

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



**Venus clouds in  
ultraviolet light**

**Claire Max**  
**October 7, 2010**  
**Astro 18: Planets and Planetary Systems**  
**UC Santa Cruz**

Astronomy Club | Astronomy and Astrophysics

http://www.astro.ucsc.edu/astronomy\_club

Astronomy Club | Astronomy and...

# Astronomy & Astrophysics


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## Astronomy Club

### Welcome to the Astronomy Club at UCSC!

We are a student led UCSC registered organization whose mission is to provide outreach events such as star gazing parties, observing classes, and guest speakers. Our events are free and open to anyone who is interested.



### Upcoming Events

**Please Note: All Star Gazing Parties have the possibility of being cancelled at the last minute due to bad weather. Please check this website prior to departing for the event!**

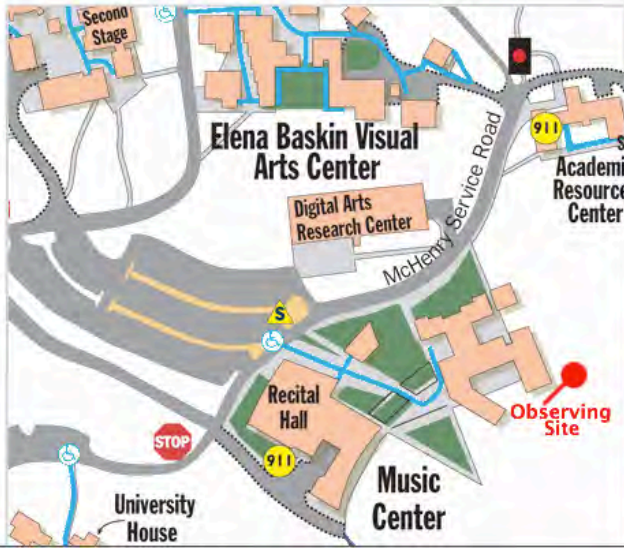
#### Hartley 2 Comet Star Party

**Oct 13, 2010 @8pm**  
**On the field behind the Music Center**  
**Please join us to see the night sky!**

Objects of interest include:  
 Hartley 2 Comet, the moon(1st hour), Jupiter (the brightest it has been in 50yrs!), Uranus, various globular clusters, nebulae, star clusters and local binaries.

**Dress warmly and bring a flashlight**

Below is a map to help you find the event location.



**Astronomy & Astrophysics**  
 211 Interdisciplinary Sciences Building (ISB)  
 Santa Cruz, CA 95064  
 Phone: (831) 459-2844  
 Fax: Business Hours M-F (831) 459-5265  
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[Maps & Directions](#)

**Related links**

- [Center for Adaptive Optics \(CFAO\)](#)
- [Center for Origin, Dynamics, and Evolution of Planets \(CODEP\)](#)
- [Division of Physical & Biological Sciences](#)
- [High-Performance AstroComputing Center \(HIPACC\)](#)
- [Institute for Geophysics and Planetary Physics \(IGPP\)](#)
- [International Summer Institute for Modeling in Astrophysics \(ISIMA\)](#)
- [Laboratory for Adaptive Optics \(LAO\)](#)
- [Lick Observatory](#)

# *Outline of this lecture*

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- **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*

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

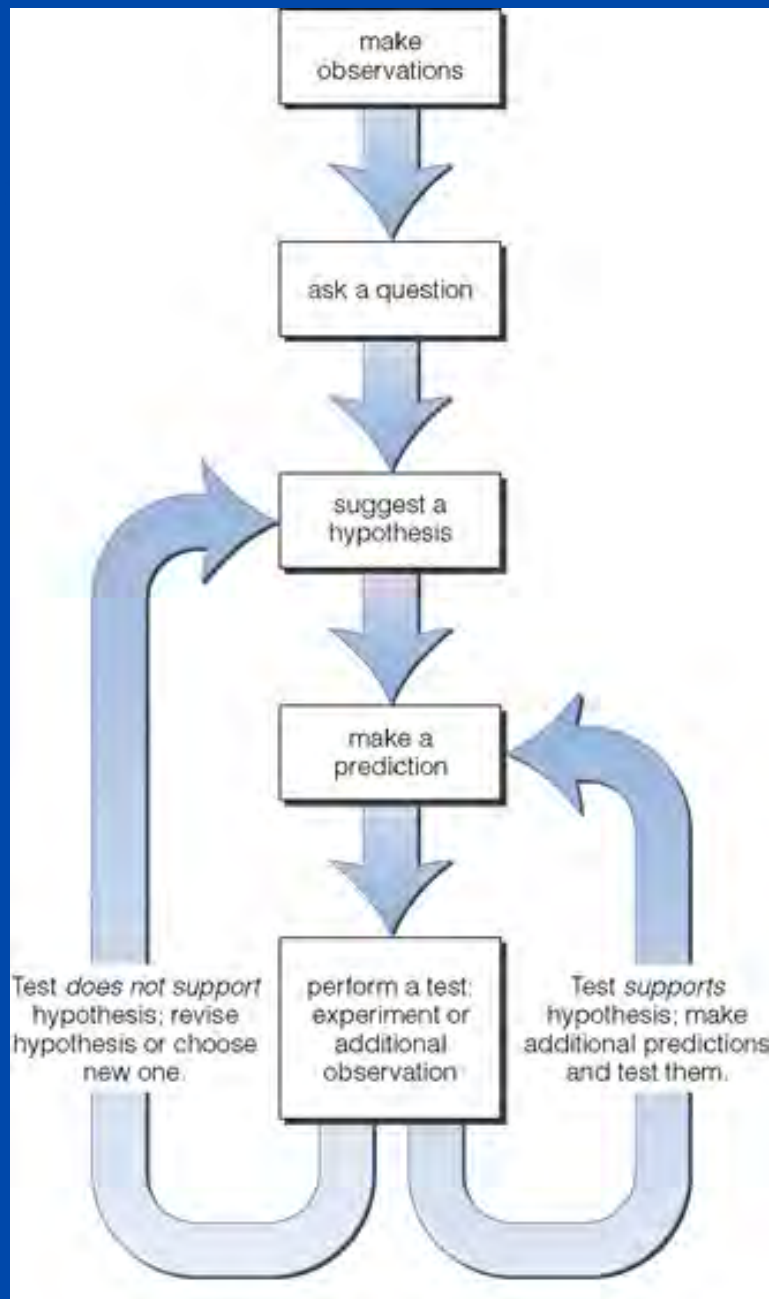
# *What is a scientific theory?*

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- **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





## *The idealized scientific method*

- Based on proposing and testing hypotheses
- Hypothesis = educated guess

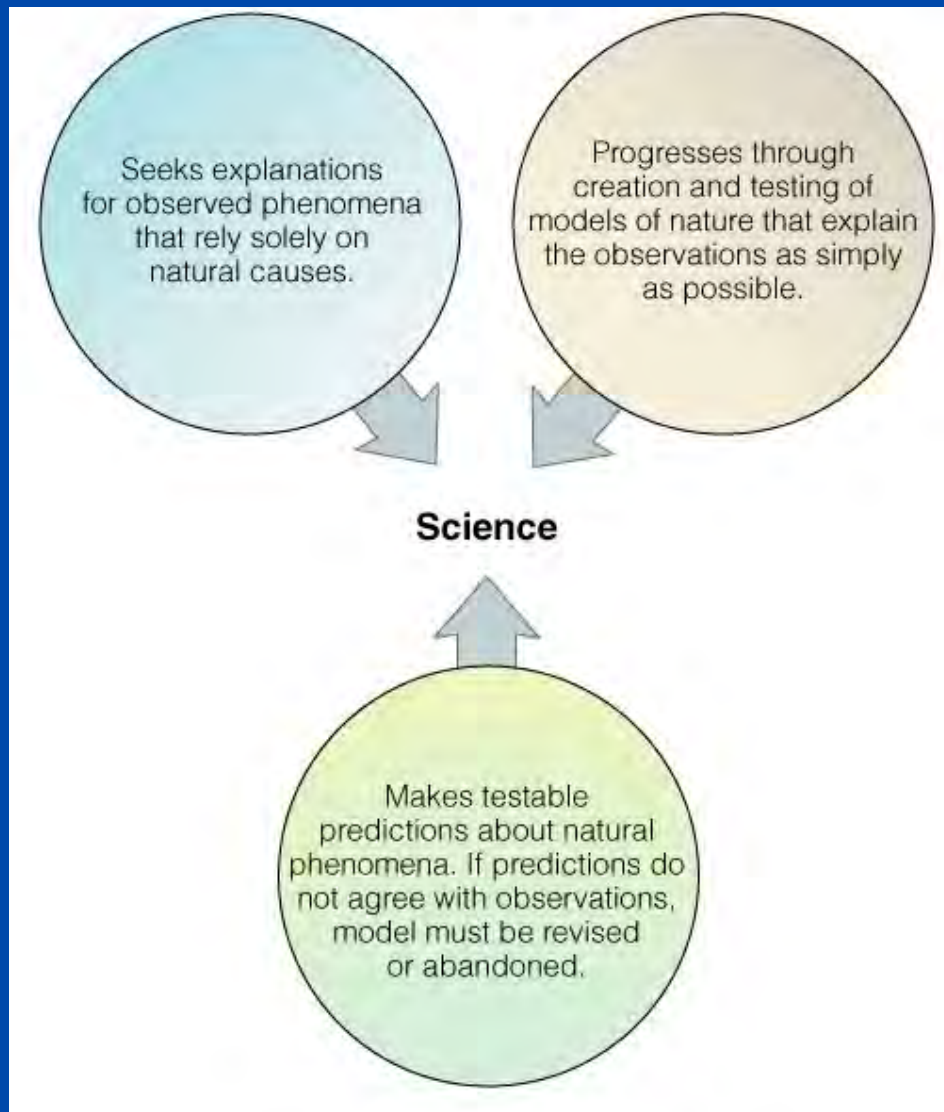
***But science doesn't always proceed in this idealized way!***

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- **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*

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- **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***

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- **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*

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- **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*

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- 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?***

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- **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 on human lives based on the positions of planets and stars in the sky.

## Horoscope.com Daily

WEDNESDAY, OCT 6, 2010 - PLANETARY INDEX: 2/5

The Moon opposes Jupiter and Uranus before moving into Libra this afternoon and squaring Pluto. Surprises and upsets may bring challenges in relationships early in the day. It will be important to leave the lines of communication open in order to prevent possible misunderstandings.

## ***Does astrology have scientific validity?***

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- 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.

# *What have we learned?*

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- **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*

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- **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*

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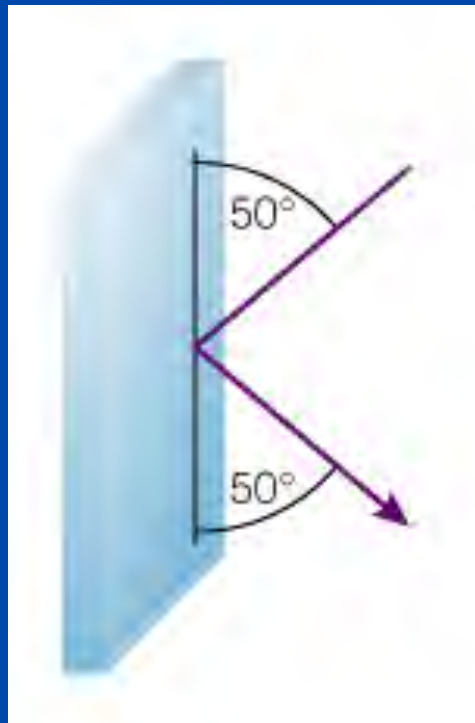


Much of what we have learned about the universe is based on observing light, and understanding how it has interacted with matter

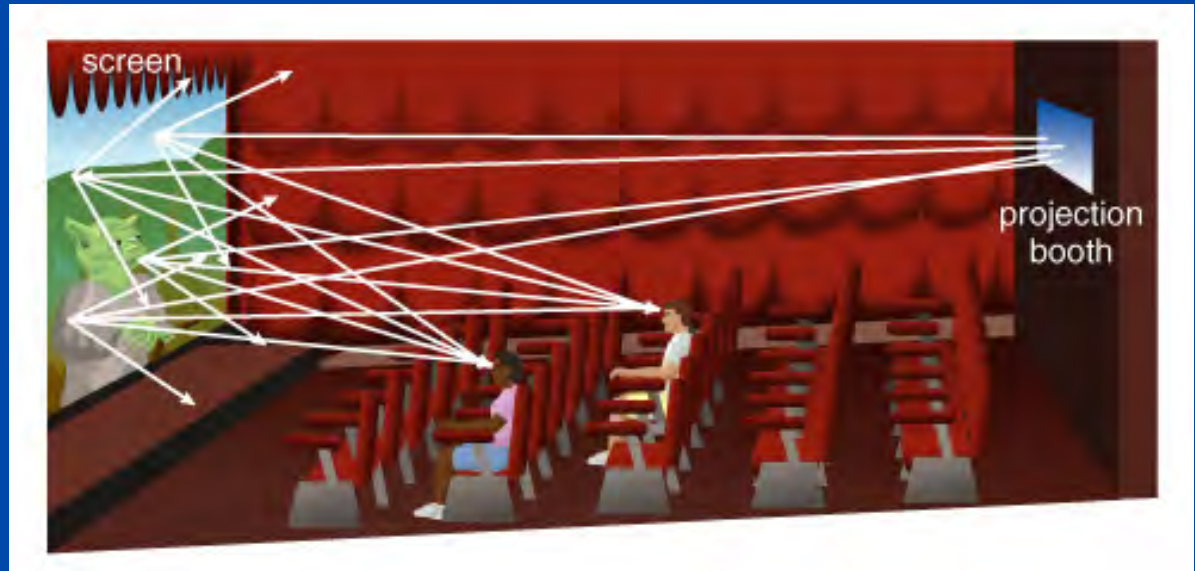
- **Properties of light**
- **Properties of matter**
- **How light interacts with matter**



# Reflection and Scattering

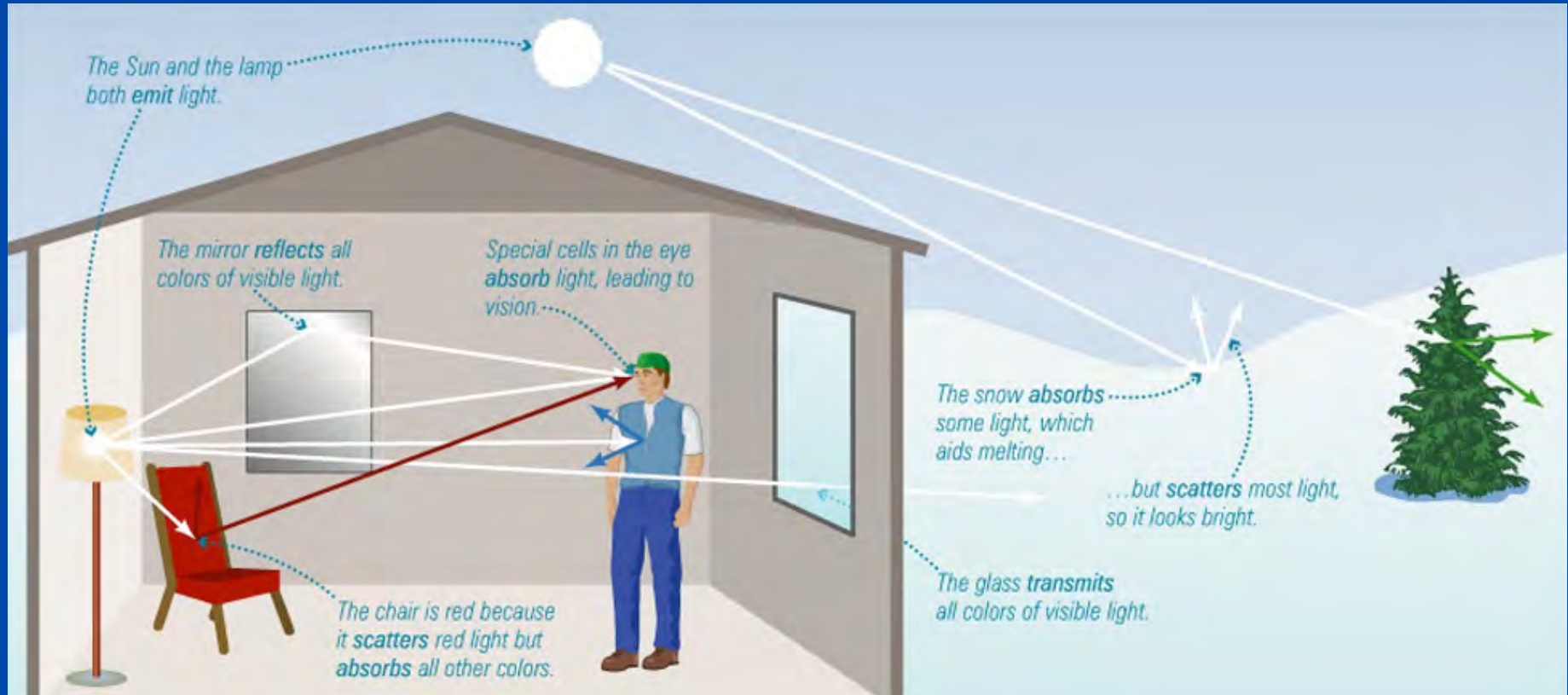
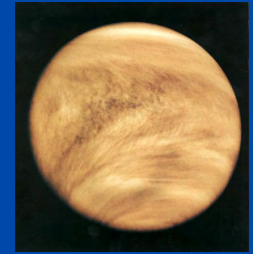


