

## Lecture 2

# The Nature of Light

Moonbow with Sailboats (Matt BenDaniel)

# Homework

Problems:

FGK10: Chap 5. Question 27, 32, 34, 35

Due date: September 14, Wednesday

# Guiding Questions

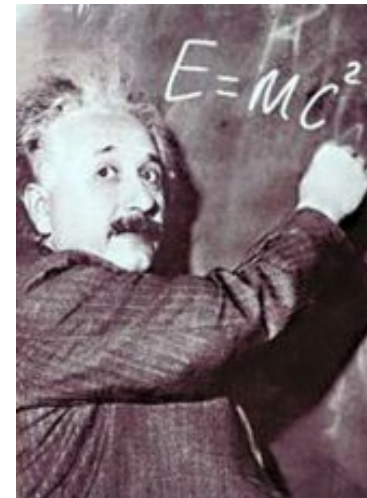
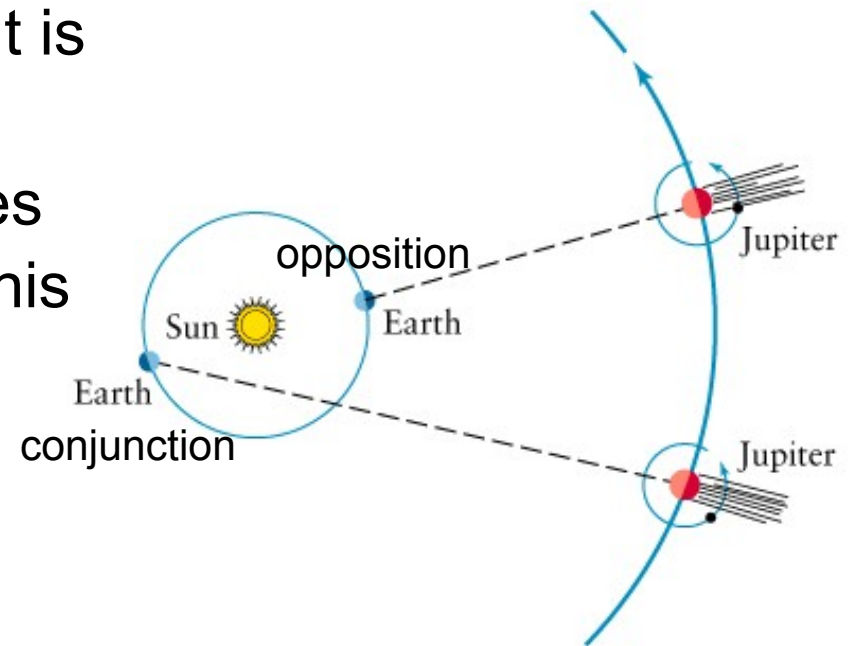
1. How fast does light travel? How can this speed be measured?
2. How is the light from an ordinary light bulb different from the light emitted by a neon sign?
3. How can astronomers measure the temperatures of the Sun and stars?
4. How can astronomers tell what distant celestial objects are made of?
5. How can we tell if a celestial object is approaching us or receding from us?

## 2.1 Light travels with a very high speed (reading assignment)

- Galileo first tried but failed to measure the speed of light . He concluded that the speed of light is very high.
- Romer first proved that light does not travel instantaneously from his observations of the eclipses of Jupiter's moons.
- Modern technologies are able to find the speed of light;  
in an empty space:

$$c = 3.00 \times 10^8 \text{ m/s}$$

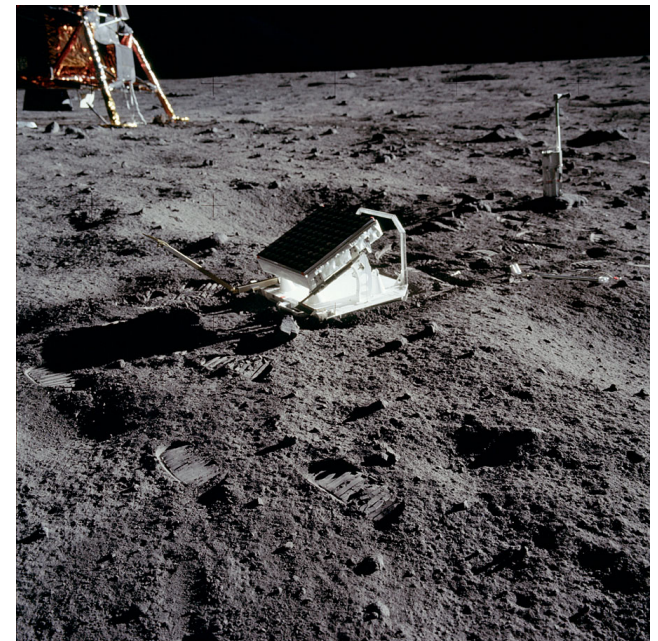
one of the most important numbers in  
modern physical sciences!



Ex.1: The distance between the Sun and the Earth is 1AU (=  $1.5 \times 10^{11}$ m). (a) how long does it take the light to travel from the Sun to an observer on the Earth? (b) A concord airplane has a speed of 600 m/s; how long does it take a traveler on a Concord airplane to travel from the Earth to the Sun?

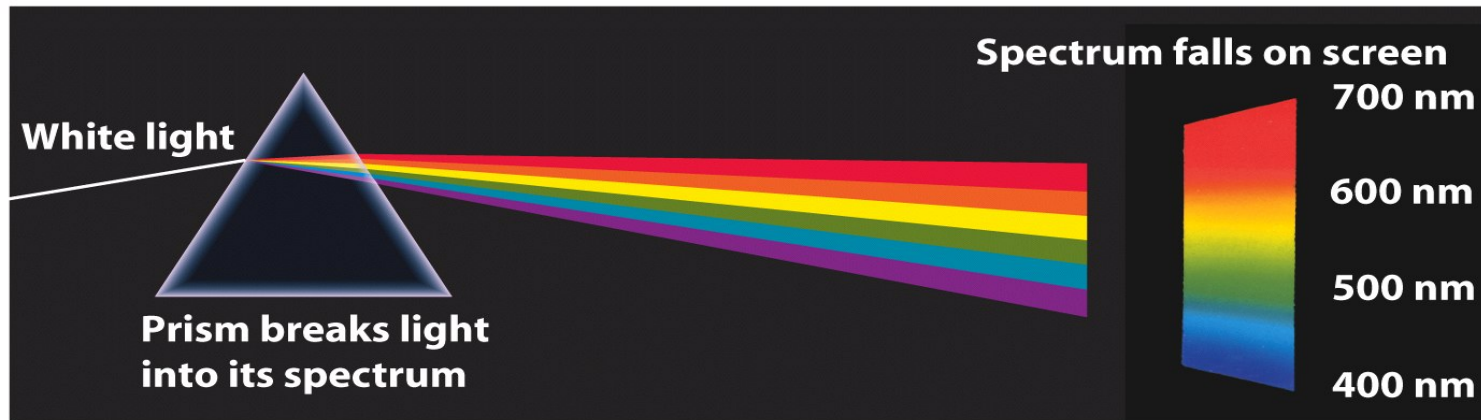
Ex.2: A lunar laser ranging retro-reflector array was planted on the Moon on July 21, 1969, by the crew of the Apollo 11. Since then, the distance between the Earth and the Moon has been measured many times.

