoscope.Com Daily

WEDNESDAY, APR 16, 2014 - PLANETARY INDEX: 1/5

The sting of sharp tongues and tendencies to jump to conclusions become the norm during the Mercury/Mars opposition. You can actually learn a lot if you focus on reading between the lines. You need to be aware of another's feelings - they are also difficult to express when the Moon aspects Mercury tonight.

Does astrology have scientific validity?

- In principle the stars *might* influence human affairs.
- Scientific tests consistently show that astrological predictions are no more accurate than we should expect from pure chance.
- Proponents of astrology say that the act of doing controlled experiments ruins the "aura" and that's why predictions aren't accurate when tested in a lab.
- In my opinion this means that astrology doesn't come under the heading "science", since it can't (or won't) make testable predictions.

In December 1985, Shawn Carlson published "A double-blind test of astrology" in the journal Nature. The purpose was to test the fundamental thesis of astrology, as agreed by the astrologers involved, which was the proposition that:

> the position of the "planets" (all planets, the Sun and Moon, plus other objects defined by astrologers) at the moment of birth can be used to determine the subject's general personality traits and tendencies in temperament and behaviour, and to indicate the major issues which the subject is likely to encounter.

http://skeptico.blogs.com/skeptico/2007/06/testing-astrolo.html

There were two tests. In the first test, subjects were asked to pick their own horoscope out of three (their own and two controls). In the second test, astrologers were asked which one of three California Personality Index (CPI) results belonged to the subject whose natal data they had been given. Astrology failed both tests – the results were no better than chance.

What have we learned?

- **A scientific theory should:**
  - — **Explain wide variety of observations with a few simple principles,**
  - — **Be supported by a large, compelling body of evidence,**
  - — **Must not have failed crucial tests of its validity,**
  - — **Be amenable to modification if new data require this.**
- **Astrology**
  - **Search for hidden influences on human lives based on the positions of planets and stars**
  - **Thus far scientific tests show that astrological predictions are no more accurate than we should expect from pure chance**

Light: The Main Points

- Most of what we know about the universe comes to us in the form of light
- The visible light that our eyes can see is only a small part of the electromagnetic spectrum
  - Also radio waves, infrared light, ultraviolet light, x-rays, gamma-rays
- By spreading light out into different "colors" (taking a spectrum) we can learn about the physical conditions of the light-emitter and of intervening material
  - Composition, temperature, motion toward or away from us, rotation rate, atmospheric structure, ...

Light and Matter: Outline

Much of what we have learned about the universe is based on observing light, and understanding how it has interacted with matter

- Properties of light
- Properties of matter
- How light interacts with matter

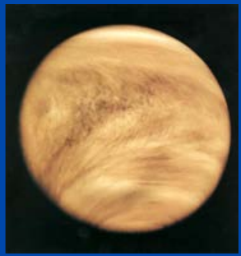
How do we experience light?

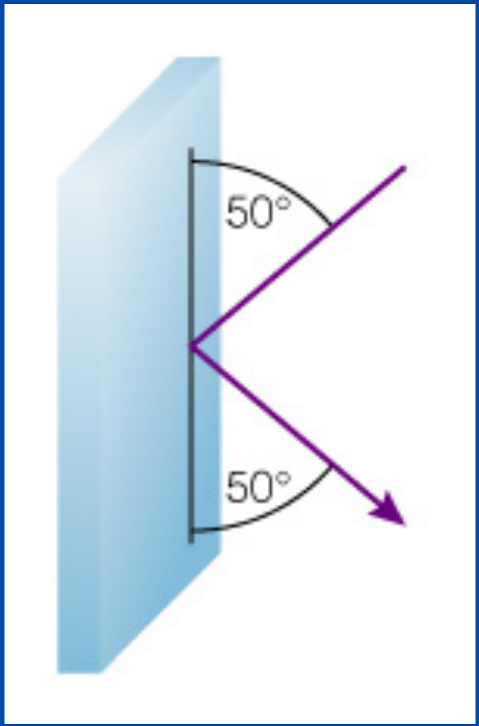
- The warmth of sunlight tells us that light is a form of energy!
- We measure the flow of energy in light in units of watts: 1 watt = 1 joule/s.

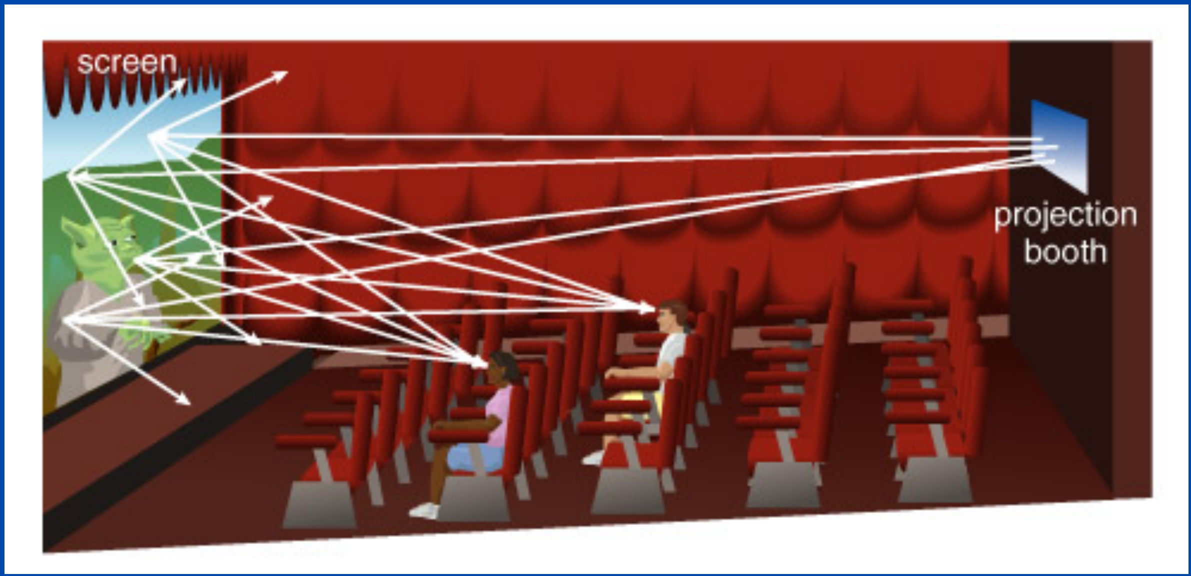
How do light and matter interact?

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

Reflection and Scattering



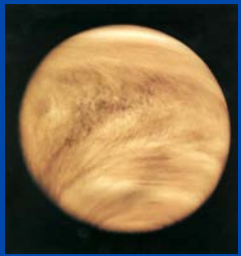


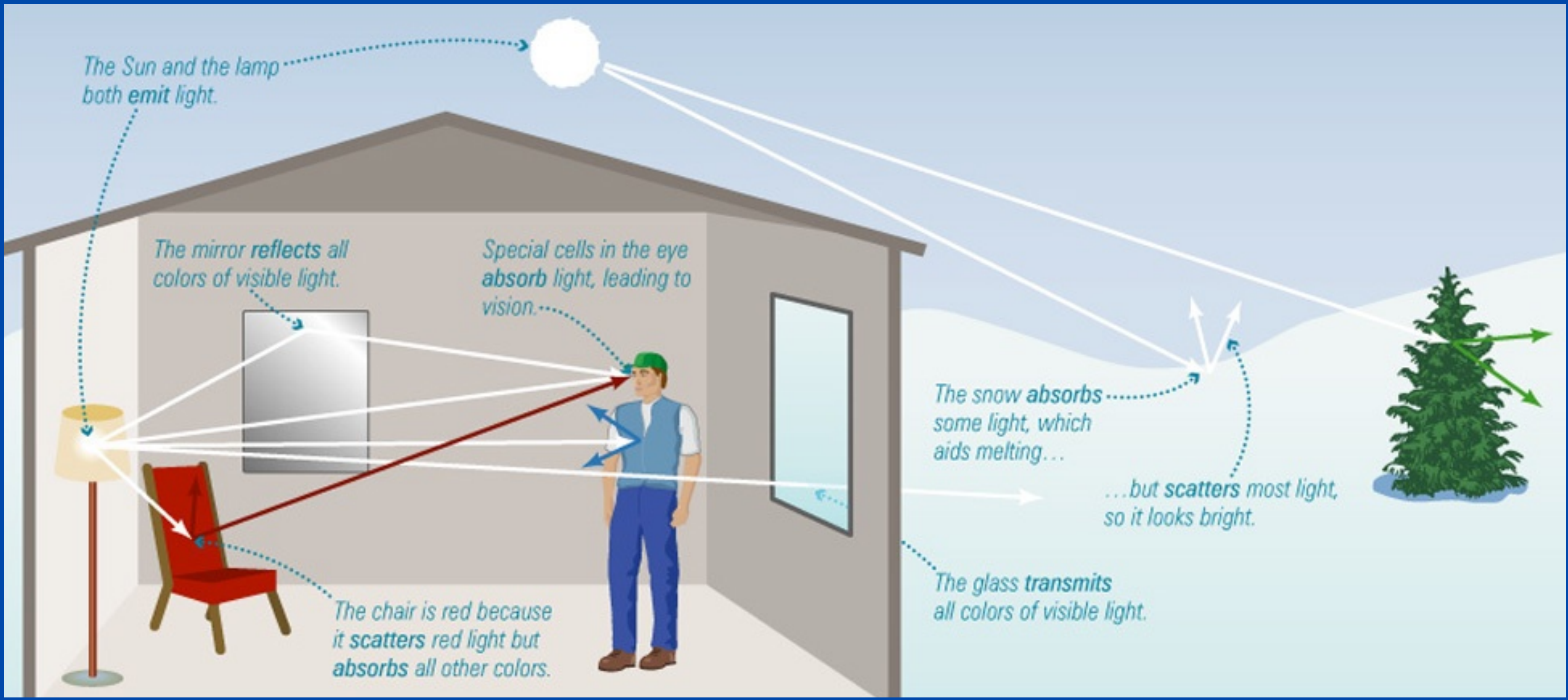


Mirror reflects light in a particular direction

Movie screen scatters light in all directions

Interactions of Light with Matter





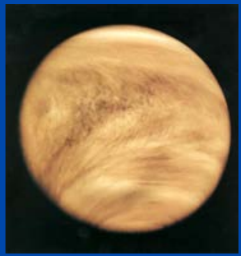
- Interactions between light and matter determine the appearance of everything around us

What is light?

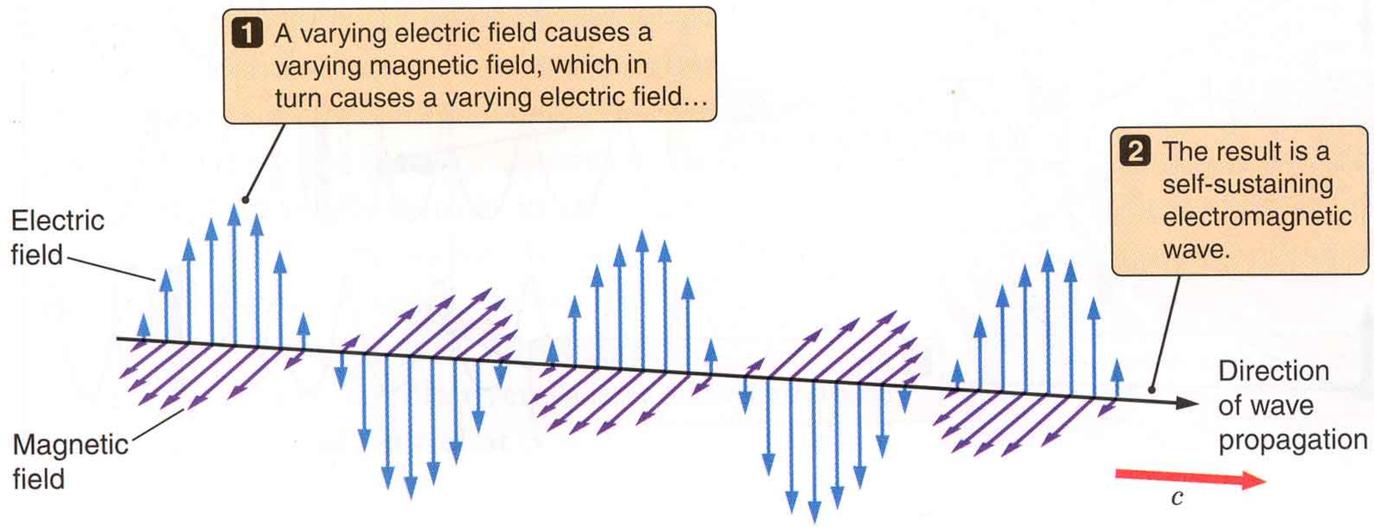
- **Light can act either like a wave or like a particle.**

- **Particles of light are called photons.**

What is light?



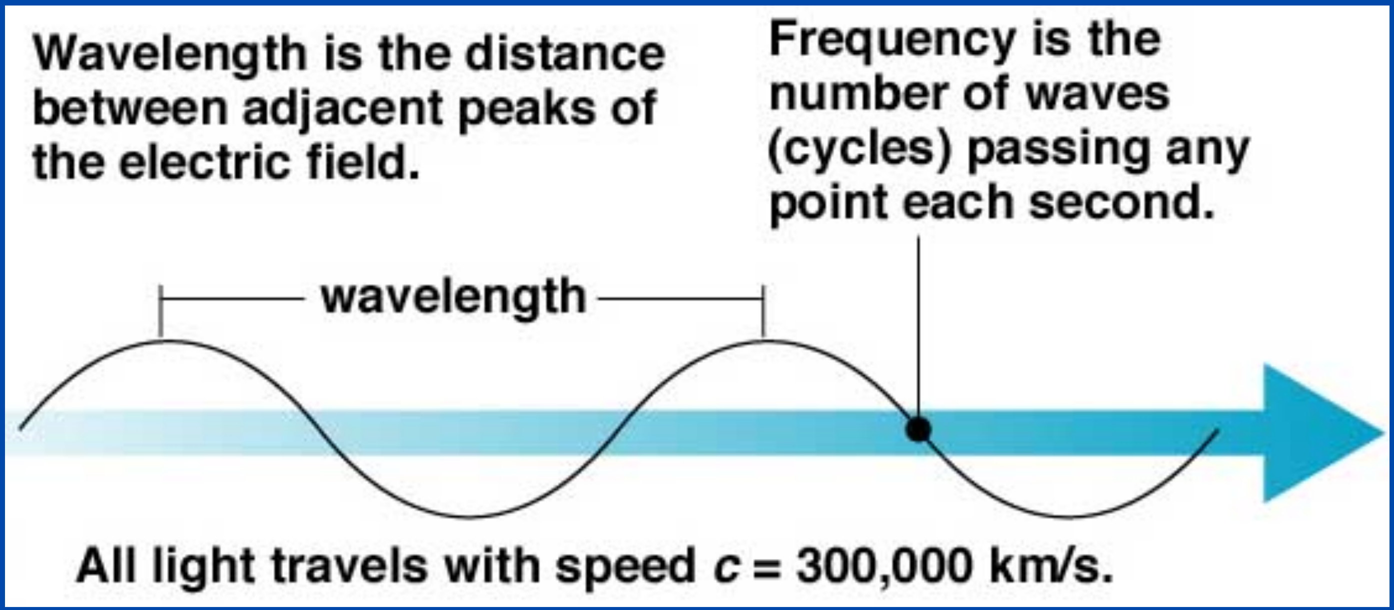
- **Oscillating electric and magnetic fields, traveling at "speed of light" (300,000 km/sec)**



Far from its source, an electromagnetic wave consists of oscillating electric and magnetic fields that are perpendicular both to each other and to the direction in which the wave travels.

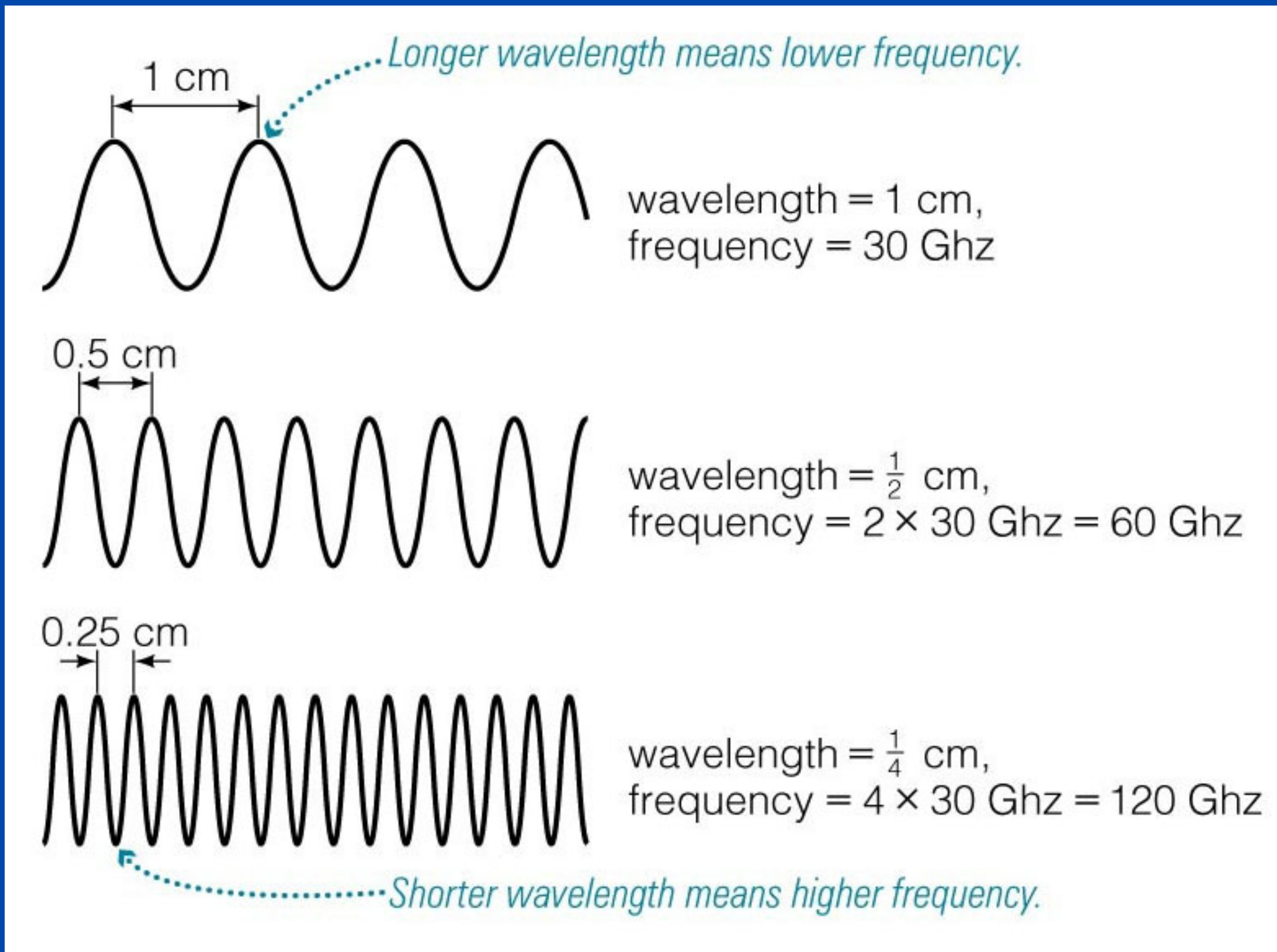
Light can be described as a wave

- Wave: a periodic disturbance that travels through space and time
  - Wavelength λ (e.g. meters)
  - Frequency *f* (cycles per sec or Hertz)
  - Propagation speed *c* (e.g. meters / sec)