**Mirror reflects light in a particular direction**



**Movie screen scatters light in all directions**

# Interactions of Light with Matter

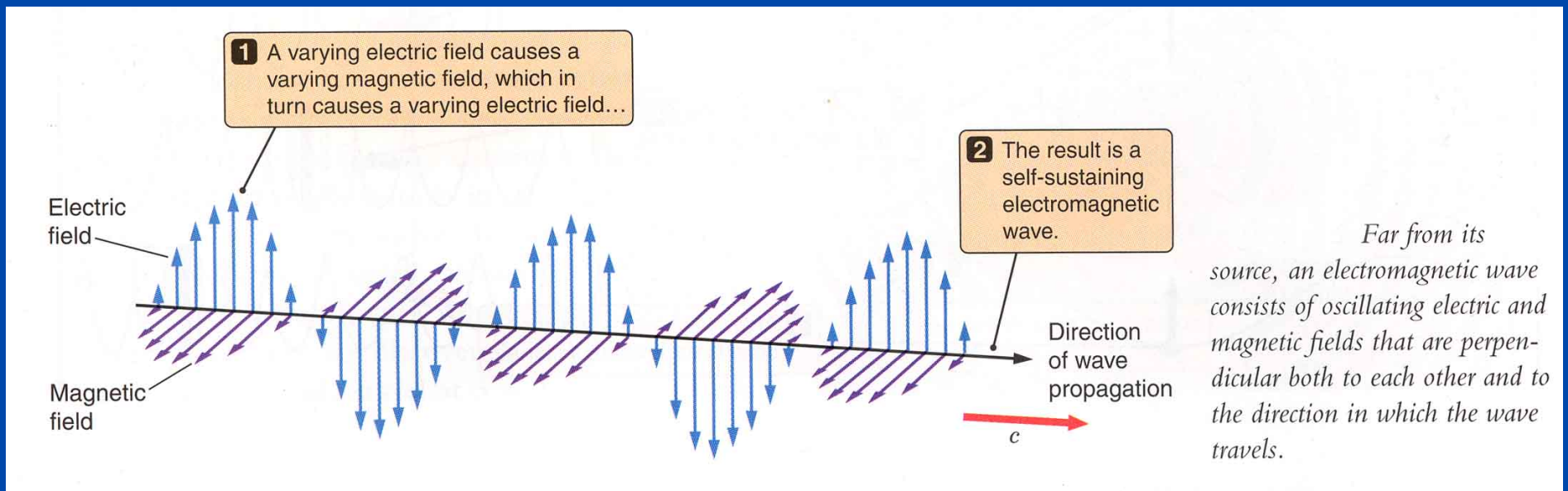


- Interactions between light and matter determine the appearance of everything around us

# What is light?



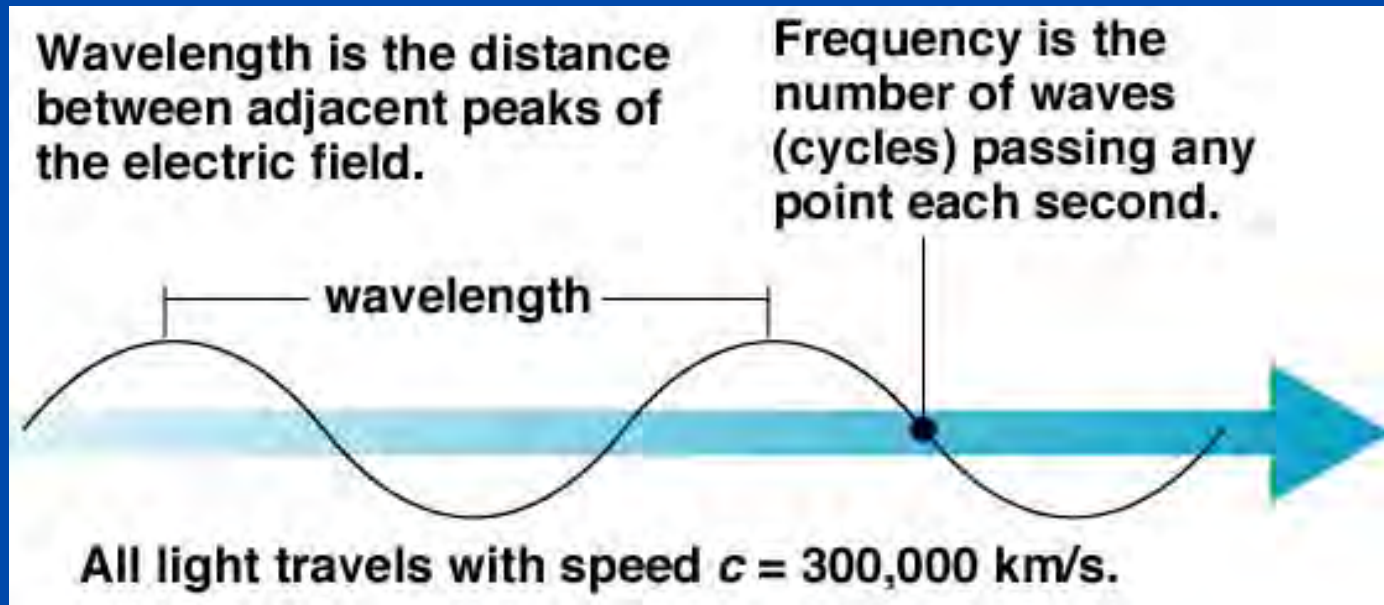
- Oscillating electric and magnetic fields, traveling at “speed of light” (300,000 km/sec)



# *Light can be described as a wave*



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







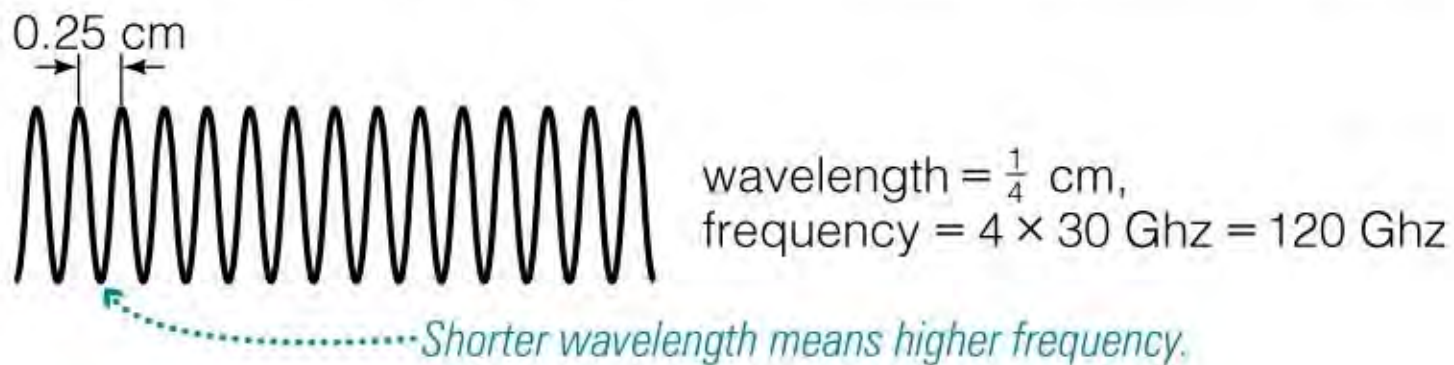
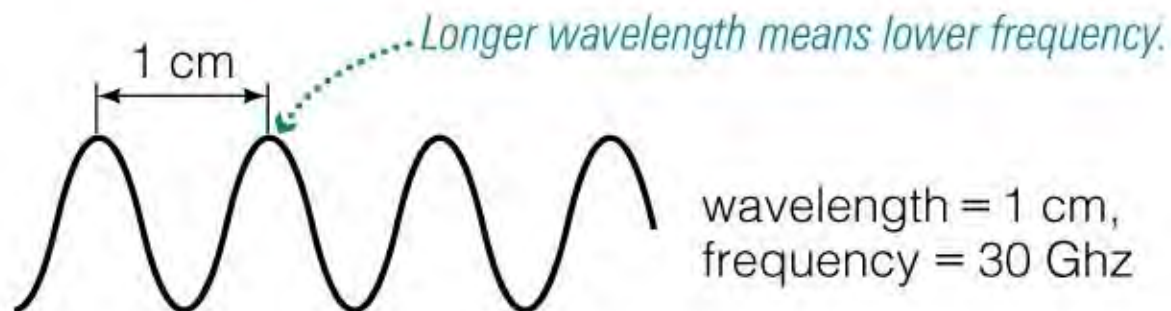
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# Anatomy of a Wave





# Wavelength visualized



# ***Relation between frequency and wavelength of a light wave***

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- **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  $\lambda$**

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

# *Units of frequency and wavelength*

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

# *Units used for wavelength*

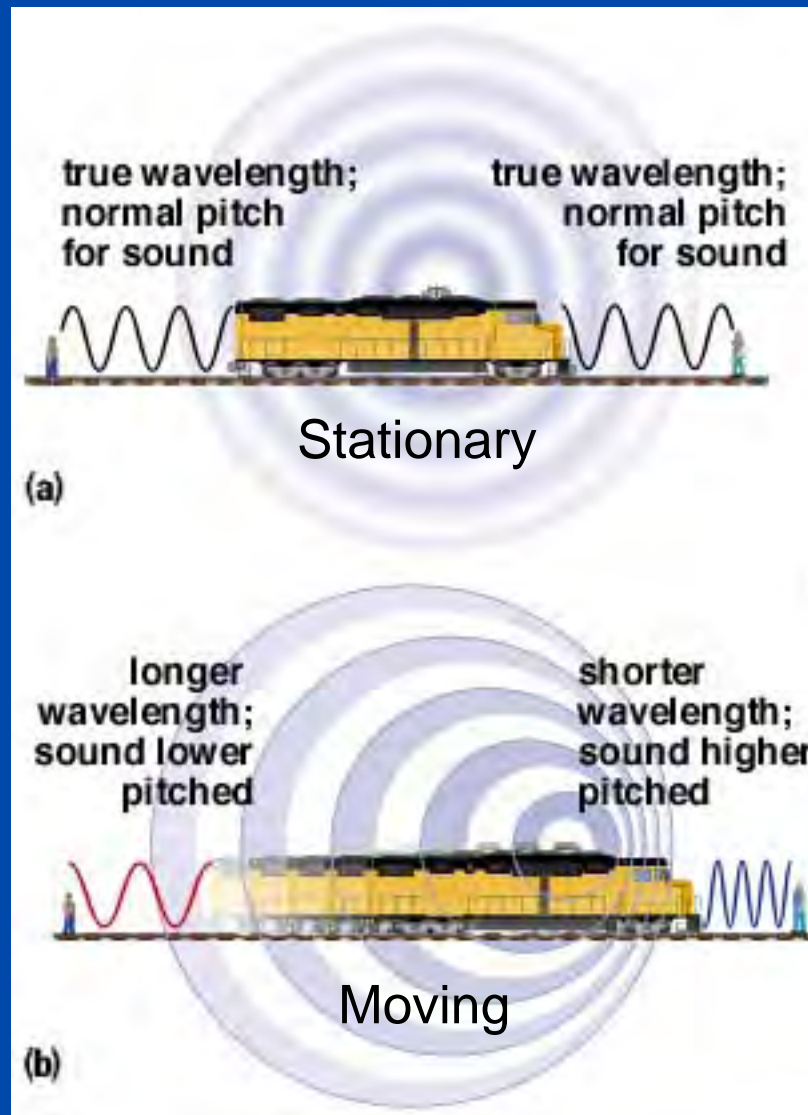


<b>Units of Wavelength</b>		
<b>Unit</b>	<b>Symbol</b>	<b>Length</b>
centimeter	cm	$10^{-2}$ meters
Angstrom	Å	$10^{-8}$ centimeters
nanometer	nm	$10^{-9}$ meters
micron	μm	$10^{-6}$ meters

