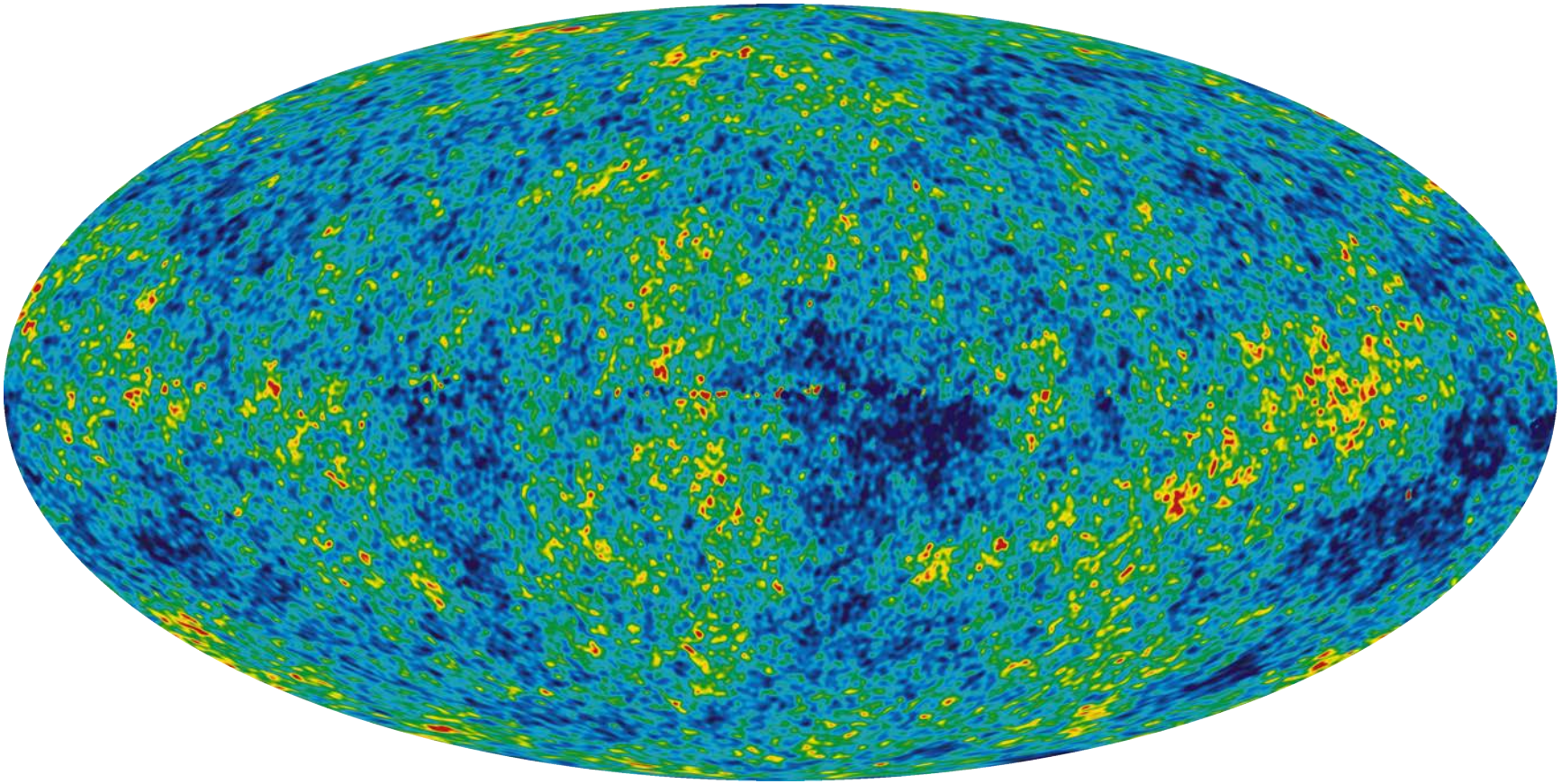
The Nature of Light and Matter



My Teaching website in located at:
http://chartasg.people.cofc.edu/chartas/Teaching.html

Lecture: Tuesday and Thursday
Location: Harbor Walk, HWWE room 112
Time: TR 11:20 am-12:35 pm

Instructor: Dr. George Chartas
Office: 206 J. C. Long
Office hours: TR 3:00-5:30 pm
Phone: (843) 953-3609
Email: chartasg@cofc.edu

Syllabus
Required materials:
The textbook for the course is Universe 10th Edition (8th and 9th Editions are OK as well) by Roger A. Freedman, Robert M. Geller, and William J. Kaufmann. You will also need a scientific calculator capable of computing exponential functions.

Midterm Exams Homework and Quizzes:
There will be 3 midterm exams over the semester. The worst score of the three may be dropped. Homework will be assigned after each chapter and I expect it to be turned in by the assigned due date listed on the schedule web site. Several quizzes will be given during lectures. The quizzes will be based on material already presented in lectures. There will be a final exam that will cover most of the material presented in the lectures.

Grades

Your final grade will be calculated as follows:

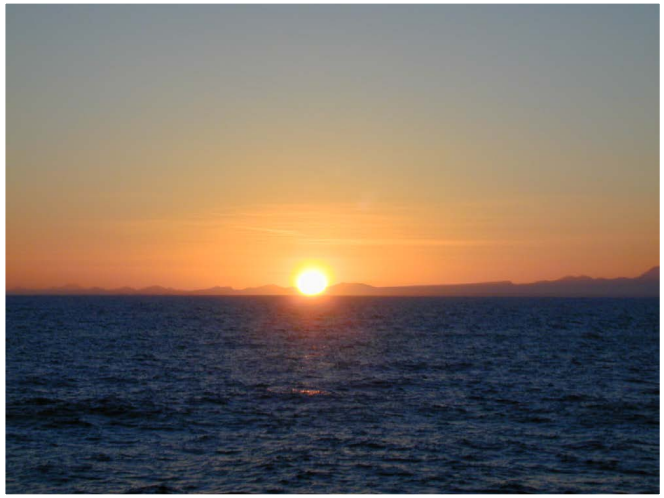
Homework	5%
Quizzes	15%
Midterms	40%
Final + signature assignment	30% + 10%

Your number grade will be converted into a letter grade as follows.

The Sun – Eight Minutes ago

Distance from Sun = 1.5×10^8 km, c = 3×10^5 km/s
Time = ?

The Sun – Eight Minutes ago



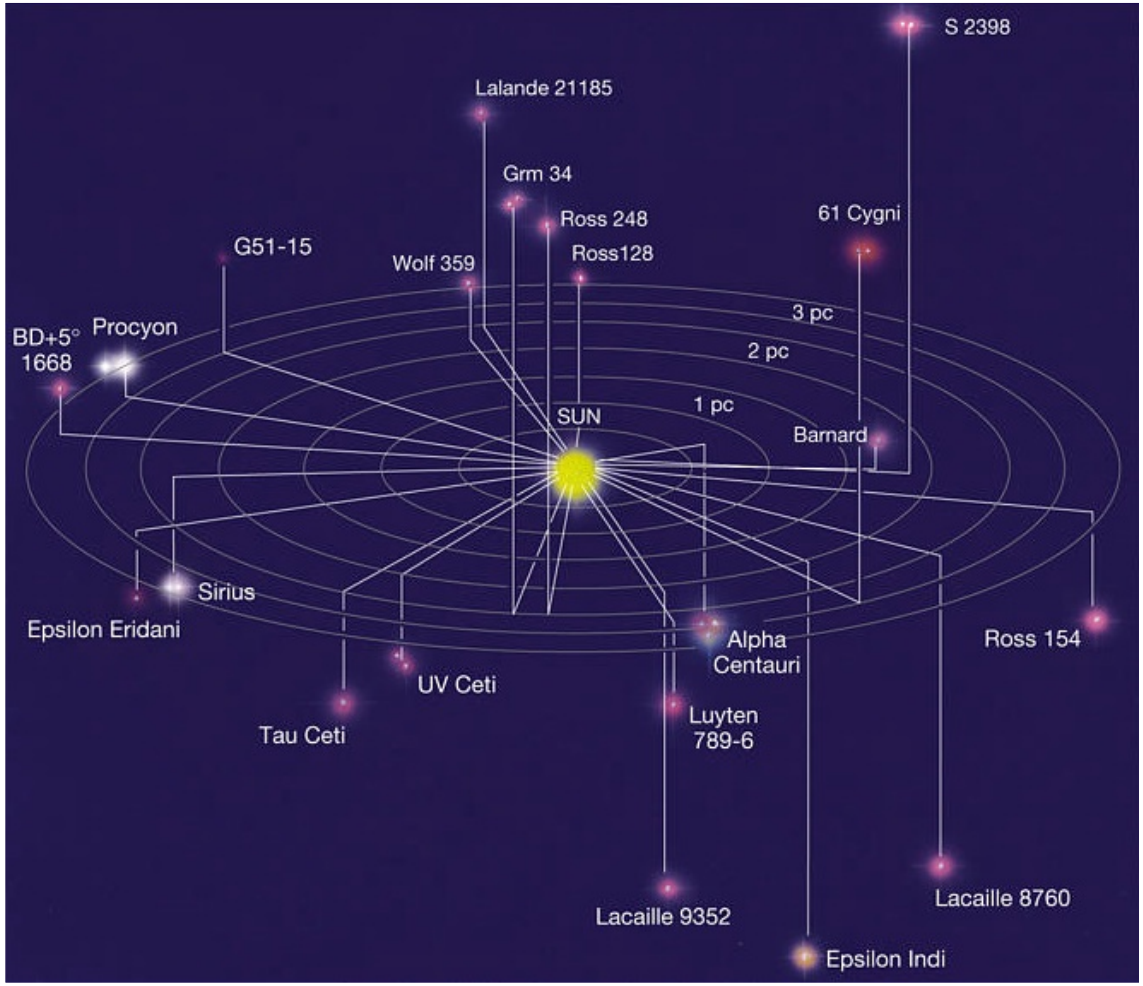
Distance from Sun = 1.5×10^{11} m
c = 3×10^5 km/s

c = s/t
→t = s/c = 1.5×10^8km/3×10^5 km/sec
→t = 500 sec

Light Year = ly : distance light travels in one year

1 ly = c×1yr = 3×10^5 km/s ×1yr = 3×10^5 km/s ×3.1557×10^7s
1 ly = 9.46×10^{12} m

The Nearest Stars – Few Years Ago



1 pc = 3.26 ly

Andromeda Galaxy – 2.5 Million Years Ago

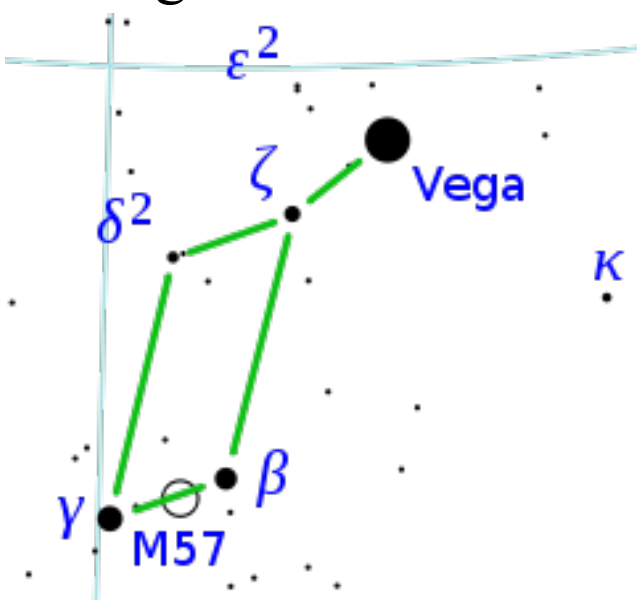
disk radius ~ 110,000 ly

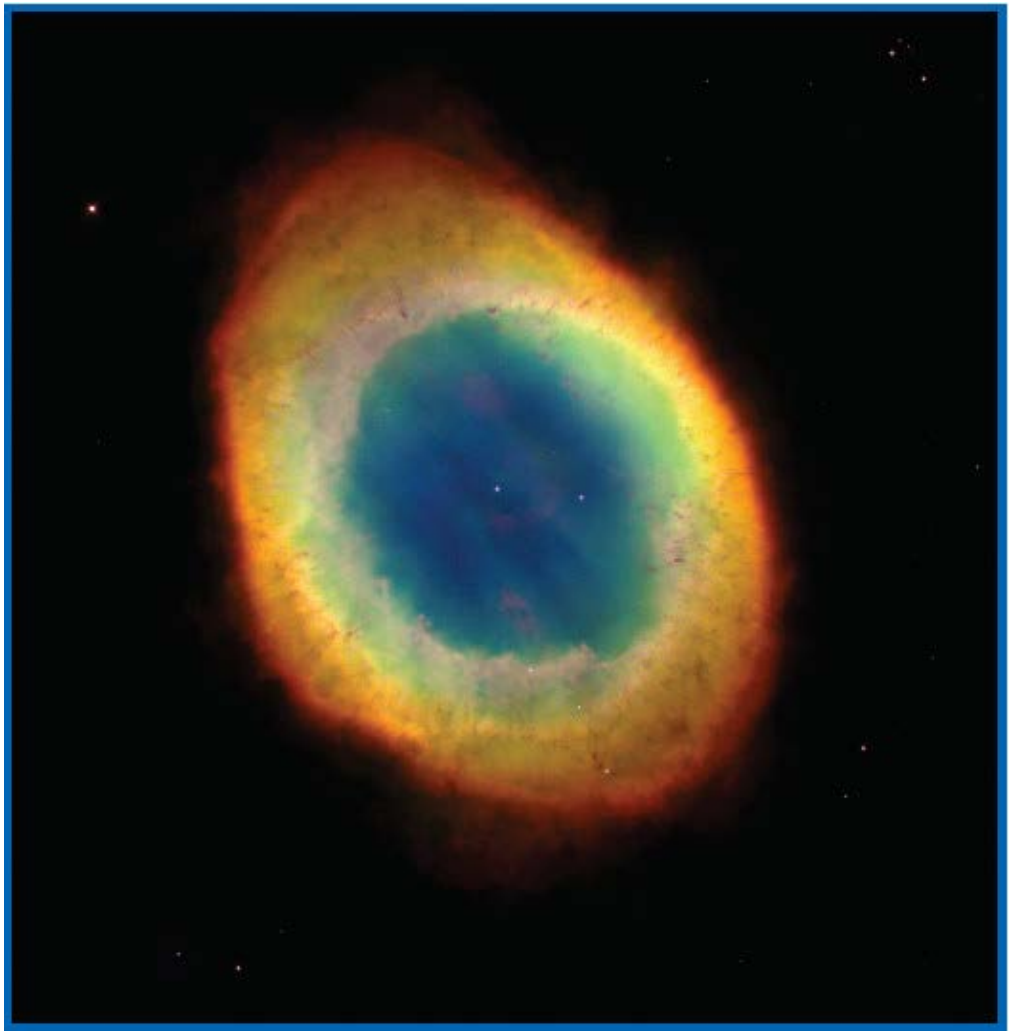
Distant Galaxies – Billions of Years Ago

The Nature of Light

The Ring Nebular (M57):
A shell of glowing gases surrounded by a **white dwarf**.

- red light from nitrogen
- green light from oxygen
- blue light from helium





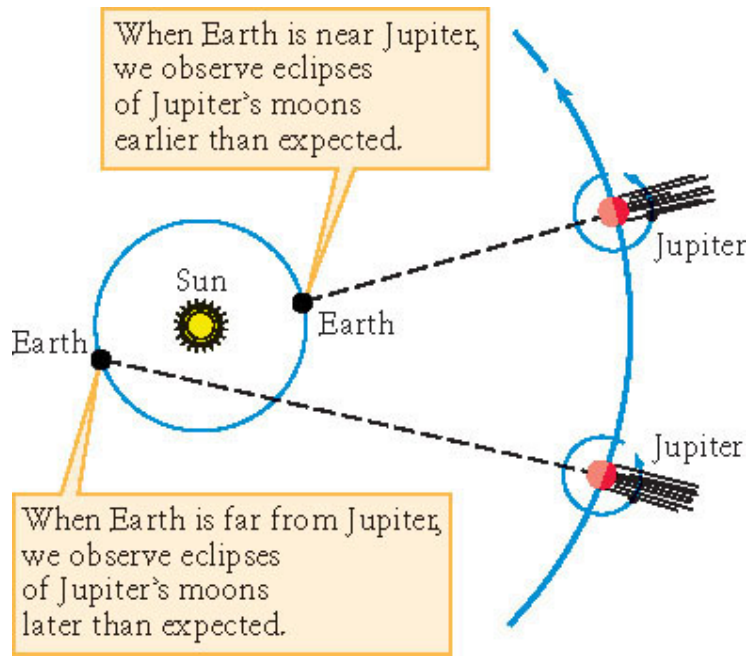
Measuring the Speed of Light

1. **Galileo**

→ concluded that the speed of light was too fast for him to measure.

2. **Olaus Romer**

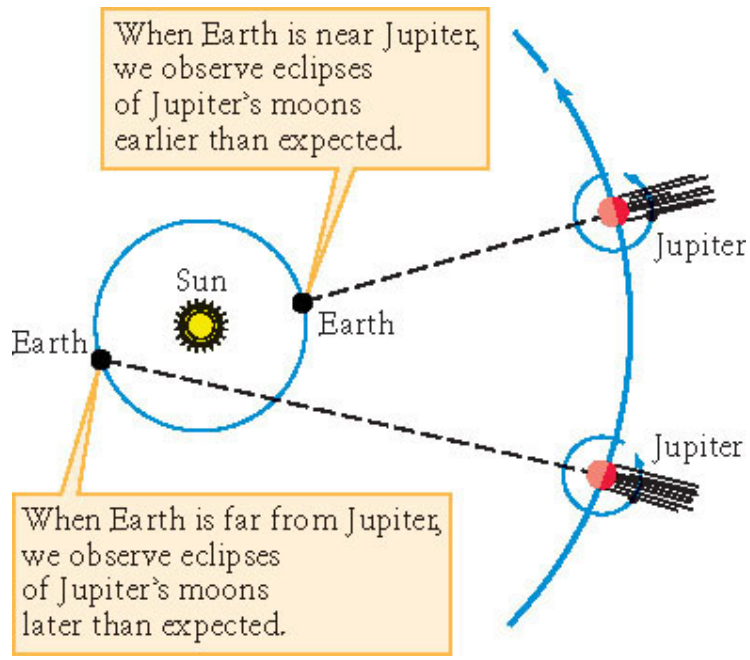
→ By recording the time of eclipses of Io Romer noticed that they occurred several minutes later when the earth was far from Jupiter (in conjuction) and earlier when closer the Jupiter.



