The Nature of Light

Chapter Five

ASTR 111 – 003 **Fall 2007**
Lecture 05 Oct. 01, 2007

Introduction To Modern Astronomy I: Solar System

Introducing Astronomy
(chap. 1-6)

Planets and Moons
(chap. 7-15)

Chap. 16: Our Sun
Chap. 28: Search for
Extraterrestrial life

Ch1: Astronomy and the Universe
Ch2: Knowing the Heavens
Ch3: Eclipses and
the Motion of the Moon
Ch4: Gravitation and
the Waltz of the Planets

Ch5: The Nature of Light

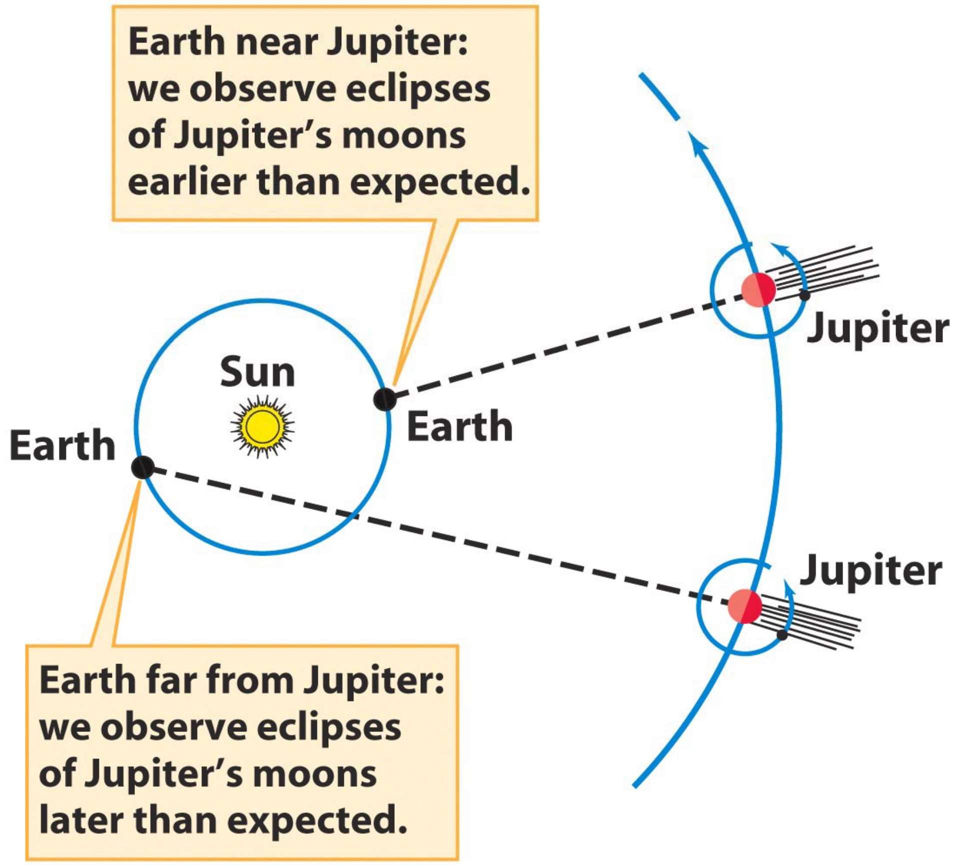
Ch6: Optics and Telescope

Speed of Light

- The speed of light in the vacuum
  - **C = 299,792.458 km/s, or**
  - **C = 3.00 X 10^5 km/s = 3.00 X 10^8 m/s**
- It takes the light 500 seconds traveling 1 AU.
- It takes the light 4.2 years to the nearest star Proxima Centauri
- Milky way diameter ~ 100,000 lys

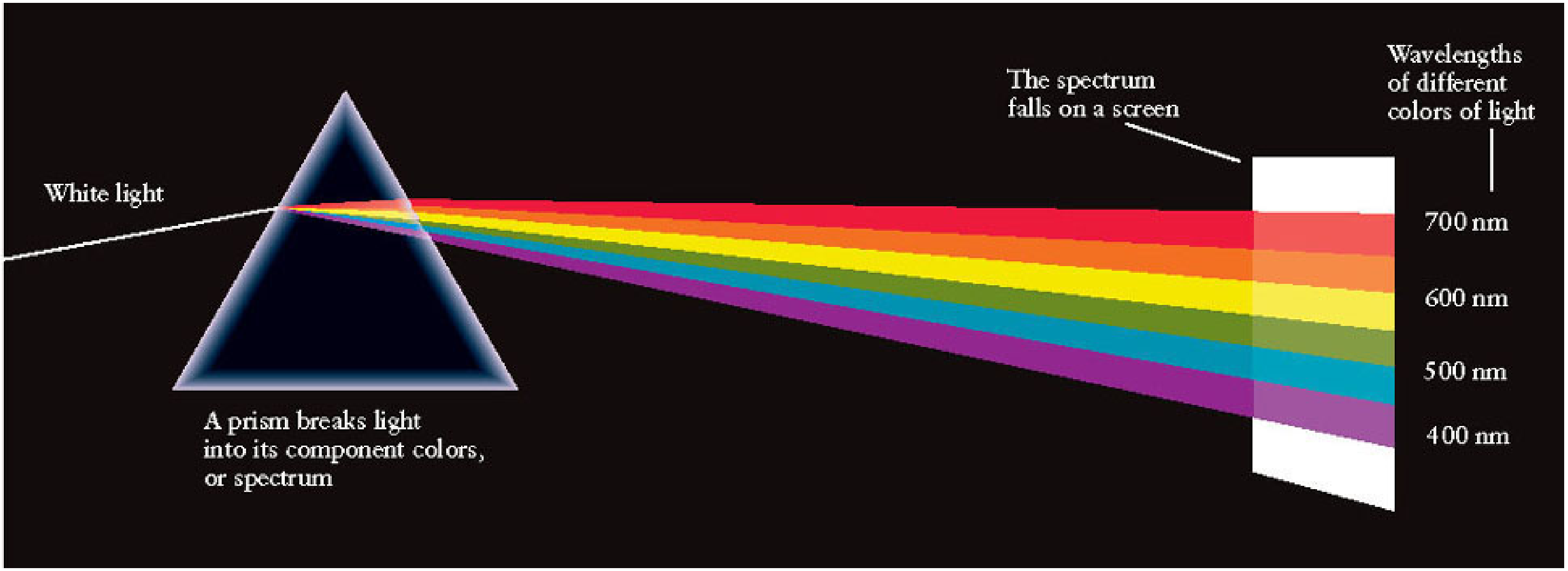
Speed of Light

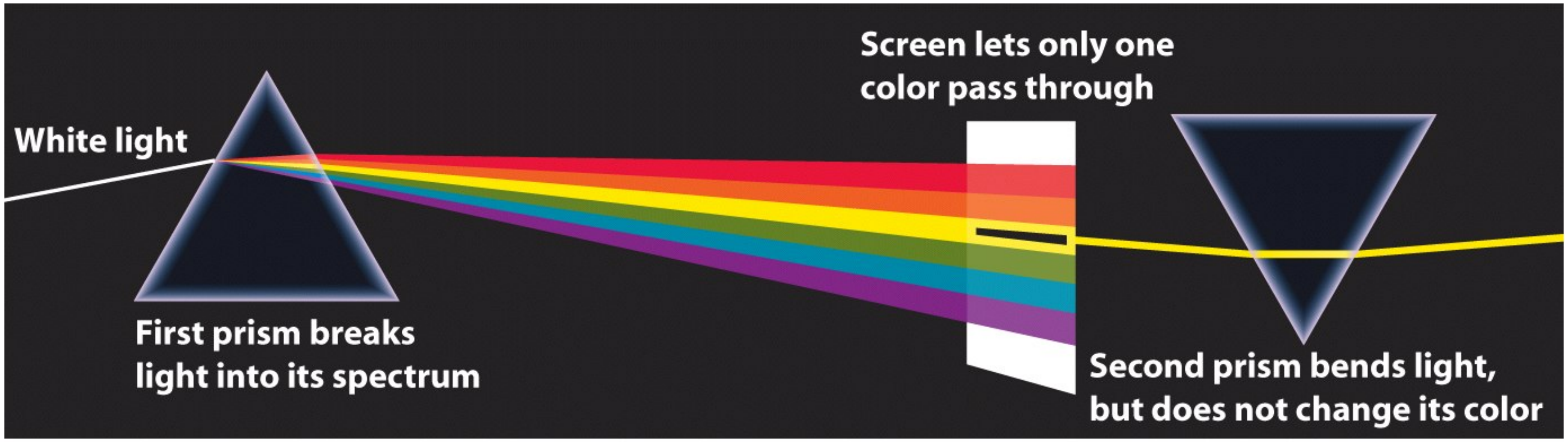
- In 1676, Danish astronomer Olaus Rømer discovered that the exact time of eclipses of Jupiter's moons depended on the distance of Jupiter to Earth
- The variation is about 16.6 minutes (or 1000 seconds)
- This happens because it takes varying times for light to travel the varying distance between Earth and Jupiter (varying by up to 2 AU)



