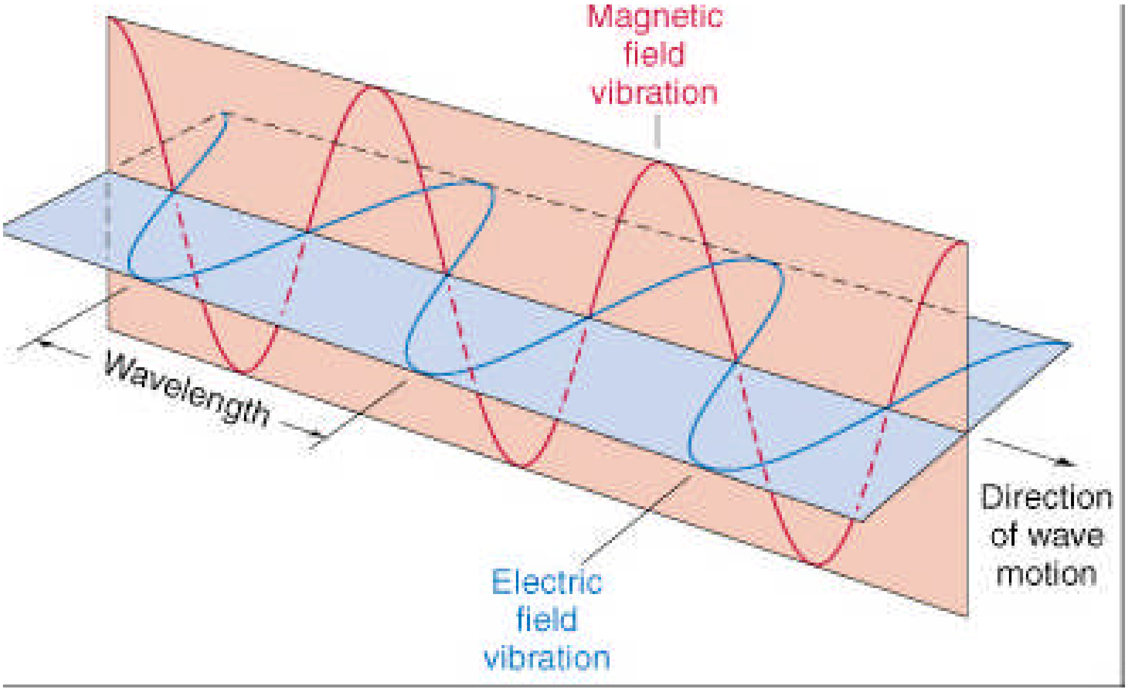
# Atoms and Radiation

The information about astronomical objects (planets, stars, galaxies) can be obtained by studying the electromagnetic radiation emitted by those objects. Astronomers use the laws of physics, as we know them here on Earth, to interpret the **electromagnetic radiation** emitted by these objects.

**Radiation** is any way in which energy is transmitted through space from one point to another without the need for any physical connection between those two locations.
The term **electromagnetic** just means that the energy is carried in the form of rapidly fluctuating electric and magnetic fields.
**Virtually all information about the universe beyond Earth's atmosphere has been obtained from analysis of electromagnetic radiation received from afar.**

**All types of electromagnetic radiation travel through space in the form of *waves*.**
A **wave** is a way in which energy is transferred from place to place without physical movement of material from one location to another. In wave motion, the energy is carried by a disturbance of some sort. This disturbance, whatever its nature, occurs in a distinctive repeating pattern. Ripples on the surface of a pond, sound waves in air, and electromagnetic waves in space, despite their many obvious differences, all share this basic defining property.

The disturbance produced by the moving charge actually consists of vibrating electric *and* magnetic fields, always oriented perpendicular to one another and moving together through space. These fields do not exist as independent entities; rather, they are different aspects of a single physical phenomenon: **electromagnetism.** Together, they constitute an electromagnetic wave that carries energy and information from one part of the universe to another.
Consider a real cosmic object—a star. When some of its charged contents move around, their electric fields change, and we can detect that change. The resulting electromagnetic ripples travel outward in waves, requiring no material medium in which to travel.