With our knowledge, nothing travels faster than light!

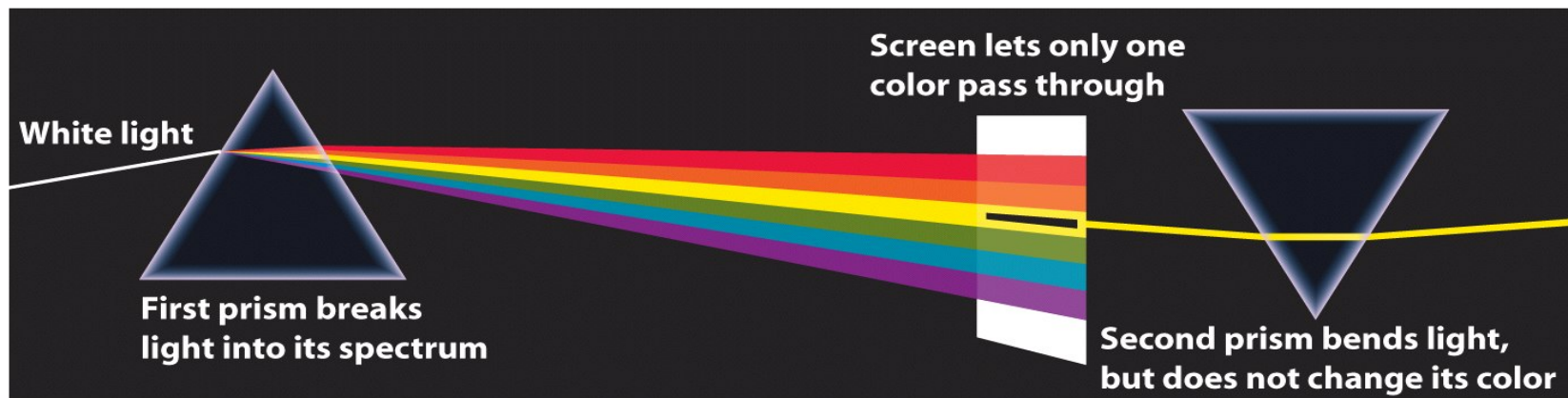


## 2.2 Light is colorful

Newton found that when sunlight passes through a glass prism, it spreads into the colors of a rainbow. This is a **spectrum**.



Sunlight is a mixture of all the colors of a rainbow.



- Light is **electromagnetic radiation** - electric field and magnetic field travel through the space in the form of waves,  
Now think about water ripples:



wavelength ( $\lambda$ ):  
distance from one  
peak to the next peak

frequency( $\nu$ ): how  
many wavelengths  
passes a point within  
1 second.

Q: sound is also a train of waves. What's the sound speed?  
What does its frequency determine?

- Light is characterized by its **wavelength** or **frequency**, which determine the color of the light.

### Frequency and wavelength of an electromagnetic wave

$$\nu = \frac{c}{\lambda}$$

$\nu$  = frequency of an electromagnetic wave (in Hz)

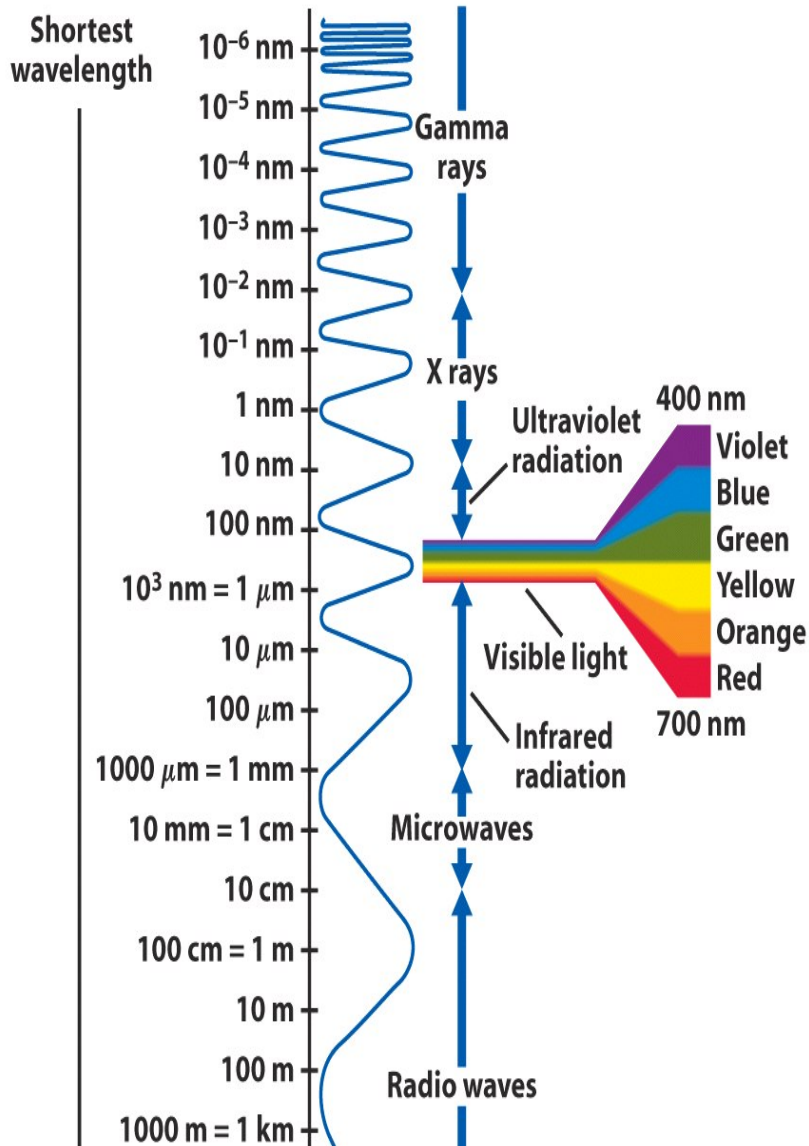
$c$  = speed of light =  $3 \times 10^8$  m/s

$\lambda$  = wavelength of the wave (in meters)

$$[1\text{m} = 10^9 \text{ nm} = 10^{10} \text{ \AA} \text{ (Angstroms)}]$$

Ex.3: The wavelength of yellow light is 550 nm, or a half of a millionth of a meter, and its frequency is 500 trillion Hz. In comparison, the audible frequency range of sound waves is 20 - 20,000 Hz.