Electromagnetic Waves

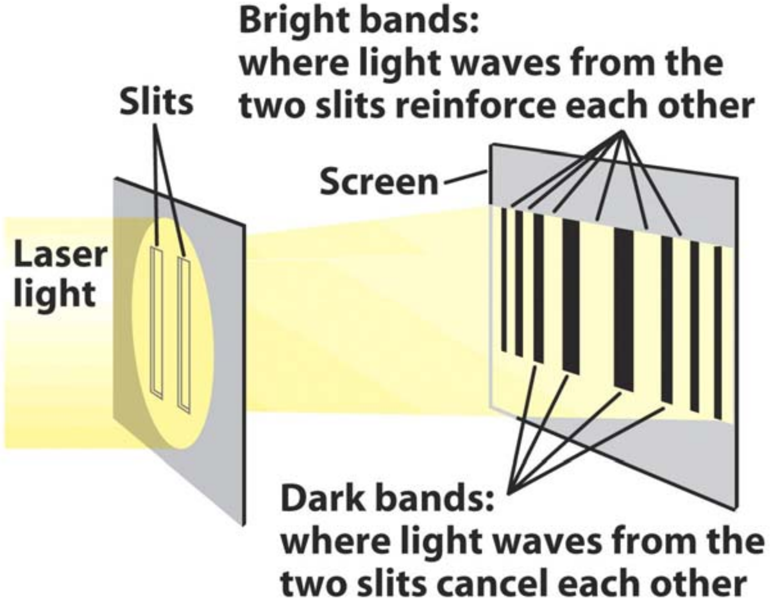
- Newton (in 1670) found that the white light from the Sun is composed of light of **different color, or spectrum**

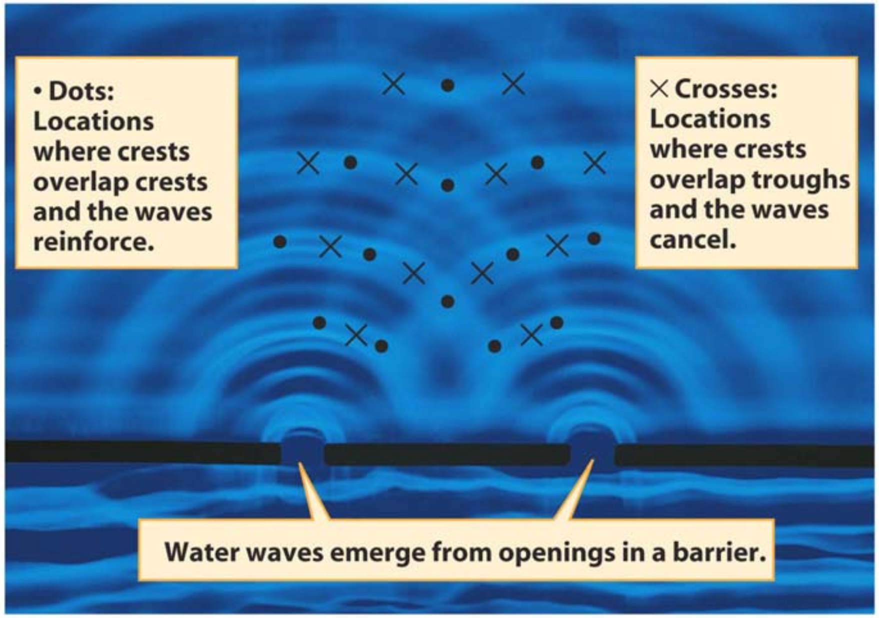




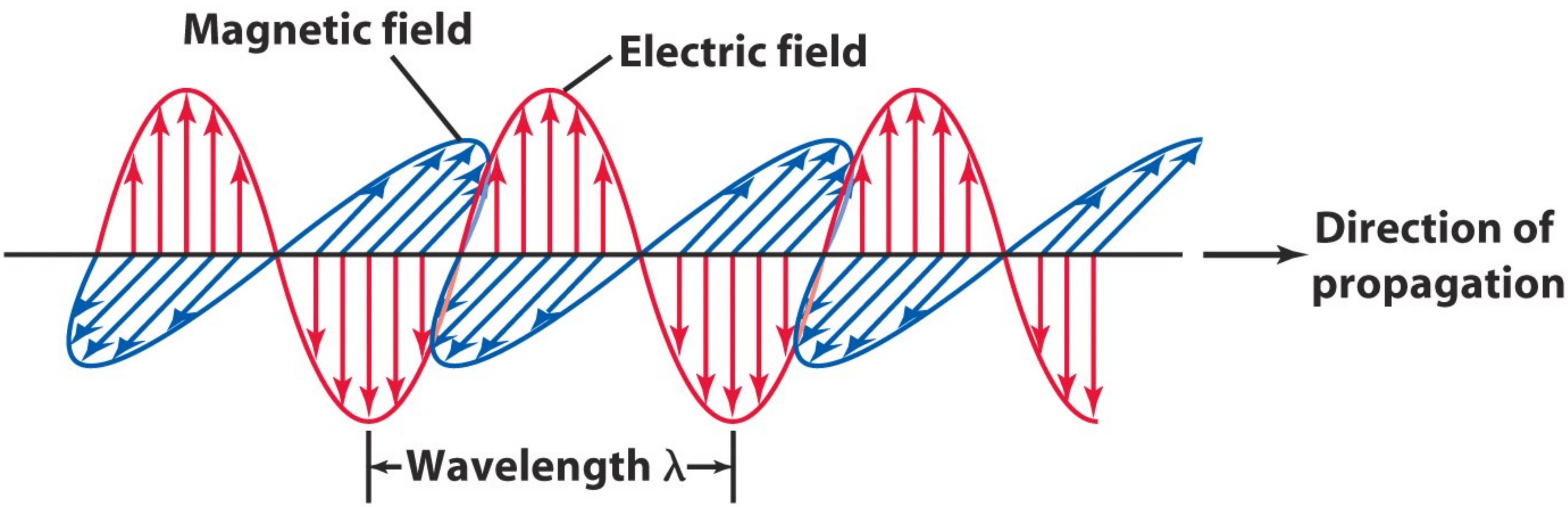
Electromagnetic Waves

- **Young's Double-Slit Experiment** (in 1801) indicated light behaved as a wave
- The alternating black and bright bands appearing on the screen is analogous to the water waves that pass through a barrier with two openings



