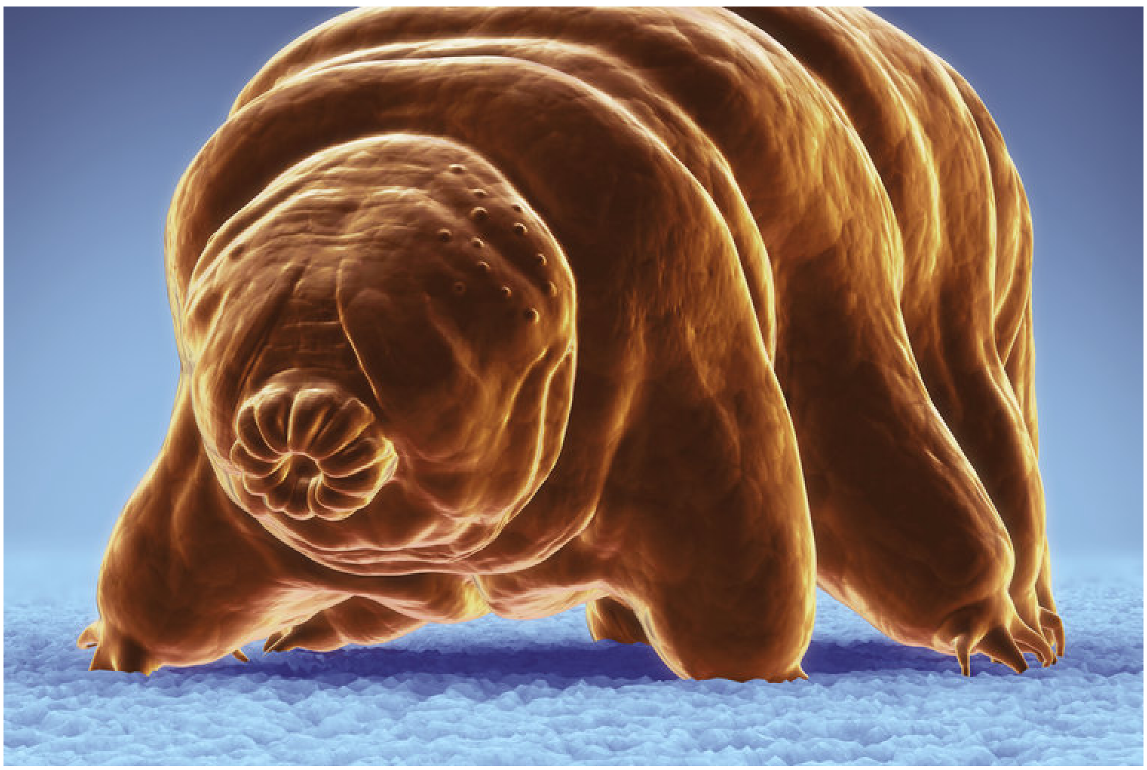
Abstract

The purpose of this experiment is to test the effects of varying levels of the geomagnetic field on the mortality levels of the tardigrade species, Hypsibius dujardini, since different magnetic fields are present on other planets and tardigrades are extremophiles. Due to their extreme resilience, tardigrades could be a solution to humanity's overpopulation problem and its eventual migration to other planets through the possibility of biological terraformation. However, the effects of planetary factors such as magnetic fields must be tested to know if tardigrades can survive on those planets and start the terraformation process. In order to perform this experiment, a geomagnetic inhibitor was set at 0-1400mv at 200mv intervals, with 800mv as the control (Earth's magnetic field level). Since tardigrades have lived on Earth for the past 500 million years, they should survive the most at 800mv and the least at levels farther from 800. 5 trials for each were set with 15 tardigrades each for every field level. The tardigrades were set to dry in the geomagnetic inhibitor for 24 hours at a time then rehydrated with spring water for 24 hours. Afterwards, the amount alive and dead were counted. The results show that the survivability of the tardigrades increased from 0mv to 800 at a logistic growth rate. However, from 800mv to 1400mv, the survivability decreased at a linear rate. Even though some tardigrades did not survive, every trial showed that at least 3 of the 15 tardigrades had survived. The high survivability at the Earth's magnetic field proved that tardigrade resistivity has evolved to be most effective on Earth but also works with other magnetic fields as well. So, even though my hypothesis was proven correct, these tardigrades could still survive on exoplanets and jumpstart their ecosystem, making terraformation a reality.

The Effects of the Geomagnetic Field on Tardigrade Survivability



By: Divy Kumar
Niles North High School

Table of Contents

Acknowledgements

I would like to thank Mrs. Camel for her support for my research. Even when I was not able to perform my original experiment due to a shipping mishap, she still believed that I could do another experiment in the small amount of time that I still had. I would also like to thank my family for encouraging me to continue working and research something new. Everyone helped a lot when this project went through complications as well, encouraging me to persevere. Also, I would like to thank them for sitting through many speeches and giving me tips and tricks on how to improve them.

