INTERNATIONAL BACCALAUREATE

DIPLOMA PROGRAM

MAY 2018 EXTENDED ESSAY

Physics

"Investigation of The Effect of The Strength of a Magnetic Field and The Initial Energy of Electrons on The Movement of Electrons"

Word Count: 4000

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1. Introduction

1.1 Background

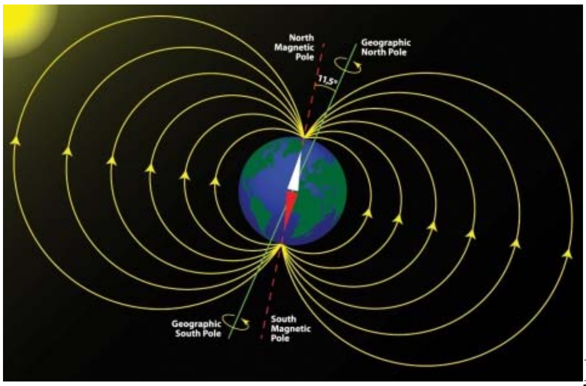
Ever since I was a child, I have always been fascinated by the wonders of physics. Although I was mesmerized by all areas of physics, the realms that caught my attention the most were electricity and magnetism. I grew up with idolizing superheroes and fictional characters that I have seen in media such as Azula, Storm and Electric Eve; who were strong and powerful female characters that were able to control electricity and magnetism. As a little girl, I was captivated by their strength and I wanted to be like them, which made me interested in those realms.

Then, this interest of mine gravitated towards a more aesthetic part of those realms, northern lights. Looking at all the spectral colors that are formed during the physical process of “aurora borealis” formation, watching the “dance” of light and seeing the breath-taking view that occurs during the northern lights became one of the biggest dreams of mine since I was a little girl. A few months ago, my dream came true when I visited Finland to watch the northern lights. Shortly after seeing those lights, a new question mark appeared in my mind- what really was this phenomenon, and what was the real reason behind the formation of northern lights? After doing some research about northern lights, also known as “aurora borealis”, I learned that it is formed when charged particles that radiate from the sun with high speed are caught in Earth’s magnetic field and are propelled towards the poles, causing them to react with various gases in atmosphere and creating a colorful view.[1] Later, I decided that I wanted to focus on the natural phenomenon “aurora borealis”, and find the relation between it and Earth’s magnetic field strength.

Before I start, I want to define Earth's magnetic field, the particles that flow out from the sun, and the journey of these particles from the sun to our planet.

A magnetic field is formed by the effect of electric currents. Examples of magnetic field can be seen at the current in wire and a bar magnet. It can be thought that the Earth is like a giant magnet, forming a magnetic field. It's known that our planet's inner layer, magma, contains a high amount of iron, so it acts like a moving molten iron. This movement makes electrical currents flow in magma, which is assumed to be the cause of the Earth's magnetic field.[2]

During my researches, I learned that the magnetic field strength of the Earth has changed dramatically over the time. It is guessed that our planet has lost at least 10% of its magnetic field strength, which is a great value. [9] I believe that if this changing continues, our planet will have a lot weaker magnetic field in future. And then, would the grandchildren of our grandchildren observe the same phenomenon of aurora borealis that we do now?



<u>Figure 1:</u> Earth's magnetic field[6]

The electrically charged particles that travel from the sun form the "solar wind", which is a natural phenomenon. When the outermost layer of the Sun, which is called "the corona" reach high temperatures like 1.1 million degrees Celsius, rapidly moving particles defy the star's gravity and emanate from the Sun. When the “solar wind”, which can be described as electrically charged particles that come from the surface of the sun, meets the magnetic field of our Earth, those charged particles form light scattering, and therefore the magnificent “aurora borealis” occurs.

Even though this natural process occurs at every point of the Earth’s atmosphere, it can only be observed near the South and North poles. The reason behind that is the magnetic field lines come from the two poles, being perpendicular to them, as you can see in figure 1. Since those invisible field lines are the densest at the poles, the magnetic field is the strongest at North and South Pole, compared to the other parts of Earth. Thus, the electrically charged particles, that are electrons from the electromagnetic waves from the sun are dragged to the two poles by the Earth’s magnetic field. Because of this event, the charged particles enter our planet’s atmosphere and combine with the gases in the atmosphere. When they combine with gases, they bring those gases to excited state where one of their electrons move to a higher lever orbital. This excited state makes gases quite unstable, and when they return to their original state, they release energy by releasing photons. Those released photons form light scattering, and this creates the fascinating phenomenon of aurora borealis. According to which gas molecule is being contracted by those electrically charged particles, light scattering takes place in various colors. For instance, when the particles combine with the oxygen molecules that flow freely in the atmosphere, they form yellow and green light, and when they collide with nitrogen, colors like red, violet, and blue are produced by their contact.[4] This physical process forms “aurora borealis” at the area near the North Pole, and “aurora Australis” at the places neighboring the South Pole.

<u>Figures 2 & 3:</u> Photos of aurora borealis my family and I took during our visit to Finland.

After observing the phenomenal northern lights, "aurora borealis", and doing lots of research about the event, I learned about the solar winds, the Earth's magnetic field, the cause of the formation of northern lights, the reason why the colorful light scattering is only visible near the two poles, and what gives the northern lights the vivid colors, I found several answers to the questions I was asking to myself. However, the one question that is still in my mind is; what are the effects of the magnetic field strength of Earth and the initial energies those particles have when they are released from the surface of Sun on the formation of aurora borealis?

Venus, for instance, doesn't have a magnetic field, so there are arguments on whether it is possible or not for an event like "aurora borealis" to take place in Venus.[5] In contrast, Jupiter has the strongest magnetic field among the planets of our solar system, and a process like our "aurora borealis" occurs in Jupiter. Moreover, the auroras are both enormous in size and are more energetic than the auroras we observe on our planet. While the source of auroras on Earth is the solar winds, Jupiter has another source for its auroras, too. Since the magnetic field of Jupiter is strong, it grabs charged particles and electrons from the environment surrounding it [8]

Hence, what prepossesses me is that if our world had a stronger magnetic field like Jupiter's or a weaker or none magnetic field like Venus's would we still be able to observe the northern lights the same way as we do now? Or if the charged particles had a higher energy when they are released from the sun, would our auroras change?