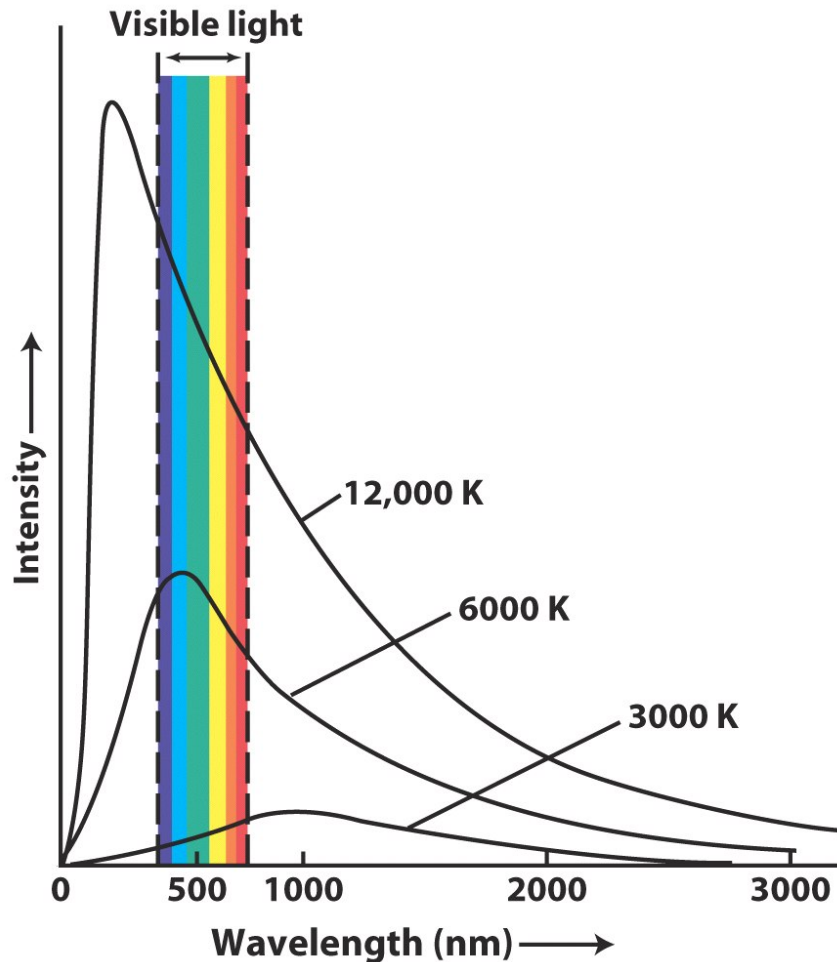




- Like visible light, radio waves, microwaves, infrared, ultraviolet, X-rays, Gamma-rays are all electromagnetic waves with different wavelengths.
- Visible light falls in the 400 to 700 nm range. Red light has longer wavelength than blue light.
- The Sun, stars, galaxies, and other objects emit light in all wavelengths.

Q: why Sunlight is white-yellowish, and stars appear red/yellow/blue?

## 2.3 An opaque object (often called blackbody) emits EM radiation according to its temperature



Blackbody Continuum Curves  
(blackbody is NOT black!)

- An object, like the Sun, does not emit equal amount of radiation at all wavelengths.
- At a higher temperature, an object emits more intensely.
- At a higher temperature, an object emits most strongly at the shorter wavelength.

Ex.4: The brightest star, Sirius A, is a blue star and has a higher temperature than the Sun.



Q: astronauts in the space see Earth as a blue planet. Does it mean that Earth's temperature is higher than the Sun's? Or is Earth's ocean hotter than deserts?

Radiation versus reflection!

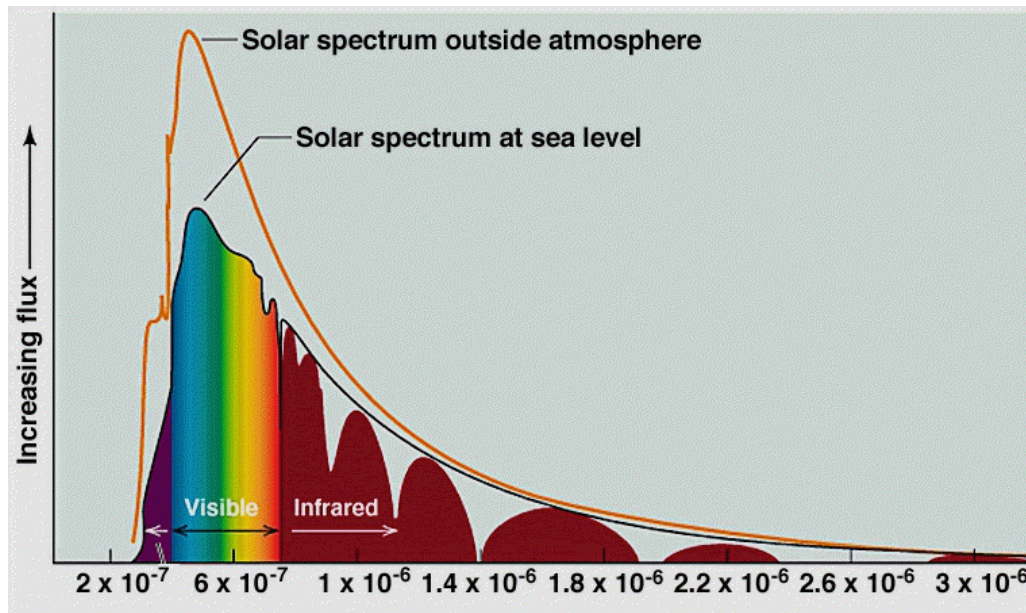
Q: instead, how will you sketch the blackbody radiation curve by the Earth, eg., compared with the Sun?

**Wien's Displacement law** tells how to find the **temperature** of a star if we know the wavelength of its maximum emission (this can be obtained in **spectral** observations)

$$\lambda_{\max} = \frac{0.0029 \text{ K m}}{T}$$

$\lambda_{\max}$  : wavelength of maximum emission of the object (in meters)

$T$  : temperature of the object (in kelvins)



Ex.5: The maximum intensity of sunlight is at roughly 500 nm =  $5.0 \times 10^{-7}$  m. What's the surface temperature of the Sun?

$$\begin{aligned} T &= \frac{0.0029 \text{ K m}}{\lambda_{\max}} \\ &= \frac{0.0029 \text{ K m}}{5.0 \times 10^{-7} \text{ m}} = 5800 \text{ K} \end{aligned}$$

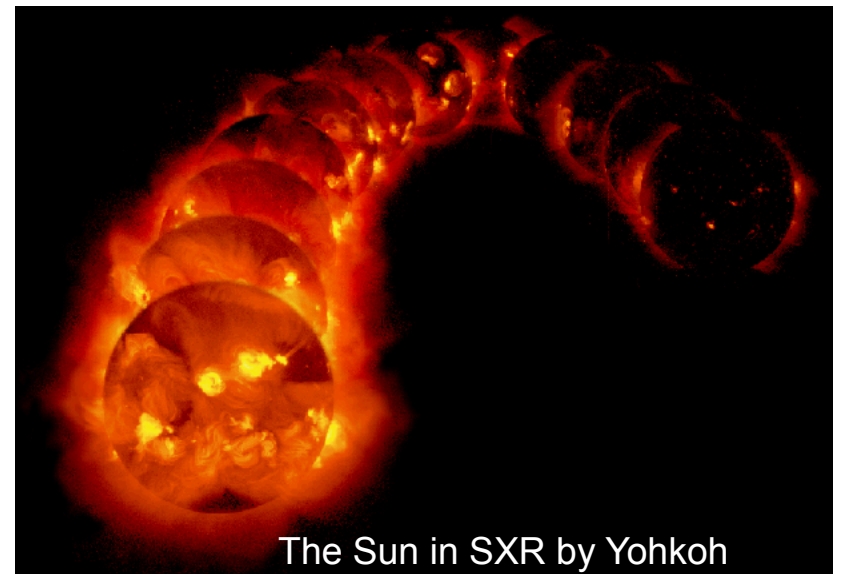
The **Stefan-Boltzmann law** states that a blackbody radiates electromagnetic waves with a total **energy** flux  $F$  at the surface of the star directly proportional to the fourth power of the Kelvin temperature  $T$  of the object:

$$F_{\text{surface}} = \sigma T^4 \text{ (J m}^{-2} \text{ s}^{-1}\text{)}$$

$F$  = energy flux, in joules per square meter of surface per second

$\sigma$  = a constant (Stefan-Boltzmann constant) =  $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

$T$  = object's temperature, in Kelvin



The **intrinsic luminosity** of a star -- its total radiation energy -- is given by  $L = 4\pi R^2 \sigma T^4$  ( $\text{J s}^{-1}$ ), where  $R$  is the radius of the star.