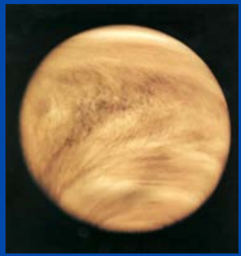


Anatomy of a Wave

Wavelength visualized



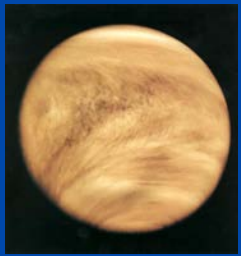
Relation between frequency and wavelength of a light wave



- **If a wave oscillates *f* times a second, its frequency is *f* cycles per sec or Hertz**
- **Period of a wave is time for two crests to pass a given point in space: *P = 1 / f* sec**
- **Relation between frequency *f* and wavelength λ**

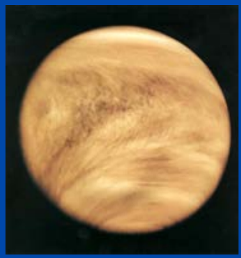
$$\lambda = \frac{c}{f} \quad \text{or} \quad f = \frac{c}{\lambda}$$

Units of frequency and wavelength



$$\lambda(length) = \frac{c\left(\dfrac{length}{\cancel{time}}\right)}{f\left(\dfrac{1}{\cancel{time}}\right)} = \left(\frac{c}{f}\right) length$$

Units used for wavelength

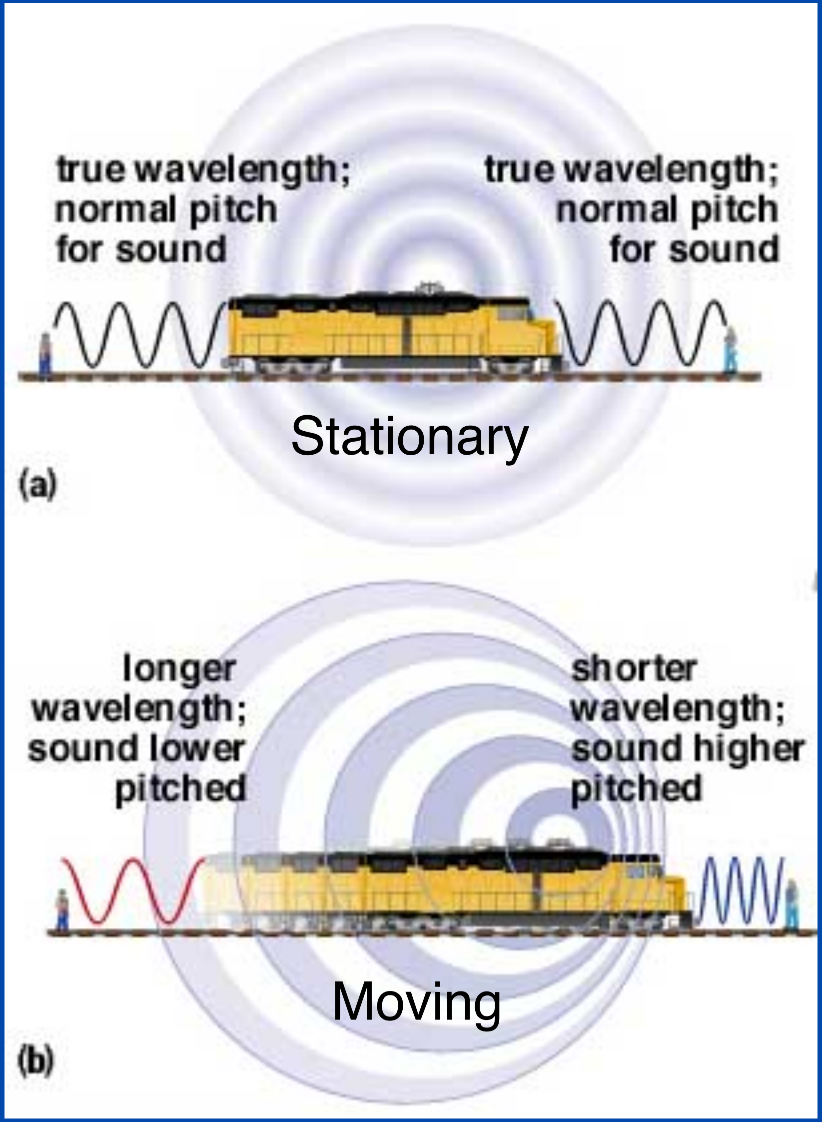


Unit	Symbol	Length
centimeter	cm	10^{-2} meters
Angstrom	Å	10^{-8} centimeters
nanometer	nm	10^{-9} meters
micron	µm	10^{-6} meters

Units of Wavelength

Doppler shift: a moving object can change frequency of emitted or reflected waves

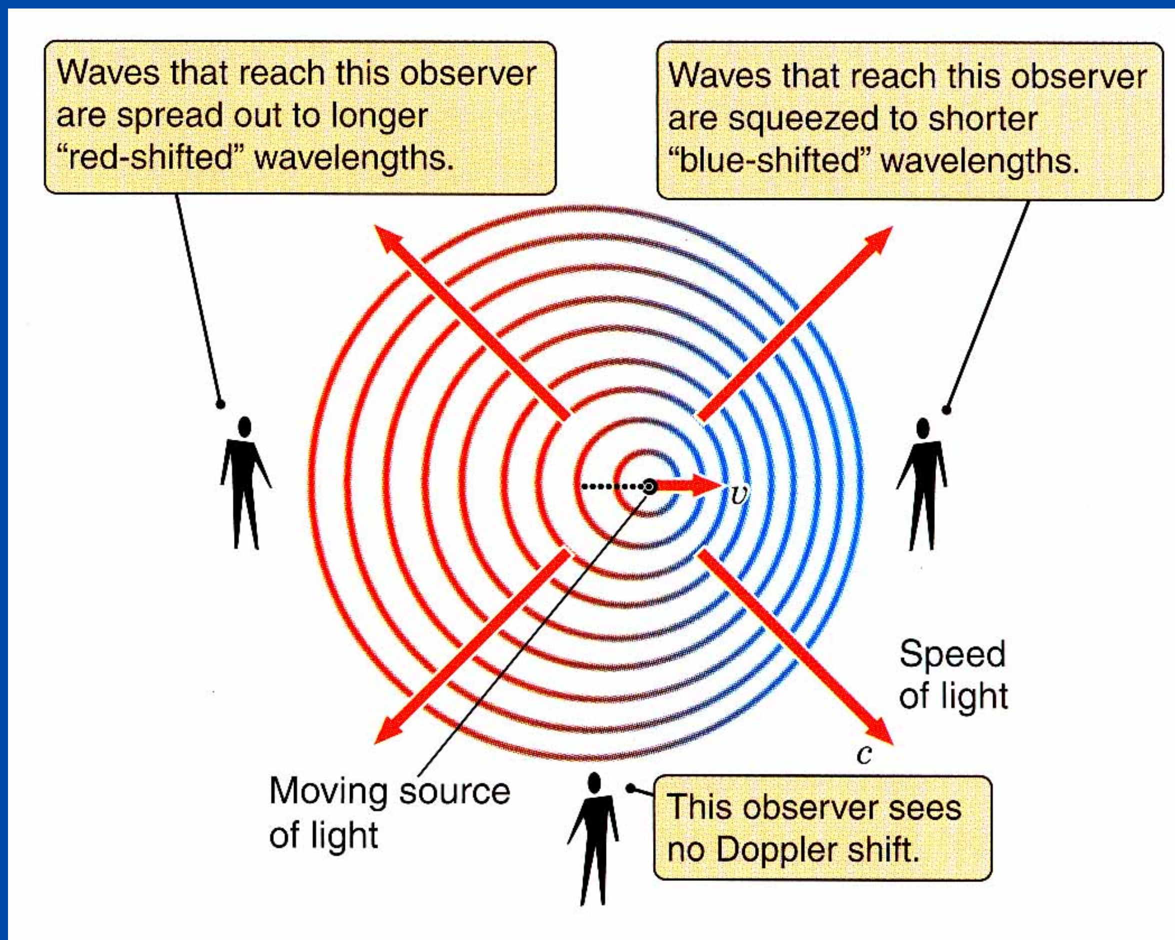
Sound waves:



- <u>**Hearing the Doppler Effect**</u>

Doppler shift: a moving object can change frequency of emitted or reflected waves

Light waves:



Size of Doppler shift depends on speed v

$$\frac{\text{velocity}}{\text{speed of light}} = \frac{\text{shifted wavelength} - \text{rest wavelength}}{\text{rest wavelength}}$$

$$\frac{v}{c} = \frac{\lambda_1 - \lambda_0}{\lambda_0}$$

Example of Doppler shift

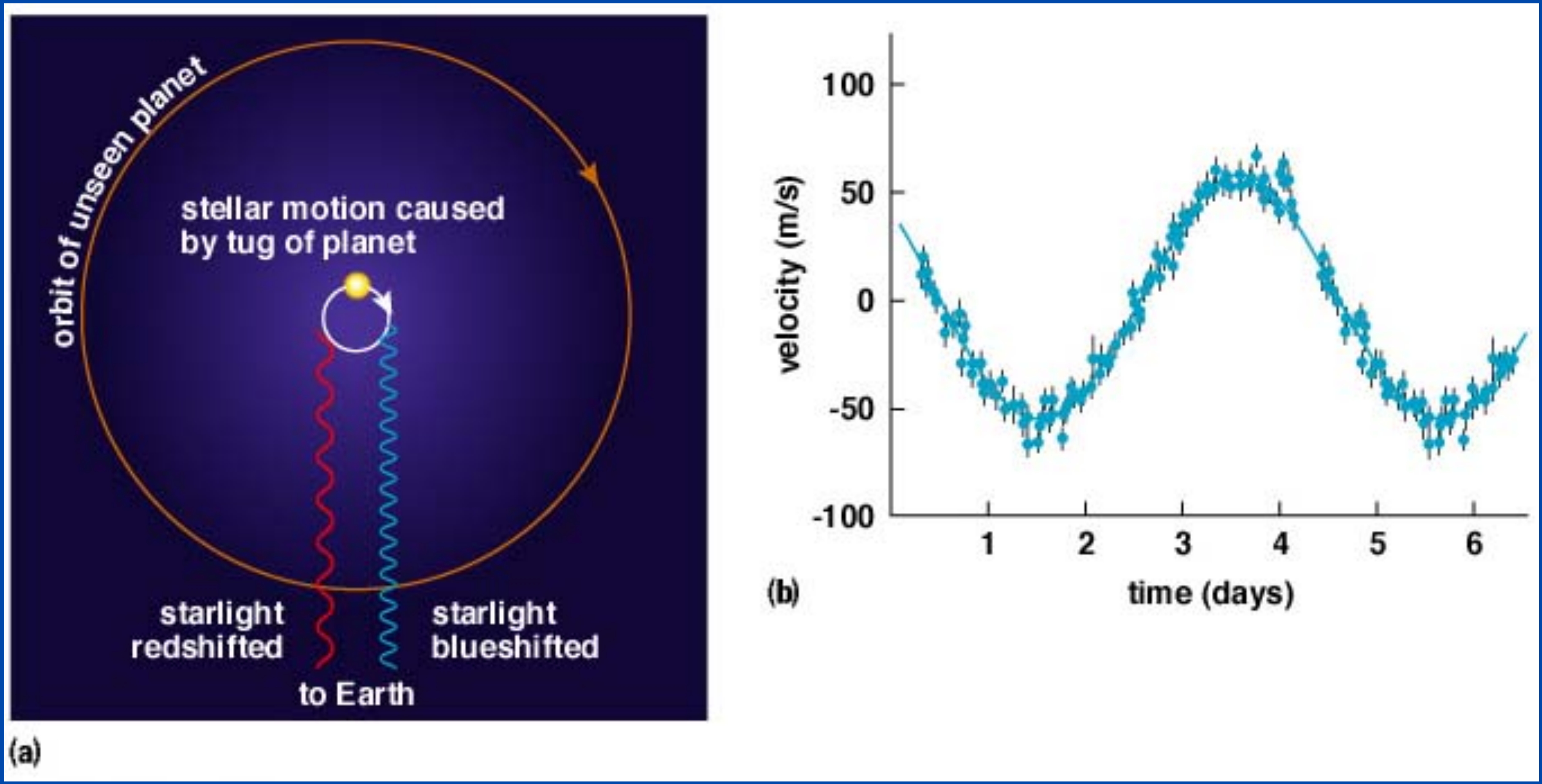
- The "rest wavelength" of light being emitted by a planet is 6562.85 Å, and we observe this light to be shifted to a wavelength of 6562.55 Å
- What velocity does light's source have?

$$\mathrm{v} = \left(\frac{\lambda_1 - \lambda_0}{\lambda_0} \right) \times c$$

$$\mathrm{v} = \left[\frac{(6562.55 - 6562.85) \times 10^{-8}\, cm}{6562.85 \times 10^{-8}\, cm} \right] \times \left(3 \times 10^{10} \frac{cm}{\mathrm{sec}} \right)$$

$$= -1.37 \times 10^{6} \left(\frac{cm}{\mathrm{sec}} \right) = -13.7 \left(\frac{km}{\mathrm{sec}} \right) \text{ toward us}$$

Extrasolar planets: one method of detection relies on Doppler shift



Concept Question

- **Which of the following are ways to detect the velocity of a star towards us or away from us?**

  a) **taking photographs 6 months apart**
  b) **applying the inverse square law of brightness**
  c) **measuring the shift in wavelength of its light**
  d) **measuring the shift in distance of the star**

Light as a particle: photons

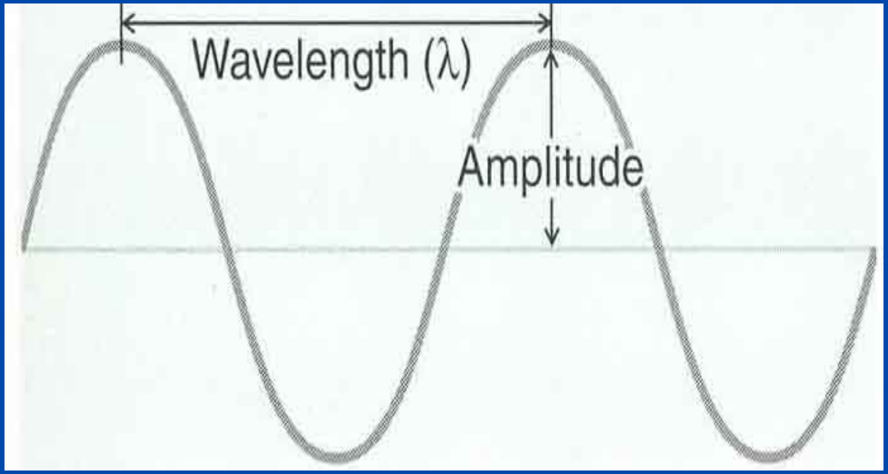
- **A paradox: light behaves <u>both</u> as a particle <u>and</u> as a wave!**
- **Just as a baseball carries a specific amount of kinetic energy, each light particle or "photon" of light carries a specific amount of radiative energy:**

$$E = hf = \frac{hc}{\lambda}$$

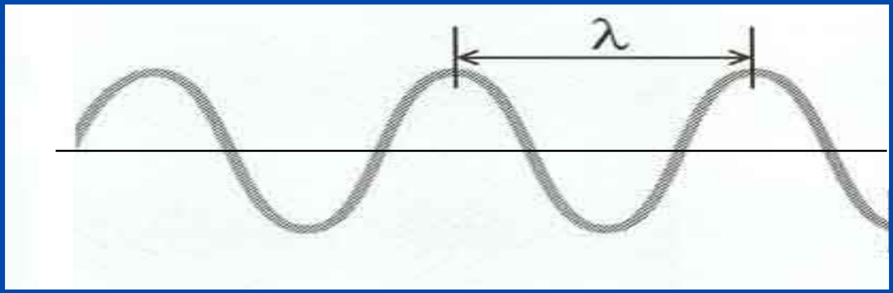
$$h = 6.63 \times 10^{-34} \text{ joule sec=Planck's constant}$$

$$\text{Check units: } E \text{ (joules)} = h \text{ (joule sec)} \, f \left(\frac{1}{\text{sec}}\right)$$

