Can We Employ Magnetic Fields to Shield Astronauts from Cosmic Rays?

Michael McEllin April 2020

The original suggestion for this project came from a student who wanted to study the problems astronauts would experience travelling to Mars. We quickly started to focus on exposure to cosmic rays, and whether it would be possible to shield astronauts from their effects.

The normal approach to shielding is putting material between the person at risk and the radiation source. The more mass there is between you and the source the more radiation is absorbed. Lead is quite often employed because you can get a lot of mass in a relatively thin sheet - but it is the mass along the radiation trajectory that matters, so we could, for example, use a greater thickness of steel with equal effect. Unfortunately, the radiation comes from all directions you would need to coat the entire outer surface of the craft which might require a large amount of shielding.

Unfortunately, the last thing you want in a spacecraft is more mass. It costs a great deal of money to lift a kilogram off the surface of the Earth, and it costs even more to move it to Mars, because we have to burn more fuel to accelerate the mass and it costs more money to lift that extra fuel into orbit. Shielding the entire spacecraft with a high density material would probably be prohibitive, but it might be possible to shied a small refuge with the craft - say a small room surrounded by the water that the spacecraft would have to carry anyway to keep the astronauts alive. Radiation fluxes, however, are not constant in space: there is a steady background but astronauts may also experience much higher doses at time when the Sun is particularly active and throwing off *coronal mass ejections.* The radiation exposure due to the constant background is by no means negligible, but given the other risks associated with space travel it is not the astronauts primary concern - eliminating it would not have a large effect on the overall risk. The high radiation fluxes experienced during a coronal mass ejection are. however, a matter of concern. We might therefore mitigate risk for astronauts to a desirable extent by monitoring the Sun and the Solar Wind and from time to time warning the astronauts to “take cover” in their refuge.

Is there a better way? Could we not shield the entire spacecraft using strong magnetic fields from a superconducting coil? After all magnetic fields deflect charged particles and they have no (or negligible mass). Furthermore, once we have started up our superconducting coil, we do not need to feed in new energy all the time.

Not so fast! Running a current round a coil produces a magnetic field, but basic electricity and magnetism shows that the magnetic field also exerts a force on the current. The stronger the current the bigger the field, the bigger the field *and* current the stronger force. (Notice that the force will therefore be proportional to the square of the current - or the square of the field.) Hence, the stronger the field, the stronger the structure of the magnet needs to be in order to resist that force, and therefore the heavier we will need to make the magnet in order to give the required strength.

Admittedly, because the magnetic field will be trying to expand the coil outwards, the stresses generated in the coil will be “loop stresses” along the direction of the windings. (This is not quite obvious, you will have to think about it and calculate the loop-stress associated with a given outward force.) We can oppose this stress by supporting the conductors with further windings from a strong fibre - we do not need to provide resistance to bending. This makes the strength calculation much easier.

So, here is the problem we need to examine: just how heavy will our magnet need to be in order to provide a strong enough field to deflect cosmic rays from our spacecraft? It turns out we can make a pretty good estimate using just A-level physics and maths (and the student I referred to at the start got his EPQ award on this basis with a very good project report). The challenge is seeing how to bring together several different elements of their knowledge that perhaps they have never seen in the same context.

This brief is not going to provide you with all the answers, but I will point you towards various things you will need to know. It will be up to you to read up the science and then work out how to put it all together.

The first thing we need to understand is that the detailed design problem of a real magnetic field design is probably too difficult to solve with the tools we have available. We can, however, look at simpler versions of the problem which exhibit the same elements and where the outcome will at least tell us, in a broad sense, whether the idea could be feasible or not. This is a very common practice in physics and engineering. There are times when we just do not know whether our design idea is a likely runner, just about possible or miles away from feasibility. It is not worth trying the solve the real problem in detail (putting is a great deal of expensive effort) unless we have some idea that it may work. Hence, we often try "ball-park" calculations of simplified versions of the problem. If our results are, say, within a factor of 10 of looking feasible we then start to refine and elaborate our calculations: they may now pay off.

