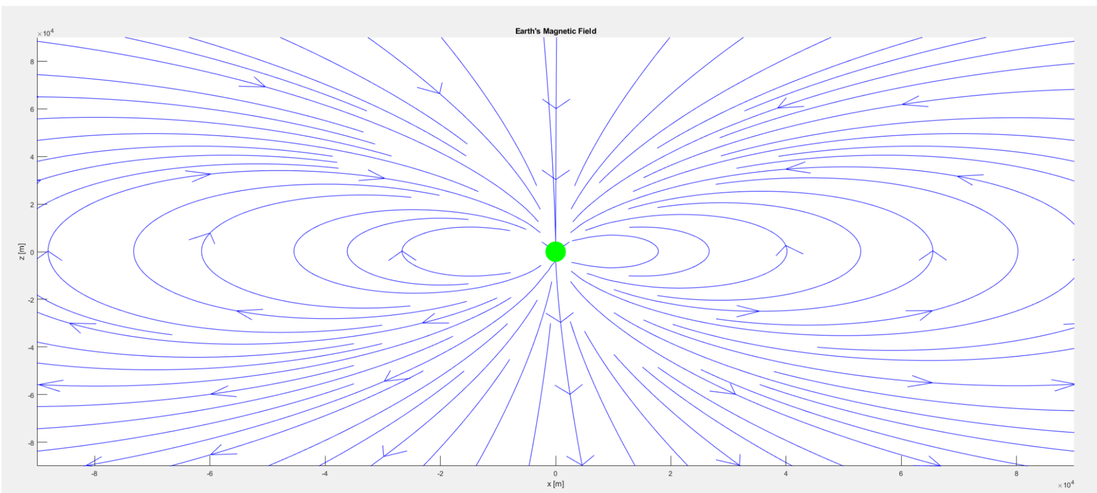
Solar Wind

Introduction:

The Earth has a permanent magnet that is created by its solid, iron core. High energy particles, specifically protons and electrons, are emitted and stream towards the Earth. This Solar Wind then comes into contact with the Earth's Magnetosphere. When this occurs, the Earth can be shielded and deflect the incoming particles, the particles could penetrate the atmosphere, exciting air molecules and creating the Aurora Borealis, or be caught in the Van Allen Belts. The goal of this project is to quantify the Earth's atmosphere, and to analyze these high energy particles and the situations that occur when they stream towards the Earth.

Methods:

There are two main equations we need to describe the trajectory of the high energy particles. The first is the equation that defines Earth's Dipole Field. This is a 3 dimensional equation, and can then be used in defining the second order differential equation that is needed for the problem.



The acceleration of the particles can be described as the force placed on the particles, divided by their mass, where their force is represented by the charge times the velocity crossed with the Magnetic Field.

$$\vec{F} = q\vec{v} \times \vec{B}$$

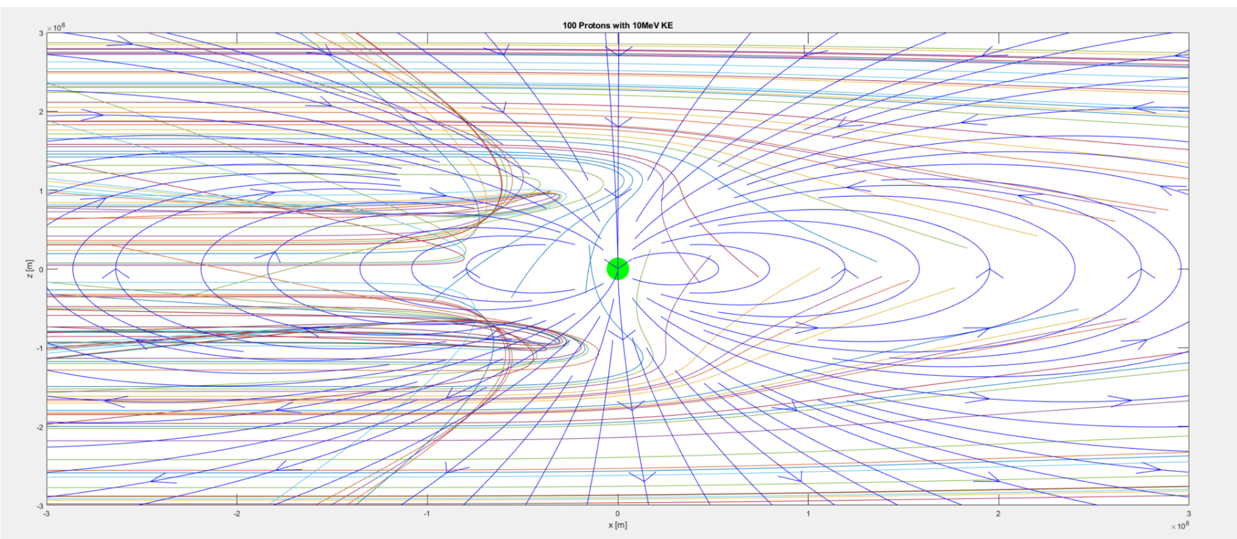
To account for the relativistic velocities, the velocity is divided by gamma, the lorentz factor.