1.2 Objective

The objective of this exploration is to determine if there is a relation between magnetic field, and more specifically, magnetic field strength; or the potential energy difference (Voltage) of electrons, and the visual process of the movement of electrons, which forms the northern lights, a phenomenon that is also known as "aurora borealis". Moreover; with this investigation I plan to come with an answer to the theories about would there be a difference at the way we observe "aurora borealis" now, if the magnetic field of our Earth was stronger, weaker; or if our Sun released charged particles with a different energy. Since the effects I want to investigate are on two different variables, I have two research questions to investigate separately. Thus, I want to find an answer to my two research questions, which are;

"What is the effect of the strength of a magnetic field on movement of electrons, and therefore the formation of "aurora borealis", indicated by the change of radius of the circular path electrons follow, when the magnetic field strength of a model sample is changed?" and;

"What is the effect of the initial energy of electrons on movement of electrons, and therefore the formation of "aurora borealis", indicated by the change of radius of the circular path electrons follow, when the voltage of a model sample is changed?"

2. Selection and Control of Variables

2.1 Independent Variables

I wanted to observe the change in movement of electrons with respect to the aurora borealis model, and there were two different variables with possible effects. Since having two independent variables at the same time leads to miscalculations and makes the investigation impossible, I will investigate them separately.

I chose two different independent variables separately to explore this phenomenon more extensively. The independent variables I chose for my experiment are current and voltage. The current will represent the magnetic field of Earth, and the voltage of my setup will represent the initial energy of electrons that come with solar wind.

I chose current as an independent variable because there was not a device to measure the magnetic field strength in the laboratory I worked. However, a current generator/amperemeter was available. Hence, I decided to use it, keeping in mind that current and magnetic field are directly proportional. This proportion means that when current increases, magnetic field would be stronger, which is the effect I aimed to observe in my experiment.

I chose voltage as my other independent variable to observe the effect on electron movement. It will represent the initial energy of charged particles that leave the sun to form the solar wind. With changing its value, I plan to observe any changes in electrons' movements.

Since the initial energy of electrons in solar wind and magnetic field of earth are the main components that form aurora borealis, I wanted to explore this phenomenon with respect to those two independent variables separately. Therefore, I will investigate their effects in different experiments, and combine them in my data processing part.

2.2 Dependent Variable

I want to observe if any changes occur in the movement of electrons in my assessment. The dependent variable I chose for my experiment is radius of the circular path electrons follow. I will use the Helmholtz Coil setup, so I plan to work with radius, since it is easier to observe it with the setup I have. I will explore the change in radius of electrons' circular path with respect to current and voltage of the system. It will represent the movement of electrons in our atmosphere, and the change of it will represent any changes that could happen in the formation of aurora borealis.

2.3 Controlled Variables

I will control the placement of the setup, it will be parallel to Earth's original magnetic field lines, so there will not be any resultant vectors that would effect the movement of electrons. My setup was already placed according to this control variable in the laboratory I worked, so I just tried not to move it a lot. I will do my experiment in a dark room with almost no light, so I can observe the electron bundle clearly. I will also avoid using any magnetic objects around the setup of my experiment to make sure that the electron bundle does not lose its path, which would give me different results, effecting my experiment in a negative way.

Since I have two independent variables, I will experiment on them seperately. Therefore, the independent variable that I do not use will be my control variable while I experiment with the other separately. For instance, I will keep the voltage of my setup controlled while I increase the current value, and vice versa. If I experimented on these two variables at the same time, the results would deviate, so I will use one as an independent variable while the other one stays steady.

		Units	Range
Independent Variable**	Voltage (V)	Volt (V)	150V- 200V- 250V- 300V
Dependent Variable	Radius of the path electrons follow (r)	Meter (m)	
Control Variables*	**Units**	**Possible Effect on Results**	
Current	Ampere	It would change the result of my experiment, making it more complex, since I plan to work with two independent variables separately.	
Placing of the experiment	_	It would give me different results affecting my results.	

<u>Table 1:</u> Variables Selected for this Experiment to explore the effect of Voltage

		Units	Range
Independent Variable**	Current (I)	Ampere (A)	
Dependent Variable	Radius of the path electrons follow (r)	Meter (m)	
Control Variables*	**Units**	**Possible Effect on Results**	
Voltage	Volt	It would change the result of my experiment, making it more complex, since I plan to work with two independent variables separately.	
Placing of the experiment	_	It would give me different results affecting my results.	

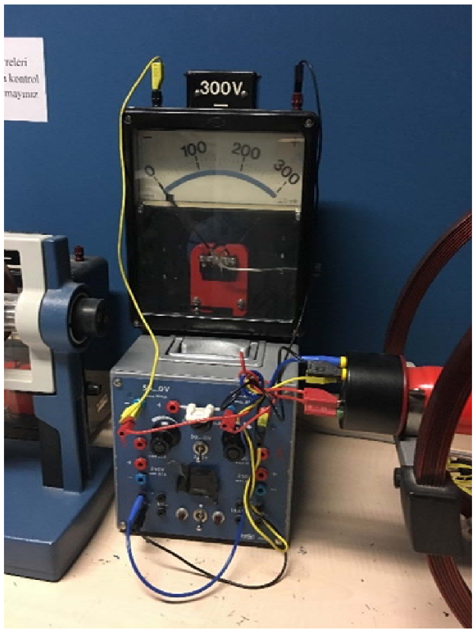
Table 2: Variables Selected for this Experiment to explore the effect of Current

*I will control my control variables by;

- Not changing the place of the setup of my experiment or moving it.
- Keeping one independent variable controlled and steady while I experiment with the other independent variable.

**I chose these variables and ranges because I wanted to represent the magnetic field of Earth and the initial energy of the electrons that leave the sun to form the solar wind. These variables will represent the natural phenomenon of aurora borealis.

3. Equipment and the Setup



<u>Figures 4 & 5:</u> Photos of the setup of my experiment.

The setup I used was already available in the laboratory I did my experiment in. I did not construct the same system again because it would cost more than I could afford, and the risk of error and uncertainty would increase dramatically if I tried to reconstruct a complex system like this by myself. It would also be time consuming, and it would need a lot of effort that would shade the main goal of my experiment. Therefore, I used this setup to explore the movement of electrons.

