ASTR-1010: Astronomy I
Course Notes
Section IV

Dr. Donald G. Luttermoser
Department of Physics and Astronomy
East Tennessee State University

Edition 2.0

Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1010: Astronomy I taught by Dr. Donald G. Luttermoser at East Tennessee State University.

IV. Light and Matter

A. The Nature of Light

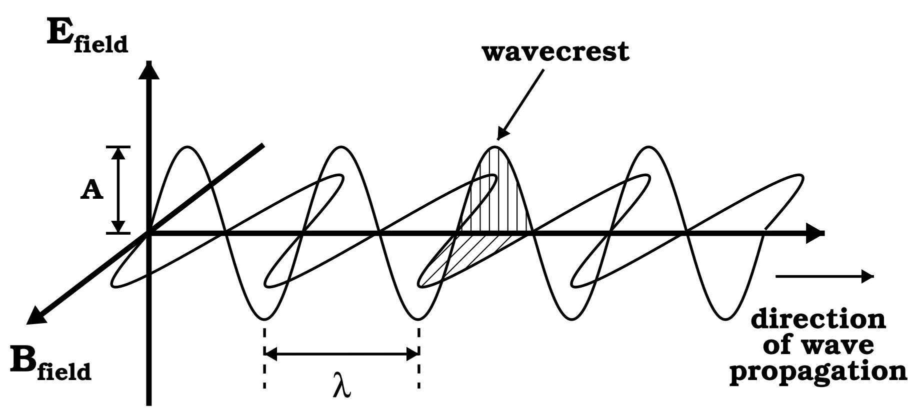
1. Light travels in empty space at 3.00×10^8 m/s = 3.00×10^5 km/s. More precisely, c (**speed of light**) = 2.99792458×10^8 m/s.

2. Light behaves both as a *wave* and a *particle* $\Longrightarrow$ a *wavicle*. Planck introduced the term **photon** which means *particle of light*.

a) **Diffraction** and **interference** are two wave-like phenomena that light exhibits.

b) The **photoelectric effect** is a particle-like phenomenon that light exhibits $\Longrightarrow$ when a photon collides with certain metals, the photon can knock off electrons from the atoms in the metal like a particle collision.

3. Light is **electromagnetic** (E/M) **radiation** which consists of oscillating electric and magnetic fields which self-propagate at c.



a) The separation of 2 successive wavecrests is called a **wavelength**, λ.

b) E/M radiation is characterized by its wavelength.

c) The frequency, ν, of an E/M wave is defined to be the number of wavecrests per second that pass a given point. It is related to wavelength by:

$$\nu = \frac{c}{\lambda}. \qquad \text{(IV-1)}$$

d) The amplitude, A, of the electric field of the photon does not indicate the brightness of the light $\rightarrow$ instead, the **number of photons** per area per second in a beam of light corresponds to the **brightness** of the light.

4. Visible light is just one form of E/M radiation $\Longrightarrow$ **the electromagnetic spectrum**:

a) **Gamma rays:** Highest energy, shortest wavelengths: $0 < \lambda < 0.1$ Å (1 Å $= 10^{-10}$ m $= 10$ nm).

b) **X-rays:** 0.1 Å $< \lambda <$ 100 Å.

c) **Ultraviolet (UV):** 100 Å $< \lambda <$ 4000 Å.

d) **Visible (visual):** 4000 Å $< \lambda <$ 7000 Å.

e) **Infrared (IR):** 7000 Å $< \lambda <$ 1 mm.

f) **Microwaves:** 1 mm $< \lambda <$ 10 cm.

g) **Radio waves:** 10 cm $< \lambda < \infty$.

5. A spectrum is defined to be the *brightness* (intensity or flux) as a function of *wavelength* (or frequency or energy).