Measuring the Speed of Light

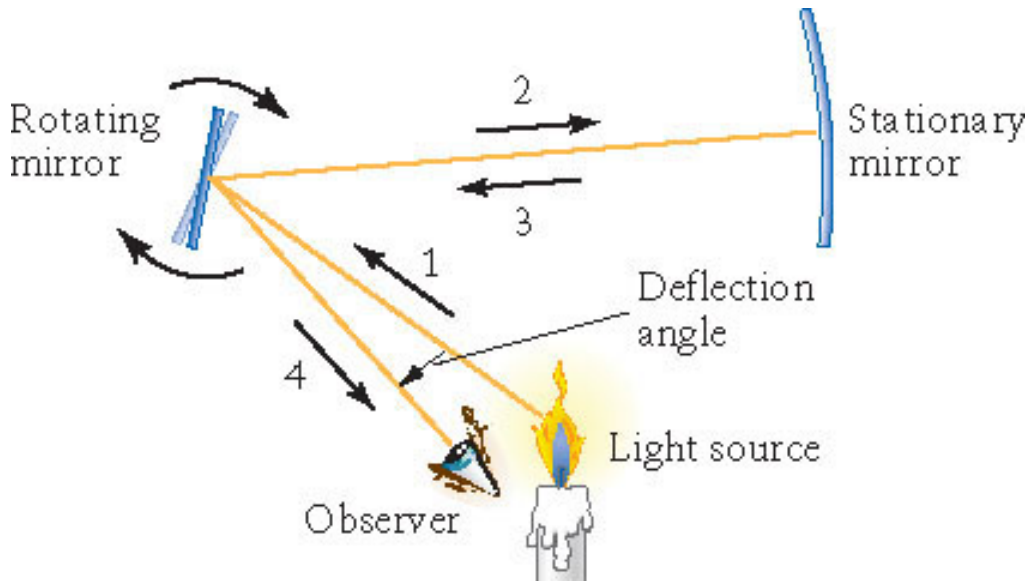
2. **Olaus Romer**

Question : Estimate the speed of light if the range in variation in the times at which eclipses are observed is about 16.6 min. hint: light has to travel an extra 2*AU to reach Earth in opposition. 1 AU = 1.5×10^8 km



Measuring the Speed of Light

3. The Fizeau-Foucalt Method

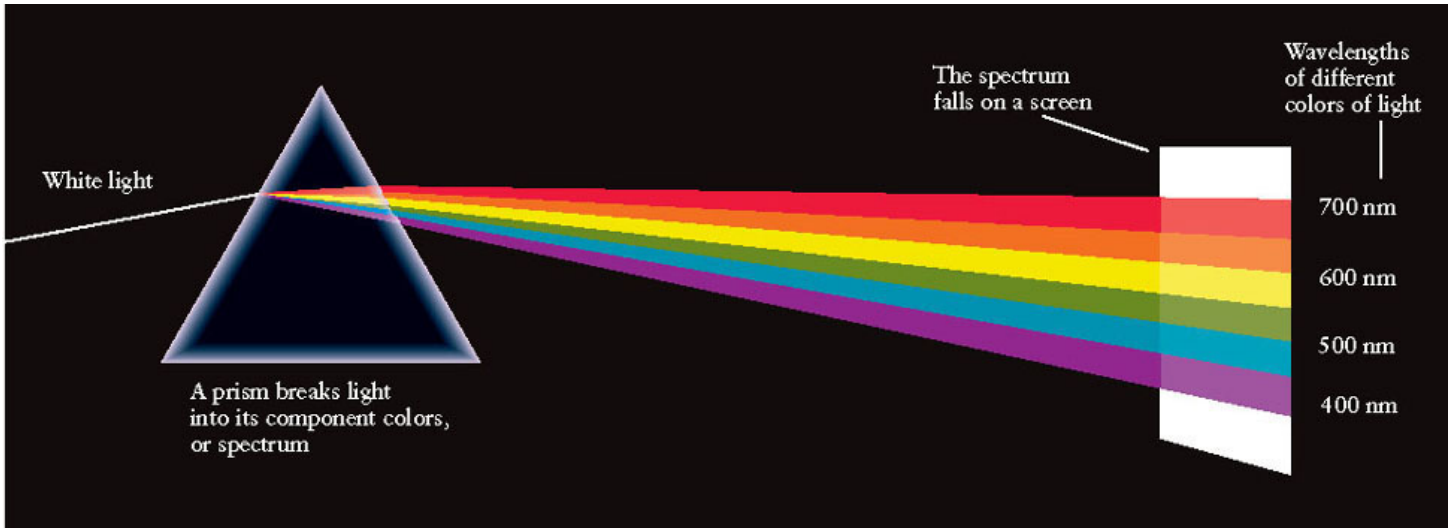


4. By 1975 the speed of light was known to be 299,792,458 m/s with a relative measurement uncertainty of 4 parts per billion. In 1983 the meter was redefined in the International System of Units (SI) as the distance travelled by light in vacuum in 1⁄299,792,458 of a second.

The Nature of Light

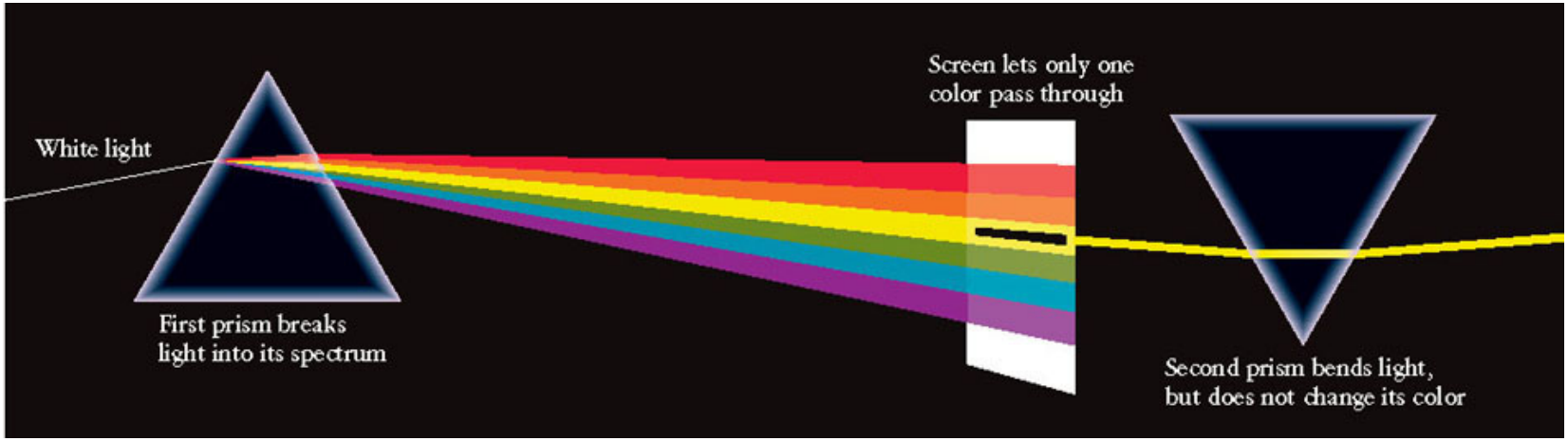
What is light? How is it produced? What is it made of? How does it propagate?

1. Newton's experiments showed that white light is a combination of all the colors that appear in its spectrum.



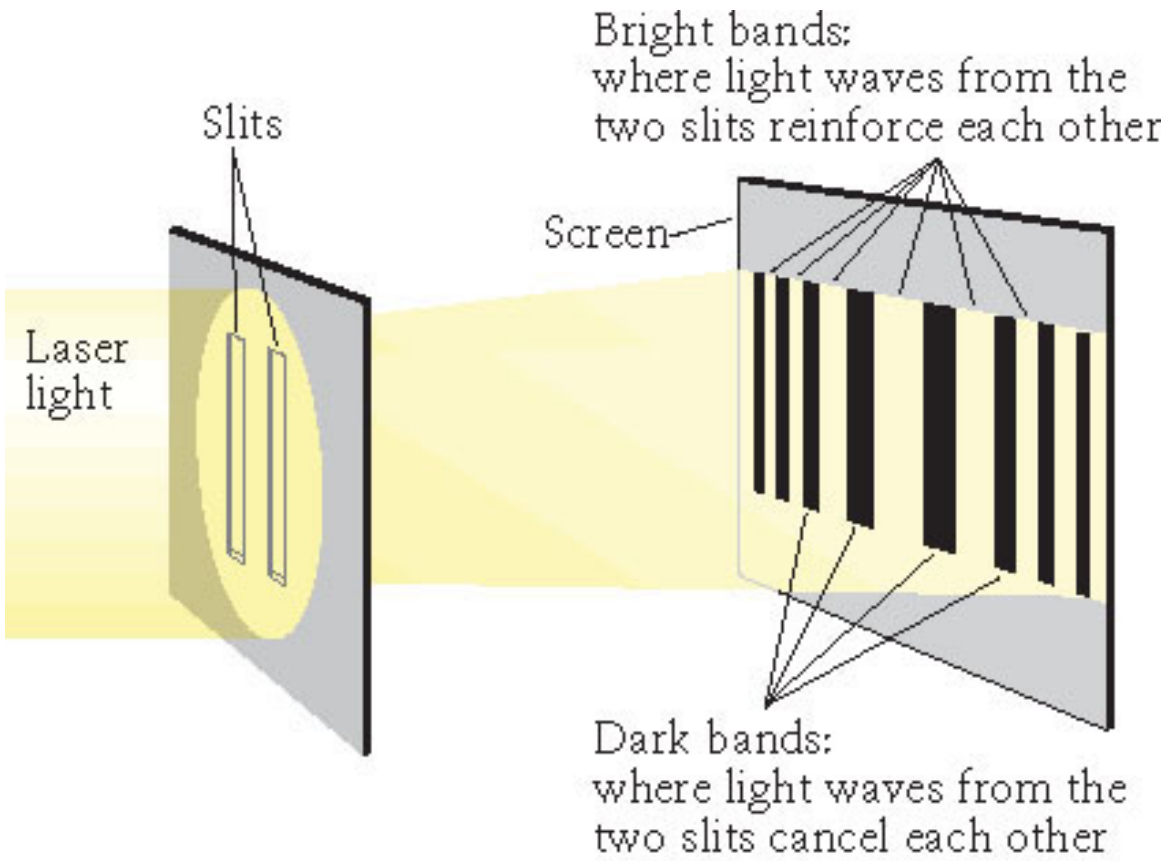
The Nature of Light

A second prism bends the light but does not change the color thus indicating that it actually separates the white light into the colors its made up of. Newton suggested that **light is composed of particles** too small to detect individually.



The Nature of Light

2. Huygens and Young: **Wavelike nature of light**.

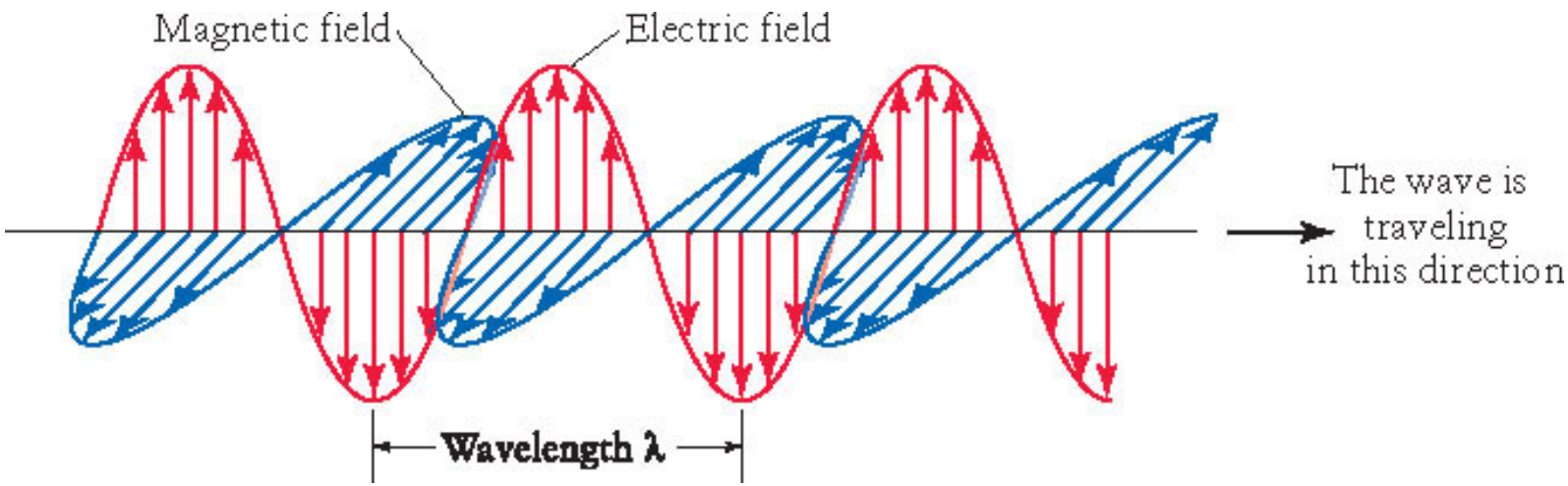


(a) An experiment with light

The Nature of Light

3. **Maxwell**: light is electromagnetic radiation

- Light is electromagnetic radiation that consists of oscillating electric and magnetic fields.
- Maxwell showed that electromagnetic waves travel through space at the speed of light.
- The distance between successive wave crests is called the wavelength of the light.



The Nature of Light

λ = wavelength

Visible light

λ: 400 nm (violet) – 700 nm (red) (1 nm = 1×10^{-9}m)

William Herschel discovered **infrared radiation**

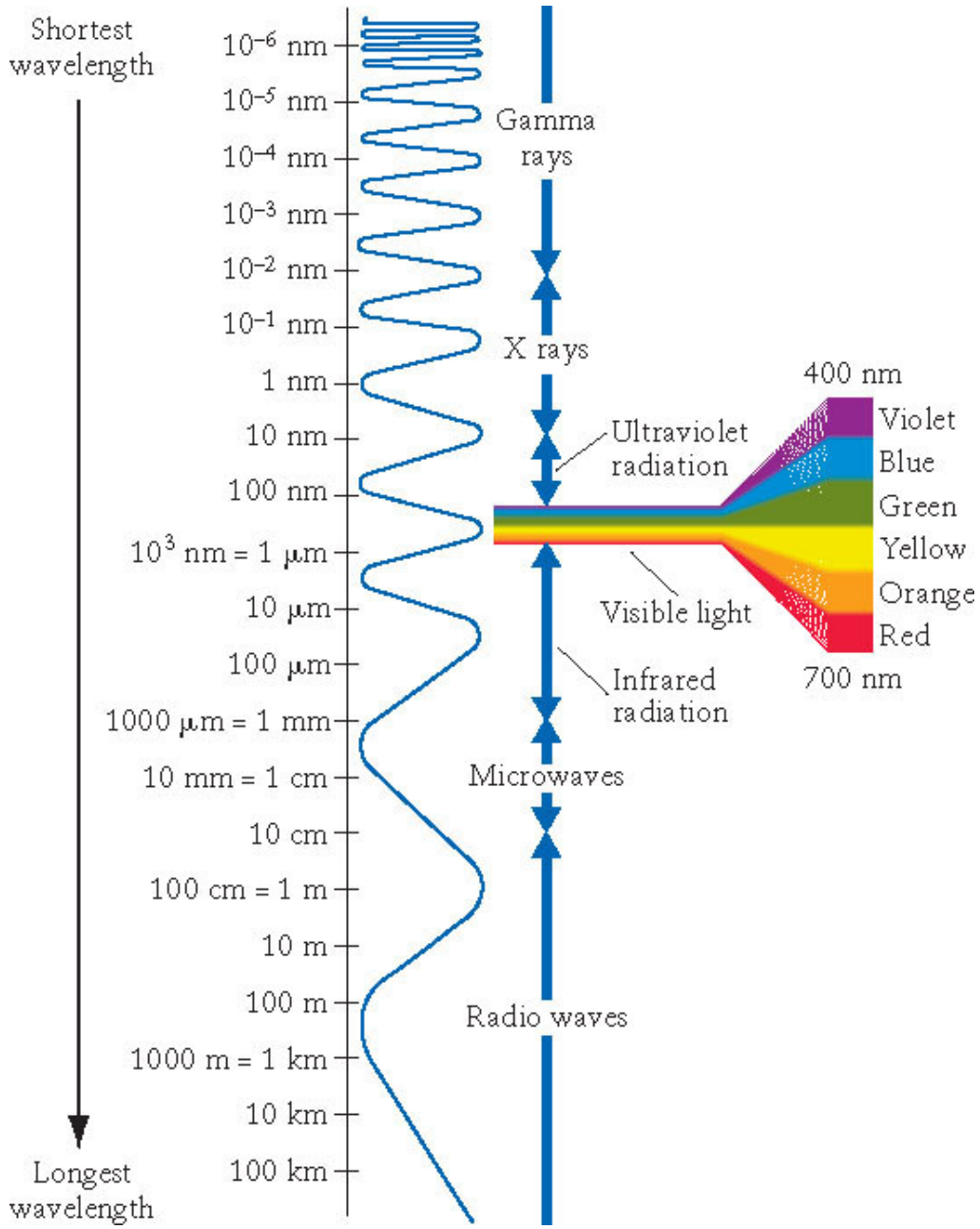
λ : 700 nm – 1000 μm (1 μm = 1×10^{-6}m)

In experiments using electric sparks **Heinrich Hertz** discovered **radio waves**

λ : 10 cm – 100 km (1 km = 1×10^{3}m, 1 cm = 1×10^{-2}m)

Wilhelm Rontgen discovered **X-rays** by bombarding targets with high energy particles

λ: 10^{-2} nm – 10 nm


Shortest wavelength
Longest wavelength
10^{-6} nm
10^{-5} nm
10^{-4} nm
10^{-3} nm
10^{-2} nm
10^{-1} nm
1 nm
10 nm
100 nm
10^{3} nm = 1 μm
10 μm
100 μm
1000 μm = 1 mm
10 mm = 1 cm
10 cm
100 cm = 1 m
10 m
100 m
1000 m = 1 km
10 km
100 km
Gamma rays
X rays
Ultraviolet radiation
Visible light
Infrared radiation
Microwaves
Radio waves
400 nm
Violet
Blue
Green
Yellow
Orange
Red
700 nm

Frequency and Wavelength of light

The **frequency** of a wave is just the number of crests that pass a given point per sec or the number of complete cycles that pass per sec.

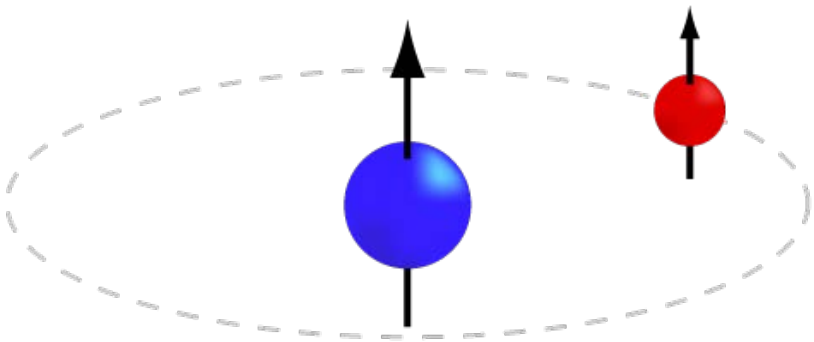
$c = \lambda/T_{crest} = \lambda\nu$

ν= frequency of an electromagnetic wave
c = speed of light = 3×10^8 m/s
λ= wavelength of the wave in meters

Unit of frequency 1 Hz = s^{-1}

AM radio: 535 kHz - 1605 kHz
FM radio: 88 MHz - 108 MHz

Frequency and Wavelength of light

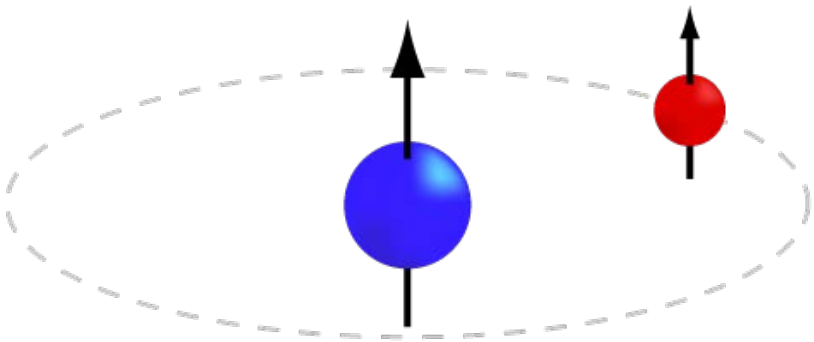


21-centimeter line An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

Question:
Neutral Hydrogen emits radio waves with a wavelength of 21.1cm. What's the frequency, Kenneth?

Use $c = 3 \times 10^8$ m/s

Frequency and Wavelength of light



21-centimeter line An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

Question:
Neutral Hydrogen emits radio waves with a wavelength of 21.1cm. What is the frequency?

Answer:
$\nu = c/\lambda = 3\times10^{10}\text{cm s}^{-1} / 21.1\text{cm} =$
~ 1420 MHz

Thermal Radiation

Thermal radiation is electromagnetic radiation emitted from an object's surface and is related to its **temperature**.

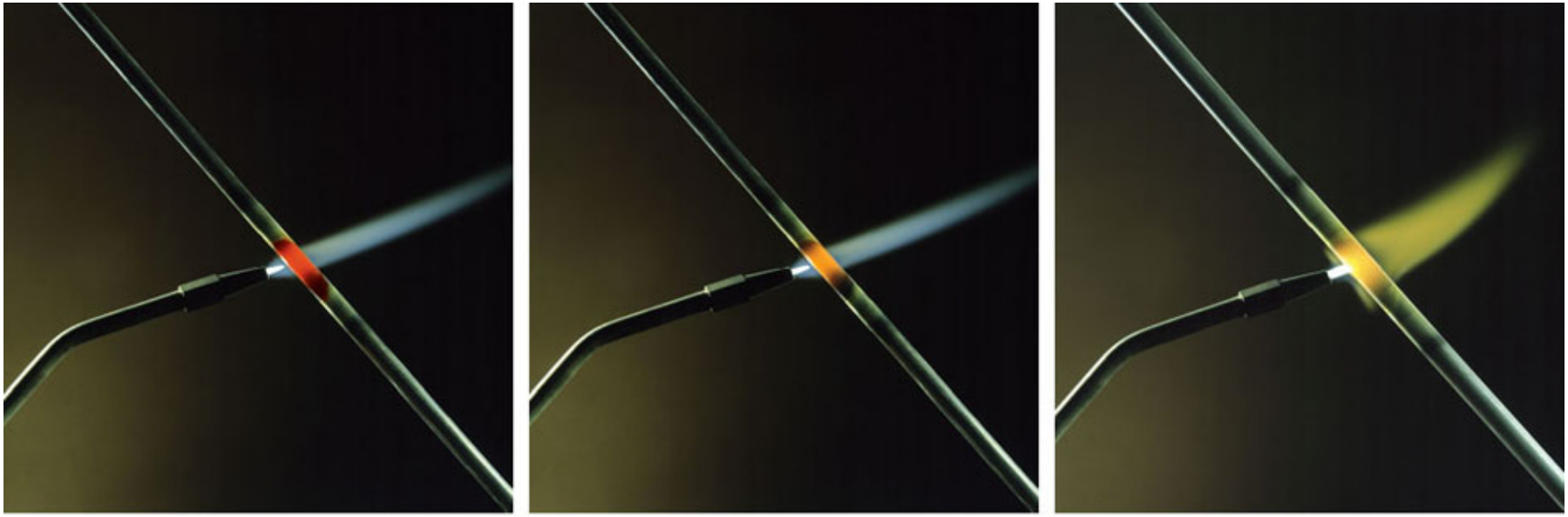
Thermal radiation is generated when **kinetic energy** from the movement of charged particles within atoms **is converted into electromagnetic radiation.**

Examples of objects that emit thermal radiation:
The **solid filament** of a light bulb emits white light that is a mixture of light of many wavelengths.