**Electromagnetic Wave** Electric and magnetic fields vibrate perpendicular to each other. Together they form an electromagnetic wave that moves through space at the speed of light in the direction perpendicular to both the electric and the magnetic fields comprising it.
**Both theory and experiment tell us that all electromagnetic waves move at a very specific speed—the speed of light (always denoted by the letter *c*). Its exact value is 299,792.458 km/s in a vacuum (and somewhat less in material substances such as air or water). We will round this value off to *c* = 3.00 $10^5$ km/s. If the currently known laws of physics are correct, then the speed of light is the fastest speed possible.**

## Electromagnetic Radiation

Light is a form of electromagnetic radiation. Other forms of electromagnetic radiation include
- radio waves,
- microwaves,
- infrared radiation,
- ultraviolet rays,
- X-rays, and
- gamma rays.

All of these, known collectively as the **electromagnetic spectrum**, are fundamentally similar in that they move at 186,000 miles per second, the speed of light. The only difference between them is their wavelength, which is directly related to the amount of energy the waves carry. *The shorter the wavelength of the radiation, the higher the energy.*

The rainbow of colors that we see in visible light represents only a very small portion of the electromagnetic spectrum.

- On one end of the spectrum are radio waves with wavelengths billions of times longer than those of visible light.
- On the other end of the spectrum are gamma rays. These have wavelengths millions of times smaller than those of visible light.

The following are the basic categories of the electromagnetic spectrum, from longest to shortest wavelength:

**Radio waves** are used to transmit radio and television signals.
Radio waves have wavelengths that range from less than a centimeter to tens or even hundreds of meters.
- FM radio waves are shorter than AM radio waves. For example, an FM radio station at 100 on the radio dial (100 megahertz) would have a wavelength of about three meters.
- An AM station at 750 on the dial (750 kilohertz) uses a wavelength of about 400 meters.
- Radio waves can also be used to create images. Radio waves with wavelengths of a few centimeters can be transmitted from a satellite or airplane antenna. The reflected waves can be used to form an image of the ground in complete darkness or through clouds.

**Microwave** wavelengths range from approximately one millimeter (the thickness of a pencil lead) to thirty centimeters (about twelve inches).
- In a microwave oven, the radio waves generated are tuned to frequencies that can be absorbed by the food. The food absorbs the energy and gets warmer. The dish holding the food doesn't absorb a significant amount of energy and stays much cooler.

- Microwaves are emitted from the Earth, from objects such as cars and planes, and from the atmosphere. These microwaves can be detected to give information, such as the temperature of the object that emitted the microwaves.

**Infrared** is the region of the electromagnetic spectrum that extends from the visible region to about one millimeter (in wavelength).
Infrared waves include thermal radiation. For example, burning charcoal may not give off light, but it does emit infrared radiation which is felt as heat.

- Infrared radiation can be measured using electronic detectors and has applications in medicine and in finding heat leaks from houses.
- Infrared images obtained by sensors in satellites and airplanes can yield important information on the health of crops and can help us see forest fires even when they are enveloped in an opaque curtain of smoke.

The rainbow of colors we know as **visible light** is the portion of the electromagnetic spectrum with wavelengths between 400 and 700 billionths of a meter (400 to 700 nanometers).
Visible light is the part of the electromagnetic spectrum that we see, and coincides with the wavelength of greatest intensity of sunlight.
Visible waves have great utility for the remote sensing of vegetation and for the identification of different objects by their visible colors.

**Ultraviolet radiation** has a range of wavelengths from 400 billionths of a meter to about 10 billionths of a meter.
Sunlight contains ultraviolet waves which can burn your skin. Most of these are blocked by ozone in the Earth's upper atmosphere.
A small dose of ultraviolet radiation is beneficial to humans, but larger doses cause skin cancer and cataracts.