This system works with a voltage generator that I used while changing the voltage as an independent variable, a current generator that I also used to change the current as my other independent variable, and a system formed by Helmholtz Coils. The coils are large coils that are formed by overlapping current carrying wires with 154 windings, and the radiuses of those coils, which are 0.2 m are equal to each other and the distance from the path of electron movement. Between those coils, there is a glass sphere which is vacuumed, but has just a little bit of nitrogen gas (with $\mu = 4\pi \times 10^{-7}$) in it so it will represent the atmosphere of our world. This sphere has a cathode ray tube and a system to measure the radius of the circular path of electrons. The cathode ray tube basically works as an electron gun, and electrons that leave it will represent the movement of electrons around Earth and the formation of aurora borealis in my experiment. The voltage generator will represent the initial energy of electrons that form the solar wind, and the current generator will represent the magnetic field of Earth. Now, to get the cathode ray tube started, both of them are needed. This also shows us why there is not aurora borealis in Venus, where the magnetic field is almost non-available. The cathode ray tube is heated to a level that it releases electrons, the voltage generator creates an electron bundle from it, and current effects the electron bundle so the is moves in a circular path. The radius of that circular path is measured with the system inside the glass sphere which basically works like a ruler.

4. Procedure

Since I have two different independent variables, I must investigate their effects separately. However, doing experiments and trials on them one by one would be too time consuming. Moreover, drawing raw and processed data graphs separately for each of them would make a lot of graphs, consume too much time and space, would make the data more complex and harder to understand. So, I will investigate their effects separately with different trials, but I will combine the results to make my experiment cleaner. To obtain this, I will explore the change in the radius of the circular path electrons follow with respect to these two variables. I will gradually increase the voltage, and change the ampere to obtain the radius I want in each voltage value again, and write down the current needed to obtain 2, 3, 4, and 5 cm of radius of circular path. So, I will observe the current needed to obtain a specific radius for each voltage value, which will make them my independent variables. The procedure of my experiment is;

1. Turn the lights off and keep any magnetic objects away from the setup of the experiment.
2. Set the voltage of the system to 150V, and control it at steps 3 to 5.
3. Turn of the current generator/ ammeter on.
4. Slowly change the current, and write down the values of current when the radius of the circular path the electron bundle follows is 2, 3 ,4 and 5 cm.
5. Repeat the experiment 4 times and write down the results of each trial.
6. Repeat the steps 1 to 5 for different voltage values (150-200-250-300 V), write down the raw data.

5. Data Collection and Processing

Raw Data:

In my experiment, I observed that the electrons that are emerged from the cathode ray tube do circular motion due to the magnetic field, and the radius of the circular path electrons follow changes with respect to the values of voltage and current. The current values I found were really close to each other, since I used an electronic current generator/ amperemeter.

Voltage (V±5V)	Radius (cm±0.2cm)	Trials	Current (A±0.01A)
150	2	1	2.78
		2	2.77
		3	2.76
		4	2.81
	3	1	1.80
		2	1.80
		3	1.81
		4	1.79
	4	1	1.22
		2	1.20
		3	1.24
		4	1.22
	5	1	1.00
		2	0.99
		3	0.98
		4	1.03
200	2	1	3.30
		2	3.29
		3	3.30
		4	3.31
	3	1	2.19
		2	2.21
		3	2.18
		4	2.18
	4	1	1.59
		2	1.60
		3	1.59
		4	1.58
	5	1	1.26
		2	1.22
		3	1.30
		4	1.26

250	2	1	3.69
		2	3.70
		3	3.67
		4	3.68
	3	1	2.51
		2	2.52
		3	2.49
		4	2.52
	4	1	1.85
		2	1.86
		3	1.85
		4	1.84
	5	1	1.43
		2	1.41
		3	1.45
		4	1.43
300	2	1	3.97
		2	3.99
		3	3.96
		4	3.98
	3	1	2.75
		2	2.74
		3	2.75
		4	2.76
	4	1	2.04
		2	2.00
		3	2.07
		4	2.05
	5	1	1.62
		2	1.63
		3	1.61
		4	1.62

Table 3: Current values needed to obtain 2, 3, 4 and 5 cm of the radius of the circular path electrons follow in 150, 200, 250 and 300 V of voltage.

Figure 6: Picture of the circular path the electrons follow in my experiment

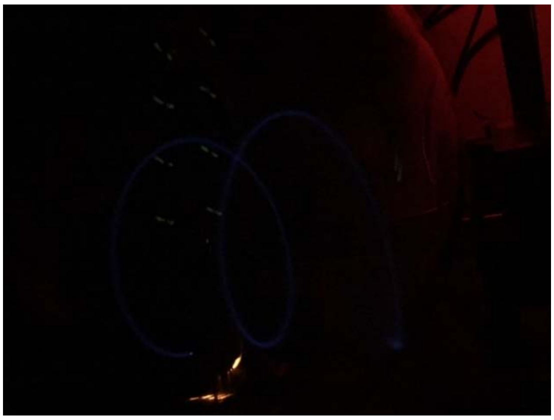


Figure 7: Picture of the circular path the electrons follow when the magnetic field is not parallel to the magnetic field lines of Earth in my experiment

The radius of the circular motion electrons follow increased when the current values decreased, so there is an inverse proportion between them. The radius also increased when the voltage applied to the system increased, so they are directly proportional. The ray of electrons started to do a spiral motion, as seen in figure 7, when the placement and the slope of the system changed. This showed that when the magnetic field generated by the Helmholtz coils were not parallel to the magnetic field lines of the Earth, a resultant magnetic field occurs, and this makes the electrons deviate from their circular path to make a spiral motion.

After creating the raw data table, I calculated the average current values for 4 trials with the formula: $\frac{n1+n2+n3+n4}{4}$, (n= the values from trials). Then, I created a table that shows the relation between the average current and radius for each voltage value.

Example Calculation for the average current:

$$\frac{2.78 + 2.77 + 2.76 + 2.81}{4} = 2.78\,A$$

Voltage (V±5V)	Radius (cm±0.2cm)	Average Current (A±0.01A)
150	2	2.78
	3	1.80
	4	1.22
	5	1.00
200	2	3.30
	3	2.19
	4	1.59
	5	1.26
250	2	3.69
	3	2.51
	4	1.85
	5	1.43
300	2	3.97
	3	2.75
	4	2.04
	5	1.62

Table 4: Average current values needed to obtain 2, 3, 4 and 5 cm of the radius of the circular path electrons follow in 150, 200, 250 and 300 V of voltage.

6. Presentation and Analysis

After drawing tables that show the effect of current and voltage on the radius of the circular path, I drew graphs with the average current values for each voltage value to see their effects clearly and comment on the slope and shape of the graphs, and observe the relation and proportion between them separately.