$\vec{F} = \frac{q}{\gamma} \vec{v} \times \vec{B}$

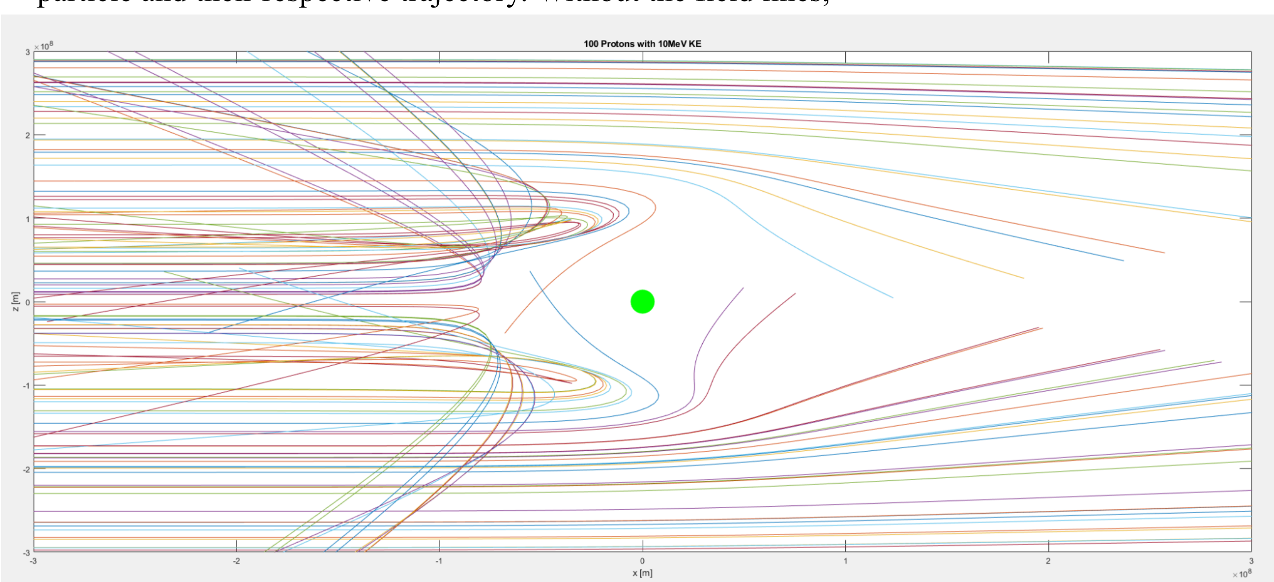
Both the magnetic field and the cross product can be split into their cartesian components and used by matlab's ODE solver, to then show and describe the trajectory of the high energy particles emitted by the sun, as they travel towards Earth. Monte Carlo simulations were used to show how multitudes of particles behave, from different initial conditions.

Shielding:

