

Introduction to Spectroscopy: a technique to decode the information in the light

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Spectroscopy is the technique of measuring spectra produced when matter interacts with or emits electromagnetic radiation. The spectrum is the result of the spectral decomposition of the light, this is the decomposition of a beam into its constituent wavelengths. Spectroscopy is a relatively simple yet powerful technique that allows us to obtain information about a source. From Isaac Newton using a prism to disperse light, to the advanced equipment of today, the principles are still the same; light is like a barcode for objects that cannot be directly measured, and once we separate it, we can begin determine things that were once unknown to us.

Introduction

My project over two weeks entailed various stages; Firstly, I built a basic spectrometer using a goniometer, and used different dispersive elements to study incandescent light. Secondly, I chose which dispersive element I believed to be more suitable, and studied the emission lines from various spectral lamps. I had to devise a method that keeps the uncertainty to a minimum without being too impractical. Finally, I observed the sun's spectra, and decoded the information contained in its light.

Equipment

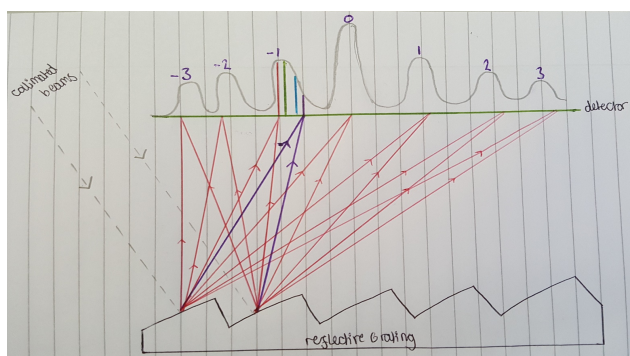
A Spectrometer is an instrument that disperses the light into its constituent wavelengths, obtaining a spectrum. We used a goniometer to build a basic spectrometer, which contains 5 main elements. First, is the slit, which allows only a small proportion of the light to pass into the goniometer depending on its width. Next, is the collimator which can either be a curved mirror or convex lens. Both collimate the light so the rays are parallel to each other. Third, is the dispersive element, which disperses the beams. Fourth, is the camera, which focuses the dispersed light rays. Again this can be a lens or a mirror. Finally, is the detector, where the spectra are observed by either a camera or the naked eye. The goniometer was inside a black out box, to reduce light interference. Our first dispersive element was a diffraction grating in

reflection which utilises a large number of parallel mirrors, allowing a small portion of light to be focused and visualised. The grating used had 600 mirrors per mm. Light coming from the collimator is dispersed into lots of beams travelling in all directions. Where beams with the same order and colour interfere constructively, that colour is observed, creating a diffraction pattern. The second dispersive element we used, was a prism. As light enters the prism, the dispersion begins, and when it leaves the accumulated dispersion is preserved. Hence as rays change medium, they change direction and refractive index is a function of the wavelength. Throughout our project we used two different light sources; white light and spectral lamps. White light produces a continuous spectrum due to the light coming from an incandescent filament lamp. However, not all frequencies are given off at the same intensity. Spectral lamps produce fine bands of colour called emission lines; A current provides energy to heat up the vapour in lamp and as the atoms gain thermal energy, they transfer it into kinetic energy and begin to move faster. As they collide with each other, there is enough energy to excite their electrons into a higher energy state. Electron can only exist in discrete energy levels and therefore absorb very specific energies as they jump up levels. As they drop back to a lower energy level, a photon is released with a specific energy and hence frequency.

Method- Spectral Lamps

After experimenting with both dispersive elements, we decided on the grating in reflection, due to its higher dispersive power allowing us to observe more orders. It also has a higher resolution, reducing the uncertainty in our measurements. A specific equation must be used when using a diffraction grating;

$$d(\sin\theta_{\text{input}} + \sin\theta_{\text{output}}) = m\lambda$$



$d = (\text{number of mirrors per mm})^{-1}$ $m = \text{Order number}$
 $\lambda = \text{Wavelength / nm}$ $\theta = \text{angle / }^\circ$

For practicality, we used 180° as a reference angle. The input angle was the difference between 180° and the new position of the grating. The output angle was calculated by finding the difference between 180° and the new position of the camera arm, subtracting the input angle, and then adding on 80° , (the difference between where the marker on the scale lies in relation to the camera arm.) We used these angles to calculate orders and wavelengths of certain emission lines. The scale used was a vernier scale, with the smallest division on the main scale being 20 arcmins and on the sub scale being 30 arcsecs, giving us an accuracy of ± 0.5 arcmin, (120^{th} of a degree.) There was two ways to improve the focus of the emission lines. Firstly, we could adjust the focal length to focus our image and allow us to more accurately position the cross hair to the centre of the emission line. Secondly, we could adjust the slit width to resolve and focus finer details, such as doublet lines. Reducing the slit width, does reduce the amount of light passing through the collimator, which can make some of the emission lines too faint to see. Therefore, always start with a wider slit until you want to measure a specific emission line.

