Astronomy 210
Section 1– MWF 1500-1550
134 Astronomy Building

This Class (Lecture 9):

The Two-Body Problem

Next Class:

Electromagnetic Radiation

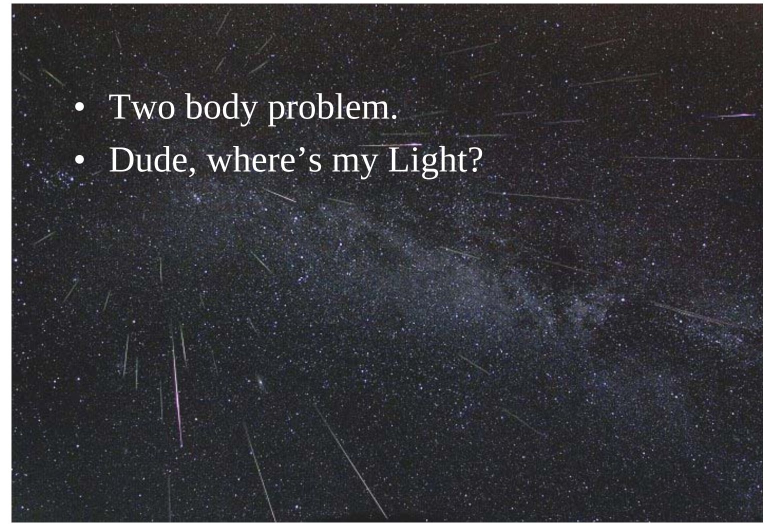
Planetarium Observing

Stardial Observing

HW#3 due on Friday

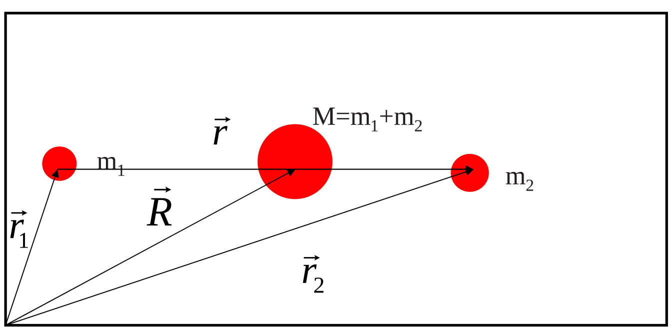
Music: *Particle Man* – They Might be Giants

Outline



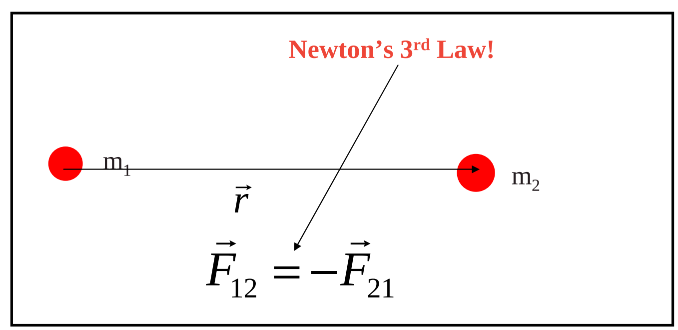
- Two body problem.
- Dude, where's my Light?

Center of Mass (COM)



Force in the Box

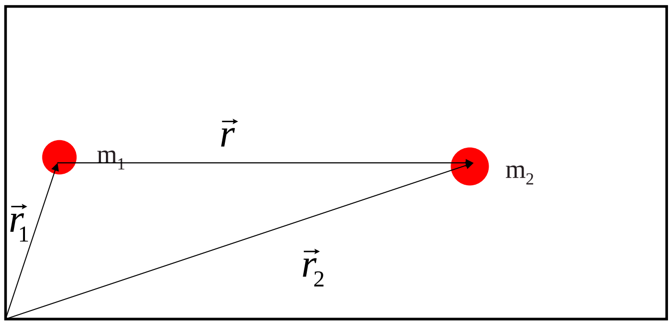
$$\vec{F}_{12} = G\frac{m_1 m_2}{r^2}\hat{r} = G\frac{m_1 m_2}{r^3}\vec{r} \qquad \vec{F}_{21} = -G\frac{m_1 m_2}{r^3}\hat{r}$$