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



## **Sound waves:**

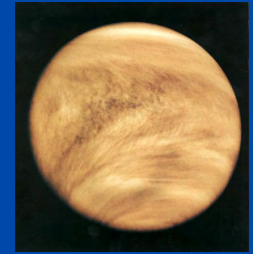




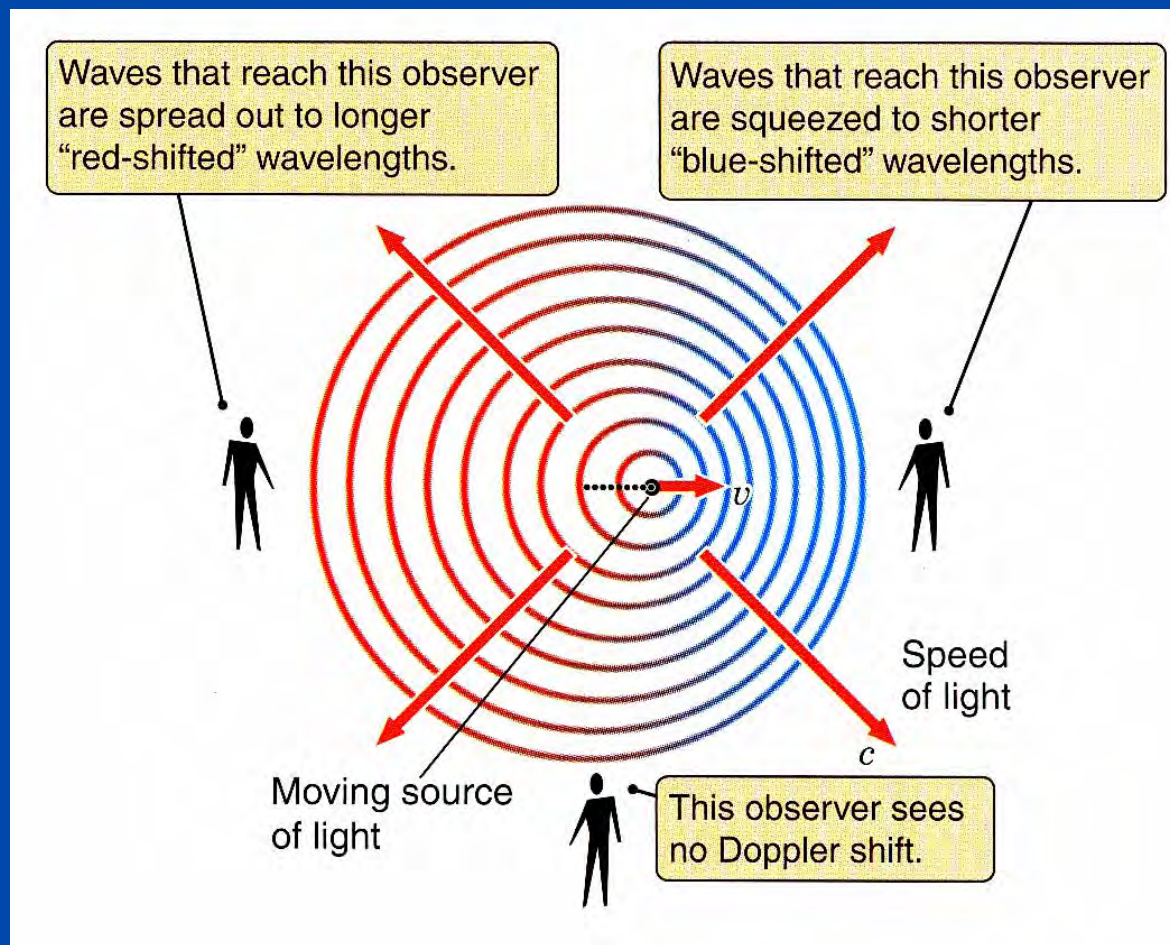


- 
- Hearing the Doppler Effect

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



## Light waves:



# *Size of Doppler shift depends on speed $v$*

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

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

## Example of Doppler shift

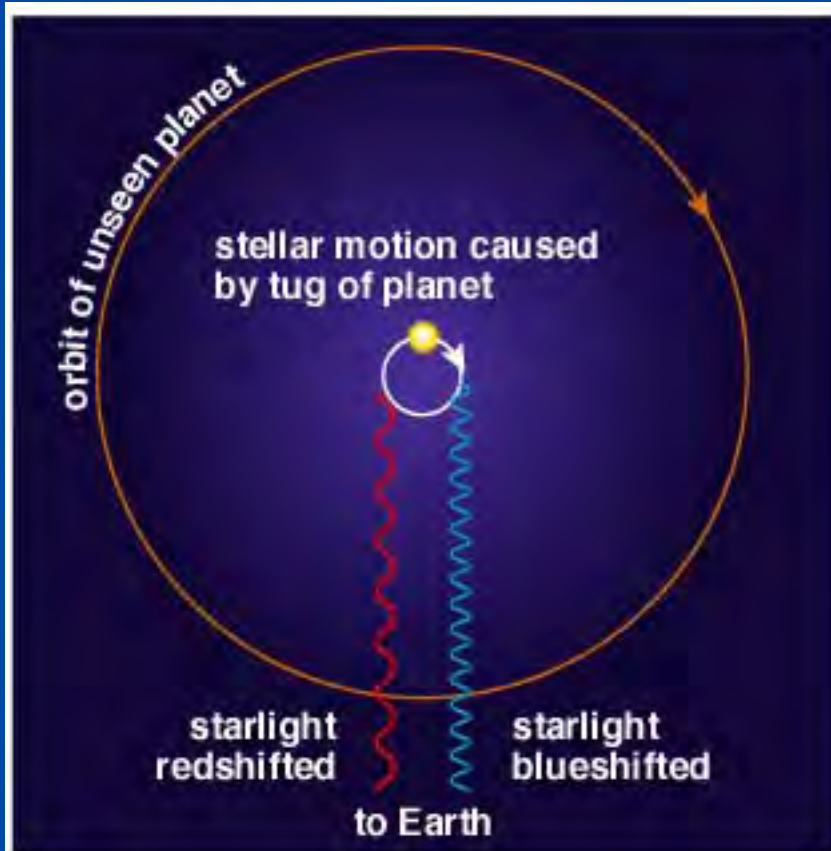


- The “rest wavelength” of light being emitted by a planet is 6562.85 Å, and we observe this light to be shifted to a wavelength of 6562.55 Å
- What velocity does light’s source have?

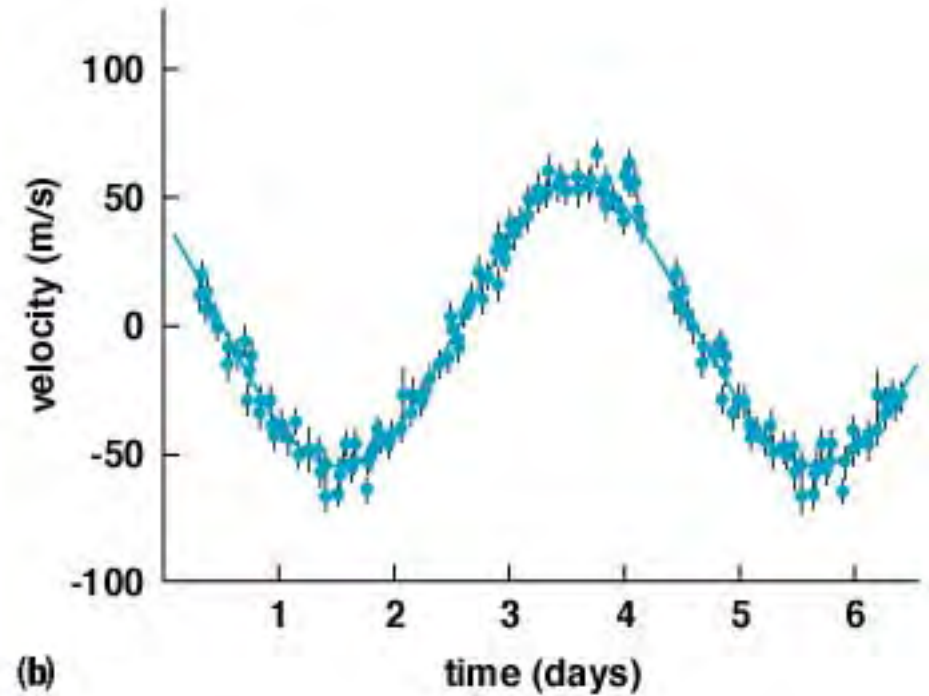
$$v = \left( \frac{\lambda_1 - \lambda_0}{\lambda_0} \right) \times c$$

$$v = \left[ \frac{(6562.55 - 6562.85) \times 10^{-8} \text{ cm}}{6562.85 \times 10^{-8} \text{ cm}} \right] \times \left( 3 \times 10^{10} \frac{\text{cm}}{\text{sec}} \right) = -1.37 \times 10^6 \left( \frac{\text{cm}}{\text{sec}} \right) = -13.7 \left( \frac{\text{km}}{\text{sec}} \right) \text{ toward us}$$

# Extrasolar planets: one method of detection relies on Doppler shift



(a)



(b)



## ***Concept Question***

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- **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*



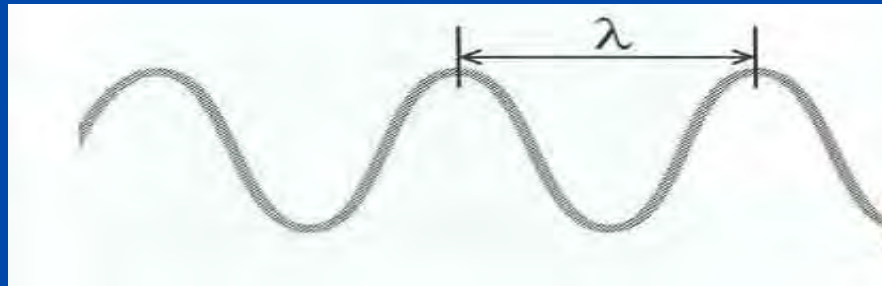
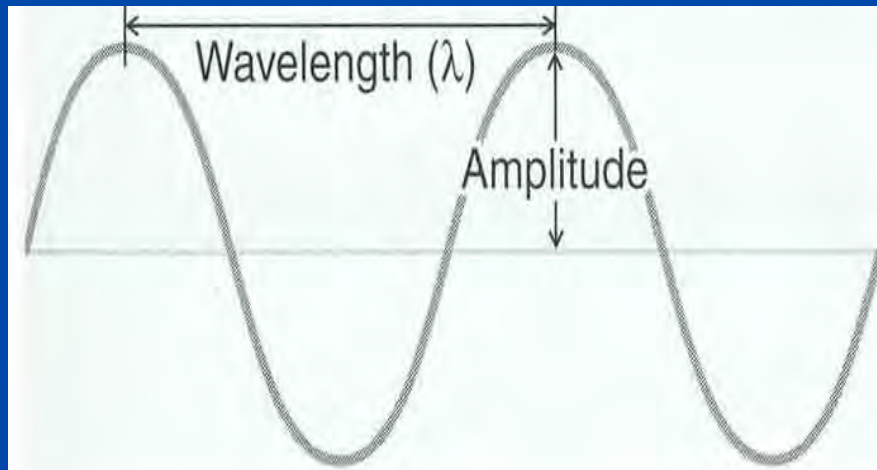
- **A paradox: light behaves both as a particle and as a wave!**
- **Just as a baseball carries a specific amount of kinetic energy, each light particle or “photon” of light carries a specific amount of radiative energy:**

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

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

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

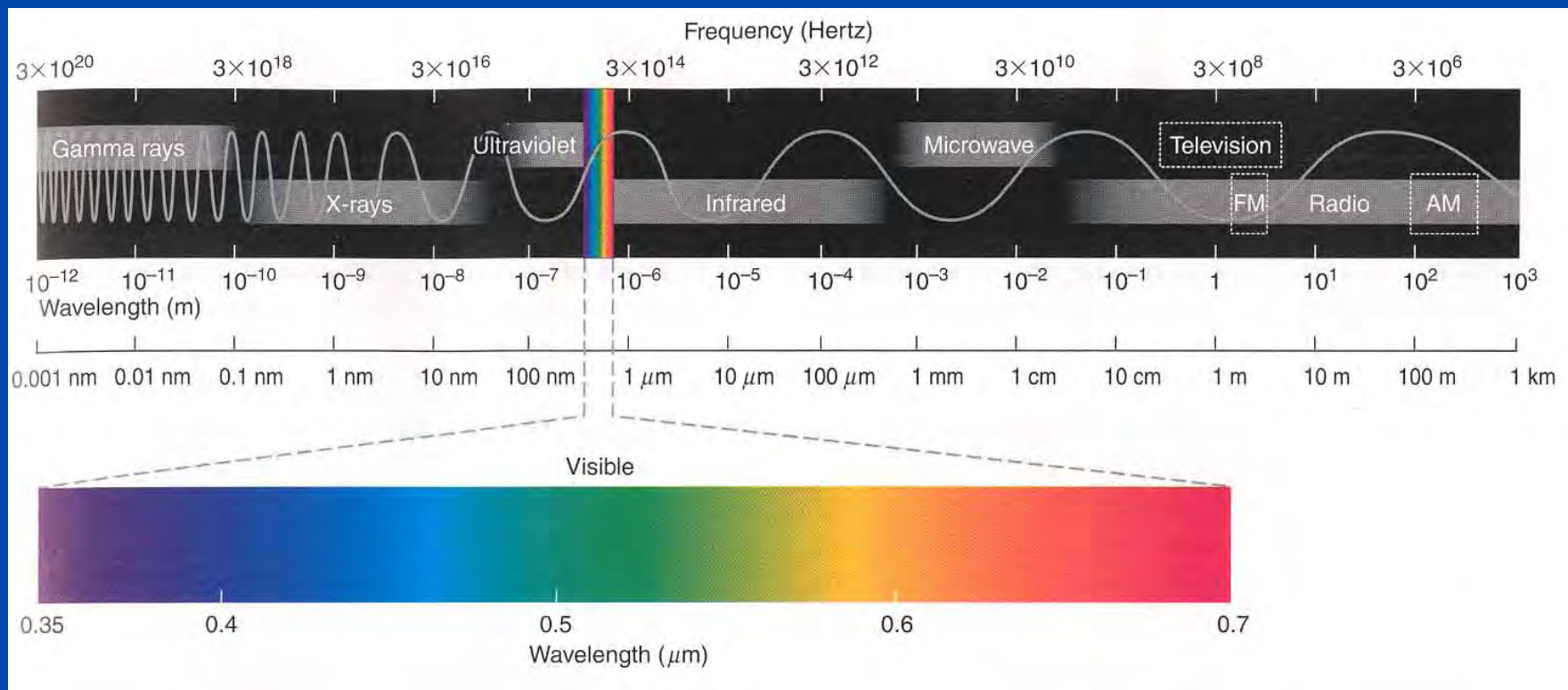
# Distinguish between light energy and light intensity



- **Higher amplitude and intensity**
  - Intensity is just square of amplitude
- **Higher frequency and photon energy**

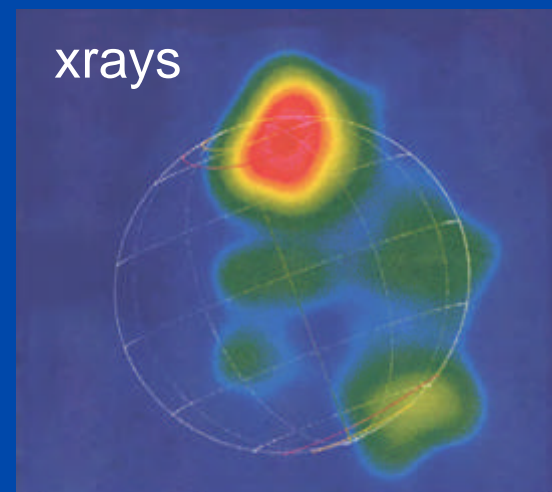
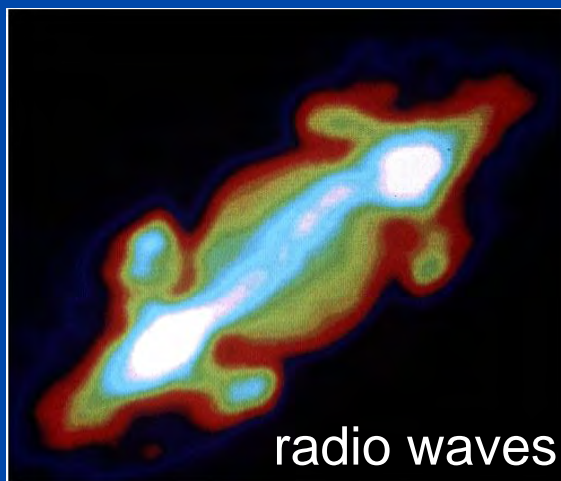
$$E = h \times f = \frac{hc}{\lambda}$$

# Visible light is only a small fraction of the electromagnetic spectrum





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





# *Properties of Matter*

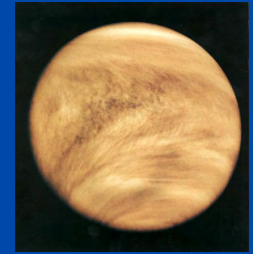
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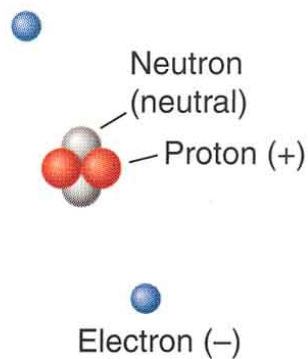
- **What is the structure of matter?**
- **What are the phases of matter?**
- **How is energy stored in atoms?**



# Atomic structure

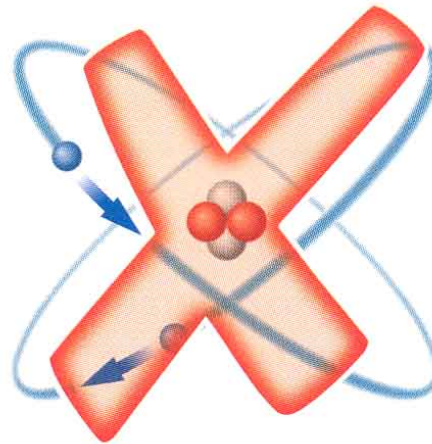


(a) Parts of an atom



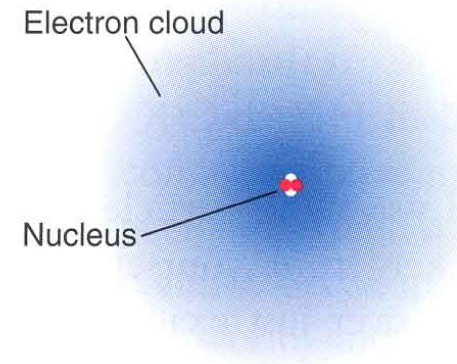
This is a helium atom (2 protons, 2 neutrons, and 2 electrons).