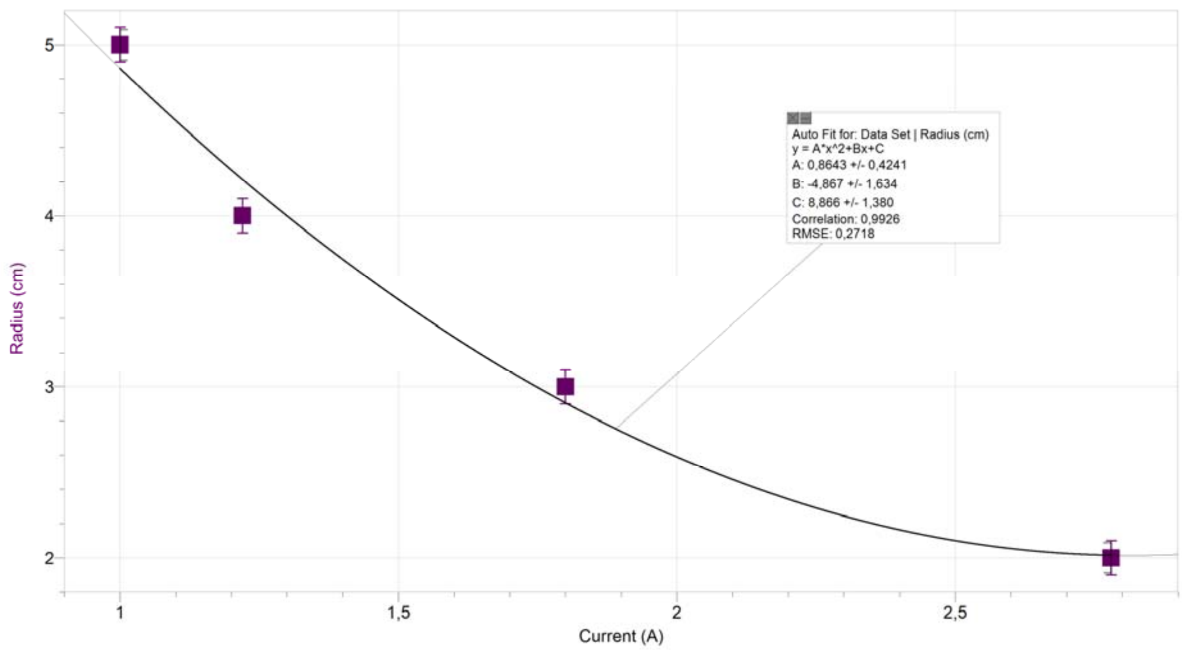


Figure 8: Graph of the relation between current and radius of the circular path the electrons follow at 150V.

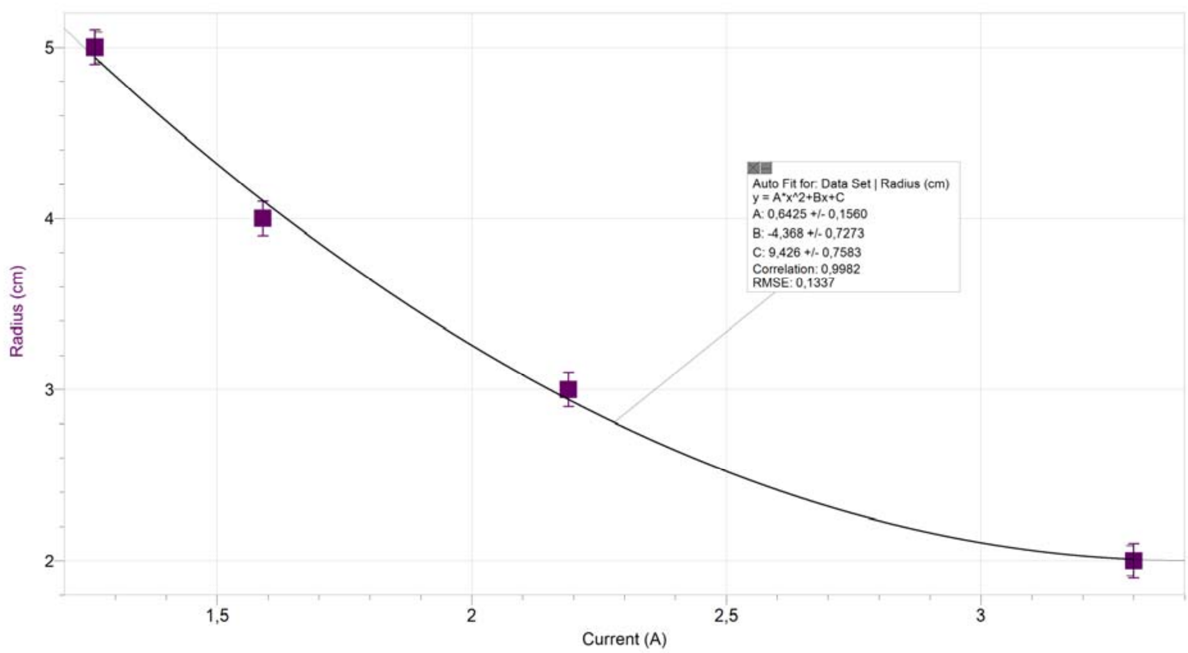


Figure 9: Graph of the relation between current and radius of the circular path the electrons follow at 200V.