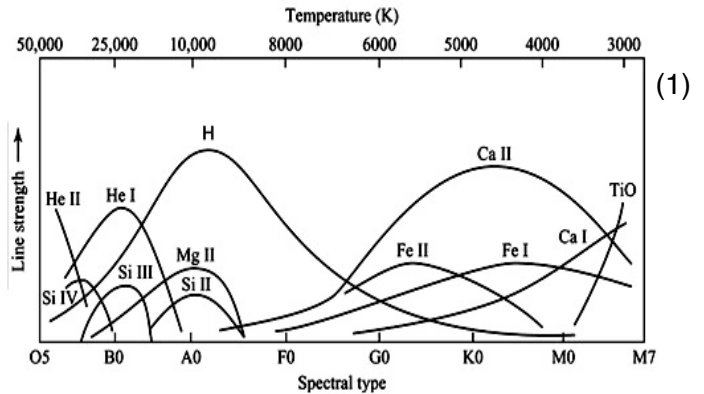
Method- Solar Spectroscopy

We used the same method to obtain the sun's spectra, with a few minor adjustments. Firstly, an optical fibre was attached to the slit and pointed to the sun to allow enough sunlight to pass into the collimator. Secondly, the detector used became a phone camera, as sunlight is too dangerous for the naked eye. Using various theoretical concepts, I devised how we could use this spectra to find out things about the sun. The first thing we can deduce from solar spectroscopy is the chemical composition of the sun. Different atoms lose electrons and become ions at certain temperatures. Each ion has a specific set of emission lines that will be observed due to the remaining electrons becoming excited into a higher energy level, and then returning to ground state whilst releasing a photon of specific energy, hence frequency. We can match up the emission lines seen from the sun, with known emission spectra to deduce the elements in the sun. Another piece of information we can obtain from the spectra, is the sun's effective surface temperature. The diagram below is showing the various strength of emission lines for different elements and compounds, at a star's known surface temperature. From knowing what ions are present in the sun and the relative intensities of each emission line, we can predict the surface temperature range of the sun. By approximating the sun as a black body, we can also

confirm the effective temperature of the sun's surface using

Weins Law: $\lambda_{\text{max}} T = 2.9 \mu\text{K}$

λ_{max} = calculated wavelength of the brightest emission line. T = effective surface temperature / K



Spectral type is determined by a star's surface temperature, hence once we know the temperature we can deduce which spectral class the sun is in. We can also determine the absolute magnitude of the sun using its apparent magnitude.

$$m - M = 5 \log (d/10)$$

m = apparent magnitude M = absolute magnitude d = distance from earth to star / parsecs.

Absolute magnitude, is a star's apparent magnitude at 10 parsecs away. Hipparchus first invented the apparent magnitude scale in 150 BC. His logarithmic scale went from 1-6, with a magnitude 1 star being 100 times greater than a magnitude 6 star. (each jump increase by a factor of approximately 2.51) With the invention of telescopes, we can now see stars dimmer than magnitude six, hence the scale has been extended, with all stars being measured relative to Vega at 0 magnitudes. The Hertzsprung-Russell diagram is a graph showing the plot of lots of stars' absolute magnitude/luminosity against spectral class/effective surface temperature. This shows a pattern for different types of stars in the sky, hence once the absolute magnitude is known, we can deduce which stage of life the sun is currently in, what it has previously been like, and what it will become, way into the future.

Results- Spectral Lamps

With the sodium lamp I decided to use my measurements to determine the order of the emission lines I was observing, as it was difficult to determine this with my eye. I used a sodium spectrum image to identify which emission lines I was observing and then used known values for the wavelengths along with my angle measurements and the slit width measurement to

determine the order. With Sodium, I observed six different emission lines; red, orange, green, blue, indigo and violet. The orange, red and green were bright enough to resolve into doublets, but the other three were too dim and I couldn't reduce the slit width enough to resolve them. I also realised that the spectrum I was observing was a mirror image to the one I was comparing too, I have therefore concluded that I am observing negative orders.