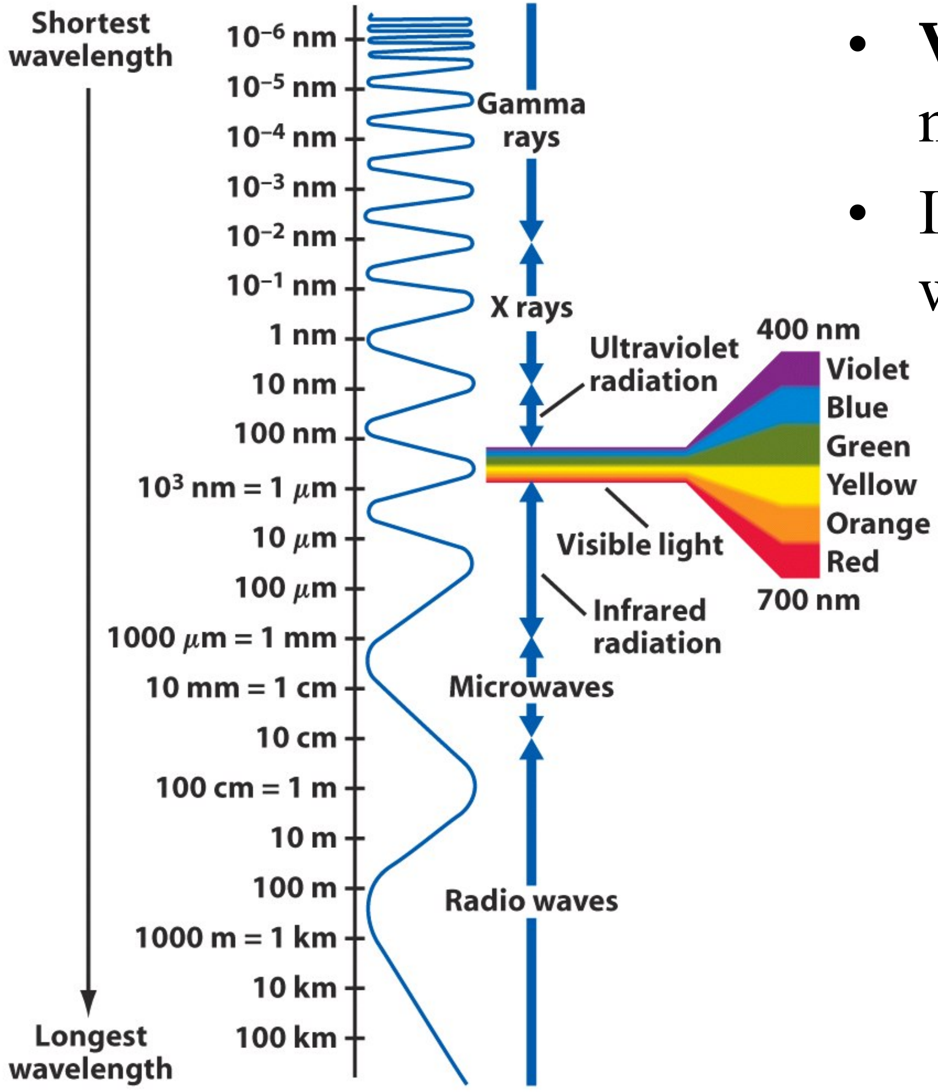


Electromagnetic Waves



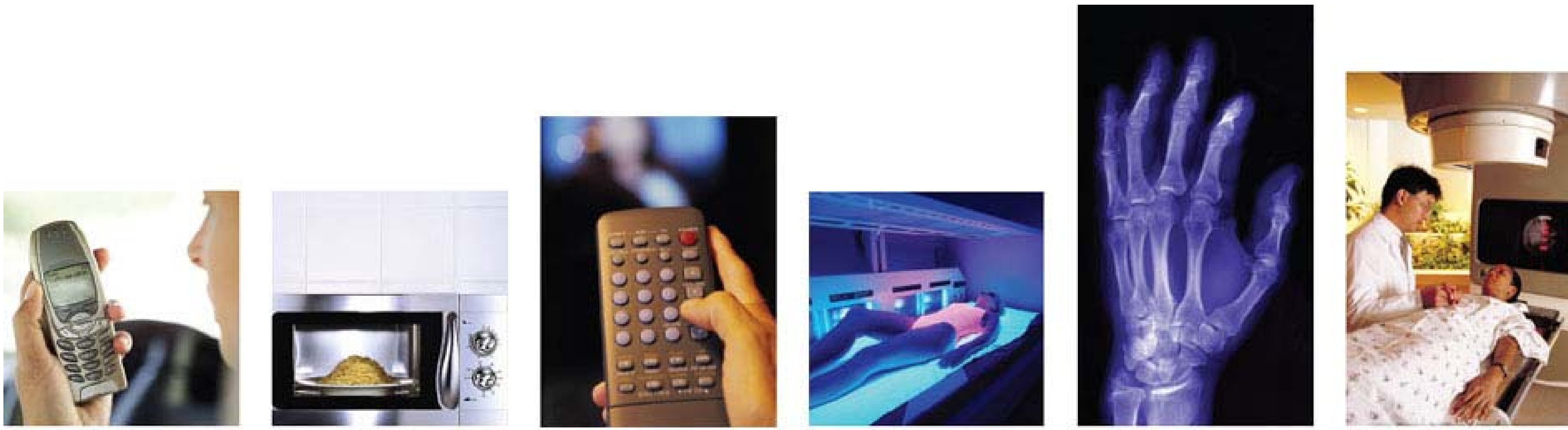
- **The nature of light is electromagnetic radiation**
- In the 1860s, James Clerk **Maxwell** succeeded in describing all the basic properties of electricity and magnetism in four equations: the Maxwell equations of **electromagnetism.**
- Maxwell showed that electric and magnetic field should travel in space in the form of waves at a speed of 3.0 X 10^5 km/s

Electromagnetic Waves



- **Visible light** falls in the 400 to 700 nm range
- In the order of decreasing wavelength
  - Radio waves: > 10 cm
  - Microwave: 1 mm – 10 cm
  - Infrared: 700 nm – 1mm
  - Visible light: 400 nm – 700 nm
  - Ultraviolet: 10 nm – 400 nm
  - X-rays: 0.01 nm - 10 nm
  - Gamma rays: < 0.01 nm

Electromagnetic Waves



(a) Mobile phone: radio waves

(b) Microwave oven: microwaves

(c) TV remote: infrared light

(d) Tanning booth: ultraviolet light

(e) Medical imaging: X rays.

(f) Cancer radiotherapy: gamma rays

Uses of Non-visible Electromagnetic Radiation

Electromagnetic Waves

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

ν: Frequency (in Hz)

λ: Wavelength (in meter)

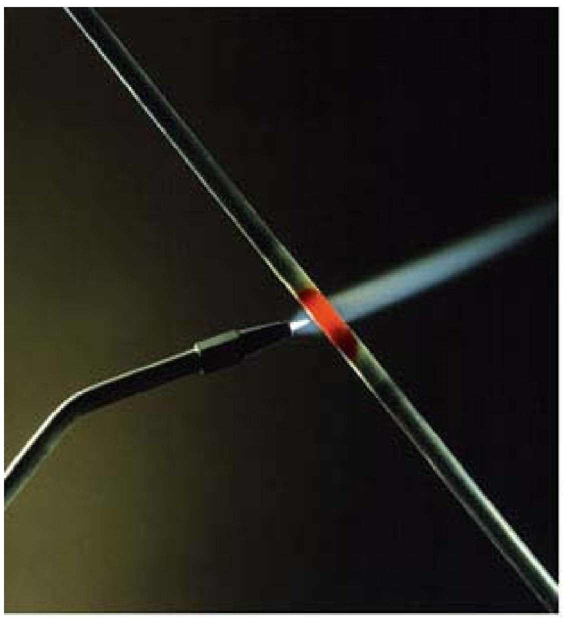
c: Speed of light = 3×10^8 m/s

- Example
  - FM radio, e.g., 103.5 MHz (WTOP station) => $\lambda = 2.90$ m
  - Visible light, e.g., red 700 nm => $\nu = 4.29 \times 10^{14}$ Hz

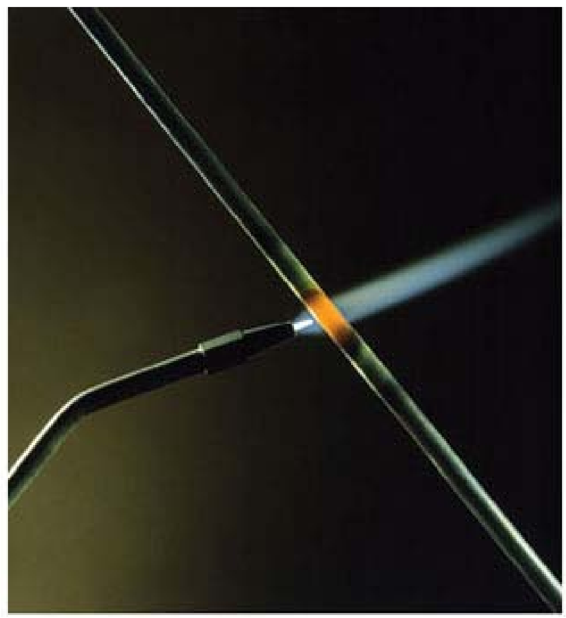
Blackbody Radiation

Heated iron bar: as the temperature increases

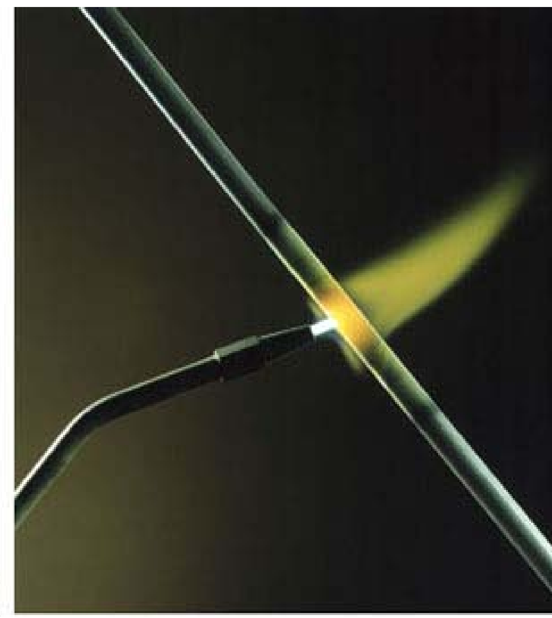
- The bar glows more brightly
- The color of the bar also changes



(a) Hot: glows deep red



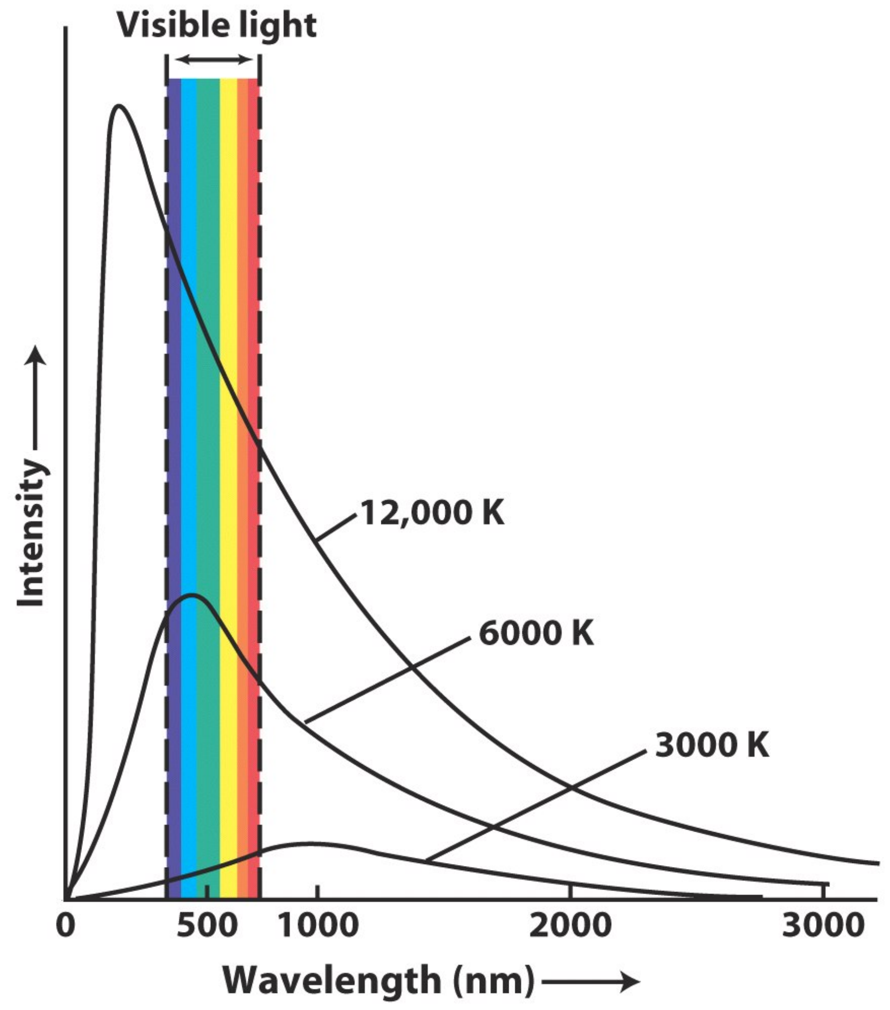
(b) Hotter: glows orange



(c) Even hotter: glows yellow

Blackbody Radiation

- **Blackbody curve**: the intensities of radiation emitted at various wavelengths by a blackbody at a given temperature
  - **The higher the temperature, the shorter the peak wavelength**
  - **The higher the temperature, the higher the intensity**