The **sun and stars**, even though are gaseous, emit light that is very similar to that emitted by a very hot solid.

Thermal Radiation

Example : Imagine a bar of iron being heated up. As the bar starts to glow it will first appear to glow with a deep red color. As the temperature of the bar increases the color of the bar goes from red to orange to yellow.



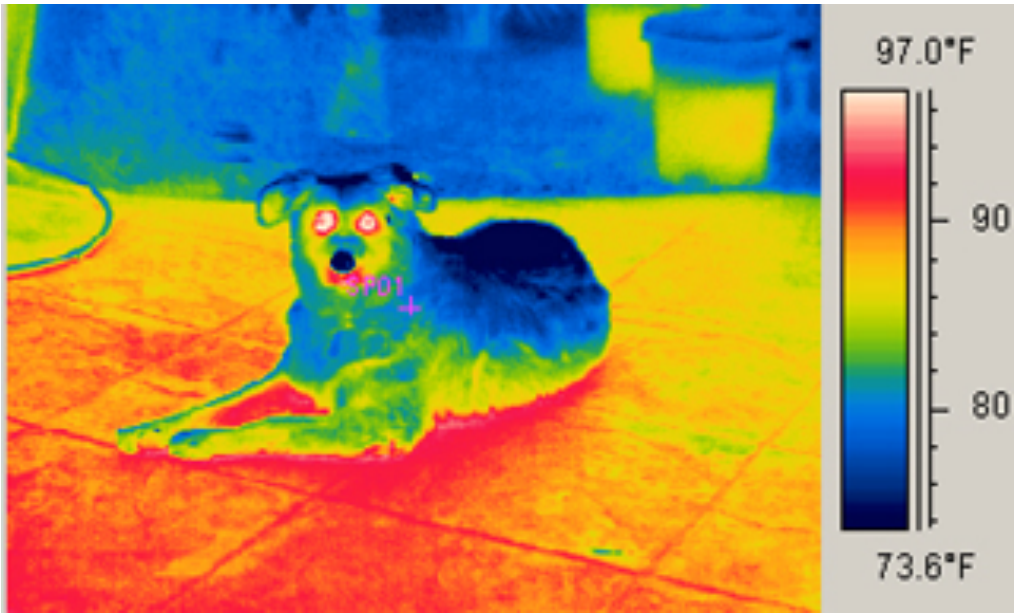
(a) Hot: glows deep red (b) Hotter: glows orange (c) Even hotter: glows yellow

Thermal Radiation

The **amount of energy** and the **dominant wavelength** of the light emitted **depends on the temperature** of the object. *Higher temperatures result in shorter wavelengths and more energy emitted per unit time.*

The reason we don't see bodies in the dark is that the dominant wavelength emitted by bodies is in the infrared.

Our eyes are not sensitive to infrared.



Kinetic Energy

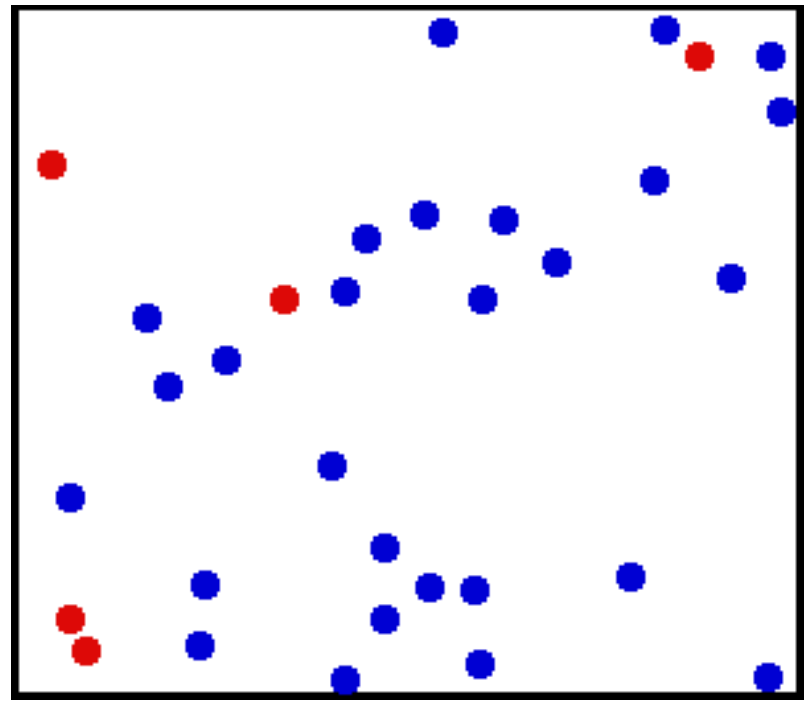
The kinetic energy of an object of mass m and velocity v is:

$$E_k = \frac{1}{2}mv^2$$

If m is expressed in kg and v in m/s, the kinetic energy is expressed in Joules (J).

Temperature of a Gas

The temperature of a gas is a direct measure of the average amount of kinetic energy per atom or molecule. The average kinetic energy of a gas atom or molecule is:



$$E_k = \frac{3}{2}kT$$

E_k = average kinetic energy of a gas atom or molecule in joules (J)

$k = 1.38 \times 10^{-23}$ J/K (Boltzmann constant)

T = temperature of gas, in kelvins

Absolute Temperature Scale

The SI unit for temperature (T) is the kelvin. The Kelvin scale is a thermodynamic (absolute) temperature scale where absolute zero, the theoretical absence of all thermal energy, is zero kelvin (0 K).

$$T(K) = T(°C) + 273.15°$$

For example the average surface temperatures of Mercury and Mars are about 700 K and 300 K, respectively.

The temperatures in the upper atmospheres of Jupiter and Neptune are about 125 K and 55 K, respectively.

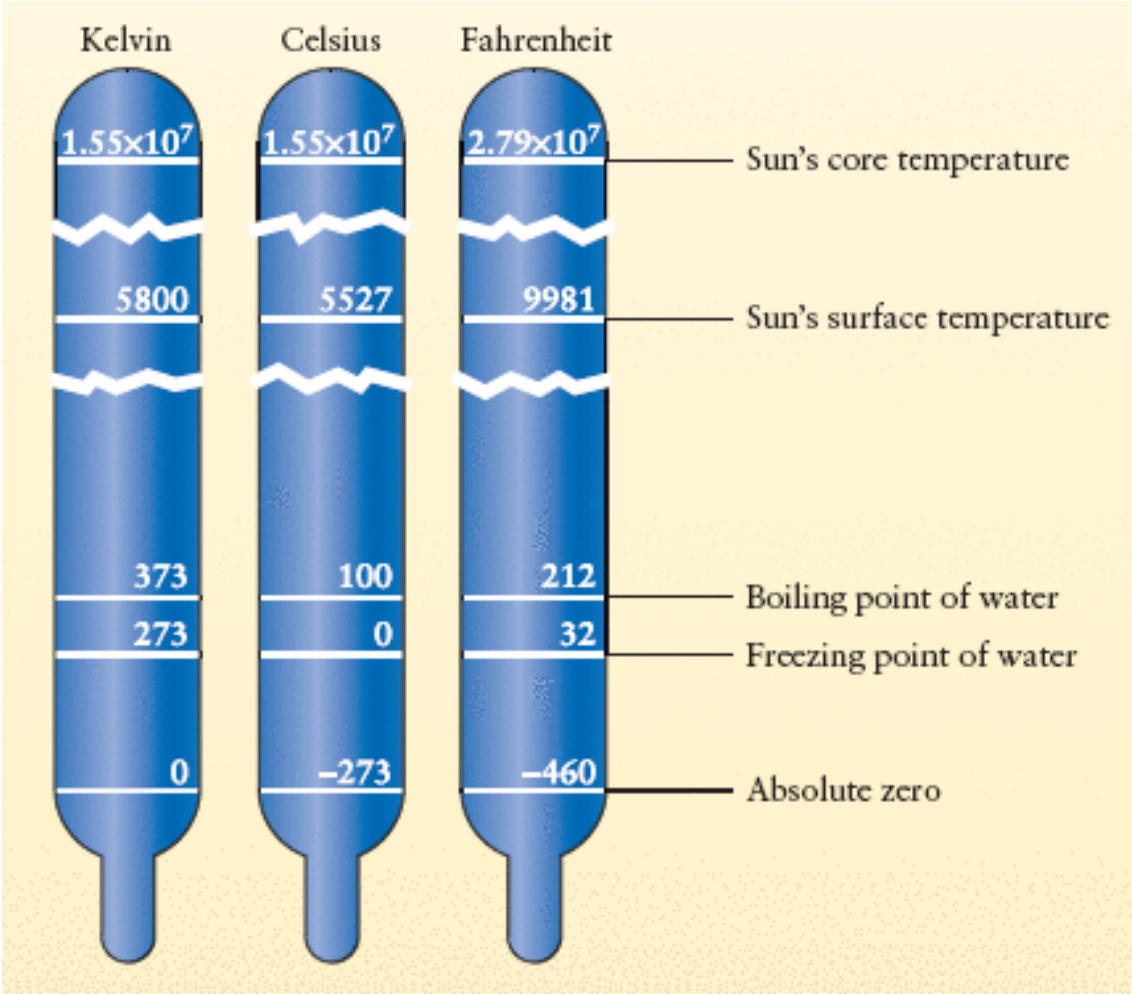
$$T_C = \frac{5}{9}\left(T_F - 32\right)$$

$$T_K = T_C + 273.15^\circ$$

T_C temperature in degrees Celsius

T_F temperature in degrees Fahrenheit

T_K temperature in kelvin



Average speed of a gas molecule or atom

The average speed v (m/s) of a gas molecule or atom is:

$$\frac{1}{2}mv^2 = \frac{3}{2}kT \Rightarrow v = \sqrt{\frac{3kT}{m}}$$

$k = 1.38 \times 20^{-23}$ J/K (Boltzmann constant)

T = temperature of gas, in kelvins

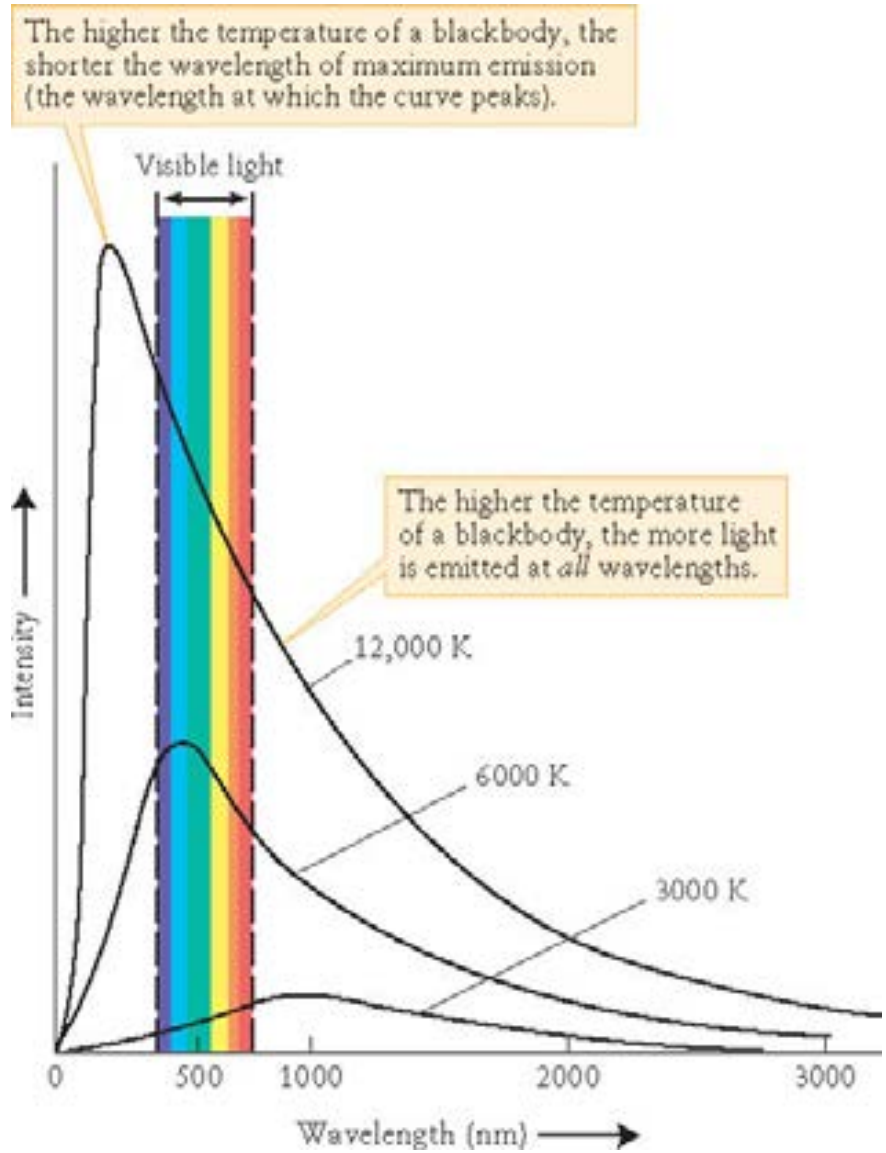
m = mass of atom or molecule in kg

The average speed of the oxygen molecules that you breathe at a room temperature of 20°C is about 0.478 km/s.

Intensity *vs*. Wavelength : Spectra

This figure shows the intensity of light emitted by a solid as a function of wavelength for three different temperatures of the emitting solid.

Notice that the dominant wavelength decreases with increasing temperature.

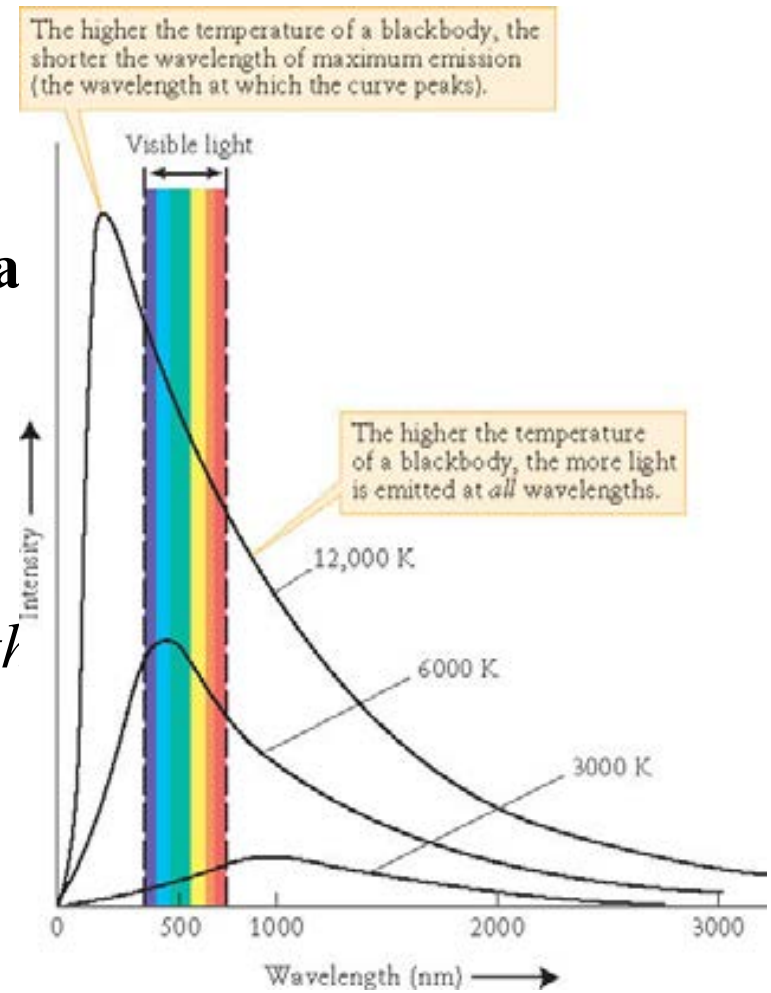


Temperatures of Stars

An ideal **blackbody absorbs** all the radiation that falls on it.

The spectra of stars are often approximated with blackbody spectra

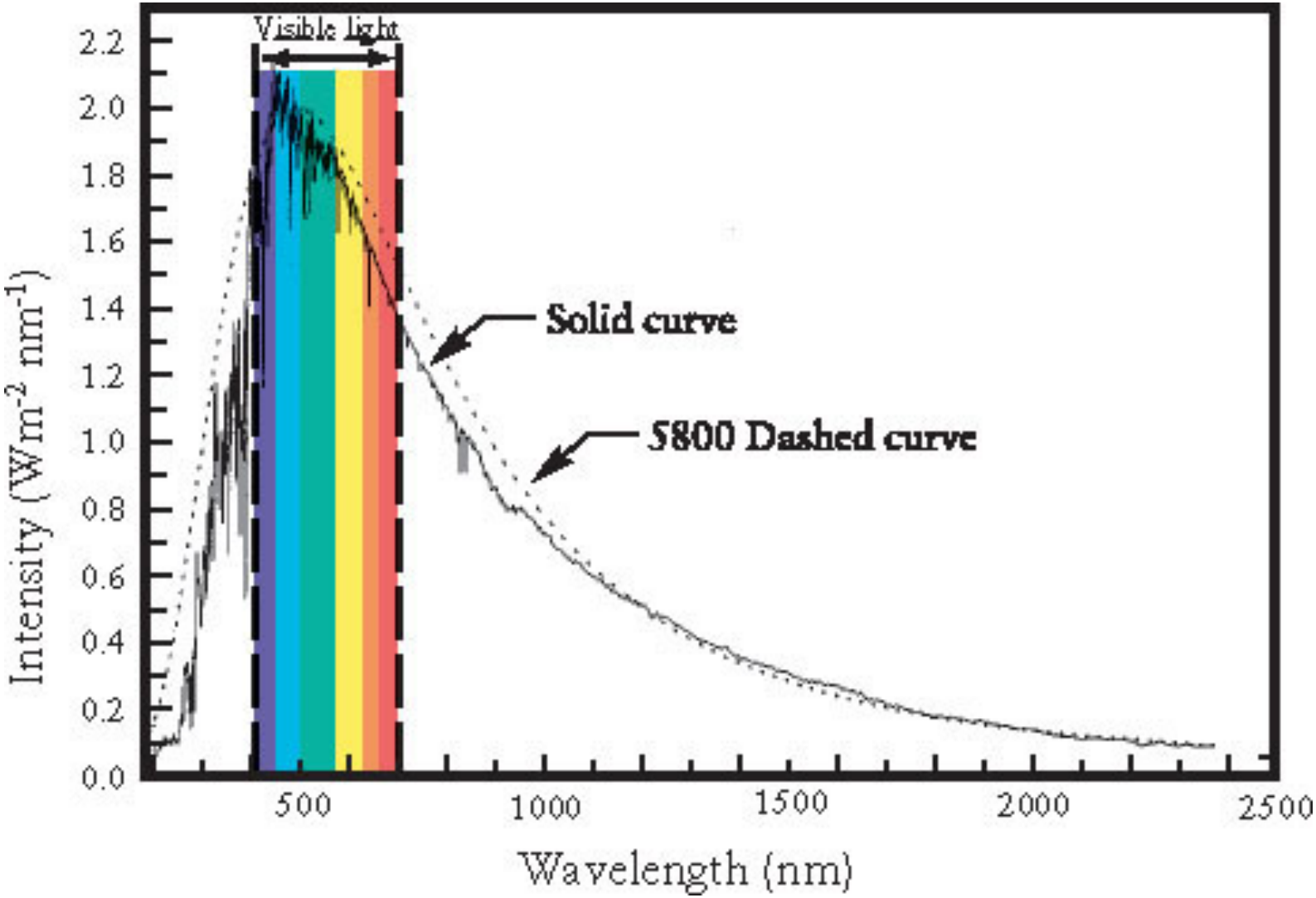
Property of blackbody spectra:
The higher an objects temperature the more intensely the object emits EM radiation and the shorter the wavelength it emits more strongly.