(b) "Solar system" model



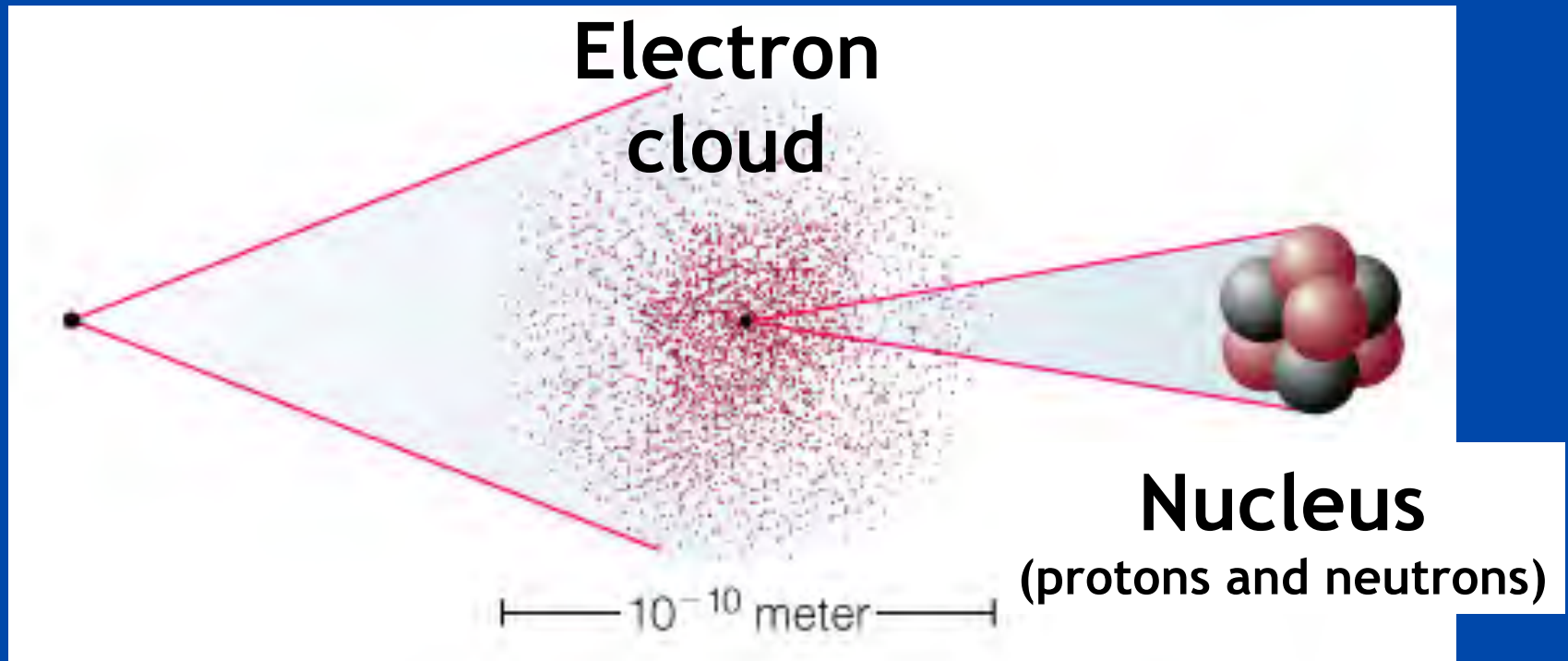
Electrons do not move in orbits like planets...

(c) Quantum mechanical model



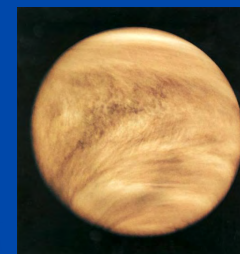
...but rather are waves "smeared out" in a cloud of probability held in place by the electric attraction of the nucleus.

# What is the smallest-structure of matter?

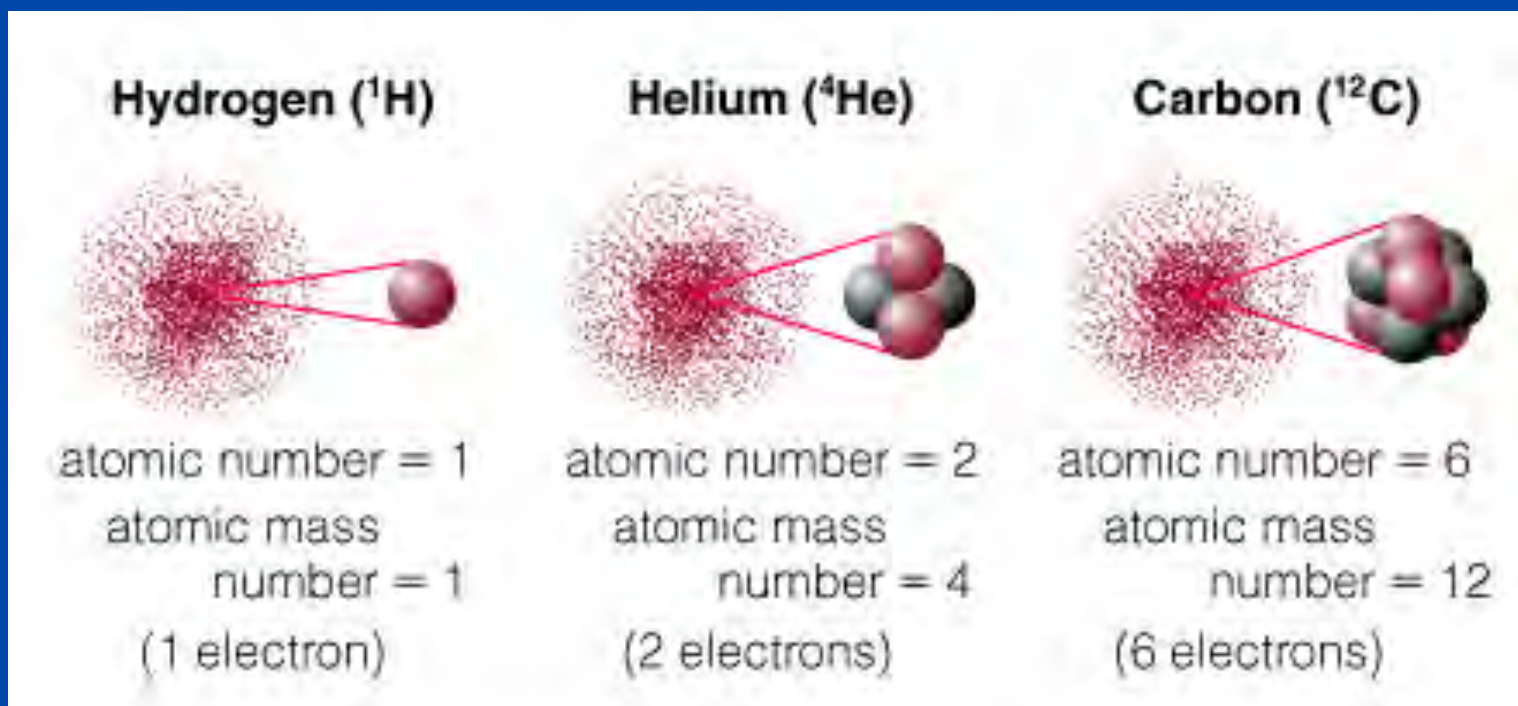


## Atom

# Atomic Number and Mass



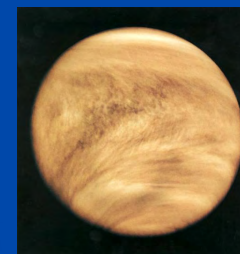
- **Atomic Number** = # of protons in nucleus
- **Atomic Mass Number** = # of protons + neutrons



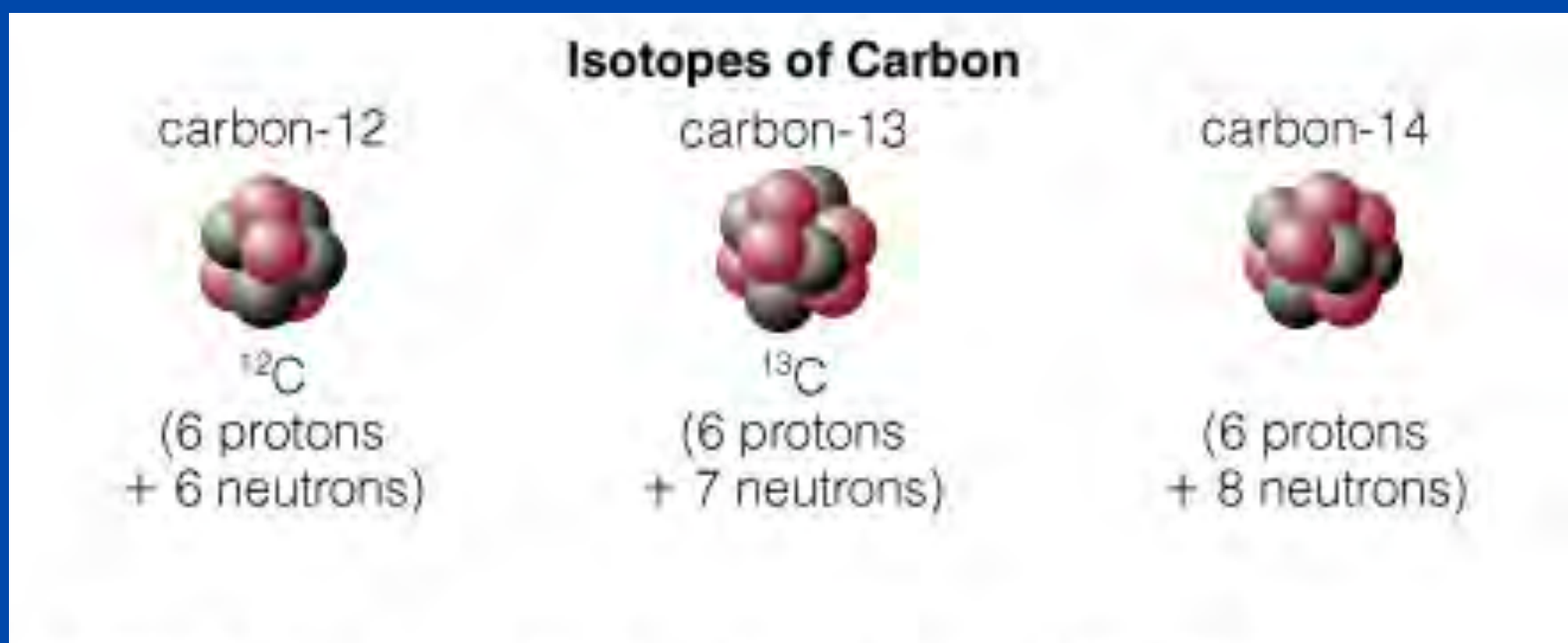
- **Molecules: consist of two or more atoms ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ )**



# Atomic Terminology



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



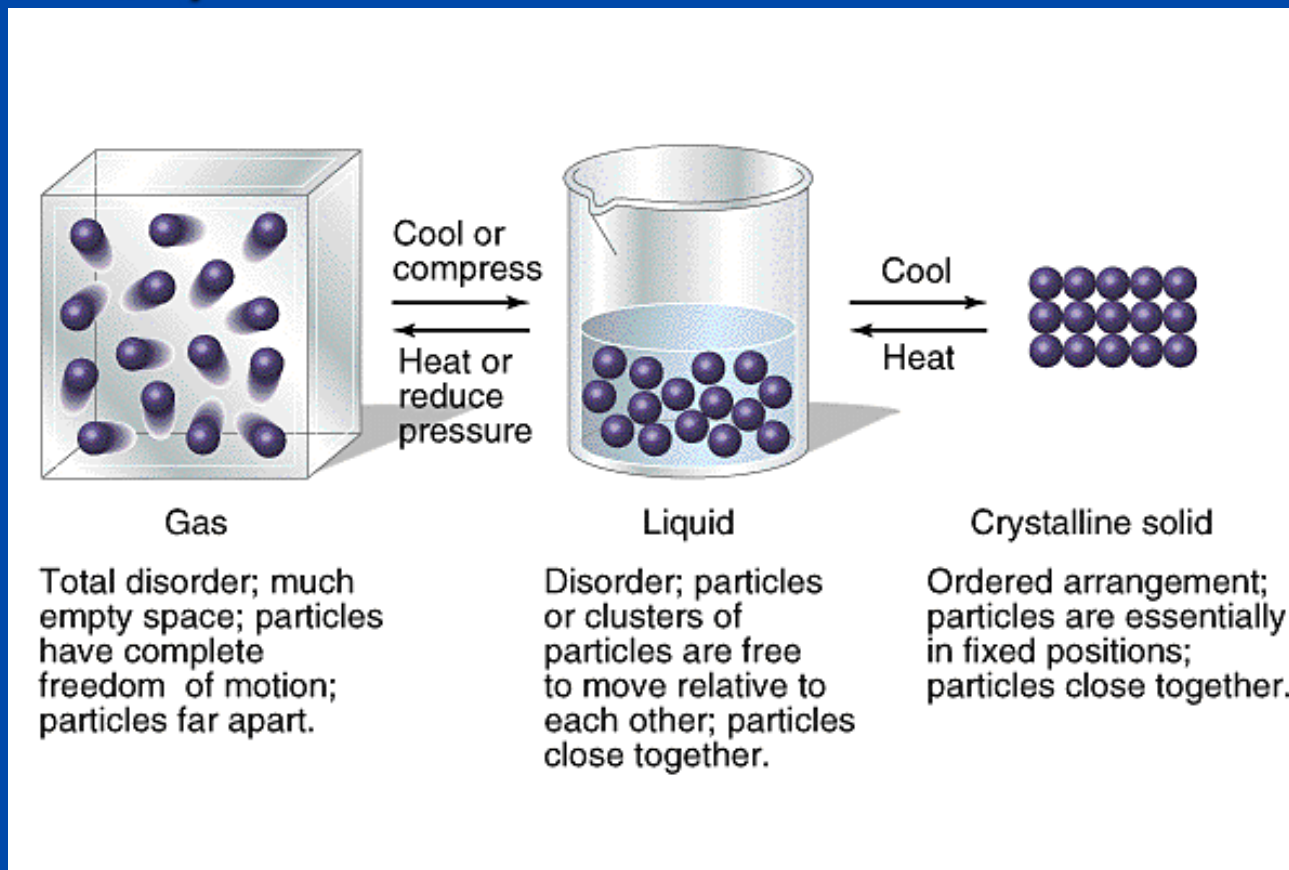
- **All are carbon: 6 protons, atomic number 6**