Blackbody curve

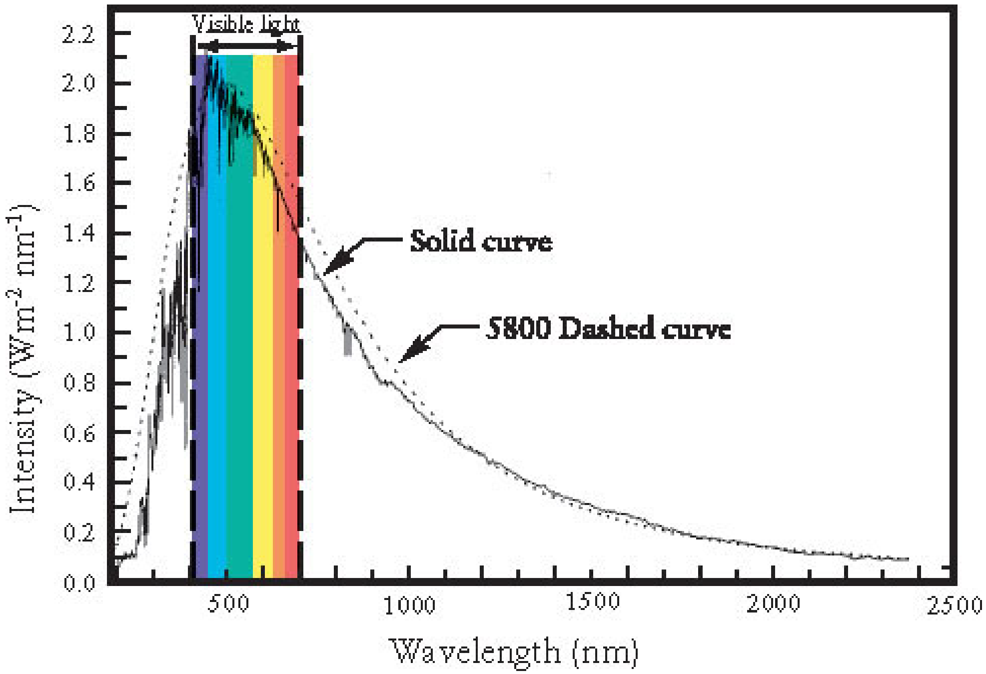
Blackbody Radiation

- A **blackbody** is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths
  - **The radiation of a blackbody is entirely the result of its temperature**
  - **A blackbody does not reflect any light at all**

- Most dense objects can be regarded as a blackbody
  - e.g., a star, a planet, a human body
  - but not a thin cloud, a layer of thin gas (lights get through)

Blackbody Radiation

- The Sun's radiation is remarkably close to that from a blackbody at a temperature of 5800 K



The Sun as a Blackbody

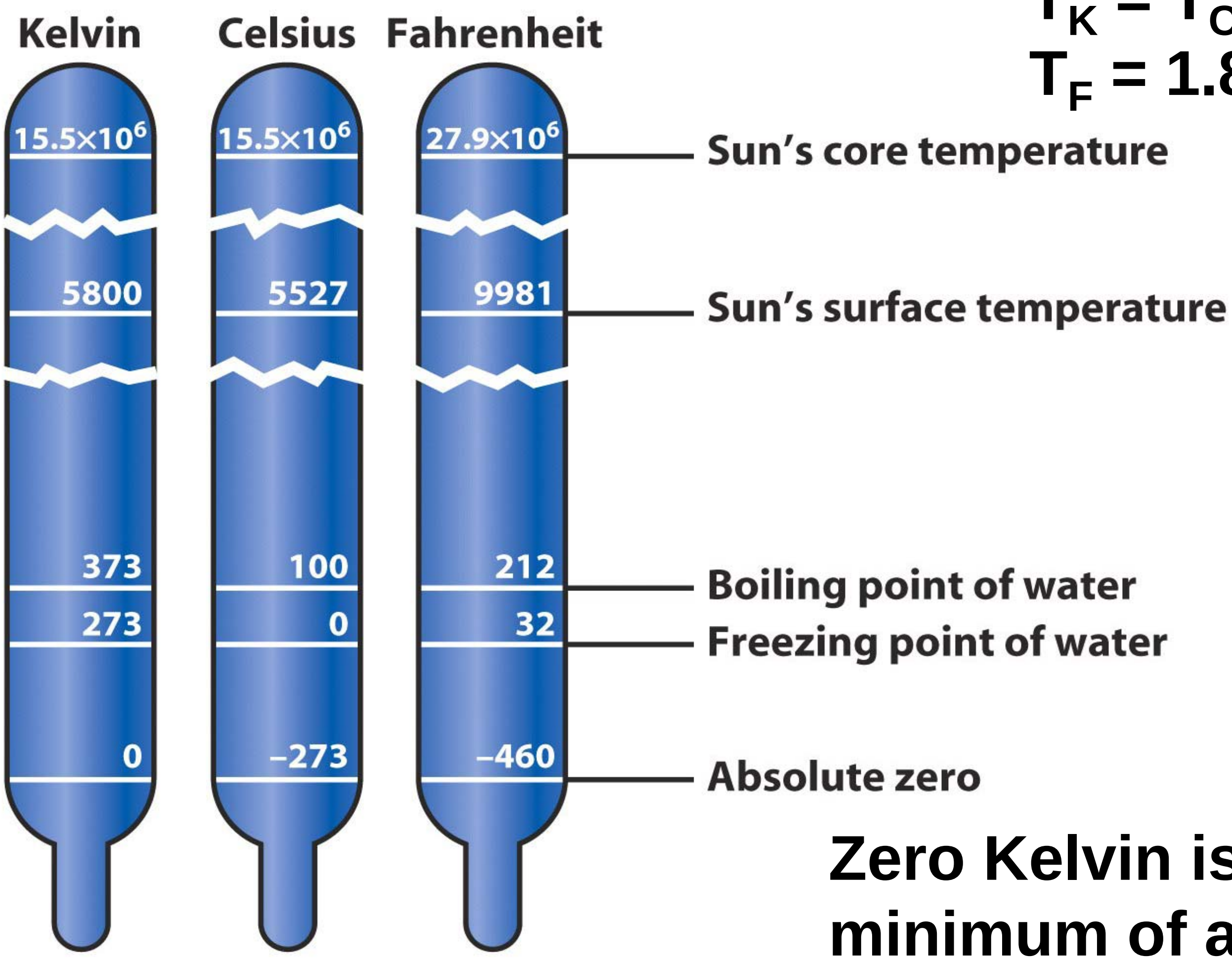
A Human Body as a Blackbody

(Box 5-1) Temperature Scales

Temperature in unit of Kelvin is often used in physics

$$T_K = T_C + 273$$

$$T_F = 1.8\ (T_C + 32)$$



Zero Kelvin is the absolute minimum of all temperatures

Wien's Law

- **Wien's law states that the wavelength of maximum emission of a blackbody is inversely proportional to the Kelvin temperature of the object**

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

λ_{max} = wavelength of maximum emission of the object (in meters)

T = temperature of the object (in kelvins)

For example

- The Sun, λ_{max} = 500 nm → T = 5800 K
- Human body at 100 F, what is λ_{max}?

(Box 5-2) Wien's Law

Sirius, the brightest star (also called dog star, in Canis Major) in the night sky, has a surface temperature of 10,000 K. Find the wavelength at which Sirius emits most intensely?

Stefan-Boltzmann Law

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

$$F = \sigma T^4$$

- F = energy flux, in joules per square meter of surface per second
- σ = Stefan-Boltzmann constant = 5.67 X 10^{-8} W m^{-2} K^{-4}
- T = object's temperature, in kelvins

- 1 J = kinetic (energy) of a 2 kg mass at a speed of 1 m/s
- 1 W = 1 J/s (power)
- F: energy flux: $J/m^2/s$ (flux)

(Box 5-2) Stefan-Boltzmann Law

Sirius, the brightest star (also called dog star, in Canis Major) in the night sky, has a surface temperature of 10,000 K. How does the energy flux from Sirius compare to the Sun's energy flux?