Reduced Mass

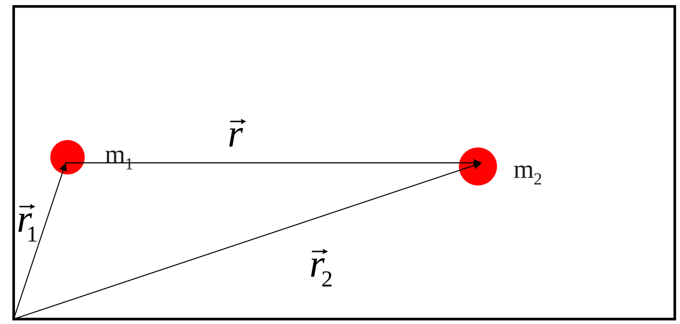
$$m_1\ddot{\vec{r}}_1 = \vec{F}_{12}$$
$$m_2\ddot{\vec{r}}_2 = \vec{F}_{21}$$

$$but\ \ddot{\vec{r}} = \ddot{\vec{r}}_2 - \ddot{\vec{r}}_1$$



Reduced Mass

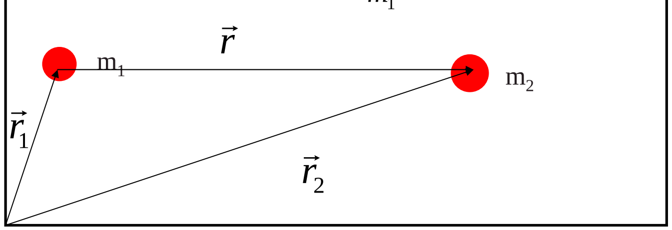
$$\ddot{\vec{r}} = \frac{\vec{F}_{21}}{m_2} - \frac{\vec{F}_{12}}{m_1} = \vec{F}_{21}\left(\frac{1}{m_2} + \frac{1}{m_1}\right)$$



Reduced Mass

$\mu\ddot{\vec{r}} = \vec{F}_{21}$ Identical to simplified case, but now mass is modified.

$$note: if\ m_2 << m_1\ then\ \mu \approx \frac{m_1 m_2}{m_1} = m_2 \ \text{or}\ \ddot{\vec{F}}_{21} = m_2\ddot{\vec{r}}$$



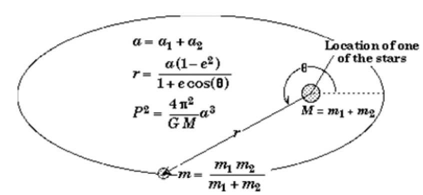
Reduced Mass Frame

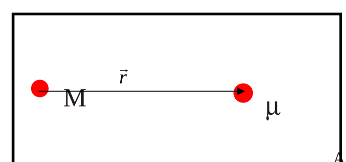
$\mu\ddot{\vec{r}} = \vec{F}_{21}$

- System can be thought of a *test particle* of reduced mass that is orbiting a mass M = $m_1 + m_2$

$$\mu\ddot{\vec{r}} = -G\frac{M\mu}{r^3}\vec{r}$$

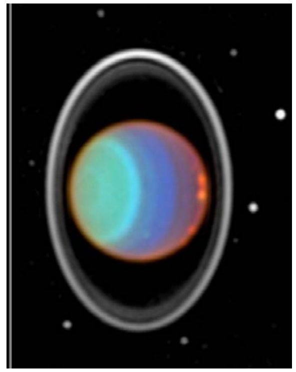
$$\ddot{\vec{r}} = -G\frac{M}{r^3}\vec{r}$$

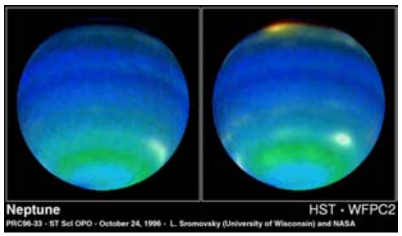




Problem with Gravity?

