



Atoms and Starlight

We have already concluded that stars are very much distant objects. The great gulf of distance between the stars and our own solar system makes the study of stars, their structure, composition, and lives, all the more taxing and difficult. Science has taken great strides in bridging the immense distances and drawing conclusions by using only the most abundant information that we can get from stars - LIGHT. The only beacon of information we can obtain from these distant stars is from the light that they themselves produce. You might think that this will only provide paltry evidence and understanding, but in fact, the starlight from the stars is one of the most important sources of information. It is the intricate intertwining of light and matter (atoms) that yields a plethora of knowledge and ideas about not only stars but the universe as well.

First, we will start with the smallest puzzle pieces that once put together help create all that there is in the universe - ATOMS.

Atoms – Planetary Model of the Atom:

It is an astonishing idea and observation: All the matter around you (including you) is made of atoms, and all atoms are made of only three types of subatomic particle, protons, electrons, and neutrons. Furthermore, all protons are exactly the same as other protons, all neutrons are exactly the same as other neutrons, and all electrons are exactly the same as other electrons. Protons and neutrons have almost exactly the same mass. Electrons have a mass that is about $1/1836^{\text{th}}$ the mass of a proton. (Even more outrageous is that nuclear physicists Gell-Mann and George Zweig

independently proposed that electrons, protons, and neutrons can even be broken down into four smaller "quarks" - beauty, charm, strange, truth)

Ancient Greece is the birthplace of the "Atomic" Theory of matter. A Natural Philosopher (ancient world observers not experimenters), Democritus, proclaimed that matter was composed of incredibly small indestructible particles. The Greek word "atomos" was used to describe these particles ("atomos" loosely translates indestructible particle). **Natural Philosophers** did not experiment (as science does today), but made educated logical declarations based upon honed observations of the natural world. For example, Democritus inspected the sea coast beaches



Figure 1: Democritus
(460 BCE – 370BCE)

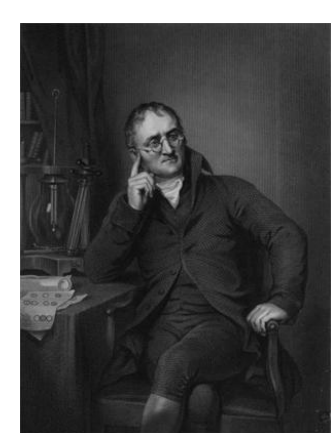


Figure 2: John Dalton
(1766 - 1844)

of the Aegean Sea (a large single structure) and noticed that the beaches were created by endless tiny grains of sand. Therefore, Democritus contended that matter itself could be composed of like tiny "atomos" that together formed the cohesiveness of matter. This was quite a departure from the "common-sense" ideas of the time that all matter was formed from the four substances of "earth," "wind," "fire," and "water." In fact, this was not a popular idea and did not last beyond the lives of the Greek philosophers. It was much later, in the 1800's, when this idea was revived, the Modern Nuclear Atomic Theory of Matter, by John Dalton.


The **atom** is the smallest unit of an element that retains the chemical properties of that element. An atom has a "cloud" consisting of electrons surrounding a dense nucleus. The nucleus contains the protons and neutrons. How do protons, neutrons, and electrons mostly differ? Electrons have a unit negative charge. Protons each have a positive charge. These charges are genuine electrical charges. Neutrons do not have any charge.

A Twist: Here is a bit of an interesting note. Everyone uses the term "charge" frequently in chemistry, physics, and even biology to describe the "charge" of an atom, nuclei, ion, proton, etc. If you ever feel like causing someone a moment of "pause" try and ask someone that is talking about "charge" the question; "Hey,

exactly what is 'charge,' anyway? I mean, what is it? What creates a 'charge' on a proton, for instance?" You see, we really don't "know" what charge is, what manifests a particle like an electron to have "charge." (There are, of course, many theories mostly involving "quarks." But, then quarks are said to have "color" which is another whole interesting ball of wax.)