Purpose, Hypothesis, and Rationale

Purpose: The purpose of this experiment is to determine the effects of Earth's geomagnetic field as well as other magnetic fields on the survivability of tardigrade species *Hypsibius dujardini*. Since tardigrades are extremophiles, they have the ability to survive very harsh conditions and so could have the potential to live on other planets as well. However, this experiment is testing the effects of the magnetic field on these microorganisms due to its effects on various animals and it being naturally created by our planet. Its effects on tardigrades show one factor of the organism's potential ability to live on other planets, leading to the idea of terraforming parts of outer space in order to create a new home for humanity.

Hypothesis: If the tardigrade species *Hypsibius dujardini* is exposed to varying levels of a magnetic field during anhydrobiosis, then the group that will survive the most will be the control, with lower and higher fields having higher mortality rates.

Rationale: Tardigrades are extremophiles, which mean that they are able to survive a variety of devastating conditions such as extreme heat and cold. They do this by anhydrobiosis, which is when they dry up almost all of their cells. Due to this ability, researcher Weronika Erdmann tested the negation of the geomagnetic fields on tardigrades and discovered that they had a higher mortality rate when entering anhydrobiosis than when previously dried up during the experiment. Its mortality rate when the field was negated was also higher than when it was not in the geomagnetic inhibitor machine. Also, since tardigrades, like all other animals, have evolved on Earth, their present state must be accustomed to the Earth's magnetic field. So, higher magnetic fields than Earth's should see a higher mortality rate as well

The Possibility of Life in Outer Space: Starting Small

Our world has slowly been dying due to human influences. According to NASA, “most climate scientists agree the main cause of the current global warming trend is human expansion of the ‘greenhouse effect’” (A blanket around the Earth, 2018). Due to the greenhouse effect, our world is slowly deteriorating and sometime in the future, our descendants will have to leave the planet in search of a new place to live. However, since there is no way of colonizing other planets as of now, humanity must start small and work their way up. This process is called terraforming and is one of the ideas scientists are thinking about for future space colonies (Williams, 2016). The evolutionary process on earth had began with microorganisms and gradually went from unicellular to multicellular. Some of these early multicellular organisms included those such as the tardigrade, or water bear, which first appeared over 500 million years ago (Maaz & Waloszek, 2001). These water bears were discovered to be extremophiles, which are organisms that are able to survive very harsh conditions. Experiments have been done on tardigrades, testing the effects of various environmental conditions on these organisms. However, these experiments mainly tested physically prevalent conditions such as heat and lack of oxygen. On the other hand, the magnetic field has always been a factor in organism behavior as well, and could affect the tardigrade ability to survive harsh conditions. This magnetic field is different for different planets and is one of the reasons life can survive on our planet. However, once the journey to other planets begins, this planetary magnetic field will also be one of the major factors in our choice for a new home. So, by studying the effects this field has on an extremophile, it is possible to understand how humans could survive on other planets as well as see if extremophiles such as tardigrades could be the spark behind terraforming processes.

Even though humans have never been to the center to the earth, we can still understand the composition of our planet through the examination of earthquake shockwaves that reach the surface. The earth has different layers that form it, and the crust is the one we live on, only making up 1% of the total composition of the earth as shown in Figure 1. The center of the Earth is the solid inner core while the outer core is liquid. Scientists have calculated that the core is about 85% iron (The composition and structure of Earth, n.d.). These metals in the core are vital to the Earth's magnetic field. Since the outer core contains liquid iron, its flow "generates electric currents, which in turn produce magnetic fields. Charged metals passing through these fields go on to create electric currents of their own, and so the cycle continues. This self-sustaining loop is known as the geodynamo" (What causes the Earth's magnetic field?, n.d.). Since this magnetic field is created naturally by Earth, it is able to be assumed that other planets have this capability as well if their compositions are similar.

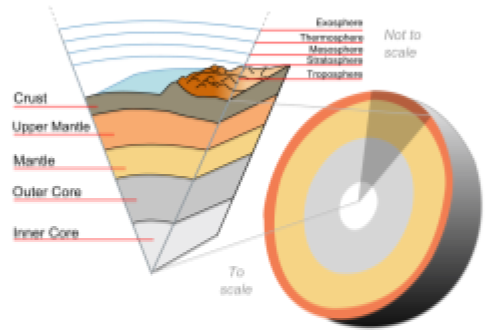


Fig. 1 (Composition of the Earth, n.d.)

The geomagnetic field has many properties, one of which is its effect on animals. Some animals, such as migratory birds, are able to sense the Earth's magnetic field and use it in migration (Hand, 2016). Even though researchers know that animals are able to use magnetoreception, they do not know why this occurs. As a result, they created models as hypotheses for possible reasons behind magnetoreception. For example, Ritz and his colleagues created a three-dimensional model and hypothesized that animals such as birds can sense the magnetic field by simply seeing it using a magnetic sensory organ (Ritz et al., 2000). Others, such as Nordmann and his colleagues proposed different ideas such as a light-sensitive chemical-based mechanism, electronic induction, or a magnetite-based magnetoreceptor (Nordmann et al., 2017). Similar to how magnetism works for birds, it is also effective in bacteria. Behind this is an idea called mechanical reception which is where animals could be able to use small magnetic particles to sense the field. Research have tried this with magnetotactic bacteria and showed that they could be “rotated by a magnetic field” (Ritz & Schulten, 2007). Since the the magnetic field can affect both complicated multicellular organisms such as birds as well as simple, unicellular bacteria, researchers have tried to apply the geomagnetic field to other organisms such as the tardigrade.

