Radiation Shielding In the Space Environment

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Abstract - *The astronaut traveling deep into space will not only be bombarded by cosmic particles but could be exposed to radiation on cancer causing levels. Understanding the Sun's role on the space environment will lead to a thorough explanation on where protons and heavy ions, solar particle events, and trapped radiation originate from and how they influence our design envelope. To achieve the necessary protection of space vehicles and crewmembers it is imperative to design, understand, and implement proper shielding techniques. Current technology limits our infrastructure to near orbit exploration and development. This paper reviews technological advances and novel ideas for radiation shielding particularly from lower Earth orbit to interstellar space. Several ideas are presented and discussed that can shed light on what our main space radiation challenges are and what type of systems will be needed to shield against harmful particles. New technology and ideas are constantly being developed and researched, such as magnetic shielding, electrostatic shielding, material design, and biomedical enhancements. These ideas are all discussed and presented such as biomedical research where a scientist will try to harness the human body's natural healing process to protect against radiation cell damage. More complicated designs to either simulate Earth's magnetic field or charging the space vehicle to some voltage to repel cosmic particles are also analyzed and summarized. Finally, the challenges and realism of our goals are discussed in terms of political landscape, financial incentives, and public perception concerning traveling and exploring our space environment.*

Keywords: Radiation, shielding, magnetic, electrostatic, galactic cosmic rays, solar particle events, space environment.

1 Space Environment

To properly shield space vehicles and personnel from harmful radiation imparted from outer space, we must first understand in depth the environment and energies that our space vehicle will journey through or land on. In comparing Earth's atmosphere and deep space there is a vast difference between what humans can physically tolerate and appreciate. For instance our Earth has a magnetic shield that protects humans from harmful cosmic and solar particles emitted from the Sun. If not for this protection we would have severe cases of radiation poison here on Earth. Within Earth's orbit is a layer of matter called the Van Allen Belt located approximately 250-750 miles above Earth. This defined region is the boundary of how far we can travel without major harm to space vehicles and personnel. As highly charged particles in the form of electrons and protons are emitted from the Sun and other background events Earth is protected by this layer. This is a luxury we have on Earth. Unfortunately, other planets and distant galaxies do not have this barrier of protection.

Galactic cosmic rays (GCR), trapped radiation, and solar particle events (SPE), which originate in our space environment are considered the primary measures to protect from in deep space. The GCR's are generated primarily from stars and other effects throughout the space environment; whereas SPE's are primarily generated from the Sun's effects. These particles located everywhere throughout the universe can generate high omnidirectional energies which can be very penetrating to spacecraft systems and crewmembers. The SPE generally travel in a linear path primarily originating from the direction of the Sun. As for GCR and trapped radiation they are mostly present as background radiation. GCRs have always played a significant part for scientists and researchers in every aspect of space applications. The radiation environment of space contributes significantly to the total dosage which can cause single event effects (SEE) and failure of shielding materials [1]. In electrical equipment there can be trapped photons and electrons that have to be accounted for and protected against. Secondary photons or bremstrahlung from electrons slowing down interacts with the shielding material which can also contribute significantly to the total dose [1].

Having knowledge of the space weather is one of the primary protection methods essential to planning successful missions. The Sun's contribution to the space weather and solar activity is one of the major threats to the overall role of radiation in outer space. The solar activity peak is based on periods when the sunspots on the Sun are aligned with Earth. Sunspots are caused by disturbances in the Sun's magnetic field that build up to the Sun's visible surface. The powerful magnetic fields in the vicinity of sunspots produce active regions on the Sun, which will develop disturbances such as solar flares and Coronal Mass Ejections (CMEs). Because sunspots are associated with solar activity, knowledge of space weather forecast and tracking features help predict outbursts of these solar storms that produce high levels of radiation [2].

Sunspots form over periods lasting from days to weeks, and can last for weeks or even months before dying down. The average number of spots visible on the face of the Sun is not constant, but varies within a multi-year cycle. Historical data of sunspot activity counts go back many years, which verifies that the sunspot cycle has an average period of approximately eleven years. The amount of sunspots on the Sun's surface is proportional to the level and amount of solar flare activities emitted. Therefore, the Sun is known to emit three types of radiation effects during solar maximum or minimum events:

1. Background noise from the overall radio spectrum of the sun.
2. Sunspots that can vary with solar flares.
3. Solar flares that can be emitted in a random manner, which is a solar activity effect of most concern.