Distinguish between light energy and light intensity



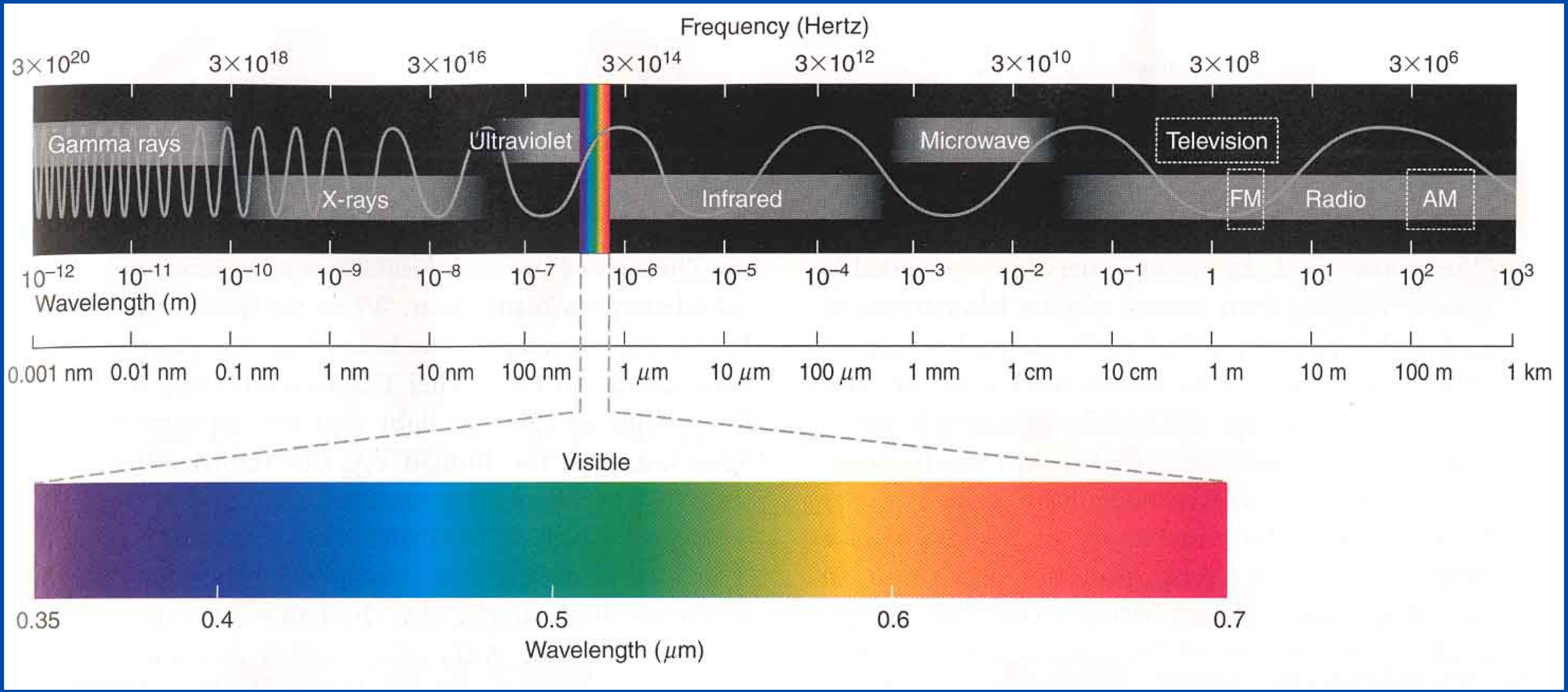
- **Higher amplitude and intensity**
  - **Intensity is just square of amplitude**



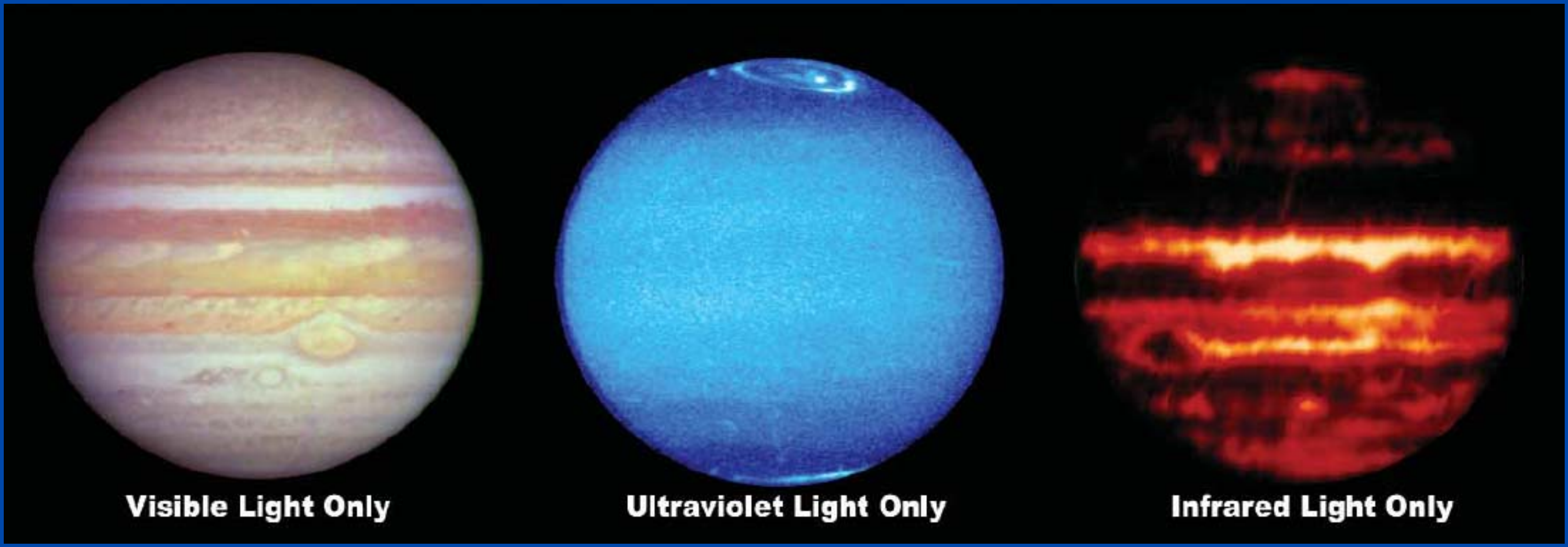
- **Higher frequency and photon energy**

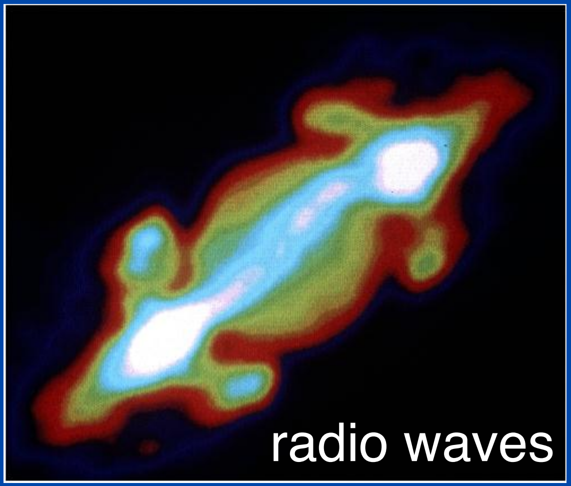
$$E = h \times f = \frac{hc}{\lambda}$$

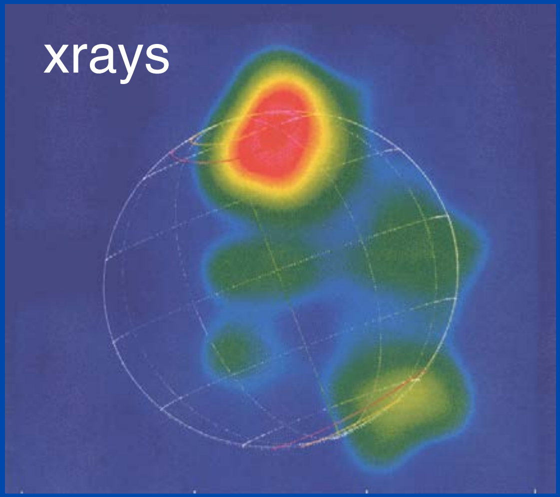
Visible light is only a small fraction of the electromagnetic spectrum



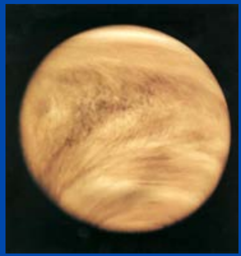
Jupiter at many wavelengths: Each tells us something different about the planet







What have we learned?

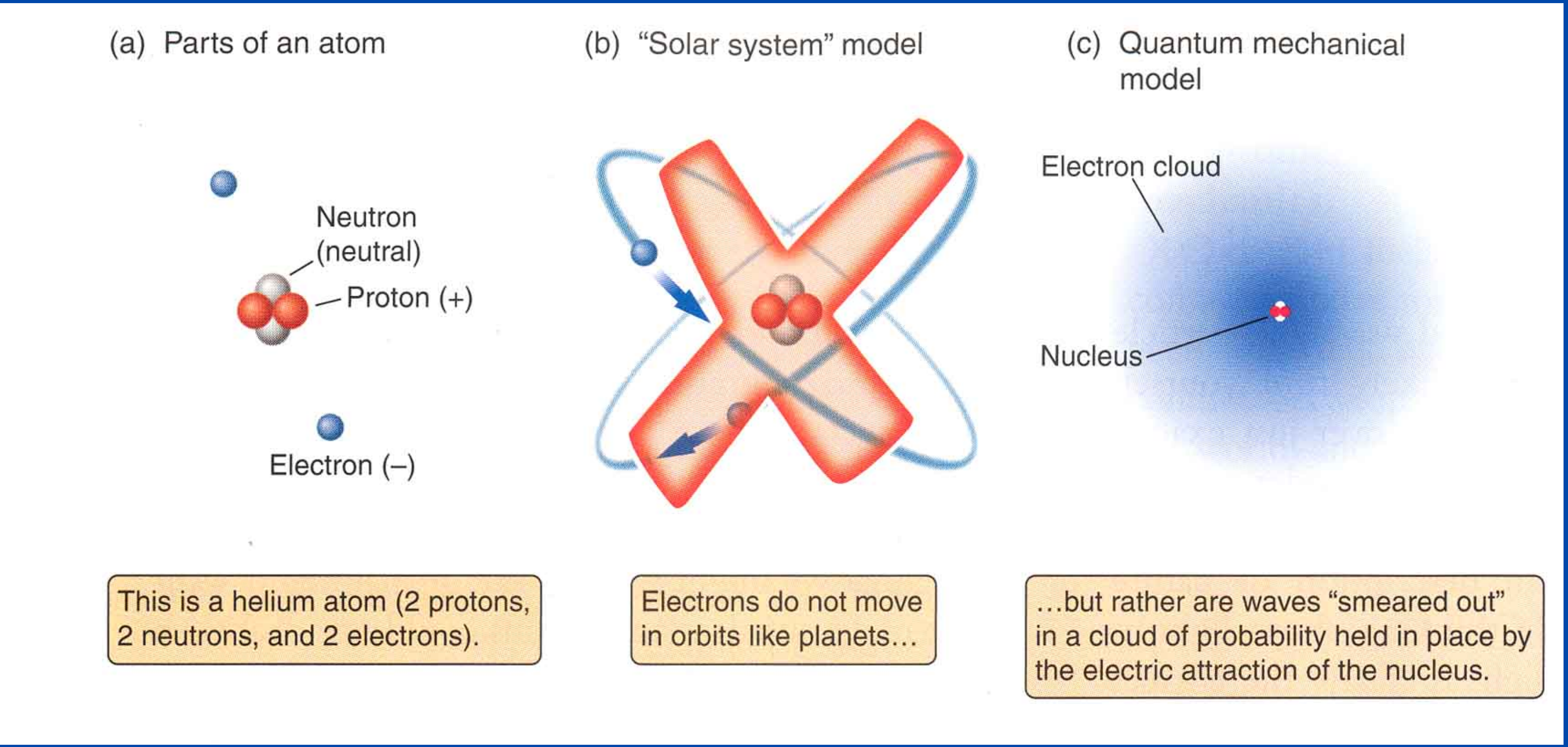


- **What is light?**
  - Light can behave like either a wave or a particle.
  - A light wave is a vibration of electric and magnetic fields.
  - Light waves have a wavelength and a frequency.
  - Photons are particles of light.
- **What is the electromagnetic spectrum?**
  - Human eyes cannot see most forms of light.
  - The entire range of wavelengths of light is known as the electromagnetic spectrum.

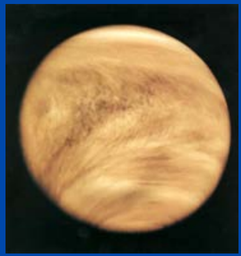
Properties of Matter

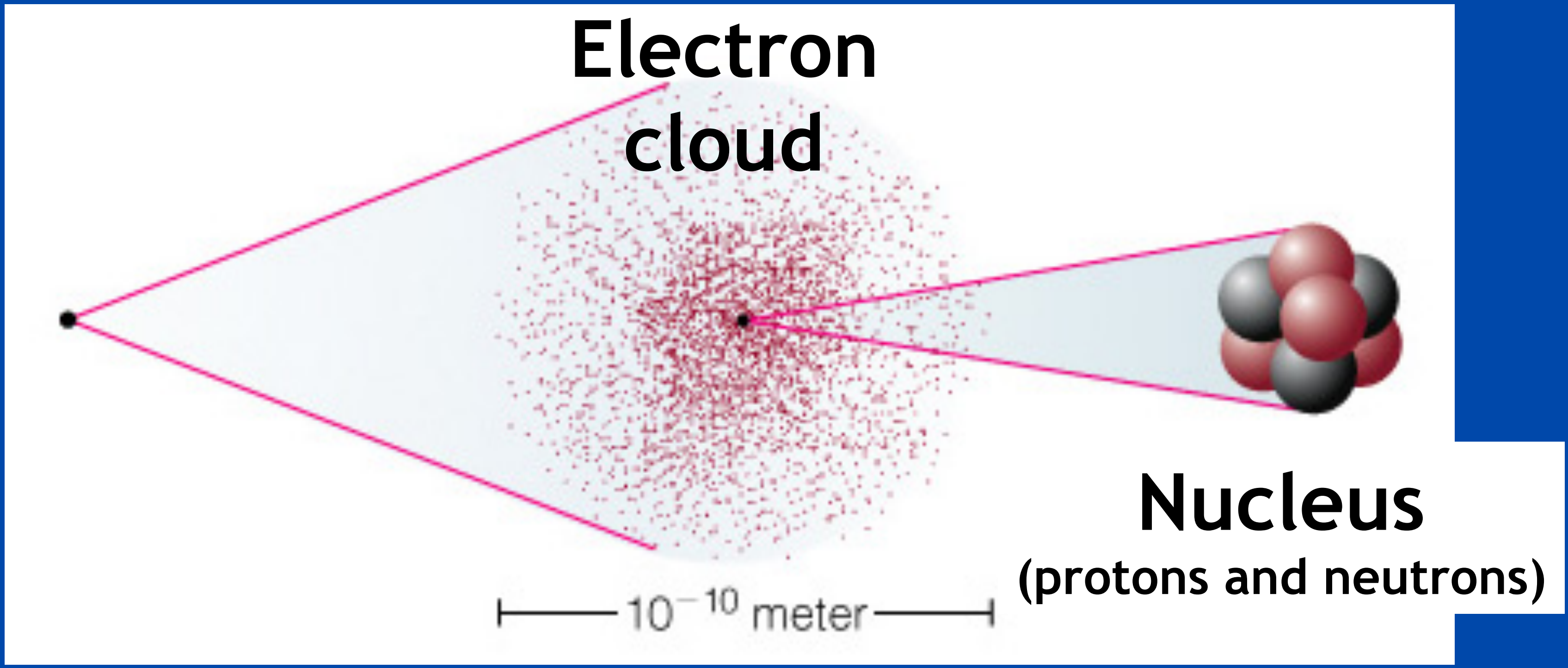
- **What is the structure of matter?**
- **What are the phases of matter?**
- **How is energy stored in atoms?**

Atomic structure



What is the smallest-structure of matter?