So, what is "charge" and why do we say that an electron is "negatively charged," a proton is "positively charged," and a neutron is "neutral?" Charge is really used as observational nomenclature to separate out differing "electric" behaviors of these particles. For instance, physicists can run an electromagnetic experiment and the electron will be observed to move to the right, the proton to the left, and the neutron will be unaffected. So, we picked the proton being "positive" and since the electron did the opposite we say it is "negative." The neutron was not affected, thus "neutral."

Even more interesting is the general shape of atoms with these three subatomic particles. The neutrons and protons are only found in the center of the atom - **nucleus**. The electrons are found "orbiting" ("orbiting" in quotes because it is not circling around in the classic sense, it is just found outside the nucleus) the nucleus in **electron shells** that are in different shapes at different distances (and hence different energies) from the nucleus. Shockingly, **the atom is mostly empty space**. That is a genuinely outrageous idea. Nearly all the mass of an atom is concentrated in the tiny nucleus. The mass of a proton or neutron is 1.67×10^{-27} kg. The mass of an electron is 9.05×10^{-31} kg. This number is a trillionth of a trillionth of a gram.

- Small central nucleus surrounded by electron(s).
- Nucleus size $\sim 0.0000016\text{nm}$ \rightarrow small!!!
- Nucleus \sim two parts
- Proton (+ charge)  Net (+ charge) on the nucleus
- Neutron (0 charge)
- Electron(s) (- charge) – "orbit" around the nucleus
- In a normal neutral atom the number of electrons = the number of protons.

→ The differing arrangements of these three fundamental particles are responsible for what we call the periodic table of elements. We denote different elements by the number of protons (**Atomic Number**) they have in their respective nucleus.

Scientists frequently have an enormous amount of data to analyze. Imagine, for instance a botanist trying to study all of the different kinds of trees in the world – it would be impossible for anyone to know everything about every kind of tree. To simplify their work, scientists tend to group together those things that have similar properties. With trees, for example, we have groups called maple, pine, and many, many more. There are different kinds of maple trees, but they all have certain features in common.

In chemistry over the last couple of centuries an overwhelming amount of qualitative and quantitative data about the elements has been collected. In an effort to bring some order to the study of the elements, they have been organized in a systematic way in the **periodic table**. The



Figure 4: Julius Lothar Meyer

principle behind this organization, now known as **the periodic law**, was developed in 1869 by Russian Chemist Dmitri Mendeleev and, independently, by

J. Lothar Meyer. The periodic law states that *when the elements are arranged in order of increasing atomic number, the chemical properties repeat in a periodic manner.*

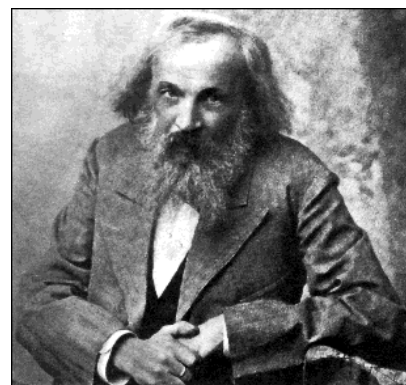
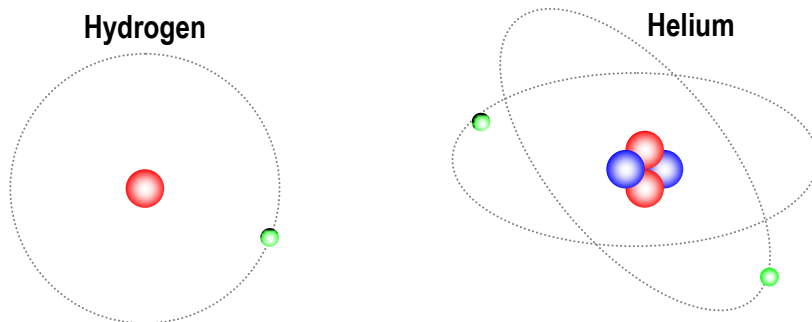


Figure 3: Dmitri Mendeleev (1834 – 1907)

By organizing the periodic table according to chemical properties, we greatly simplify the study of chemistry. The periodic law gives us the ability to predict the properties of elements based on their positions in the periodic table. In fact, when Mendeleev prepared his first periodic table, several elements (e.g., Ge & Ga) had not been discovered. Mendeleev left spaces in his table for these elements, and predicted with remarkable accuracy their properties. Indeed, because of the predictive power it gives us, and due to the wealth of information it contains, the periodic table may well be one of the most useful tools available to scientists.