# Solids, liquids, gases are different phases of matter



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



# *Properties of Matter*

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

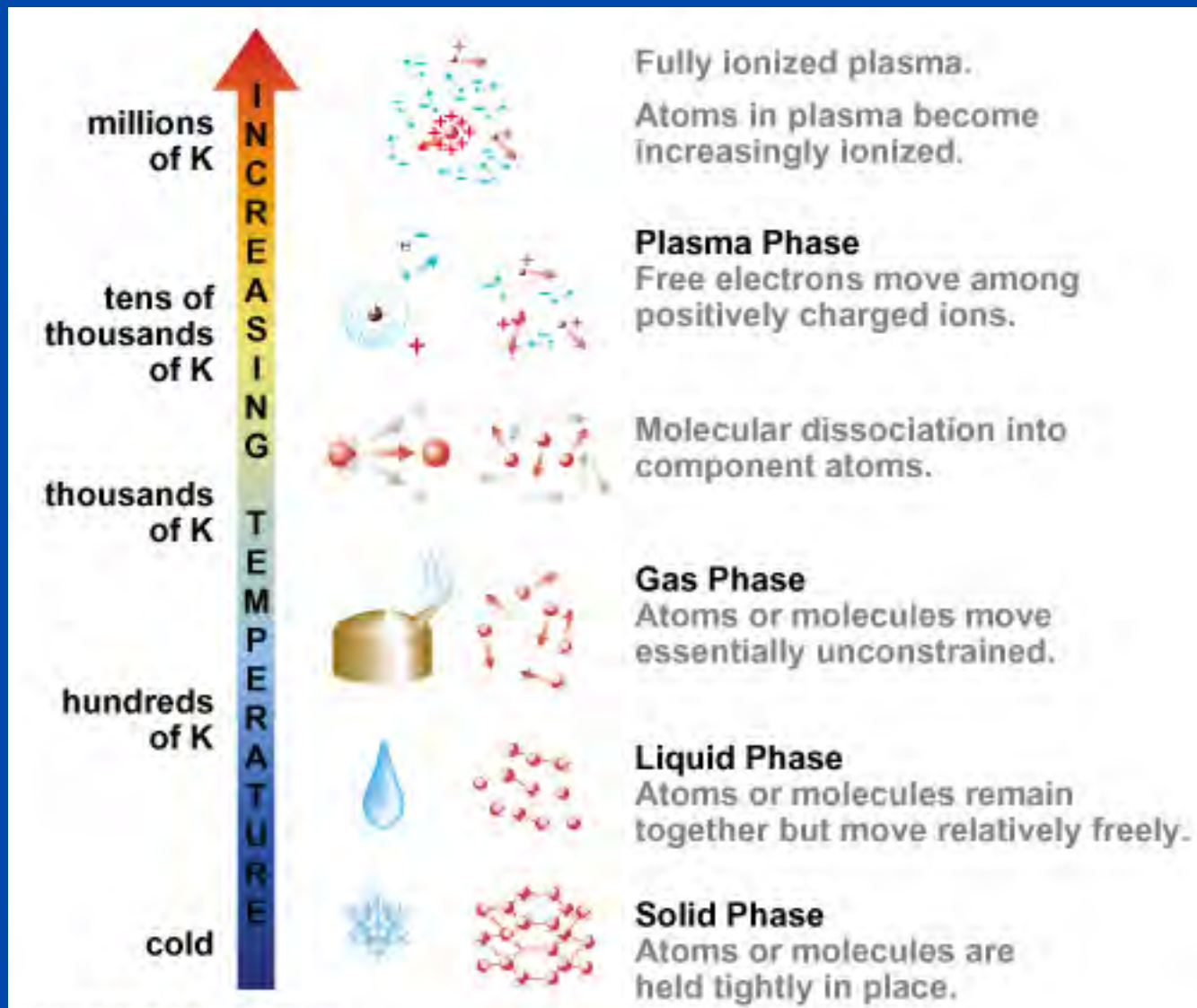


# *All three phases have random motions*

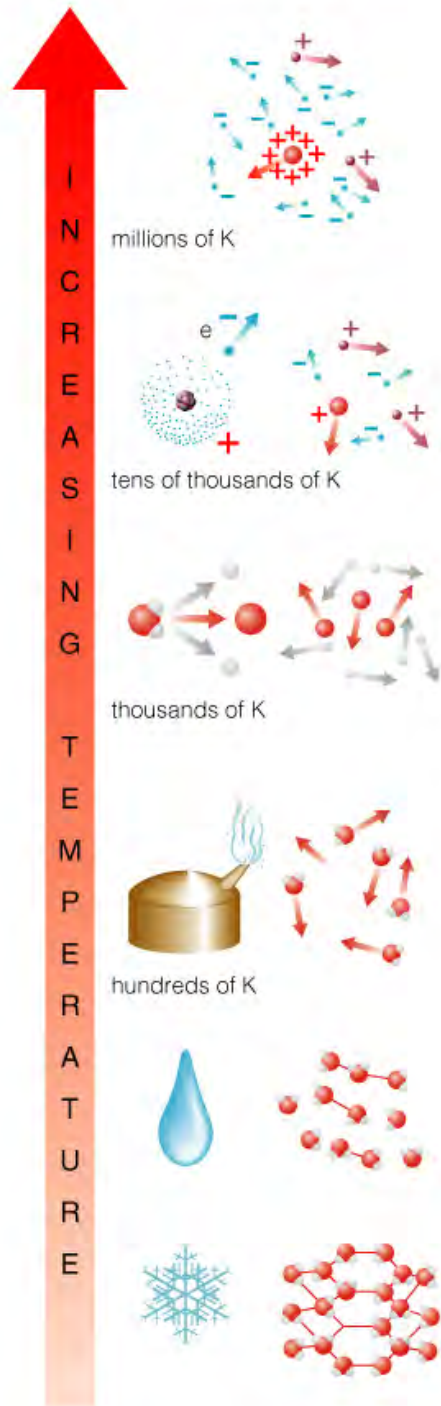
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- Temperature and phases of water



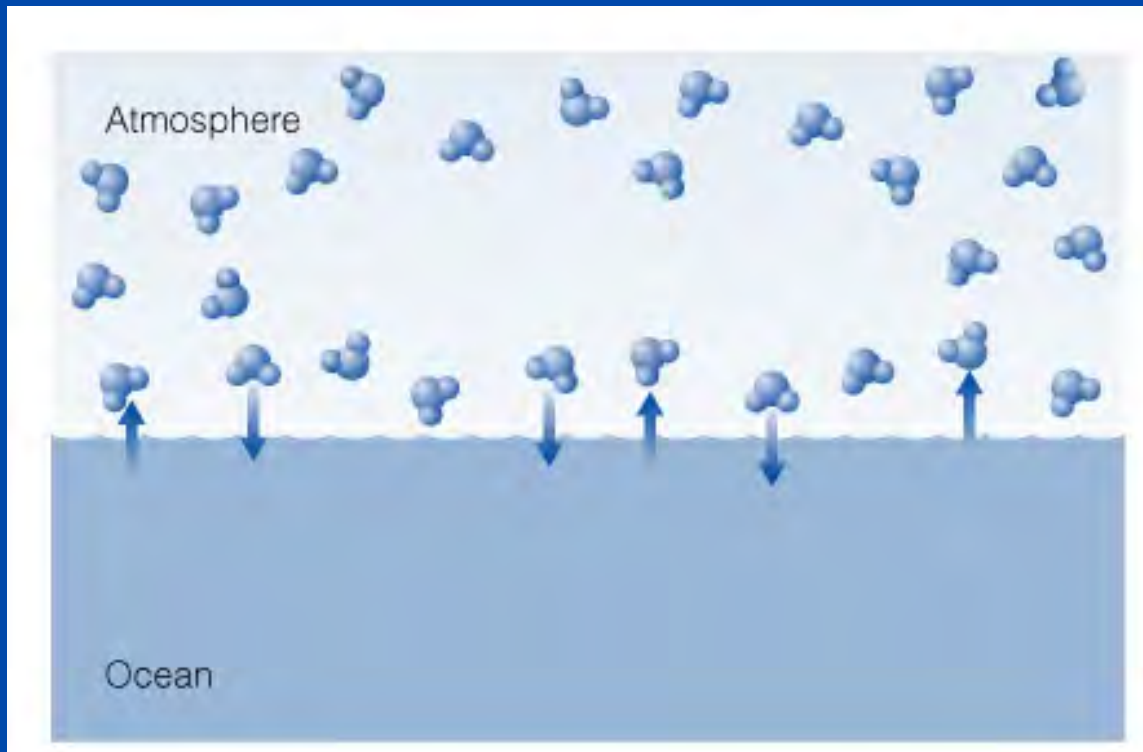
# Phase Changes: Terminology



- **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

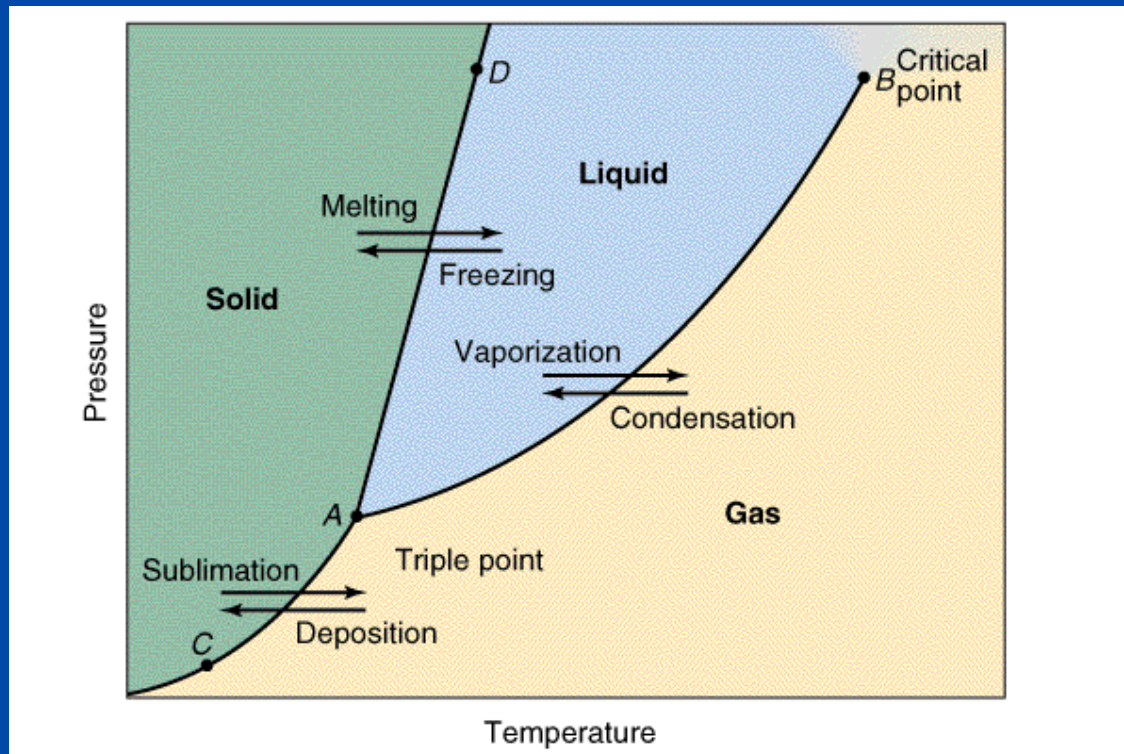


- Phase of a substance depends on both temperature and pressure
- Often more than one phase is present

# Phase Diagram: plots pressure against temperature



- Phase of a substance depends on both temperature and pressure

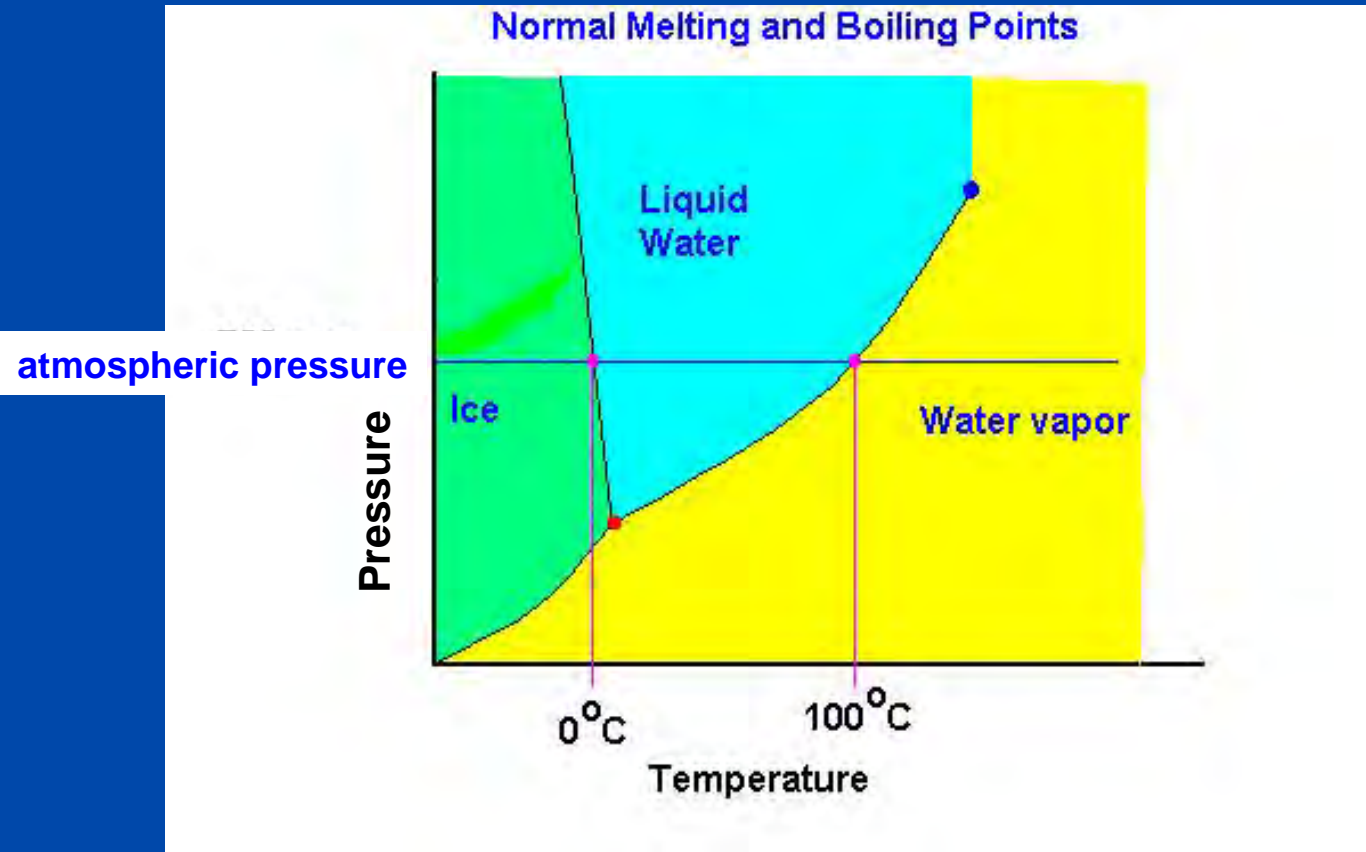


- Above critical point, gas makes continuous transition to liquid
- No phase transition
- Happens inside the giant planets

# Phase Diagram: plots pressure against temperature



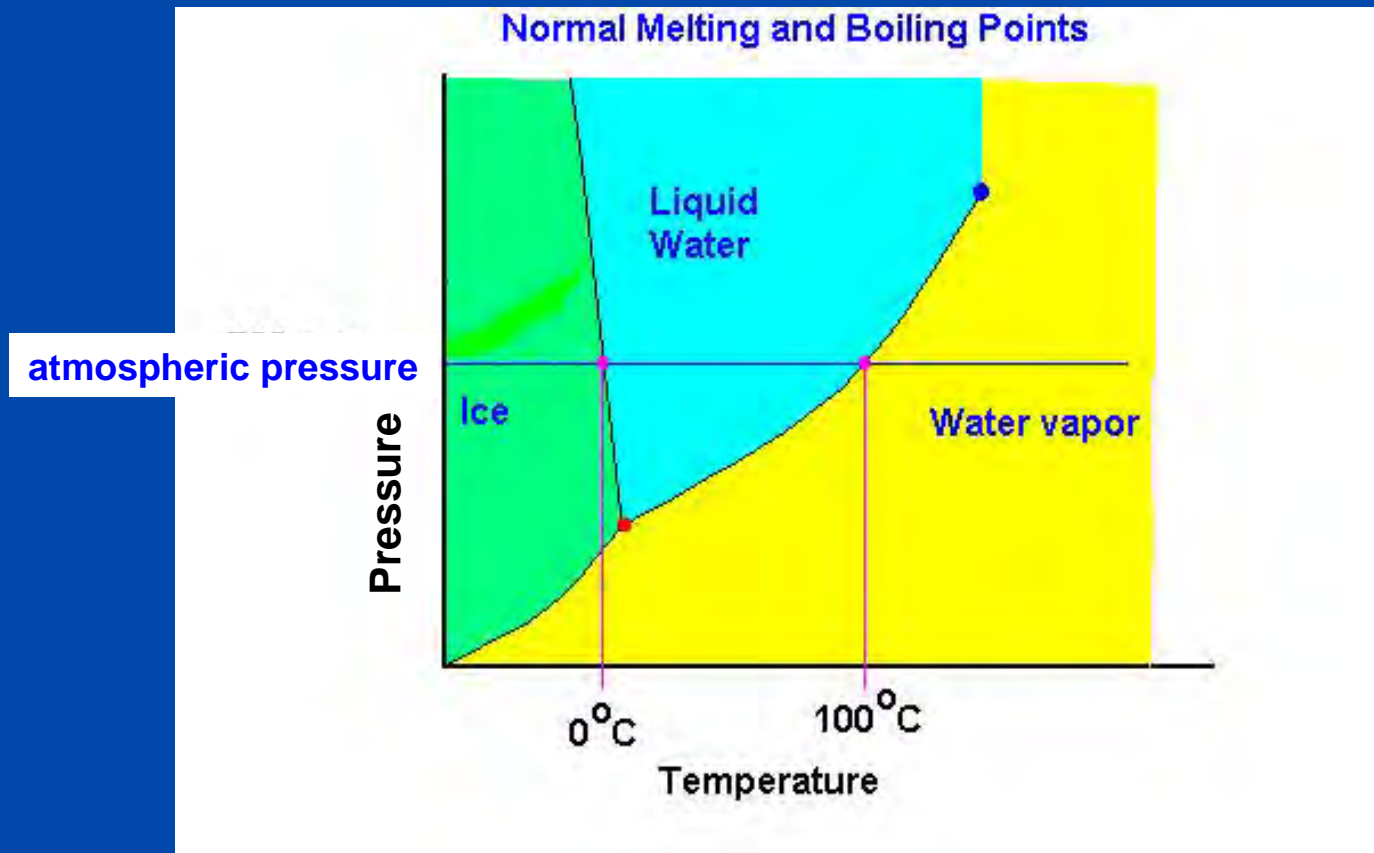
- Phase of a substance depends on both temperature and pressure