In order to test the magnetic field’s effect on tardigrades, an anti-magnetic chamber must be used. These can work in a variety of ways such as shielding whatever is inside by surrounding the testing region with sheets of very high magnetic permeability (Erdmann et al., 2017). Another way to do this is by creating a chamber with wires running through the sides. This way, a variable battery is used to inject electricity into the machine. A magnetic field meter, such as in Figure 2, is placed on the inside of the machine and the readings from it show what the magnetic field is in the center of the machine

Fig. 2 (EMF meter, n.d.)

The idea of a tardigrade reacting to the geomagnetic field had been tested by researcher Weronica Erdmann of Adam Mickiewicz University and her colleagues. However to understand their experiment, one must understand how tardigrades survive such harsh conditions. Tardigrades are the eight-legged microorganisms shown in Figure 3, and live in moist environments such as moss. These microscopic extremophiles are able to live in the most harsh conditions where most animals would easily die. They can live on both sides of the heat spectrum, surviving in extremely

Fig. 3 (Nelson, 2017)

hot and cold temperatures. In addition to this, they can survive in many other places as well. The tardigrade resilience can easily be seen through the research done by K Ingemar Jonsson and his team. In their well-known experiment, the researchers sent tardigrades into low-earth orbit. As a result, the tardigrades were exposed to various extremely dangerous conditions such as the vacuum of space. As well as this, it was discovered that they could were one of the most "radiation-tolerant animals and have been shown to survive extreme levels of ionizing radiation" (Jönsson et al., 2008). The tardigrade is able to live in all these dangerous places due to its desiccation ability where it dries itself out, called anhydrobiosis. By extracting all the water in its body, the tardigrade curls up into a dry shell as seen in Figure 4. This state is called Tönnchenform, or commonly known as tun and the metabolism of a tardigrade in this state slows down to 0.01% of the normal rate (Fox-Skelly, 2015). Usually, if the cells of an organism dries up, the DNA gets damaged and the organism will also likely die. Similarly "If a tardigrade stays in its dry tun state for a long time, its DNA gets damaged. But after it reawakens it is able to quickly fix it" (Fox-Skelly, 2015). This ability of the tardigrade allows it to survive extreme pressures, radiation, extreme cold, extreme heat, and many other harsh conditions.

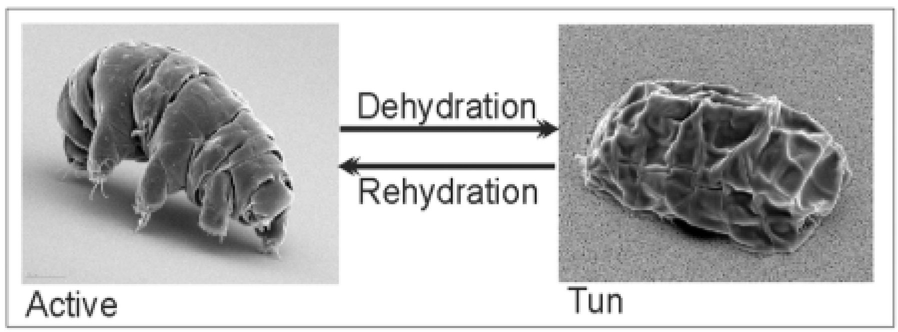


Fig. 4 (Schokraie, 2010)

In Weronika Erdmann's geomagnetic field research mentioned before, the researchers studied its effect on a tardigrade's desiccation ability. In their experiment, Erdmann and her colleagues nullified the geomagnetic field in an anti-magnetic chamber like in Figure 5. Using this, they conducted three different forms of the same experiment on the tardigrade species *Hypsibius dujardini*. First, they placed tardigrades previously desiccated into the anti-magnetic chamber. Afterwards, they tested the nullification of the geomagnetic field on tardigrades drying up and those reviving again. Through their tests, they discovered that tardigrades with the magnetic field nullified died more than exposed to the geomagnetic field. Also, tardigrades were most susceptible to the magnetic field when reviving through receiving water and the mortality rate was a bit lower when entering anhydrobiosis as shown in Figure 6. In this figure, experiment 1 is the tardigrade in anhydrobiosis, experiment 2 is entering, and experiment 3 is the tardigrade being revived (Erdmann et al., 2017). Now, the next step is testing the effects of different levels of the magnetic field on tardigrades in order to understand an important factor of their ability to survive on different planets.