Atoms & Starlight

For instance, consider the "Hydrogen" atom. The first element on the periodic table contains one proton and one electron. And "Helium" contains two protons, two neutrons, and 2 electrons.



PERIODIC TABLE OF THE ELEMENTS

1 H 1.01																	18 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.30											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.90	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po 209	85 At 210	86 Rn 222
87 Fr 223	88 Ra 226.0	89 Ac 227.0	104 Rf 261	105 Db 262	106 Sg 263	107 Bh 264	108 Hs 265	109 Mt 268									

58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm 145	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np 237.1	94 Pu 244	95 Am 243	96 Cm 247	97 Bk 247	98 Cf 251	99 Es 252	100 Fm 257	101 Md 258	102 No 259	103 Lr 260

Different Kinds of Atoms:

Although the number of protons is fixed within atoms of a certain name (hydrogen, helium, lithium, gold, tin, carbon, etc), we find many atoms with differing numbers of neutrons and/or electrons that do not significantly change the element.

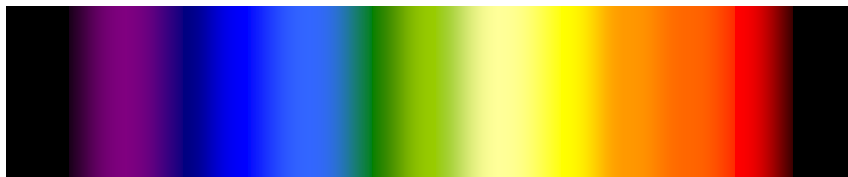
- Isotopes – atoms that have the same number of protons but different number of neutrons.
- Ionization – removing electrons from an atoms outer shells ~ called and “ion.”
- Molecule – two or more atoms bound together by sharing electrons (H₂O for example)

Joe Physics: You have made ions without knowing it. When two different materials come into close contact -- for example, your hair rubbing against a balloon (or comb), wool socks on the shag rug, or say two air masses in a storm cloud -- electrons may be transferred from one material to the other **-ionization**. When this happens, one material ends up with an excess of electrons and becomes negatively charged, while the other ends up with a deficiency of electrons and becomes positively charged. This accumulation of unbalanced charges on objects results in the phenomena we commonly refer to as static electricity. ZAP a loved one!

Now, taking a historical point of view, we will talk about light before meshing atoms and starlight together into a consistent diagnostic tool for the exploration of stars and many other objects and processes.

The Formation of Spectra

From a completely observational view, it has long been established that certain physical situations can result in different spectra; **continuous spectra**, **absorption spectra**, and **emission spectra**. The physical interpretation and explanation of these discrete spectra came along when a consistent model of the interaction of atoms and light was formulated by Niels Bohr.



Blackbody Radiation

We have already talked a bit about one way of making an object produce light. One way for an object (star, electric oven coil, blacksmith horseshoe, etc) glow (produce light) is to heat it up.

If you have experience with electric oven, the heated coil acts just like a blackbody. The piece of iron glows red-hot (set on low), then orange (set on medium), then yellow (set on med-high), then (set on super-high)white-hot.



An object is hot when the atoms (or molecules, or ions) of which it's made are in rapid random motion. The temperature of an object is a measure of the average random velocity of the atoms (or molecules, or ions). A high temperature means the atoms are moving rapidly. As atoms move more and more slowly, the temperature drops.

Blackbody radiation is described by two very simple relations. In fact, since so many objects in the galaxy (and beyond) behave like blackbodies, these are two very powerful tools for astrophysical analysis.

Wien's Law:

The wavelength of **maximum intensity** of a blackbody is inversely proportional to its temperature (in Kelvin degrees).

$$\lambda_{\max} = \frac{3,000,000}{T}$$

- λ_{\max} : wavelength of maximum emission of the heated dense object.
- T : temperature of object (in Kelvins).