- What's going on?
- What do you think?
- Throw out Newton? No one complained when I threw out Ptolemy (around longer)





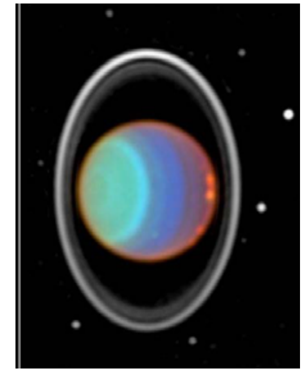
Unknown mass, right at predicted location in 1846.

Victory snatched from jaws of defeat!!!!

 http://lyra.colorado.edu/sbo/hubble/ss/ss.html

Problem with Gravity?

- 1830's: Uranus observed orbit did not follow predictions of Newtonian solar system model.
- Was this the death of Newton's gravity?
- Not good. Theory has to agree with all data, not just some.
- So despite great job with planets, moons, other stars, even one clear failure is enough. (e.g. Mars forced us to throw out circular orbits.)



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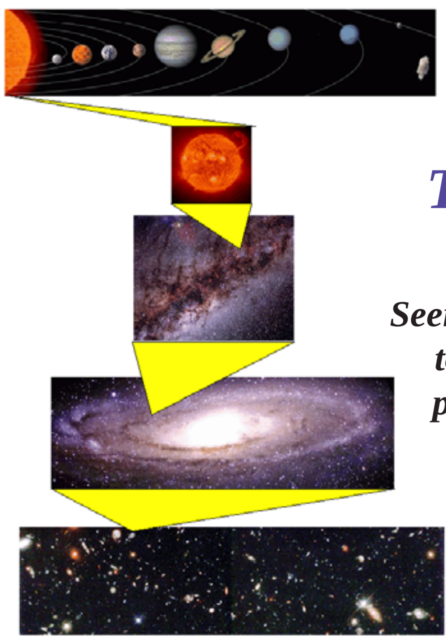


Astronomy: The Big Picture

Seeing how all these pieces fit together into a coherent picture of our Universe!

Lighten Up

- In astronomy, we usually **cannot** perform experiments.
- The only way to get information from our subject of study (stars, planets, galaxies) is by ***observing*** their light
- We use telescopes to collect the light that comes to the Earth from distant objects
- To be able to extract the valuable information out of the light we collect, we must understand light.

Light my Fire

- Human beings are *visual*
- We have relied mostly on sight in our existence
  - In ancient times, to find food and shelter
  - Today, to interact with our modern world
- But what is light?
  - Why does light come in different colors?
  - How does light behave?
  - What is infrared? Ultraviolet? X-rays? Radio waves?

What is Light?

- Light is ***radiant energy***
- On a nice sunny day, you can feel the energy of the sunlight as it warms your skin.

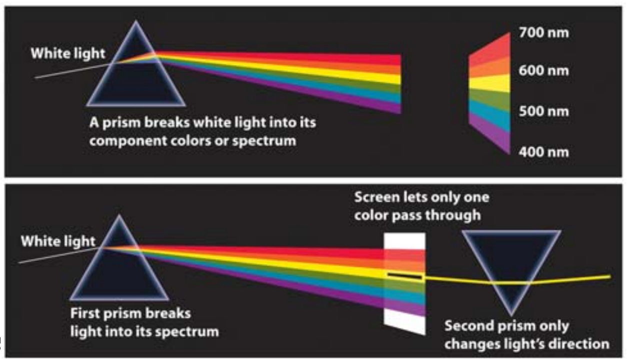
Name Some things that shine by (emit) their own light?