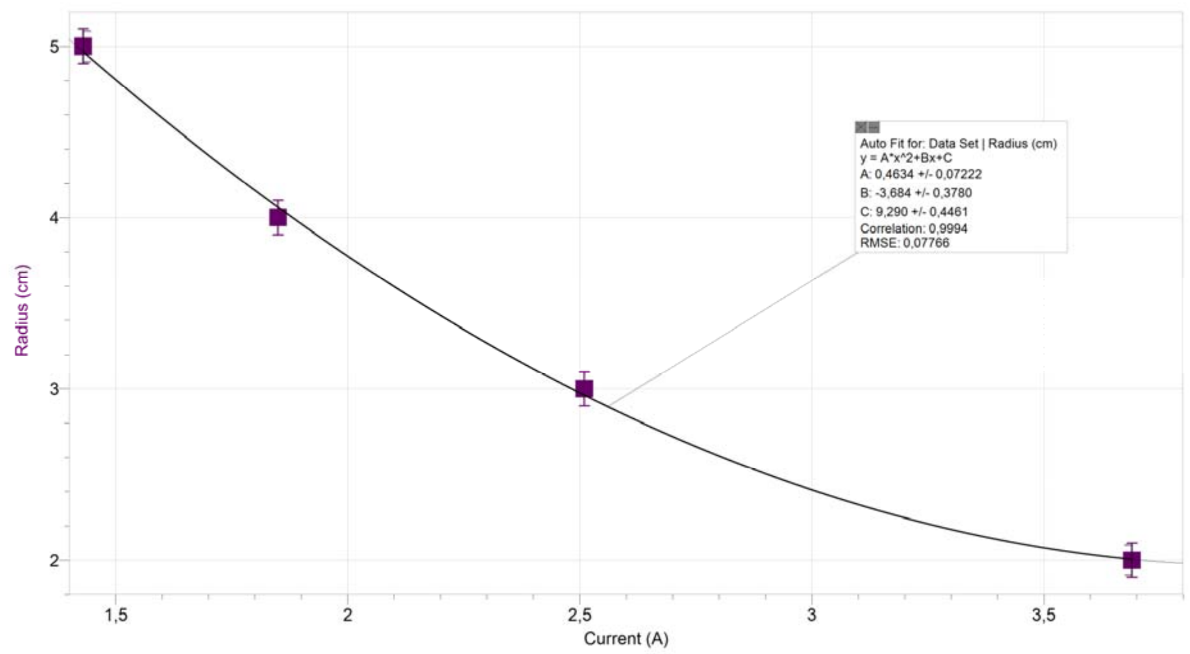


Figure 10: Graph of the relation between current and radius of the circular path the electrons follow at 250V.

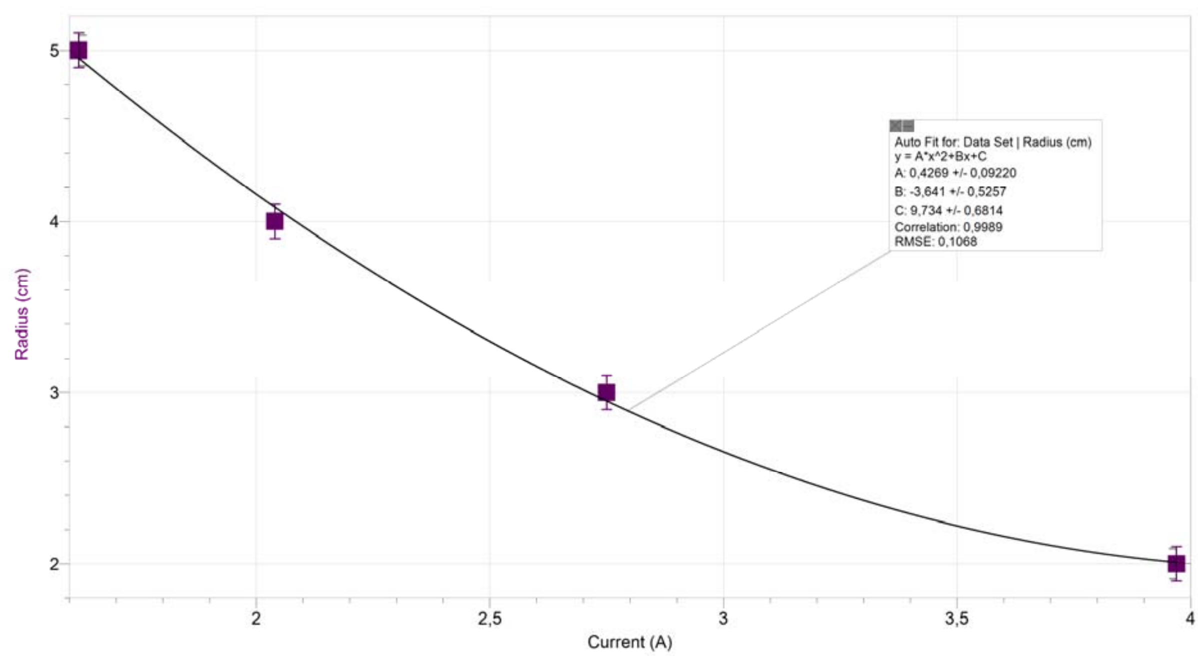
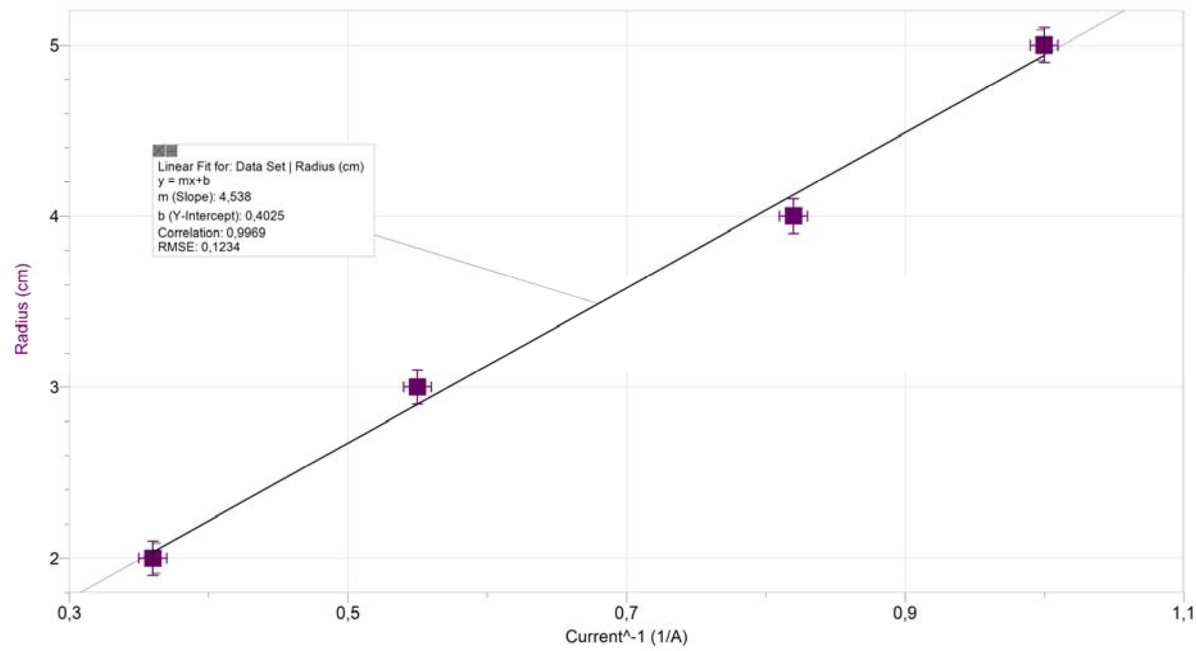


Figure 11: Graph of the relation between current and radius of the circular path the electrons follow at 300V.