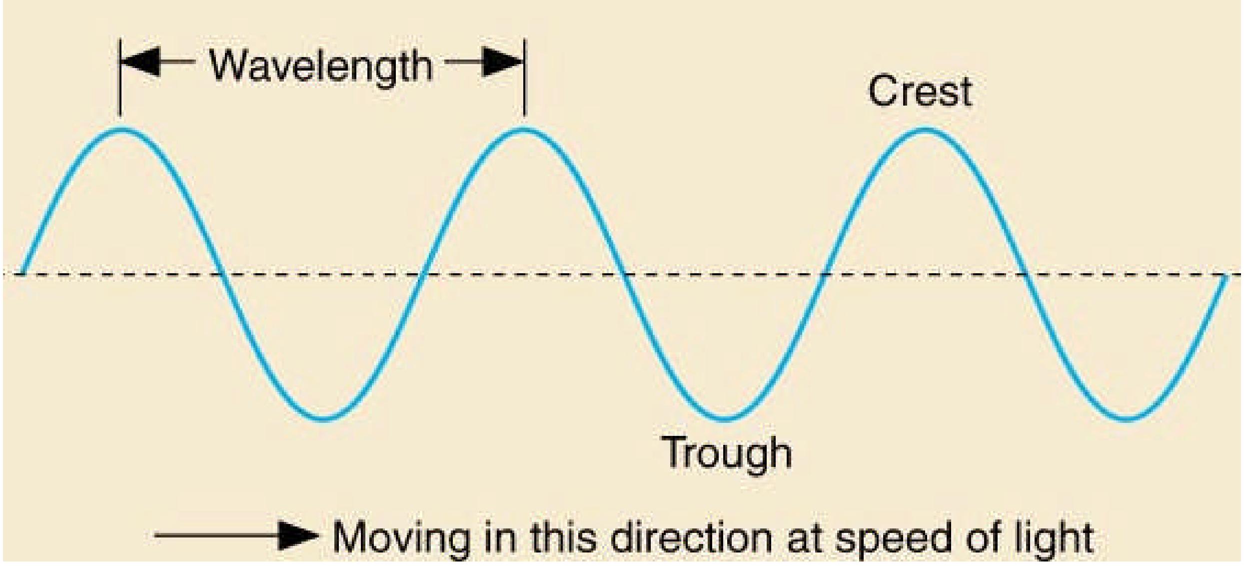
- Ultraviolet wavelengths are used extensively in astronomical observatories.
- Some remote sensing observations of the Earth are also concerned with the measurement of ozone.

**X-rays** are high energy waves which have great penetrating power and are used extensively in medical applications and in inspecting welds.
The wavelength range is from about ten billionths of a meter to about 10 trillionths of a meter. X-ray images of our Sun can yield important clues to solar flares and other changes on our Sun that can affect space weather.

**Gamma rays** have wavelengths of less than about ten trillionths of a meter. They are more penetrating than X-rays.

- Gamma rays are generated by radioactive atoms and in nuclear explosions, and are used in many medical applications.
- Images of our universe taken in gamma rays have yielded important information on the life and death of stars, and other violent processes in the universe.

## Properties of Waves



**The wave period** is the number of seconds needed for the wave to repeat itself at some point in space. **The wavelength** is the number of meters needed for the wave to repeat itself at a given moment in time. It can be measured as the distance between two adjacent wave *crests*, two adjacent wave *troughs*, or any other two similar points on adjacent wave cycles (for example, the points marked in the figure). **The amplitude** is the maximum departure of the wave from the undisturbed state—still air, say, or a flat pond surface**. The wave's frequency** is the number of wave crests passing any given point per unit time is called.

