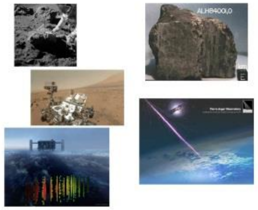
Light and Matter(LC)

Every astronomy book that I've seen has at least one chapter dedicated to the physics of light. **Why are astronomers so interested in light?**

Everything* that we know about Astronomical Objects comes from the light that they emit or reflect.

***There are a few exceptions to this:**

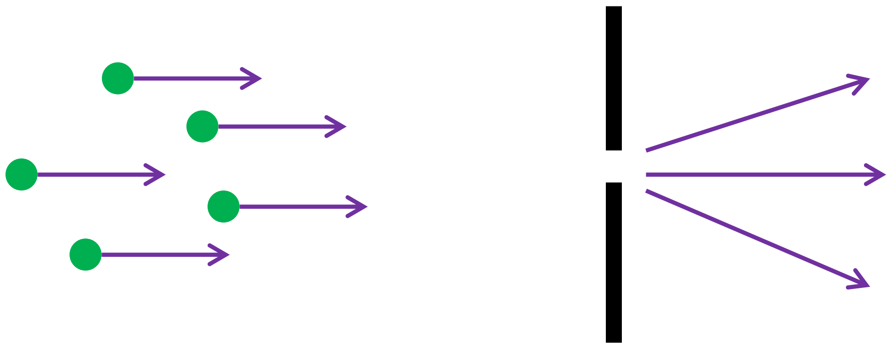
- Material brought back from the Apollo moon missions
- Material analyzed by robot spacecraft on Mars, Venus, Titan, atmosphere of Jupiter, and a few asteroids and comets
- Meteorites found all over the Earth
- Neutrinos, Cosmic Rays, and (just a few years ago) Gravity Waves



So, in astronomy, almost all of the information that we receive from the heavens is in the form of light – or, more precisely, Electromagnetic Radiation. That's why it's so important.

What is Light?

As we saw in the video, **Isaac Newton** was very interested in the nature of light. In his work “Optiks,” he proposed **The Corpuscular Theory of Light,** i.e. light is a stream of particles:



But, what about Diffraction and Interference?

This is characteristic Of waves.

Even in Newton’s time, people like **Christian Huygens** had proposed a Wave Theory of Light, but this was not demonstrated until the early 19th century by Thomas Young in his double slit experiment.

Today, we work with two descriptions of light: **A Wave Description** from Maxwell and the **Photon Description** from quantum mechanics.

The Wave Description of Light

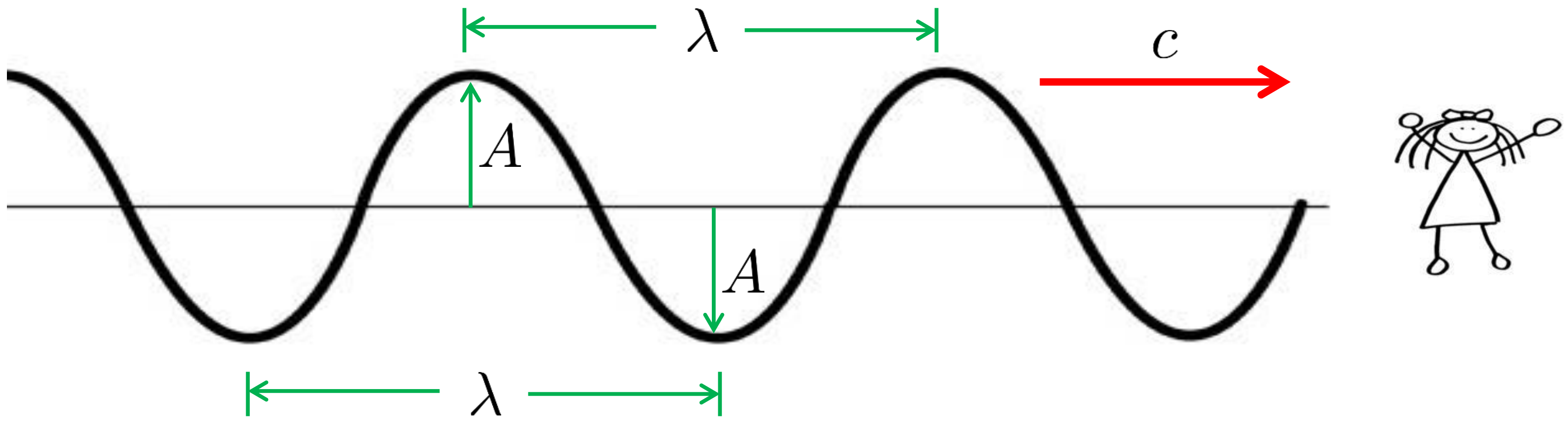
Before we talk about light as a wave, **what is a wave?**