After drawing these graphs, I saw that the radius of the circular path the electrons follow is indirectly proportional to the current that generates the magnetic field. Therefore, I drew the graphs again by using values I calculated with $\frac{1}{current}$. Then, the graphs had straight lines and they proved that the radius of the circular path the electrons follow is indirectly proportional to the current that generates the magnetic field.



<u>Figure 12:</u> Graph of the relation between 1/current and radius of the circular path the electrons follow at 150V.

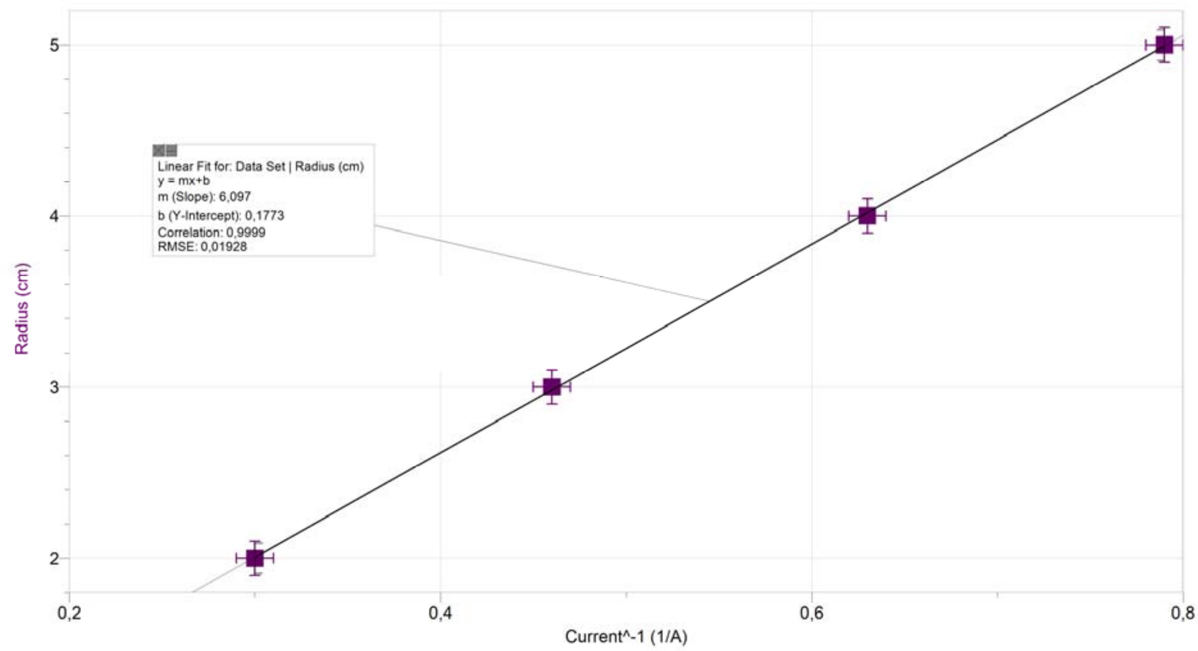


Figure 13: Graph of the relation between 1/current and radius of the circular path the electrons follow at 200V.

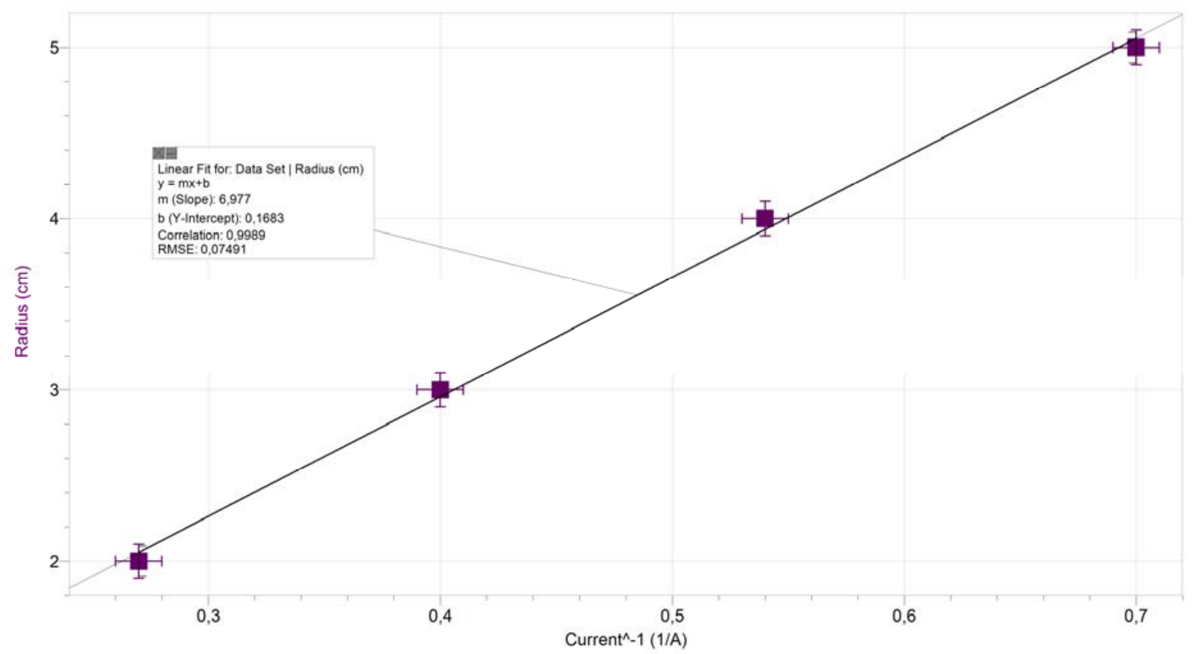


Figure 14: Graph of the relation between 1/current and radius of the circular path the electrons follow at 250V.