## Opacity of the atmosphere

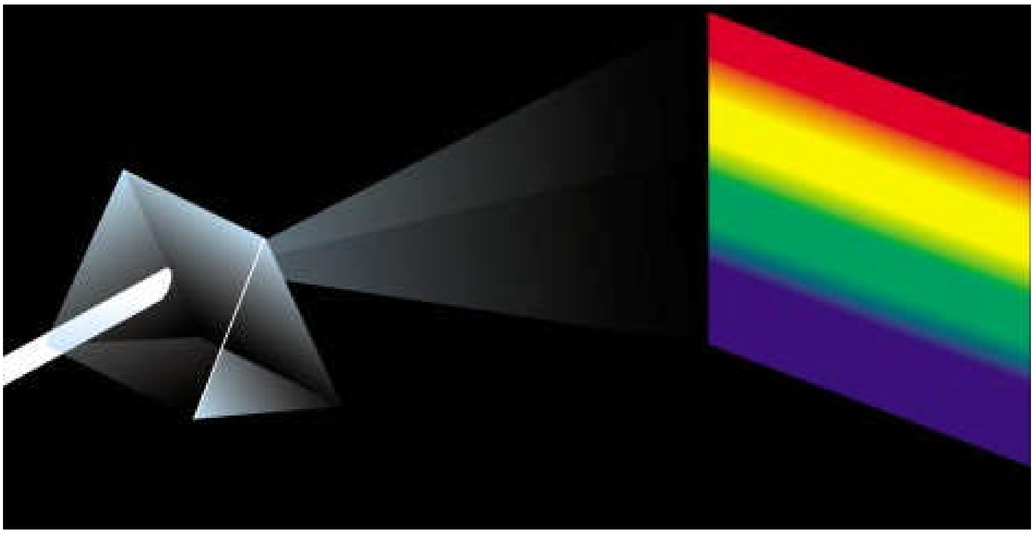
Only a small fraction of the radiation produced by astronomical objects actually reaches Earth's surface because of the ***opacity*** of our planet's atmosphere.

Opacity is the extent to which radiation is blocked by the material through which it is passing—in this case, air. The more opaque an object is, the less radiation gets through it: Opacity is just the opposite of transparency. Earth's atmospheric opacity is plotted along the wavelength and frequency scales at the bottom of the Electromagnetic Spectrum Figure. The extent of shading is proportional to the opacity. Where the shading is greatest, no radiation can get in or out. Where there is no shading at all, the atmosphere is almost completely transparent.

What causes opacity to vary along the spectrum? Certain atmospheric gases absorb radiation very efficiently at some wavelengths. For example, water vapor ($H_2O$) and oxygen ($O^2$) absorb radio waves having wavelengths less than about a centimeter, while water vapor and carbon dioxide ($CO_2$) are strong absorbers of infrared radiation. Ultraviolet, X-ray, and gamma-ray radiation are completely blocked by the *ozone layer* ($O_3$) high in Earth's atmosphere. A passing but unpredictable source of atmospheric opacity in the visible part of the spectrum is the blockage of light by atmospheric clouds.

# The Action of a Prism

When we pass a beam of white sunlight through a prism, we see a rainbow-colored band of light that we call a continuous spectrum.



White light is a mixture of colors, which we conventionally divide into six major hues—red, orange, yellow, green, blue, and violet. we can separate a beam of white light into a rainbow of these basic colors—called a *spectrum* (plural, *spectra*)—by passing it through a prism. This experiment was first described by Isaac Newton over 300 years ago.

A prism splits a beam of light up into separate colors because light rays of different frequencies are bent, or *refracted,* slightly differently as they pass through the prism—red light the least, violet light the most. The other colors we see have frequencies and wavelengths intermediate between these two extremes, spanning the entire visible spectrum shown in the figure below. Radiation outside this range is invisible to human eyes.

Scientists often use a unit called the **nanometer** (nm) when describing the wavelength of light. 1 meter = $10^9$ nanometers. An older unit called the **angstrom** (1 Å = $10^{-10}$ m = 0.1 nm) is also widely used.