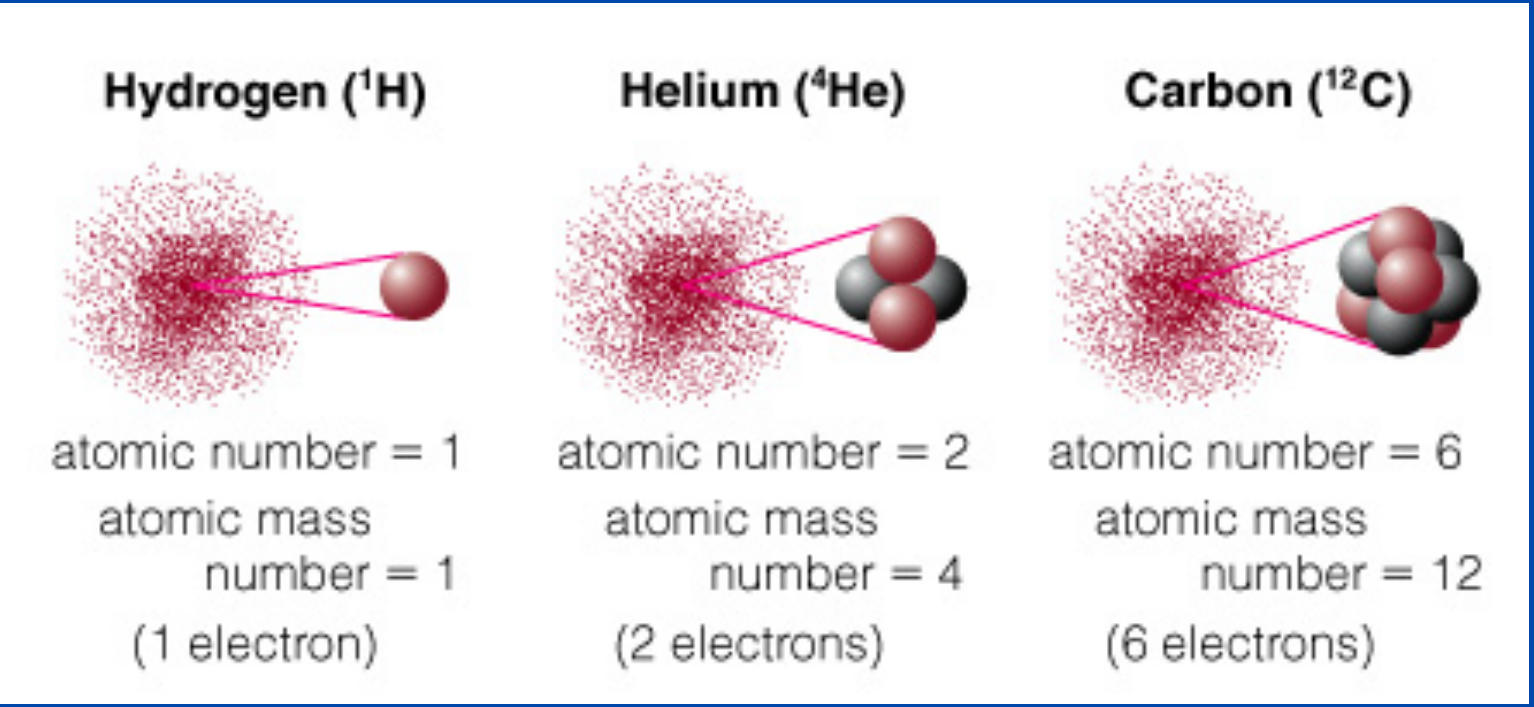




Atom

Atomic Number and Mass

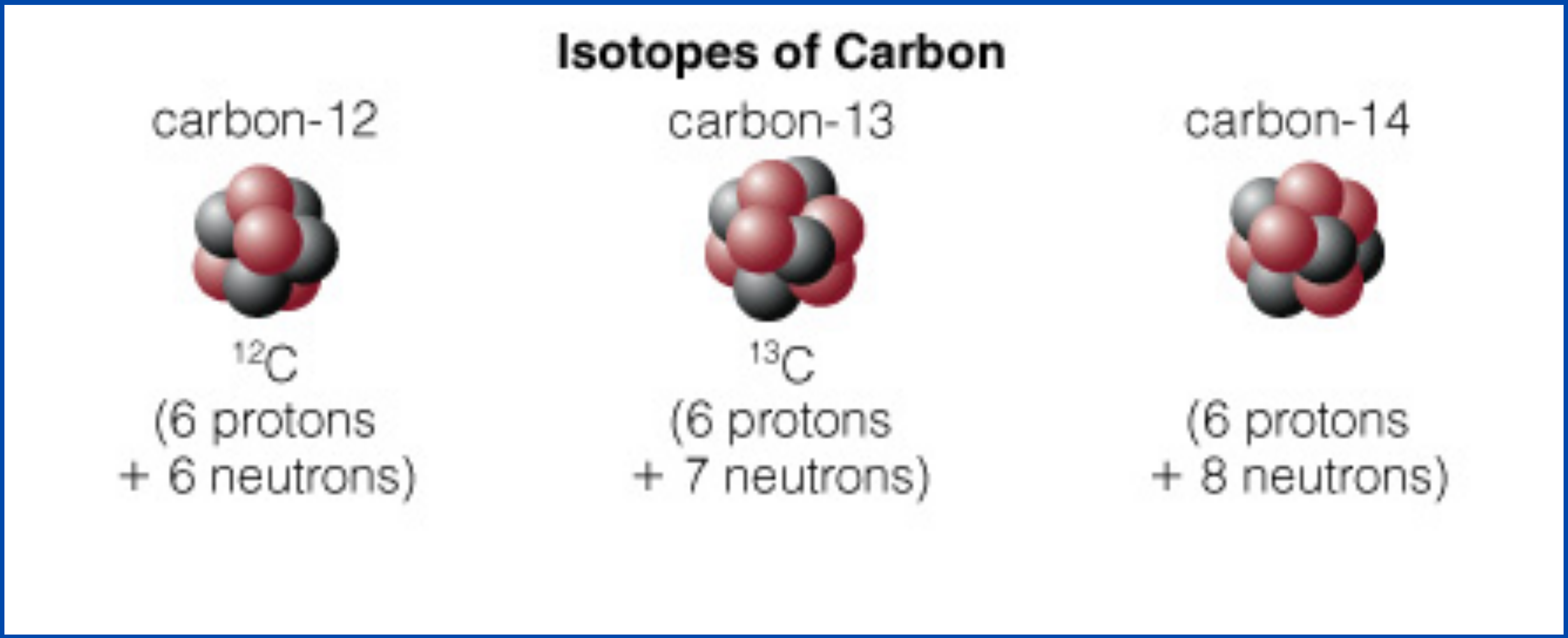
- **Atomic Number = # of protons in nucleus**
- **Atomic Mass Number = # of protons + neutrons**



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

Atomic Terminology

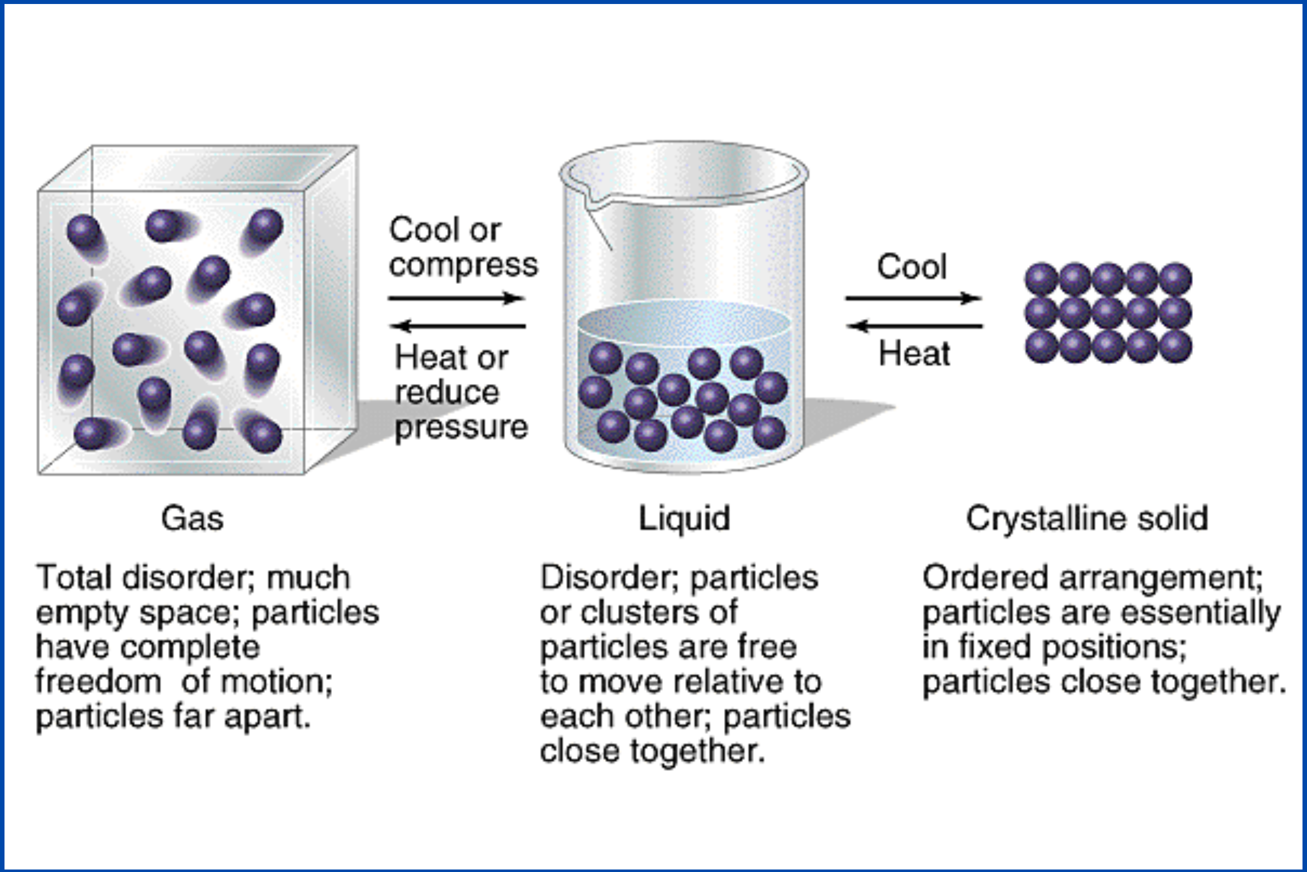
- **Isotope: same # of protons but different # of neutrons. (^4He, ^3He)**



- **All are carbon: 6 protons, atomic number 6**

Solids, liquids, gases are different phases of matter

- Matter is made of atoms and molecules (groups of atoms)

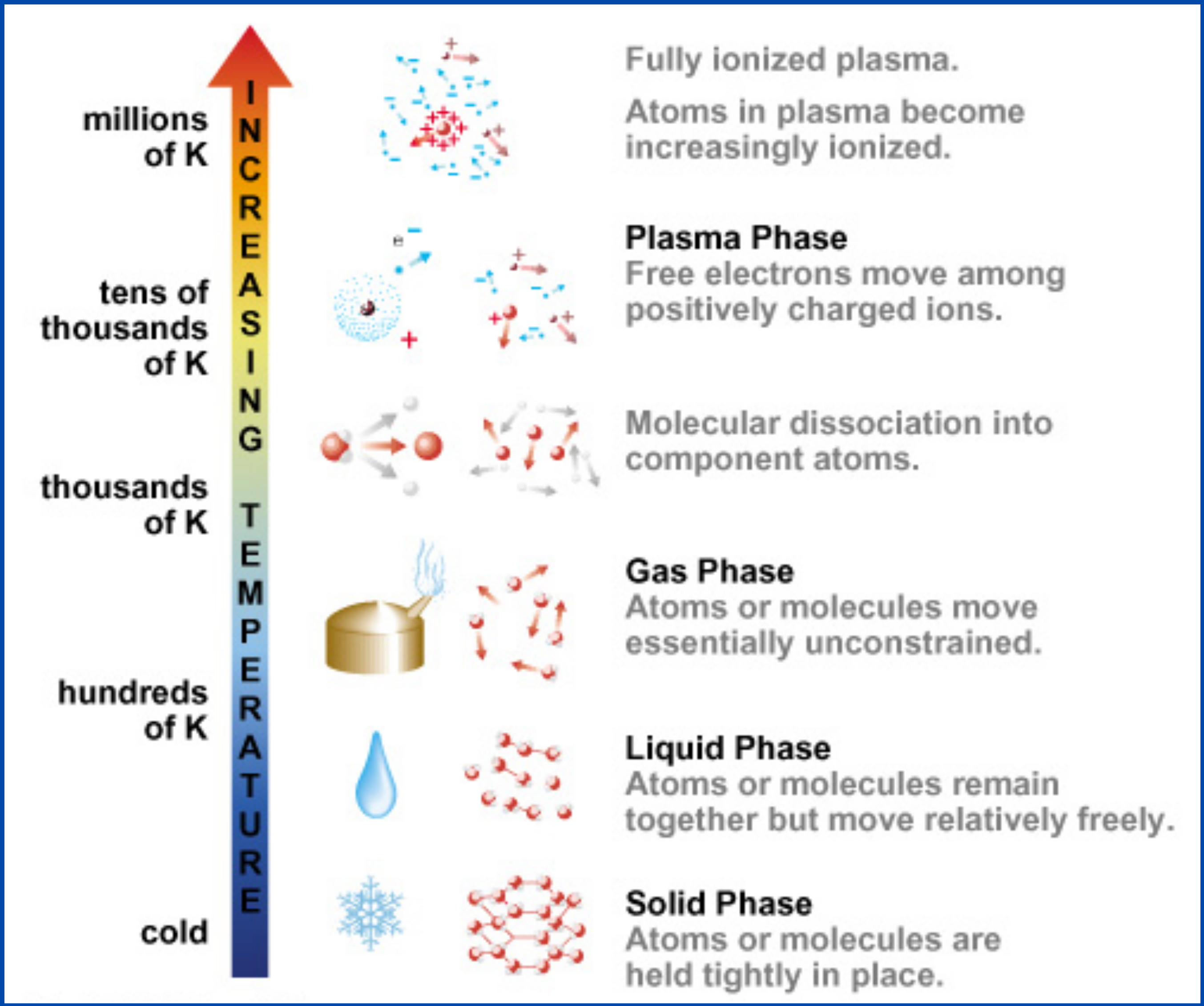


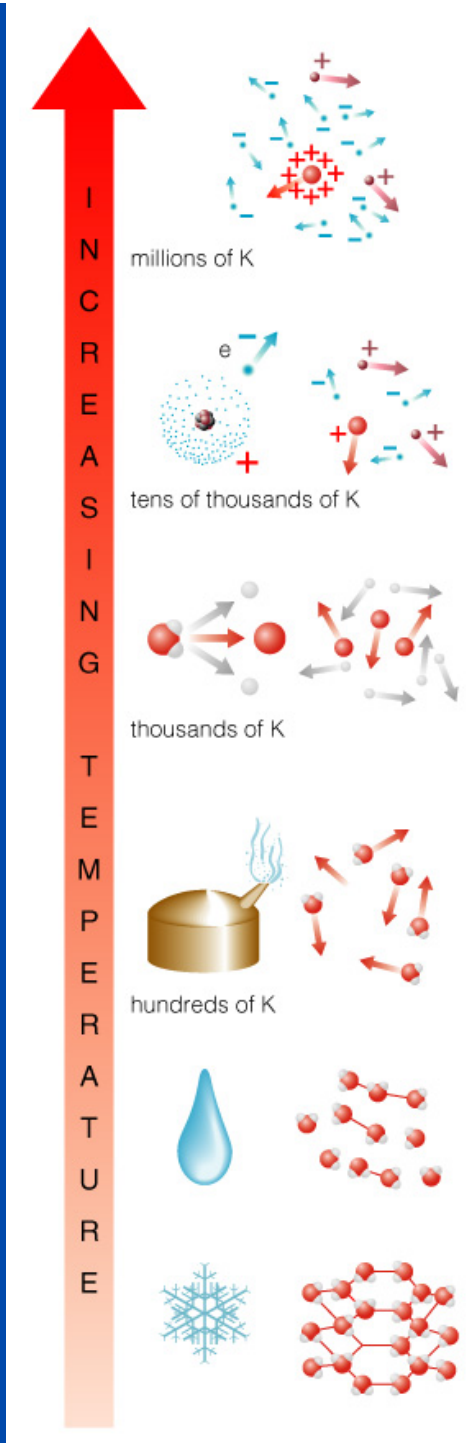
Properties of Matter

- **What are the phases of matter?**
- **How is energy stored in atoms?**
- **What makes matter change from one phase to another?**

All three phases have random motions

- Temperature and phases of water

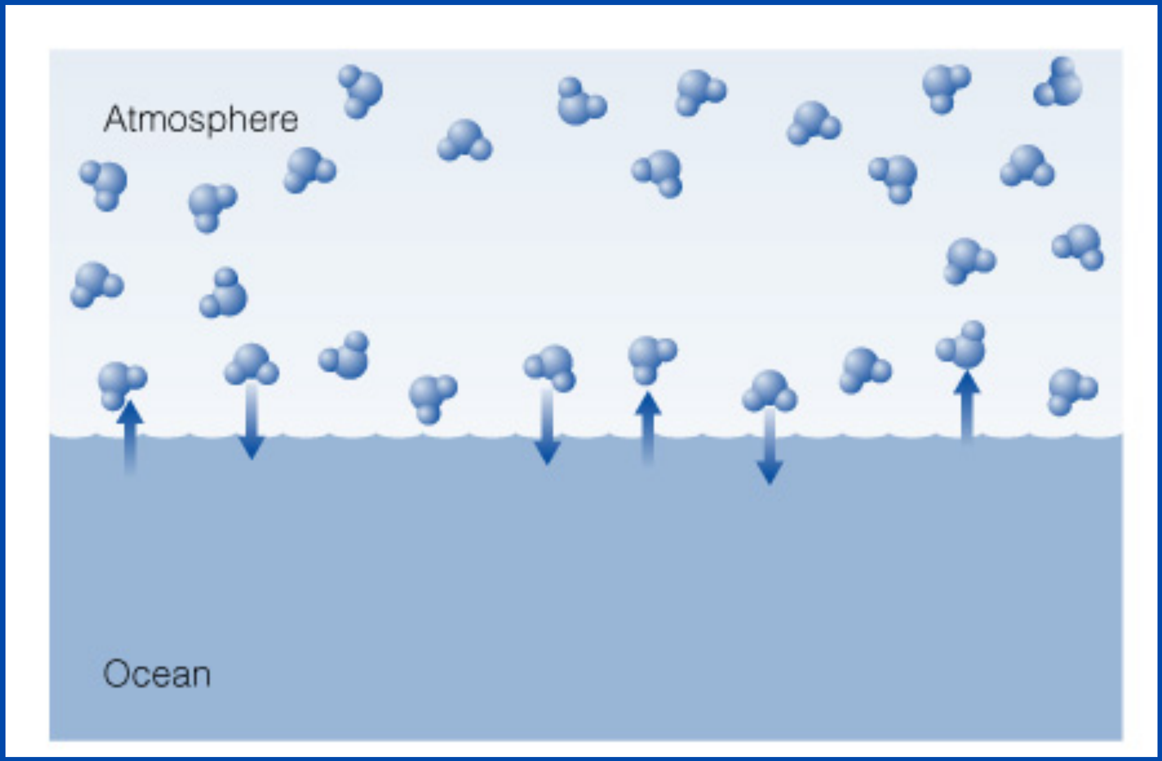

millions of K
tens of thousands of K
thousands of K
hundreds of K
cold
INCREASING TEMPERATURE
Fully ionized plasma.
Atoms in plasma become increasingly ionized.
Plasma Phase
Free electrons move among positively charged ions.
Molecular dissociation into component atoms.
Gas Phase
Atoms or molecules move essentially unconstrained.
Liquid Phase
Atoms or molecules remain together but move relatively freely.
Solid Phase
Atoms or molecules are held tightly in place.