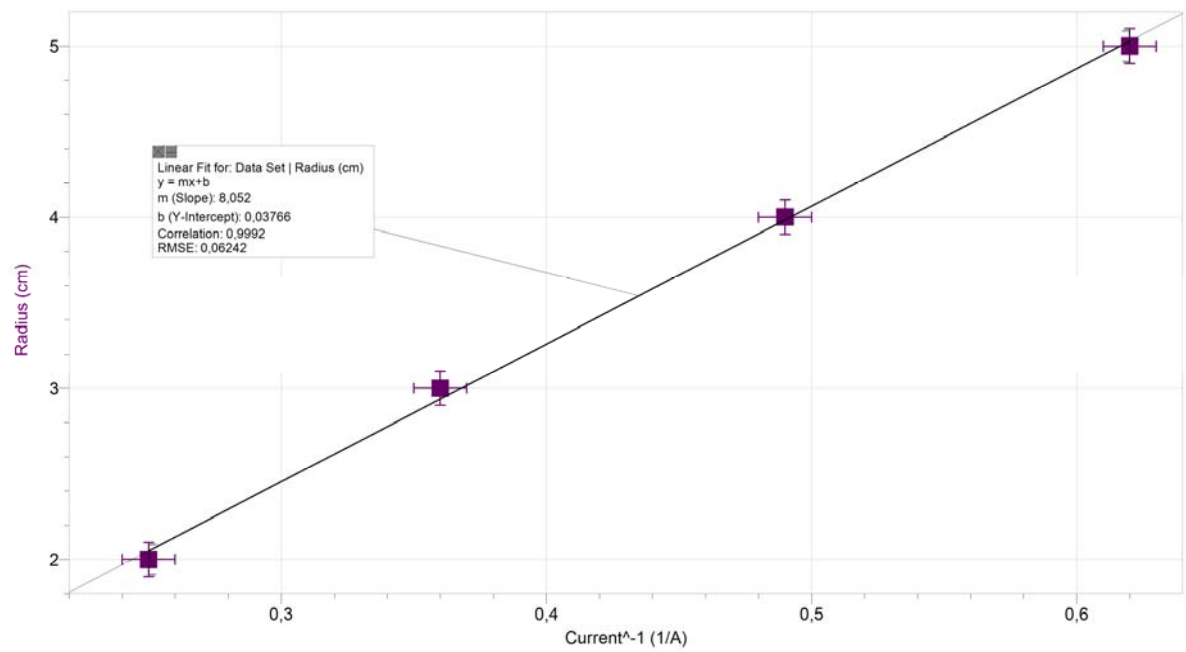


Figure 15: Graph of the relation between 1/current and radius of the circular path the electrons follow at 300V.

The values I found and these graphs showed me that the radius of the circular path electrons follow is indirectly proportional with the current, and directly proportional with the voltage. The slopes of my graphs which show the relation between 1/current and the radius of the electrons' circular motion for each voltage value were 4.54, 6.09, 6.98 and 8.04 for the voltage values of 150 V, 200 V, 250 V and 300 V. this proved the direct proportion between voltage and radius, and the inverse proportion between current and radius.

Therefore, I can state that $r \propto \frac{1}{I}$ and $r \propto V$.

7.Further Research

I found that the radius of the circular path electrons follow is indirectly proportional with the current, and directly proportional with the voltage, which answered my research questions. But, after two of the questions in my mind found answers, a new question was born. Would all these effects that changed the radius of electrons' circular path change the charge per mass ratio of electrons? The answer I found theoretically was that this ratio is always constant, since it is one of the unchangeable properties of electrons. Yet, I still wanted to calculate it for each radius value and draw a graph to test this furtherly.

To calculate the e/m ratio, I used the formula $\frac{2V \cdot R^2}{r^2 \cdot n^2 \cdot (\mu_0)^2 \cdot I^2}$, where R= radius of Helmholtz coils and is 0.2 m. I derived this formula by $\frac{e}{m} = \frac{2V}{r^2 \cdot B^2}$ when $B = \frac{(\mu_0) \cdot n \cdot I}{R}$. μ value is constant and = 4π x 10^{-7} (it was stated on the setup of my experiment). n is the number of winding, that is constant and is 154, which is also stated in the setup.

<u>Example calculation where r= 0.02 m, average I= 2.78 A, V= 150V:</u>

$$\frac{2 \times 150 \times (0.2)^2}{(0.02)^2 \times (4\pi \times 10^{-7})^2 \times 154^2 \times (2.78)^2} = 0.926 \times 10^{11} Coulomb/kg$$

I then researched the normal e/m ratio I should have got, and it was 1.76 x 10^{11} C/kg[1]. The values I found were slightly different, which probably is due to random errors, but still, disregarding that small difference, my findings proved that I did and calculated my experiment right.

[1] https://www.nyu.edu/classes/tuckerman/adv.chem/lectures/lecture_3/node1.html

Radius (cm±0.2cm)	Charge per Mass ($x10^{11}$) (C/kg±1.166 $x10^{11}$ C/kg)
2	0.926
3	0.821
4	0.746
5	0.806

Table 5: Charge per mass values of electrons at different radiuses

After this table, ANOVA is applied to find the variance and P value of my investigation. ANOVA is preferred over T test since there are more than two treatments.

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 2	4	3,299	0,82475	0,005606
Column 1	4	14	3,5	1,666667

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	14,31393	1	14,31393	17,11913	0,006095	5,987378
Within Groups	5,016819	6	0,836136			
Total	19,33074	7				

Table 6: ANOVA calculation for my values

Since my P value is smaller than 0.05, and the variance of my values is relatively small, my values are precise, my calculations are right and my research questions found their answers. The charge per mass values are not accurate but precise, so there must be a systematic error rather than random errors. Still, my suggestions about aurora borealis is proved to be right.