Some examples of waves:

- Surface waves on water: oscillations in the height of the water level
- Sound Waves: oscillations in pressure or density in a medium
- Waves on Strings: oscillations in the position of the string
- People Waves? Oscillations in the sitting position of large group of people.

A wave is a disturbance that propagates at a well-defined speed and carries energy and momentum.

Characteristics of a Wave



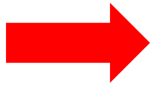
Wavelength, $\lambda =$ Distance for the wave to repeat

Amplitude, $A =$ Maximum displacement from the undisturbed state

Wavespeed, c

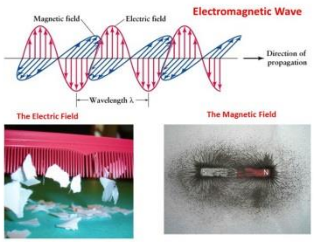
Frequency, $\nu =$ number of wavecrests per second passing a point

$$= \frac{c}{\lambda}$$ *(the source of that awful physics joke!)*



(remember, the wave is moving)

The Wave Description of Light



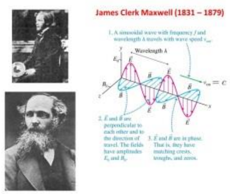
So, if light is a wave, What is doing the Waving?

Oscillating Electric and Magnetic Fields

And what are electric and magnetic fields?

Regions of influence around electrically charged objects or magnetized objects.

In the 1860's, the Scottish physicist, **James Clerk Maxwell**, showed that certain types of electric and magnetic fields are intimately related:



A time-varying electric field creates a time-varying magnetic field and vice - versa.

Maxwell was able to calculate that the **speed of these electromagnetic disturbances (waves) is**:

$$c = 3 \times 10^5 \ km/s \text{ the speed of light}$$

In Maxwell's theory, how is electromagnetic radiation created?

One way is to just wiggle charges . . . This is how a radio works.

The Photon Description of Light

In the early 20th century, physicists studying the nature of the atom found that light is not purely wavelike. It also has **particlelike properties - this is especially important when light interacts with matter.**

- Light has both Wave and Particle Properties
- **The particle of light is the Photon**; has zero rest mass and always travels at speed c
- Energy of a photon is related to its wavelength or frequency:

$$\text{Energy, } E = \frac{hc}{\lambda} \quad = \; h\nu \qquad h = \text{Planck's constant}$$

$$\text{Note:} \quad \text{Short } \lambda \Rightarrow \text{High } E$$

$$\text{Long } \lambda \Rightarrow \text{Low } E$$

<u>The Electromagnetic Spectrum</u>

When we let sunlight or a lightbulb light pass through a prism, we see the colors of the rainbow, i.e. **The Visible Spectrum**.

<u>The Visible Spectrum</u> consists of light for which the human eye is sensitive.

Red $\lambda = 700\ nm$ $1\ nm = 10^{-9}\ m$

Orange

Yellow

Green

Blue

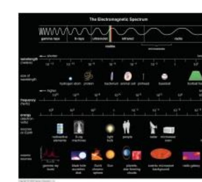
Indigo

Violet $\lambda = 400\ nm$

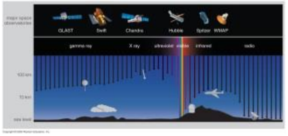
What about electromagnetic radiation with wavelengths greater than 700 nm or less than 400 nm?

The Entire Electromagnetic Spectrum

(Figure 5.2 in your text; also see Narrated Figure in your HW)



The Electromagnetic Spectrum



The Transparency (or Opacity) of the Earth's Atmosphere

The atmosphere of the Earth is **transparent**
(i.e. can propagate from the top of the atmosphere to the surface)
only in the Visible and parts of the Radio, UV, and IR band.

All other wavelengths are absorbed by molecules in the atmosphere.

This is good for us since things like gamma-rays, X-rays, & UV can kill us!
But it's bad for astronomy if you want to study all of the available radiation.