The Colors of Light

- In ancient times, it was thought that light's fundamental color was *white*
- Colors were created by interactions with objects
  - For example, light would be "colored" by the flowers
- It wasn't until the 1600's that Isaac Newton discovered that "white light" is a *mixture* of all the colors of the rainbow

Colors of the Rainbow

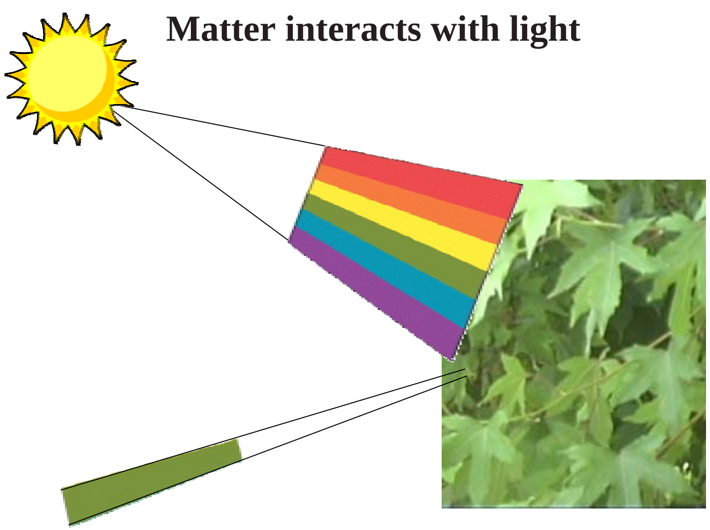
- Newton used a prism to separate white light into its component colors
  - Called a **spectrum**
- Then used a second prism to recombine the spectrum back into white light
- Showed white light is a mixture of many colors



Where Do Colors Come From?

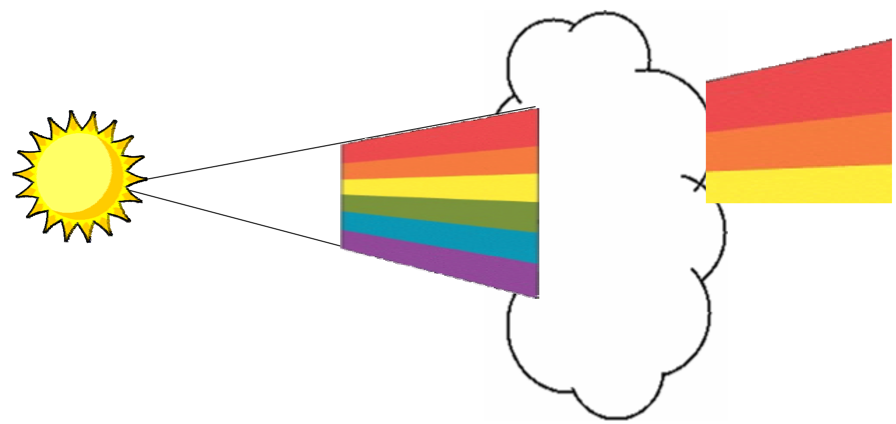
- The color of light is determined by its wavelength
- Visible light has extremely small wavelengths
  – Wavelengths range from 400 nm (violet light) to 700 nm (red light)
- Colors, from longest wavelength to shortest: **red**, **orange**, **yellow**, **green**, **blue**, **violet**

Matter interacts with light



Reflection

Matter interacts with light



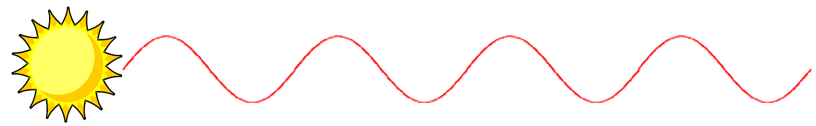
Absorption

Matter interacts with light

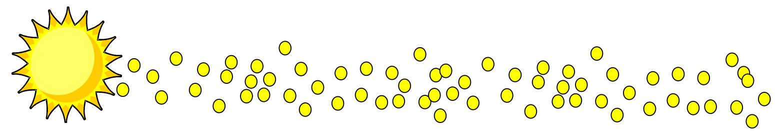
Scattering

Particle or Wave?