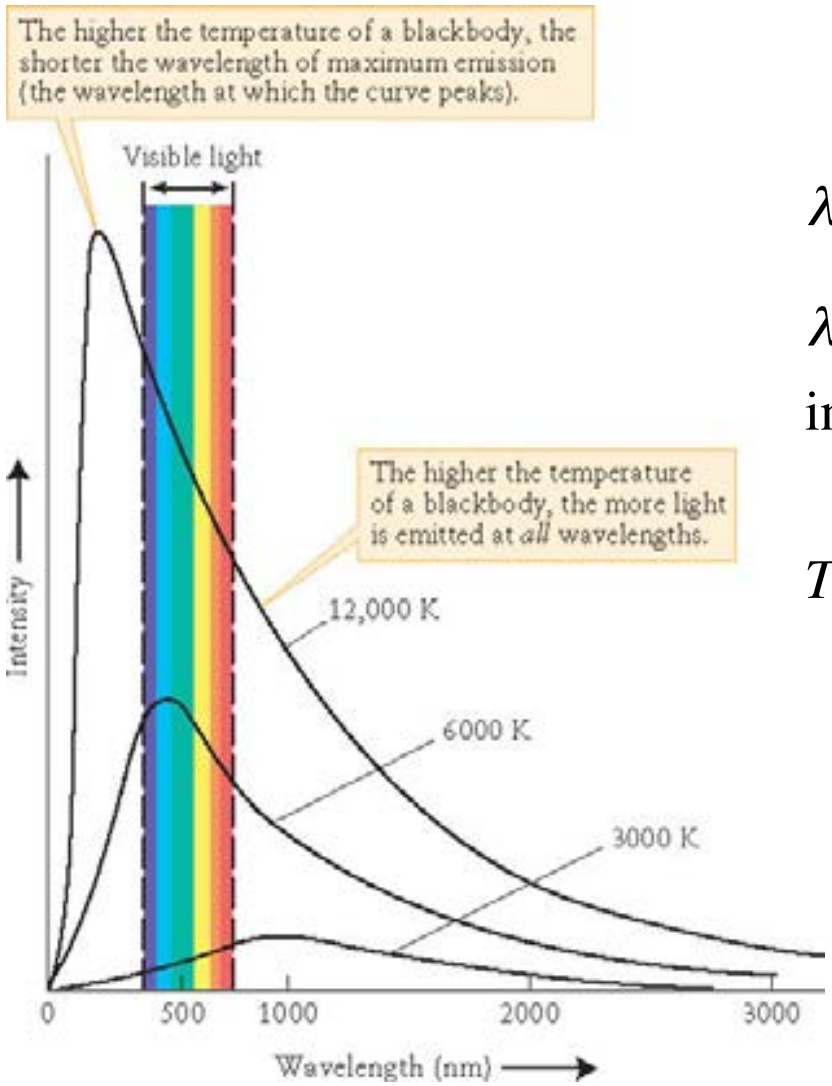
Temperatures of Stars

Example: The star Bellatrix in Orion that looks blue has a higher temperature than the red star Betelgeuse.

The Sun's Spectrum



Blackbody Radiation: Wien's Law



Wien's Law

$$\lambda_{\max}(m) = \frac{0.0029\,K\,m}{T(K)}$$

$\lambda_{\max}$ = wavelength of maximum emission in meters

T = temperature of object in kelvins

Wien's Law: Sun

The maximum intensity of sunlight is at a wavelength of roughly 500 nm = 5.0×10^{-7} m. Use this information to determine the surface temperature of the Sun.

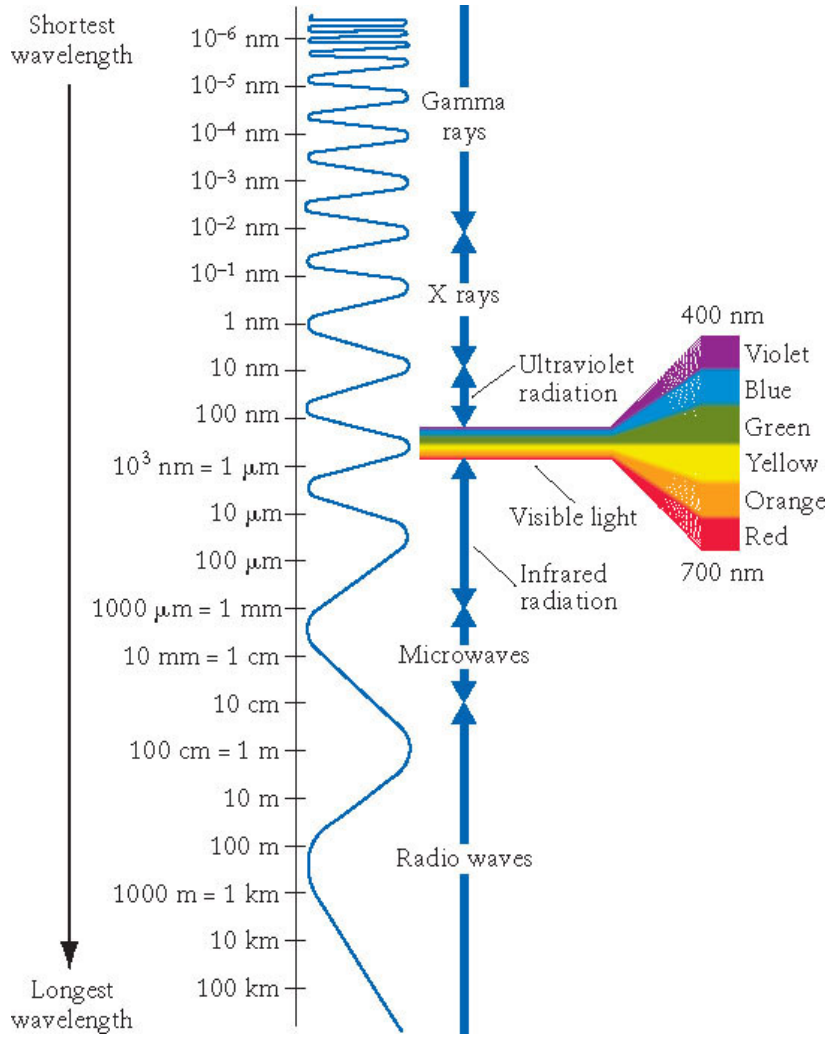
Wien's Law: Sun

The maximum intensity of sunlight is at a wavelength of roughly 500 nm = 5.0×10^{-7} m. Use this information to determine the surface temperature of the Sun.

Sun: $\lambda = 0.0029$ Km / T(K)

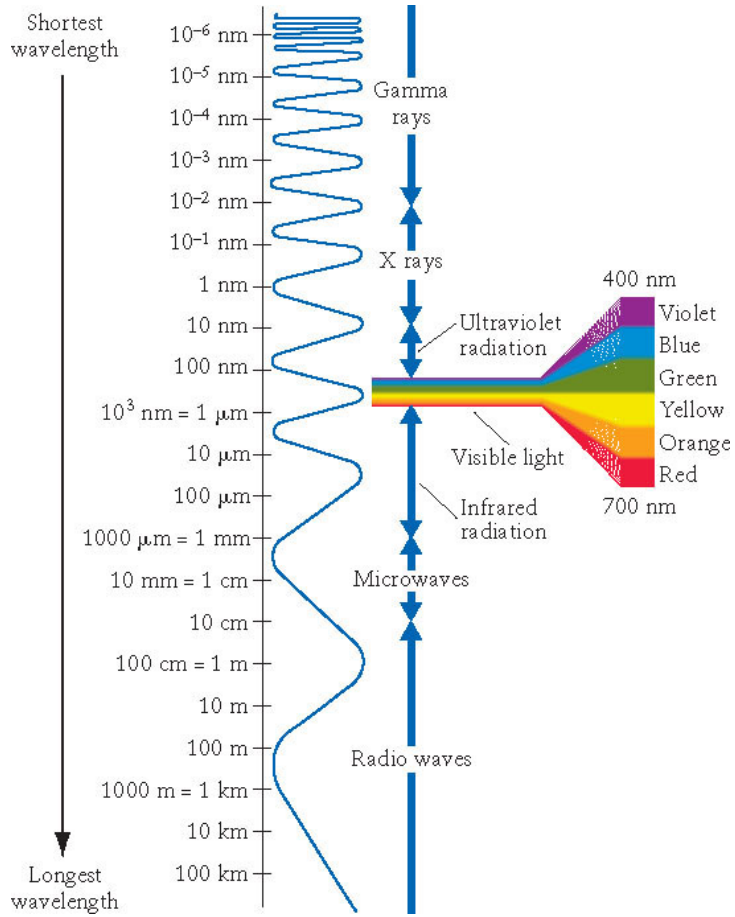
--> $T_{sun} = 0.0029$ K m / 5×10^{-7} m = 5800 K

Wien's Law: Sirius



Sirius, the brightest star in the night sky, has a surface temperature of about 10,000 K. Find the wavelength at which Sirius emits most intensely.

Wien's Law: Sirius



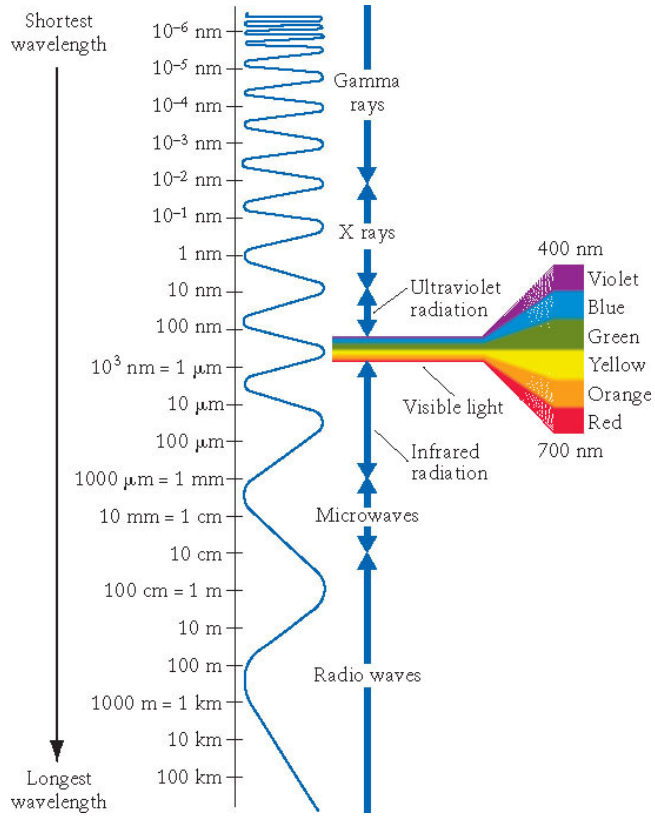
Sirius, the brightest star in the night sky, has a surface temperature of about 10,000 K. Find the wavelength at which Sirius emits most intensely.

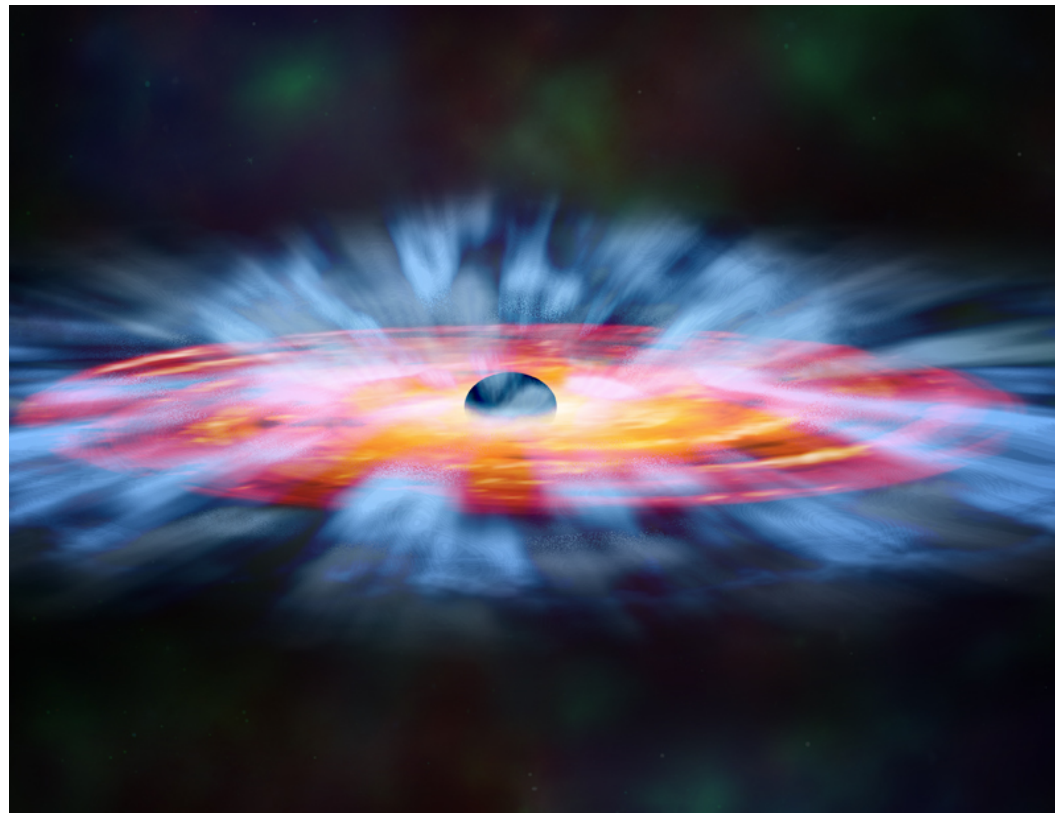
Sirius: $\lambda = 0.0029/T \rightarrow$

$\lambda = 0.0029 \text{ K m} / 10{,}000 \text{ K} \rightarrow$

$\lambda = 2.9 \times 10^{-7} \text{ m} = 290 \text{ nm}$ (UV band)

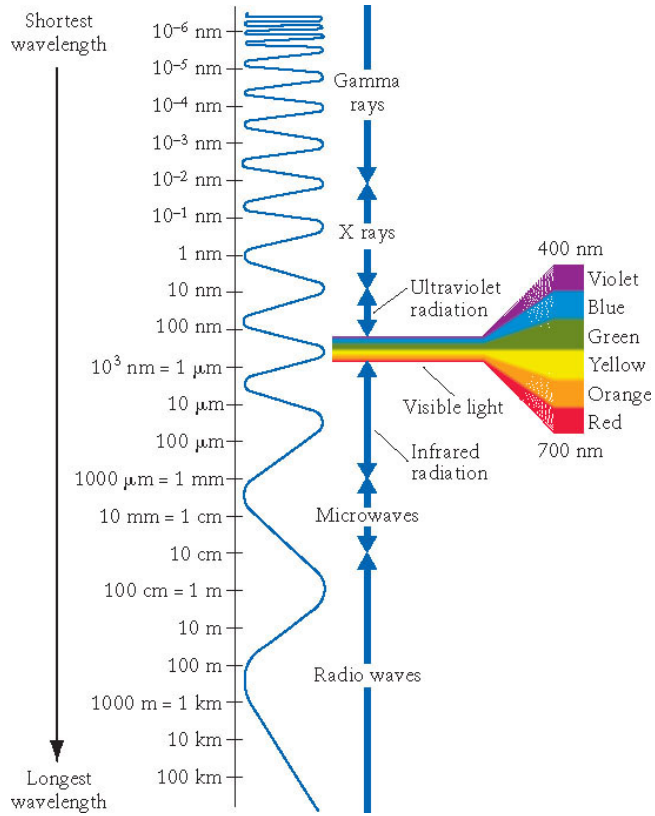
Wien's Law: Black Hole Accretion Disk

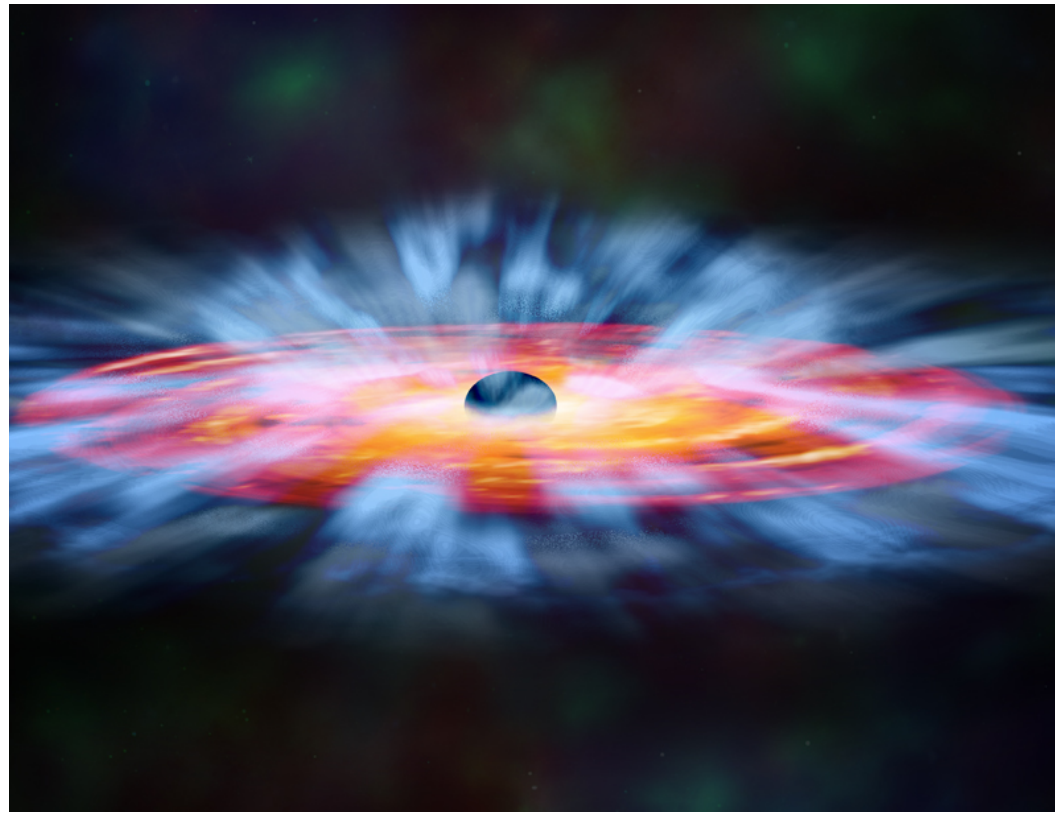




$T_{disk} \sim 10^6 K$, $\lambda = ?$

Wien's Law: Black Hole Accretion Disk





T_{disk}~10^6K, λ= ?