The radiant flux (apparent brightness) of the star drops off quickly with the distance  $d$  at which it is observed:

$$F_{\text{observed}} = \frac{L}{4\pi d^2} = \frac{\sigma T^4 R^2}{d^2} \quad (\text{J m}^{-2} \text{ s}^{-1})$$

The farther away,  
the less bright.

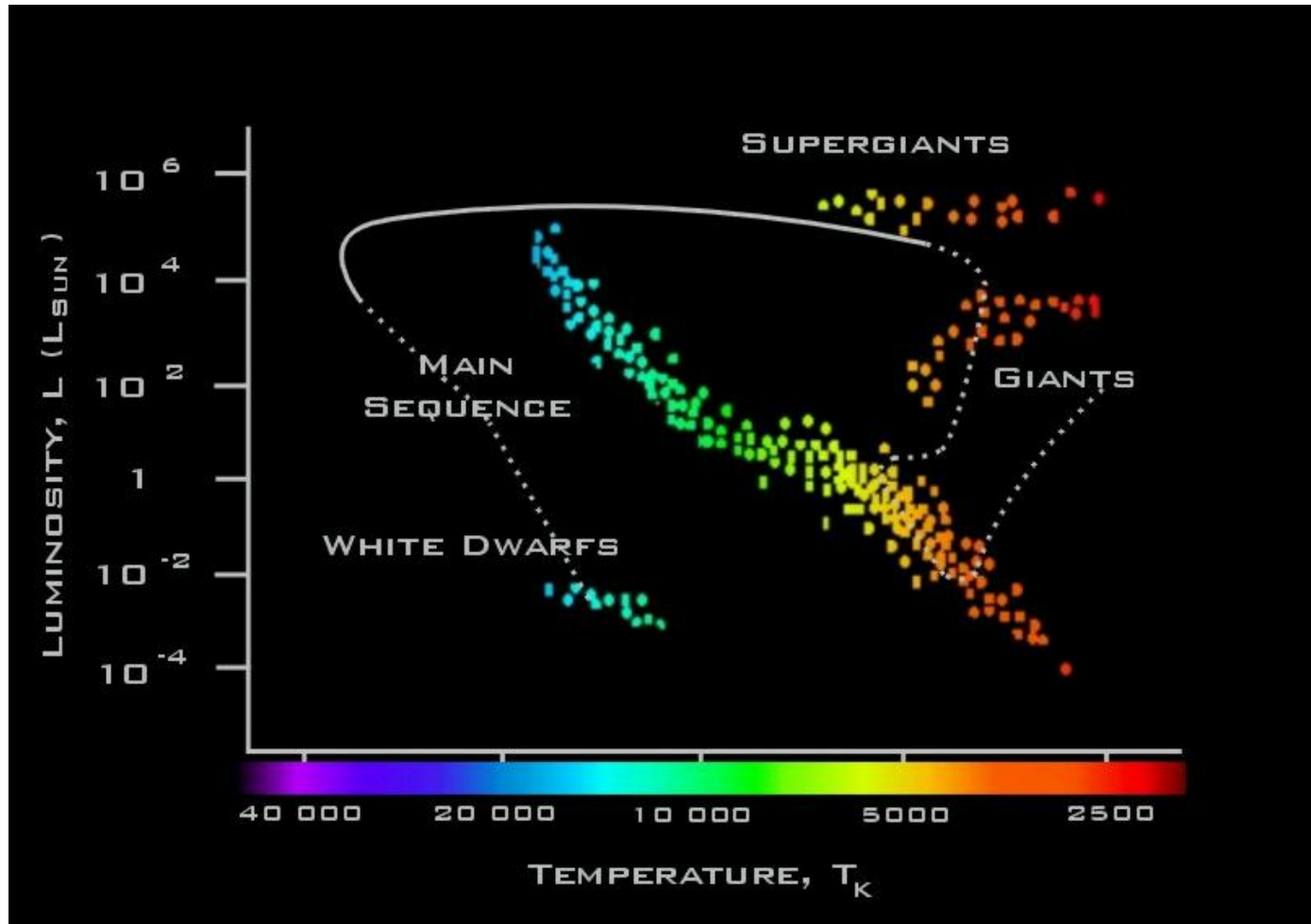
The **apparent magnitude** of a star is given by  $m = -2.5 \log(F_{\text{obs}})$ . Greater magnitude refers to dimmer stars. An m1 star is brighter than an m6 star by 100 times. The brightest star (Sirius A) in the sky is -1.4 in magnitude.

Ex.6a: the intrinsic luminosity of the Sun is  **$3.8 \times 10^{26} \text{ W}$** , and its radiant flux (solar constant) observed on Earth ( $d = 1 \text{ AU}$ ) is  $1370 \text{ W m}^{-2}$ . Its apparent magnitude is -26.8.

Ex.6b: the intrinsic luminosity of Sirius A is about 20 times the Sun's luminosity; at its distance (8.6 ly), its apparent magnitude is -1.4.

Ex.6c: If placed at where Sirius is, the Sun's magnitude would be +1.8 (dimmer than Sirius, of course).

Ex.7: the H-R diagram shows that the color of a main-sequence star is related to its temperature and luminosity.

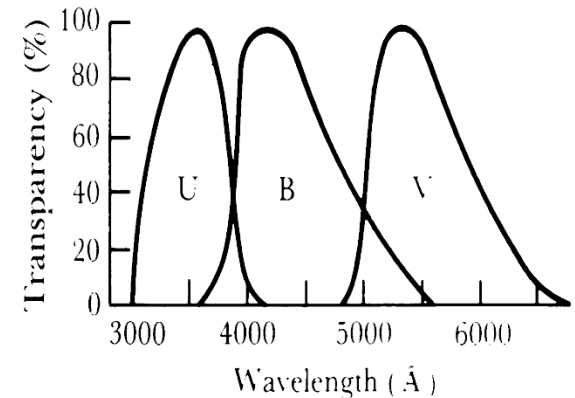


(optional) In practice, a star's radiant flux can be only measured within a certain wavelength range. The standard *UBV* system is used to make measurements.

