# Light and Matter (No LC Today)

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, and in 2024, pieces of the asteroid Bennu.
- 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:





Even in Newton's time, people like **Christian Huygens** had proposed a **Wave Theory of Light**, but this was not demonstrated until the early 19<sup>th</sup> 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 –usually in a stadium.

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

### **Characteristics of a Wave**



Wavelength,  $\lambda = \text{Distance}$  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**:

 $c = 3 \times 10^5 \ km/s$  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 20<sup>th</sup> 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: Energy,  $E = \frac{hc}{\lambda} = h\nu$  h = Planck's constantNote: Short  $\lambda \Rightarrow$  High ELong  $\lambda \Rightarrow$  Low E

# **The Electromagnetic Spectrum**

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

The Visible Spectrum consists of light for which the human eye is sensitive.

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, frequency, and energy.
- All EM radiation travels at the speed  $c = 3 \times 10^5 \text{ km/s}$  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.

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

# Wavelength of Maximum Intensity A<sub>max</sub>

#### So hotter objects radiate strongest at shorter wavelengths

• Stefan – Boltzmann Law: the total emitted energy flux,

Luminosity = area under the BB curve,

increases as the 4<sup>th</sup> power of the temperature

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

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.  $_{10}$ 

# **The Structure of Atoms**



What holds the atom together? The electric force between the positive protons and the negative electrons. Opposite charges, so the force is attractive.

## **The Structure of Atoms**

So an atom is like a little solar system:



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.

H-atom PhET

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.

#### Where do these lines come from and what good are they?

### Figure 5-8 from your text

(Part of your HW will be using the animated version of a figure similar to this one.)

**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.

#### 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.





ard you or away from you