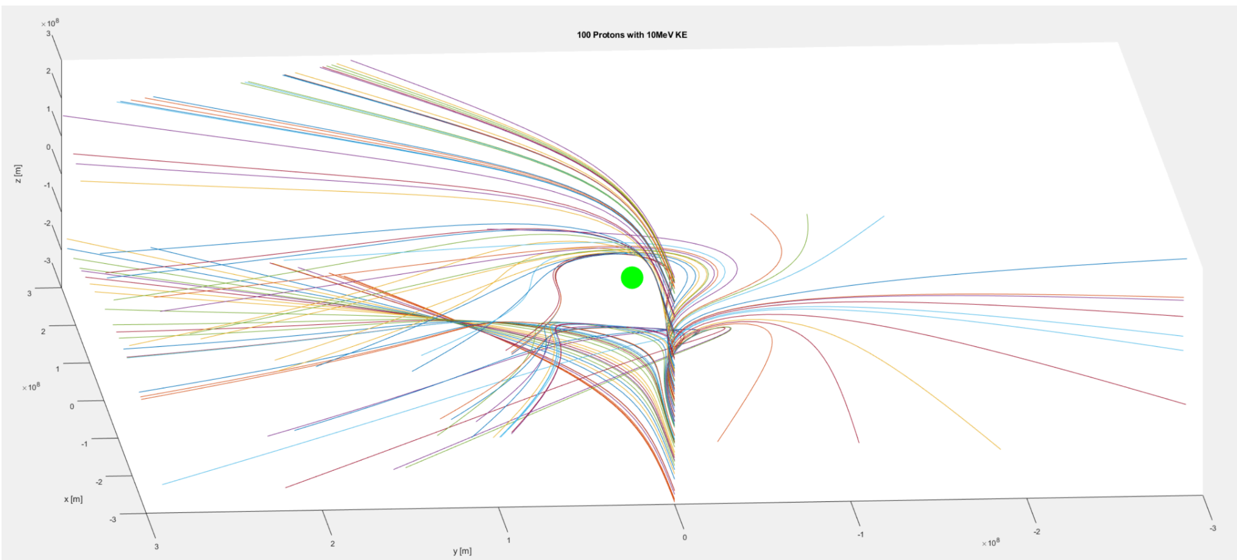
First, 100 protons with 10 MeV of kinetic energy start with initial conditions of x = -300,000 km and randomly placed on the z-axis from -300,000 km to 300,000 km. These particles interact with the magnetic field and are then dictated by the differential equation above.



The blue lines represent the Earth's magnetic field while the colored lines each represent a single particle and their respective trajectory. Without the field lines,

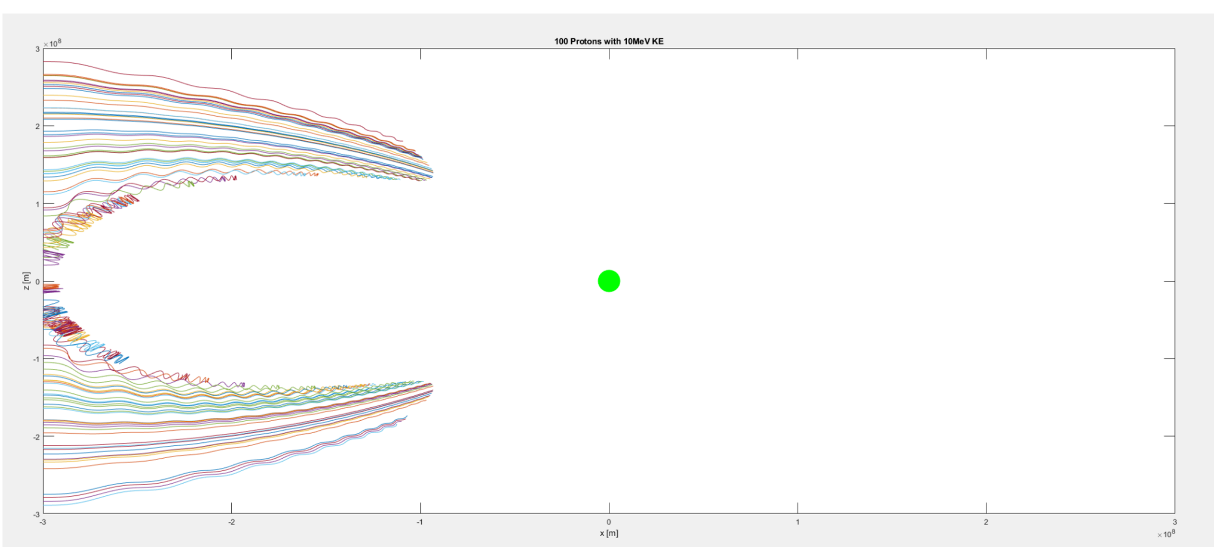


we can see that each particle is deflected by the Earth's magnetic field. It acts as a shield, protecting the Earth from high energy particles. The right hand rule is used to describe the direction of the force, depending on the directions of both the velocity and B-field. The index finger points in the direction of the velocity, the middle fingers goes in the direction of the B-field, and the thumb then points in the force. With index finger pointing to the right, since the particles are traveling to the right, and middle finger pointing up, in the direction of the B-Field for about z=0, we should expect the force to be coming at you, out of the screen. This can be seen in the 2-d plot as some of the particles bend up and back away from the Earth. This can more easily be seen in a 3 dimensional plot.