Phase Changes: Terminology

- 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**

Phases and Pressure

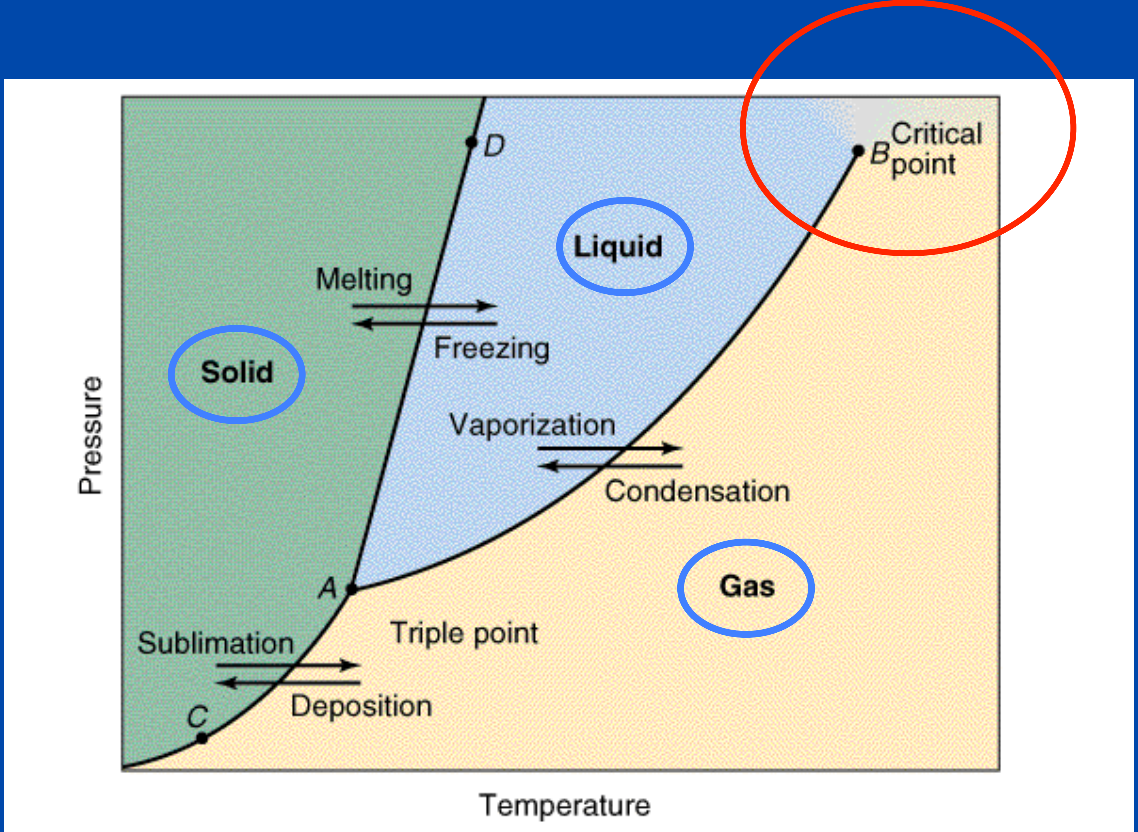


- Phase of a substance depends on both temperature and pressure

- Often more than one phase is present

Phase Diagram: plots pressure against temperature

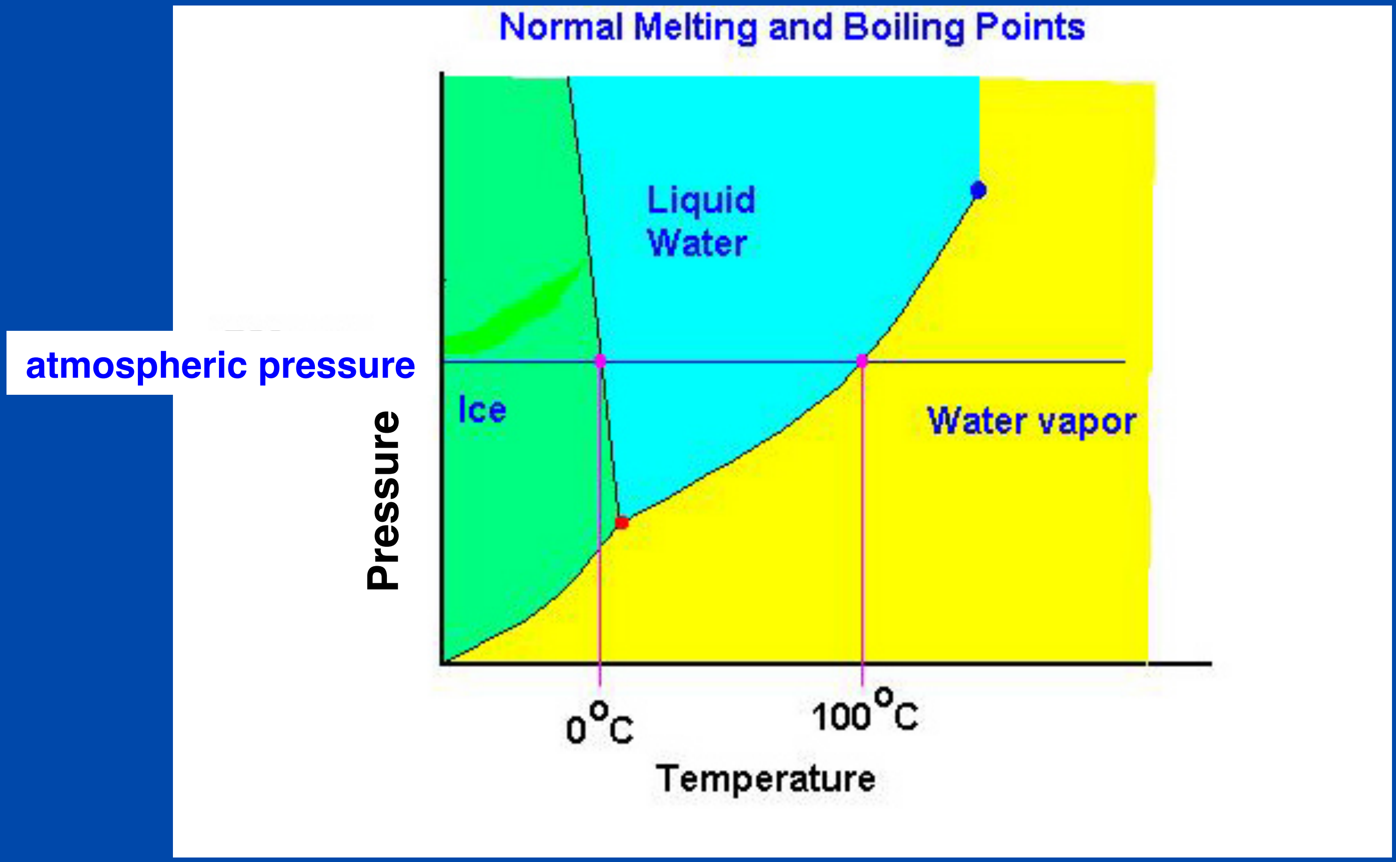
- Phase of a substance depends on both temperature and pressure



- Above critical point, gas makes continuous transition to liquid
- No phase transition
- Happens inside the giant planets

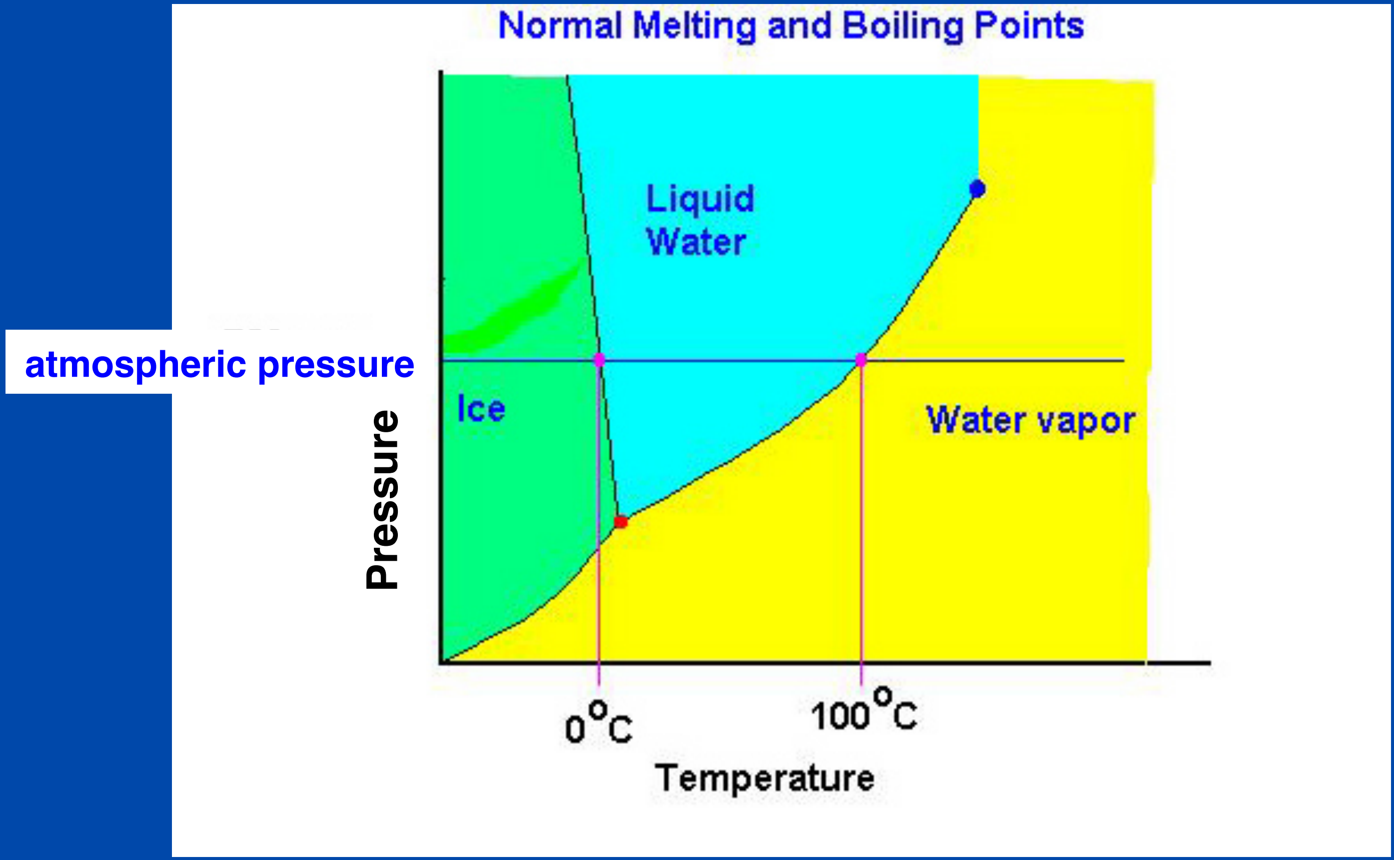
Phase Diagram: plots pressure against temperature

- Phase of a substance depends on both temperature and pressure



Concept Question

- Can you use the phase diagram below to show that a pressure cooker makes boiling water hotter than 100 ºC?



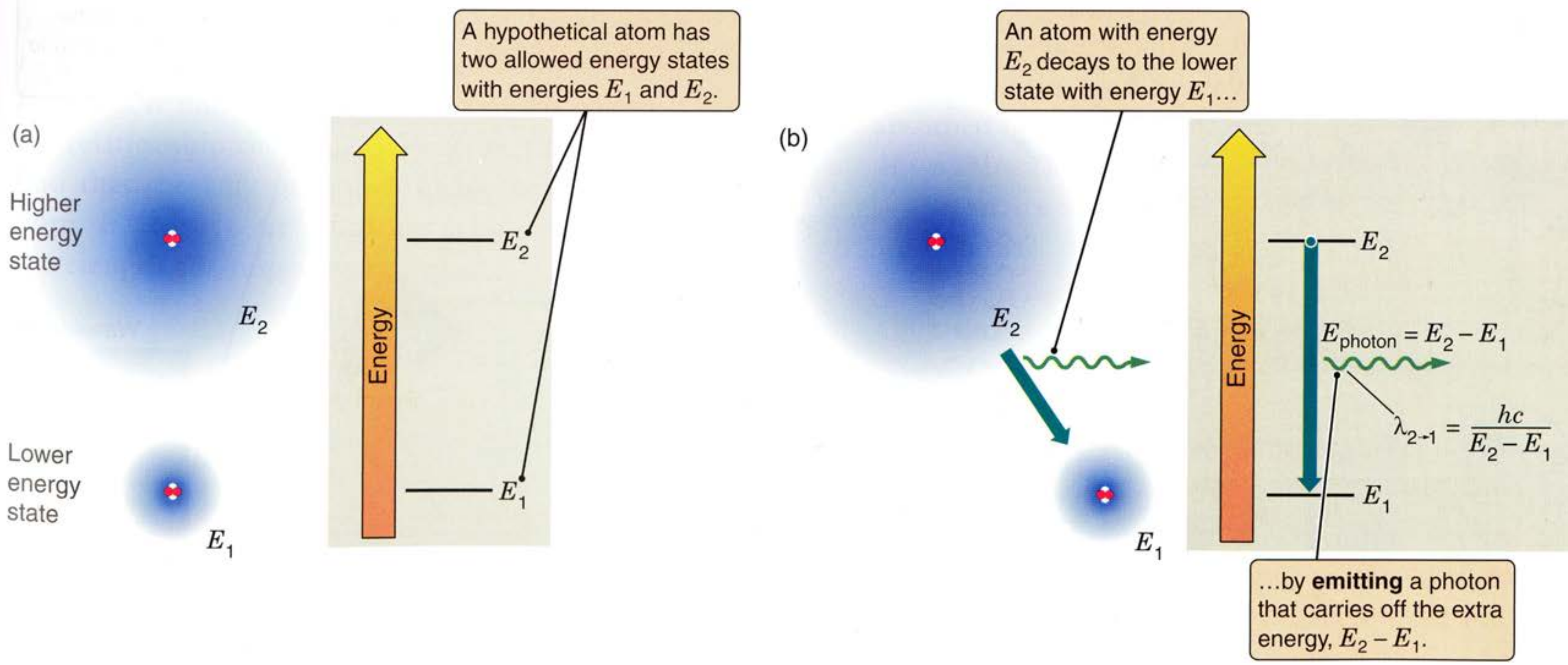
How can light tell us about the physical conditions of its source?

- **Emission of light by matter**

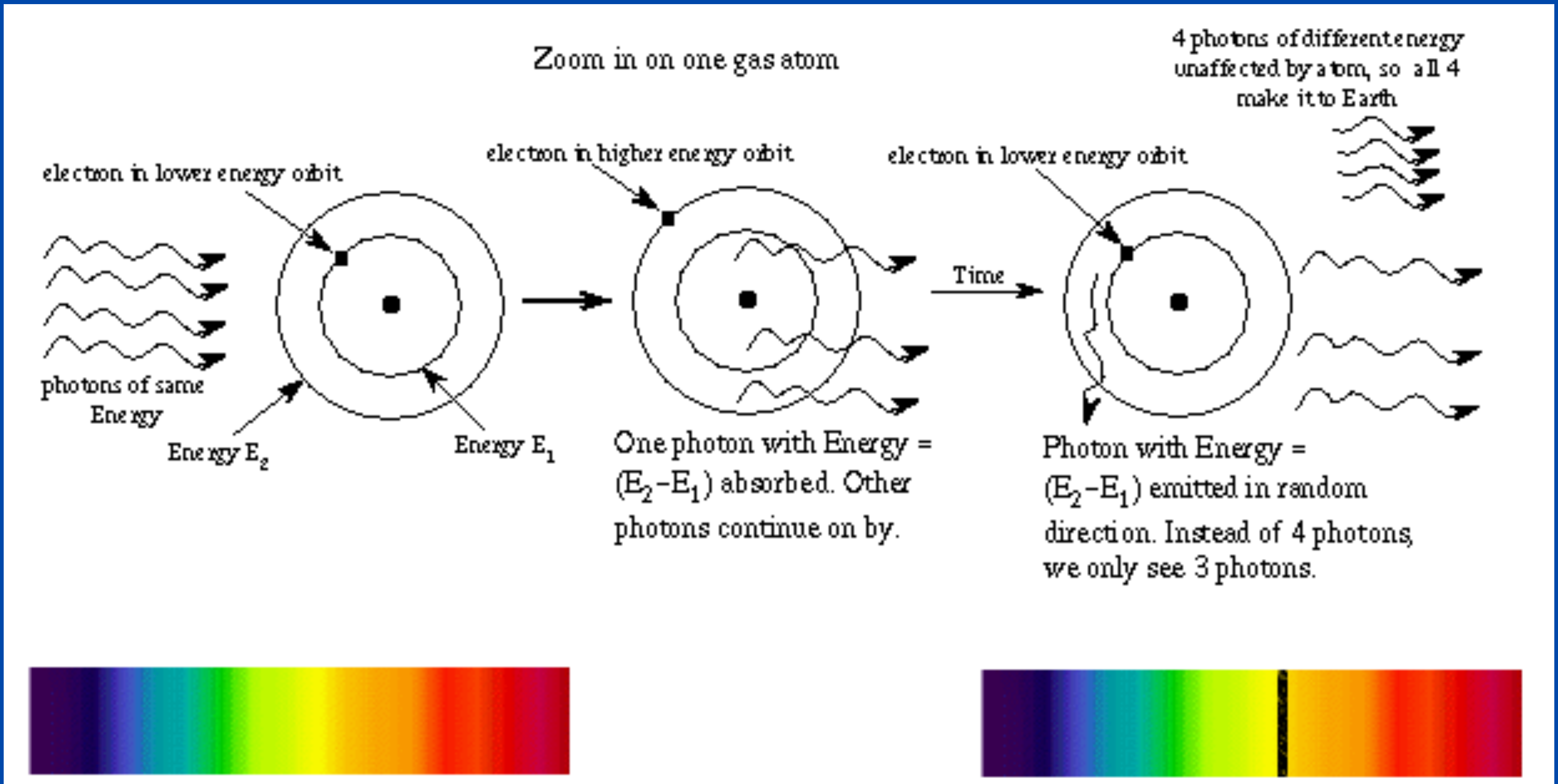
- **Absorption of light by matter**

Emission of light by an atom

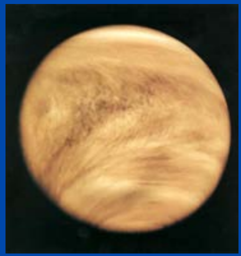
(a) *The energy levels of a hypothetical two-level atom.* (b) *A photon with energy* hf = $E_2 - E_1$ *is emitted when an atom in the more energetic state decays to the lower energy state.*