B. Thermal Radiation

1. Objects that are in **thermal equilibrium** are objects that are at uniform temperature throughout their volume.

2. **Temperature** is a quantity that reflects how vigorously atoms are moving and colliding in matter. There are 3 different temperature scales that are used in science:

   a) **Kelvin** is the unit of temperature used in the SI system $\Longrightarrow$ it is the <u>absolute</u> temperature scale.

      i) 0 K $\equiv$ coldest obtainable temperature $\rightarrow$ no atomic motion.

      ii) Room temperature $\approx$ 300 K.

   b) The **Celsius** (once called *Centigrade*) scale is based on the freezing and boiling points of water. It is related to the Kelvin scale by:

$$T_C = T_K - 273.16 \qquad \text{(IV-2)}$$

      i) 0 °C $\equiv$ water freezes at the Earth's surface pressure.

      ii) 100 °C $\equiv$ water boils at the Earth's surface pressure.

      iii) 0 K $= -273.16$ °C.

   c) The **Fahrenheit** scale (English system) is related to the Celsius scale by:

$$T_F = 32 + \frac{9}{5}\, T_C \qquad \text{(IV-3)}$$

      i) 32 °F $\equiv$ water freezes.

      ii) 212 °F $\equiv$ water boils.

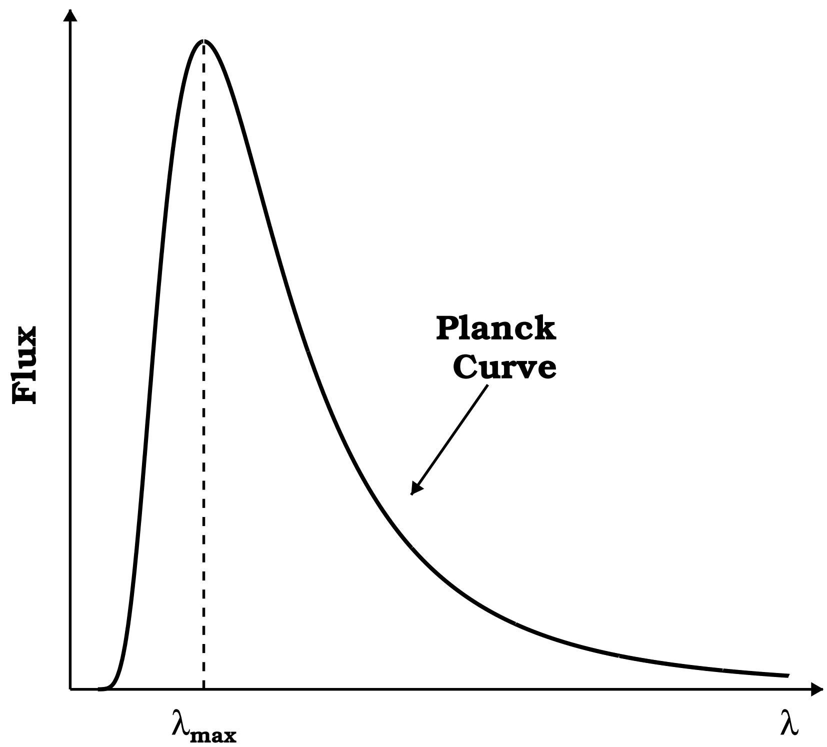
      iii) 0 K $= -459.69$ °F.

3. An object at thermal equilibrium emits a thermal spectrum and is called a **blackbody radiator**.

a) A blackbody does not reflect any light, it absorbs all radiation falling on it.

b) All radiation it does emit results from its temperature.

c) A blackbody spectrum is represented by a **Planck curve:**



d) The **energy flux** (F) is the amount of energy emitted from each square meter of an objects surface per second. The flux of a blackbody is a function only of its temperature and is given by the **Stefan-Boltzmann Law**:

$$F = \sigma\, T^4, \qquad \text{(IV-4)}$$

where T is the temperature and $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant.

e) The total brightness, or **luminosity** (L), of a blackbody is just the flux integrated over all of the surface of the object. For a spherical object, the surface area is $4\pi R^2$, so

$$L = 4\pi R^2 F = 4\pi \sigma R^2 T^4. \qquad \text{(IV-5)}$$

Note that we can eliminate the constants in the above equation by dividing both sides by *solar* values:

$$\frac{L}{L_\odot} = \frac{4\pi \sigma R^2 T^4}{4\pi \sigma R_\odot^2 T_\odot^4}$$

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4. \qquad \text{(IV-6)}$$

f) The <u>hotter</u> a blackbody, the <u>bluer</u> its peak emission of light $\Longrightarrow$ the <u>cooler</u>, the <u>redder</u> its light. The wavelength of peak brightness for a blackbody is given by **Wien's Displacement Law**:

$$\lambda_{\rm max} = \frac{0.0029 \text{ m K}}{T}. \qquad \text{(IV-7)}$$

4. The energy of a single photon is proportional to the frequency or inversely proportional to the wavelength of the photon:

$$E = h\,\nu = \frac{h\,c}{\lambda}, \qquad \text{(IV-8)}$$

where $h = 6.625 \times 10^{-34}$ J s is **Planck's constant** and c is the speed of light.