This is the style of physics calculation that I was taught at the Cavendish Laboratory in Cambridge: you learned to calculate a first guess at almost anything on "the back of an envelope". My final examination even had a paper with "impossible problems" - we had to use the best approximations that we could invent, and there was no definitive answer, just marks for ingenuity.

The Basic Science

Cosmic Rays

Cosmic rays in space are mostly high energy protons. (Cosmic ray showers on Earth have a different mix of particles because we are seeing the effect of multiple collisions with air molecules cascading from the original particle.)

Their energy distribution follows a *power law*. Which means that the flux of particles (the number that cross unit area each second) that we can count in a particular energy band, dE, will vary according to the relationship:

$$F = E^{-\gamma} dE$$

Note that the power law index, γ has a negative sign, which means that as we go to higher energies there are fewer particles. This is an approximation, in reality the index varies a bit with energy, and there has to be a lower-cutoff point to avoid getting an infinite flux near zero energy.

You will need to look up the information and obtain some ideas about the cutoff and the value of the index.

We may need to think about the energy band of cosmic rays that will cause us most trouble: is it the low energy particles that are present in large numbers, or the high energy particles that carry more oomph and can cause more damage to human tissue? There is some interesting information available about radiation effects on tissue if you research cancer therapy using proton beams. Look up the "Bragg Effect" which shows that it may not be the highest energy particles that cause the most problems, but those that can be slowed down so they spend more time within the body causing more damage.

Electric Currents Produce Magnetic Fields

This is basic A-level physics. (Sometimes called the *Biot Savart* law.) In particular you should be able to work out the magnetic field inside a long solenoid of given dimensions from the current flowing through the coil (given that you know turns-per-unit length).

Magnetic Fields Exert a Force on Currents

This is basic A-level physics. For a given magnetic field and a given current along a wire perpendicular to the field, you should be able to calculate the force per unit length on the wire.

If you think about the combined effect of the laws relating current and fields you will see that each part of a coil carrying a current will experience a radially outward force. For a simple coil this is not so easy to calculate because the magnetic field varies across the coil. You could look it up, but we do not need it. It is much easy to think about long solenoids where the field strength is uniform. We can straightforwardly calculate the outward pressure on each part of a solenoid - but there is also a short-cut to this which we examine below.

Magnetic Fields deflect Charged Particles

The force on a moving charged particle is the fundamental mechanism explaining the effect of a magnetic field on a wire carrying a current. When we are thinking about individual particles the combined effect of electric and magnetic fields is usually referred to a the *Lorentz Force*.

A charged particle moving perpendicular to the magnetic field experiences a force perpendicular to the field direction and its own velocity vector. Hence, it starts to accelerate in this direction. The change in direction means that the force which has to remain perpendicular to velocity must also change direction. The net effect is that the charged particular moves in a circle. You have probably studied circular motion (e.g. orbits in maths and physics) hence for a given magnetic field, particle mass, velocity and charge (usually just the proton mass and charge) you should be able to calculate the radius of the circle. This is sometimes known as the *gyromagnetic radius*.

It should be fairly obvious that the heavier the particle the less it will be bent, and the faster the particle the less it will be bent. (We also have the complication from Einstein's *Theory of Relativity* that very high energy protons get heavier as their velocity approaches the speed of light - but we can also assume that all particles we want to stop will be moving very close to light-speed, as near as makes no difference.) The bigger the charge and the bigger the magnetic field, however, the more it will be bent.

The Earth's magnetic field, for example, is quite effective at deflecting charged particles form the Sun. They are bent away when the move towards the Earth.

Hence, for the energy of particles that we want to stop reaching our spaceship, we will need a sufficiently strong magnetic field to bend particles around half a circle within the radius of our magnetic coil.

Loop Stresses

If we have a current carrying coil, subject to a radially outward force at each point along the loop, it is fairly easy to see that in a stable situation the outward force must be opposed by a force along the windings of the coil. When we divide this force by the cross-section area of the windings we have a stress: the *loop stress*. If the loop stress is less than the *tensile strength* of the material, then the loop will not break. If we increase the current to the point where the stress exceeds the strength then we will see a fracture.