*U* ( $m_U$ ): *ultraviolet* magnitude,  $\lambda = 3650 \text{ \AA}$ ,  $\Delta\lambda = 680 \text{ \AA}$ .

*B* ( $m_B$ ): *blue* magnitude,  $\lambda = 4400 \text{ \AA}$ ,  $\Delta\lambda = 980 \text{ \AA}$ .

*V* ( $m_V$ ): *visual* magnitude,  $\lambda = 5500 \text{ \AA}$ ,  $\Delta\lambda = 890 \text{ \AA}$ .



A star's **color index**:  $U - B$ ,  $B - V$

A star with a smaller  $B - V$  is bluer (hotter!)

The **color index** of a star can be used to determine its **temperature**, using the following approximation for stars like the Sun (main-sequence stars):

$$B - V = -0.865 + 8540 / T \quad (4000 \text{ K} < T < 10000 \text{ K}).$$



(optional) Planck function describes radiation by a blackbody:

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \quad (\text{J s}^{-1} \text{ m}^{-2} \text{ A}^{-1} \text{ sr}^{-1})$$

$B_{\lambda}$  : specific intensity, energy per unit time per unit surface area per unit solid angle per unit wavelength.

$\lambda$  : wavelength

$T$  : temperature (in K degree)

$k$  : =  $1.6 \times 10^{-23}$  J/K, Boltzmann constant

$c$  : =  $3 \times 10^8$  m/s, speed of light in vacuum,

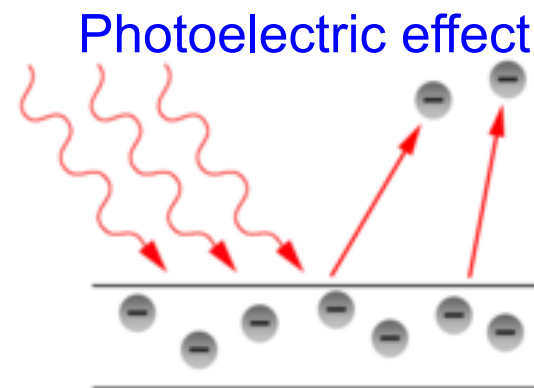
$h$  : =  $6.625 \times 10^{-34}$  J s, Planck's constant

Planck function leads to all the following:

- Wien Displacement law - peak radiation wavelength inversely proportional to temperature (find the maximum of the function by setting  $dB_{\lambda}(T) / d\lambda = 0$ )
- Stefan-Boltzmann Law - luminosity increases as the fourth-power of the temperature (integrate  $B_{\lambda}(T)$  over all wavelengths)
- Rayleigh-Jeans Law - intensity decreases rapidly with the wavelength at long wavelengths (expand  $e^{hc/\lambda kT}$  in  $B_{\lambda}(T)$  for  $hc \ll \lambda kT$ )
- Wien Law - intensity decreases exponentially at short wavelengths (approximate  $B_{\nu}(T)$  for  $h\nu \gg kT$  to get  $B_{\nu}(T) = (2h\nu^3/c^2) e^{-hc/\lambda kT}$ )

Ex. 8: Rayleigh-Jeans law, the UV catastrophe, Planck function, and the particle nature of light.

Light can also behave like particles, we call such light particles “photons”. Each photon carries an amount of energy related to its frequency or wavelength - **Planck’s law**.



- $E$  = energy of a photon
- $h$  = Planck’s constant;
- $c$  = speed of light;
- $\lambda$  = wavelength of light

$$E = h\nu = \frac{hc}{\lambda}$$

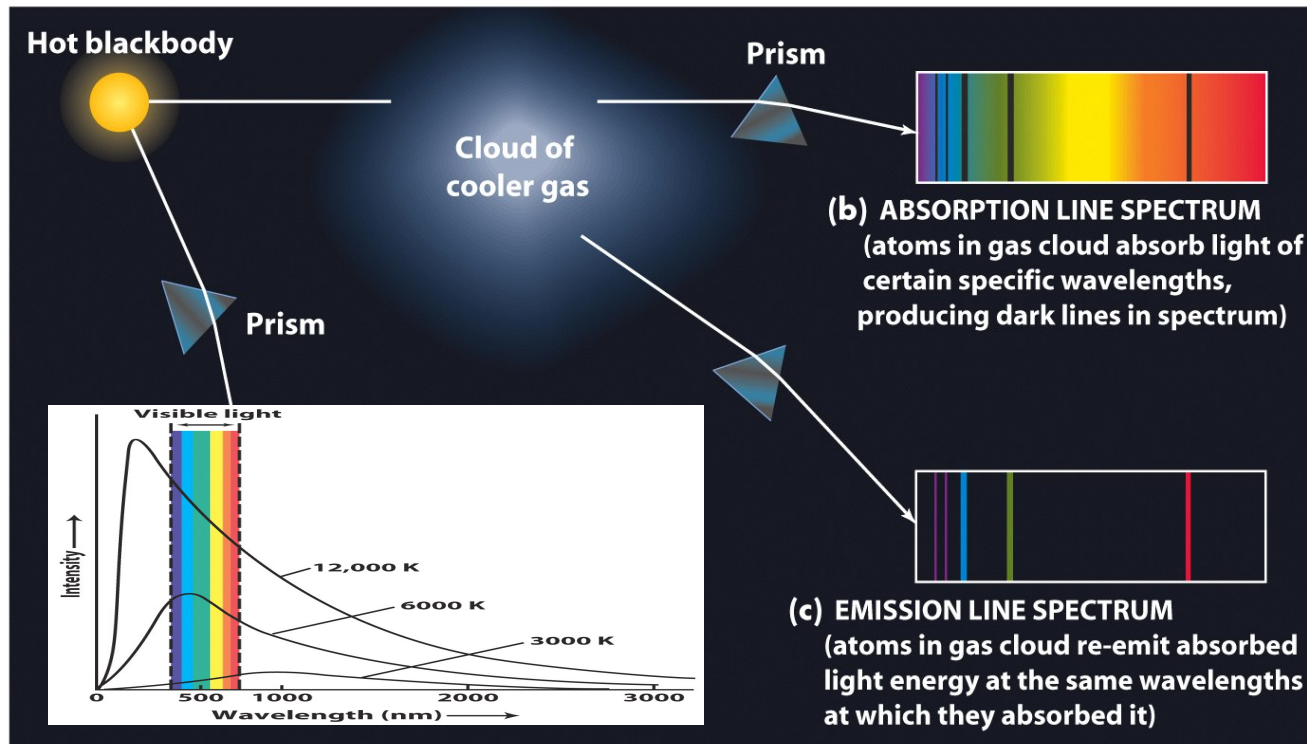
wave-particle duality of light

The value of the constant  $h$  in this equation, called **Planck’s constant**, has been shown in laboratory experiments to be  $h = 6.625 \times 10^{-34}$  J s.