Black Hole: $\lambda = 0.0029/T = 0.0029$ K m / 1×10^6 K →

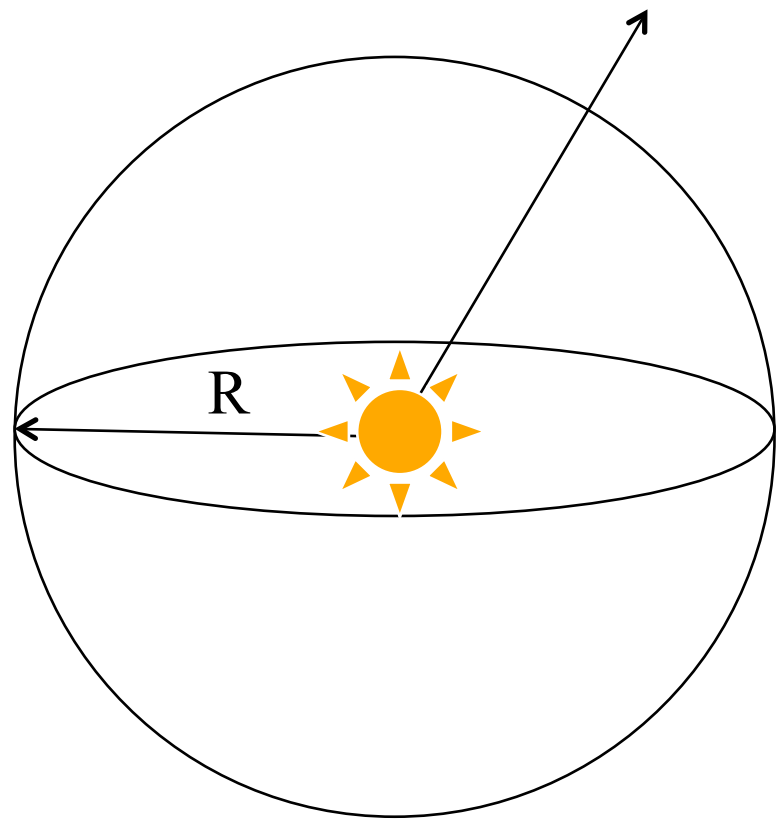
$\lambda = 2.9\ 10^{-9}$ m = 2.9 nm (X-ray band)

Flux Energy Density and Luminosity

Flux Energy Density = F = $\frac{E}{At}$ (J m^{-2} s^{-1})

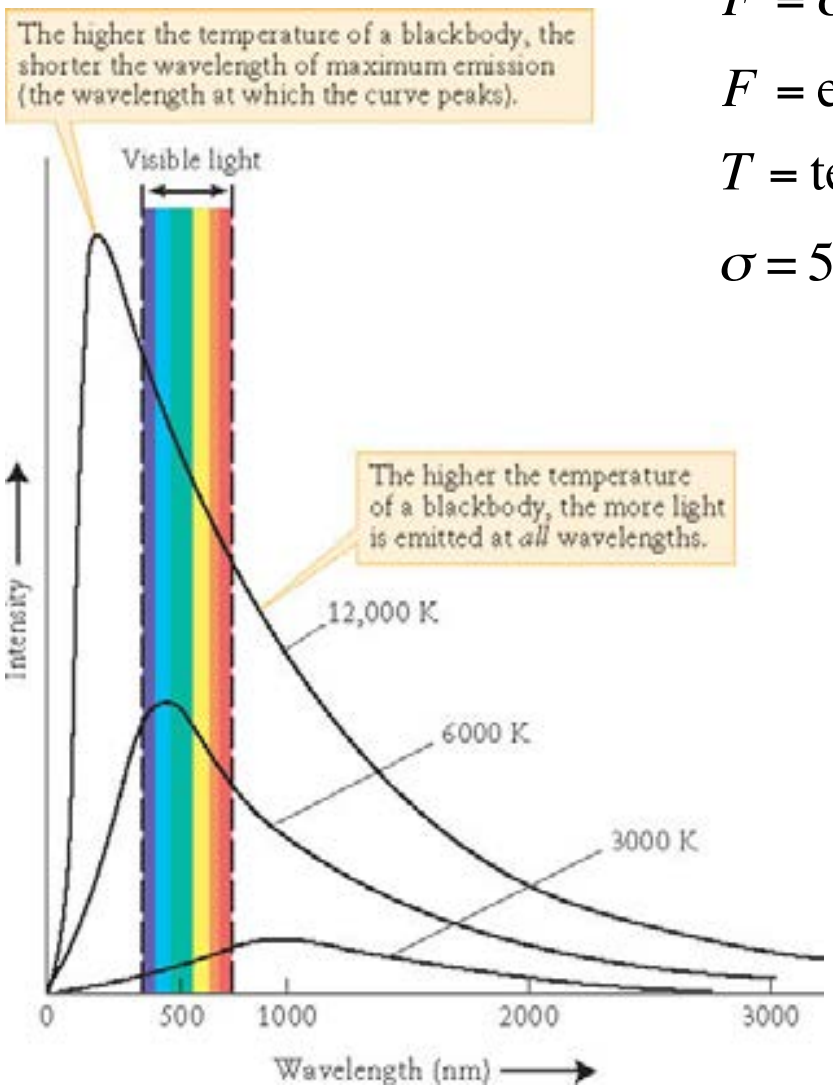
Luminosity = L = $\frac{E}{t}$ (J s^{-1})

E = energy crossing an area A within a time t



Since the area of a sphere is $4\pi R^2$, as one moves away from the source the flux will decrease by $1/R^2$

Blackbody Radiation: Stefan-Boltzmann

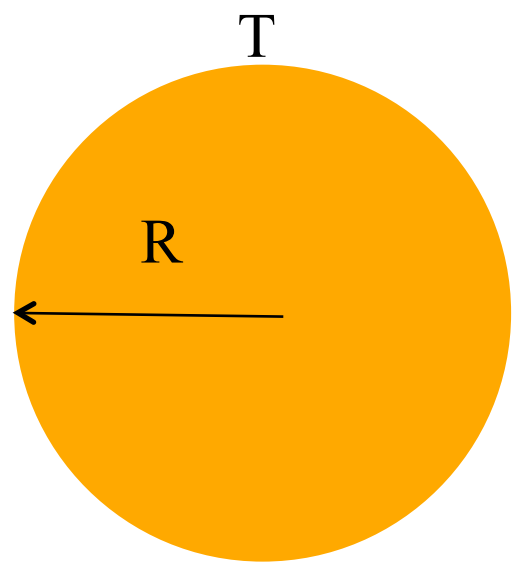


$$F = \sigma T^4$$

F = energy flux at the surface of a star, ($W\ m^{-2}$)

T = temperature of object, (kelvin)

$$\sigma = 5.67 \times 10^{-8} W\ m^{-2} K^{-4}$$



Stefan-Boltzmann's Law: Sirius *vs.* Sun

How does the energy flux from Sirius compare to the Sun's energy flux?

T_{sirius} = 10,000 K, T_{sun} = 5,800 K

Stefan-Boltzmann's Law: Sirius *vs.* Sun

How does the energy flux from Sirius compare to the Sun's energy flux?

$F_{sirius}/F_{sun} = \sigma T^4_{sirius}/\sigma T^4_{sun} = (10{,}000\ K/5800\ K)^4 = 8.84$

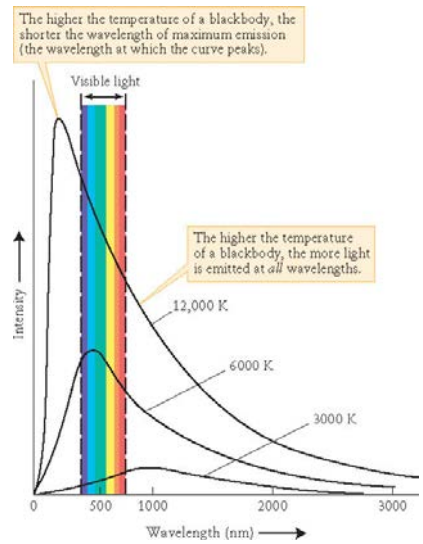
Stefan-Boltzmann's Law: Sun's Surface Temperature

Using detectors above Earth's atmosphere, astronomers have measured the average flux of solar energy arriving at Earth. This value, called the solar constant, is equal to 1370 W m^{-2}. Use this information to calculate the Sun's surface temperature. (This calculation provides a check on our result from the preceding example.)

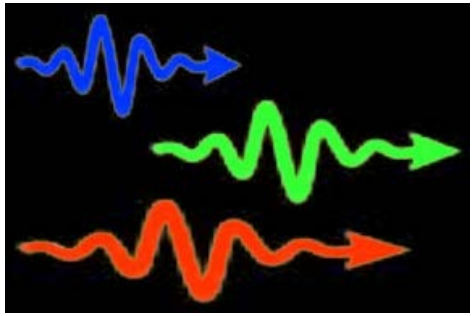
$R_\odot$ = 695,500 km, 1 AU = 1.5×10^{11} m,
$\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4}

Photon Hypothesis

In 1900 **Planck** formulated a theory to explain blackbody radiation curves.



In 1905 **Einstein** postulated that light is composed of discrete, particlelike packets that he called quanta, now known as photons.



Planck's Law: Energy *vs* Frequency

The dual nature of light is evident in the formula that relates the energy of a photon to its wavelength :

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

$E = energy\, of\ photon\,(eV)$

$\nu = frequency\, of\ photon\,(s^{-1})$

$h = 4.135 \times 10^{-15}\, eV\ \ s$ (Planck's Constant)

c = speed of light = 3×10^{8} m s^{-1}

λ = wavelength of the wave (m)

Planck's Law: Energy *vs* Frequency

The dual nature of light is evident in the formula that relates the energy of a photon to its wavelength :

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

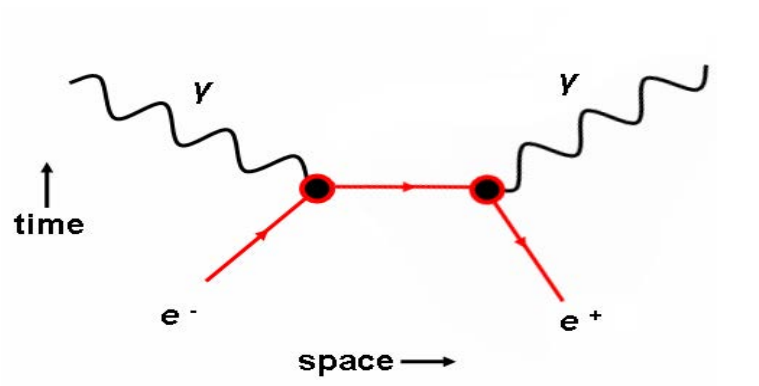
$$E = energy\, of\ photon\,(J)$$

$$\nu = frequency\, of\ photon\,(s^{-1})$$

$$h = 6.625 \times 10^{-34}\, J\, s \text{ (Planck's Constant)}$$

Planck's Law: Energy *vs* Frequency

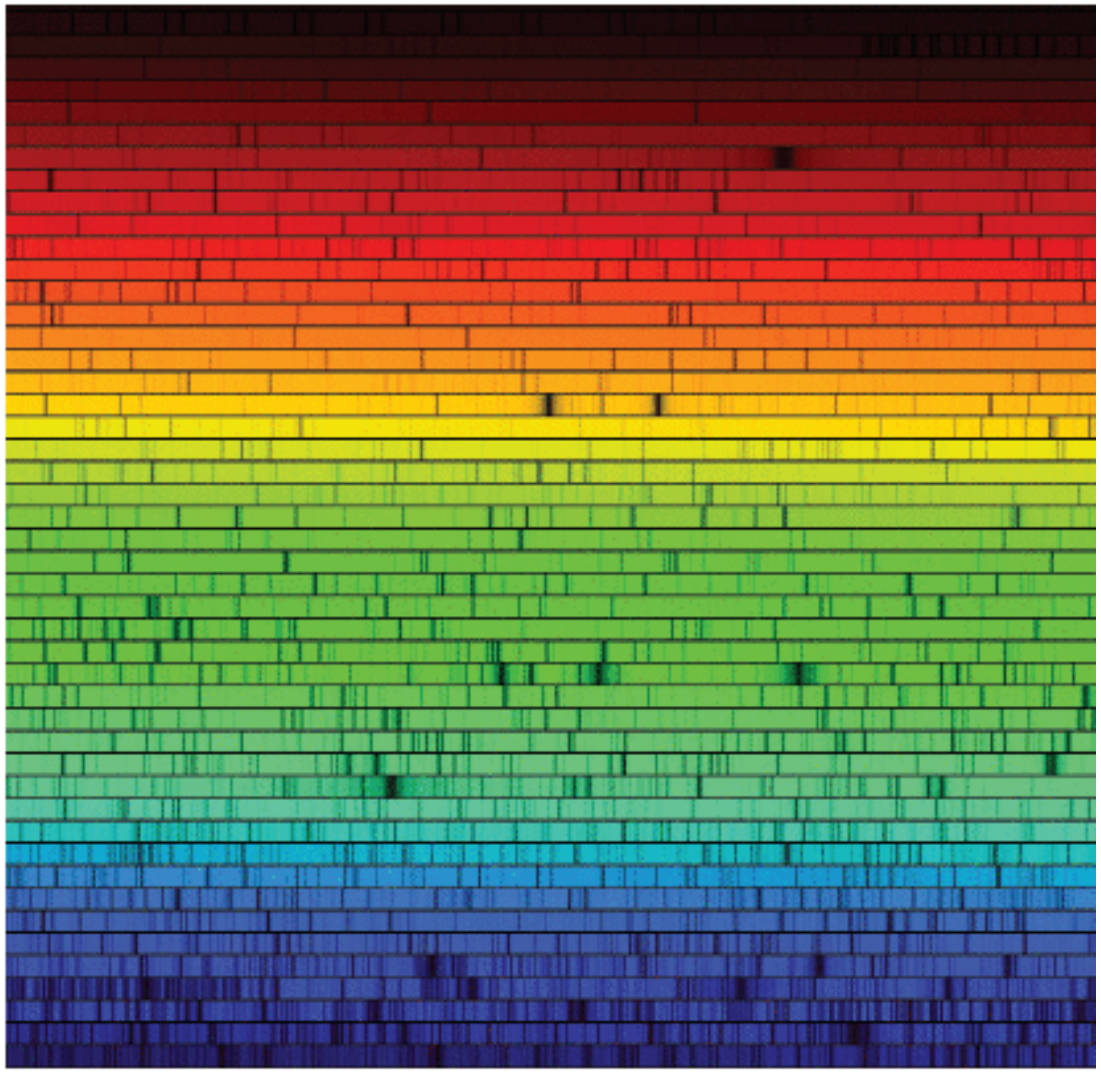
Electron-positron annihilation



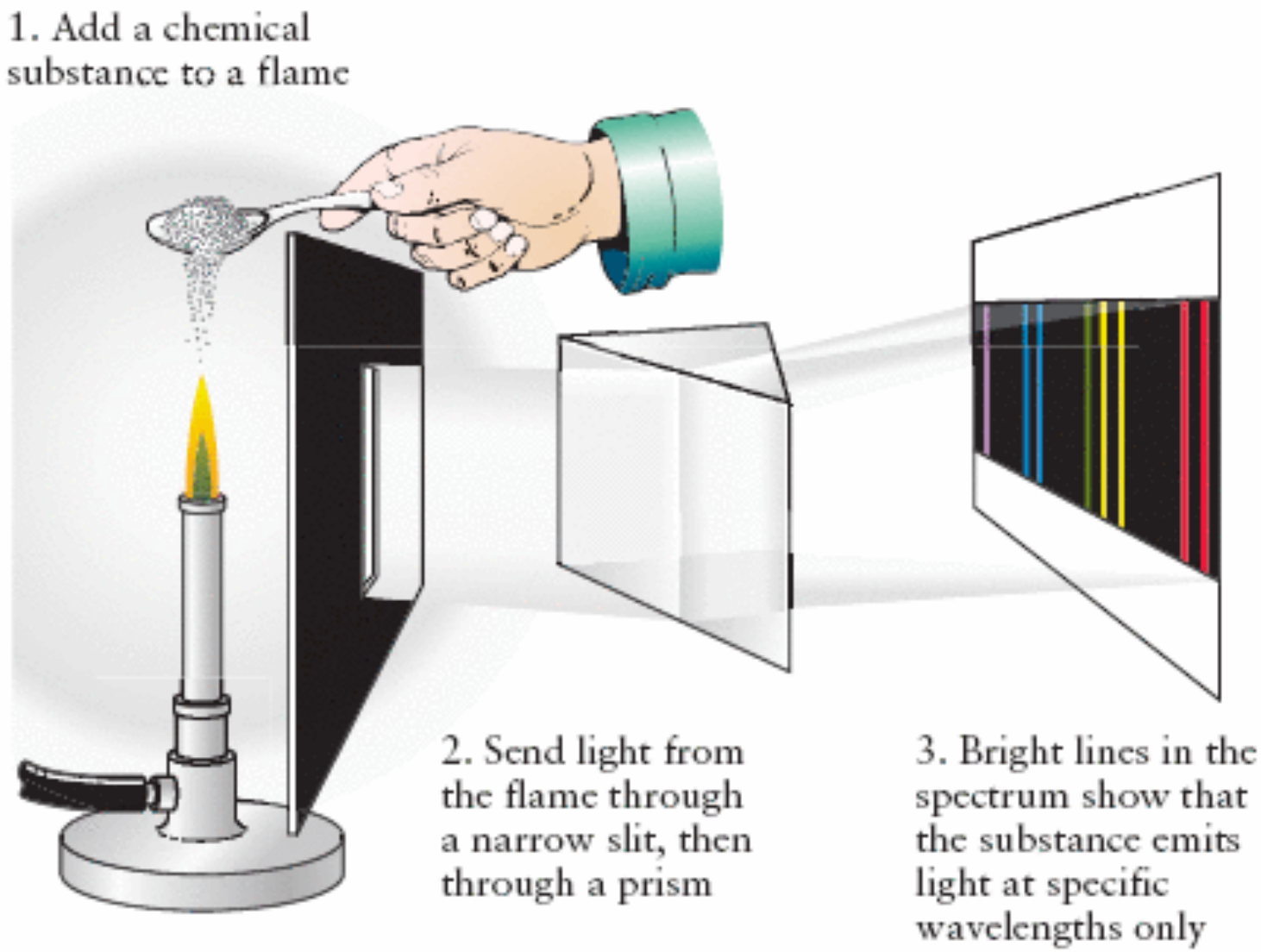
$$E_{photon} = 511\text{keV}, \lambda = ?$$

Spectral Lines in the Sun's Spectrum

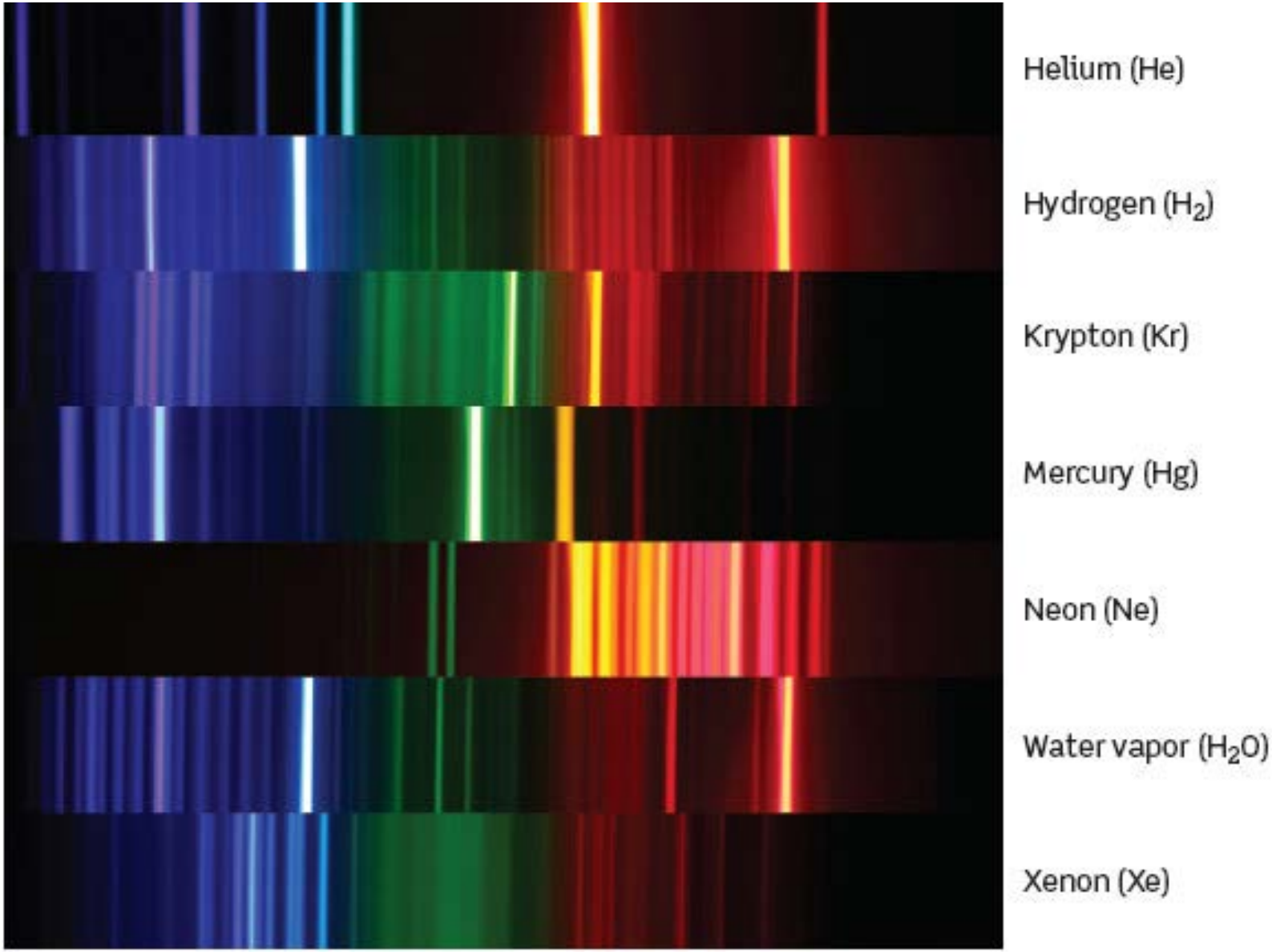
Numerous dark spectral lines are seen in this image of the **Sun's spectrum**. The spectrum is spread out so much that it had to be cut into segments to fit on this page.