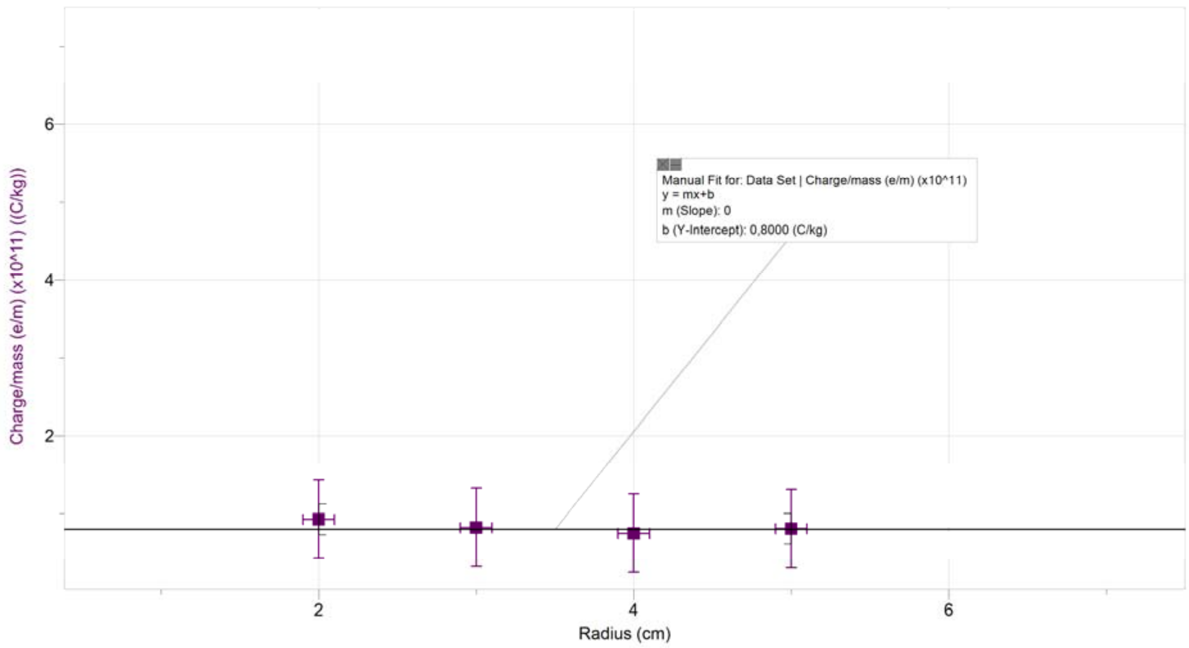


Figure 16: Graph of the relation between the radius of the circular path the electrons follow at and the charge per mass ratio I found for each voltage and current value.

The slope of this graph is 0, so I proved that while the radius of the circular path electrons follow changes with respect to current and voltage, the charge per mass ratio of electrons stays constant under any circumstances.

8. Uncertainty Calculations

Uncertainty of measurements:

δV = ± 5V, δI = ± 0.01A, δr = ± 0.2cm*

*These uncertainty values are selected for measurements since they were the smallest units of my setup.

Uncertainty for each charge per mass value at 150V is found by this formula:

$$\delta = \frac{\delta \frac{e}{m}}{|a|} = \sqrt{\left(\frac{2\delta I}{I}\right)^2 + \left(\frac{2\delta r}{r}\right)^2 + \left(\frac{2\delta V}{V}\right)^2}$$

Total uncertainty at 150V is found by this formula: $\delta t = \frac{1}{\sqrt{\sum \delta_n^{-2}}}$

Example Calculation:

$$\delta_1 = \frac{\delta \frac{e}{m}}{|a|} = \sqrt{\left(\frac{2\times 0.01}{2.78}\right)^2 + \left(\frac{2\times 0.002}{0.02}\right)^2 + \left(\frac{2\times 5}{150}\right)^2} = \pm 0.223 \text{ x}10^{11}$$

$$\delta_2 = \frac{\delta \frac{e}{m}}{|a|} = \sqrt{\left(\frac{2\times 0.01}{1.80}\right)^2 + \left(\frac{2\times 0.002}{0.03}\right)^2 + \left(\frac{2\times 5}{150}\right)^2} = \pm 0.146 \text{ x}10^{11}$$

$$\delta_3 = \frac{\delta \frac{e}{m}}{|a|} = \sqrt{\left(\frac{2\times 0.01}{1.22}\right)^2 + \left(\frac{2\times 0.002}{0.04}\right)^2 + \left(\frac{2\times 5}{150}\right)^2} = \pm 0.075 \text{ x}10^{11}$$

$$\delta_4 = \frac{\delta \frac{e}{m}}{|a|} = \sqrt{\left(\frac{2\times 0.01}{1.00}\right)^2 + \left(\frac{2\times 0.002}{0.05}\right)^2 + \left(\frac{2\times 5}{150}\right)^2} = \pm 0.291 \text{ x}10^{11}$$

$$\delta t = \frac{1}{\sqrt{0.223 \text{ x}10^{-22} + 0.146 \text{ x}10^{-22} + 0.075 \text{ x}10^{-22} + 0.291 \text{ x}10^{-22}}}$$

= ±1.166 x10^{11} C/kg

My uncertainty being bigger than the calculated e/m values prove that there is a systematic error rather than random errors, so my exploration is still precise.

9. Conclusion and Evaluation

In conclusion, this investigation found answers to many questions that kept my mind busy about the fascinating natural phenomenon of aurora borealis.

I learned that electrons do circular motion when they enter a magnetic field, and the radius of that circular motion depends on the current which creates the magnetic field and the voltage which is the initial energies of electrons.

The relation between radius and current is inversely proportional, and the relation between radius and voltage is directly proportional. Moreover, the change in current, voltage and radius has no effect on the charge per mass ratio of electrons no matter what. This ratio is always constant and is not affected by external variables.

This exploration taught me that if the magnetic field strength of the Earth, which is represented by the current was increased, the radius of the circular path electrons follow in the atmosphere would have decreased.

If the initial that the electrons have while leaving the sun by the electromagnetic waves of the sun, which is represented by voltage, have increased, the radius would have also increased. So, if both increased, there would not be a significant change in the way we observe aurora borealis.

The strengths of my experiment were using an available setup, which minimized systematic errors while being a nice way to model the Earth's atmosphere, the solar winds, and the phenomenon of aurora borealis. I believe that using this setup as a model is creative and time conserving.

I also managed to find the effect of current and voltage on the radius of circular path electrons follow, and proved that the charge per mass ratio of electrons is constant under any circumstances. Working on two different research questions and a further research is also a strength, since it helped to develop my investigation.

My weaknesses and limitations were not doing more trials which would decrease the random errors, finding the charge per mass ratio slightly different than its normal value, which means that there were systematic errors.

Also, some of my graphs did not start from origin, which could be considered as a limitation. The setup I used could only measure between 2 and 5 cm, which could also be a limitation and increase the risk of random errors.

Despite these weaknesses, my experiment was successful, since I managed to find answers to my questions. My advice for future explorations would be doing more trials to minimize errors.

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