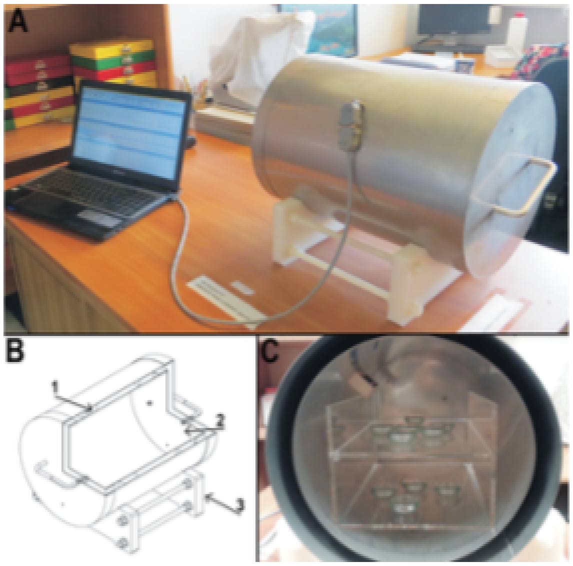


Fig. 5 (Erdmann, 2017)

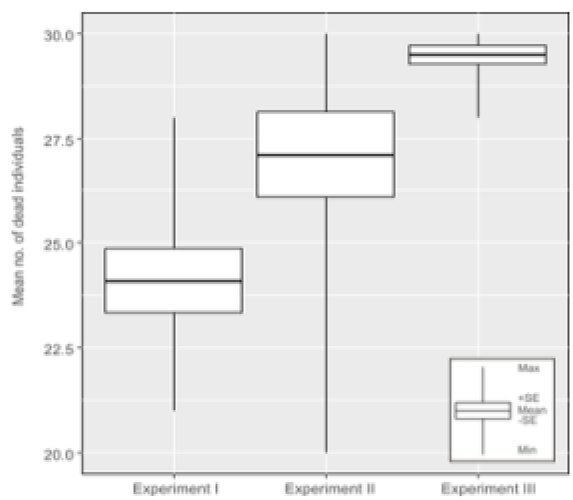


Fig. 6 (Erdmann, 2017)

All in all, tardigrades can be the perfect organism to study in order to understand the possibilities of life on other planets. Since these organisms can survive almost anything, they should be able to survive for at least a little while on other planets such as the recently discovered earth-like exoplanets. The magnetic field of these types of planets will most likely be different than Earth's, so the tardigrades will not have the same behavior as they do on our planet. Since their mortality rate increases when entering anhydrobiosis as shown by Erdmann's experiment, this is a good area to test its ability to survive different magnetic field levels. Even though tardigrades are seen as invincible, many are sacrificed in order for one to live. In fact, in Erdmann's experiment more than half of the tested tardigrades had died in the control. However, the ones that survive are those that hold the future of human progress and innovation.

Materials

- Tardigrades: Hypsibius dujardini
  - 12 cultures from Flinn Scientific
- Algae: Chlamydomonas
  - 2 cultures from Flinn Scientific
- Geomagnetic Field inhibitor
  - Containing a magnetic field reader
  - On loan from FermiLab
- 2 microscopes
  - One with objectives under stage
  - One with computer connection for photos
- Well Plates
  - 8 3x4 plates
- 40 sterile petri dishes
- 2 20-200 µl Micropipettes
  - One set to 30 µl
  - Other set to 50 µl
- 80 20-200 µl micropipette tips
  - 40 for micropipette set to 30 µl and 40 for the 50 µl micropipette
- 53 sterile pasteur pipettes
  - 13 for aerating cultures
  - 40 for well plates

- Marker
- Fluorescent light bulbs
- Ruler
- One gallon of spring water
- 100 ml Erlenmeyer flask
- Autoclave
- Non-latex gloves
- Closed-toe shoes
- Laptop

Procedure

***Gloves must be worn at all times after washing hands**

Receiving the tardigrades and algae:

1. Mark tardigrade culture covers with marker from 1 to 12
2. Open tardigrade culture 1
3. Aerate with sterile pasteur pipette 10 times and save pipette
4. Repeat step 3 with tardigrade cultures 2-8 and the algae culture
5. Taking care of cultures:
    a. Aerate cultures daily
    b. Turn on fluorescent bulbs
    c. Keep all cultures 45.72 cm (18 in) from fluorescent bulbs to allow for growth
    d. *Always* leave caps on cultures a bit loose to allow airflow
    e. Use algae pasteur pipette to feed tardigrade cultures every week
        i. Fill pipette with algae once for each feeding process

Setting up the experiment:

1. Bring one tardigrade culture, 5 petri dishes, micropipette (set to 30 µl), micropipette tips, 5 pasteur pipettes, and 1 well plate to lab bench with microscope (with objective under stage)
    a. Open tardigrade culture and use sterile pasteur pipette to extract enough of culture to cover the bottom of 4 wells
    b. Close tardigrade culture and save pipette
    c. Using microscope, view the 4 wells and look for tardigrades

   d. When a tardigrade is found, use 30 µl pipette to extract it from the well and place droplet into petri dish (tardigrade must be moving and have no eggs)
   e. Repeat step 5 until 15 tardigrades have been extracted then dispose of pipette tip
   f. Using the saved pasteur pipette, place remaining culture from well plates back into tardigrade stock culture and dispose of pipette
2. Repeat steps a-f 4 more times with new petri dishes and unused well plates
   a. Check to make sure well plates have been fully used and three petri dishes are closed and ready to be tested
   b. Mark trials 1, 2, 3, 4 and 5 on petri dishes as well as magnetic field setting to be tested