# Concept Question



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



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

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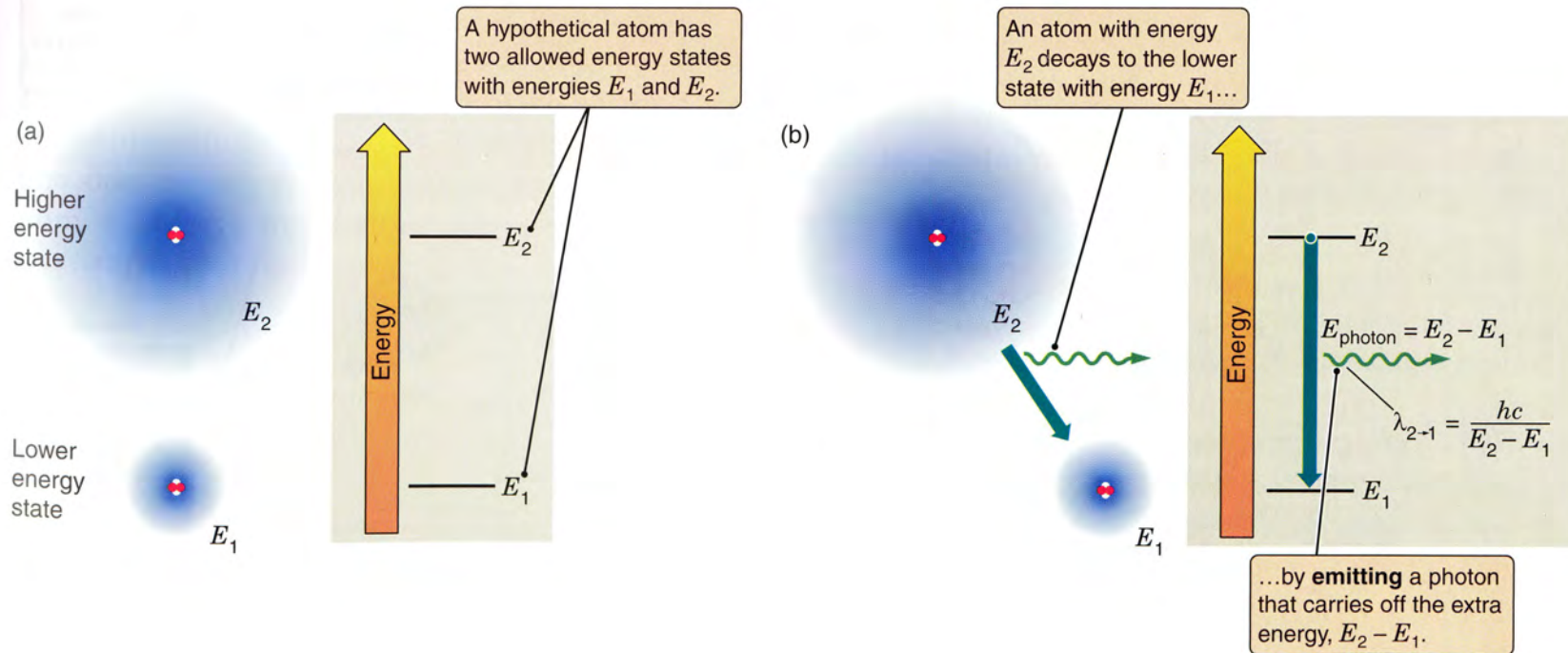
- **Emission of light by matter**
- **Absorption of light by matter**



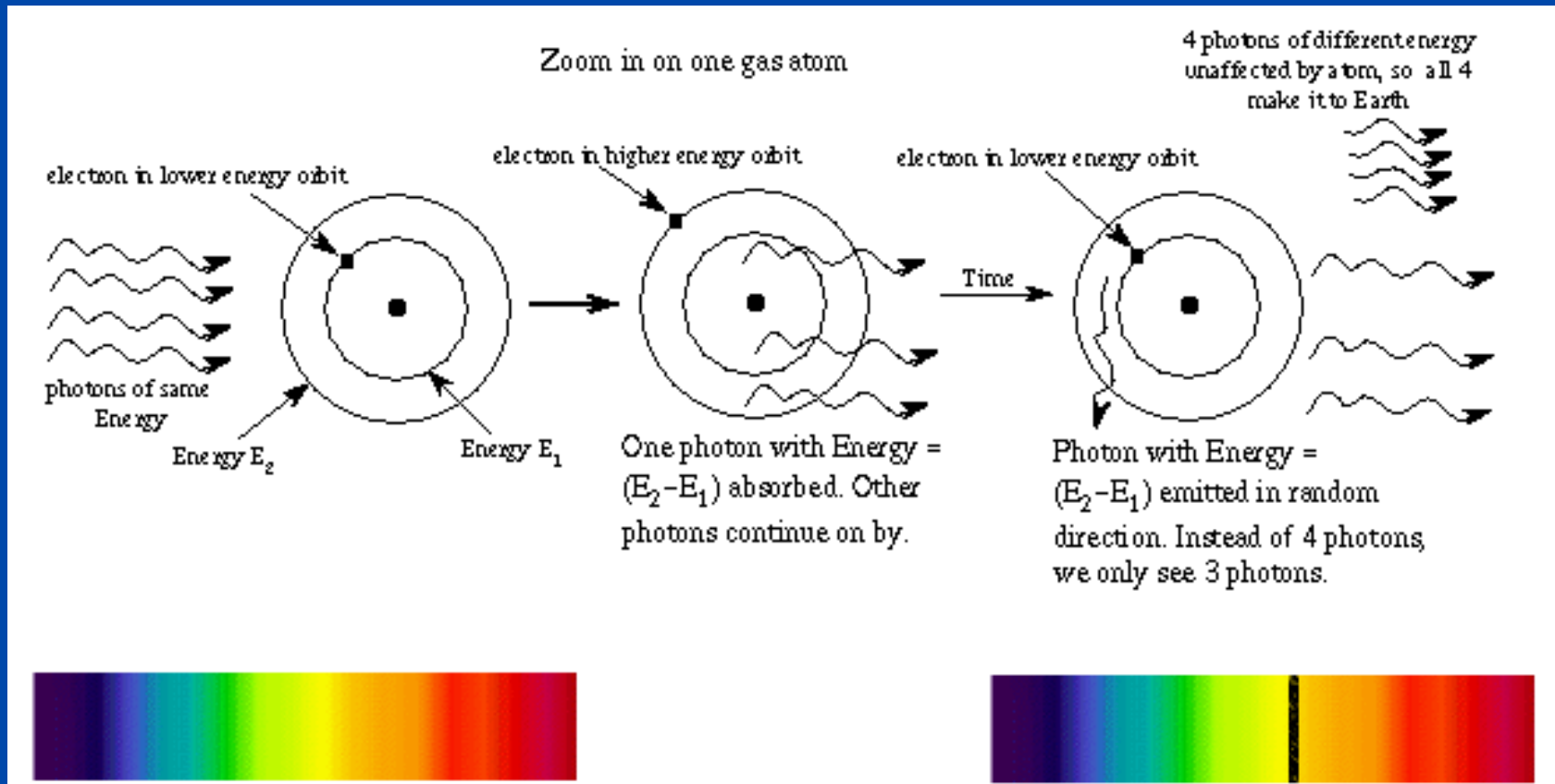
# Emission of light by an atom



(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.

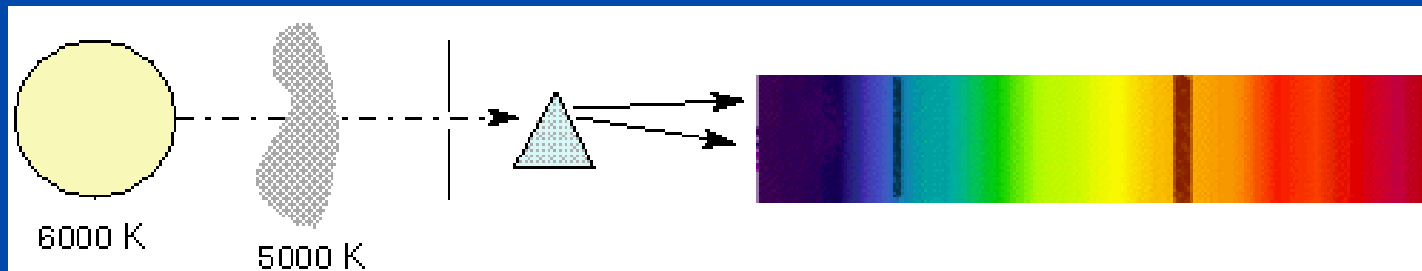


# Absorption of light by an atom

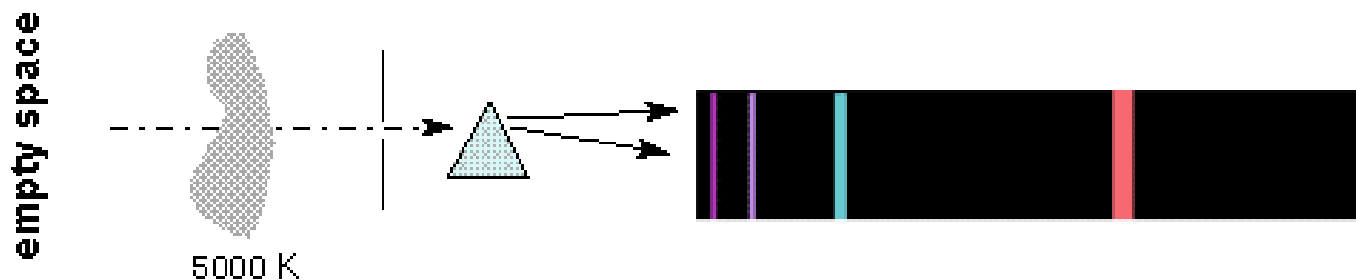


© Nick Strobel

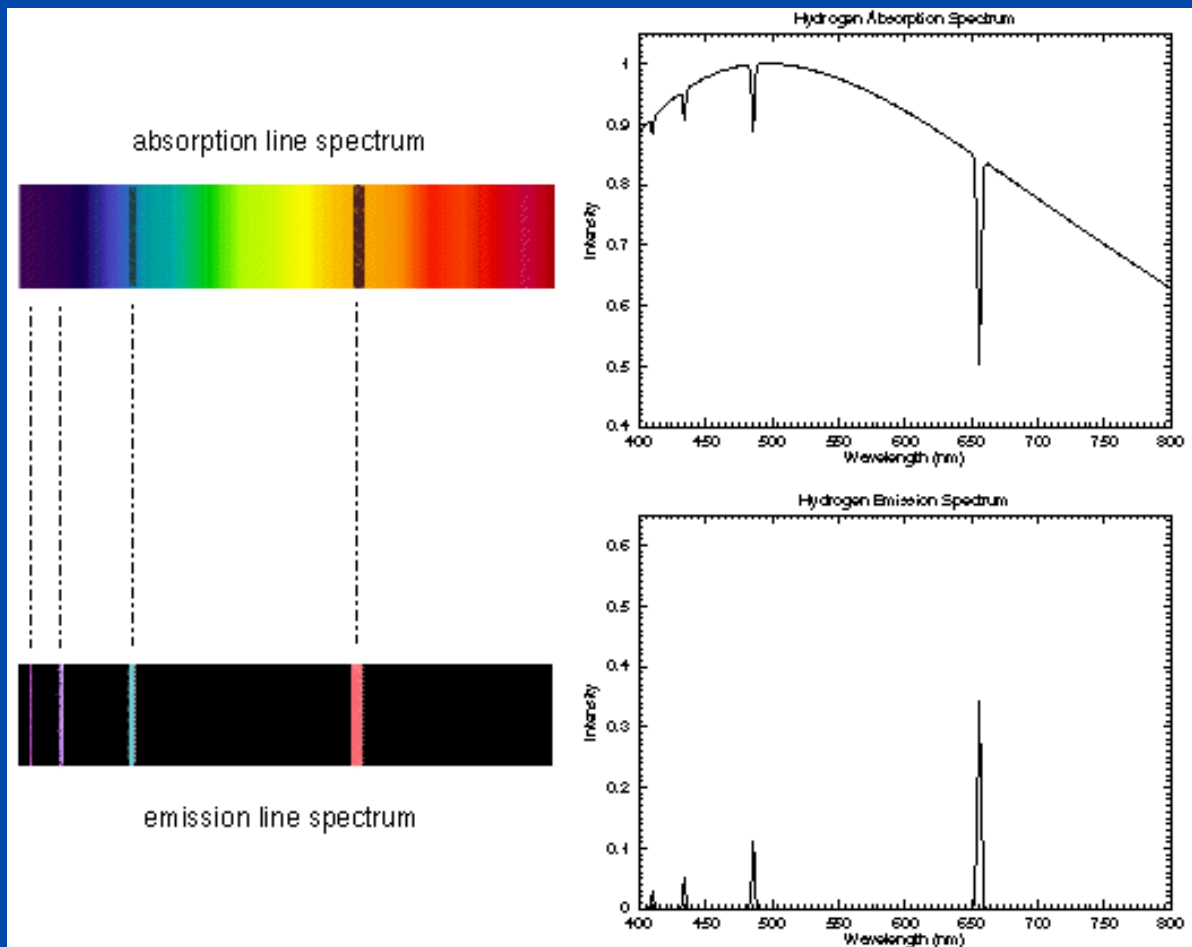
# Emission and absorption lines



Type of spectrum seen depends on the temperature of the thin gas **relative to** the background. TOP: thin gas is *cooler* so **absorption lines** are seen.  
BOTTOM: thin gas is *hotter* so **emission lines** are seen.