**Blue light photons** are more energetic than **red light photons**!

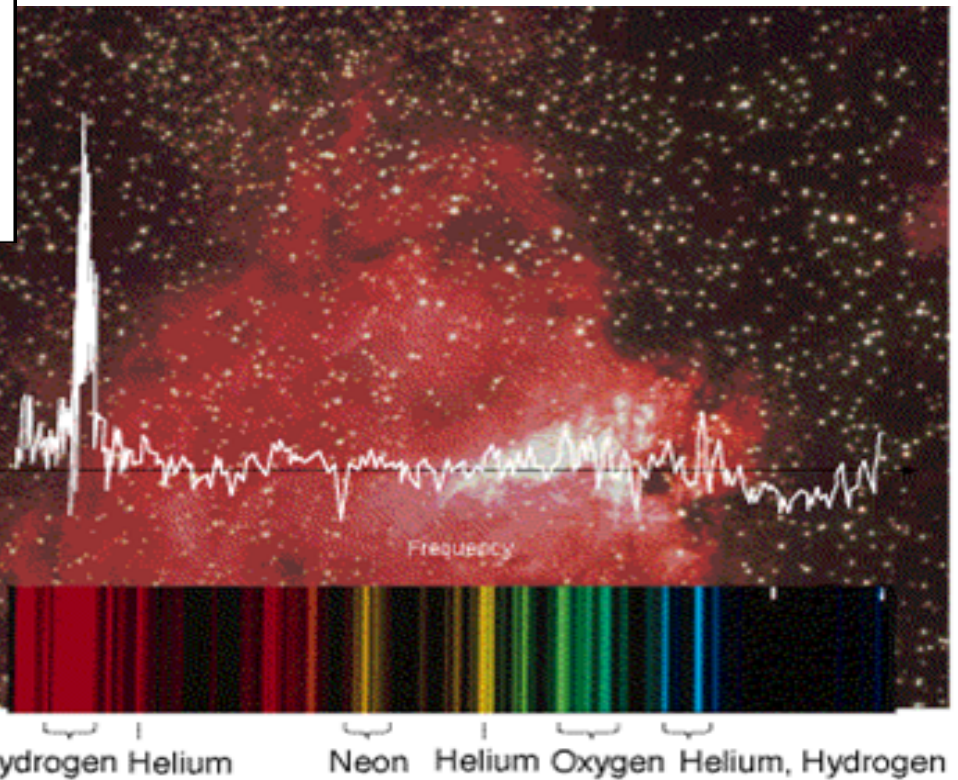
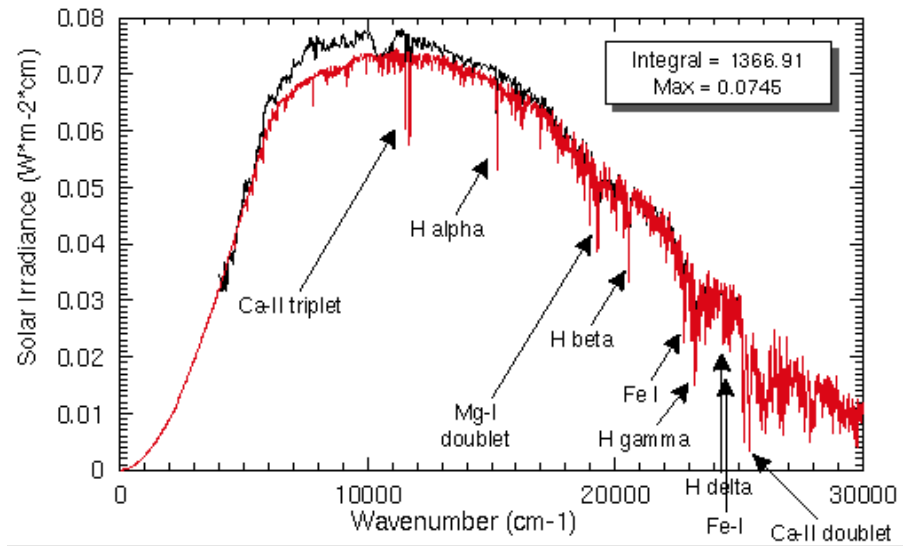
The intensity of light at a color is determined by both its **wavelength** and the **number of photons** at that wavelength.

## 2.4 Emission and absorption lines



Each chemical element produces its own unique set of spectral lines at fixed wavelengths. Therefore, if we know the spectral lines emitted or absorbed by remote stars and planets, we can find their **chemical composition**, for example, hydrogen, oxygen, neon ...

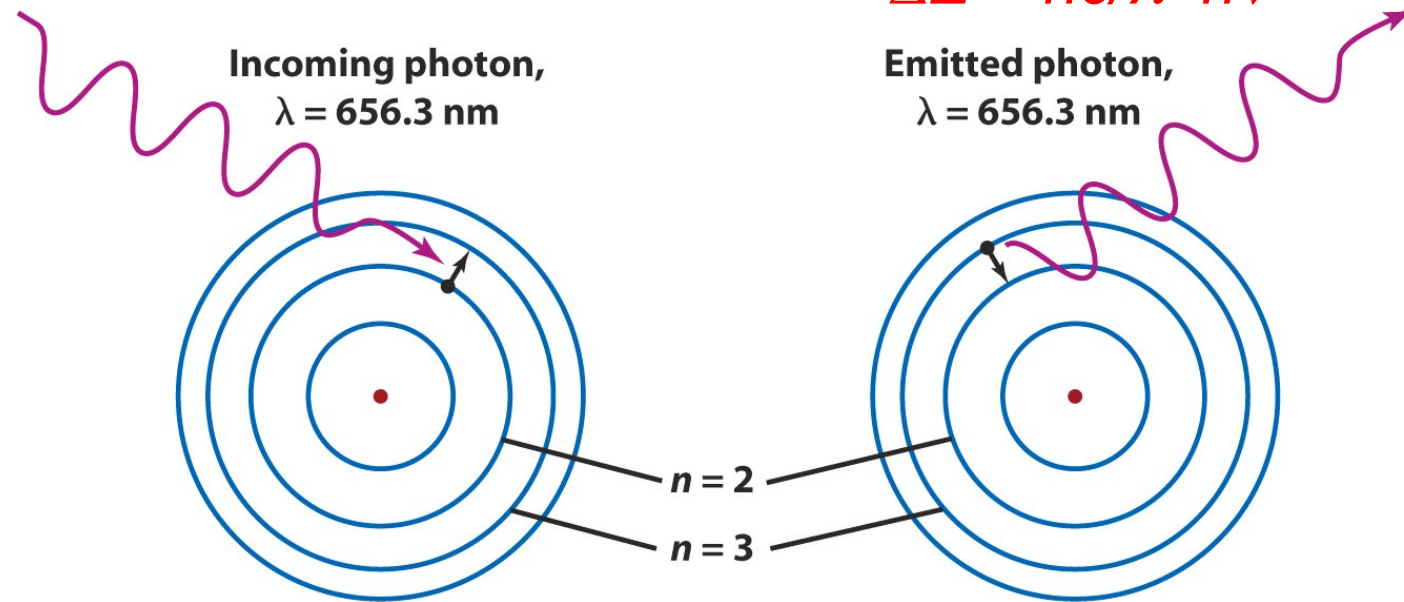
Ex.9: solar spectrum, Fraunhofer lines, and discovery of the helium element.



Ex.10: emission lines from M17 nebular

Q: how is a line formed and why each atom is characterized by more than one line?