<u>Placing petri dishes into geomagnetic inhibitor</u>

1. Immediately turn on the geomagnetic inhibitor, making sure the magnetic field reader is set to the correct axes (tardigrades should dry up inside the inhibitor)
   a. Alter the voltage and current using knobs on the inhibitor while viewing readings from the magnetic field reader
   b. Change all knobs in order to reach desired mv reading (there is not a specific voltage and current needed due to inevitable interferences from different electronic equipment in different labs) of 0 mv.
2. Place 5 petri dishes into the inhibitor (for 5 trials), next to the magnetic field reader for best accuracy
3. Wait 24 hours

<u>Rehydrating the tardigrades</u>

1. Remove the petri dishes from inhibitor and bring to lab bench

2. Autoclave Erlenmeyer flask at 121°C for 15 minutes
3. While flask is being autoclaved, bring gallon of spring water and 50 µl pipette to bench to begin rehydration
    a. Open spring water and first petri dish, connect micropipette tip
    b. Pipette out 50 µl of spring water and place onto each dry spot on petri dish
    c. Close petri dish and dispose of pipette tip
4. Repeat steps a-c for other 4 petri dish trials
5. Once flask is autoclaved, fill with spring water
6. Use flask to fill bottom of each petri dish
7. Use algae pasteur pipette to place 4 drops of chlamydomonas into each petri dish
8. Wait 24 hours
9. Count amount of alive and moving tardigrades vs the dead and immobile and record

<u>Other trials:</u>

1. Repeat Setup, placing petri dishes into inhibitor, and rehydration using the other 11 cultures for the other 7 magnetic field levels (200 - 1400 mv)
    a. This can begin once the previous test trials have been taken out of the inhibitor to save time

<u>Taking Photos:</u>

1. Extract a couple of tardigrades using same method as in the experiment
    a. These should preferably not be eating algae for better photos
2. Turn on and connect second microscope to laptop
3. Open Motic app and place petri dish with tardigrades onto microscope

4. Using microscope, view tardigrades and take a photo with the corresponding button on the laptop
5. Save photos taken

<u>Disposal:</u>

1. Autoclave used material at 121°C for 30 minutes in biohazard bag
2. Dispose in trash or flush tardigrades down the drain

Variables

Independent Variable: Magnetic field setting in geomagnetic inhibitor. This was changed 8 times with 200 mv intervals from 0-1400 mv

Dependent Variable: The dependent variable in this experiment was the amount of tardigrades that had survived in each trial after going through anhydrobiosis while in the geomagnetic inhibitor

Control: The control was when the geomagnetic inhibitor was at 800 mv. This was the control because it was the reading of the geomagnetic field when the inhibitor was turned off.

Constants: Sterile equipment was always used, always put petri dishes in same position in the inhibitor, no phones or other extra electronic devices were allowed near the inhibitor while tests were running (when I was present), same equipment used such as microscope and magnetic field readers, magnetic field reader was not moved, same measurements used for all trials.

Results

	Magnetic field level (mv)	0	200	400	600	800	1000	1200	1400
Tardigrades which survived (out of 15)	Trial 1	4	5	8	13	14	12	10	6
	Trial 2	5	6	9	14	15	11	8	7
	Trial 3	5	4	10	14	14	12	9	7
	Trial 4	3	5	8	13	13	11	9	8
	Trial 5	4	5	9	12	12	11	10	8
	Averages	4.2	5	8.8	13.2	13.6	11.4	9.2	7.2

Table 1: This table encompasses the entirety of the experiment, showing the amount of tardigrades which survived in each trial for each magnetic field level. The trials were in batches of 15 tardigrades and the magnetic field level was measured in millivolts from 200-1400 with 800 as the control. Additionally, the averages of all five trials were included as well.