Calculated the loop force from the outward force on a coil is a simple exercise in mechanics and calculus. (Just imagine a short element of the coil, say along an angle $d\theta$ subtended from the centre of the coil. Because of the small bend in this element the net force from either end of this element points inwards, opposing the outward magnetic force.)

Strength and Density of Materials

We have discovered that the coil generating our magnetic field is trying to blow itself apart. (This, by the way, is a very real effect familiar to those who work with strong magnetic fields. Their magnets can undergo a rapid, catastrophic disassembly.) We need to hold the coil together, but superconducting wires tend to be made from material that has rather low tensile strength. Hence the coil must be supported by another material that is strong enough, and ideally also having a high strength to weight ratio. (We still do not want to carry excess weight.) Fortunately, because the forces in the coil are along the direction of the windings we only need to worry about tensile strength. We do not need materials that are stiff (i.e. resistant to bending). We can think in terms of strong fibres.

When we want high tensile strength for low weight in a fibre we might naturally think about carbon fibres. (You can look up the tensile strength and their density, when compressed into an epoxy matrix.) They are stronger than steel wire with much lower weight. These properties arise from two desirable properties of carbon: it is a low mass atom and it has strong chemical bonds.

Carbon fibre is a very practicable, proven material, so we will certainly have to do some of our calculations using this as an example. Can we do even better? The new “wonder” materials are carbon nano-tubes and graphene which promise even high tensile strength - if they can be made in large quantities without significant defect. There’s the rub. We do not know if this will ever be possible. Nevertheless, it would be interesting to assume that some future manufacturing process will be able to produce fibres with the maximum theoretical strength possible with carbon bonds.

We are unlikely ever to do better than this: the other light atoms that form solid materials, such as beryllium or aluminium have weaker bonds even when in the form of the “super-strong alloys” used in aircraft manufacture. Iron or titanium alloys are just hopelessly heavy. A calculation using the theoretical maximum strength/weight assumptions would certainly tell use whether our idea is within the remote bounds of feasibility.

Radiation Damage

How much radiation can the astronauts reasonably be exposed to? There is quite a lot of material on the web and in particular in places like the NASA website that can help here. The consequences of journeys to Mars have in particular been studied very carefully.

There is a missing bit of the puzzle as far as we are concerned. You will need to dig a bit to find out which particle energies are of most concern.

In general, it is the total energy deposited in living tissue that is important, and there may well be more energy in the larger number of low energy protons.

How do we simplify to the point where we can calculate?

First of all let me recommend two excellent books, which are free to download from the publisher via the hyperlinks below (if you follow the "*Open Access*" tab). They are all about finding ways to simplify maths and physics problems to the point where they are easy to solve:

- *The Art of Insight in Science and Engineering*
  https://mitpress.mit.edu/books/art-insight-science-and-engineering.
- *Street Fighting Mathematics*
  https://mitpress.mit.edu/books/street-fighting-mathematics

Any student who intends to continue to university studying maths, physics or engineering will find these of considerable benefit.

The simplest design

A real magnetic shield design would probably involve just one or two large coils, with the spacecraft lying along the axis. The field generated by this configuration is, however, a complex dipole decreasing in strength with something like the third power of distance from the source, and we would need a computer to calculate the effect it had on cosmic rays.

We will therefore assume that our spacecraft is encased in a long solenoid. The field strength inside a solenoid is easy to calculation, using the radius, the current and the number of turns per unit length. The protection is being provided in the part of the solenoid where the field is comparatively uniform, so for any assumed energy of incoming proton, we should be able to determine the current required to turn it through a semi-circle before it strikes our spacecraft.

Naturally, the smaller the radius of the solenoid the stronger the field will need to be, because our gyromagnetic radius must also be much smaller. We do, however, potentially win from making or coils of smaller radius, in two ways. Firstly they will have a small mass, just because they are smaller. Secondly, because the fibres that support the coils have a smaller radius of curvature, the hoop stress required to oppose the outward magnetic force turns out to be smaller. (You will see this when you calculate it.)

