Chapter 4 Spectroscopy

One of the important tools of astronomers is the use of a *spectrum*. This is the breaking down of light into its components. This provides the astronomer with information about the object that he is looking at. We use an instrument called a *spectroscope* to take the spectrum of an object. In most modern instruments we use a *diffraction grating* to break down the light. This is a transparent material that is etched with thousands of lines per inch.

Emission Lines

When we look at white light we produce a *continuous spectrum*. There are no breaks in the colors and they go from one to another. The colors go from red to violet. Now if the light we are analyzing passes through a hot gas, then the only thing we will see are the bright lines that are indicative of the elements that are present. This is called an *emission line spectrum* or a bright line spectrum. Many experiments were done with different gases and what they found was that each gas had a very distinctive set of lines, just like a fingerprint.

Absorption Lines

When light is shown through a cool gas what you get is a series of dark lines. This is called an *absorption line spectrum* or a dark line spectrum. Joseph Fraunhofer studied the lines produced by the Sun and he found over 600 lines in the spectrum. It was a dark line spectrum formed by cool gases. Just like the emission spectrum, when you have a cool gas you will find all the colors present with dark lines in the spectrum. That is why you will hear it called a *dark line spectrum*. In the Sun the lines are called *Fraunhofer lines* after the man who studied the lines in great detail. The one thing you will find is that if you pass light through cool hydrogen, the dark lines on the absorption spectrum will be in the same place as the bright lines of the emission spectrum when light went through hot hydrogen gas.

Kirchoff's Laws

A German Gustav Kirchoff developed three spectroscopic laws.

1) A luminous solid or liquid or a sufficiently dense gas emits light of all wavelengths and so produces a continuous spectrum.
2) A low density hot gas emits light whose spectrum consists of a series of bright emission lines that are characteristic of the chemical composition of the gas.
3) A cool, thin gas absorbs certain wavelengths from a continuous spectrum, leaving dark absorption lines in their place on the continuous spectrum. It is characteristic of the chemical composition of the gas.

Astronomical Applications

Once astronomers knew that the light told them about the chemical composition of an object, spectroscopy took off. While working on the spectrum of the Sun, in 1868 it was found that there were lines there that they didn't know. Since it was on the Sun, and the Sun in Greek is *helios*, they called it helium. It was discovered on the Earth in 1895, 27 years later. The 19^{th} century astronomers could extract information from the spectra, but didn't understand how it happened.

The Formation of Spectral Lines

Physicists couldn't explain what was happening to form the spectral lines if light was strictly a wave. What they found was that at very small scales, light acted more like a particle.

Atomic Structure

To understand this we must understand the *atom*. Let's look at the hydrogen atom since it is the simplest. It has one *proton* that is in the *nucleus* and one *electron* that is in the first *shell* around the nucleus. The first person to really put together the model of the atom was Niels Bohr in 1912. Basically this is what it says: the electron will be found in the lowest energy state possible. This is called the *ground state*. There is also a maximum energy level that an electron may have and still be part of the atom. If that energy is exceeded the electron will leave the atom and now the atom is said to be *ionized* or charged. You will find that the electron can exist in energy levels between those 2 states. These energy levels are very specific and are often referred to as *orbitals*. This contrasts sharply with what Newtonian physics says should happen. These orbital energies are said to be *quantized* and it studied in *quantum mechanics*.

Now let's go back to the hydrogen atom. If the electron is struck by a particle of light with the correct energy, the electron will jump levels and be in what is called the *excited state*. Depending on the particle of light, it may jump more than one orbital outward. That means that you have the first excited state, the second excited state, etc. After about a hundred millionth of a second it will drop back down to the ground state.

Radiation as Particles

As we have said, an electron can jump levels only if it receives the exact amount of energy that it needs to jump. The energy absorbed or emitted by the electron is found to be in packets called *photons*. This idea was brought forth by Einstein in 1905. He found that: <u>photon energy _ radiation frequency</u> A deep red photon has half the energy of a violet photon. To determine the energy carried we use $E = hf$ where h is called Planck's Constant and f is the frequency. A gamma ray carries the amount of energy carried by a flying gnat. And yet it can cause damage to humans due to the fact that it carries millions if not billions of times more energy than visible light. The equivalence between the energy and frequency explains why we see the spectra that we do. Each atom has a different amount of electrons and they absorb photons and reemit them. This causes dark lines in the spectra. The idea that light can act like a wave and a particle has bothered physicists for years. You know what? They still don't know why it happens.