With this knowledge missions should be planned when solar activity is at its minimum, which will reduce the amount of dosage imparted on the crew and space vehicles.

The Sun displaces protons and heavy ions through its solar winds. The solar winds can be stopped by the Earth's magnetic layer, which embeds or repels a significant amount of protons and electrons. The heavier ions are low in energy and do not cause much threat and can easily be stopped by current shielding practices. However, the higher energetic particles must be considered due their penetrating power. If we are to undertake a mission to planets such as Mars, distant galaxies, or lunar surfaces these environmental radiation issues must be thoroughly considered. The planet Mars for instance does not have a layer of protection to keep harmful radiation particles from destroying humans and equipment on the planet. Therefore effective colonizing efforts will have to develop and employ a system mirrored to Earth's magnetosphere [3].

1.1 The Need to Properly Shield

What is our purpose for investing a lot of time, research, and dollars in the advancement of traveling to deep space? This is often the question that many have asked and by researching various documents the answers will vary. The need for travel to distant areas of our universe is a quest that we must try to pursue, for it's the unknown that gives man the drive to make known. We start with the personnel or crew and the vehicles used for travel. If distant planet travel is to be accomplished, the crew vehicle will need to have proper shielding to withstand bombardment of highly charged protons and electrons. During missions that can last well over months and years, this activity would do serious damage to the crew and the vehicle. The current shielding requirements for satellites and space vehicles are designed for near orbit missions. Our current technology will not allow these same vehicles to travel further without proper measures to keep the crew and electronics safe.

The health effect associated with long mission profiles is a topic that requires much attention. The risk for cancer, bone density loss, and other diseases will be elevated to uncontrollable levels. Studies have shown that the amount of dose a person would receive on Mars or in transit is approximately 80 rems per year; in comparison to nuclear industry workers it is approximately 5 rems per year. The difference between the two is dramatic. The number of deaths associated with the radiation dosage in our bodies will be very high with cancer being the most common diagnosis. The biological destruction of cells in our body is tremendous and our bodies' repair tactics cannot keep up with the damage being caused by the high levels of radiation.

The amount of dosage our bodies will be exposed to can be viewed as a function of the shielding thickness measured in density units. In Table 1 historical data shows the amount of shielding that certain space equipment offers and the level of shielding ability necessary for missions to succeed against space radiation. As the mission needs increase from lower orbit travel to distant and longer times in orbit the requirement for space equipment protection increases significantly.

Table 1. Historical Shielding Values used on Modern Space Equipment for Various Mission Requirements.

Space equipment	Shielding (g/cm^3)
Space suit	0.25
Hull of Apollo module	7-8
Modern Space Shuttle	10-11
ISS (International Space Station)	15
Future moon bases	+20

As evident from the data in Table 1 for space missions and colonization on lunar surfaces it will require a minimum of $20g/cm^3$ of shielding material, which can significantly impart a weight penalty on the mission. Obviously type of material must be considered thoroughly which could increase or decrease the density value.

1.2 Advancing Technology

Research in the area of magnetic, electrostatic, and material shielding along with biomedical advances is underway to help answer the question on how can we protect astronauts and space vehicles. Over the years a lot of time has been spent to help quantify this subject matter and find helpful data points to make future assessments on radiation shielding. The need for a system that can be launched into space with the least amount of added weight is a critical undertaking and must be analyzed thoroughly. Materials must be considered for shielding along with autonomous functions for passive systems and complicated digital electronics will have to be implemented. In this section the attempt is to shed light on current programs as well as ambitious ideas that may solve this problem.

2 Magnetic Shielding

Magnetic shielding has generated a lot of concern in space radiation shielding over the years. As with other theories magnetic shielding is not without its challenges. Here we allow charged particles to be redirected by establishing a magnetic field much greater than Earth's field. The energy levels of the incoming protons are on the order of 2 Gev and the force to repel will have to be 600,000 times as strong as Earth's magnetic field. With this technology a charged particle is deflected some 90^o from its initial direction and repelled back into space. However as with Earth there is little magnetic shielding at the poles due to the natural behavior of magnetic forces and its impact on our planet. With this knowledge it could be very worthwhile to examine the necessary capabilities for success while utilizing magnetic theory. Equatorial regions of the planet and magnetic fields offer the most amount of protection; therefore any design to be successful will have to use a doughnut ring-type shape, similar to Figure 1 where the wire carrying the current is enclosed.