The process of the calculation is therefore:

- Pick some particle energy against which we need to protect. (We will have to worry about which energy later on - for the moment just keep everything in symbols.)
  - N.B. The cosmic rays that trouble us move close to the speed of light, so we do not need to worry about the rest mass of the particle (e.g. the proton): we just use Einstein's $E = mc^2$ to obtain the *effective* mass $m = E/c^2$. This is exactly what we need for our gyromagnetic calculation.
- Assume a solenoid of some specific radius, R, (keep everything symbolic for now). We do noted to worry about the length - everything we talk about will be "per unit length".
- Work out the magnetic field that would turn a particle of energy E into a semicircle of radius R.
- Work out the outward pressure on the solenoid walls. We could do this by looking at turns/per unit length, current and force due to current in magnetic field, but there is a really quick short-cut that I am going to let you in on. We can think of the magnetic field as exerting a pressure on the walls of the solenoid. This makes sense, because if you imagine letting the solenoid expand a little, the field would do work and the field strength would decrease a bit. I shall not

take you through this calculation but it fairly quickly gets you to the conclusion that you can assume an outward pressure on the coil of:

$$p = \frac{\mu_0 B^2}{8\pi}$$

where μ_0 is the usual magnetic permeability of free space and B is the field strength. Note that we have the expected effect that pressure is proportional to field squared, because the field is proportional to the coil current and the outward force must be proportional to the product of coil current and field strength.

- We shall for the present ignore the fact that the magnetic field lines exert tension along the field lines, as well as pressure perpendicular to the field lines. In reality this will try to compress the solenoid along its length and we would need to put in some compressive strength to resist this. However, in reality we do not really expect to use a solenoid, but just one large hoop coil. We are going to assume that although our calculations will not be exactly comparable to this case, it is unlikely that they will be wrong by, say, a factor of 10. If our design looks feasible in our first crude approximation we would go back and do the calculations properly, with a computer. If we are too far away from where we would like to be by, say, a factor of 100, then we would give up.
- Now that we know the pressure that we need to resist will can calculate the hoop force in the solenoid wall. This force is distributed through the wall thickness of the solenoid.
- Remember that stress is force per unit area, so since we are still thinking about unit length of solenoid, we now need to assume a wall thickness to turn this force into a stress.
- We then compare the stress we calculate to the tensile strength we are assuming for our material.
- Then we can use the density of the assumed material, the wall thickness and radius of the solenoid to calculate its mass per unit length.
- Remember KEEP ALL THIS IN ALGEBRAIC SYMBOLS for the present.
- Now we manipulate the equations to put mass per unit length on the left hand side and everything else on the right hand side. In particular, we have a relationship between the mass per unit length and the assumed energy of a dangerous cosmic ray.
- Our right hand side also has other parameters as well, but having kept everything symbolic we can now use our basic calculus to ask what is the ideal radius for a coil that <u>minimises</u> the mass per unit length. It might be that small is best - but we would have to stop at the wall of the spacecraft. It might be that large is best, but practical structure engineering would limit what we could actually do. (In fact, I got a bit of a surprise here, when I did the calculation. Well, well, well.)
- Now you can substitute the numbers for the various parameters and constants.
- We would also ask what thickness of, say, water would give equivalent shielding. Where do we get the data? I found that it was possible to look up the attenuation of proton beams in human flesh (they are used for cancer therapy) and human bodies are basically bags of water.

This is just a sketch of the way you go through an engineering feasibility calculation. You need nothing here that is outside A-level physics and applied maths. (I have mentored Year 12 students who followed this route with satisfactory outcomes, so you can do it too.)

Keep it Symbolic!

I keep saying this because it is important. Do not put in the actual numbers for any of the constant and assumed parameters until the very end. There are several reasons why this is an very good idea:

- You are less likely to make mistakes, and the mistakes you make are easier to spot.
- In particular you can check that the things on either side of the = sign have the same dimensions at each point in the calculation when you are trying to track down the exact place of an error.
- You can do the numerical substitutions in a spreadsheet. This means that you can easily play around with the parameter values, draw graphs and so on, looking for a range of possible solutions.