Example: A cool star with a surface temperature of around 5500 K will emit most intensely at a wavelength of 545nm, which will appear yellowish. A warmer star with a surface temperature around 6700 K will have a maximum wavelength of nearly 448nm, which will appear bluish-white.

Caution: The maximum wavelength only describes the most intense light from a blackbody radiator. All the other colors (visual as well as all others) are present but not nearly so intense.

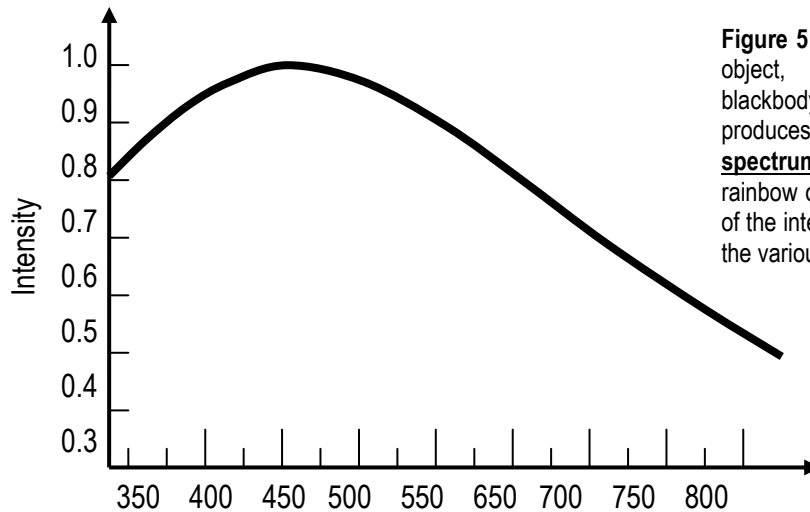


Figure 5: Above: A hot opaque object, such as a perfect blackbody or a hot, dense gas produces a **continuous spectrum** -- a complete rainbow of colors. Left: A graph of the intensity of the light along the various visual wavelengths.

Figure 8: Niels Bohr

Continuous Spectrum

We can produce a continuous spectrum of visual light using any object that behaves like a blackbody (**Figure 5**). For instance, we can produce a situation with an incandescent light bulb containing a hot filament (heated piece of metallic substance). We can use either a prism or a spectrograph to separate out the various visual colors present within the light produced by the light bulb.

The type of spectrum you see depends on the temperature of the thin gas. If the thin gas is cooler than the thermal source in the background, you see absorption lines.

Absorption Spectrum:

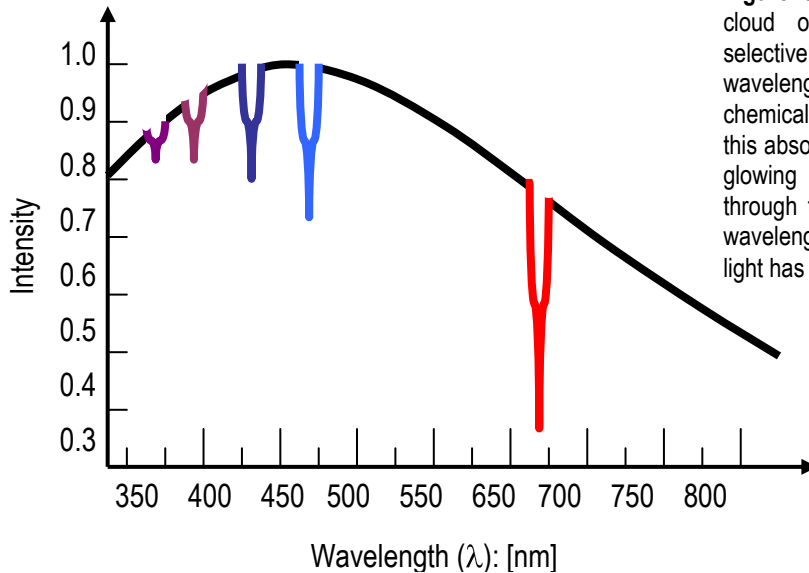
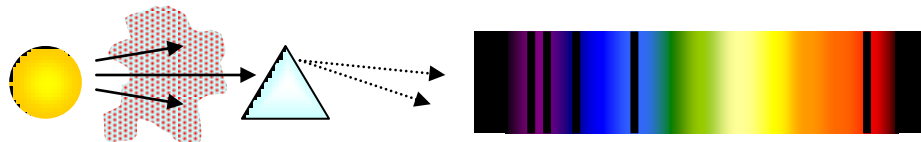