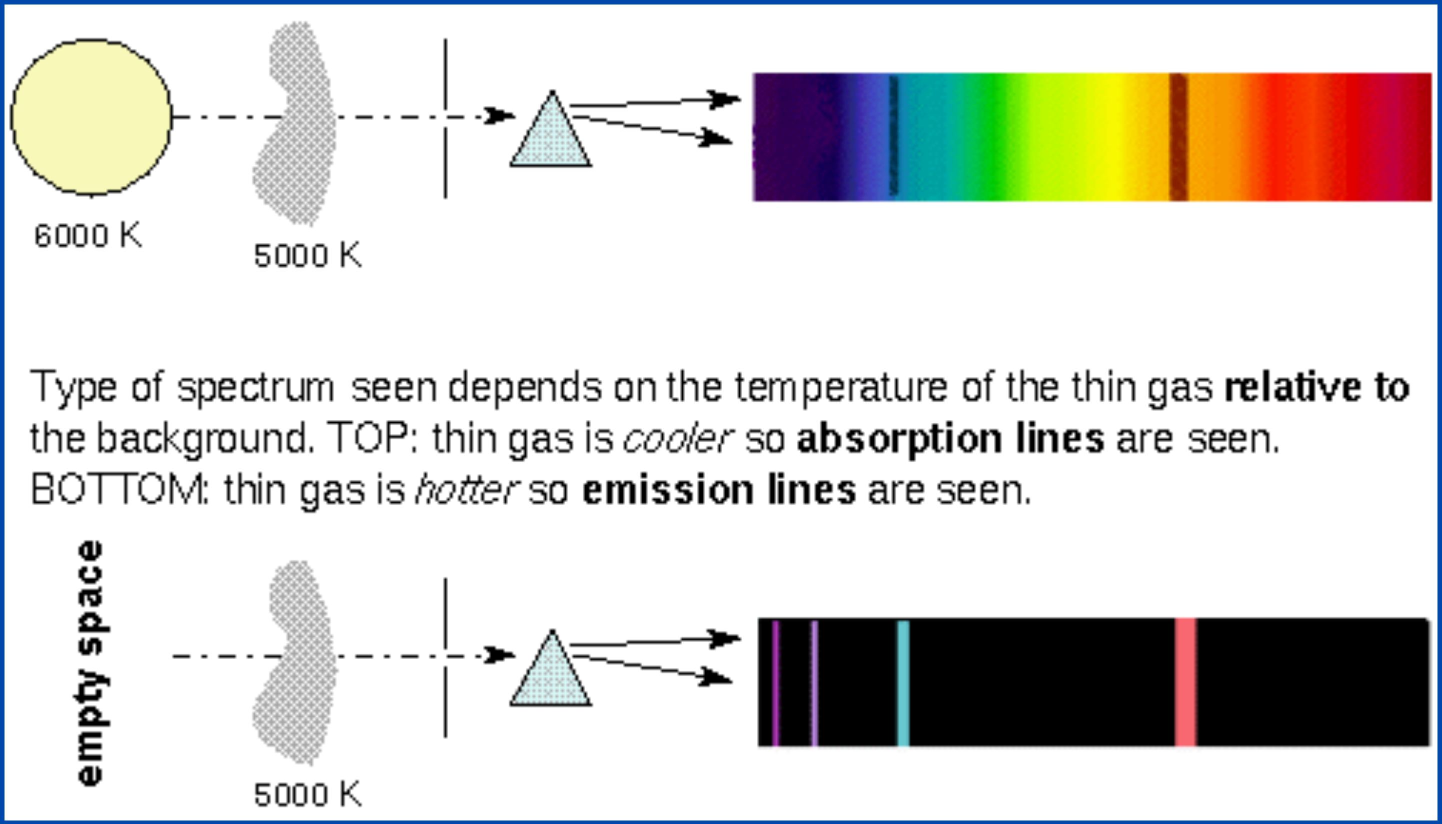


Absorption of light by an atom

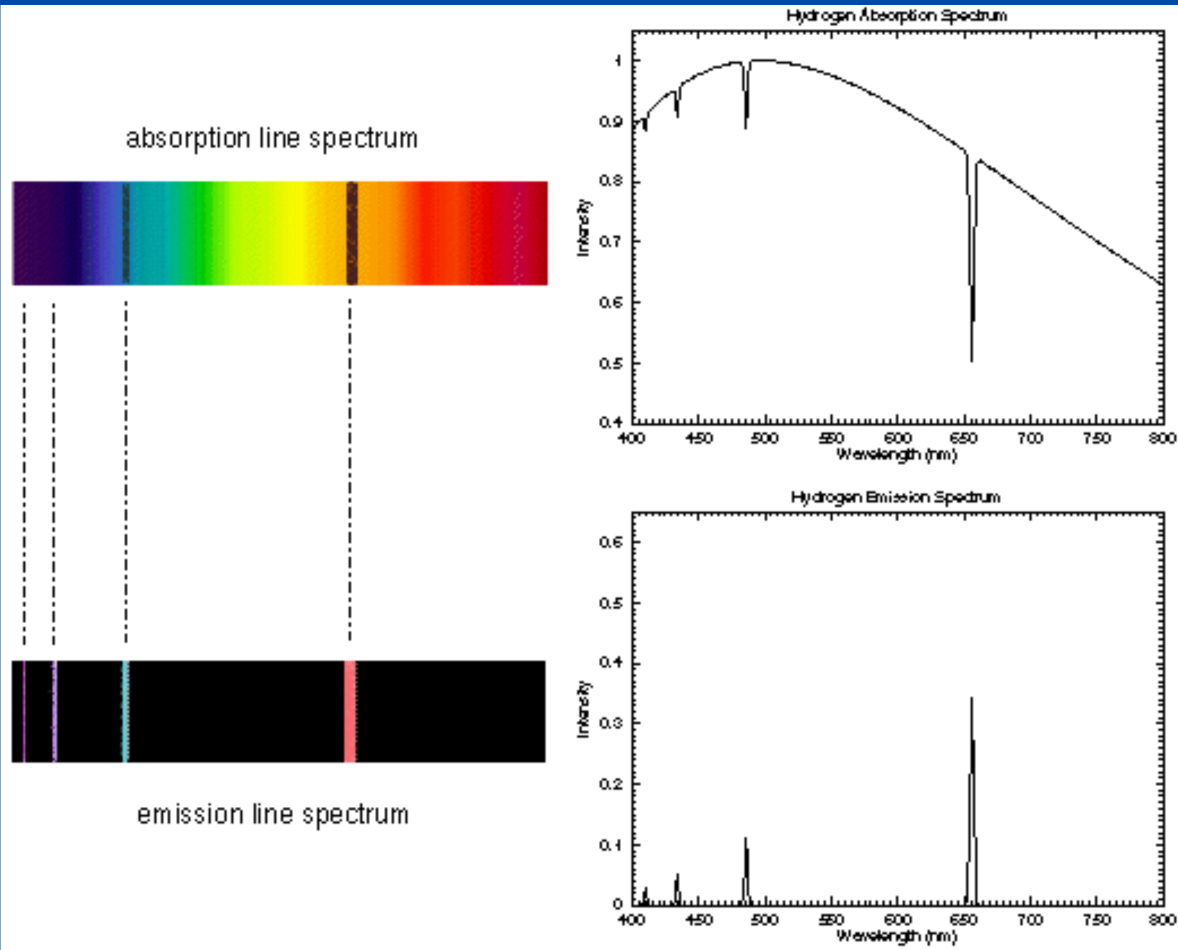


Emission and absorption lines



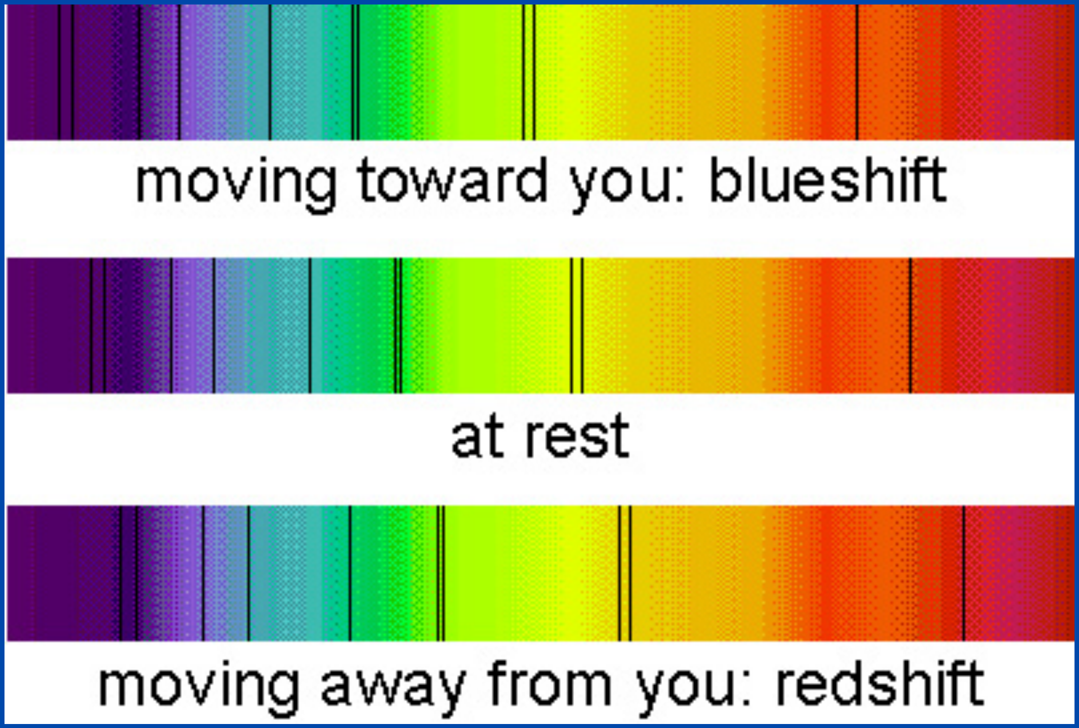


Scans of a spectrum



Two ways of showing the same spectra: on the **left** are pictures of the dispersed light and on the **right** are plots of the intensity vs. wavelength. Notice that the pattern of spectral lines in the absorption and emission line spectra are the **same** since the gas is the same.

Doppler shift of a spectrum



Concept Question

- If we observe one edge of a planet to be redshifted and the opposite edge to be blueshifted, what can we conclude about the planet?

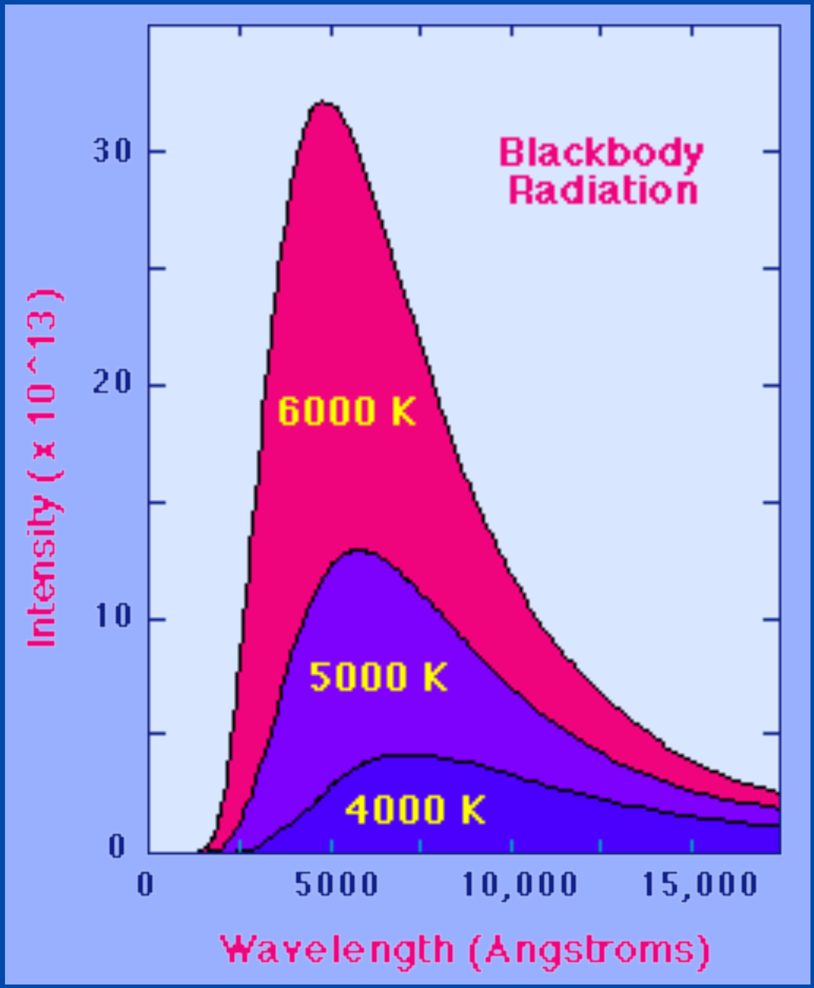
a) The planet is in the process of formation.

b) We must actually be observing moons orbiting the planet in opposite directions, not the planet itself.

c) The planet is in the process of falling apart.

d) The planet is rotating.

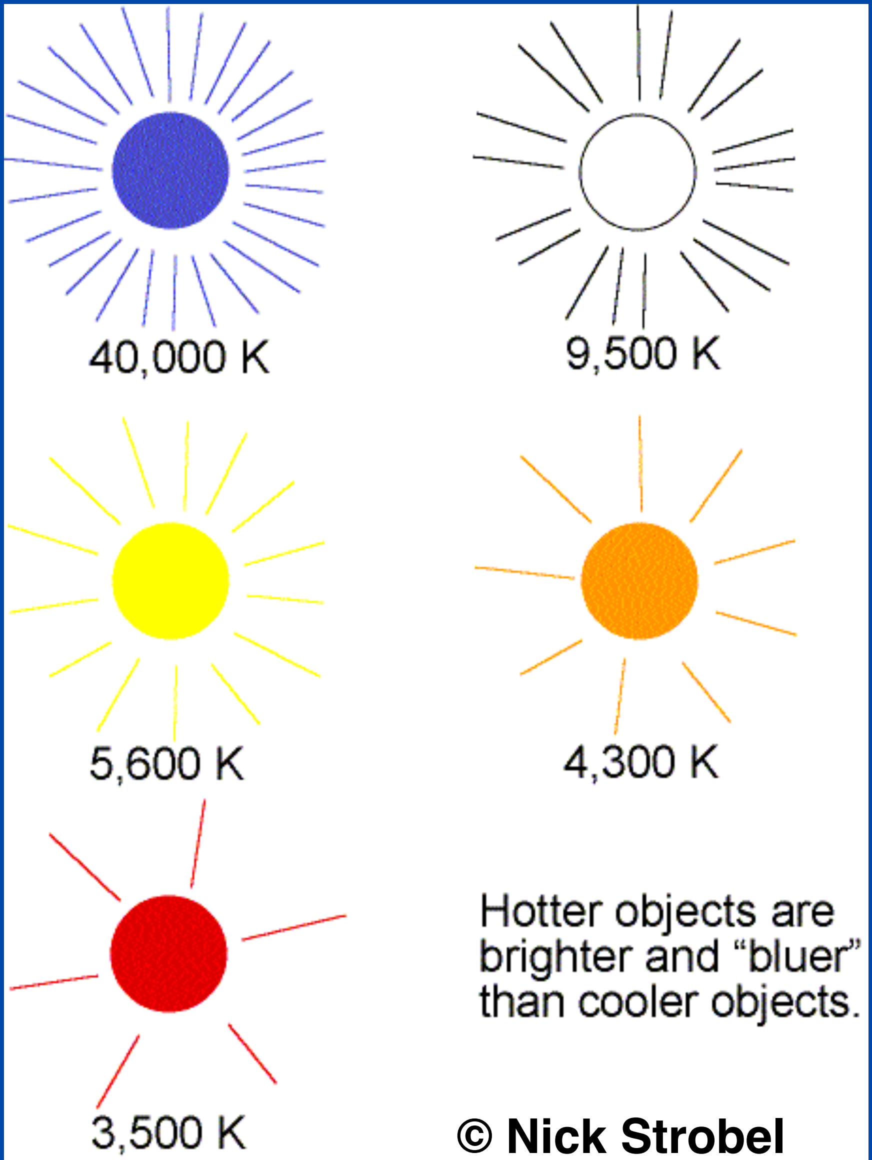
"Blackbody radiation" - spectrum of light emission due to temperature



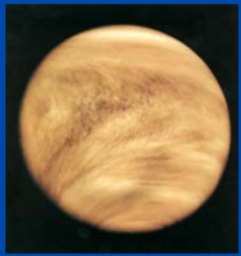
Bluer color emitted light means hotter temperature of the matter