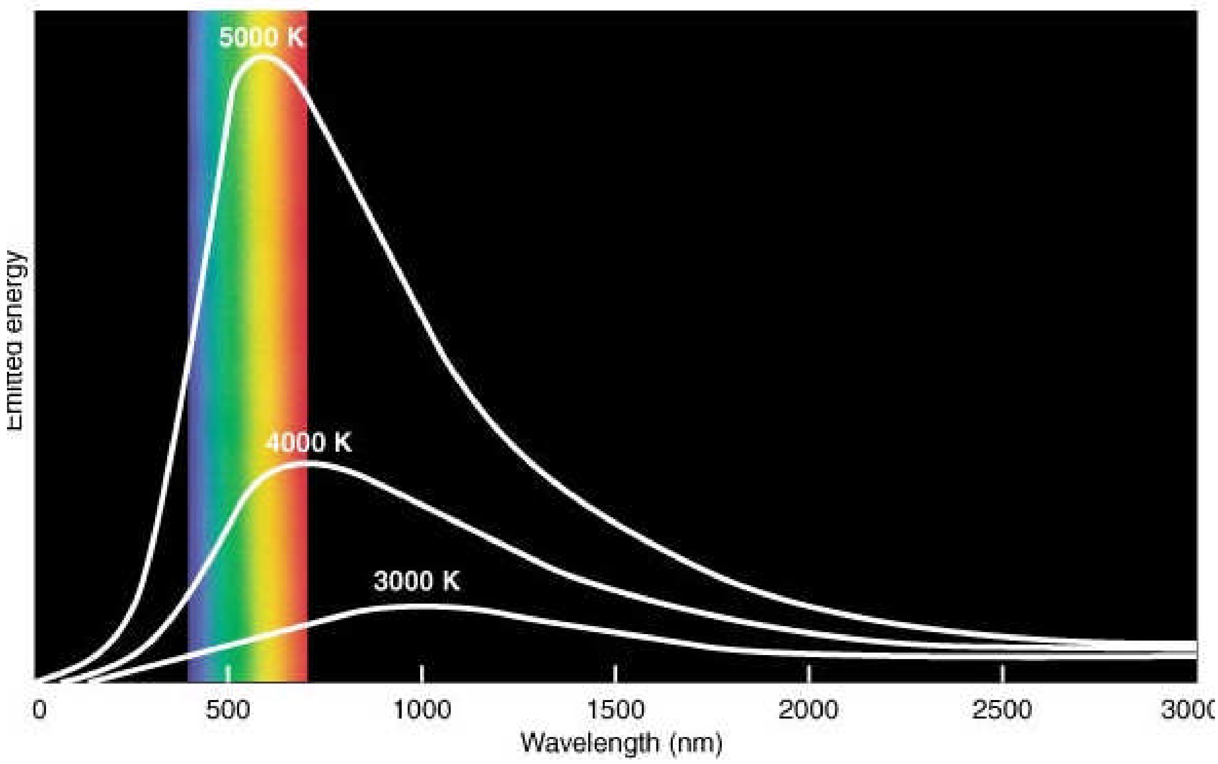
The visible spectrum covers the wavelength range from 400 nm to 700 nm (4000 Å to 7000 Å). The radiation to which our eyes are most sensitive has a wavelength near the middle of this range, at about 550 nm (5500 Å), in the yellow-green region of the spectrum. This wavelength falls within the range of wavelengths at which the Sun emits most of its electromagnetic energy—our eyes have evolved to take greatest advantage of the available light.

## Radiation and Temperature

At the microscopic level, everything in nature is in motion. A solid is composed of molecules and atoms that are in continuous vibration. A gas consists of molecules that are flying about freely at high speed, continually bumping into one another and bombarding the surrounding matter.
The hotter the solid or gas, the more rapid the motion of the molecules or atoms. The **temperature** of something is just a measure of the average energy of the particles that make it up.

## Blackbody Curves

The graph below counts the number of photons (or the total amount of energy) given off at different wavelengths for blackbodies at three different temperatures (three white curves). Note that at hotter temperatures, more energy is emitted at all wavelengths. The higher the temperature, the shorter the wavelength at which the peak amount of energy is radiated (this is called Wien's Law).