Dual properties of Light: (1) wave and (2) particle

- Light is an electromagnetic radiation wave, e.g, Young's double slit experiment
- Light is also a particle-like packet of energy
  - **A light packet is called photon**
  - The energy of photon is related to the wavelength of light
- **Light has a dual personality; it behaves as a stream of particles like photons, but each photon has wavelike properties**

Dual properties of Light

- **Planck's law** relates the energy of a photon to its wavelength (frequency)
  - E = energy of a photon
  - h = Planck's constant
    = 6.625×10^{-34} J s
  - c = speed of light
  - λ= wavelength of light

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

- **Energy of photon is inversely proportional to the wavelength of light**
- Example: 633-nm red-light photon
  - $E = 3.14 \times 10^{-19}$ J
  - or E = 1.96 eV
  - eV: electron volt, a small energy unit = 1.602×10^{-19} J

(Box 5-3) Planck's Law

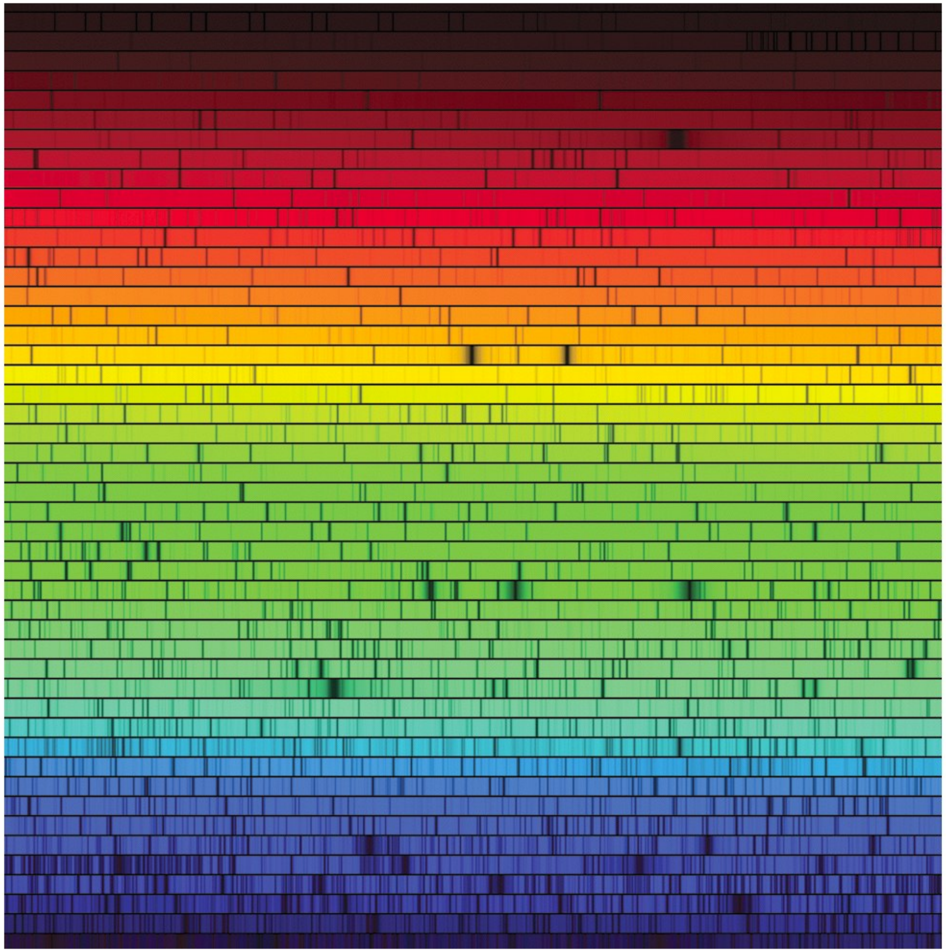
The bar-code scanners used at supermarket emit orange-red light of wavelength 633 nm and consume a power 1 mW. Calculate how many photons are emitted by one such scanner per second?

Spectral Lines

- The Sun's spectrum: in addition to the rainbow-colored continuous spectrum, it contains hundreds of fine dark lines, called **spectral lines** (**Fraunhofer**, 1814)

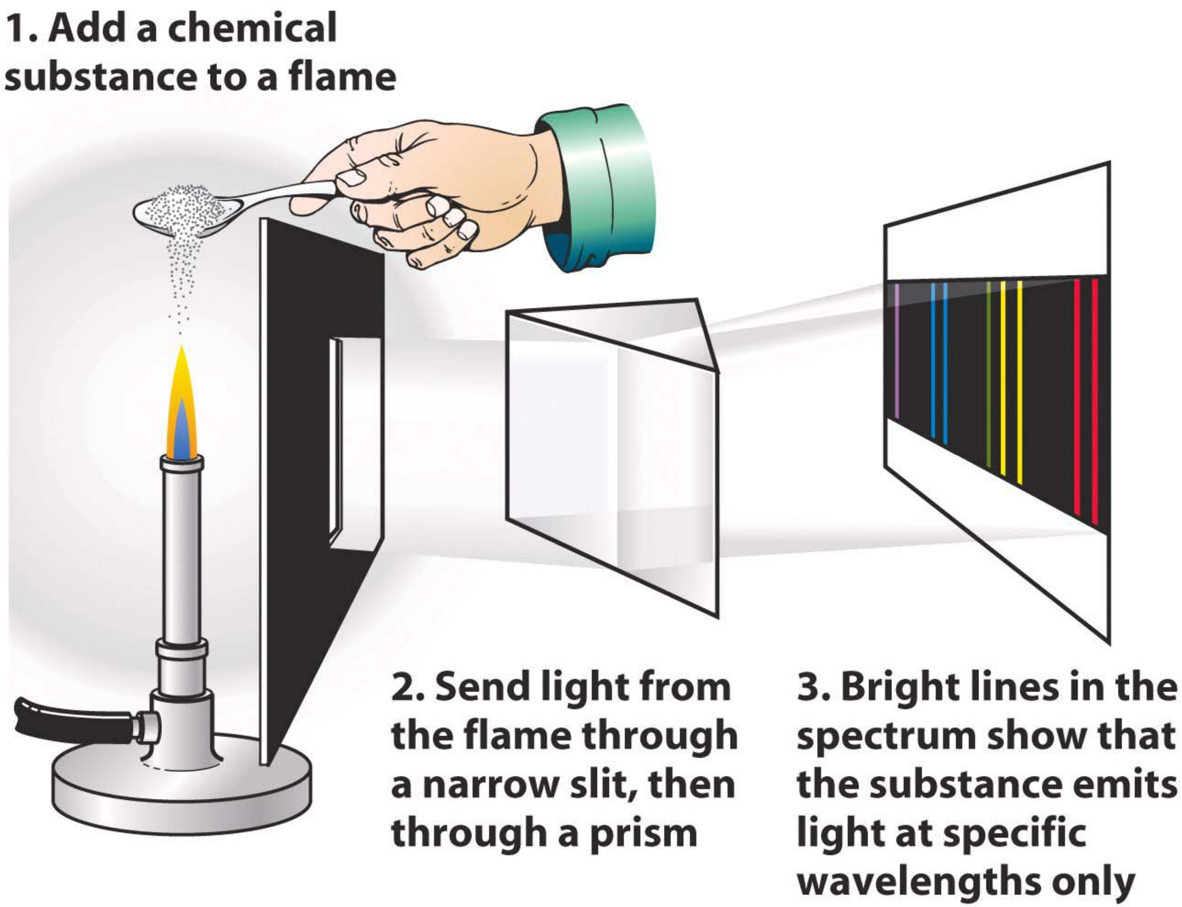
- A perfect blackbody would produce a smooth, continuous spectrum with no dark lines