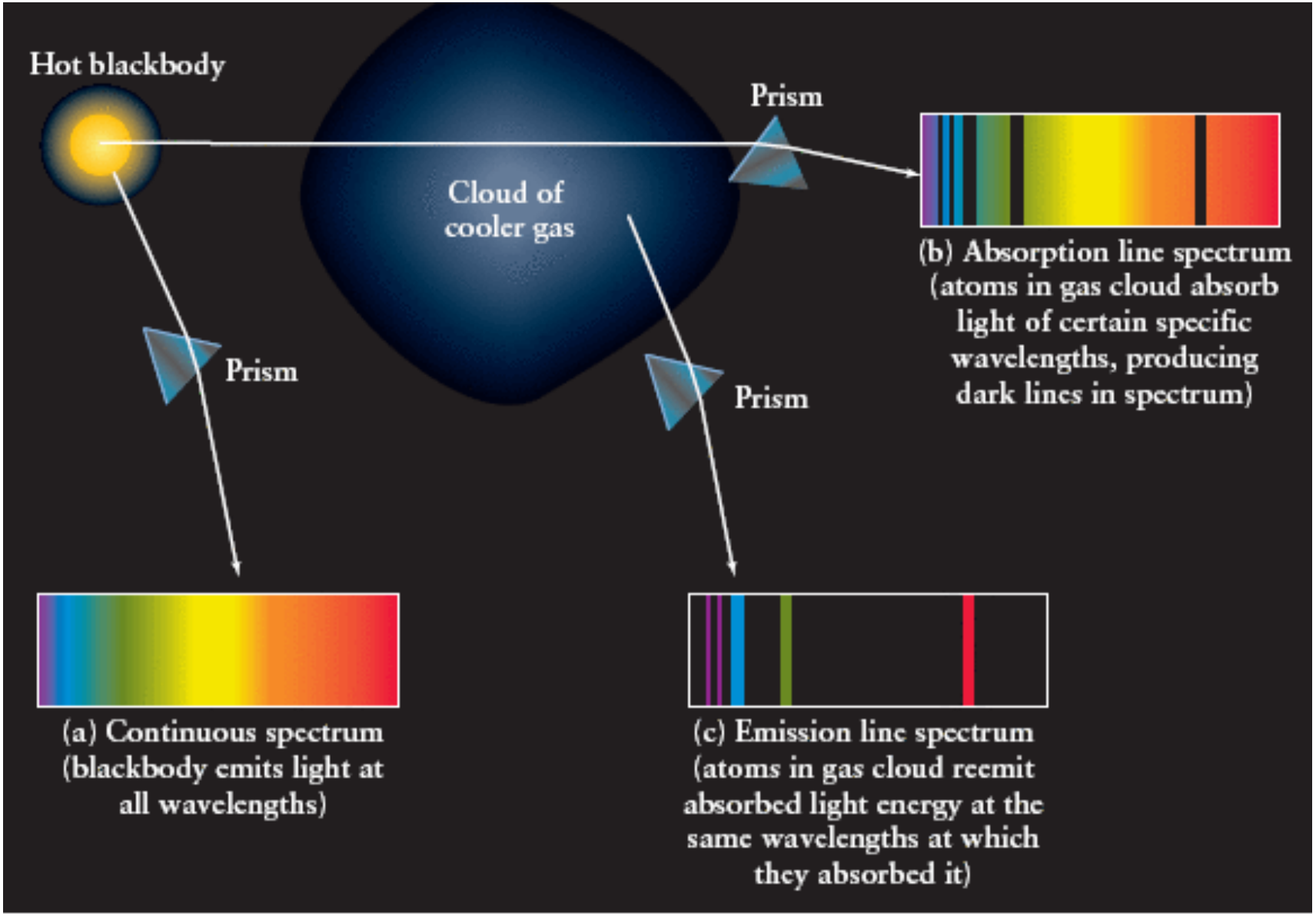


Emission Lines



Each Chemical Produces a Unique Pattern of Spectral Lines




Hot blackbody
Cloud of cooler gas
Prism
Prism
Prism
(b) Absorption line spectrum (atoms in gas cloud absorb light of certain specific wavelengths, producing dark lines in spectrum)
(a) Continuous spectrum (blackbody emits light at all wavelengths)
(c) Emission line spectrum (atoms in gas cloud reemit absorbed light energy at the same wavelengths at which they absorbed it)

Kirchoff's Laws

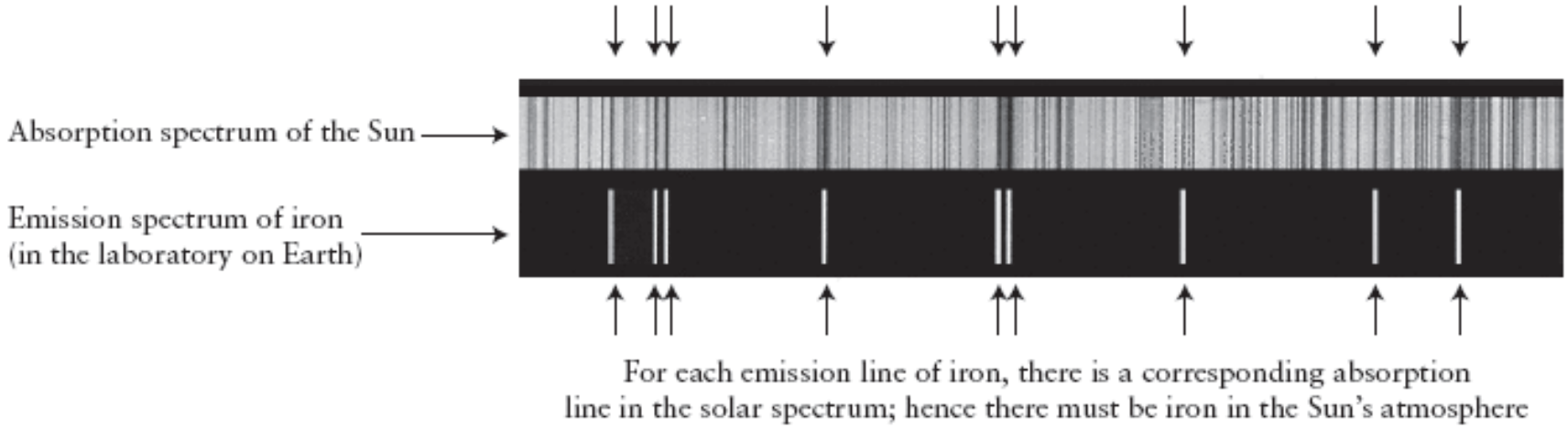
(a) A **hot opaque body** (such as a blackbody) or a hot dense gas produces a **continuous spectrum**.

(b) A **cooler transparent low density gas** placed in front of a source of a continuous spectrum produces **absorption lines.**

(c) **Emission lines** are produced from a **low density transparent gas.**

The field of spectroscopy was thus born. **Spectroscopy** is the systematic study of spectra and spectral lines.

By studying the spectral lines from an object we can learn about its chemical composition, the density and temperature of the gas, the velocity of the gas and more…

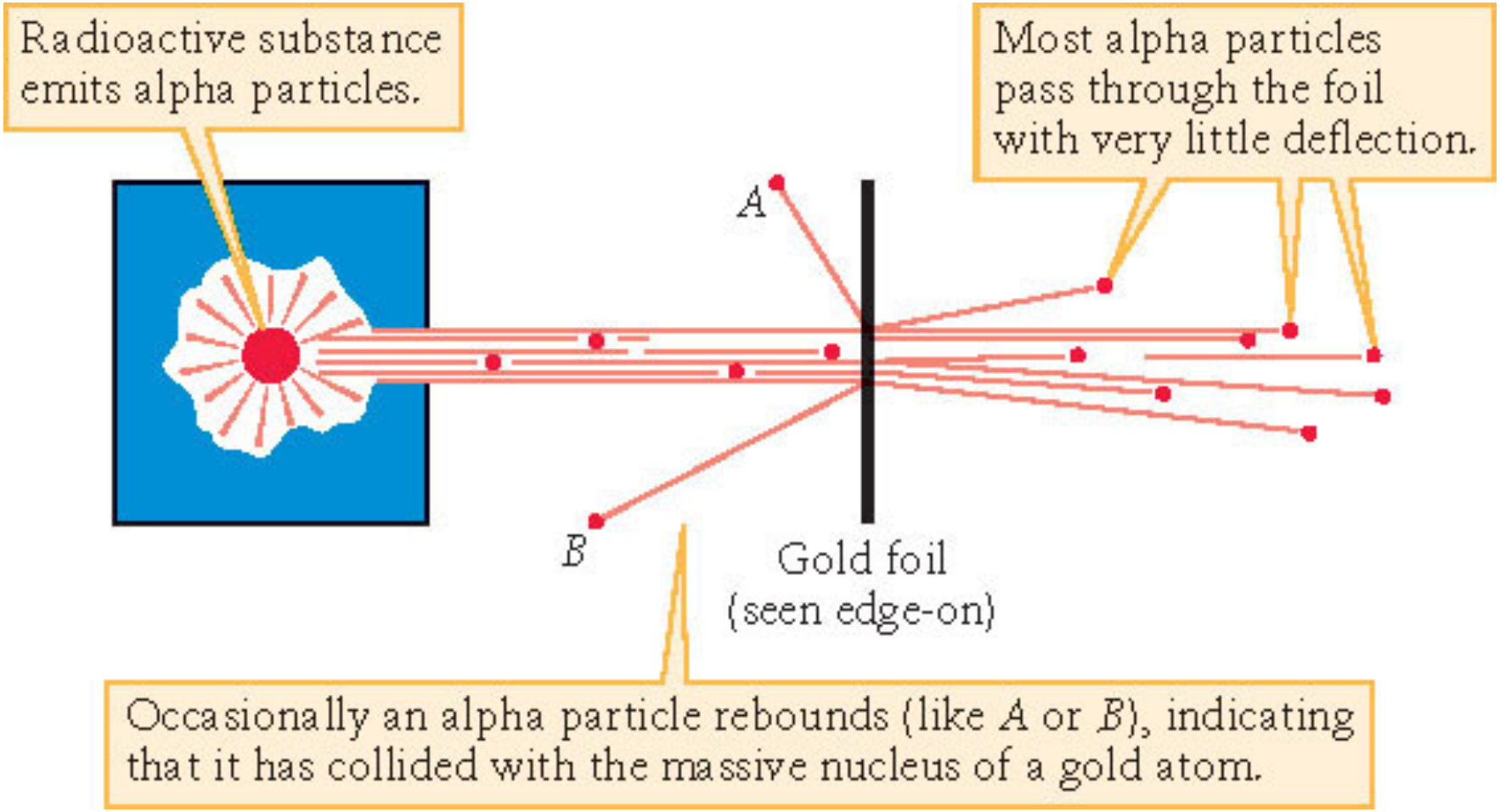


Iron in the Sun's Atmosphere: The upper part of this figure is a portion of the Sun's spectrum at violet wavelengths, showing numerous dark absorption lines. The lower part of the figure is a corresponding portion of the emission line spectrum of vaporized iron. The iron lines coincide with some of the solar lines, which proves that there is some iron (albeit a relatively small amount) in the Sun's atmosphere.

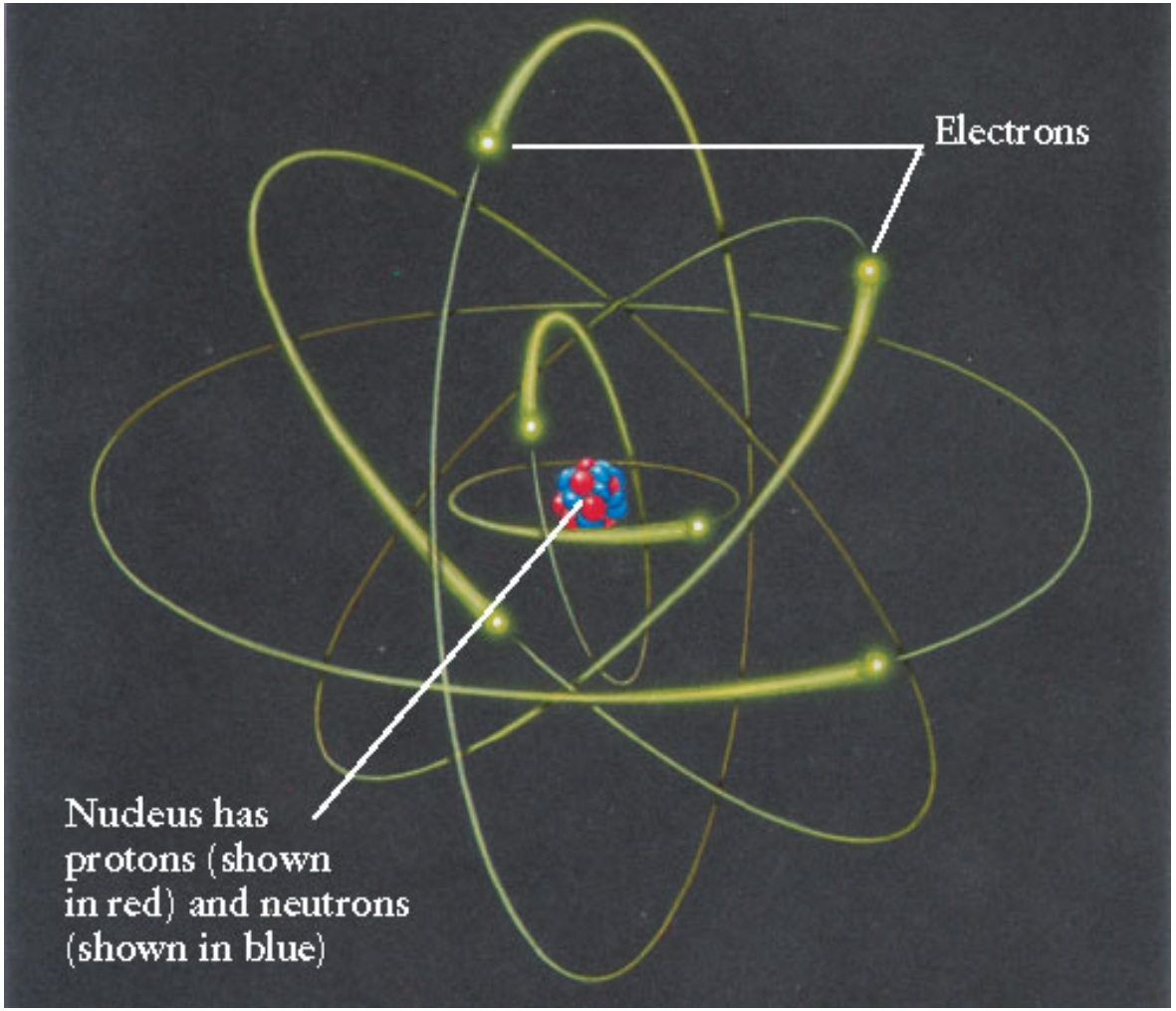
Hot stars within the nebular **NGC 346 (a star forming region in SMC)** emit high energy ultraviolet photons that are absorbed by the surrounding gas to heat it up to high temperatures.

What is remarkable is that the emission spectrum produced by heated hydrogen gas on Earth contains the same 656 nm red line as the one found in the spectrum of NGC 346 located 210,000 light years away.

Rutherford's Experiment

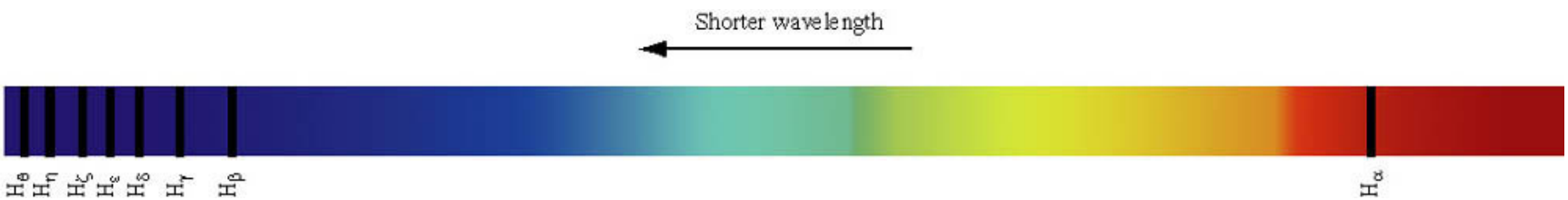


Rutherford's Model of the Atom



The number of protons in the nucleus of an atom determines the **element** that the atom represents.

Balmer Lines of Hydrogen

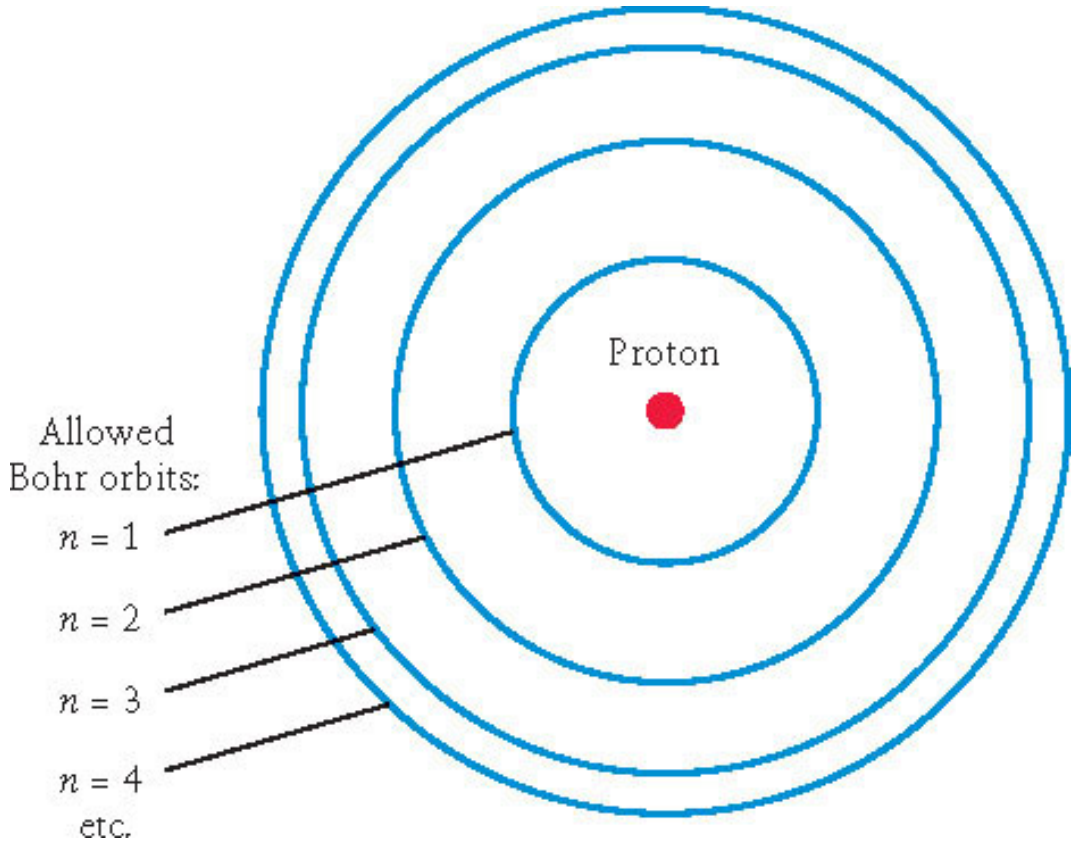


$$\frac{1}{\lambda} = R\left(\frac{1}{4} - \frac{1}{n^2}\right), \text{ for } n \geq 3$$

R is the Rydberg constant

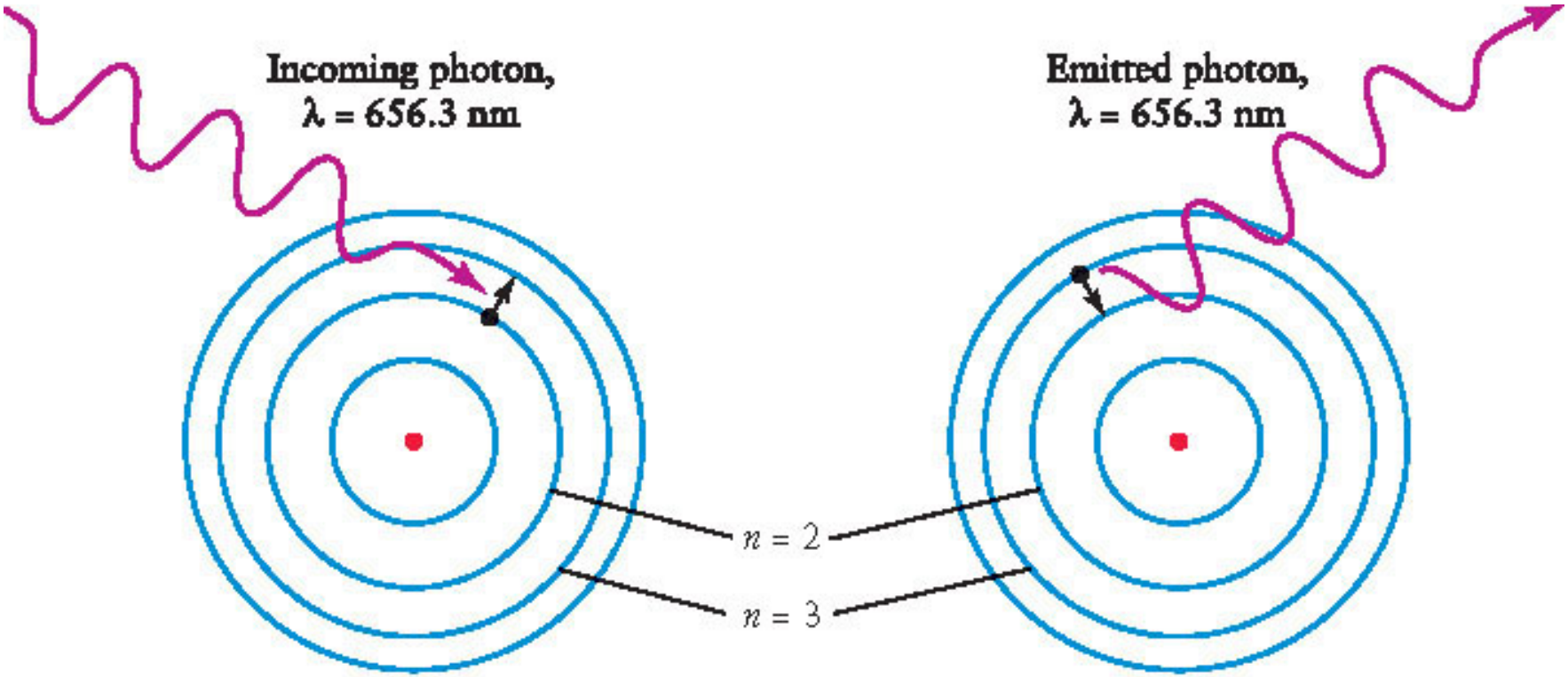
$$R = 1.097 \times 10^7 \text{m}^{-1}$$

Niels Bohr's Model for the Atom



$$\frac{1}{\lambda} = R\left(\frac{1}{n_{in}^{2}} - \frac{1}{n_{out}^{2}}\right)$$