The Spectrum of Hydrogen

If we look at a hydrogen atom, we can see what may happen when the electron absorbs a UV photon. If the energy is great enough, it can jump out to the second excited state. It will reside there for a short time and then fall back. It may fall in one of two ways: 1) it may fall directly back to the ground state and emit a photon of UV light, or 2) it may fall back in a stair step fashion. As it falls from the second excited state to the first excited state it emits a photon of visible light (red). When it falls from the first excited state to the ground state it will emit a photon of UV. Young, hot star that is emitting in the UV can excite a cloud of hydrogen gas and it will emit a reddish glow as the atoms drop back down into the ground state. This is called *fluorescence*. Depending on the photons that strike the hydrogen atom, you may have electrons dropping down out of many different levels, thus emitting many different photons.

Kirchoff's Laws Explained

You may think that the electron jumps up, stays for a short time and falls back down in such a little time that we shouldn't see any lines. The reason we see the lines is 2 fold. 1) The photons released can be released in any direction, not just back to our line of sight so the chances are it moves off away from us. 2) The electron may fall back down in stair step fashion and release several photons of lower energy so that we don't see the light.

More Complex Spectra

Each element has different numbers of protons, neutrons and electrons. If we look at iron, it has 26 protons, 30 neutrons and 26 electrons. With 26 electrons it has any number of possible transitions that can occur. But you also have the possibility that the electrons may be stripped away, called ionization, which alters the electromagnetic characteristics. Spectroscopy is a powerful tool especially when there are several gases mixed together. We can look at all of the lines and since each element has its own fingerprint, we can see what wavelengths of lines are gone and determine what elements or molecules are present.

Molecules

A molecule is a group of tightly bound atoms by what is called *chemical bonds*. Since molecules are more complex than atoms, the physics behind them is also more complex. Not only can electrons jump levels, within molecules you can get *rotation* in the molecule as well as a *vibration* in the molecule. This also causes photons to be released. As a rule of thumb: 1) electron transitions within a molecule will produce visible light as well as UV, 2) molecular vibration produces infrared spectral lines, and 3) molecular rotation produces spectral lines in the radio part of the spectrum.

Spectral Line Analysis

Light from distant objects is how we determine many things about them. We analyze their spectra to determine things like temperature, composition and rotation of the object. Let's see how we do this.

A Spectroscopic Thermometer

At the cooler surfaces of the stars (cooler than the cores) some atoms retain their electrons. The strength of the line is determined by the number of atoms that are present. The more atoms, the broader the lines you see. The strength of the line is also determined by the temperature because the temperature determines how many atoms are in the right orbital to undergo any particular transition or jump. Take hydrogen for example. At the low surface temperatures of our Sun, 5800 K, very few hydrogen atoms have electrons in an excited state. Thus visible hydrogen lines are quite weak. As we increase the temperature, now you will have most of the electrons in the first excited state and we are picking up more UV lines. If it gets hotter still, we will see lines in the visible light and in the UV. At higher temperatures it becomes ionized and no hydrogen is seen at all.

Measurements of Radial Velocities

We can use the Doppler effect to determine radial velocities of an object. Since an object may move towards us or away from us the light waves are stretched or compressed. The amount of compression or stretching allows us to calculate the velocity. On page 98 they go through an example of how this is done.

Line Broadening

If you look at the lines of the spectrum, you will see that the center of the line is the brightest and then it fades off to each side. You would think that since the electrons absorb or emit at very specific wavelengths that the line should be the same all the way across. It is not so. Several factors can cause this effect. The Doppler effect can cause this broadening. This happens because the object emitting the photon of light is moving towards or away from us and the spectrum is shifted slightly.

Rotation of the object can cause line broadening. Many objects that we look at are so small that we see only a point. Therefore we get light from both sides of the rotating object and the light is spread on both sides of the line due to the Doppler shift.

Turbulence within the cloud of material that you are taking the spectrum of can cause line broadening. The principle is the same as it was for rotation.

Broadening will occur if the atoms are in collision while the electron is jumping levels.

Finally, magnetic fields can cause line broadening. This is called the *Zeeman Effect*. The strong magnetic field will spread out the lines in the spectrum.

The Message of Starlight

We can determine many factors about an object from its light. The difficult part is determining whether any factors are affecting the information before we get it. The challenge is to decode the spectral line profiles to obtain meaningful information.