- So, how does light behave?



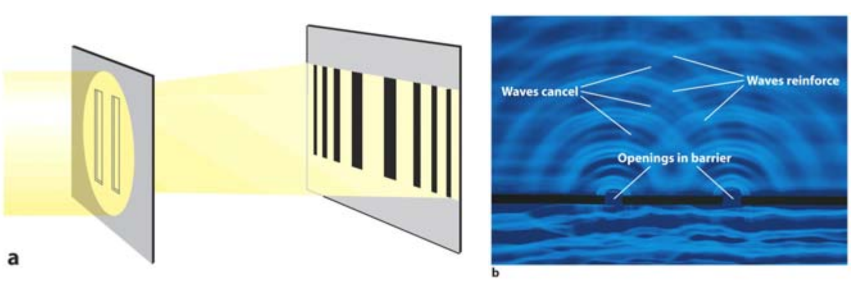
- **Huygens:** light travels in the form of waves of energy



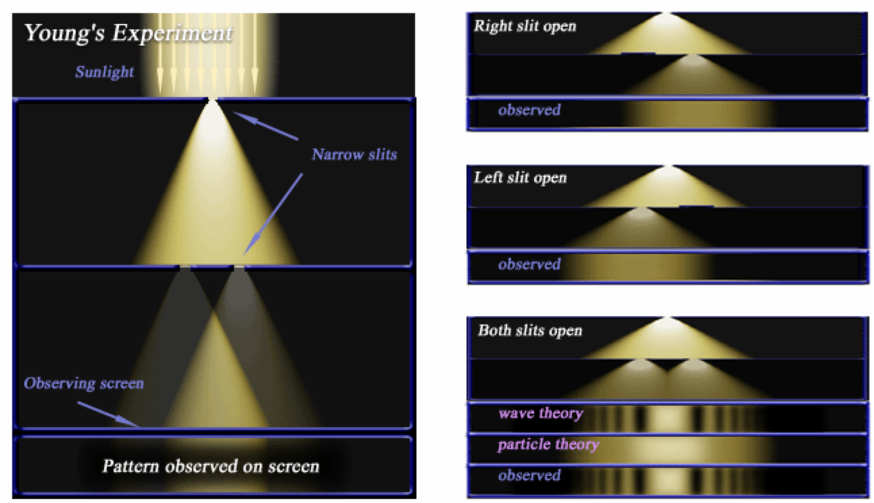
- **Newton:** light is composed of a large number of particles

Light is a Wave!

- In 1801, an English physicist demonstrated that light travels as a wave
- When a single color of light is passed through a double slit, a pattern light and dark bands is produced
- Can only be explained by wave-like behavior



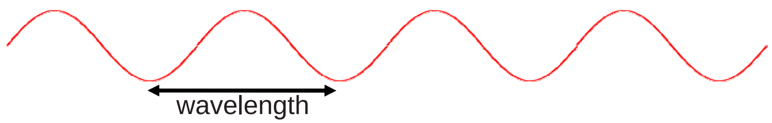
Thomas Young: Light is a wave
Double-slit experiment (1801)



Wikipedia

Light as a Wave

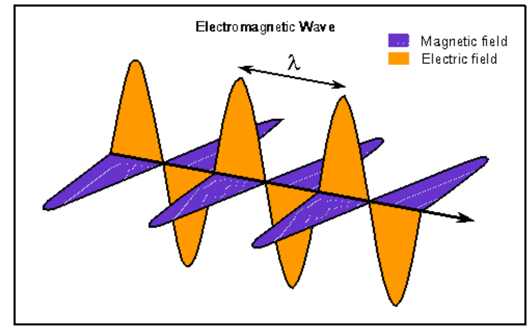
- The fundamental properties of a wave are its *wavelength* and *frequency*