Figure 6: If light passes through a cloud of cooler gas, the cloud selectively absorbs light of certain wavelengths depending on its chemical composition. As a result of this absorption, the light from the hot, glowing object that passes directly through the cloud is depleted in the wavelengths, and the spectrum of light has dark absorption lines.

A cooler, transparent (very thin) gas in front of a source of a mostly continuous spectrum produces an absorption spectrum (**Figure 6**) -- a series of dark spectral lines among the bright colors of the continuous spectrum. Below is also a graph of intensity of the light versus the wavelengths (visual) with the corresponding spectral lines removed from the rest of the light.

Emission Spectrum

A hot, transparent gas produces an emission line spectrum (**Figure 7**) -- a series of bright spectral lines against a dark background. Furthermore, the dark lines in the emission spectrum of a particular gas occur at exactly the same wavelengths as the dark lines in the absorption spectrum of the same gas (same chemical composition).

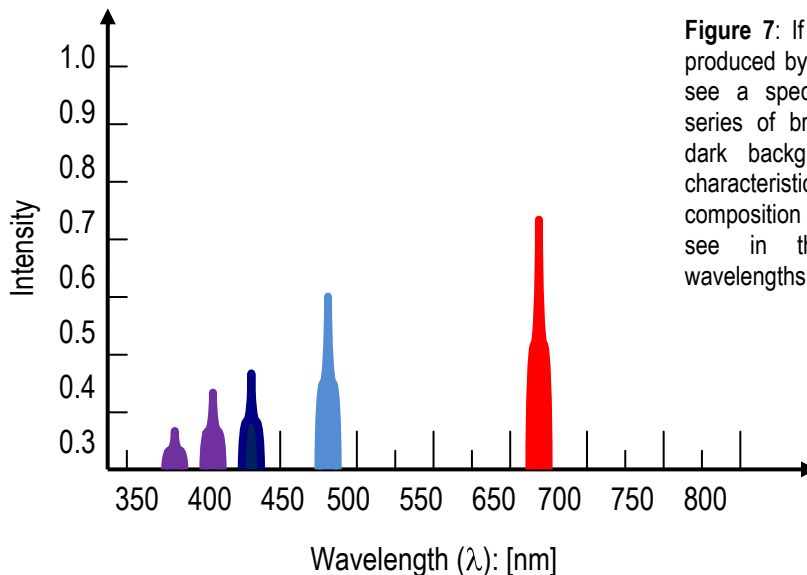
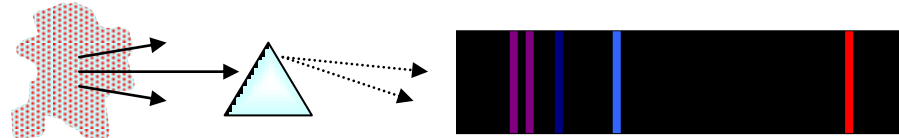


Figure 7: If we just observe the light produced by a hot low density gas we see a spectrum that consists of a series of bright emission lines on a dark background. These lines are characteristic to the discrete chemical composition of the gas. Also you can see in the graph only those wavelengths that were produced.

The Interaction of Light and Matter:

At the beginning of the 20th century, scientists were perplexed by the failure of classical physics to explain the characteristics of atomic spectra.

- Why did atoms of a given element only emit certain lines?
- Why did those same atoms absorb only those wavelengths that they emitted?