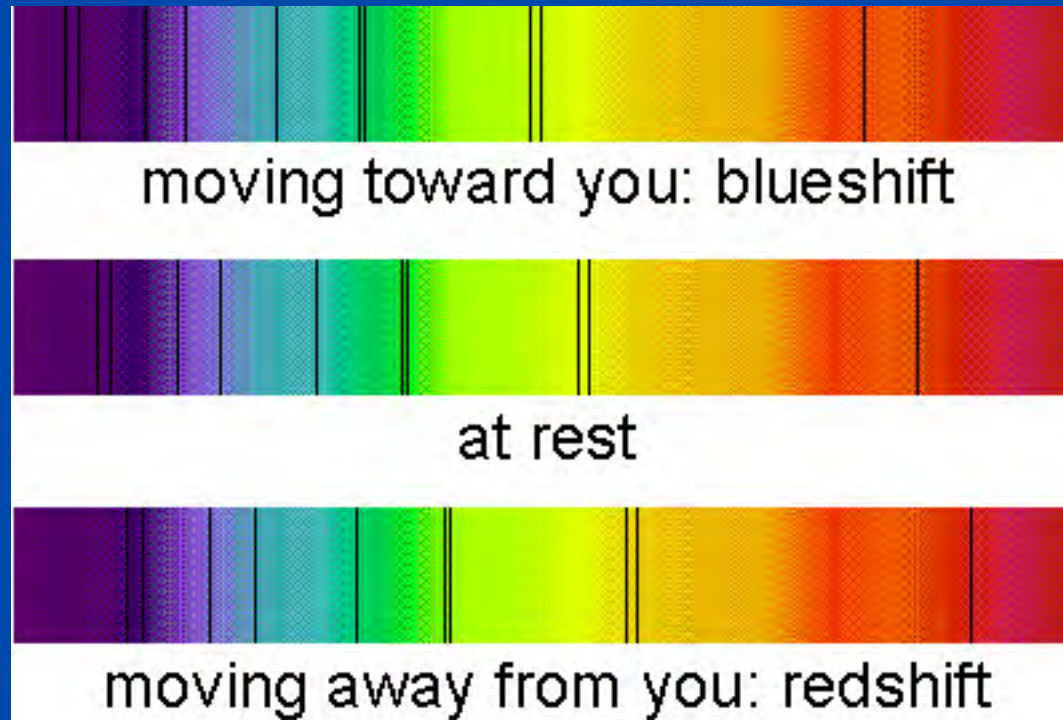


# Scans of a spectrum



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*





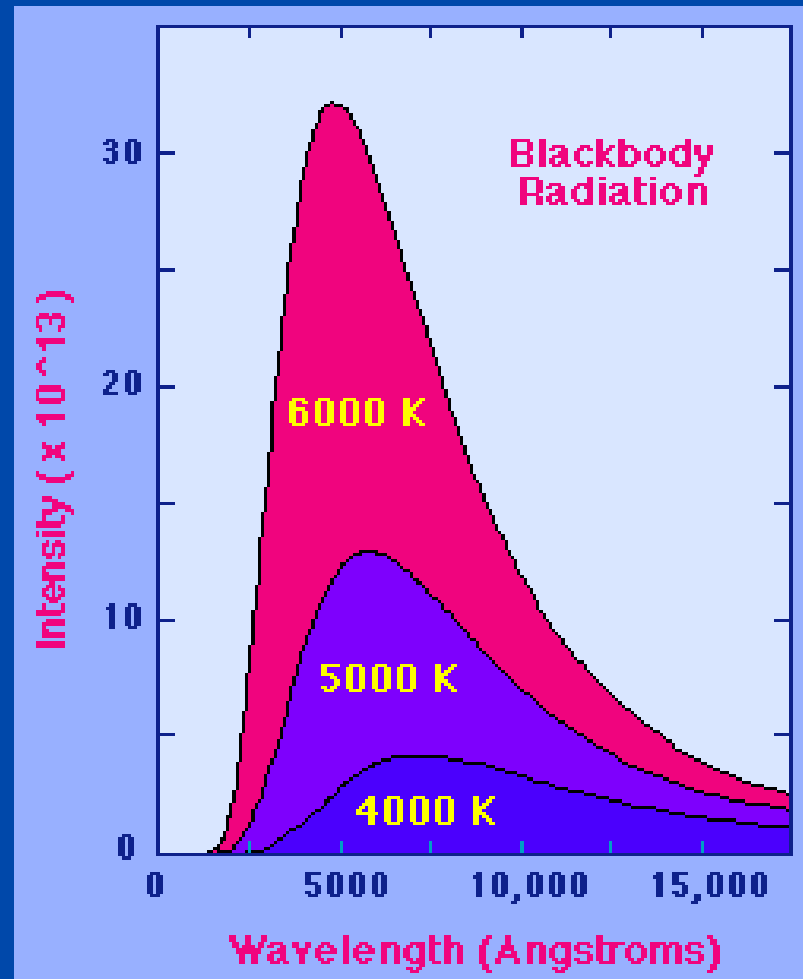
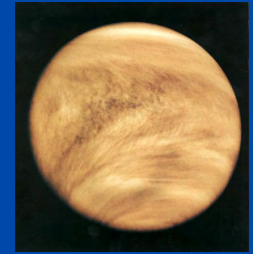
# ***Concept Question***

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- **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*

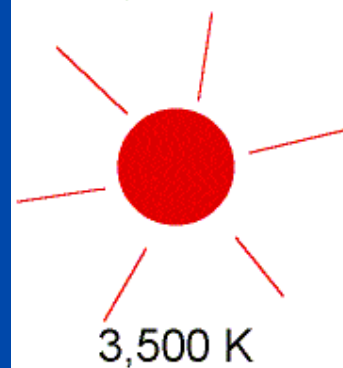
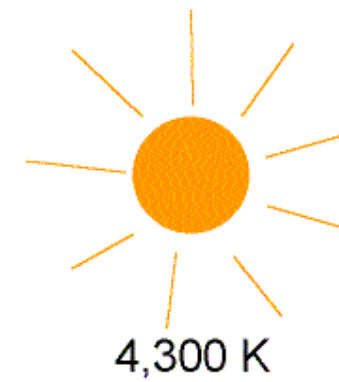
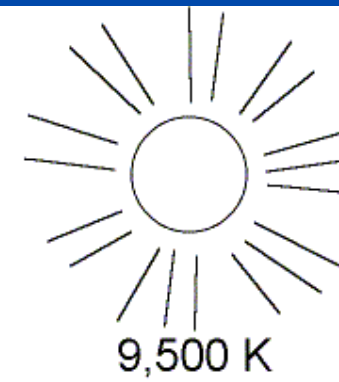


# Bluer color emitted light means hotter temperature of the matter



Wien's law

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



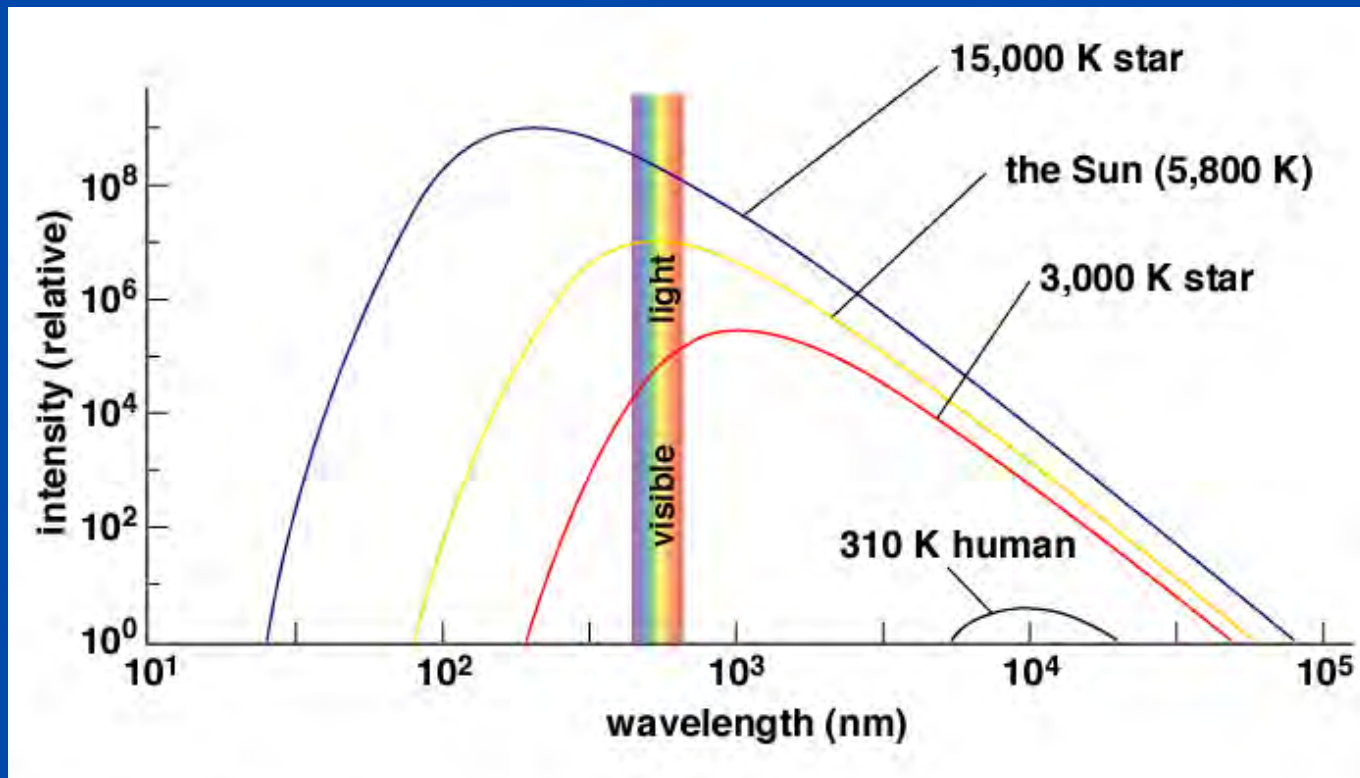
Hotter objects are brighter and "bluer" than cooler objects.

# Total flux emitted by a body at temperature $T$



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

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

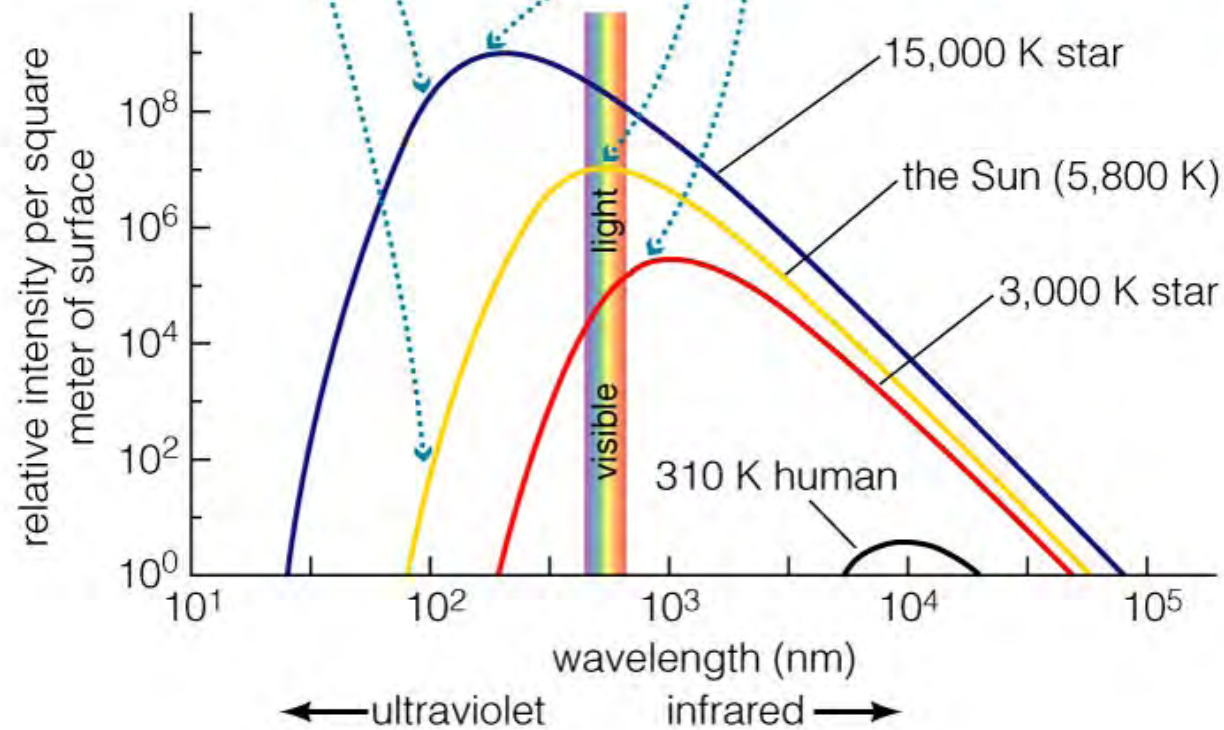


# Total flux emitted by a body at temperature $T$



The curve for a hotter object is everywhere above the curve for a cooler object, showing that hotter objects emit more radiation per unit surface area at every wavelength.

The peak wavelength is further to the left for hotter objects, showing that hotter objects emit more of their light at shorter wavelength (high energy).



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

## Wien's Law



# Wavelengths of peak emission, from radio to gamma ray wavelengths



Some Blackbody Temperatures			
Region	Wavelength (centimeters)	Energy (eV)	Blackbody Temperature (K)
Radio	> 10	< 10 <sup>-5</sup>	< 0.03
Microwave	10 - 0.01	10 <sup>-5</sup> - 0.01	0.03 - 30
Infrared	0.01 - 7 x 10 <sup>-5</sup>	0.01 - 2	30 - 4100
Visible	7 x 10 <sup>-5</sup> - 4 x 10 <sup>-5</sup>	2 - 3	4100 - 7300
Ultraviolet	4 x 10 <sup>-5</sup> - 10 <sup>-7</sup>	3 - 10 <sup>3</sup>	7300 - 3 x 10 <sup>6</sup>
X-Rays	10 <sup>-7</sup> - 10 <sup>-9</sup>	10 <sup>3</sup> - 10 <sup>5</sup>	3 x 10 <sup>6</sup> - 3 x 10 <sup>8</sup>
Gamma Rays	< 10 <sup>-9</sup>	> 10 <sup>5</sup>	> 3 x 10 <sup>8</sup>

## 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**

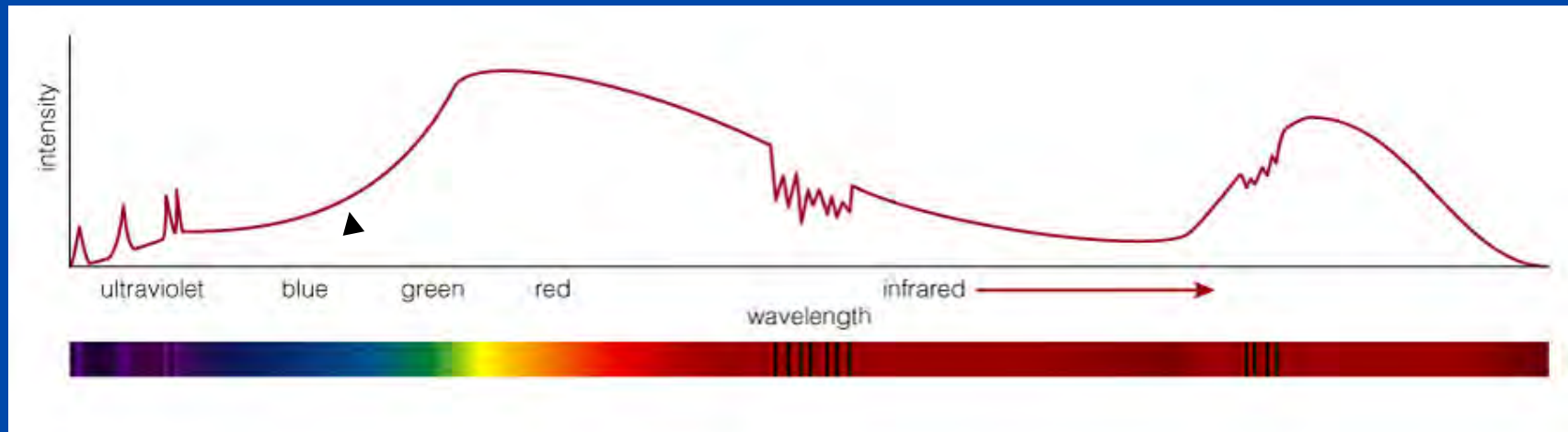
# *Some things you can learn from a spectrum*