The Sun's Spectrum

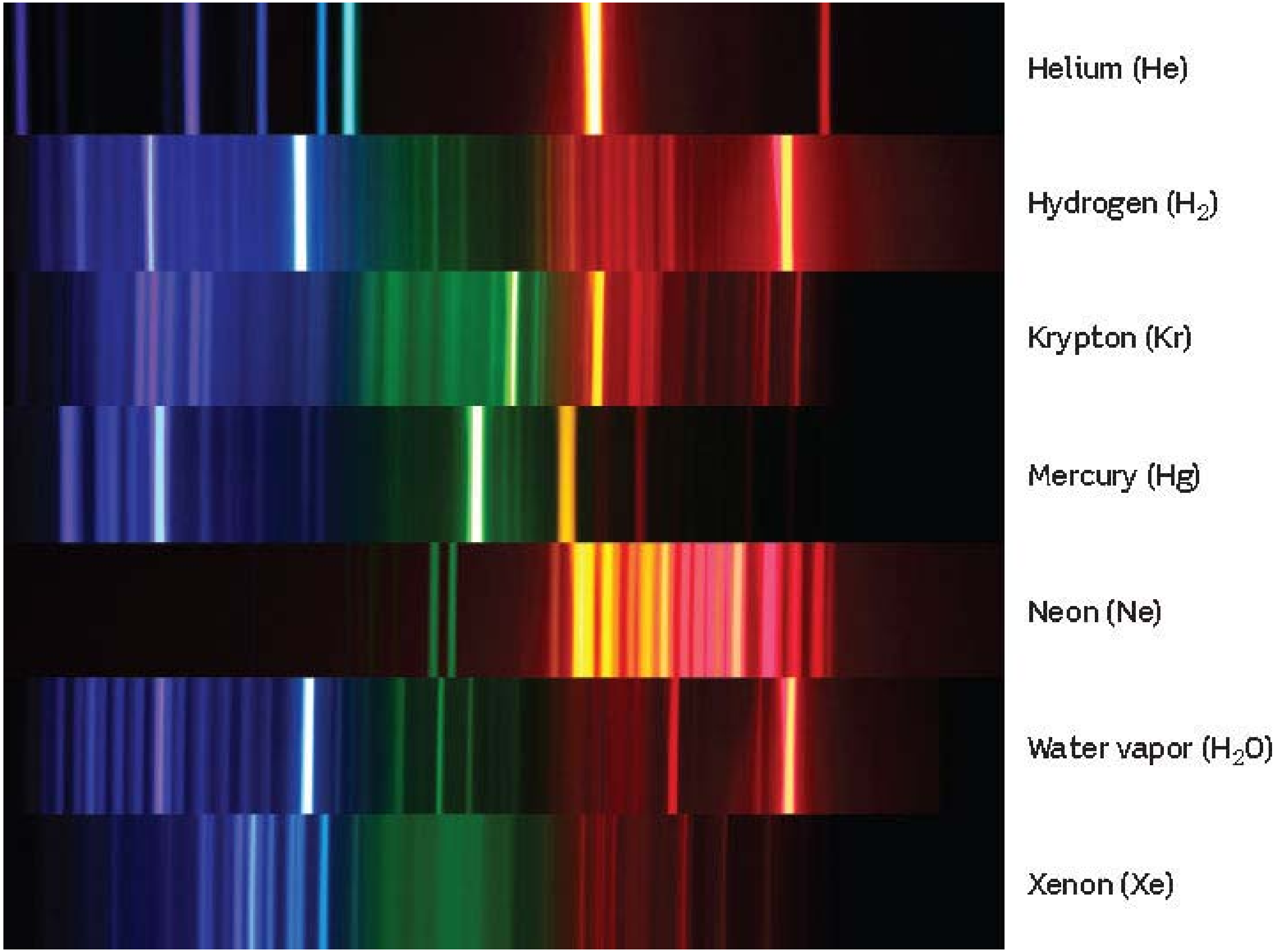


Spectral Lines

- Bright spectrum lines can be seen when a chemical substance is heated and valoprized (**Kirchhoff, ~1850**)



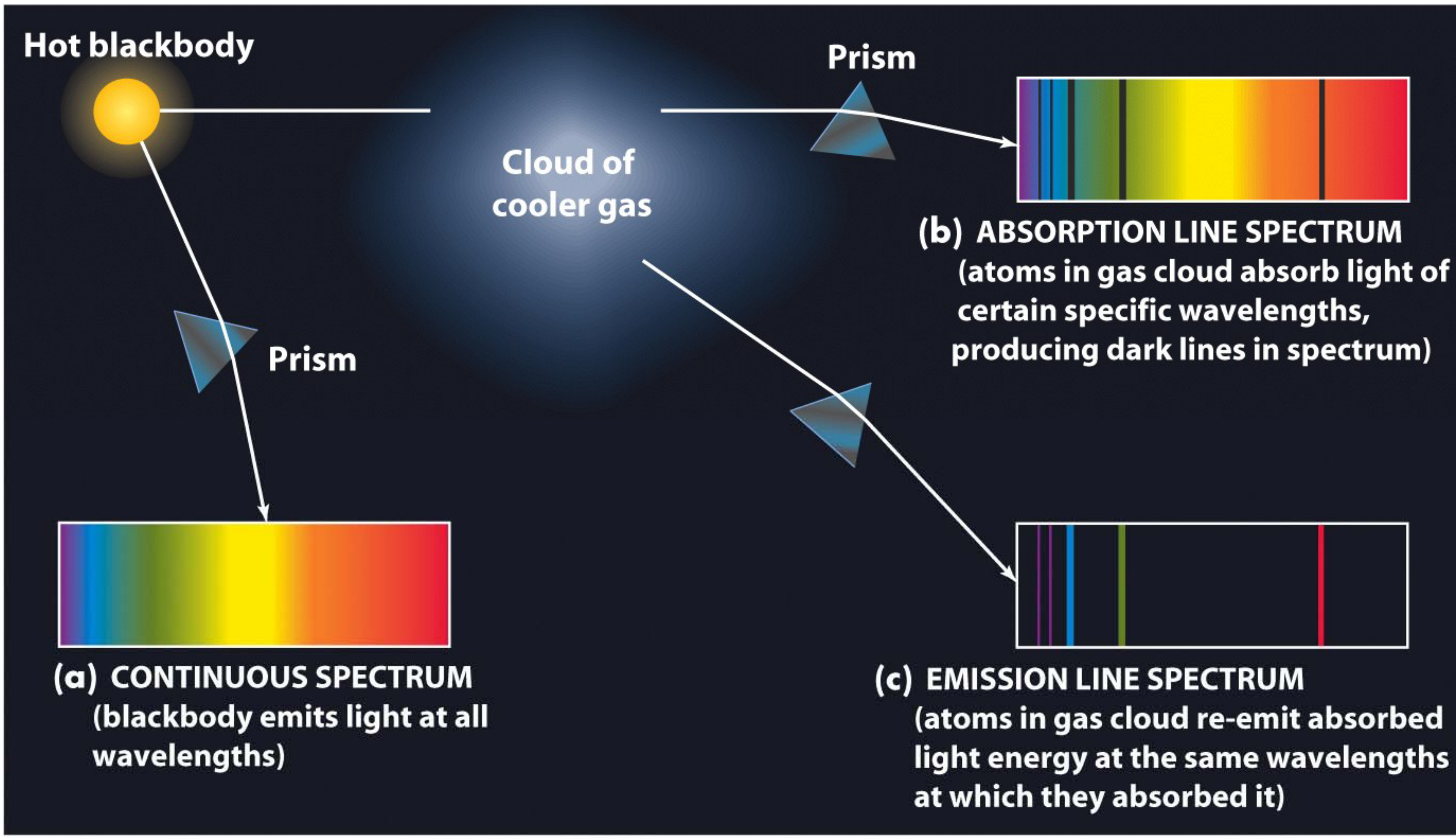
Spectral Lines



Each chemical element has its own unique set of spectral lines.

Kirchhoff's Laws on Spectra

- Three different spectra: **continuous spectrum, emission-line spectrum, and absorption line spectrum**

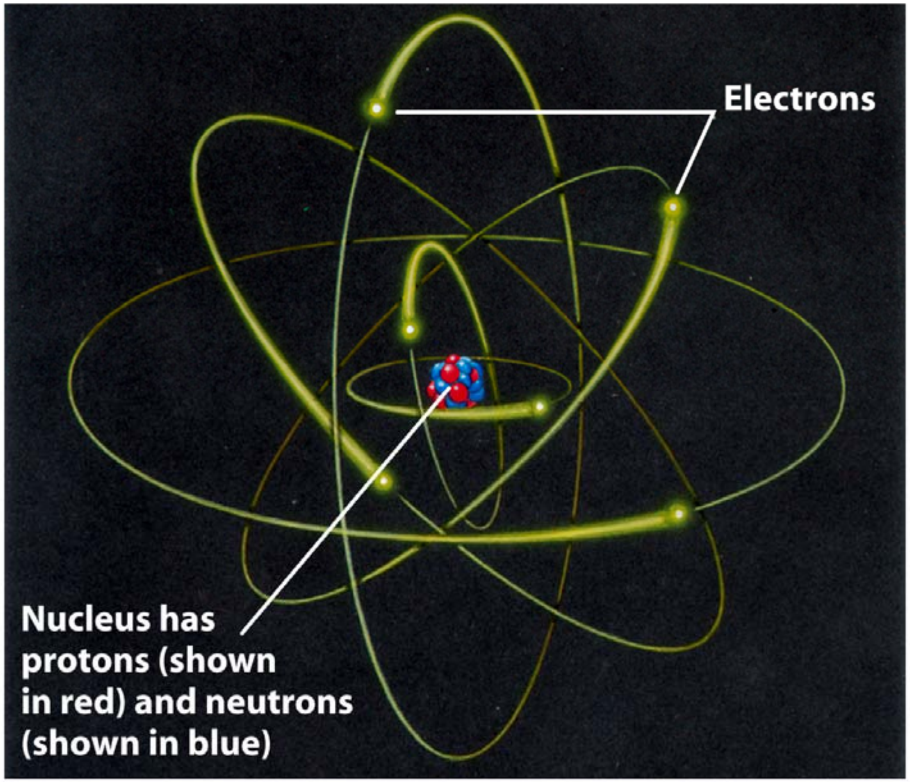


Kirchhoff's Laws on Spectra

- **Law 1- Continuous spectrum**: a hot opaque body, such as a perfect blackbody, produce a continuous spectrum – a complete rainbow of colors without any spectral line
- **Law 2 – emission line spectrum**: a hot, transparent gas produces an emission line spectrum – a series of bright spectral lines against a dark background
- **Law 3 – absorption line spectrum**: a relatively cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum – a series of dark spectral lines amongst the colors of the continuous spectrum. **Further, the dark lines of a particular gas occur at exactly the same wavelength as the bright lines of that same gas.**