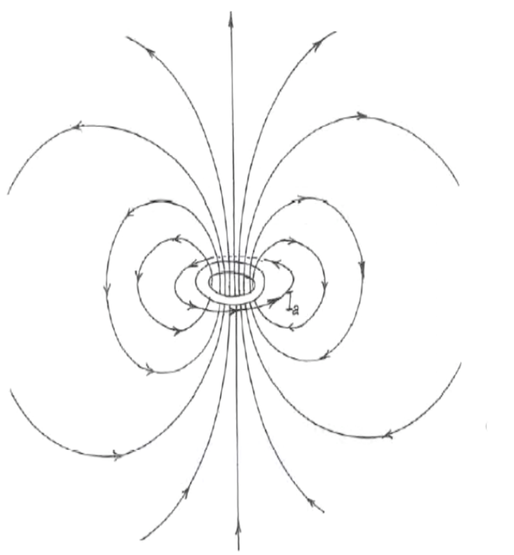


Figure 1. Effective doughnut rings showing the equatorial locations of the strongest magnetic field intensities. [Image courtesy of NASA]

The magnetic fields required to turn a proton with an energy level of 2 Gev would have to be considerably large. To adequately deflect a 2 Gev proton 90^o will require a magnetic source of 0.84×10^7 Gauss-cm. This involves the radius R of a proton, the mass M, and kinetic energy ηMc^2 traveling perpendicular to the magnetic field. By far this is a very strong and intense magnetic field. How realistic can this be accomplished with the space vehicle and its crew if we consider the astronaut in the middle of the magnetic field? What type of energies will the astronauts be subjected to over time? Considering a circle of radius a along with a superconducting wire carrying a current of I_a. The magnetic moment can be represented by

$$M_a = \frac{\pi a^2 I_a}{c} \quad (1)$$

where a extends outward from the wire.

Outside of the circle, the magnetic field formula in the equatorial plane is as follows, where $r > a$.

$$B(r) \approx \frac{M_a}{r^3} \quad (2)$$

The magnetic flux in terms of Gauss-cm between radius $r = a$ and $r = \infty$ of the magnetic induction is given by

$$G = \int_a^\infty dr B(r) \approx \frac{M_a}{2a^2} = \frac{\pi I_a}{2c} \quad (3)$$

At the center of the circle the magnetic field B_c is shown to be

$$B_c = \frac{2M_a}{a^3} \quad (4)$$

To get the magnetic field at the center the above equation must be solved in terms of G, using $G = 0.84 \times 10^7$ Gauss-cm.

$$B_c = \frac{4G}{a} \quad (5)$$

Therefore with a radius of 2 meters or 10 meters our magnetic field becomes 1.68×10^5 Gauss and 3.36×10^4 Gauss respectively. This is a very extreme amount of a magnetic field that the astronauts are expected to endure. It is almost clear to see that a shield would have to be used to protect the crew from the original operating magnetic shield. Overall being in the center of this magnetic field may prove to be very detrimental to the human.

We just developed a relationship between the magnetic field strength that will be needed to adequately change the direction of a proton when entering a magnetic field. As evidence shows protons are not the only particles in space that can cause damage. To demonstrate the energies needed from the magnetic field to bend the radii take a particle of resting mass m_o (amu), momentum p and charge qe, where e is the electron charge and q an integer that enters a magnetic field B. With a radius, R perpendicular to its velocity the magnetic rigidity equation BR is given by

$$BR = \frac{p}{qe} \qquad (6)$$

Knowing the particles' rest energy E_o , kinetic energy E_k, and the Lorentz factor

$$\gamma = 1 + \frac{E_k}{E_o} \qquad (7)$$

The expression for magnetic rigidity can be rewritten as the following, where *BR* is noted in units (T-m):

$$BR = \frac{(\gamma^2 - 1)^{1/2} E_o}{300q} \qquad (8)$$

Table 2 is constructed for various particles to demonstrate the magnetic rigidities for different kinetic energies.

Table 2. Various Energies Required for Magnetic Deflection as a Function of Incident Particles [4].