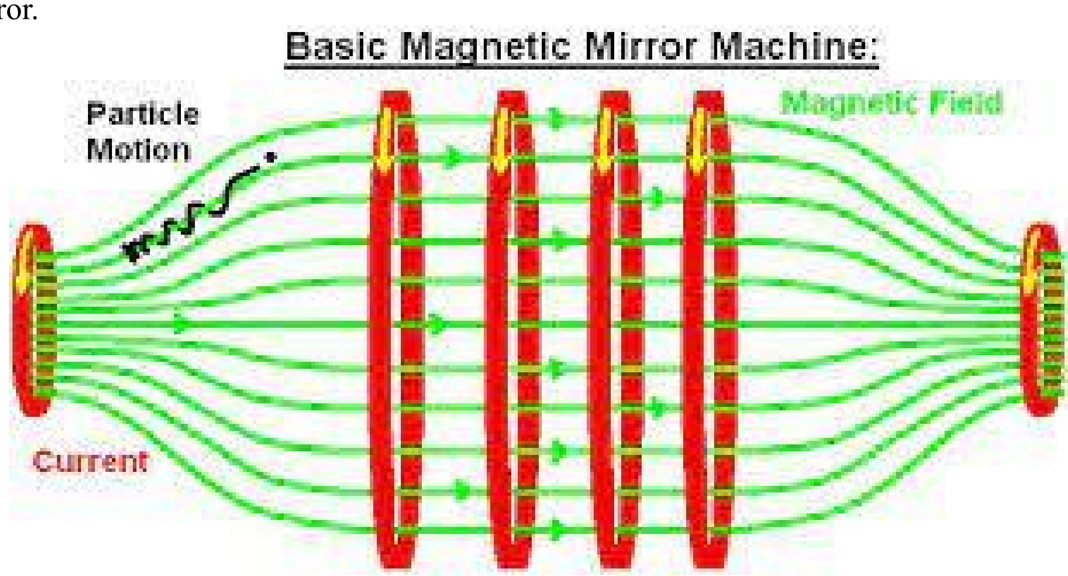


Here, the y-axis represents into, or out of the monitor. The acceleration of the particles do follow the right hand rule.

Now, instead of protons, the particles are now electrons. All other conditions are the same. However; the velocity of the electrons are now significantly higher, since the mass of the electron is significantly less than the mass of the proton.

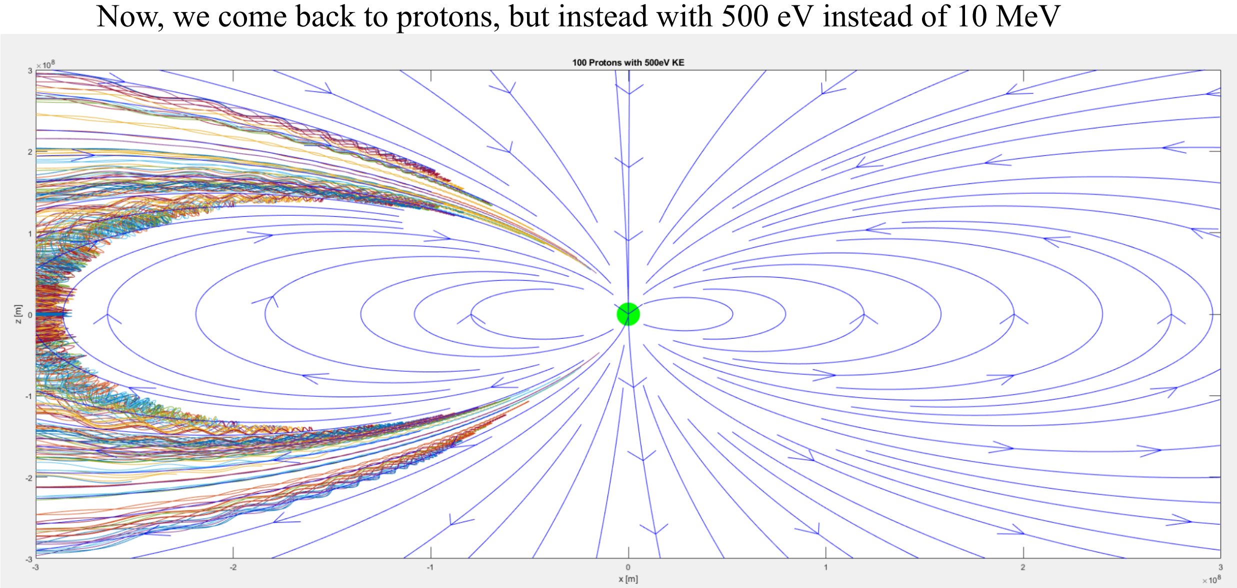


My simulation could not run for the full 3 second time span. It would take too long to run. The best I could get was about 1 second for the simulation. However, the electrons are moving very close to the speed of light. They will not be able to reach the Earth. The bottom stream will be deflected up and to the left, while the top stream will be deflected down and to the left. The middle pack of electrons exhibit interesting behavior. They seem to be rotating around an axis as they also move through space. The electrons are rotating around the field lines while also traveling in the direction of their velocity. This effect is the reflection off of a magnetic mirror.