Some early models of the atom were very much like the current one -- the positive charges were concentrated in a central nucleus (along with neutrons) and the negative charged electrons were swarming around it. Unfortunately using classical physics ideas the atoms would be predicted to be unstable. Why? As the electrons move around the nucleus, they should radiate light and spiral into the positively charged nucleus in about 10^{-16} second. Well, this was obviously not the case. Why? Well, the atom is a very stable structure and they (and most of the universe) do not suddenly emit a huge amount of light and destroy themselves.

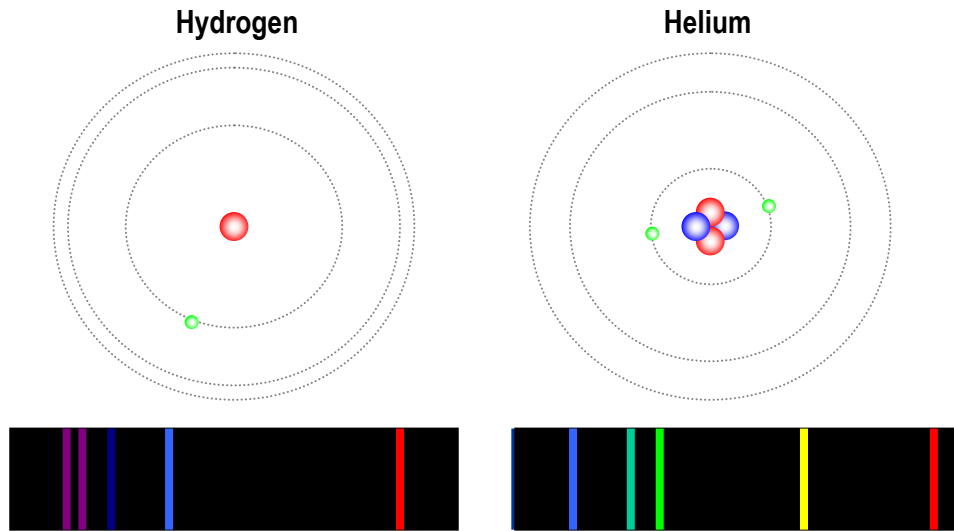
In 1913 Niels Bohr provided an explanation of the atomic spectra that included some features of the currently accepted theory of the atoms structure. The overall idea about the structure and placement of the proton, neutron and electron did not change. However, the ideas about how, where, and why the electron orbited the nucleus did change.



Figure 8: Niels Bohr
(1885 - 1962)

- The negatively charged electrons orbit around the nucleus in certain stable specific levels (energy levels).
- The unique arrangement of an atom's energy levels depends on the number of protons and neutrons in the nucleus and the number of electrons moving around the nucleus.
- Since every type of atom has a unique, discrete, and specific arrangement of the energy levels -- these atoms will produce a unique pattern (a "light fingerprint" if you will...) of absorption or emission lines as the electrons move between these energy levels.

● Proton
 ● Electron
 ● Neutron
Energy levels



The above diagram illustrates the different discrete pattern of permitted energy levels and unique emission spectra of the two most common elements on the periodic table (Only the first few energy levels are shown for each). Notice how the structure of the levels is different and that the wavelengths that each can produce are unique. It is easy to understand why astronomers find this a very powerful tool in determining the chemical composition of stars and other objects.

Electron Energy Shells:

- Electrons are bound to the atom by the interaction between their negative charge and the positive charge on the nucleus. This attraction is known as the **Coulomb Force**.
- Coulomb Force (+ -) attractive; (+ +), (- -) repulsive

Binding Energy

The amount of energy required to remove an electron completely away from an atom. Each orbit represents a specific amount of binding energy, so we refer to each possible discrete electron orbit as an energy level.

- Electron orbit close to the nucleus – more energy
- Electron orbit far from the nucleus – less energy
- Electron in lowest energy level is called the **ground state**, any of the levels above that are called **excited states** (more energy).

Joe Astrophysics: It is sometimes best to use a metaphor to understand a physical model. For instance, think of the permitted discrete energy levels within an atom as a staircase. You can place the nucleus standing down at the base of the staircase. An electron can be a tennis ball. You can place a tennis ball anywhere you want on the staircase, on a step, but you can not place the ball, say.. hovering in between two steps. The lowest stair is the ground state and anything about those are excited states. Now!!