Particle	mass (amu)	Eo (Mev)	q	BR (T-m)					
				0.1 Mev	1 Mev	10 Mev	100 Mev	1Gev	10 Gev
Electron	0.0005486	0.511	1	0.001	0.005	0.035	0.335	3.335	33.335
Proton	1.007	938.272	1	0.046	0.144	0.458	1.482	5.654	36.327
Deuteron	2.014	1875.613	1	0.065	0.204	0.647	2.069	7.266	39.089
Alpha	4.003	3728.4	2	0.046	0.145	0.455	1.449	4.847	22.021
Carbon	12	11178	6	0.026	0.083	0.263	0.833	2.685	9.993

Knowledge of the particles initial direction and their energies to be deflected is the key to achieving deflection as noted in Table 2. We must appreciate the relationship between the field strength needed to repel a particle 180^o or some other reasonable value for deflection. In the small deflection angle θ, with a magnetic deflector of length *l (m)* and field strength *B* (*Tesla)* a deflection angle necessary to keep the particles away can be computed with Equation 9:

$$\theta(rad) \cong \frac{300qBl}{(\gamma^2 - 1)^{1/2} E_o} \qquad (9)$$

where $\tan \theta \cong \theta$ and E_o is in MeV [4].

Even if a magnetic field could be constructed that can adequately deflect highly charged particles, the long-term exposure to the strong magnetic fields could pose a significant problem. Magnets on this order have a very strong field, which can cause serious side effects to the human body, and now becomes a trade off between the effects of the magnet shield or no shielding utilized at all. Overall, this will require a system that could weigh many tons and would be very bulky, which will be a major weight penalty to launch into orbit. One notable advantage still is that the weight restrictions on this system are minor when compared to using material properties such as water or hydrogen as the primary method of shielding which could weigh up to 400 tons.

3 Electronic Shielding

The use of electrostatic shielding is an attractive possibility for travel to distant planets or establishing colonies there. Active and passive shielding are two candidates for possible solutions. They both use an electric field to deflect charged particles developed from single particle events as well as galactic cosmic rays. Active shielding practices utilize the Lorentz force (*F*), the force exerted on a charged particle in an electromagnetic field to deflect the particles away.

$$F = qE + qv \times B \qquad (10)$$

In Equation (10), *q* is the electric charge of a single particle, *v* is the particle's velocity, *E* is the electric field of the shield, and *B* is the magnetic field component of the shield. Here three time independent shields can be considered: magnetic, electrostatic, and plasma. Figure 2 shows a schematic on how both positive and negatively charged particles are deflected using the Lorentz force theory.

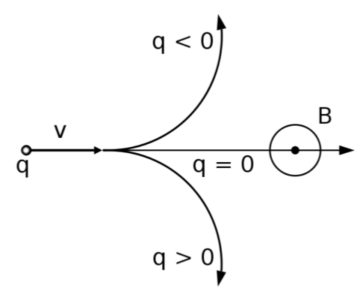


Figure 2. Charged particles of velocity *v* are being repelled away due to the electromagnetic force exerted.

For passive shielding design, the particles are stopped by several collisions with the material used for shielding. The force can generate multiple collisions and thus create radiation by-products. These by-products are in the form of charged particles with less energy value than the previous collision. This collision event will continue until all the energy has disappeared. As with magnetic shielding knowledge of the necessary angles needed for deflection must be considered along with the power requirements to achieve this. For an electrostatic deflector the angles represented here are direct functions of the particle's velocity perpendicular to the field of a parallel plate deflector of length *l*. The deflecting potential *V* and the gap *d* will give an ideal value of the deflection angle θ:

$$\theta(rad) = 10^{-3} \frac{q\gamma}{(\gamma^2 - 1)E_o} \cdot \frac{vl}{d} \quad (11)$$

where V is in kV for electrostatic deflectors.

There are several design constraints for electrostatic shielding, where the limits to the electrical system and the possible electrical breakdown of the materials must be accounted for. The power supply to generate enough voltage for both single particle events, which occupies the lower energy band spectrum, and galactic cosmic rays, which are at the higher energy bands, could be considered as a major pitfall. The amount of energies considered here are well in the $2x10^9$ voltage range, much greater than what power plants are producing in the US today. For space travel electrostatic shielding will have to charge the space vehicle to energy levels much greater than the penetrating electrons. The mechanical constraints for this system involves the strength of material used to construct the shielding apparatus along with the size and weight that has to be transported to lunar surfaces or fixed to space vehicles. Concerns over the construction and assembling of the electrostatic system on lunar surfaces will be challenging considering the environment where this system will be used will need to employ adequate machinery. The impact on the environmental surface where dust and free electrons collect can be damaging to the high voltage system. This could also introduce bremsstrahlung x-rays that could lead to biological damage to the habitants. Buhler [5] suggests using a combination of magnetic and electrostatic shielding, but points out the drawbacks of the magnetic shielding, such as weight and power requirements could be the major setback. The development of an efficient voltage generation system and eliminating voltage breakdown of the system could be possible solutions in progressing in this direction.