The particle spins around the field lines as it travels from our entrance point towards the Earth. The reason the electrons are not able to reach the Earth is due to their velocity and acceleration. The force placed on the electrons is directly proportional to their velocity. This massive amount of Kinetic Energy and speed means that it will have a high force, in a direction dictated by the right hand rule, away from the Earth. This high force means a high acceleration, so the fast moving particles will be deflected farther away, and will not be able to reach the Earth.

Now, we come back to protons, but instead with 500 eV instead of 10 MeV



These protons also exhibit the magnetic mirror behavior, but are also able to make it extremely close to the Earth. However, They seem to be heading to the left side of the Earth. This is where the magnetic field is densest, so they will most likely be able to be deflected. The force on the particles also increases as the magnetic field increases, so in order to be able to reach the Earth, the particles would need to drop into the North or South pole where the field is weakest.

For these particles, they all have constant Kinetic Energy that does not change. The numerical calculations gave a variation of + or - .5% which is fairly acceptable. The reason the Kinetic Energy is constant is due to there being no work done on the particle. The change of KE is defined as the work done. The work on the particle is defined as the -integral of F dot dr. Since the Force is defined by the cross product of v and B, we can by the right hand rule that v and F are perpendicular. So, our incremental change in direction, dr, will also be perpendicular to F, meaning the dot product will be zero. No work will be done, so the KE will be constant.

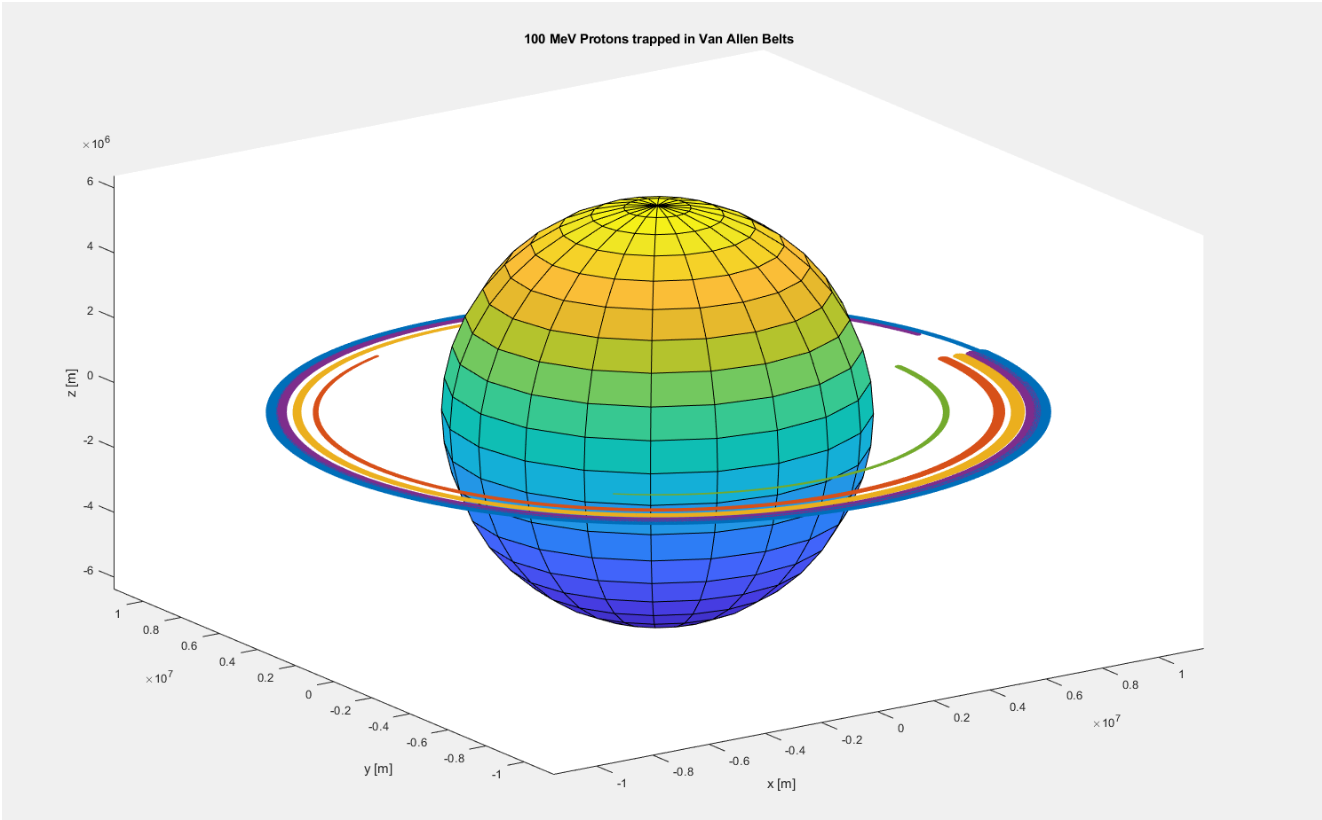
The conclusion from shielding is that it is a combination of the Earth's magnetic field and the particles themselves to protect the Earth. If the particles are too slow, they will get close to the Earth but then come to the densest field lines, then being accelerated away from the Earth. Particles that have too much kinetic energy cannot even come close to the earth, as they will have a greater acceleration placed on them. It takes a combination of the right velocity and location, in order to go through the magnetic field and into the Earth's atmosphere.