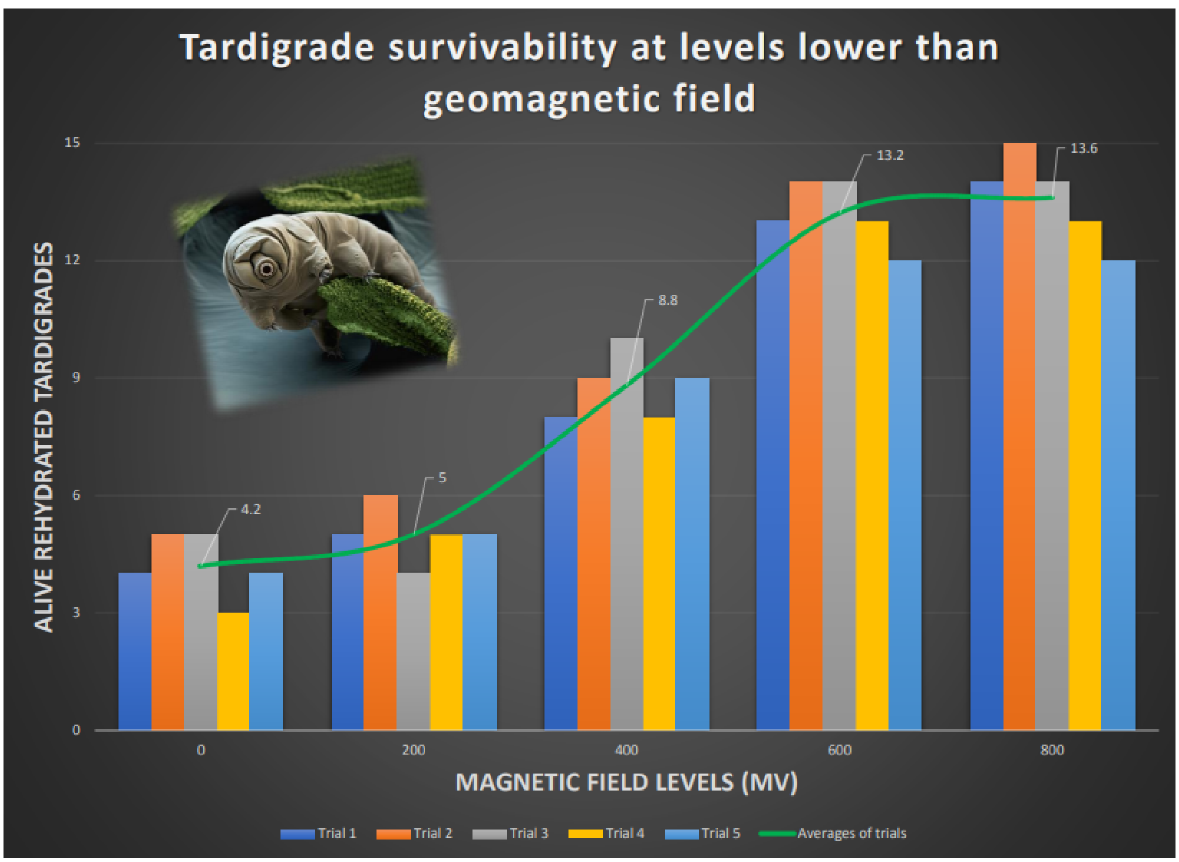


Figure 1: This graph shows the separate trials as bar graphs with the magnetic field level in millivolts on the x-axis and the survivability of the tardigrades on the y-axis. The yellow line is a depiction of the averages at each level and includes the control of 800 mv as well in order for comparison. As the magnetic field level approached 800 mv, the survivability of the tardigrades increased as well.