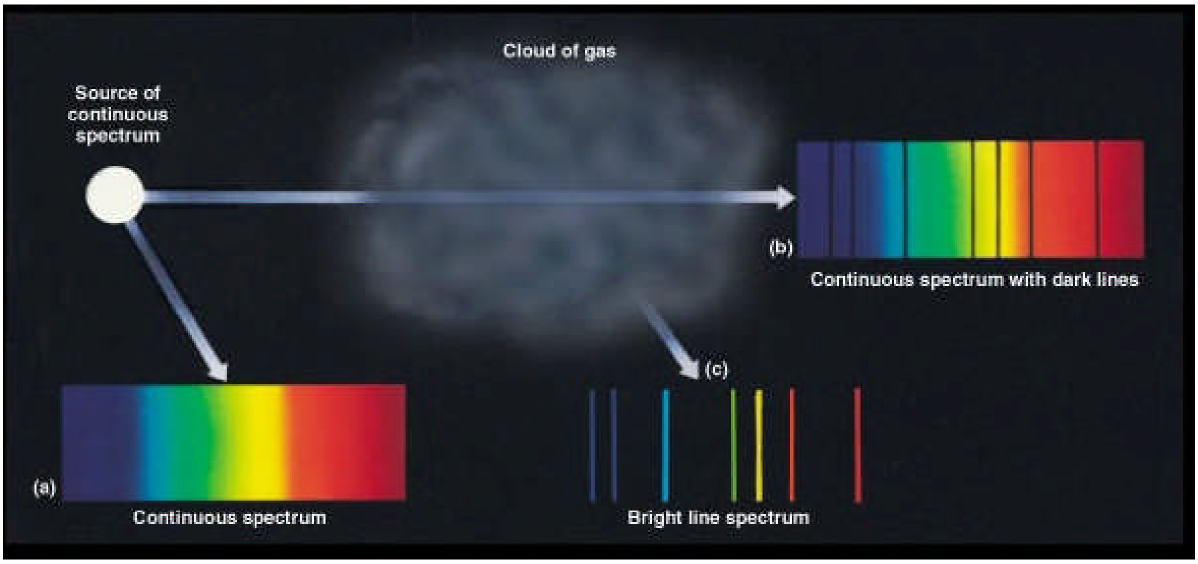
## Spectroscopy in Astronomy

Celestial bodies generate or reflect all forms of electromagnetic radiation, of which the most familiar form to us (since our eyes are sensitive to it) is light. This electromagnetic radiation, arriving at the Earth and viewed with various devices like telescopes and radio receivers, is our major (and in some cases sole) source of information about the heavens. Electromagnetic radiation carries a tremendous amount of information about the nature of stars and other astronomical objects.

- To extract this information, astronomers must be able to study the amounts of energy we receive at different wavelengths.
- Therefore, in spectroscopy, astronomers measure brightness versus wavelength, (think of an example of a prism that breaks light up into its component wavelengths, producing a spectrum (like a rainbow).

## Three Kinds of Spectra

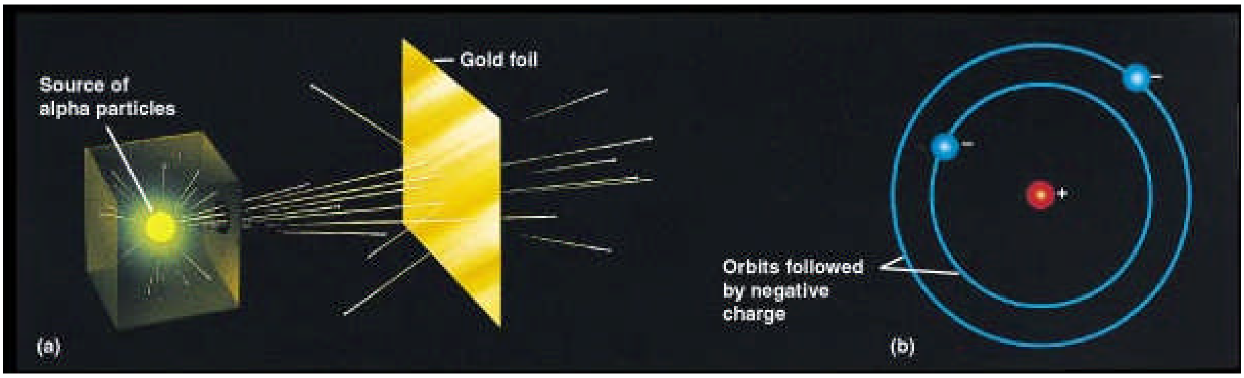
When we see a lightbulb or other source of continuous radiation
(a), all the colors are present. When the continuous spectrum is seen through a thinner gas cloud, the cloud's atoms produce absorption lines in the continuous spectrum
(b). When the excited cloud is seen without the continuous source behind it, its atoms produce emission lines
(c). We can learn which types of atoms are in the cloud from the pattern of the absorption or emission lines.