Some Important Points about the Electromagnetic Spectrum:

- All of the bands of EM radiation, visible, radio, IR, UV, etc. are the same thing; they just differ in wavelength.
- All EM radiation travels at the speed $c = 3 \times 10^5$ km/s in vacuum.
- Most wavelengths don't get through the Earth's atmosphere, so to observe at these, we must go to space.

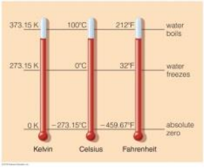
Radiation and Matter

Here, we seek to understand:

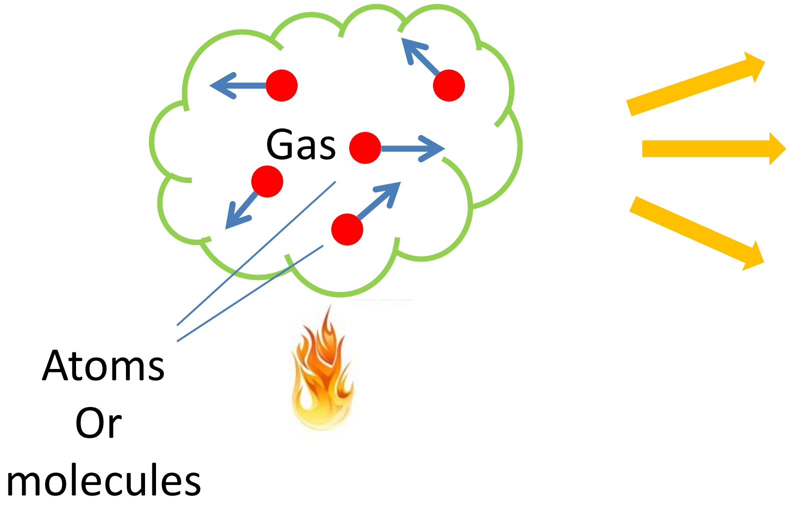
- How matter emits EM radiation
- How EM radiation and matter interact

Thermal and Blackbody Radiation:

Quick Aside: **Temperature Scales**
(almost always use Kelvin)



Thermal radiation is EM radiation emitted by any object at a non-zero temperature. **Where does it come from?**



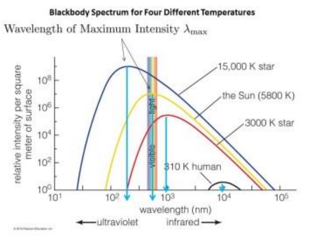
Accelerated charges radiate electromagnetic waves, i.e. light

Blackbody Radiation

A Blackbody is a perfect thermal emitter, which means that it reflects nothing so that all of the radiation measured for it, is it's own emitted thermal radiation.

Stars are very nearly blackbody radiators.

The Spectrum* of a Blackbody



Two Characteristics of BB Radiation:

- **Wien Displacement Law**: wavelength of maximum intensity decreases for higher temperatures.

$$\lambda_{\max} T = \text{constant}$$

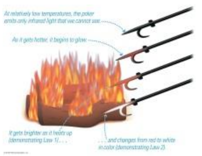
So hotter objects radiate strongest at shorter wavelengths

- **Stefan – Boltzmann Law**: the total emitted energy flux ("Luminosity") increases as the 4th power of the temperature

$$\text{Luminosity, } L = \sigma T^4 \qquad \sigma = \text{a constant}$$

So a hotter object radiates a lot more energy than a cooler object

Perhaps you've seen these two laws in action playing with a poker in a fire

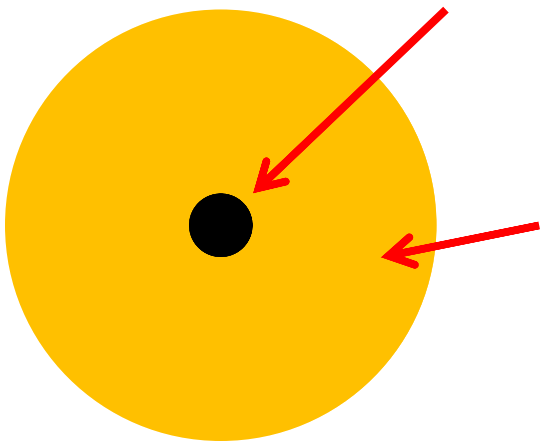


*The word spectrum here means the intensity of radiation at different wavelengths.