An atom comprises of a nucleus surrounded by electrons circling the nucleus at certain orbits. When an electron jumps from one orbit to another, the atom either emits or absorbs a photon, whose energy equals the difference in energy between the two orbits.  $\Rightarrow \Delta E = hc/\lambda = h\nu$



(a) Atom absorbs a 656.3-nm

(b) Electron falls from the  $n = 3$

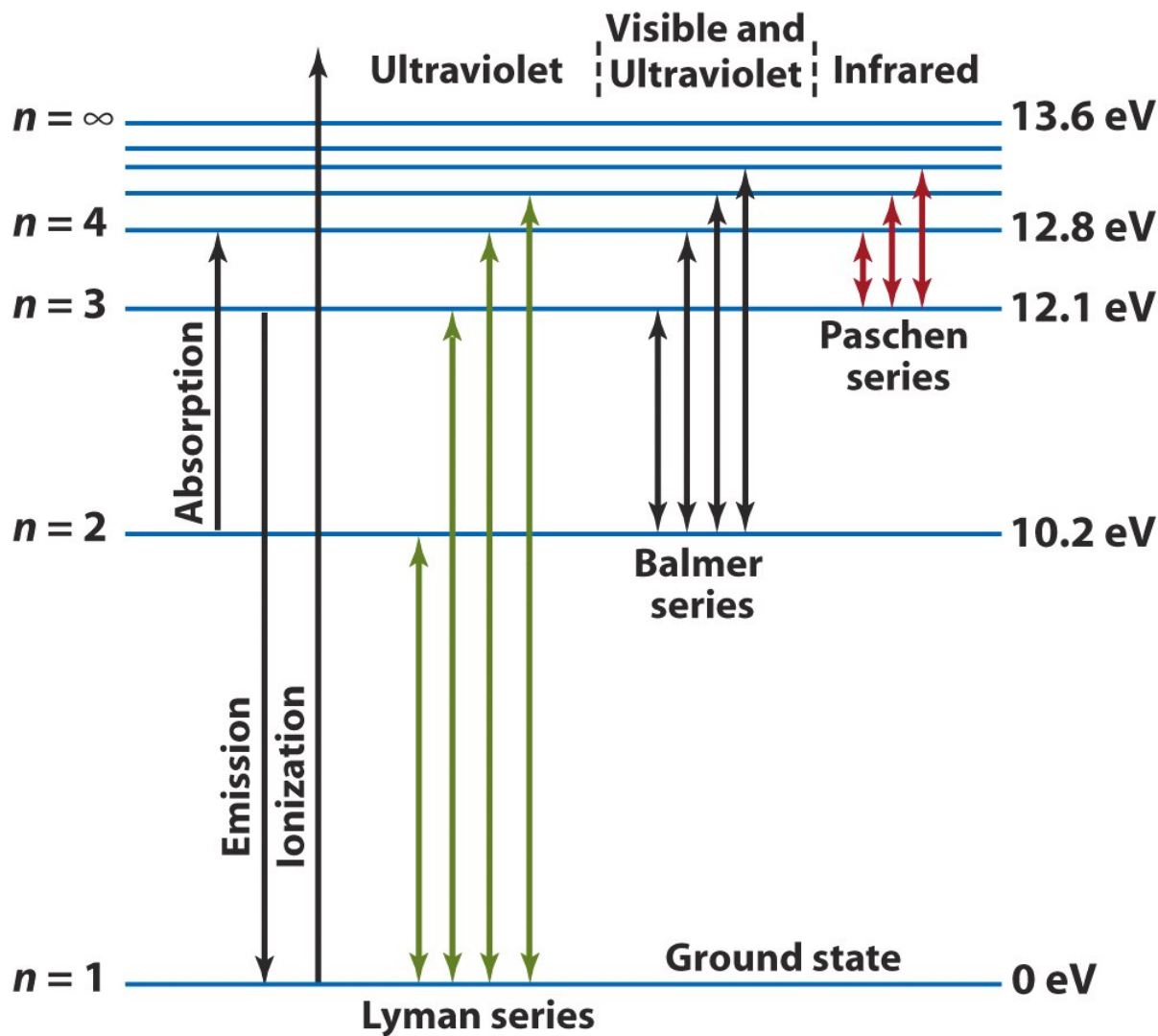
Q: which orbit, the inner orbit or outer orbit, has higher energy?

electron to jump from the  $n = 2$  orbit up to the  $n = 3$  orbit

by atom goes into emitting a 656.3-nm photon

A photon is **absorbed** for the electron to jump **from inner orbit to outer orbit**.

A photon is **emitted** for the electron to jump **from outer orbit to inner orbit**.



(eV is a unit of energy often used in atomic physics.  
 $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ )

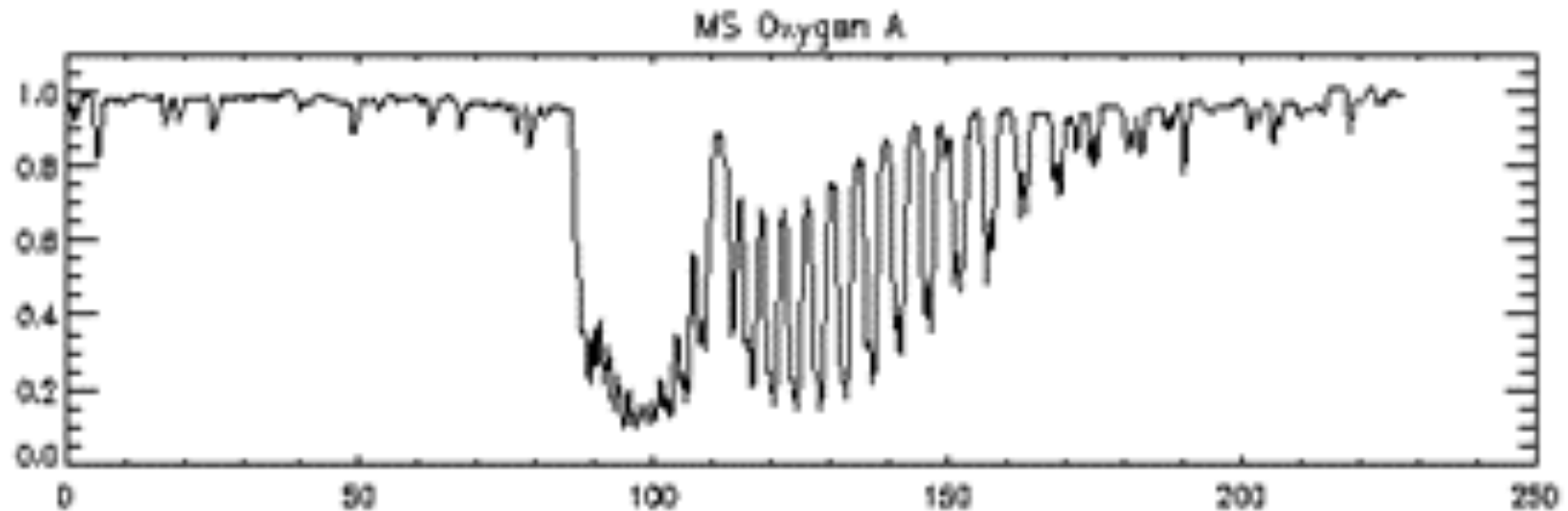
### Ex.11: Formation of Hydrogen lines.