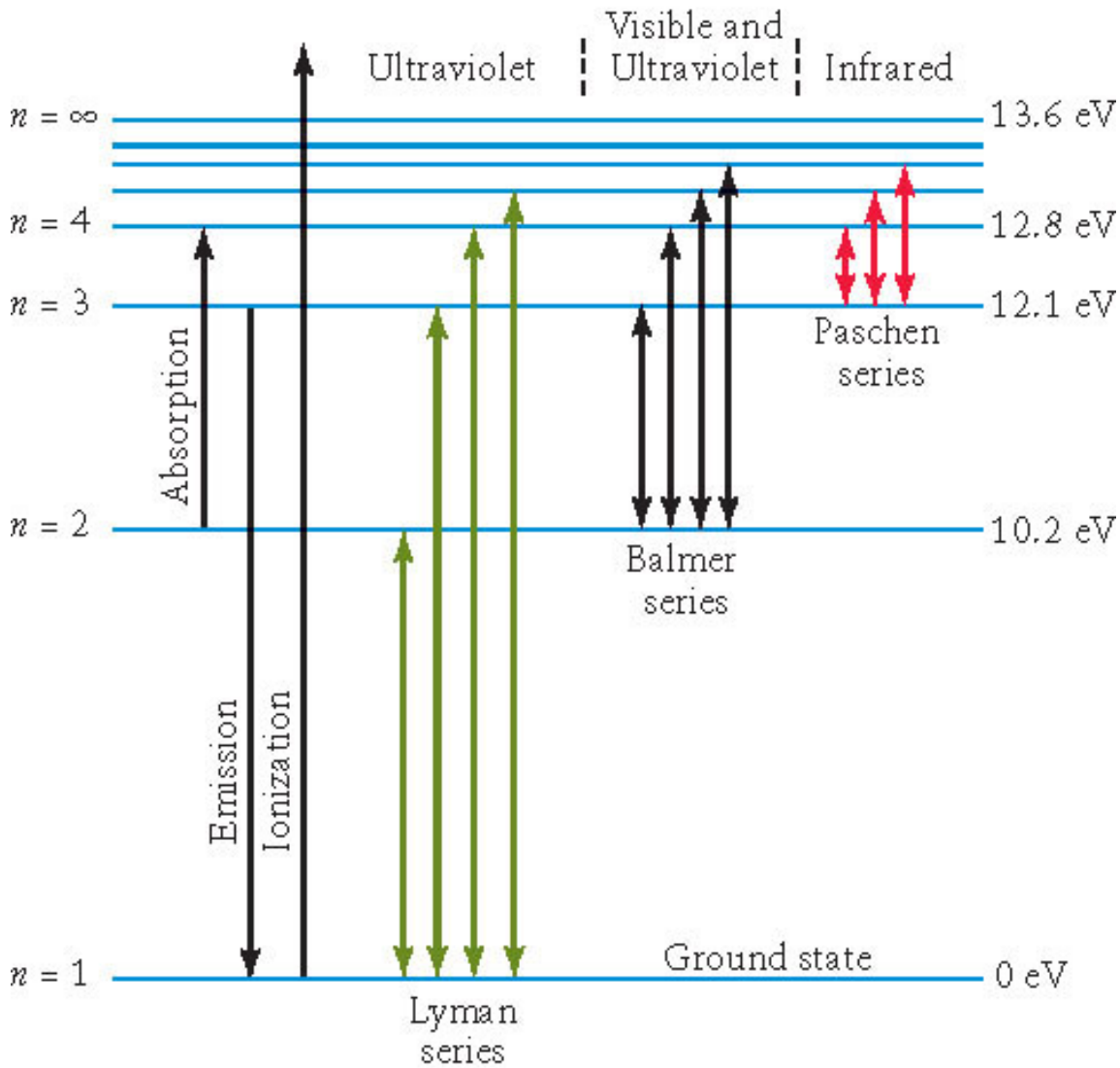
Niels Bohr's Model for the Atom



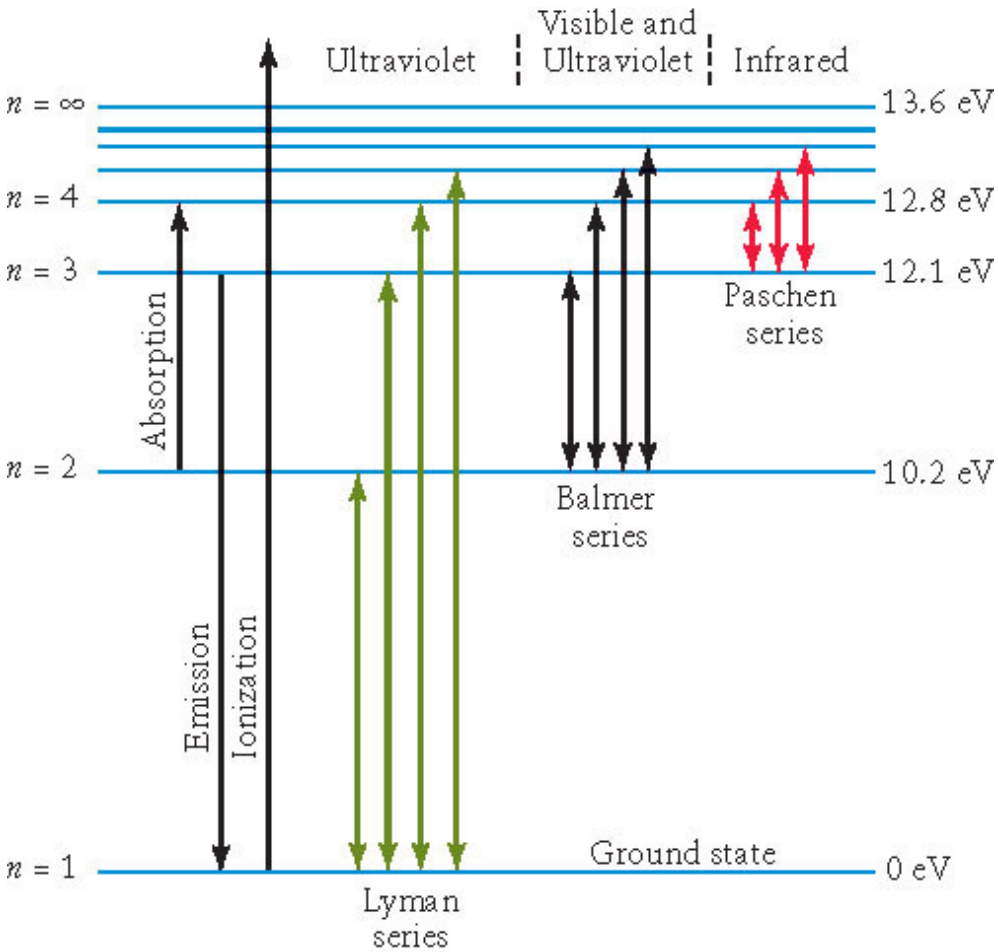
(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the n = 2 orbit up the n = 3 orbit

(b) Electron falls from the n = 3 orbit to the n = 2 orbit; energy lost by atom goes into emitting a 656.3-nm photon

Niels Bohr's Model for the Atom



Niels Bohr's Model for the Atom



1. H_δ Wavelength ?

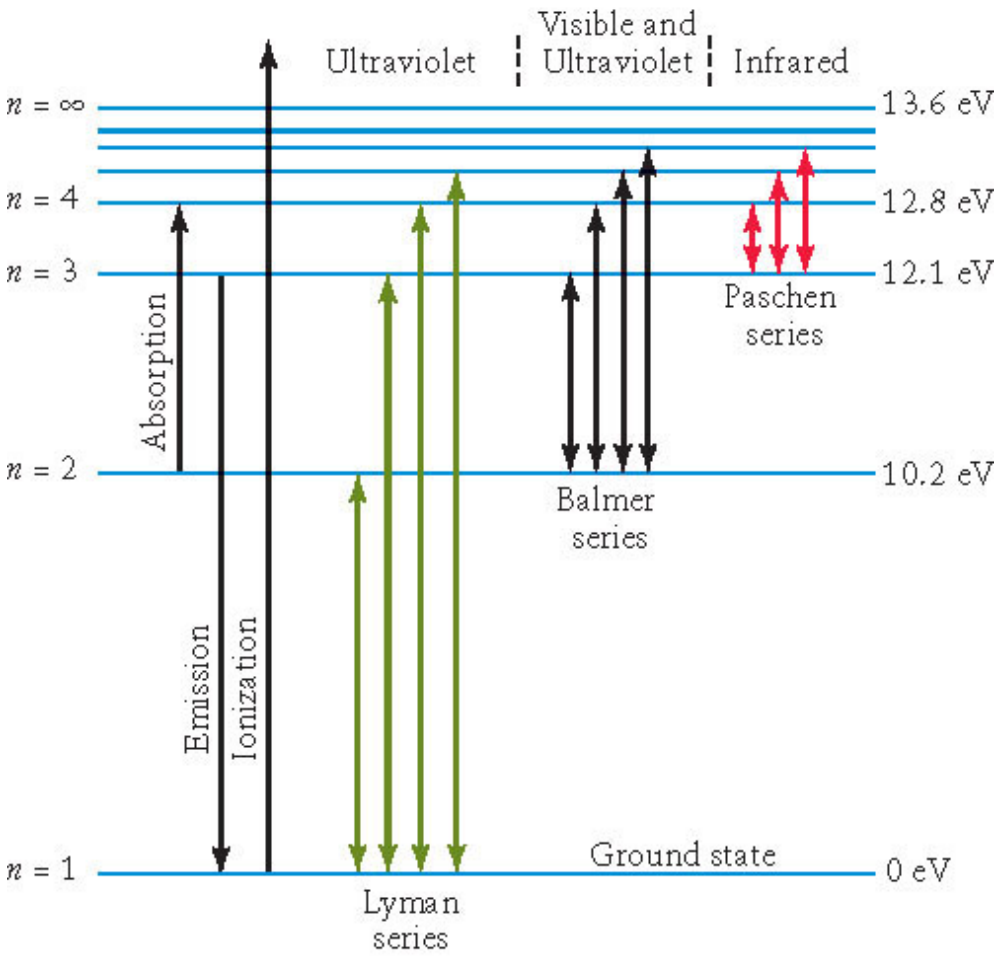
(hint $R = 1.097 \times 10^7 m^{-1}$)

2. What lines in the Balmer series fall in the UV ?

3. What are the energy ranges for the Lyman, Balmer and Paschen Series?

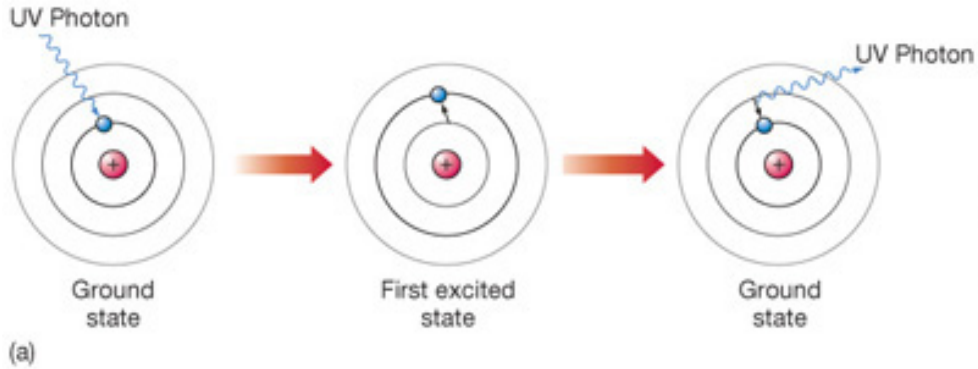
$$\frac{1}{\lambda} = R\left(\frac{1}{n_{in}^{\ 2}} - \frac{1}{n_{out}^{\ 2}}\right)$$