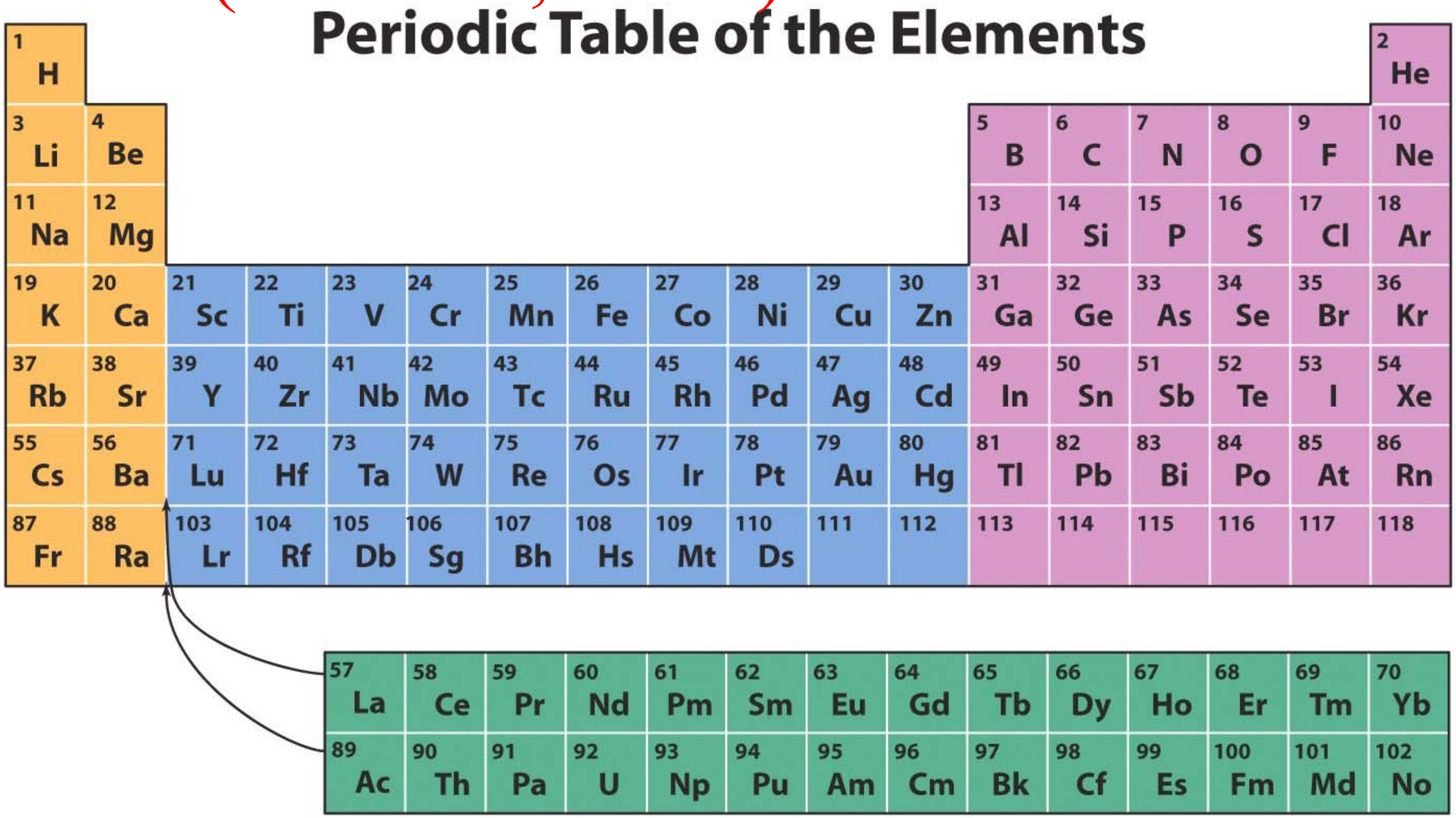
Structure of Atom

- An **atom** consists of a small, dense **nucleus** at the center, surrounded by **electrons** which orbit the nucleus.
- The **nucleus** contains more than 99% of the mass of an atom, but concentrates in an extremely small volume
- A nucleus contains two types of particles: **protons and neutrons**
- A proton has a positive electric change, equal and opposite to that of an electron.
- A neutron, about the same mass of a proton, has no electric charge.
- An atom has no net electric charge



Rutherford's Model of Atom

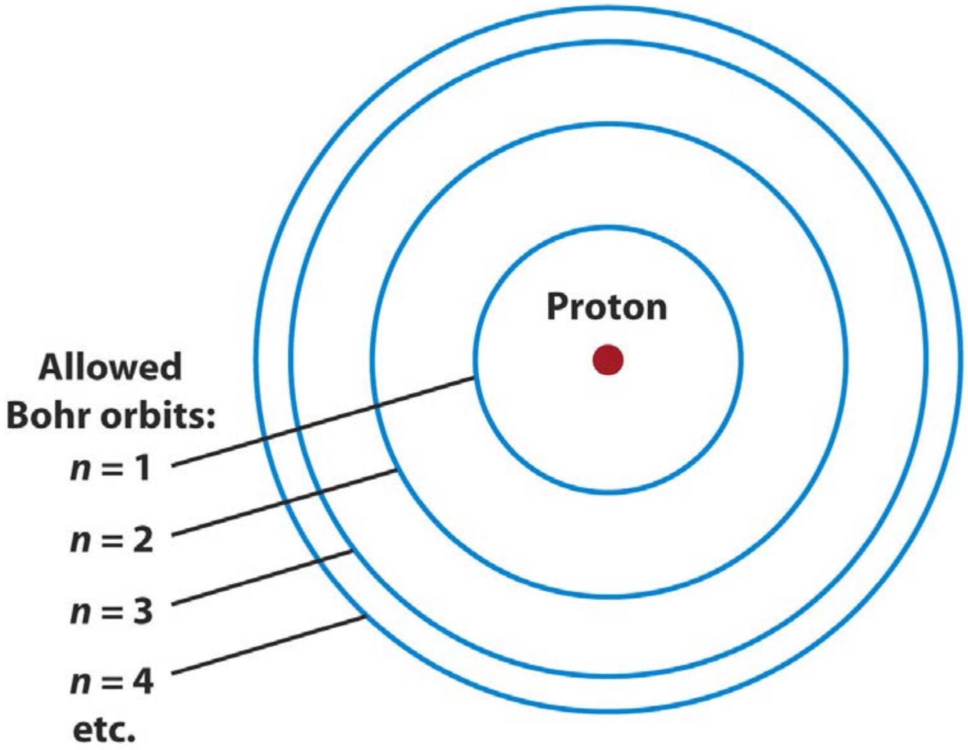
(Box 5-5, P108) Periodic Table



- **Atomic number**, the number of protons in an atom's nucleus and thus the number of surrounding electrons, determines a particular element
- The same element may have different numbers of neutrons in its nucleus, which are called **isotopes**

Bohr’s Model of Atom

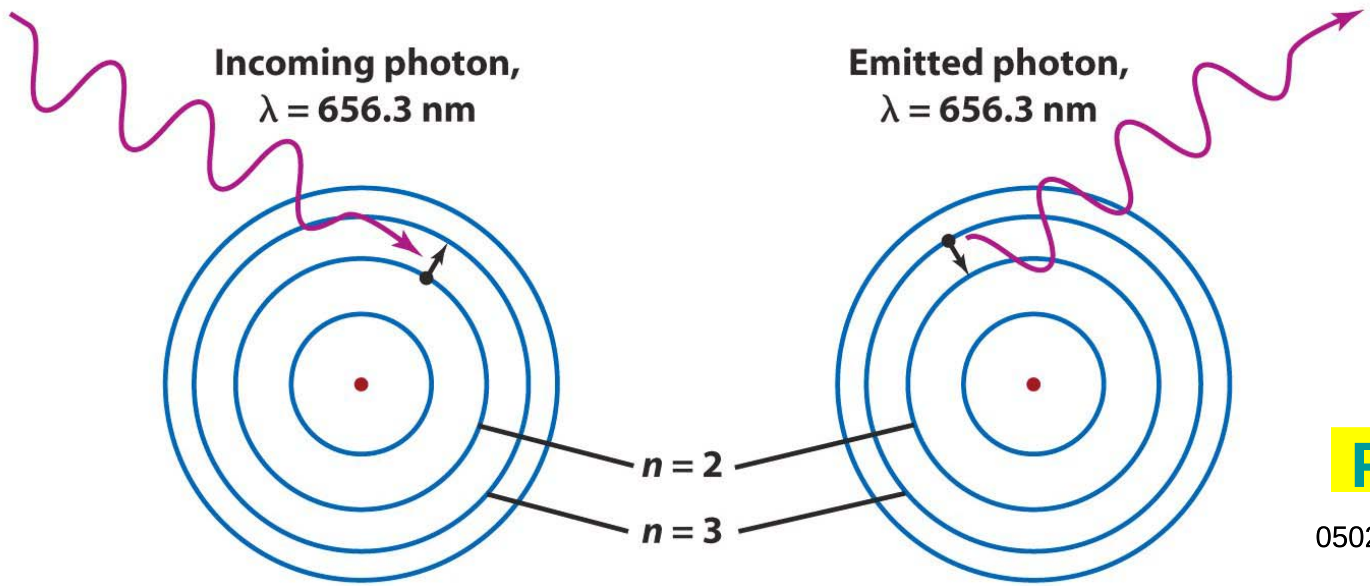
- Electrons occupy only certain orbits or energy levels
- When an electron jumps from one orbit to another, it emits or absorbs a photon of appropriate energy.
- The energy of the photon equals the difference in energy between the two orbits.