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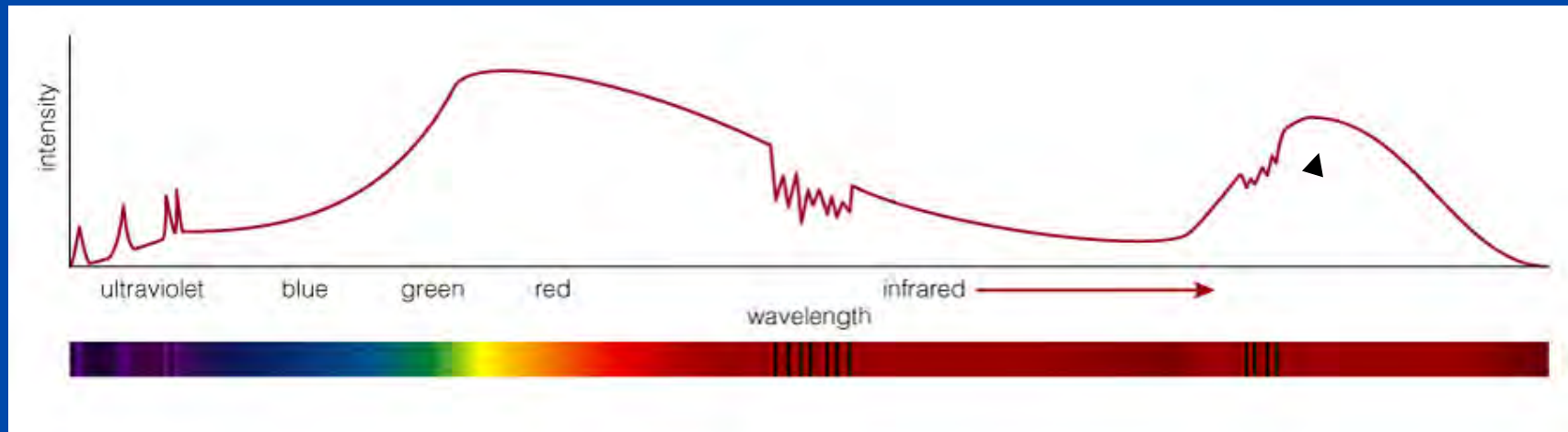
- **Temperature and density of matter at the light source**
- **Ionization state**
- **Chemical composition**
  - Example: ozone as sign of life on Earth
- **Presence of specific minerals**
  - Example: Lunar Prospector spacecraft, ice on moon
- **Structure of atmosphere**
  - Example: Neptune clouds,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

# 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

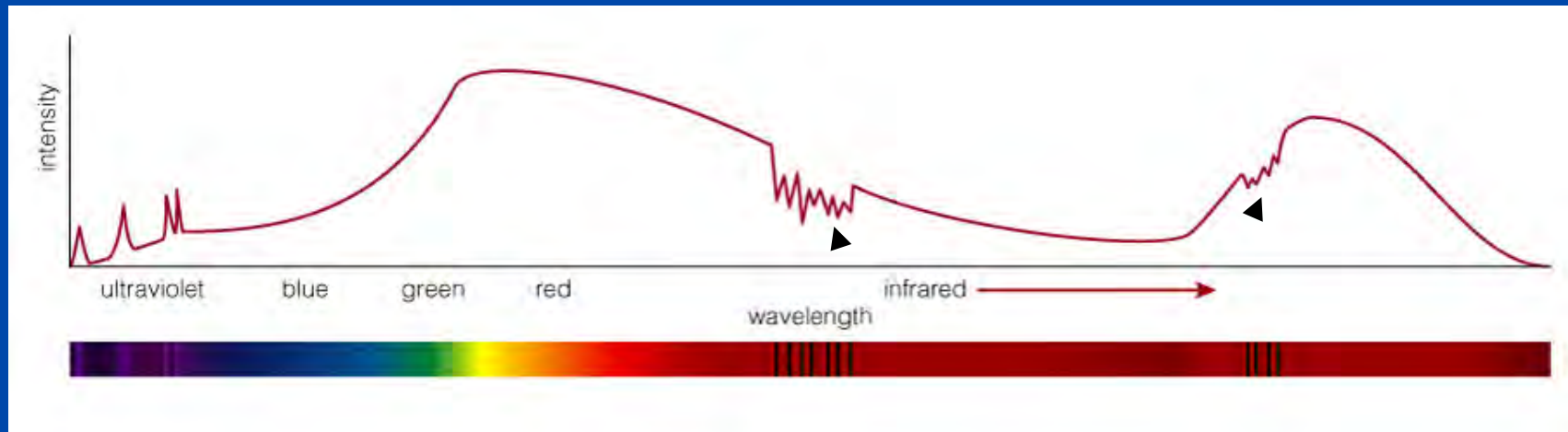
# What is this object?



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

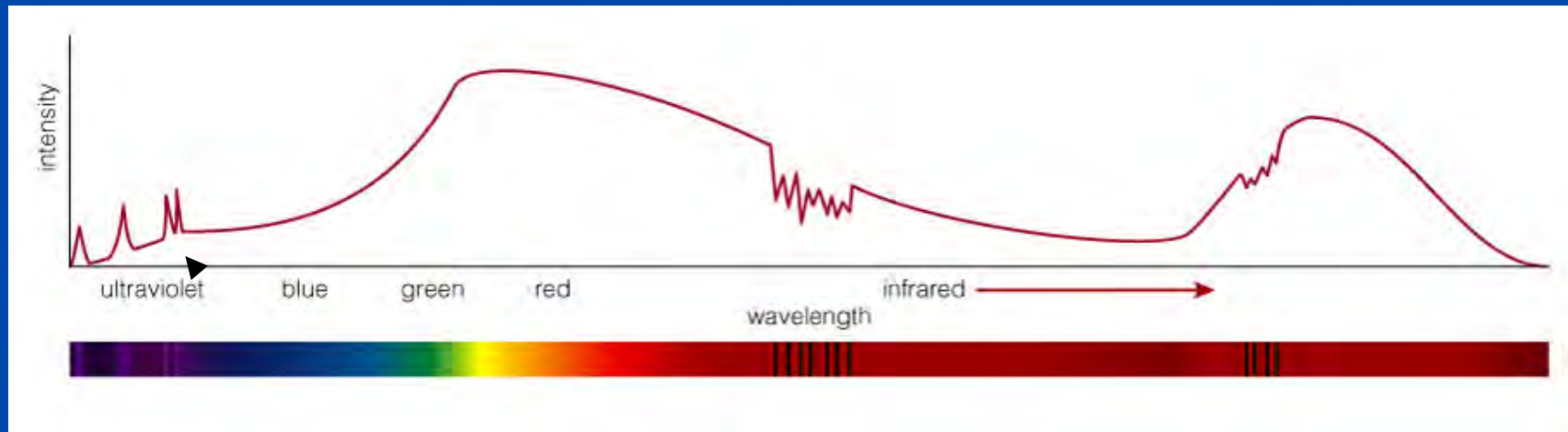
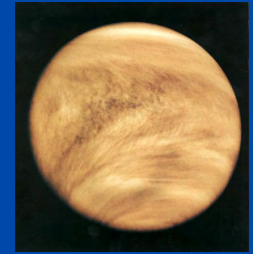


# What is this object?



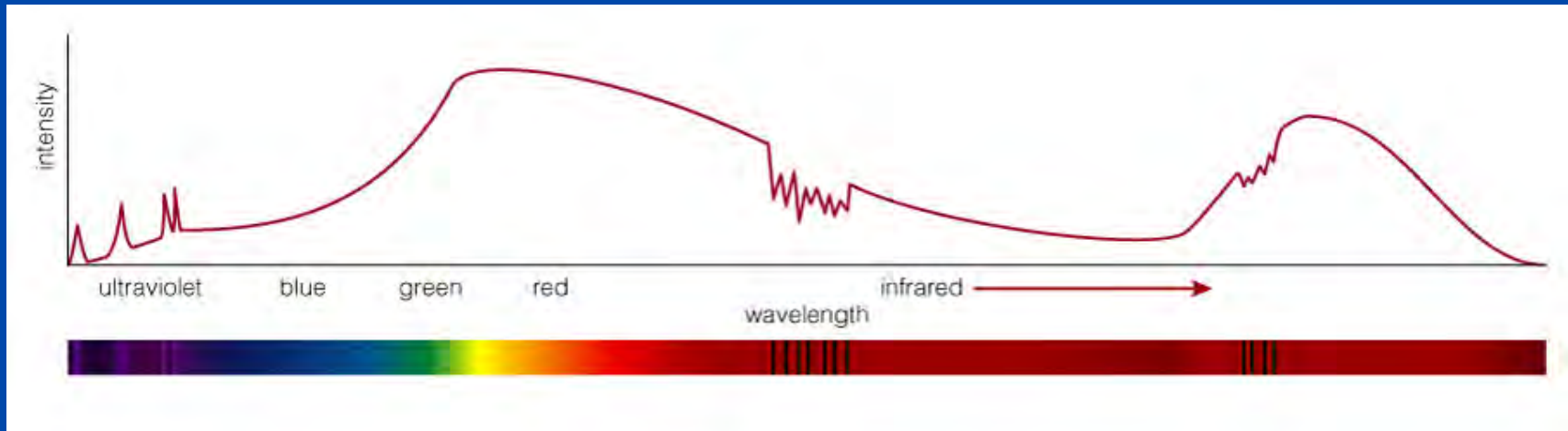
**Carbon Dioxide:**  
Absorption lines are  
the fingerprint of  $\text{CO}_2$   
in the atmosphere

# *What is this object?*



**Ultraviolet Emission  
Lines: Indicate a hot  
upper atmosphere**

# *What is this object?*

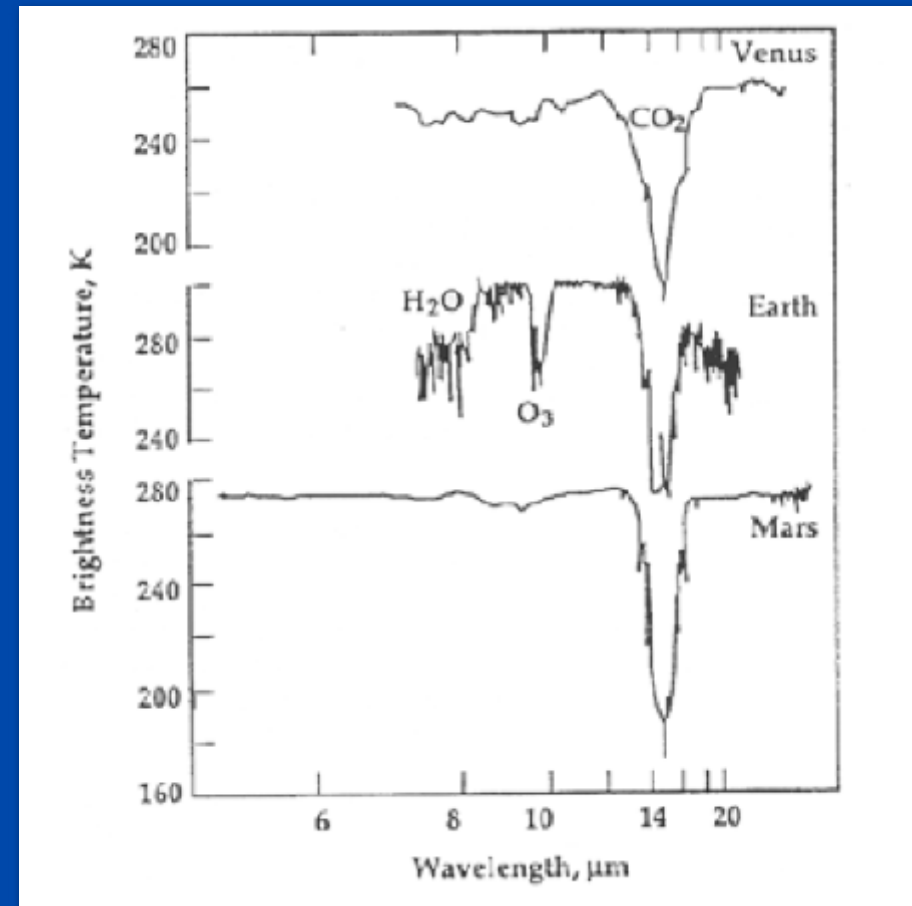


# Mars!

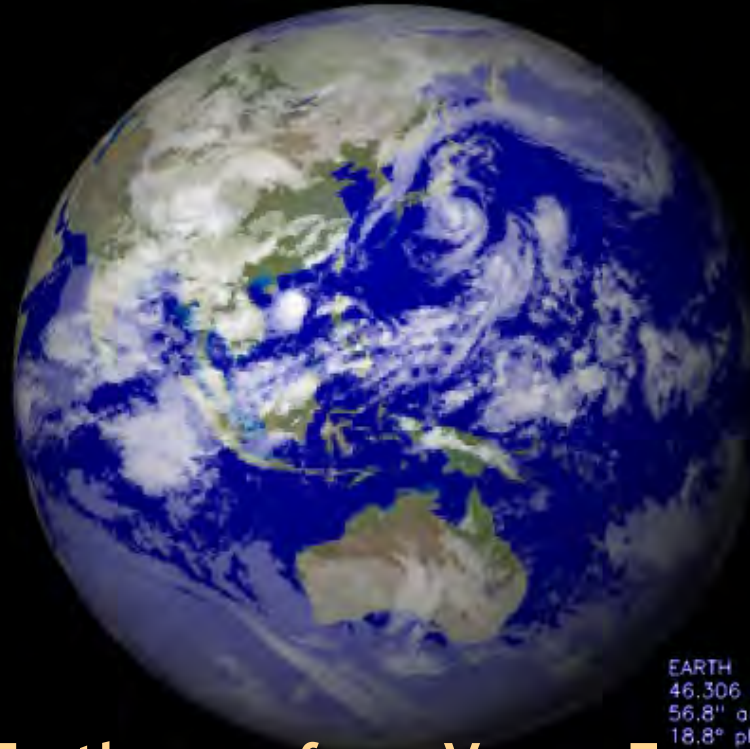
# Spectral signatures of life on Earth



- Venus and Mars (no life today): CO<sub>2</sub>
- Earth today: has water (H<sub>2</sub>O), and atmospheric composition has been altered by life
  - Ozone line (O<sub>3</sub>)
  - Water line (H<sub>2</sub>O)



View of EARTH from VENUS  
2007 AUG 06 04:30:00 UTC  
1.9° field of view

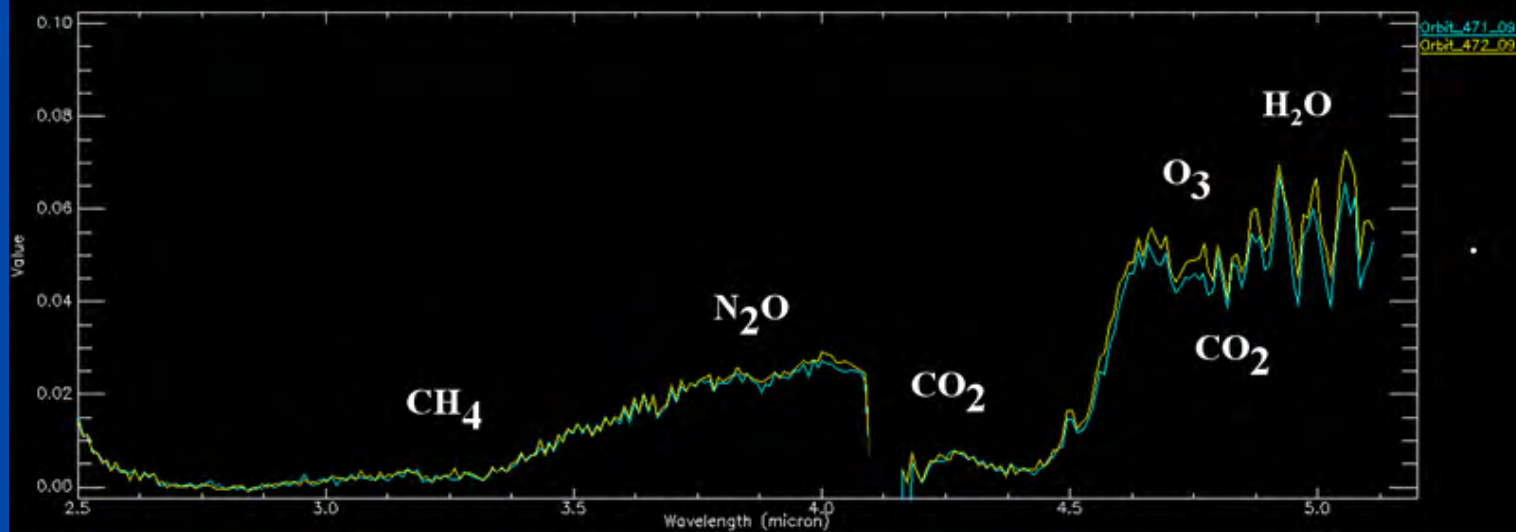


EARTH  
46.306 mil km  
56.8" arc  
18.8° phase



## Spectrum of Earth seen from Venus Express Spacecraft

Solar System Simulator v4.0





# *The Main Points*

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- **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, ....