The jump between the first orbit and outer orbits forms **Lyman** series.

The jump between the second orbit and outer orbits forms **Balmer** series. The first line (between  $n = 2$  and  $n = 3$ ) in this series is  $H\alpha$  line.

The jump between the third orbit and outer orbits forms **Paschen** series.

## Ex.12: molecular oxygen bands in Earth's atmosphere

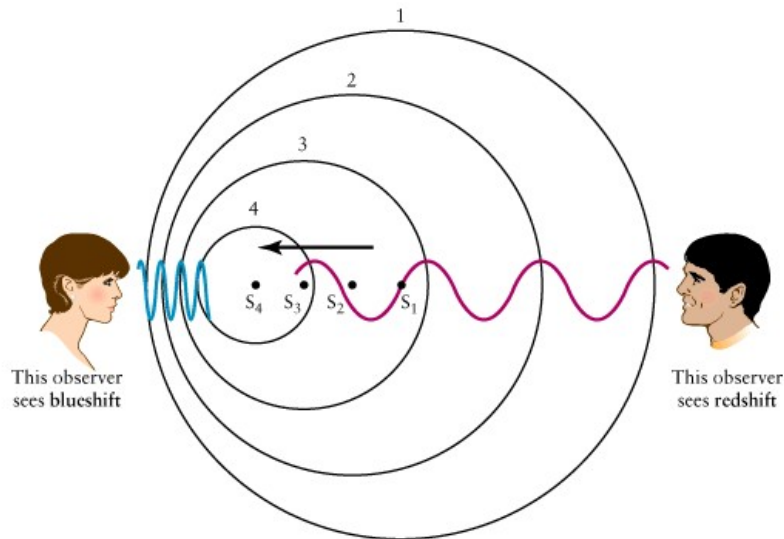


We can make spectral observations of other planets or extraterrestrial “solar” systems to find the composition of the atmosphere.



## 2.5 Doppler shift of spectral lines

The wavelength of a spectral line is affected by the relative motion between the source and the observer.



$\Delta\lambda$  = wavelength shift

$\lambda_0$  = wavelength if source is not moving

$v$  = velocity of the source measured along the line of sight

$c$  = speed of light =  $3.0 \times 10^8$  km /s

- Spectral lines of a receding source are shifted toward the longer wavelength – **redshift**.
- Spectral lines of an approaching source are shifted toward the shorter wavelength – **blueshift**.
- The amount of wavelength shift is given by **Doppler shift equation**:

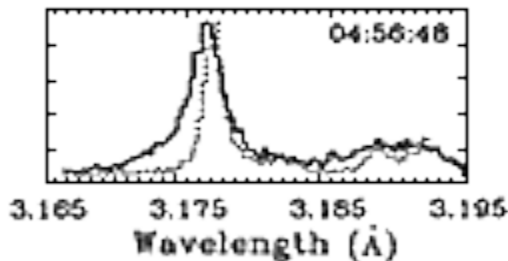
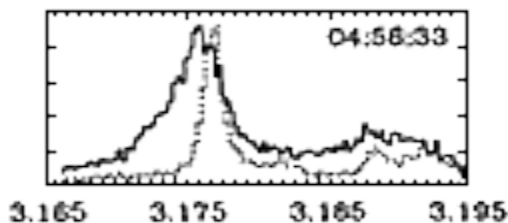
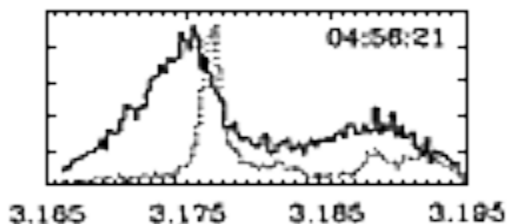
$$\frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c}$$

$$(v \ll c)$$



dashed-line: the X-ray line profile before the flare

solid-line: the X-ray line profile during the flare



Ex. 13: Doppler-shifted X-ray line is observed by a satellite during a solar flare, showing motion of plasmas in the Sun's corona.

- (a) emission line other than absorption line is observed. Is the corona hotter or cooler than the photosphere?
- (b) Is the line blue-shifted or red-shifted? Does the plasma move toward or away from the observer?

(c) suppose that the quiescent profile is centered 3.177 Angstrom, and during the flare the line splits into two components, one not shifted, and the other shifted to 3.174 Angstrom. What does this observation tell you? And what is the velocity of the moving plasma?

$$v = c \frac{\lambda - \lambda_0}{\lambda_0} = (3.0 \times 10^5 \text{ km/s}) \left( \frac{3.174 - 3.177}{3.177} \right) = -283.3 \text{ km/s}$$

(d) The spectral line has a width; part of it is caused by thermal-broadening; what is that?

## Q: why does a spectral line have a profile?

- The shape of the spectral line (e.g. line strength and width) is determined by how many atoms have electrons at certain orbits, which is further determined by temperature, density, and abundance of the atoms and can be calculated in statistical physics.
- Therefore, a given spectral line is formed at a certain temperature/density structure.
- Spectral lines are analyzed to find out properties of stellar structure, such as chemical composition, temperature, density, abundance of atoms and so on.

(Optional) Ex.14: cosmological redshift tells us the scale of the expanding universe using the Hubble law.

These Sloan Digital Sky Survey discovery images show some very faint quasars because they are extremely distant. Their distances have been indirectly gauged by noting how much the light they emit has been stretched to longer wavelengths by the expansion of the Universe. Because red light has the longest wavelengths in the visible spectrum, this stretch has come to be called "redshift". The greater the distance, the greater the redshift  $\iff$  **the Hubble law**. What's the actual distance to these quasars: about 15 billion light-years!



(the Huntington Library, CA)

The Hubble Law:

$$v = H_0 d$$

$v$  = receding speed  
(derived from redshift)

$d$  = distance

$H_0$  = Hubble constant

[\(Astronomical Picture of the Day\)](#)

## Key Words

- absorption line
- Balmer series
- blackbody radiation
- blueshift
- chemical composition
- Doppler effect
- electromagnetic radiation
- emission line
- frequency
- gamma rays
- infrared radiation
- microwaves
- photon
- radio waves
- redshift
- solar constant
- spectral line
- spectroscopy
- Stefan-Boltzmann law
- ultraviolet radiation
- visible light
- wavelength
- Wien's law
- X-rays

## Summary:

- light is electromagnetic radiation. The speed of light in the empty space is a constant,  $c = 3.0 \times 10^8$  km/s. Light has wavelike properties and can be described by wavelength and frequency:  $c = \lambda \nu$
- The Sun, stars, and other objects emits EM radiation according to their temperatures. Wien's law and the Stefan-Boltzmann law describe the peak wavelength and the total radiation power emitted by an object with a certain **temperature**.
- Emission or absorption spectral lines can be produced according to the **chemical composition** of the radiating object or the gas (e.g. atmosphere) the radiated light passes through.
- Spectral lines are produced when an electron jumps from one energy level (one orbit) to another within an atom.
- The Doppler shifts of spectral lines enable us to determine the **motion** of a light source along the line-of-sight.

**References: FKG Chap 5. & Lecture notes**