Example IV-1. A star has a temperature of 10,000 K and a radius of 20 $R_\odot$, what is its flux and wavelength of maximum flux? What is its luminosity with respect to the Sun? (Note that $R_\odot = 6.96 \times 10^8$ m and $T_\odot = 5800$ K.)

$$F = (5.67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4})\,(10,000 \text{ K})^4$$

$$
\begin{aligned}
&= (5.67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4})\,(10^4 \text{ K})^4 \\
&= (5.67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4})\,(10^{16} \text{ K}^4) \\
&= 5.67 \times 10^{8} \text{ W m}^{-2}
\end{aligned}
$$

$$\lambda_{\rm max} = \frac{0.0029 \text{ m K}}{10,000 \text{ K}} = 2.9 \times 10^{-7} \text{ m} = 2900 \text{ Å} \Longrightarrow \text{ UV light!}$$

$$
\begin{aligned}
\frac{L}{L_\odot} &= \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4 \\
&= \left(\frac{20\,R_\odot}{R_\odot}\right)^2 \left(\frac{10,000 \text{ K}}{5800 \text{ K}}\right)^4 = (400)\,(1.72)^4 \\
&= (400)\,(8.84) = 3500 \\
L &= 3500\ L_\odot
\end{aligned}
$$

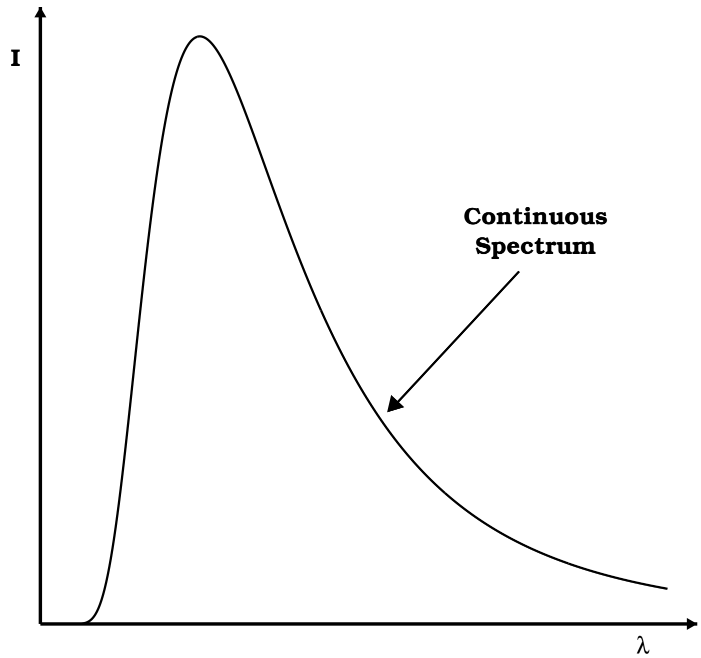
C. Spectral Analysis

1. In 1814, Joseph von Fraunhofer discovered about 600 dark lines in the solar spectrum ⟹ **spectral lines**. The darkest he labeled from "A" (in the red) to "H" (in the blue) [note that the "K" line was added later].

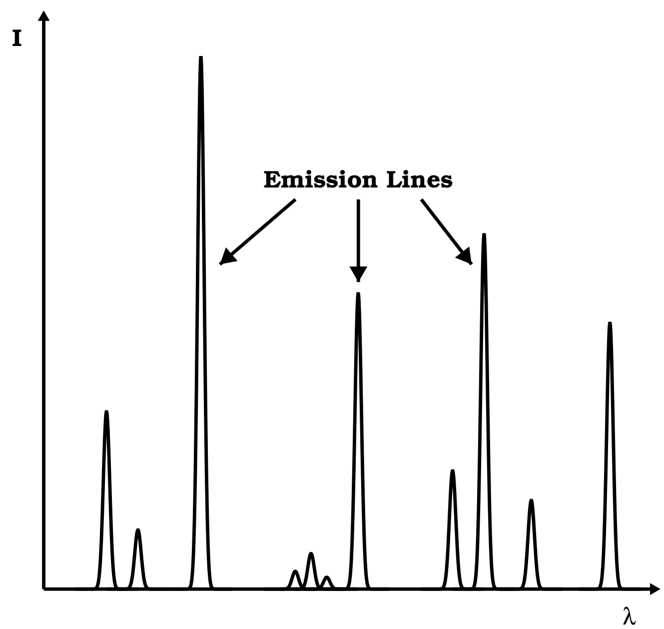
2. In 1859, Gustav Kirchhoff and Robert Bunsen discovered that each element contained a unique set of lines in their spectra ⟹ **spectral analysis**.