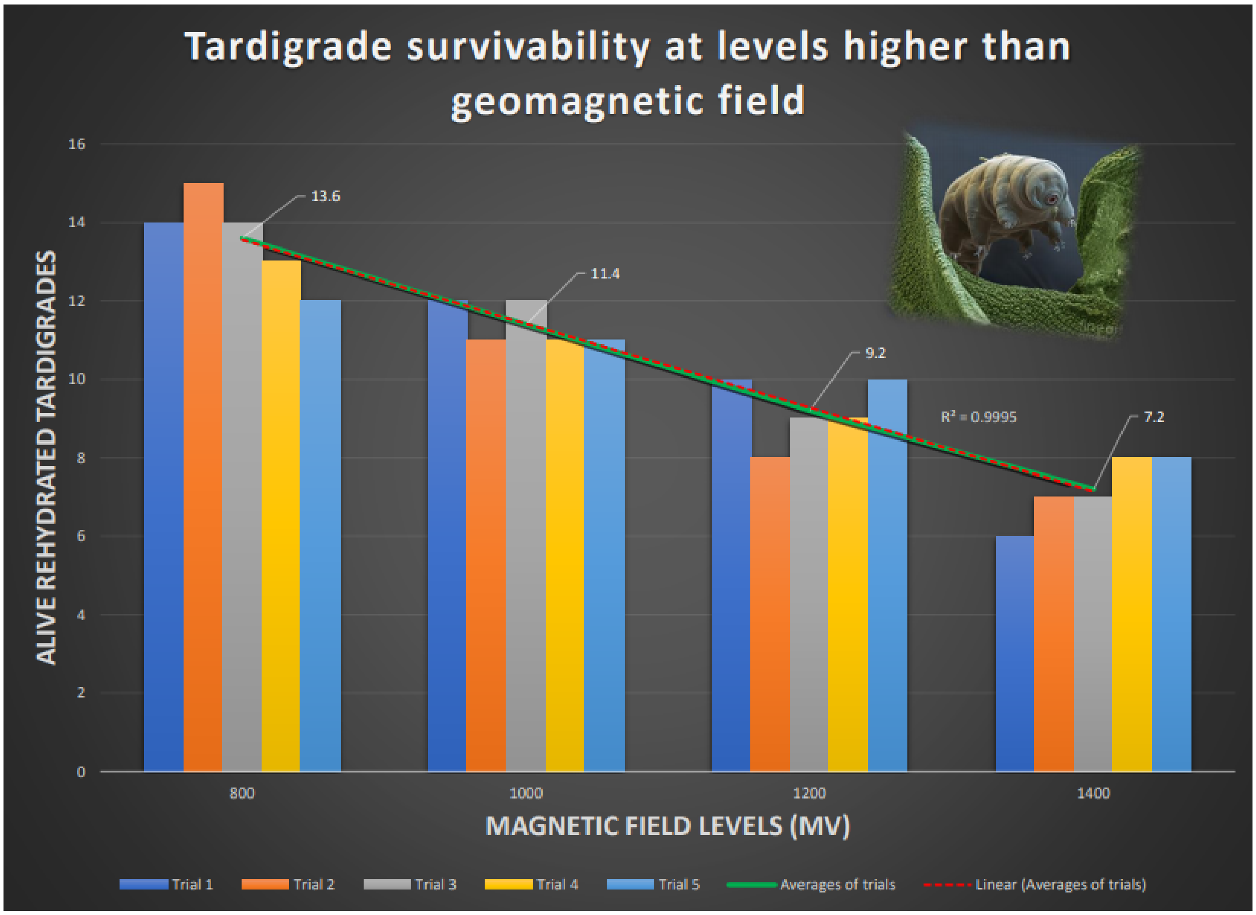


Figure 2: This graph also shows the amount of tardigrades which survived. However, these tardigrades were tested at magnetic field levels greater than the Earth's. This graph shows that the tardigrade survivability decreased with a higher magnetic field level at an almost linear rate. This trendline is shown by the red dashed line. This graph also includes 800 mv for comparison to the control

Data Analysis

Figures 1 and 2 both depict the data in Table 1. However, the graphs for the magnetic fields lower and higher than the geomagnetic field were different. Figure 2, which showed the higher magnetic fields, had a largely linear curve. As shown by the graph, the R^2 for the trendline of the average curve was 0.9995. This means that the data points were 99.95% linear, showing an easily discernible pattern for the effects of large magnetic fields on tardigrades and that any point on this graph can be approximated. This approximation can be derived as $f(x) = \frac{-6.4}{600}x + 22$ when $800 \leq x \leq 1400$. So, when the magnetic field increased above 800 mv, it is proportional to the amount of tardigrades that die. On the other hand, Figure 1, which showed the effects of lower magnetic fields on tardigrades, had a very different curve for the trial averages. On this side of the experiment, the amount of tardigrades which survived had been almost flat from 0-200 mv. However, the slope of the curve soon increased, with the steepest part at 400 mv. Soon after, the amount of tardigrades which survived flattened out again in the low teens from 600-800 mv. This type of curve can be depicted by a logistic formula which is where $f(x) = \frac{M}{1 + A e^{-kx}}$. In this formula, M is the carrying capacity, which is the highest amount possible. In this experiment, this would be 15, as each trial had a maximum of 15 tardigrades. A and k are both constants and x is the magnetic field level. In order to derive the equation for this experiment, the first value must be known which is f(0) = 4.2 in this case. Since x is 0, this makes $e^0=1$, and so the equation can be solved for A. After solving, A= 2.5714 and k can be solved with a different data point. In this case, we will use f(400) = 8.8 since it is in the middle of the curve and so will generate the approximation with the least error. After plugging it in the equation $f(x) = \frac{15}{1 + 2.5714e^{-kx}}$,

k is found to be .003237. So, the resulting equation is $f(x) = \frac{15}{1 + 2.5714e^{-.003237x}}$.

From this, a tardigrade's survivability at any magnetic field level under 800 mv can be approximated. As a result, tardigrades are more resilient at magnetic field levels a bit below 800 mv but their survivability drops in a linear fashion at levels above our geomagnetic field. However, the tardigrade is able to survive a bit more at levels above the geomagnetic field when compared to levels below the geomagnetic field such as when comparing 1400 mv to 200 mv, both of which are 600 mv away from the control. Additionally, even though the measurements were conducted in mv and not microteslas or gauss, Fermilab informed us that the inhibitor measurements in mv were directly proportional to microteslas. So, higher or lower millivolt settings did result in a higher or lower magnetic field level.

Experimental Error

Experimental error could have occured at the stage where the tardigrades were left in the geomagnetic inhibitor. Since this experiment was performed in a shared lab, other researchers could have passed by while the tardigrades were going through anhydrobiosis, the drying process. This could have caused error because electronic devices that others pass by with could alter the geomagnetic inhibitor and the magnetic field inside of it. Also, while the experiment was being done, some tardigrades were used later than others. As a result, the ages of the tardigrades were likely different from one another, potentially affecting the data received. This problem was combated by extracting only healthy, moving tardigrades.

Conclusion

As stated before, the purpose of this experiment was to test the effects of varying magnetic field levels on the anhydrobiosis, or the drying process, of tardigrades. This was done to study a factor of space, the naturally occurring magnetic fields of some planets, on an extremophile species in order to understand both how they can survive harsh conditions and whether or not they are a viable source for terraforming other planets.