4 Material Shield

The advancement of material properties on space vehicles has developed into one of the most encouraging methods for radiation shielding. Currently all the satellites in space, the ISS, the space shuttle fleet all have their shielding requirements met by material constraints and specifications. Unfortunately, the current technology is only good for space applications in near orbit positions where Earth's protective layer provides much of the protection needed to sustain missions. In order for missions to embrace distant travels, material shielding on the density order of +20 g/cm^3 must be in use. The material needed will have to be able to protect the crew from radiation and also deflect micrometeoroids. This shielding has to be able to withstand the extreme space environment and also be very durable and long lasting. The total stopping power of the material must be considered carefully utilizing materials with low Z numbers, which show the highest properties for shielding. Data has shown that materials with the most electrons per unit mass, the least excitation energies, and low atomic number make the best absorbers. Unfortunately getting material on the order of 20 g/cm^3 to launch into space is costly due to current payload limitations.

Aluminum once thought of as a highly effective shielding material has little or no effect to the higher dose amounts encountered on deep space missions. As more material codes and technologies are developed aluminum will be considered obsolete in performing long time shielding duties. For protection in the BFO (blood forming organs) and skin or lens Figure 3 shows that the aluminum's material properties are not efficient for protecting humans. In fact Wilson et al reports that aluminum may actually do more harm because of secondary particle production from cosmic rays interacting with the aluminum [6]. Currently the technology is heading towards a polymeric type of material because of the mechanical properties exhibited within their structure. Polyethylene consists of a high content of hydrogen and carbon atoms and is considered as a shielding material with great beneficial properties. Figure 4 demonstrates the capabilities of polyethylene as a much stronger shielding material than other commonplace materials such as aluminum or lead while subjected to similar dosage.

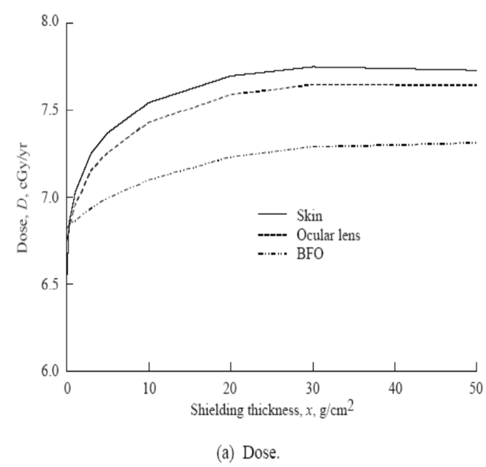
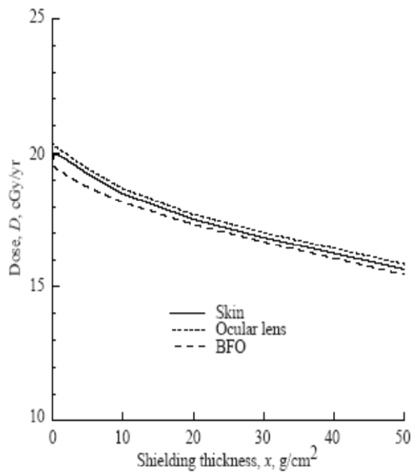


Figure 3. Galactic cosmic rays during solar maximum behind an aluminum shield of varying thickness [4].