Wien's law

$$\lambda_{peak} = \frac{2.9 \times 10^6}{\text{T (Kelvin)}} \quad nm$$

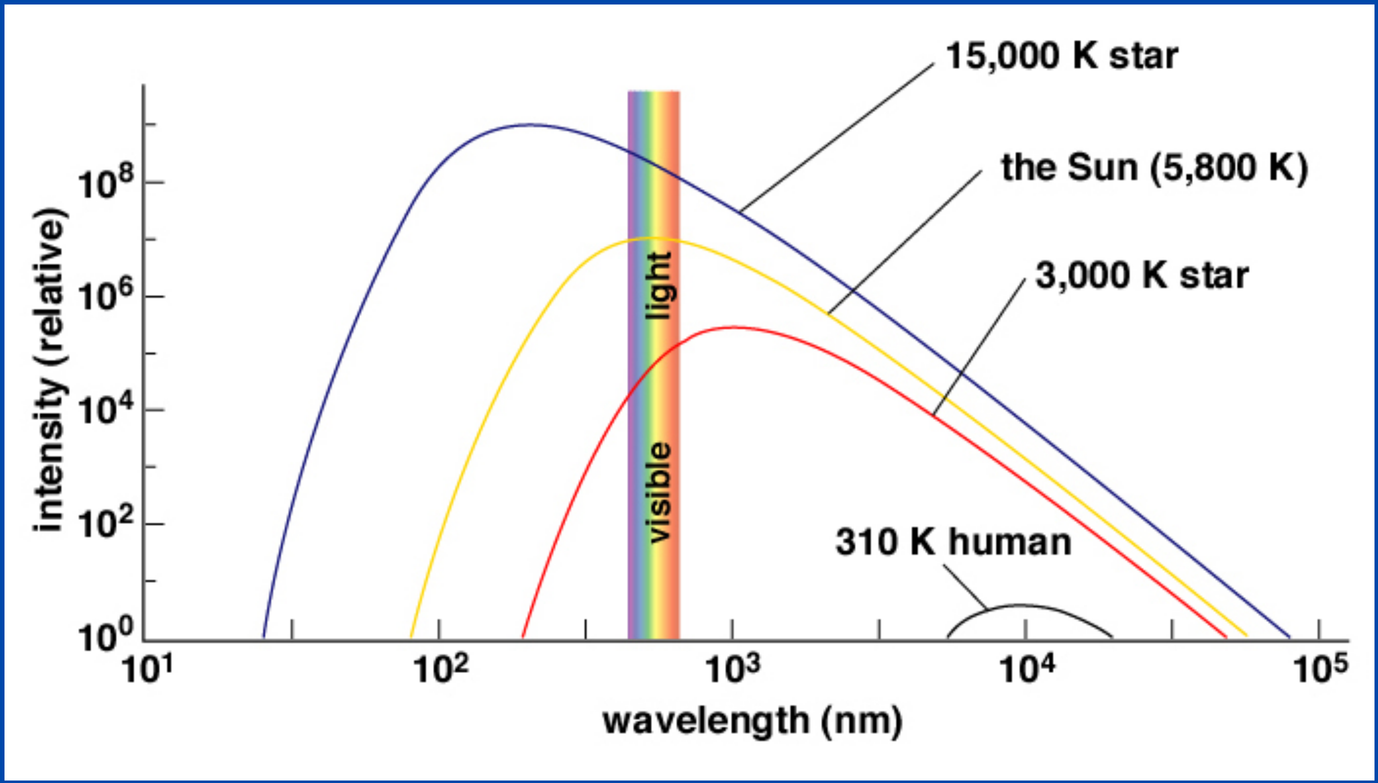


Total flux emitted by a body at temperature T

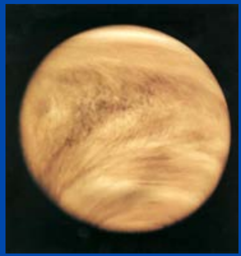


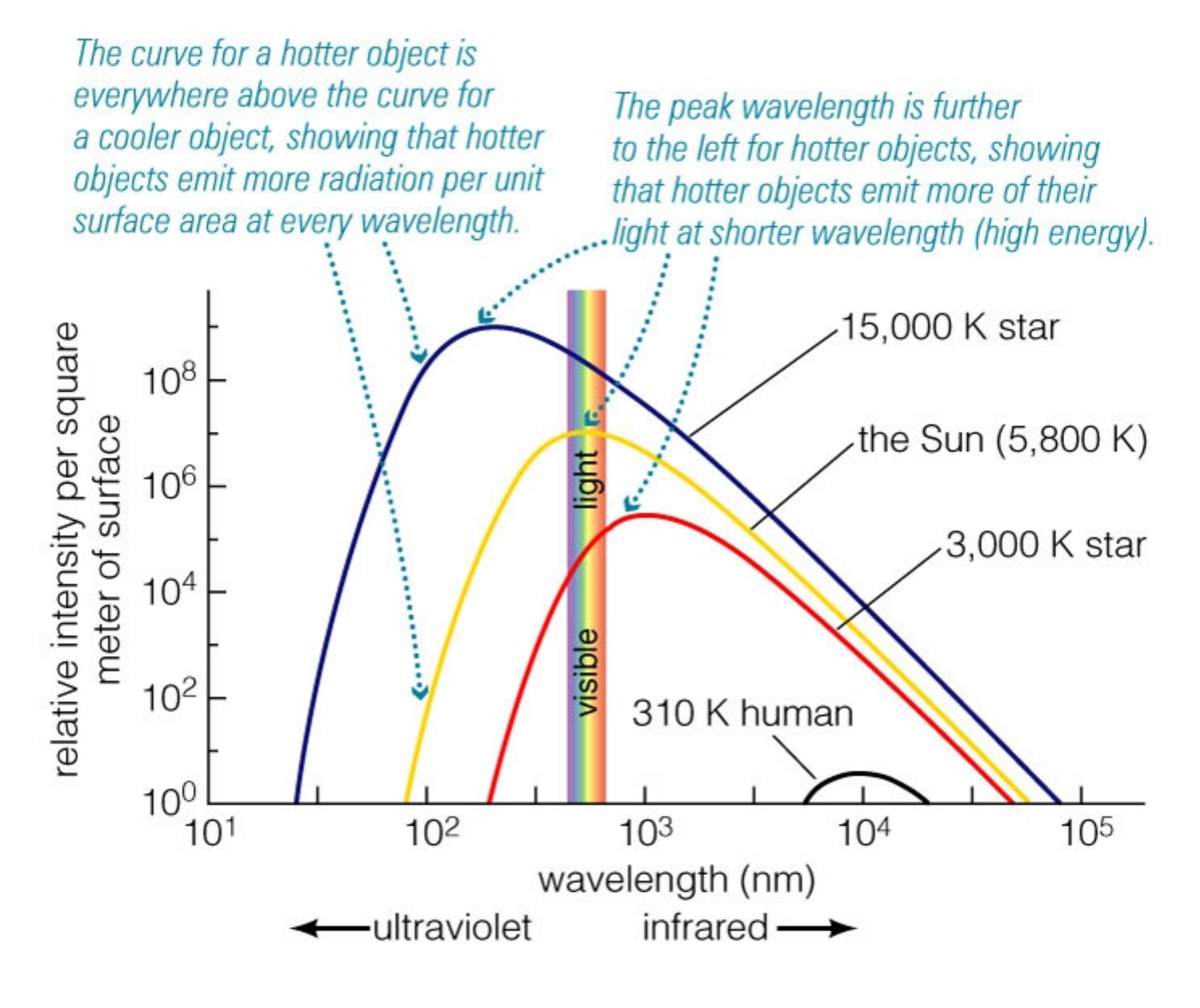
$$flux = F = \sigma T^4 \text{ joules per sec per m}^2 \text{ of area}$$

$$\sigma = \text{Stefan} - \text{Boltzmann constant} = 5.67 \times 10^{-8}\, joules\ \sec^{-1} m^{-2} K^{-4}$$



Total flux emitted by a body at temperature T

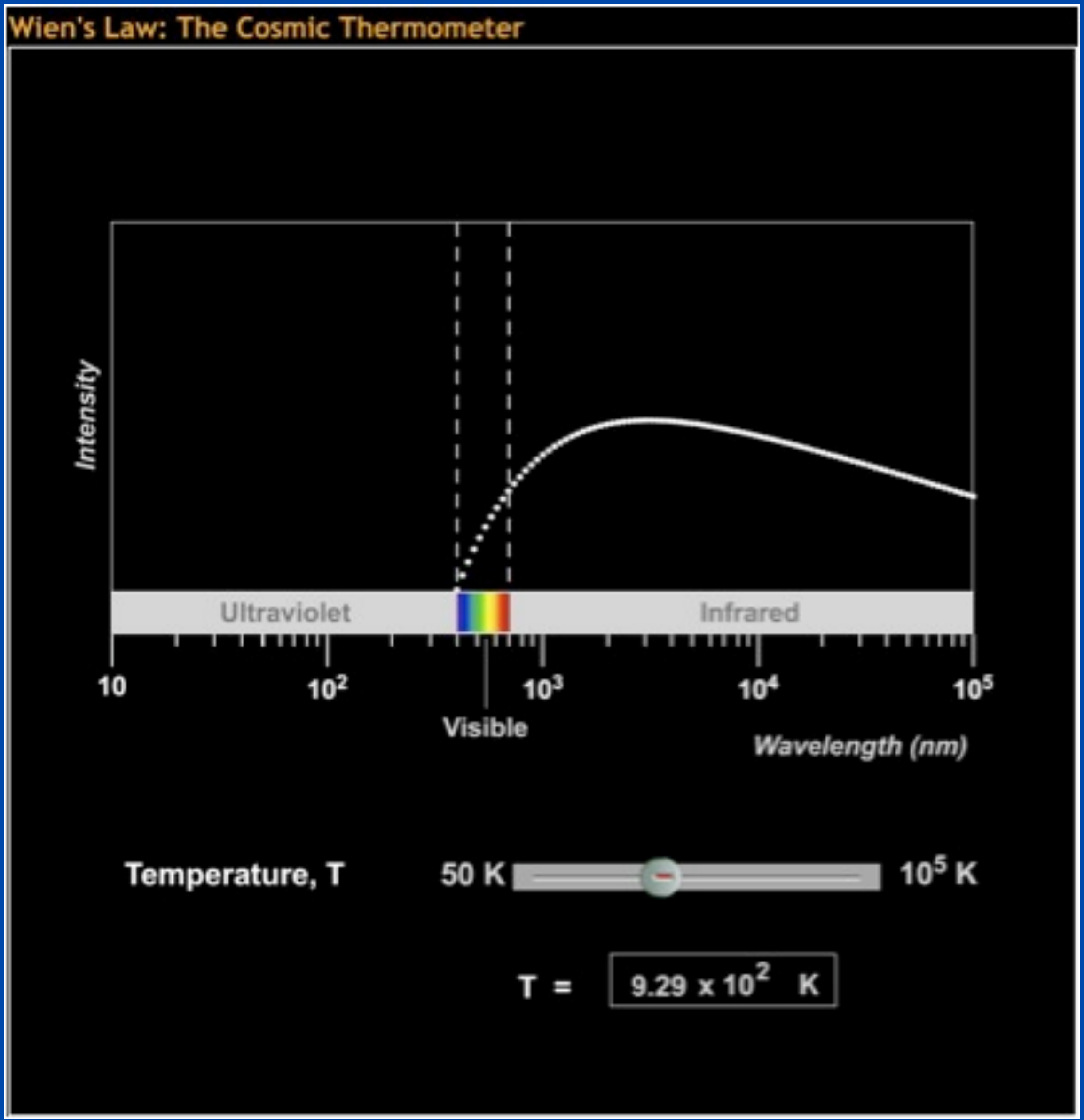




$$\lambda_{max} = \left(\frac{2.9 \times 10^6 K}{T(K)} \right) \text{ nm}$$

Wien's Law

Wien's Law



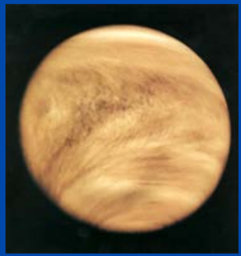
Wien's Law: The Cosmic Thermometer
Intensity
Ultraviolet
Infrared
10
10²
10³
10⁴
10⁵
Visible
Wavelength (nm)
Temperature, T
50 K
10⁵ K
T =
9.29 x 10² K

Wavelengths of peak emission, from radio to gamma ray wavelengths

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	$< 10^{-9}$	$> 10^{5}$	$> 3 \times 10^{8}$

Concept Question

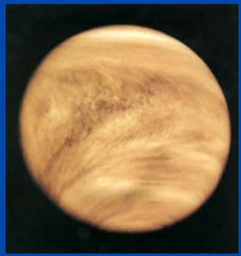


- A star with a continuous spectrum shines through a cool interstellar cloud of hydrogen gas. The cloud is falling inward toward the star. Which best describes the spectrum seen by an Earthbound observer?

  a) blueshifted hydrogen emission lines
  b) blueshifted hydrogen absorption lines
  c) redshifted hydrogen emission lines
  d) redshifted hydrogen absorption lines
  e) a redshifted hydrogen continuum

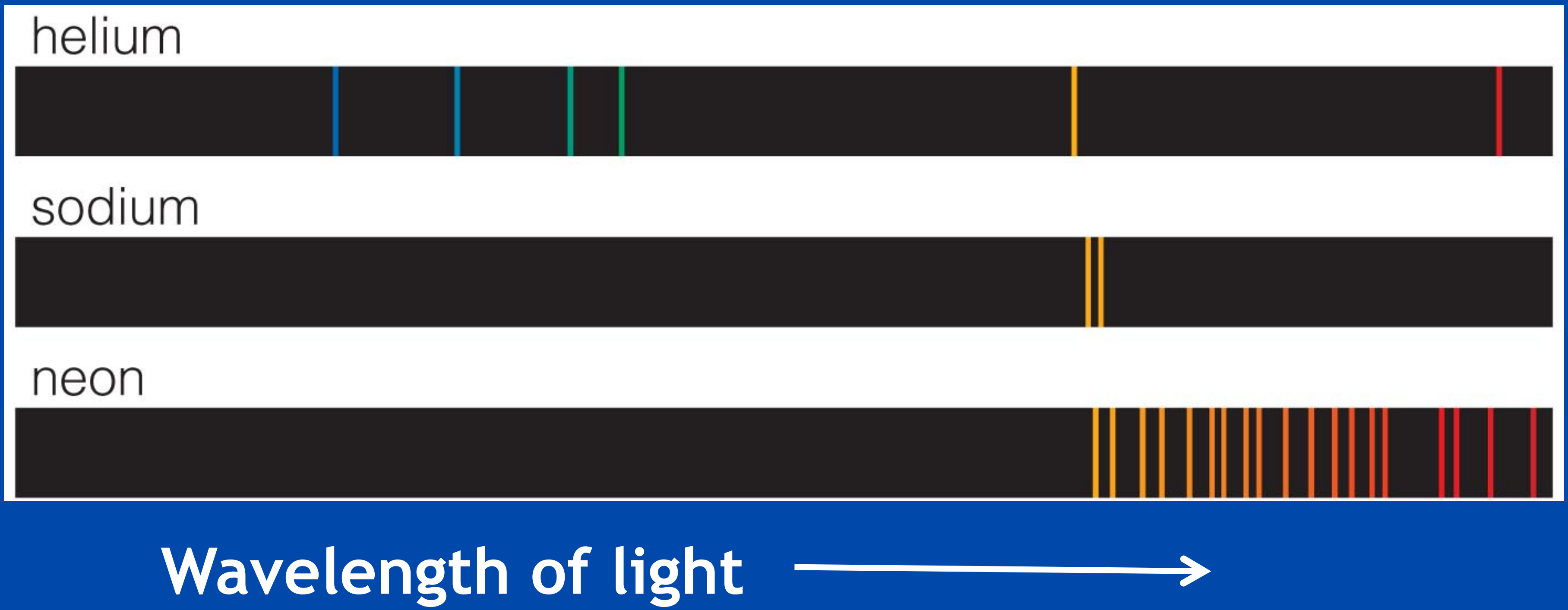
Hint: Try drawing a sketch

Some things you can learn from a spectrum



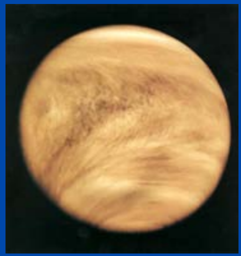
- Temperature and density of matter at the light source
- Ionization state
- Chemical composition
  - Example: ozone as sign of life on Earth
- Presence of specific minerals
  - Example: Lunar Prospector spacecraft, ice on moon
- Structure of atmosphere
  - Example: Neptune clouds, height of cloud layers
- Velocities of the material emitting or absorbing the light

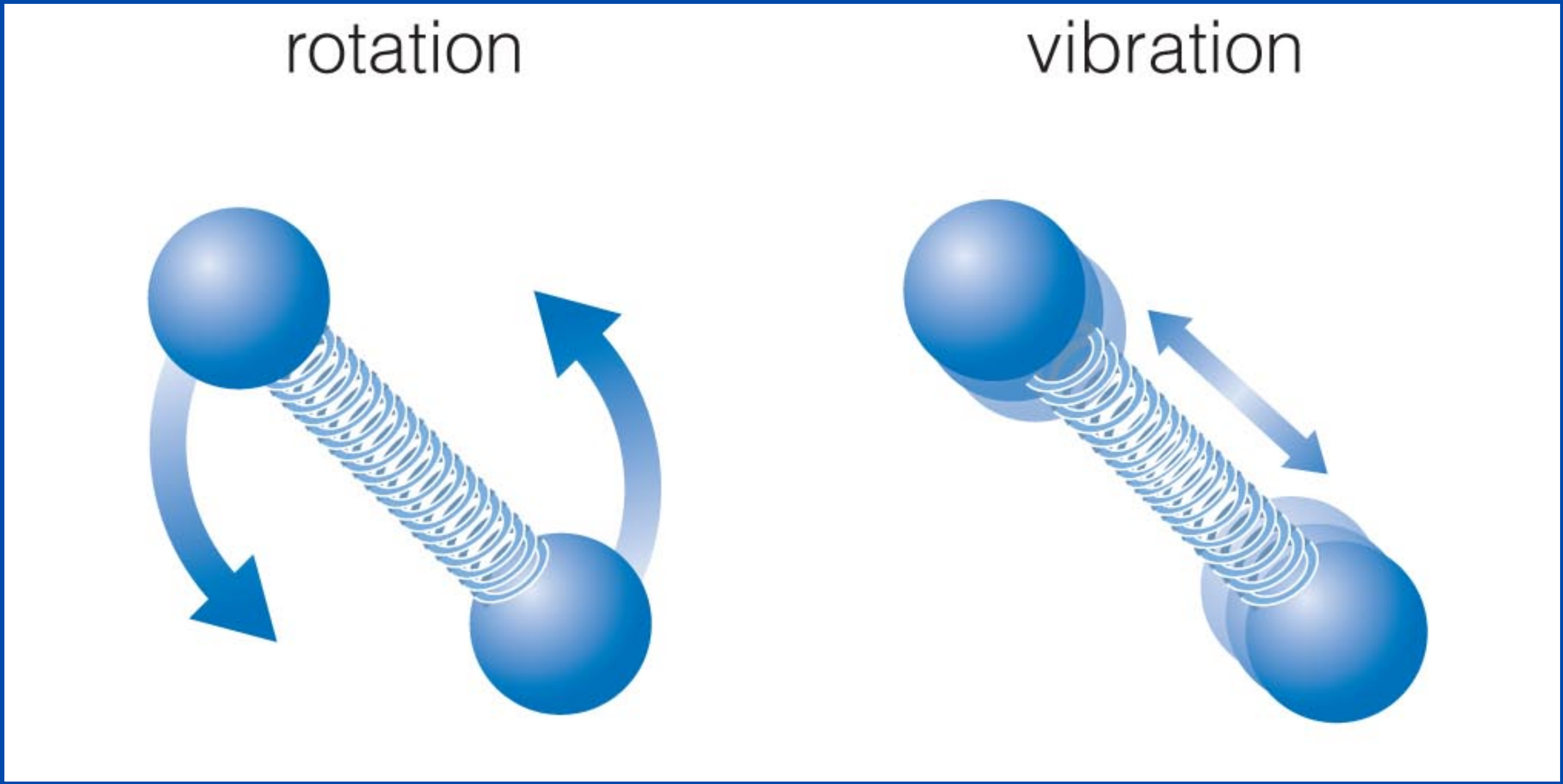
Chemical Fingerprints from Emission Lines



- **Each type of atom has a unique spectral fingerprint.**

Energy Levels of Molecules





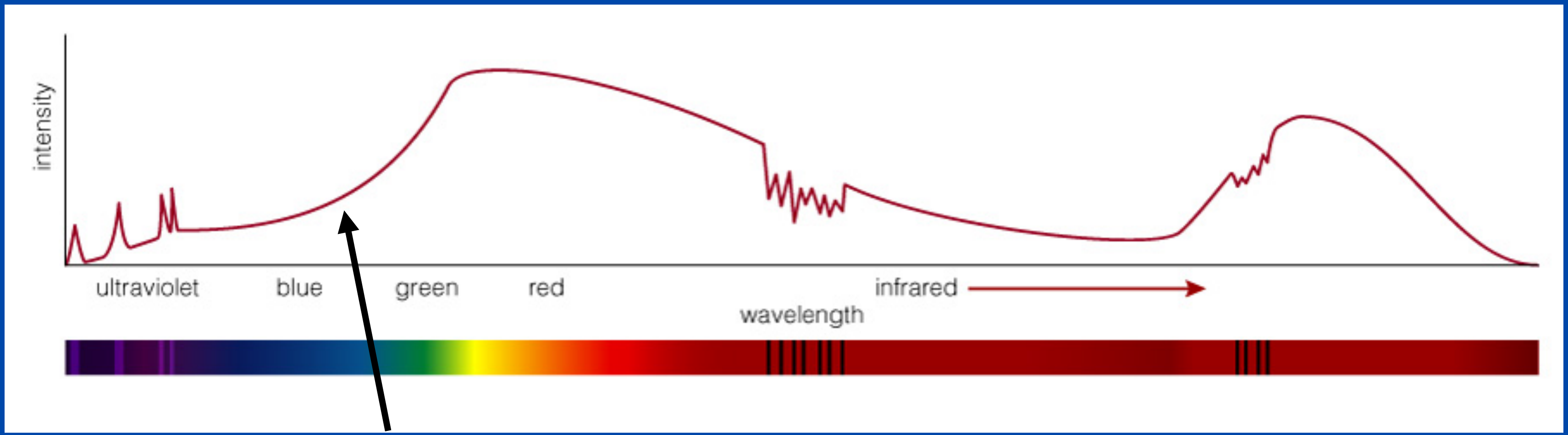
- **Molecules have additional energy levels because they can vibrate and rotate.**

Energy Levels of Molecules

Wavelength of light →

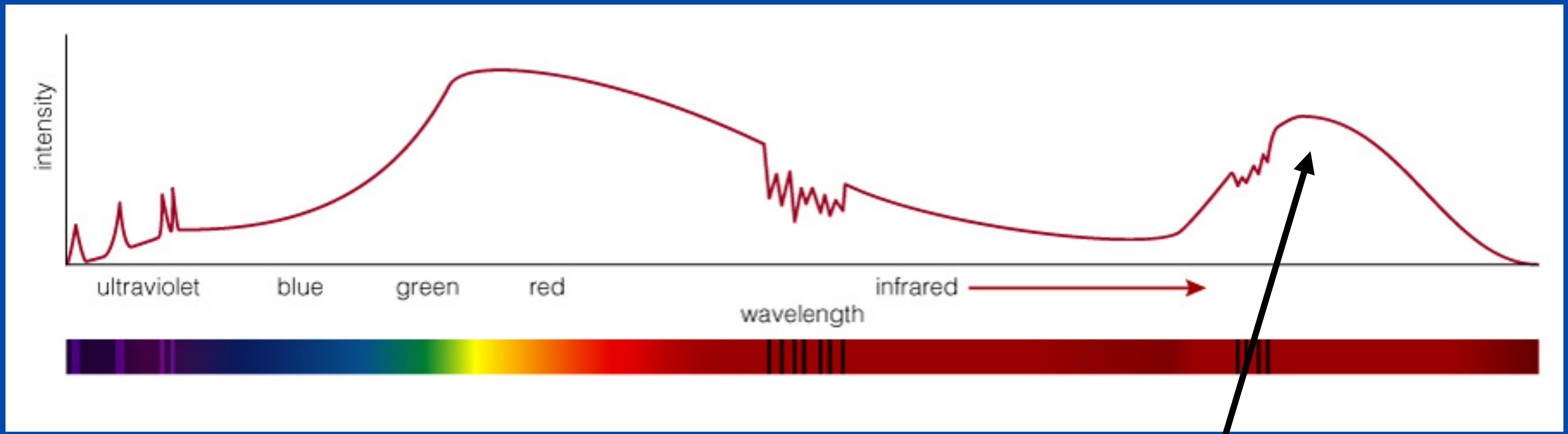
- The large numbers of vibrational and rotational energy levels can make the spectra of molecules very complicated.
- Many of these molecular transitions are in the infrared part of the spectrum.