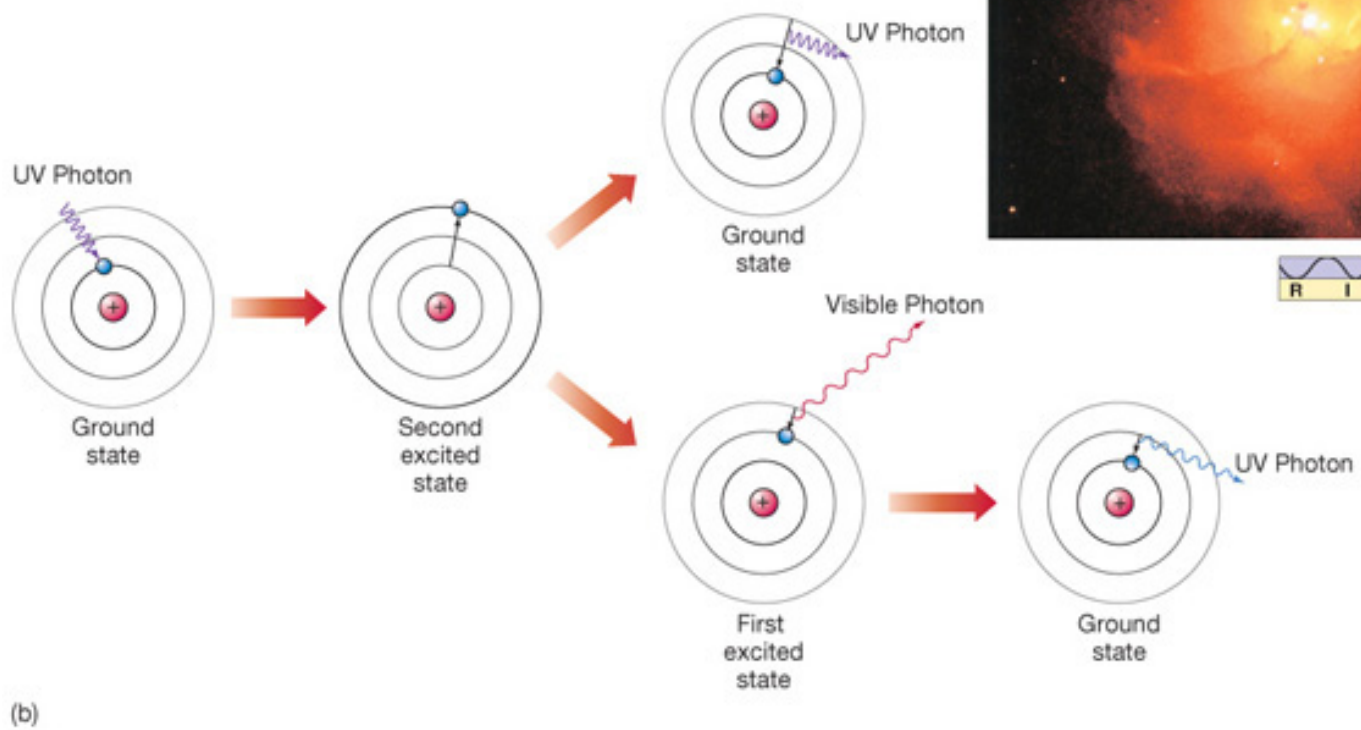
Niels Bohr's Model for the Atom

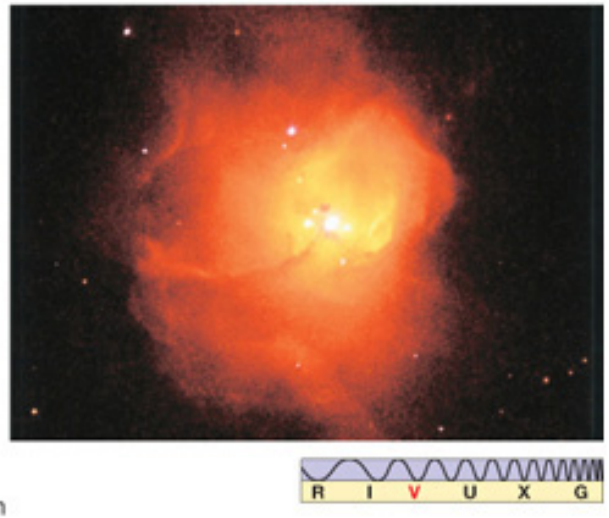


1. A Hydrogen atom in the ground state absorbs a L_β photon. What photon might that atom emit when de-excited.

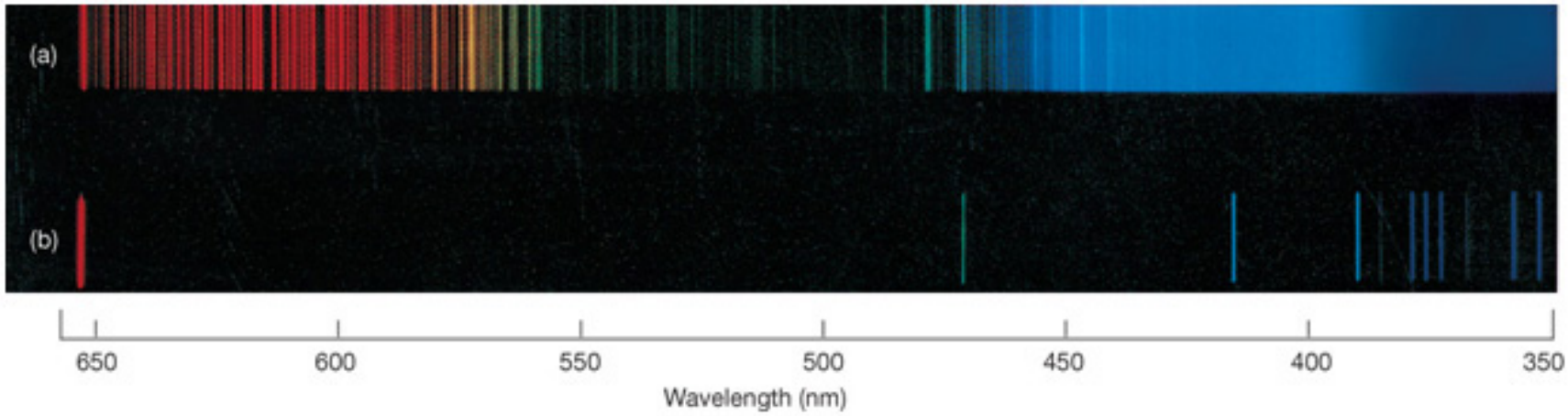
Atomic Excitation



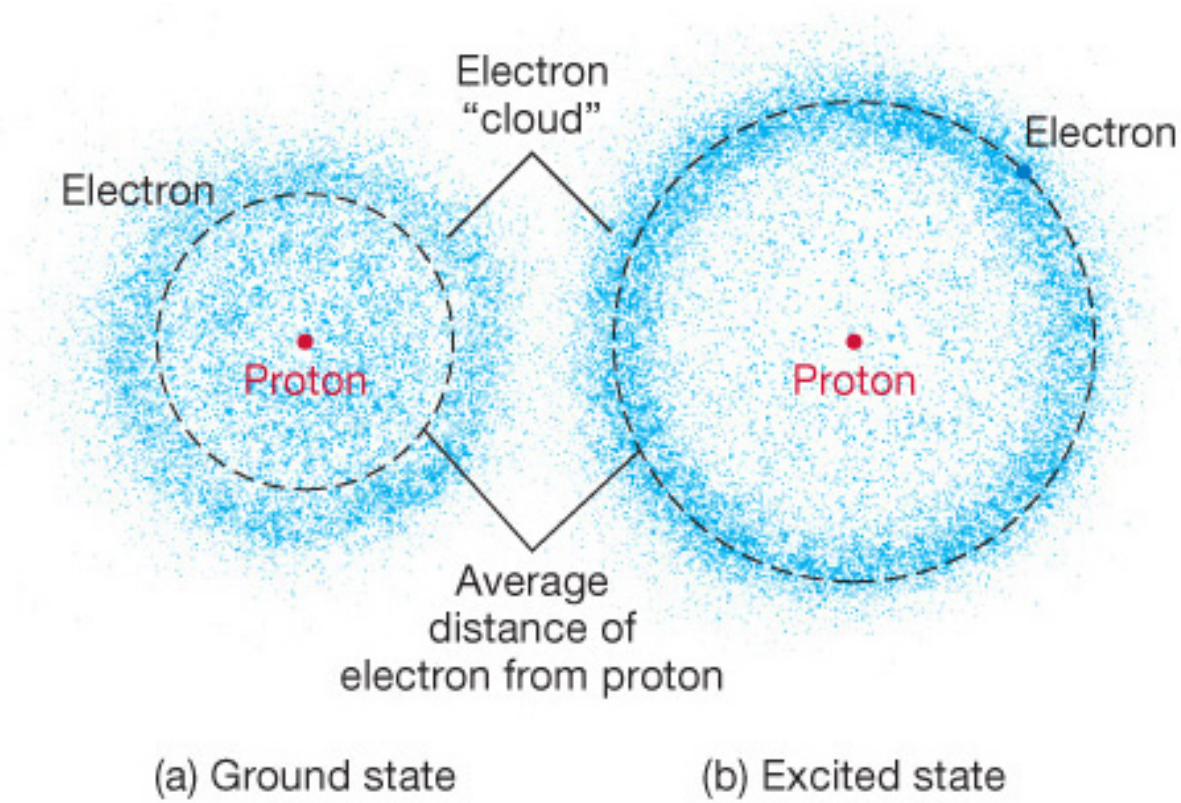




Hydrogen Spectra



Modern Model for the Atom



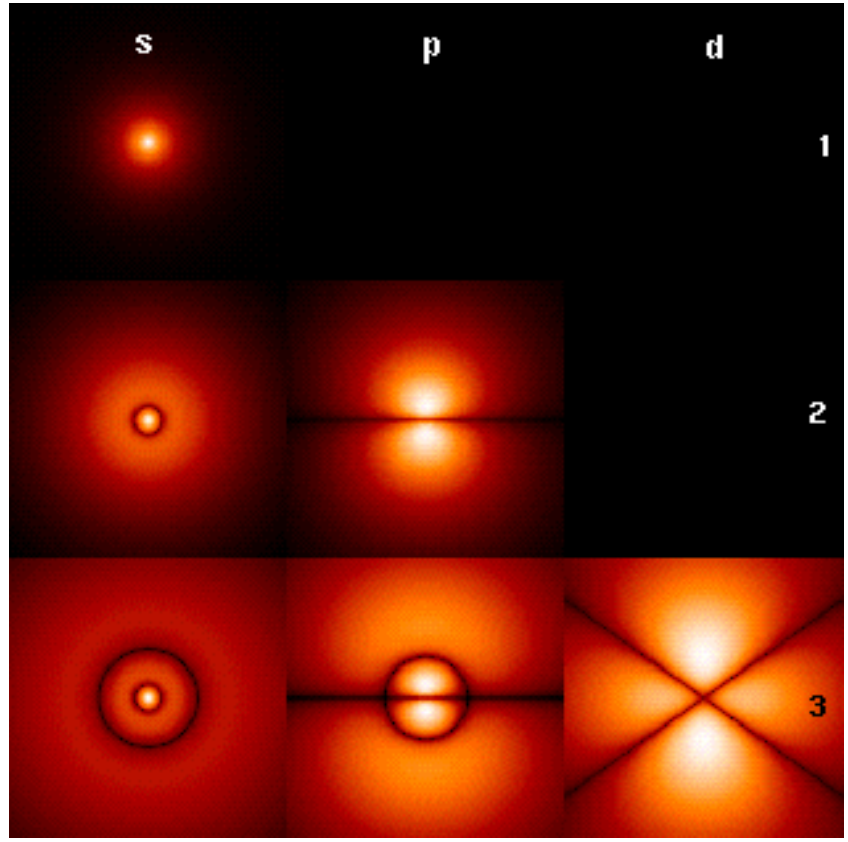
Modern Model for the Atom

$$E_{nj} = -\frac{13.6eV}{n^2}\left(1 + \frac{\alpha^2}{n^2}\left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4}\right)\right)$$

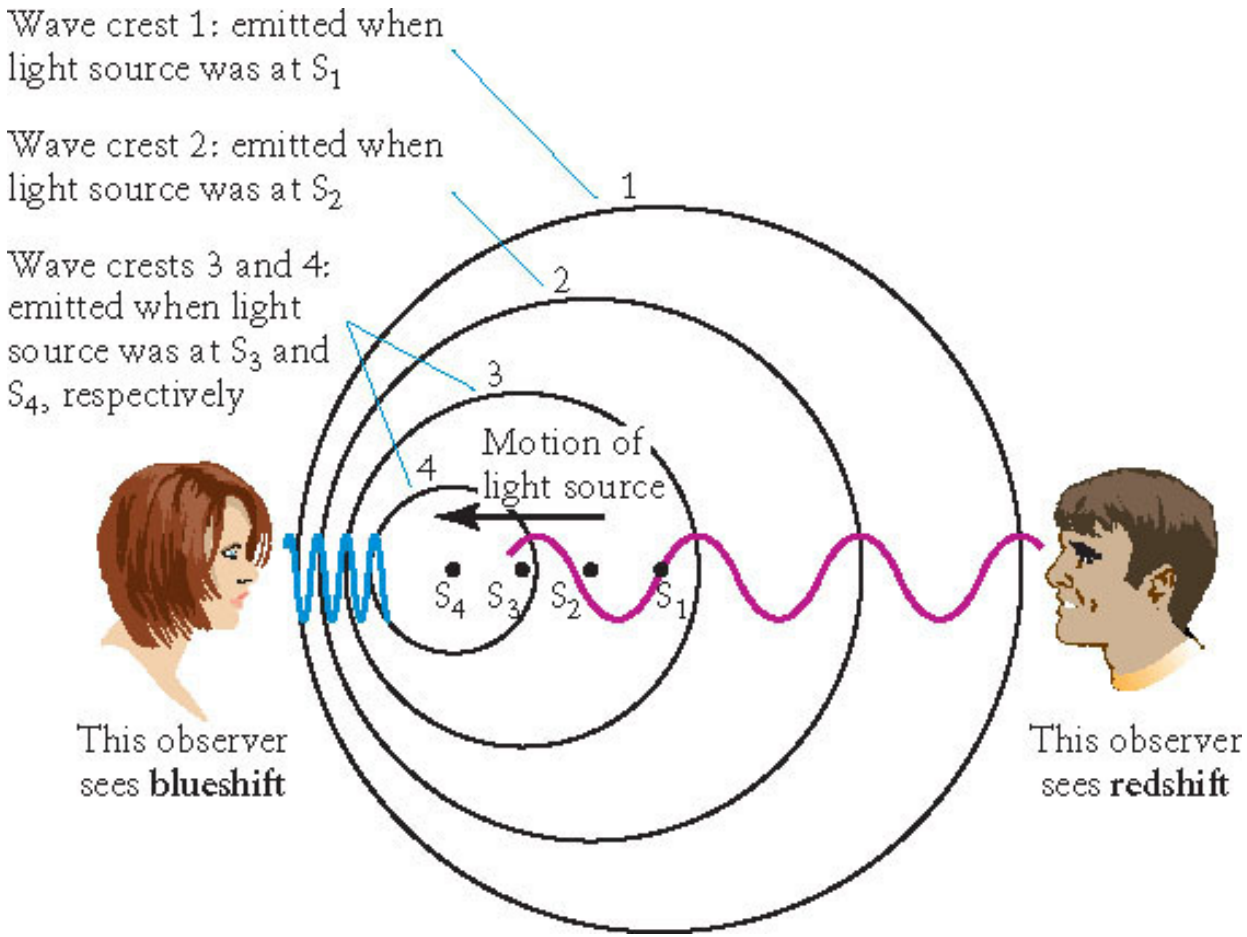
where,

$\alpha \approx 1/137$ is the fine - structure constant

j is a number which is the total angular momentum eigenvalue, i.e. $l \pm 1/2$ depending on the direction of the electron spin.

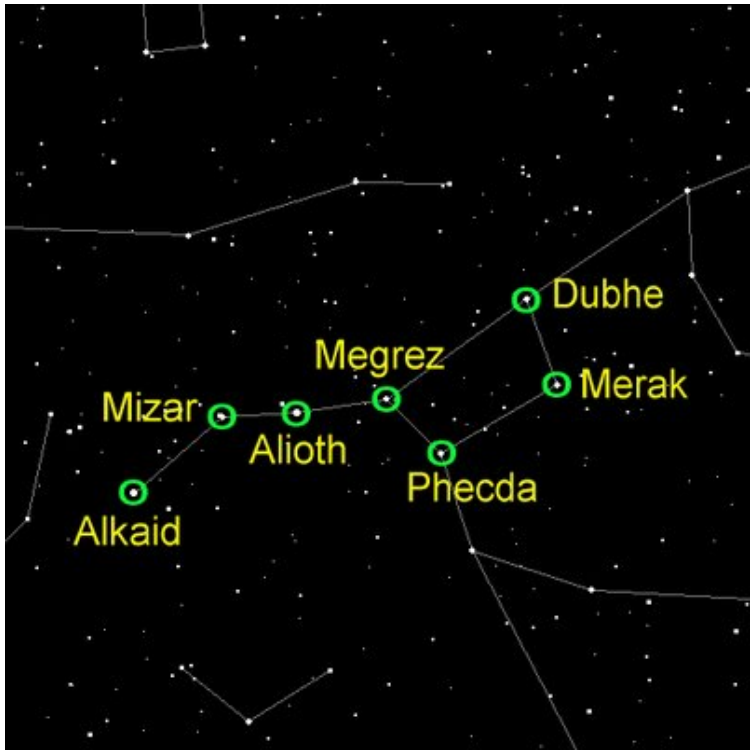


Doppler Effect



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

Doppler Effect



Megrez:

H_β observed = 486.112nm

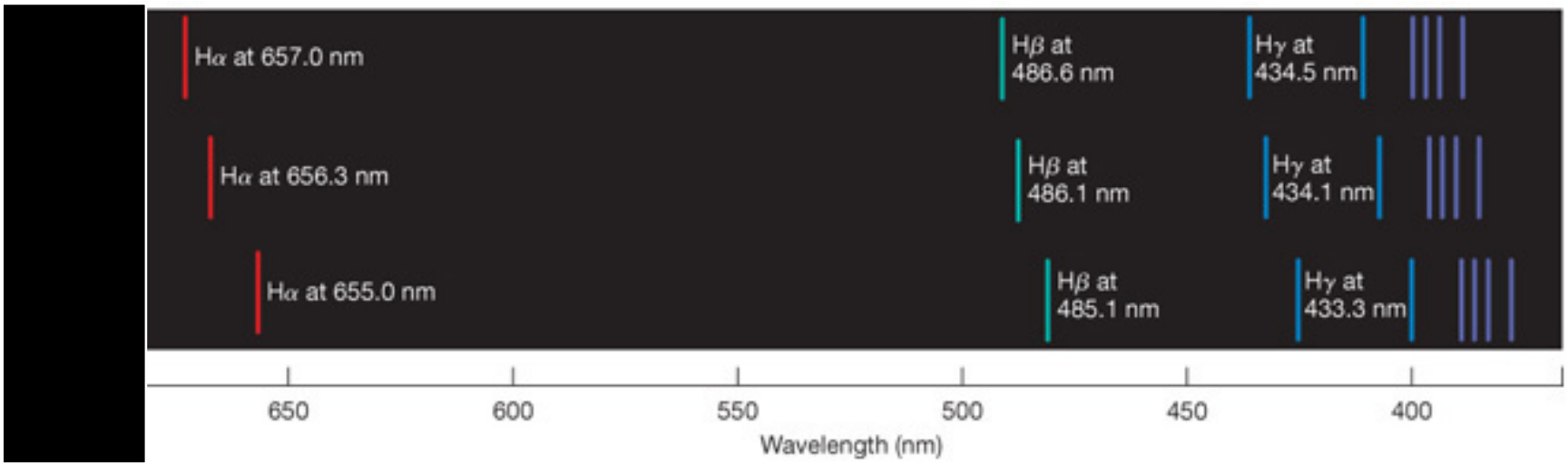
H_β laboratory = 486.133nm

Is the star coming towards us or moving away?

At what speed?

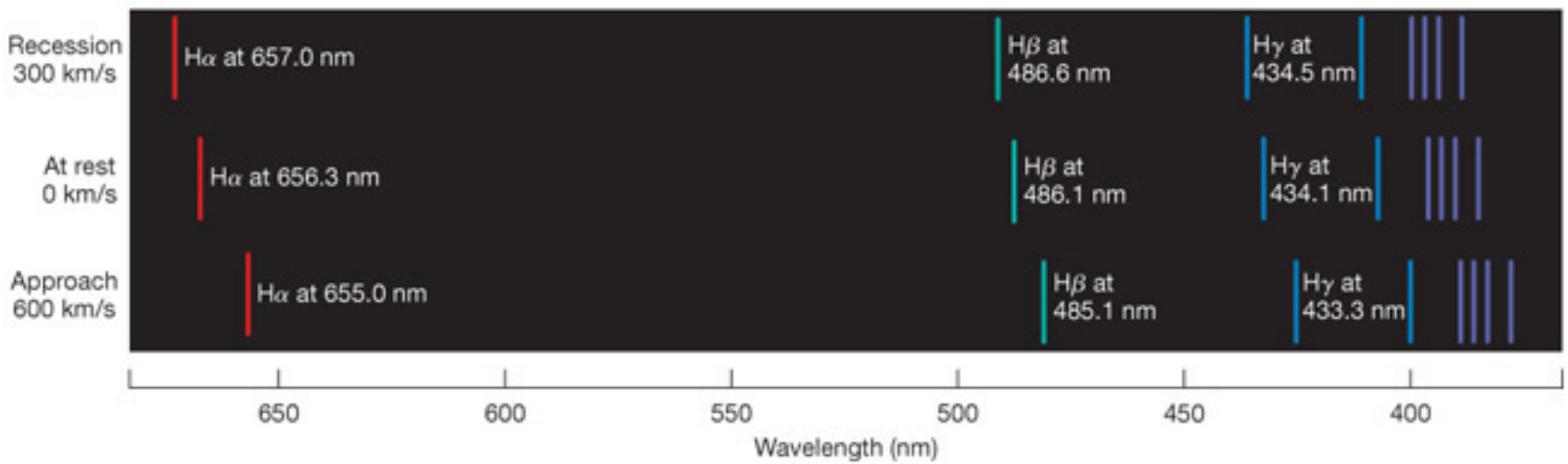
$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

Doppler Shift



H_α (Rest Wavelength) = 656.3nm

Doppler Shift



H_α (Rest Wavelength) = 656.3nm

Redshift

Gravitational Redshift:

$$\frac{\nu_{obs}}{\nu_{em}} = \frac{\left(1-2M/r_{em}\right)^{1/2}}{\left(1-2M/r_{obs}\right)^{1/2}}$$

Doppler Effect (non-relativistic):

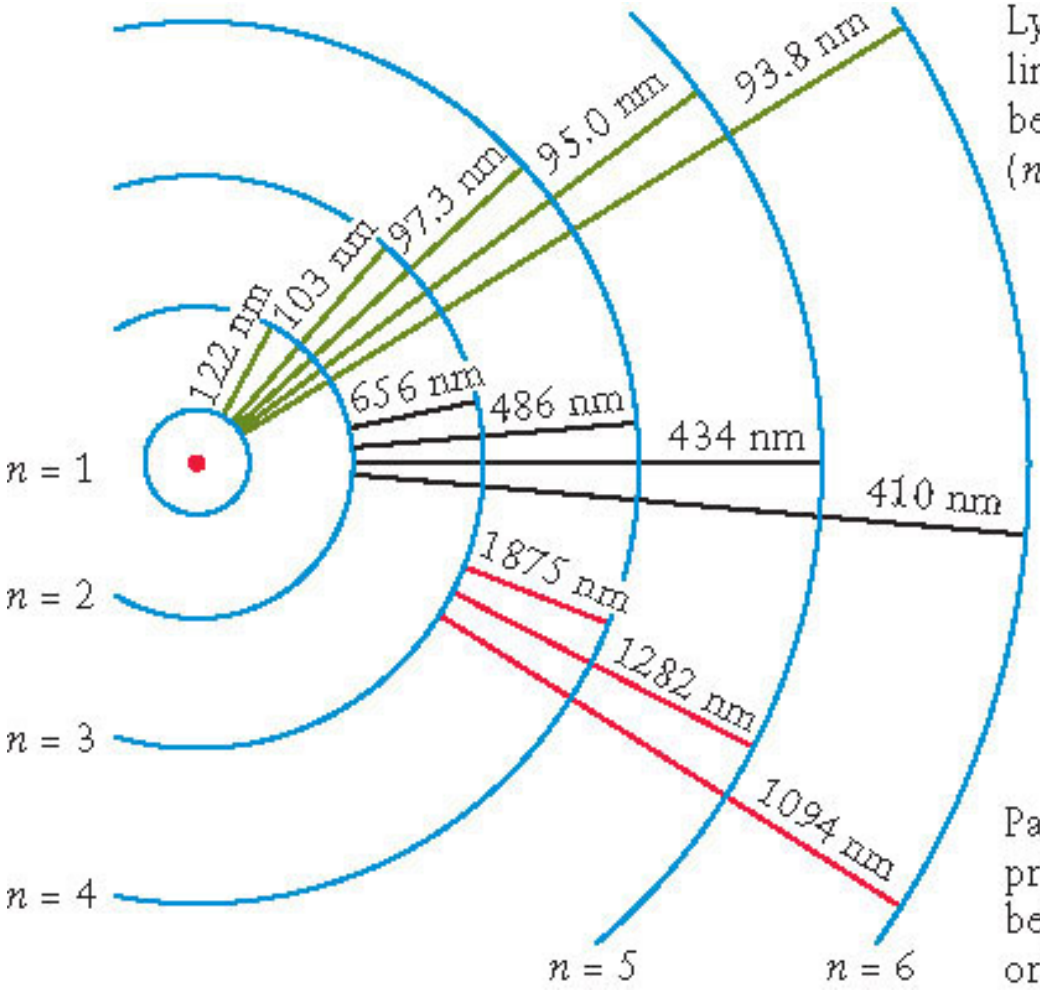
$$\lambda_{obs} = \lambda_{em}\left(1-\frac{u}{c}\cos\theta\right) \longrightarrow \frac{\lambda_{obs}-\lambda_{em}}{\lambda_{em}} = \frac{v_r}{c}$$

Doppler Effect (Relativistic):

$$\lambda_{obs} = \lambda_{em}\gamma\left(1-\frac{u}{c}\cos\theta\right) \longrightarrow \frac{\lambda_{obs}-\lambda_{em}}{\lambda_{em}} = \frac{\lambda_{em}\gamma\left(1-\frac{u}{c}\cos\theta\right)-\lambda_{em}}{\lambda_{em}} \longrightarrow \frac{\lambda_{obs}-\lambda_{em}}{\lambda_{em}} = \gamma\left(1-\frac{v_r}{c}\right)-1$$

Cosmological redshift due to expansion of the Universe:

$$\frac{\lambda_{obs}-\lambda_{em}}{\lambda_{em}} = z$$



Lyman series (ultraviolet) of spectral lines: produced by electron transitions between the $n = 1$ orbit and higher orbits ($n = 2, 3, 4, \ldots$)

Balmer series (visible and ultraviolet) of spectral lines: produced by electron transitions between the $n = 2$ orbit and higher orbits ($n = 3, 4, 5, \ldots$)

Paschen series (infrared) of spectral lines: produced by electron transitions between the $n = 3$ orbit and higher orbits ($n = 4, 5, 6, \ldots$)

Astro News

Particles Faster Than the Speed of Light? Not So Fast, Some Say

Experiments

A group of physicists from Italy claimed they had observed the subatomic particles called neutrinos traveling faster than the speed of light.

Neutrinos produced at CERN and beamed to a facility in Italy about 450 miles away, arrived about 58 billionths of a second sooner than would a light beam.

Consequences:
A neutrino or anything else that went faster than the speed of light could go backward in time.

Problems with Experiment Discovered:
It turns out connectors in the timing system were faulty resulting in the erroneous measurement. Einstein's theory of special relativity is still valid.

neutrino song

References:

New York Times Science Section

http://www.nytimes.com

Scientists Report Second Sighting of Faster-Than-Light Neutrinos
By DENNIS OVERBYE