Both graphs show that the dosage amount that polyethylene exhibits is considerably larger than the aluminum material as a function of BFO, skin, and lens. With the introduction of polyethylene approximately 30%–50% could be saved on material weight alone, which would seriously justify its usage on the space vehicle. Other advantages over aluminum are that polyethylene materials will produce less secondary radiation effects. These secondary particles interact in the material and cause chain nuclear reactions often more potent and deadlier than the initial interaction. Data has supported that polymer materials are up to 50% better for shielding against solar flare activities and 15% better for shielding against GCR, while being compared to aluminum. Studies performed more recently where researchers have combined both the polyethylene and lunar regolith as a whole composition. The results indicated that incorporating a high percentage of hydrogenous materials in the composite will result in better radiation shielding. The results obtained supported the regolith properties as being just as efficient in shielding as the current spacecraft material, aluminum [7]. The polyethylene however is not a cure all; it still has limitations that would need to be researched, such as its flammable properties and temperature tolerance. If such disadvantages are not solved the idea of using polymer materials could be lost and other materials will have to be considered.



(a) Dose.

Figure 4. Galactic cosmic rays during solar maximum behind a polymer type shield of varying thickness [4].

Carbon nanocomposites (CN's) have received a lot of attention in the research world over the past decades. The main reason attention is focused on these types of materials is due to their ability to exhibit similar characteristics of common metals but with lighter weight and better material properties. CNs are very conductive and have high modulus properties that outperform standard materials such as aluminum. These nanocomposites are known for their mechanical strengths, thermal properties, and electrical conductivity, which makes them very appealing in future space architecture.

5 Biomedical Technologies

Another alternative to shielding is a biomedical solution, which has been thought of as an alternate to some of the more common shielding theories. There are current studies that suggest biomedical as a more beneficial solution to solve the difficulties from the buildup of radiation dosage to astronauts [8]. Parker points out that the body's natural mechanism to repair cell damage from radiation should be harnessed and explored. It has often been known through years of research that the body can naturally protect and fight against harmful effects from certain levels of radiation. The extent of how much the body can handle is still left for more researching efforts to explore. This will be necessary in order to understand how the length of a space mission might be analyzed along with its biological effects on humans. NASA has collected a considerable amount of data from previous space missions that researchers can look at and try and understand the biological or DNA effects radiation will have. With the data available researchers can form stronger opinions on how to use the body as a means of radiation shielding and develop medical treatments to decrease the effects of radiation.

New technology can really benefit and make an impact on the shielding problems encountered on space vehicles and personnel. Passive shielding techniques can ultimately lessen the payload and intensities required of magnetic shields. This type of system will operate only when immense amounts of cosmic activities are detected which will set in motion a series of events to adequately repel harmful particles away from the vehicle. This system could be very beneficial because of the lower weight penalty and its ability to determine when particles are threatening the vehicle. Other technological advances could be on personal shielding materials such as a lead suit or liquid hydrogen suit that, although heavy and cumbersome on Earth, would present a negligible tradeoff in outer space. Ross et al discusses research on an advanced suit technology called the Mark III [9]. This suit is being developed for more exploratory and longer missions. It will be different than the current suit with the addition of a more complete radiation shield layer for lunar and Mars missions.

6 Conclusions

The most overwhelming question asked is how realistic is this goal of ours? Can we develop technology to the point where we can inhabit a planet that is being constantly bombarded with cosmic rays? Realizing the rationale of the subject matter must also govern our decision-making. There will be drastic consequences if missions are planned with human test subjects as guinea pigs. Not only has there been public outcry about just launching a nuclear powered rocket into space, but history shows that the masses are slow to understand and appreciate newer nuclear technology. It is prudent that as scientists we tread very cautiously and deliberate. Political pressures on space travel could lead to an early demise of the subject matter. There must be a clear and calculated goal in order to get political entities to schedule funding and keep the research going.

Can we use history to help with determining possible benefits for the shielding problem? History has little or nothing to go on due to limited technology and advancements. Due to the major complications over shielding a lot of attention has been diverted to more "realistic" space endeavors. Ever since man has been able to go to the moon it has been a dream to navigate space vehicles a little further and further at a time. So history to a certain extent cannot really lead us down a beneficial path. It only shows us what extreme engineering feats must be accomplished in order for this to be realized.

Our experiences over time and lessons learned will hopefully give us a great insight into what is needed to build and sustain the infrastructure for space travel. Radiation shielding is the primary factor for building the technological capabilities for protecting space vehicles and personnel. Without these measures in place it will be impossible to travel and inhabit distant planets. Risk assessments on space travel along with predictable space models are a few of the tools that will be needed to help achieve the goals. If we can implement our thoughts and desires into efficient shielding capabilities, our dreams of traveling deep into space can soon be accomplished.

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