Colour	Red Outer	Blue	Indigo	Orange Inner	Orange Outer
Grating Angle	205° 40' 150"	206° 9'	205° 40' 1170"	180° 40'	180°
Input Angle	25.7085	26.1500	25.9916	0.6667°	0.0000°
Camera Angle	157° 20'	150° 15'	149° 40' 660"	125° 27'	126° 40' 210"
Output Angle	22.6667	29.7500	30.1500	54.5500	53.2750
Order Value	2.0222	2.7700	3.3500	2.3380	2.2669
M =	-2	-3	-3	-2	-2
Actual λ / nm	616.0747	498.2813	411.3700	588.9960	589.9290

(2)

With the Hydrogen spectral lamp, it was very clear which order I was observing, because the zero order line was easily identifiable, as it remained white and could not be resolved. I therefore used the known order to calculate the wavelength of each emission line and compare it to the actual wavelength. Tilting the grating, I found the input angle where I could observe the 2nd and 3rd order. This input angle was 15.5°. I observed 4 different emission lines at each order; red, aqua, blue and violet, however I decided to not measure the violet as it was too faint to accurately line up with the cross hair. On average my uncertainty value is approximately 10%. When I took my first measurement, I used the red light source as a reference to confirm that I was looking at order 2 in the spectrum by inputting red's theoretical wavelength of 656.3 nm. This gave me an order of 1.81, which I rounded to the integer 2. This is my largest error and contributed to why my measurements have a significant uncertainty. I confirmed this by substituting 1.81 as my order for the red line and got a theoretical output angle of 26.5°, only 0.1° off my measured output angle. I used the fact that θ_{output} was greater than θ_{input} , to determine the order was positive, and hence which order the emission lines were in either side of my reference line.

(3)

Order	Colour	Camera Angle	Output Angle	Calculated λ / nm	Actual λ / nm	% Uncertainty
2	Red	142° 10'	26.6°	596	656.3	9.18
2	Aqua	134° 30'	19.0°	494	486.1	1.63
2	Blue	133° 25.5'	17.9°	479	434.0	10.3
3	Blue	154° 50'	39.3°	501	434.0	15.4
3	Aqua	161° 50'	46.3°	550	486.1	13.1

Results- Solar Spectroscopy

With our experiment we used both the prism and the diffraction grating to observe the sun's light. We observed a continuous spectrum with both elements, however the prism's spectra was much less dispersed and the entire spectra could be captured in one image. Unfortunately, we were not able to observe the emission lines of the sun due to our detector being a phone camera and these are not sensitive enough to detect the spectral lines. Time nor the weather was on our side and this did also make it difficult to take a large quantity of measurements. If I could have observed the emission lines, I would have found the following elements spectral lines present.

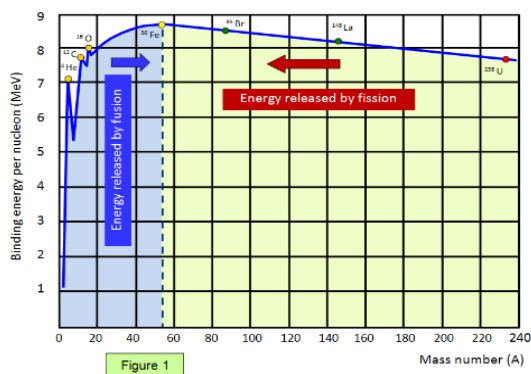
Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.06	0.8
Neon	0.008	0.05
Magnesium	0.002	0.06
Silicon	0.003	0.07
Sulfur	0.002	0.04
Iron	0.004	0.2

(4)

I would have also observed that the brightest spectral line was a green emission line, and used its calculated wavelength to determine the effective surface temperature to be 5773 K, making it a class G star. The sun's apparent magnitude is **-26.74**. Substituting this value into the apparent magnitude equation, I deduced that the sun's absolute magnitude is **4.83 (3sf)**. I used the value of 'd' to be $(1/2.06 \times 10^5)$ as I know the average distance between the centre of earth and sun is 1 AU. I plotted this temperature and absolute

magnitude onto the Hertzsprung-Russell diagram and therefore, I deduced the sun to be a main sequence star. Main sequence stars are formed when clouds of dust and gas contract under gravity to form a protostar. This protostar continues to contract, increasing in density and temperature until the core of the star is hot enough for hydrogen fusion to occur.

(5)



The graph above is showing mass number against average binding energy per nucleon. There is a huge increase in binding energy between hydrogen and helium and this is why such vast amounts of energy are released during fusion. The sun's age is approximately 4.6 billion years old, so it still has another 5 billion years as a main sequence star before its hydrogen in the core starts to run out. At this point the sun will start to swell into a red giant. Due to the sun being only an intermediate mass star, the core doesn't get hot enough for helium fusion to occur. The outer layers will be ejected in a planetary nebula leaving a hot dense core called a white dwarf to slowly cool down.

Conclusion

In conclusion, I think my project has been a success, as I have obtained lots of information about various spectral sources, with an acceptable level of accuracy. To improve my experiment, I would have liked to have more time to take more spectral line measurements and repeat the measurements I have already taken, to improve my results reliability. I would have also used a detector that is able to detect the sun's emission lines so I could actually take my own measurements, instead of just using theoretical concepts. Finally, I would have liked more time to take measurements with the prism as well, so I could have compared accuracy of emission lines wavelength using the two different dispersive elements.

References

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- (5) http://www.schoolphysics.co.uk/age16-19/Nuclear%20physics/Nuclear%20structure/text/Binding_energy_per_nucleon/index.html