The Structure of Atoms

Why is this important to us? To understand the light from stars, we have to have an understanding of the matter that creates and interacts with the light.

The Atom:



Nucleus: positive **protons** and neutral **neutrons** (contains almost all of the mass)

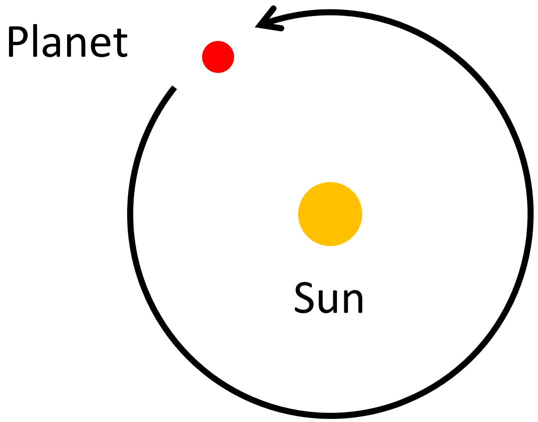
Electrons: negatively charged, same number as the number of protons

What holds the atom together? **The electric force between the positive protons and the negative electrons.**

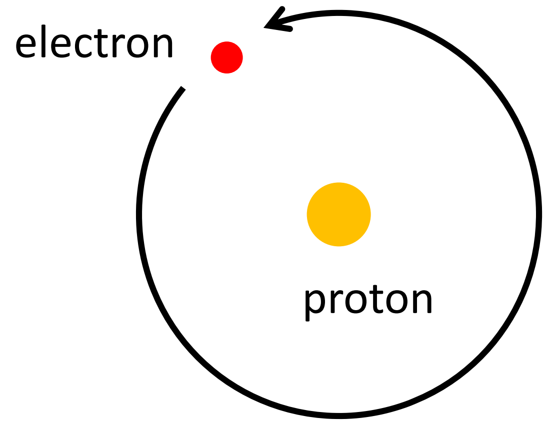
The Structure of Atoms

So an atom is like a little solar system:

Solar System (Gravity)



Hydrogen Atom (Electric Force)



But, **the physics of atoms is not the same as the physics of solar systems**.

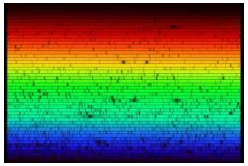
Quantum physics says that the electron can occupy only certain **"allowed orbits"** or **energy levels.**

When an atom absorbs a photon, the electron goes to a higher energy level; when the atom emits a photon, the electron drops to a lower level.

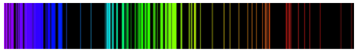
Each element has different numbers of electrons and has its own unique electron structure and allowed energy levels which gives each element its own unique spectrum.

The Interaction of Radiation & Atoms: Spectral Lines

When astronomers analyze the light from stars, they observe:



- The spectra are generally blackbody indicating that the radiation is produced by material at a high temperature
- Superimposed on the BB spectra are dark lines where radiation is missing; these are called **Absorption Lines**
- Some objects don't show a BB spectrum, but do show emitted radiation at discrete wavelengths: these are called **Emission Lines.**



<u>Where do these lines come from and what good are they?</u>

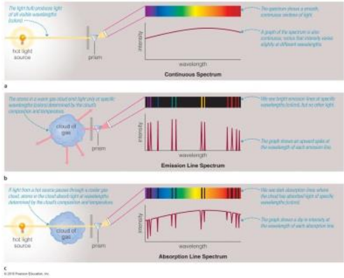


Figure 5-8 from your text

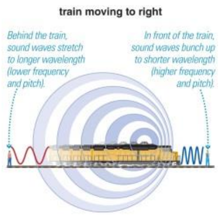
Figure 5-8 animated

Every element or molecule has it's own unique emission and absorption spectrum.

(*This allows us to determine what an object is made of!*)

The Doppler Effect

The Doppler Effect refers to the change in wavelength (or frequency) of waves emitted from a moving source or when the observer is moving.



b For a moving train, the sound you hear depends on whether the train is moving toward you or away from you.

Why does this happen for the train?

For light, the Doppler Effect is similar, but

For light, a change in wavelength means a change in color.

- Moving away (receding) is called **"Red Shift"**
- Moving toward (approaching) is called **"Blue Shift"**

What does the Doppler Effect do for us?

Finding the shift in spectral lines, allows astronomers to **measure an object's relative velocity** toward or away from us.