- **Wavelength** (λ) is the distance between successive crests of a wave
- **Frequency** (ν) the number of wave crests that pass by an observer per second (1/period)
- **Wavelength x Frequency = the speed of a wave**

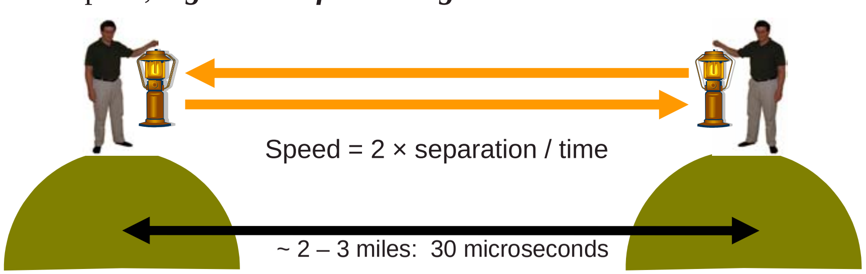
Electromagnetic Radiation

- In the 1860s, a Scottish physicist named Maxwell created new theories of electricity and magnetism
- Suggested that light is traveling electric and magnetic energy
- Geek speak for light – *electromagnetic radiation*
- Predicted "invisible" light!



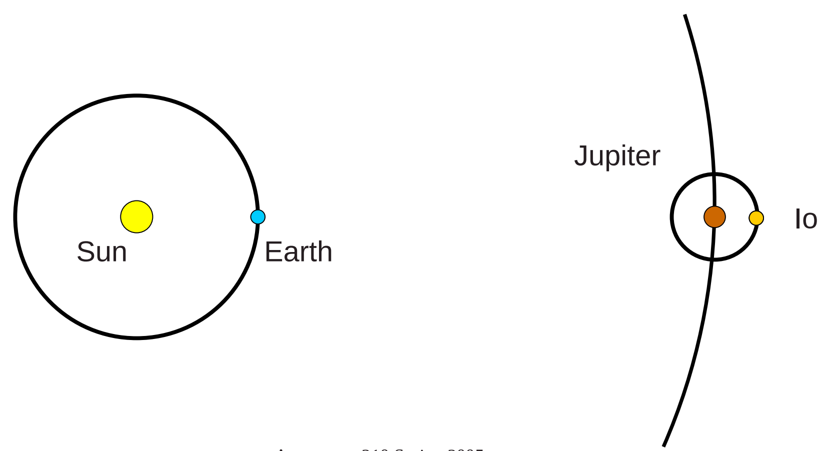
The Speed of Light

- The ancient Greeks believed speed of light was infinite
- In the 1600s Galileo realized that "very fast" is not the same as "infinite"
  - First to suggest an experiment to measure speed of light
- Maxwell theorized that light waves travel at the same speed, ***regardless of wavelength***



Light travels with a finite speed

First actual measurement by Ole Roemer in 1675 using Jupiter's moon Io – eclipses by Jupiter delayed by several minutes (16 mins) every six months because of extra light travel distance



How Fast is Light?

- Measured in 1675 at 8¼ minutes per AU
- Today, we know the speed of light to be **$c = 3\times10^8$ m/s** (186,000 miles per second)!
- How fast is that?
  - Around the Earth over 7 times in a second
  - From Earth to the Moon in under 2 seconds (it took the astronauts 2 weeks)
  - From the Sun to the Earth in a little over 8 minutes
  - From the Sun to Pluto in about 5½ hours
  - From the nearest star to Earth, about 4 years