Prediction One: What does it take to move an electron from a lower stair step to a higher one? The correct amount of energy! You must invest to energy to move that ball upwards on the steps. **Prediction Two:** What happens when the ball bounces down from higher energy steps to lower ones? It releases the energy invested earlier... the same energy. This is very similar within atoms.

What is going on to produce these spectra?

We now have an idea of the atom's structure and energy levels as well as the various types of spectra, so now we can discuss how the atoms produce these patterns or "light fingerprints."

First, let's discuss the **emission spectra** and the atom. When the electron within an atom drops from a higher to a lower energy level, it moves from a loosely bound level to one more tightly bound. The atom then has a surplus of energy -- the energy difference between the two levels -- that it can emit as a certain photon. In order to go to a lower energy level, the electron must lose energy of a certain specific amount. The atom releases the energy as a specific wavelength of light. The energy (wavelength) of the emitted light = the difference in energy between energy levels that the electron changed between.

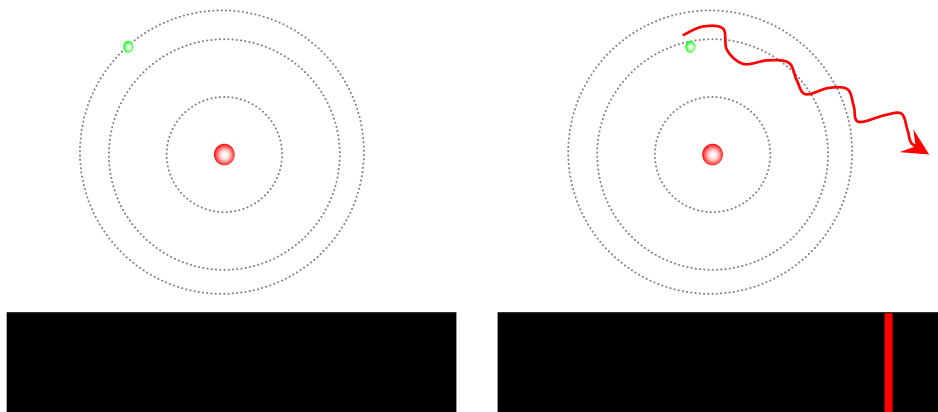


Figure 9: The electron in a higher energy state moves down to a lower energy state and produces light with energy that corresponds exactly to the specific energy difference between the two levels. The spectra of this atom before and after the energy level transition - notice that the one color corresponds to one specific unique transition within the atom.

Therefore, the full pattern of specific emission lines you see coming from a hot thin gas of a single particular element correspond to all the possible downward transitions between energy levels that the excited electron can make. You do not get a continuous spectrum because there is only a certain set of allowed downward transitions.

Now, let's discuss the **absorption spectra** and the atom. An absorption line is produced when light of the correct specific energy is absorbed by an atom (which corresponds to an exact energy level difference). This causes the electron to move to a higher energy level. The light had energy which corresponds to the difference in energy of the different levels. Since the energy levels within unique atoms are fixed -- the energy of the outward electron jumps are the same as the inward jumps. When the electron within an atom rises from a lower to a higher energy level, it moves from a tightly bound level to one more loosely bound. The atom absorbs the energy of a specific wavelength of light. The energy (wavelength) of the absorbed light = the difference in energy between energy levels that the electron changed between.