## Rutherford's Experiment

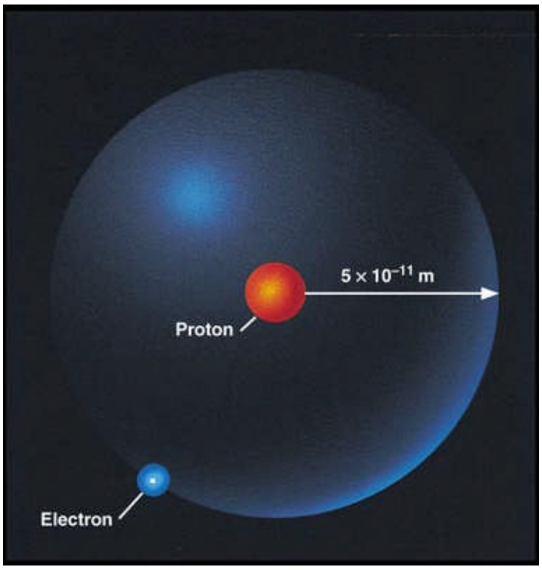
When Rutherford allowed alpha particles from a radioactive source to strike a target of gold foil, he found that, although most of them went straight through, some of them rebounded back in the direction from which they came.

From this experiment, he concluded that the atom must be constructed like a miniature solar system, with the positive charge concentrated in the nucleus and the negative charge orbiting in the large volume around the nucleus.



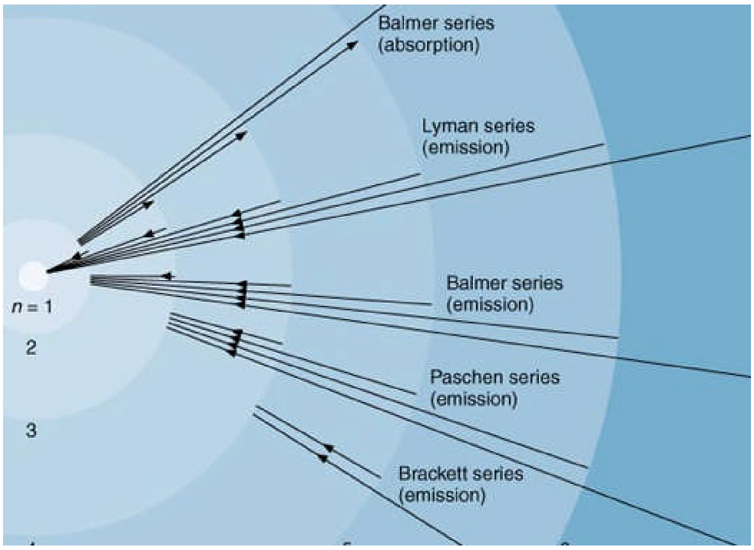
## The Hydrogen Atom

This is a schematic diagram of a hydrogen atom in its lowest energy state, also called the ground state. The proton and electron have equal but opposite charges, which exert an electromagnetic force that binds the hydrogen atom together.



## The Bohr Model for Hydrogen

Here we follow the emission or absorption of photons by a hydrogen atom according to the Bohr model. Several different series of spectral lines are shown, corresponding to transitions of electrons from or to certain allowed orbits. Each series of lines that terminates on a specific inner orbit is named for the physicist who studied it. At the top for example, you see the Balmer series; arrows show electrons jumping from the second orbit (n=2) to the third, fourth, fifth, and sixth orbits. Each time a "poor" electron from a lower energy level wants to rise to a higher position in life, it must absorb energy to do so. It can absorb the energy it needs from passing waves (or photons) of light. The next set of arrows (Lyman series) shows electrons falling down to orbit one from different (higher) levels. Each time an electron goes downward toward the nucleus, it can afford to give off (emit) some energy it no longer needs.



**Doppler Effect:** In 1842 Christian Doppler pointer out that if a light source is approaching or receding from the observer, the light waves will be, respectively, crowded more closely together or spread out.