Light travels with a finite speed

- Light has a finite speed that is the same for all observers. Regardless of the observer's speed. (Special relativity).
- In some $\Delta t = P = 1/\nu$, the wave moves $\Delta x = \lambda$, so the speed is $c = \Delta x / \Delta t = \lambda \nu$
- Nowadays we **define** the speed of light to be 2.99792458×10^8 m/s
- The **second** is defined very precisely using atomic clocks

  (9.192631770×10^9 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom near 0 K, if you must know)
- Thus, the **meter** is defined as the distance traveled by light in vacuum during $1/(2.99792458 \times 10^8)$ second

A Light Year

The **light-year**

- Distance that light travels in one year
- Speed of light: $\approx 3.00\times10^5$ km/sec
- Seconds in one year:

$$\left(60\frac{\text{sec}}{\text{min}}\right)\times\left(60\frac{\text{min}}{\text{hour}}\right)\times\left(24\frac{\text{hour}}{\text{day}}\right)\times\left(365\frac{\text{days}}{\text{year}}\right)=3.16\times10^7\,\text{sec}$$

so 1 light year = $(3.00\times10^5$ km/sec$) \times (3.16\times10^7$ sec$) = 9.42\times10^{12}$ km

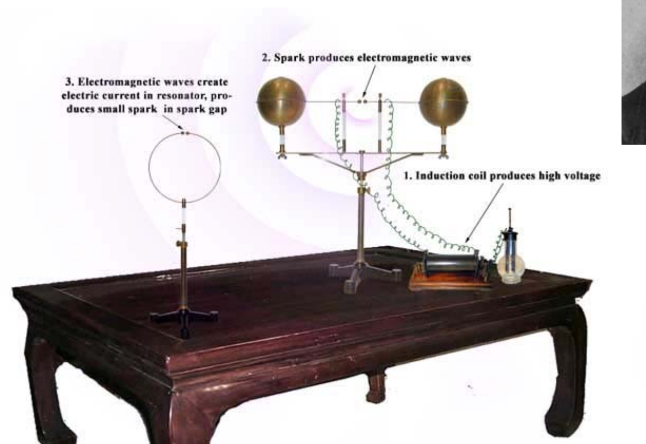
- Nearest star (Proxima Centauri) is about 4.2 light years away.
- Analogous to saying: Chicago is about 2 hours away.

Invisible Forms of Electromagnetic Radiation

- Visible light has a range of wavelengths from 400-700 nm
- But what about light with longer or shorter wavelengths?
- Maxwell's theories placed no restrictions on the wavelength of light
- There are types of light outside of the wavelength range that our eyes respond to!

The discovery of radio waves

Heinrich Hertz's experiment (1885)



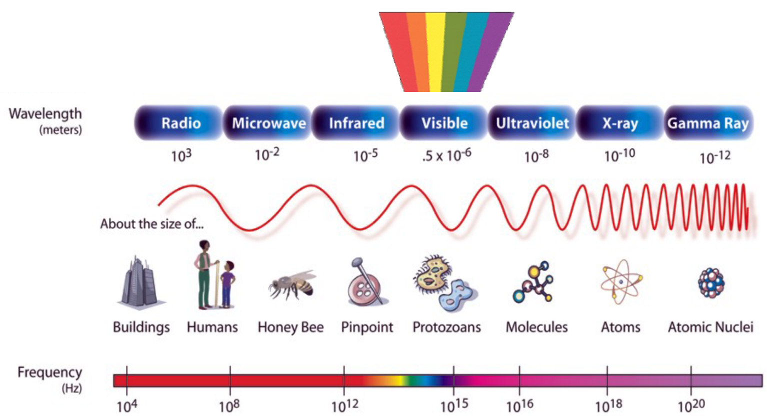
The discovery of X-rays

Wilhelm Roentgen (1895)