3. Later Kirchhoff realized that there are 3 types of spectra that objects emit which depend upon the *state* and *orientation* the object is in ⟹ **Kirchhoff's Laws**.

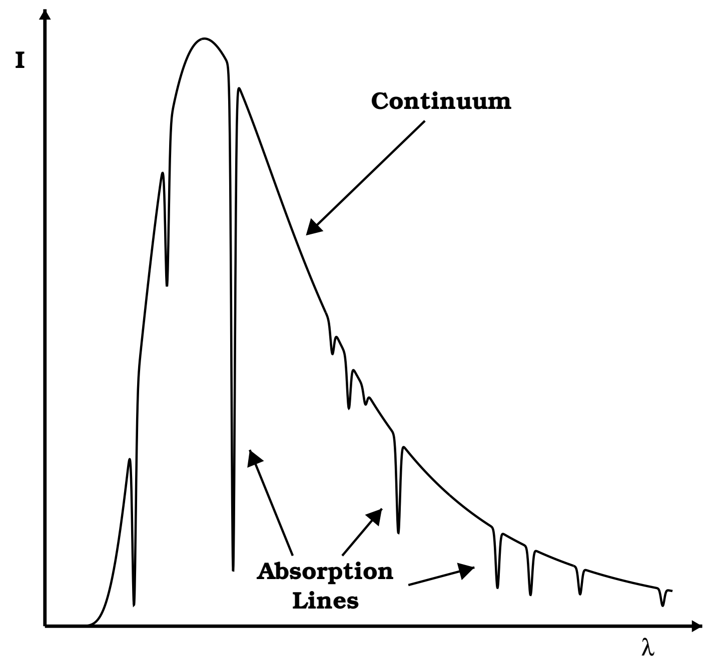
a) **Law 1:** A hot opaque body produces a **continuous spectrum** — a complete rainbow of colors without any spectral lines as plotted in the next diagram.



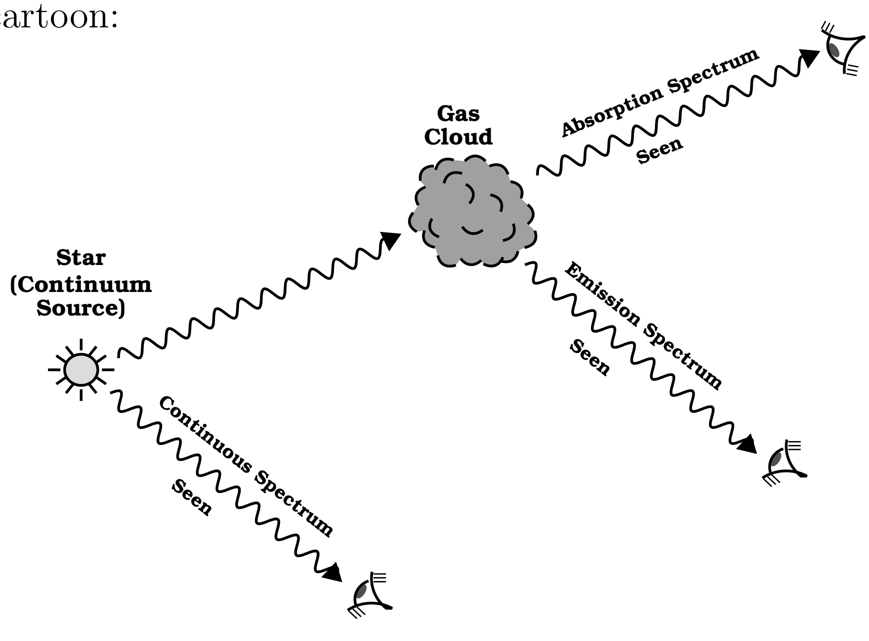
b) **Law 2:** A hot, transparent gas produces an **emission line spectrum** — a series of bright spectral lines against a dark background.