What is this object?



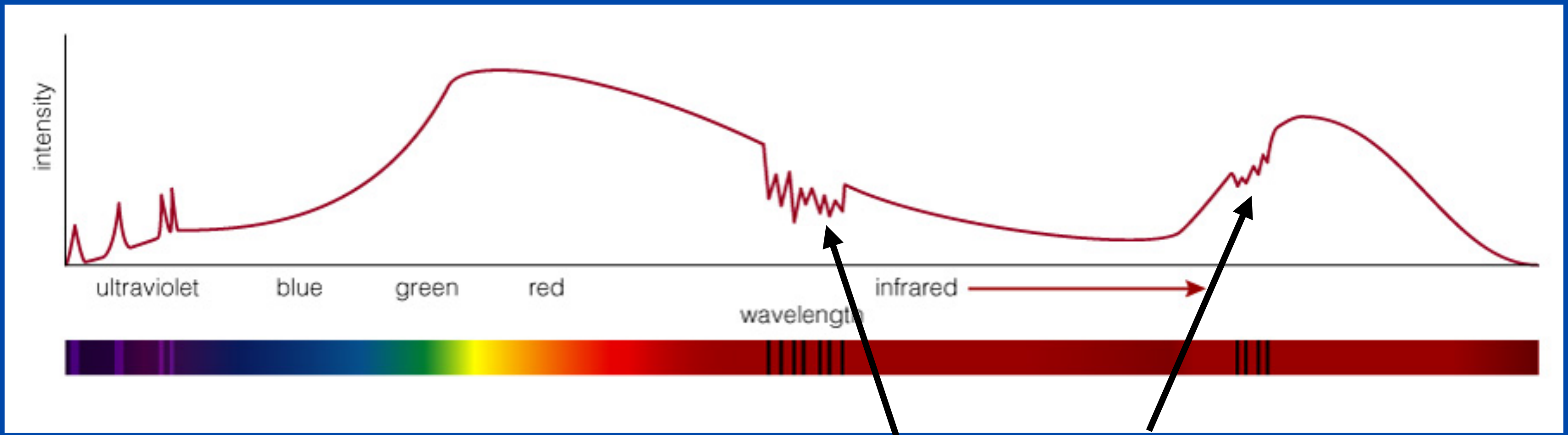
Reflected Sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed - object must look red

What is this object?



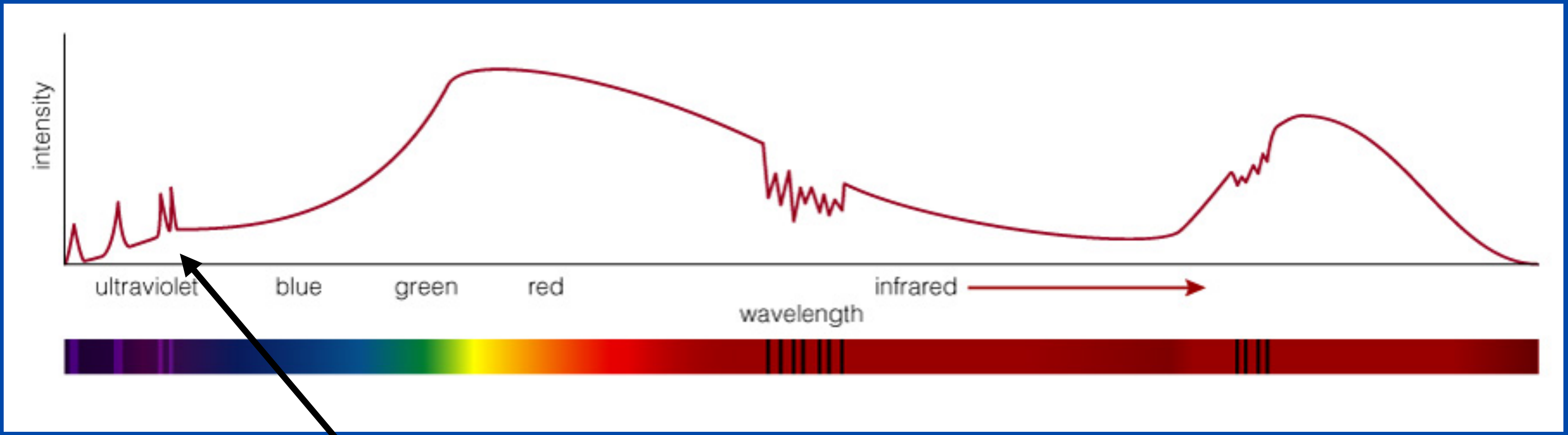
Thermal Radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K

What is this object?



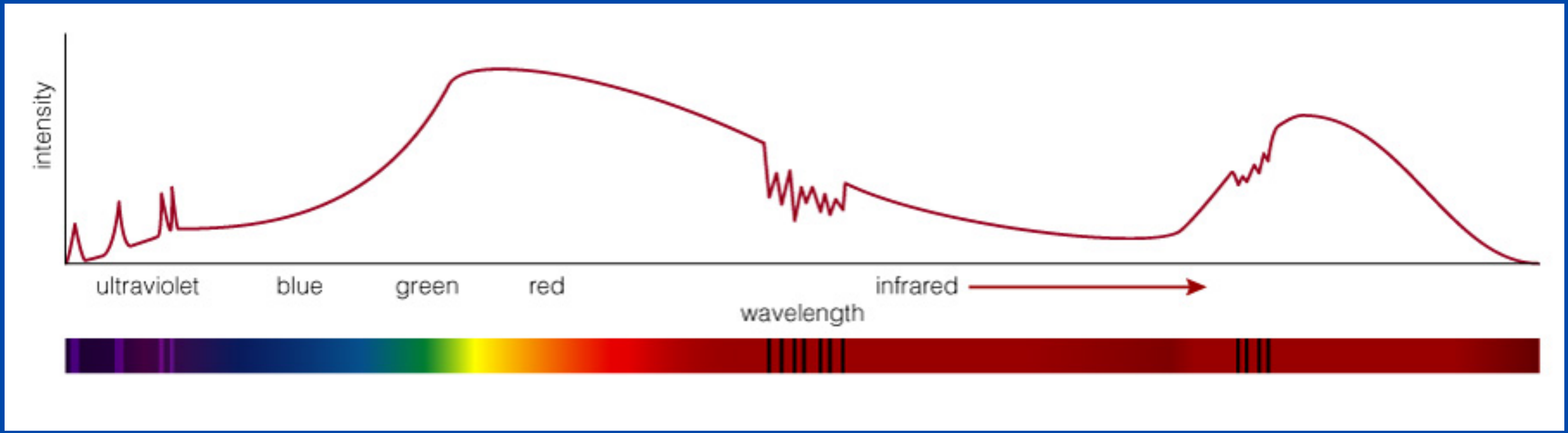
Carbon Dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere

What is this object?



Ultraviolet Emission Lines: Indicate a hot upper atmosphere

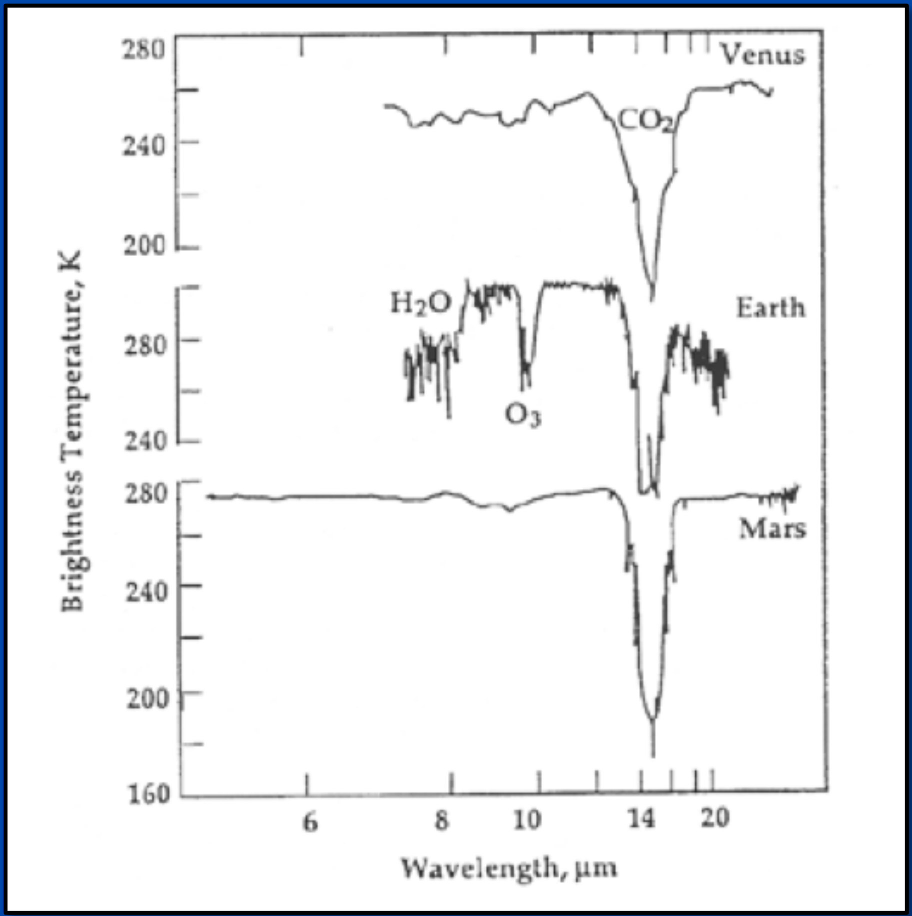
What is this object?

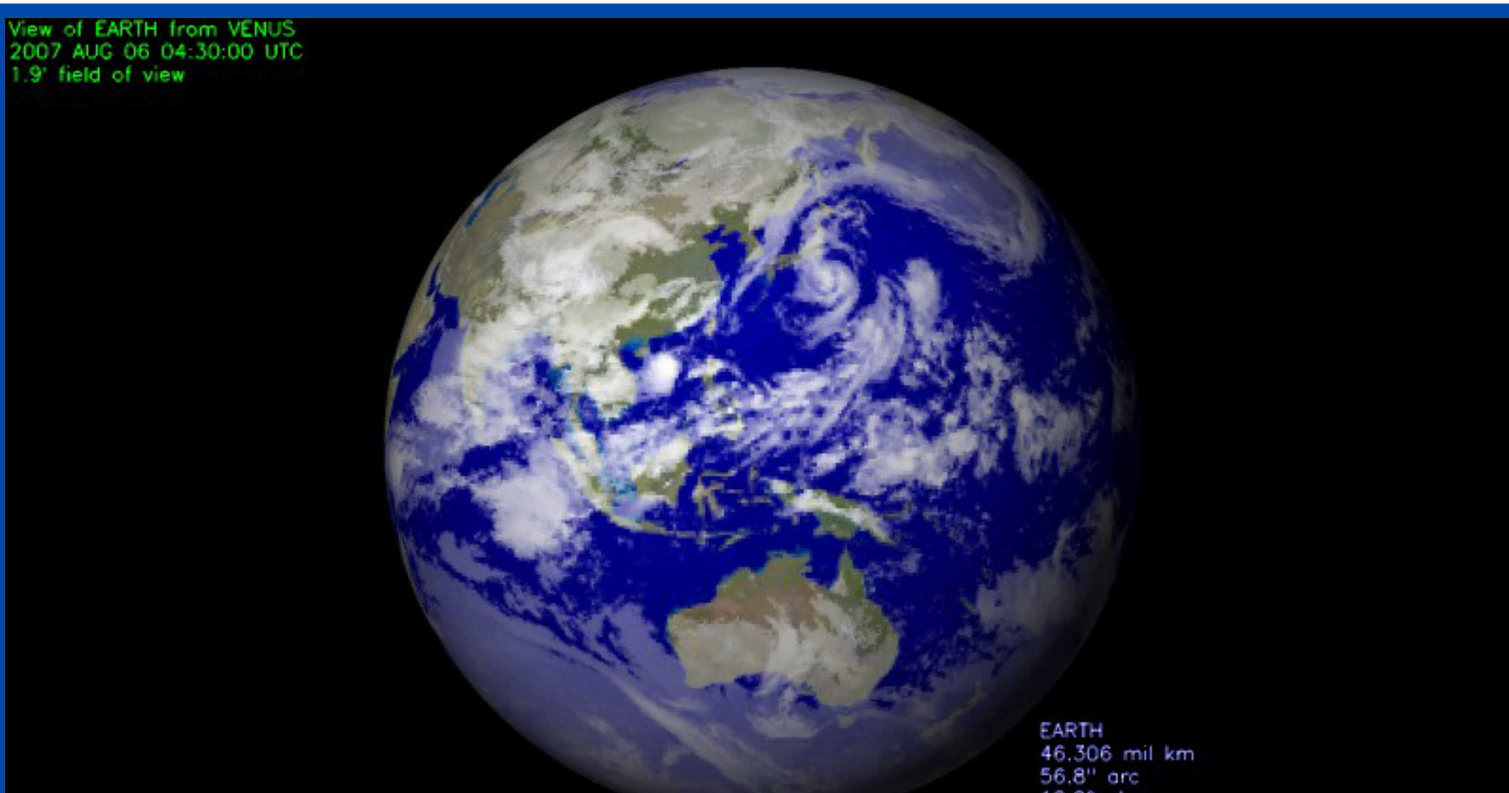


Mars!

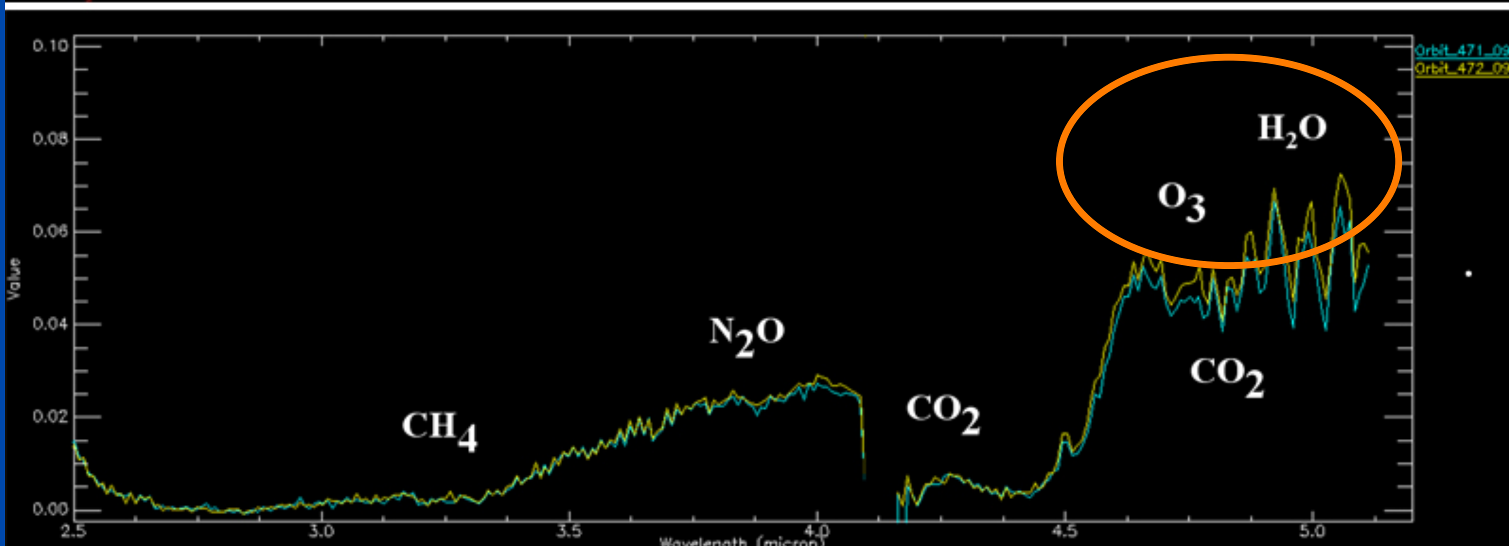
Spectral signatures of life on Earth

- Venus and Mars (no life today): CO_2
- Earth today: has water (H_2O), and atmospheric composition has been altered by life
  - Ozone line (O_3)
  - Water line (H_2O)





Spectrum of Earth seen from Venus Express Spacecraft



The Main Points

- Most of what we know about the universe comes to us in the form of light
- The visible light that our eyes can see is only a small part of the electromagnetic spectrum
  - Also radio waves, infrared light, ultraviolet light, x-rays, gamma-rays
- By spreading light out into different "colors" (taking a spectrum) we can learn about the physical conditions of the light-emitter and of intervening material
  - Composition, temperature, motion toward or away from us, rotation rate, minerals on surface, atmospheric structure, ...