Bohr’s Model of Hydrogen Atom

Bohr's Model of Atom

- **Absorption** is produced when electron absorbs incoming photon and **jumps from a lower orbit to a higher orbit**
- **Emission** is produced when electron **jumps from a higher orbit to a lower orbit** and emits a photon of the same energy



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

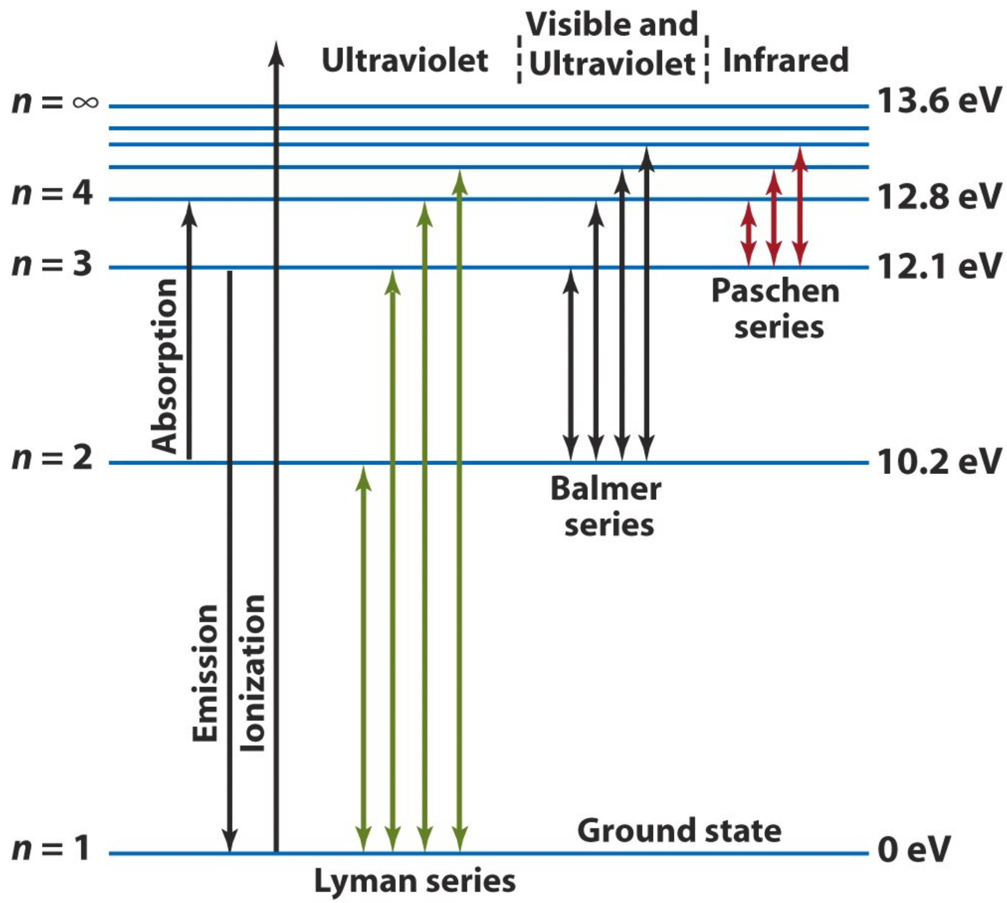
(b) Electron falls from the *n* = 3 orbit to the *n* = 2 orbit; energy lost by atom goes into emitting a 656.3-nm photon

FLASH

0502_Absorption_Photon.swf

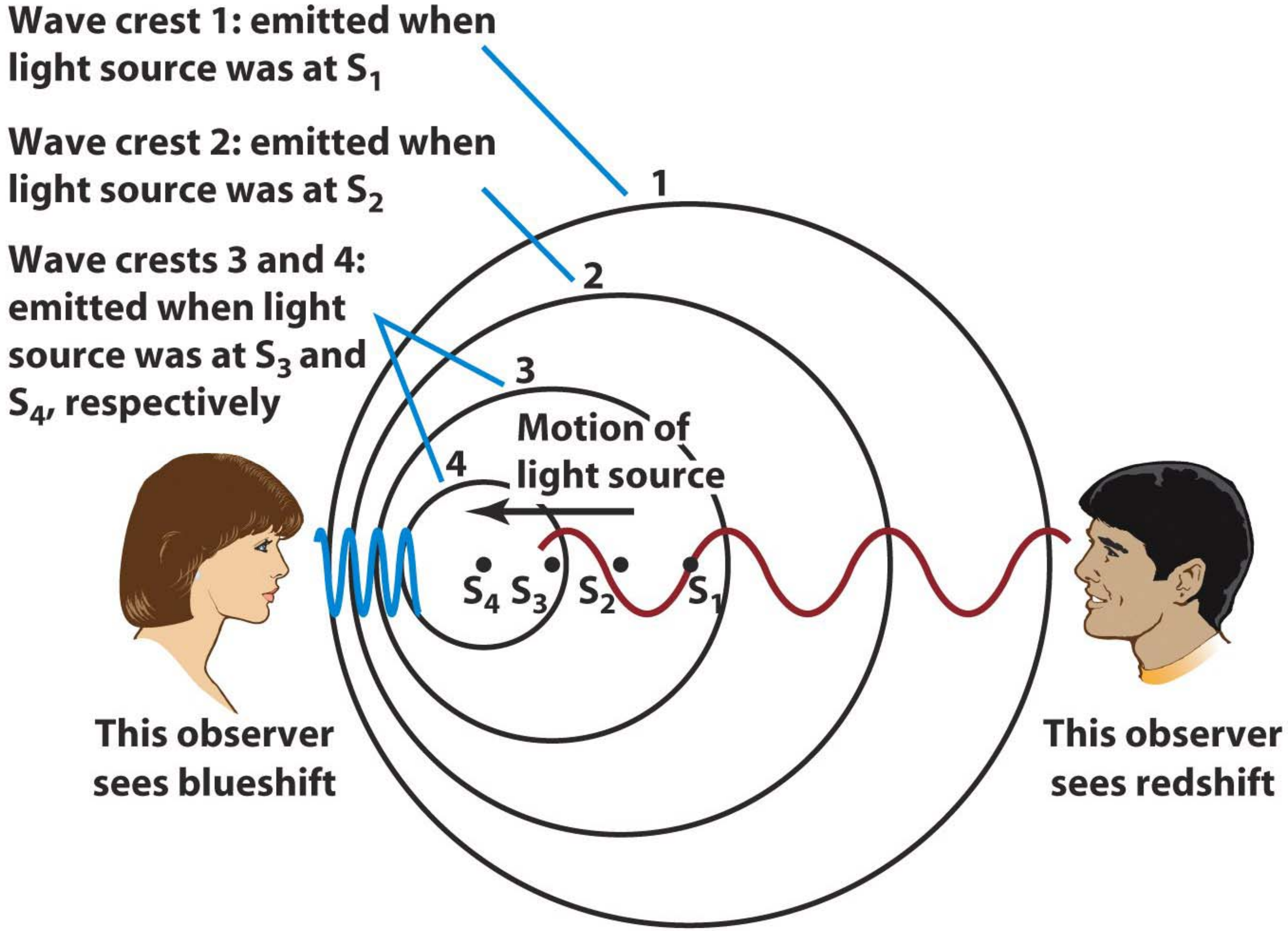
Bohr’s Model of Atom

- The strongest hydrogen spectral line from the Sun, Hα line at 656 nm, is caused by electron-transition between n=3 orbit and n=2orbit
- **Balmer series lines**: between n-2 orbit and higher orbits (n=3, 4, 5,…)
- **Lyman series lines**: between n=1 orbit and higher orbits (n=2, n=3, n=4,…) (UV)
- **Paschen series lines**: between n=3 orbit and higher orbits (n=4, n=5, n=6,…) (IR)



Doppler Effect

- **Doppler effect: the wavelength of light is affected by motion between the light source and an observer**



Doppler Effect

- **Red Shift**: The object is moving away from the observer, the line is shifted toward the longer wavelength
- **Blue Shift**: The object is moving towards the observer, the line is shifted toward the shorter wavelength

$$\Delta\lambda/\lambda_o = v/c$$

$\Delta\lambda$ = wavelength shift

λ_o = wavelength if source is not moving

v = velocity of source

c = speed of light

- Questions: what if the object's motion perpendicular to our line of sight?

(Box 5-6) Doppler Effect

In the spectrum of the star Vega, the prominent Hα spectra line of hydorgen has a wavelength λ = 656.255 nm. At laboratory, this line has a wavelength λ_0 = 656.285 nm. What can we conclude about the motion of Vega?

Final Notes on Chap. 5

- There are 9 sections. All section are covered

Advanced Question
Chap. 5, Q30 in P125

Jupitor's moon Io has an active volcano Pele whose temperature can be as high as 320°C.

(a) What is the wavelength of maximum emission for the volcano at this temperature? In what part of the electromagnetic spectrum is this?

(b) The average temperature of Io's surface is -150 °C. Compared with a square meter of surface at this temperature, how much more energy is emitted per second from each square meter of Pele's surface?