The results of this experiment have supported the hypothesis that the control would have the highest tardigrade survivability. This makes sense because tardigrades have been organisms living on Earth for the past 500 million years. As a result, tardigrades were able to evolve into the organisms they are today, and so their peak anhydrobiosis ability would naturally occur on Earth. This has been shown by the results because of the logistic curve at fields under Earth's and the negatively linear slope at fields above Earth's, causing the peak survivability to occur at the control of 800 mv. Furthermore, the logistic curve shows that at fields close to Earth's, lower fields see a larger survivability. However, when the magnetic fields are set farther from the geomagnetic field level, the setting under 800 mv has a lower survivability than its corresponding field level above 800 mv due to the linear slope at fields from 800-1400 mv. All in all, the results show that tardigrades are most suited for this planet's environment. However, since they do survive with other magnetic fields as well, it is not an impossibility of using them for terraforming. Even though terraformation is an possibility for applying the advantages of tardigrades, their magnetic field resistance can also be used in other areas. For example, a small group of people report symptoms of extreme sensitivity to the electromagnetic waves. Due to the low amount of information on this topic, many call the disease, electromagnetic hypersensitivity, a pseudoscience. However, by using the resistive abilities of tardigrades and conducting more research, these suffering people may discover a ray of hope. Furthermore, another application of tardigrade resistivity to the geomagnetic field could be with birds and other migrating animals. Since birds need to constantly fly long distances, they rely on the geomagnetic field to navigate. However, throughout Earth's history, there have been geomagnetic reversals where the magnetic north and south poles change. During the reversal, the magnetic field level of the Earth is also altered, which may cause birds to lose their navigation abilities and potentially lead themselves into dangerous environments. However, with the help of tardigrade resistivity, this outcome could be circumvented. A further study of this experiment could be to test the effects of various magnetic fields on tardigrades being rehydrated since Erdmann's experiment showed tardigrades had the highest mortality rate when going through their rehydration process. Afterwards, the effects on tardigrades already in their tun (dried up) state could be tested in order to cover all parts of its extremophile cycle. By studying these miniscule, yet extremely strong creatures, human progress for both ourselves and the planet will continue to grow.

References

A blanket around the Earth. (2018). Retrieved March 7, 2018, from NASA website: https://climate.nasa.gov/causes/

The composition and structure of Earth. (n.d.). Retrieved March 5, 2018, from Lumen website: https://courses.lumenlearning.com/geophysical/chapter/the-composition-and-structure-of-earth/

[Composition of the Earth]. (n.d.). Retrieved from https://courses.lumenlearning.com/geophysical/chapter/the-composition-and-structure-of-earth/

[EMF meter]. (n.d.). Retrieved from https://www.lessemf.com/gauss.html

Erdmann, W. (2017, September 8). *Anti-magnetic chamber* [Photograph]. Retrieved from http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0183380

Erdmann, W. (2017, September 8). *Comparisons of mortalities* [Photograph]. Retrieved from http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0183380

Erdmann W, Idzikowski B, Kowalski W, Szymański B, Kosicki JZ, Kaczmarek Ł (2017) Can the tardigrade *Hypsibius dujardini* survive in the absence of the geomagnetic field? PLoS ONE 12(9): e0183380. https://doi.org/10.1371/journal.pone.0183380

Fox-Skelly, J. (2015, March 13). Tardigrades return from the dead. *BBC*. Retrieved from http://www.bbc.com/earth/story/20150313-the-toughest-animals-on-earth

Hand, E. (2016, June 23). The body’s hidden compass - what is it, and how does it work? *Science*. Retrieved from http://www.sciencemag.org/news/2016/06/body-s-hidden-compass-what-it-and-how-does-it-work

Jönsson, K. I., Rabbow, E., Schill, R. O., Harms-Ringdahl, M., & Rettberg, P. (2008). Tardigrades survive exposure to space in low Earth orbit. *Current Biology*, *18*(17). https://doi.org/10.1016/j.cub.2008.06.048

Maas, A., & Waloszek, D. (2001). Cambrian derivatives of the early arthropod stem lineage, Pentastomids, Tardigrades and Lobopodians An 'Orsten' Perspective. *Zoologischer Anzeiger - A Journal of Comparative Zoology*, *240*(3-4), 451-459. https://doi.org/10.1078/0044-5231-00053

Nelson, D. (2017, July 14). [Electron microscope tardigrade]. Retrieved from https://www.livescience.com/57985-tardigrade-facts.html

Nordmann, G. C., Hochstoeger, T., & Keays, D. A. (2017). Magnetoreception A sense without a receptor. *PLOS Biology*. https://doi.org/10.1371/journal.pbio.2003234

Ritz, T., Adem, S., & Schulten, K. (2000). A model for photoreceptor-based magnetoreception in birds. *Biophysical Journal*, *78*, 707-718.

Ritz, T., & Schulten, K. (2007, April 2). The magnetic sense of animals. Retrieved March 5, 2018, from Theoretical and Computational Biophysics Group website: http://www.ks.uiuc.edu/Research/magsense/ms.html

Schokraie, E. (2010, March). [Tardigrade tun state]. Retrieved from https://www.researchgate.net/figure/SEM-images-of-M-tardigradum-in-the-active-and-tun-state-Tardigrades-are-in-the-active_fig3_41911002

What causes the Earth's magnetic field? (n.d.). Retrieved March 5, 2018, from Institute of Physics website: http://www.physics.org/article-questions.asp?id=64

Williams, M. (2016, February 23). The definitive guide to terraforming [Electronic mailing list message]. Retrieved from Universe Today website:

https://www.universetoday.com/127311/guide-to-terraforming/