c) **Law 3:** A cool transparent gas in front of a source of a continuous spectrum produces an **absorption line spectrum** — a series a dark spectral lines among the colors of the continuous spectrum.



d) Kirchhoff's Laws can be summarized with the following cartoon:



Kirchhoff's Radiation Laws

4. The **Doppler effect**.

a) The spectrum of an object will be **blueshifted** if it is <u>approaching</u> the observer.

b) The spectrum of an object will be **redshifted** if it is receding from the observer.

c) The wavelength shift in a spectral line is given by:

$$\frac{\Delta\lambda}{\lambda_\circ} = \frac{v}{c}, \tag{IV-9}$$

where $\Delta\lambda = \lambda - \lambda_\circ$ (negative shift = blueshift), $\lambda_\circ$ = rest (lab) wavelength, v = velocity of object, and c = speed of light.

Example IV-2. We observe a hydrogen spectral line of Polaris with a wavelength of 6562.48 Å, which in the laboratory is measured to be at 6562.85 Å. What is the radial (*i.e.*, line-of-sight) velocity of Polaris?

λ = 6562.48 Å and $\lambda_\circ$ = 6562.85 Å, so $\Delta\lambda$ = 6562.48 Å −6562.85 Å = −0.37 Å.

$$\begin{aligned} v &= \frac{\Delta\lambda}{\lambda_\circ}\, c = \frac{-0.37\ \text{Å}}{6562.85\ \text{Å}}\, 3.00 \times 10^5\ \text{km/s} \\ &= (-5.638 \times 10^{-5})\,(3.00 \times 10^5\ \text{km/s}) \\ &= -16.9\ \text{km/s} \end{aligned}$$

Polaris is moving towards us (as deduced from negative sign and the fact that the line was blueshifted) at 16.9 km/s.

D. Atomic Structure

1. Matter is composed of **atoms** (*i.e.*, the elements, H, He, C, N, O) and **molecules** (*i.e.*, water [H_2O], carbon dioxide [CO_2]), which in turn are composed of atoms.

2. Atoms are mostly empty space with a tiny **nucleus** ($\sim 10^{-15}$ – 10^{-14} m in radius) surrounded by a cloud of **electrons** (negatively charged particles, with the closest being $\sim 5 \times 10^{-11}$ m distant from the nucleus) $\Longrightarrow$ **Rutherford's model** of the atom.

3. The atomic nucleus is composed of **protons** (positively charged particles) and **neutrons** (no charge).

4. The number of protons in the nucleus <u>defines</u> the **element**: H = one proton, He = 2 protons, C = 6 protons, Mg (magnesium) = 12 protons, Fe (iron) = 26 protons, etc. (see the periodic table).

5. The model atom of hydrogen was first described by Bohr $\Longrightarrow$ **Bohr model atom**.

6. In their neutral state, there are as many electrons as there are protons in the nucleus $\Longrightarrow$ this is the lowest energy ionic state.

- **a)** As energy is added to a neutral atom, electrons can be knocked off of the atom — the atom becomes **ionized**.
- **b)** Neutral atoms are labeled with a "I" (roman numeral one) — H I, He I, C I, etc.
- **c)** Singly ionized atoms (*i.e.*, one electron removed) are labeled with "II" (roman numeral two) — H II, He II, C II, etc.
- **d)** Doubly ionized atoms: He III, C III, etc., and so on.

7. Electrons can only *orbit* a nucleus in **allowed states** or **orbits** $\Longrightarrow$ **quantum mechanics** (see the next figure).

a) The outermost electron is typically the one which photons interact with.

b) When this outermost electron is as close as it can get to the nucleus, it is called the ground state of all the states this electron can reach.

c) An electron can be *bumped* to a higher energy orbit, called an **excited level** or **state** by absorbing a photon $\Longrightarrow$ that corresponds to an **absorption line**.

d) An electron in an excited level will only remain there for a short period of time before decaying back down to a lower energy state. When it decays back down, it emits a photon corresponding to the energy difference of the 2 levels $\Longrightarrow$ produces an **emission line**.