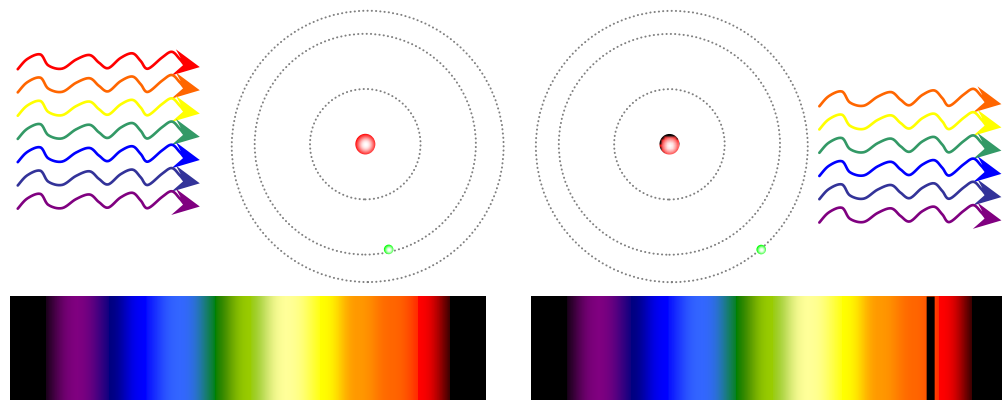


Figure 10: The electron in a lower energy state moves up to a higher energy state and absorbs light with energy that corresponds exactly to the specific energy difference between the two levels. The spectra of the impinging light before and after its interaction with the atom and its energy level transition. Notice that the one color corresponds to one specific unique transition within the atom. Notice that the atom removed this energy from all the possible energies and the electron moved to a higher energy level. Also realize that other upward absorption transitions will remove other unique wavelengths.

Hey there you cute atom, you!

Ways to excite an atom into a higher energy state.

- **Absorption:** We just talked about this above with the upward transitions of electrons. The atom can absorb light energy or photon. Only a photon with exactly the right amount of energy can move the electron from one level to another. If the photon has too much or too little energy the atom cannot absorb it.
- **Collisional Excitation** – (bang!): An atom can become excited by a collision with another atom. If two (or more) atoms collide, one or both may have electrons knocked (physically) into a higher energy state. This happens very commonly in a hot gas where atoms move very rapidly and collide vigorously because of the hot temperature.
- Electron moves down? – **De-excitation.** The technical term for the emission of a photon of light with energy and wavelength that corresponds to the energy difference between the energy levels the electron moved downward between.
- What happens? Light is given off!! A light “fingerprint” is born.

The Hydrogen Spectra:

We have already discussed the process by which hydrogen can either emit or absorb specific energies of light (photons). We have also seen parts of the spectra in the visual colors, but there are many many more transitions the electron within a hydrogen atom can make. We divide the possible transitions in a hydrogen atom into groups called series.

- Lyman Series: Represent transitions to and from the ground state.
- **Balmer Series:** Represent transitions to and from the first excited state (second energy level). (These are the transitions that involve some visual colors.)
- Paschen Series: Represent transitions to and from the second excited state (third energy level).

Stellar Spectra:

Give an astronomer a small trickle of light and the riddle will be solved. Science has decoded the Rosetta Stone of stellar spectra. The spectrum of a star tells us a great deal about such things as temperature, motion, composition and much more. A stellar spectra is like a "mug shot, finger print, and DNA test" rolled up into one science.

Balmer Thermometer

We can use the Balmer Series spectral line strengths (absorption lines) as a thermometer to find the temperatures of the stellar surface – the hotter the star the stronger the spectral lines that appear. The strength of the Blamer lines depends on the temperature of the star's surface layers. Both hot and cool stars have strong weak Blamer lines, but medium temperature stars have strong Balmer lines. This in conjunction with what we already know about blackbody, color, and temperature helps astronomers calibrate the surface temperature of the star. Surface temperatures of typical stars – 40,000K to 2000K.

A tool needs calibration and standardization so everyone can agree to us it.

Spectral Classification

The first usable calibration method was developed by a Harvard astronomer - Annie J. Cannon (Cannon camera?). After carefully inspecting over 250,000 stellar spectra (tedious but needed work), she was able to propose a Stellar Classification Scheme that was widely accepted. (Partially derived based on photographic paper types too?)

Spectral Types

- | | | | | | | |
|---------|---|---|---|---|---|------|
| 1. O | B | A | F | G | K | M |
| 2. Hot | → | | → | | → | Cool |
| 3. Blue | → | | → | | → | Red |

The Sun – our star is classified as a G2 (5800-6000K)