Aurora Borealis:

My computer did not have the time to run the 500 KeV to find electrons that cause the Aurora Borealis. However, looking at the last plot, we can see how this might occur. Electrons with this kinetic energy are able to travel along the field lines and make it to the North or South pole. It is almost similar to the 'golden speed' for a car going around aloop. At just the right angle and just the right velocity, the car can continue to go around a bank with no extra force needed. Here, the electrons have just the right speed to where the magnetic field accelerates them to a weaker point in the field. The electrons then are able to penetrate the Earth's atmosphere. When this happens, air atoms are excited, and when they then relax, photons of light are emitted. This light is what produces the Aurora Borealis in the North and South poles, where the field is weakest.

Van Allen Belts:

For the Van Allen Belts, 5 protons with 100MeV of Kinetic Energy start at a radius 1.2 to 1.8 times the radius of the Earth away in the x-direction, and at zero for both the y and z direction.



These protons have enough kinetic energy to be locked in uniform circular motion around the Earth. These protons travel around the same equipotential of the B-field. The B field lines still go from North to south, so the force will be pointing towards the Earth. However, the speed of the protons is just enough that the distance from the Earth does not change. This means that the value of the force will not change, and the particles are locked in uniform circular motion.

The magnetic field lines start at the south pole, and go up the z axis to the north pole. This means that in the xy plane, the magnetic field lines form equipotentials. Looking at the magnetic mirror image above, we are essentially putting a proton straight into where the current is. With no initial velocity to move it to a different z plane, and no force to accelerate in that direction, it will rotate around the planet given the right speed. The two magnetic mirrors are due to the field lines that are just leaving the poles pointing north, and the magnetic field lines that are pointing south. These help to create a magnetic bottle that can trap high energy particles in areas around the planet.

Taking the Project Further:

Investigations:

I would like to be able to investigate quantum behavior. Maybe how exactly the charged particles and b-field interact by simulating bosons as well. It would also be cool to simulate the Aurora Borealis themselves by simulating the air atoms and the photons that would be emitted. The last thing I'd also want to investigate would be simulating how the particles are emitted from stars, and how it changes over their lifetimes from the time they are born and if they are large enough, how they behave and emit radiation as a black hole.

Why does the Solar Wind stop? Theoretically, if only our solar system existed, the particles should continue until affected by some other force. However, our solar system is part of a larger galaxy which is part of a larger universe. The solar wind stops once it hits the heliopause. This is the region where the particles no longer have enough energy to break through the interstellar medium of the rest of the galaxy. Essentially, the wind of the galaxy meets the wind of the Earth, and our solar wind ends there.

Conclusion:

From this project, I learned a deeper understanding of particle physics and how high energy particles from the sun affect the Earth. I learned more about how to code sophisticated ode's and solve differential equations. I also learned a deeper appreciation for how complicated the stuff we can't see is, and how highly dangerous particles are constantly flying towards the Earth, while we are luckily shielded by the Earth's magnetic field.