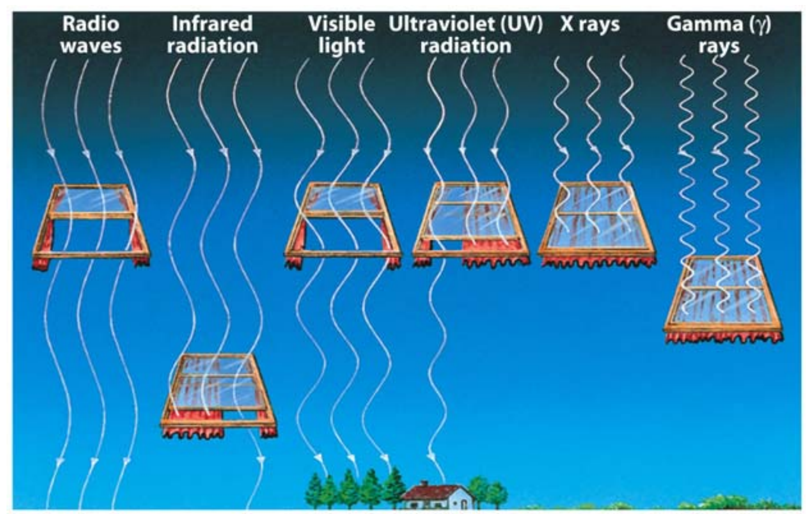
Radiograph of the hand of the anatomist Privy Councillor von Koelliker in Würzburg, taken by W. C. Röntgen in Würzburg on January 23, 1896

The electromagnetic spectrum

- Visible light is only a tiny portion of the full electromagnetic spectrum
- Red light has longer wavelength/lower frequency/lower energy than blue light
- Divisions between regions are really only from biology or technologies.

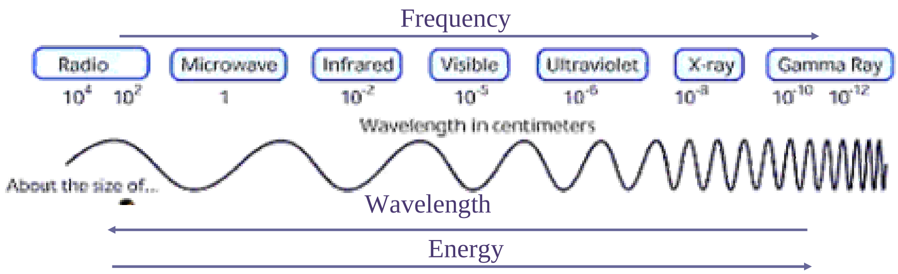


The atmosphere absorbs some wavelengths and not others



Frequency

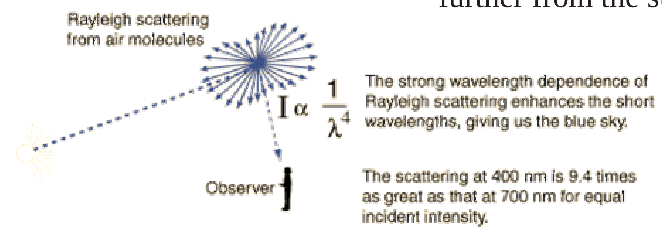
- The frequency of light depends on its color.
- The unit is Hertz, equivalent to 1 cycle a second.
- For radio waves, we normally use larger units
  - 1 kHz = 1000 Hz
  - 1 MHz = 10^6 Hz
  - 1 GHz = 10^9 Hz



Why is the Sky Blue?

Atmospheric nitrogen and oxygen scatter the blue part of the spectrum via Rayleigh scattering (when molecules are up to λ/10).

Note that the blue of the sky is more saturated when you look further from the sun.



http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html#c2

Light is also a Particle!

- In 1905, Einstein showed that light also behaves as a particle
- Light particles are called ***photons (symbol γ)***
- The energy of a photon increases as the frequency of the light increases (and the wavelength decreases)

$$E = h\nu$$

- Planck's constant (h=6.63 x 10^{-34} J s)
- That means that a 100-watt light bulb emits 3×10^{20} photons per second!
- What does this mean for a laser pointer?