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Madelyn Hoying

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Radiation Shielding: The Astronomical Problem of Protecting Astronauts on Mars

By Madelyn Hoying

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ABSTRACT

Radiation is the biggest roadblock for NASA in sending astronauts to Mars and to explore other parts of the solar system. The moon is close enough to Earth that radiation was not a significant factor in the short-term Apollo missions, but any future missions that stray further from Earth or for longer periods of time will require new radiation shielding techniques. This review explains the different types of radiation that will affect astronauts, the current mitigation techniques, and the new research being done on radiation shielding. More work is needed to find a lightweight, durable material to protect astronauts as they explore increasingly distant parts of the solar system.

KEYWORDS: Radiation, space, Mars, boron-nitride nanotubes (BNNTs), galactic cosmic radiation (GCR)

INTRODUCTION

Some of the harmful effects of radiation are well known. Chronic radiation exposure is linked to genetic mutations and other medical issues that lead to severe illness and even death [1]. Because of this threat, radiation poses a massive risk to astronauts in deep space exploration. Without the Earth's atmosphere and magnetic effects, humans have nothing protecting them from the constant radiation from the Sun and from other parts of the universe [2]. A trip to Mars, to anywhere in the solar system, or even a long-term trip to the moon could prove deadly without employing radiation shielding techniques [3]. Humans have already ventured into space without effective methods of radiation shielding, including trips to the moon, but these successful results are not guaranteed to be repeated. During the Apollo missions in the 1960s, the astronauts did not experience significant increases in radiation because the time spent beyond Earth's protection was so short, and no unusual space events took place[4]. But as we move towards longer-duration manned space travel, the risk to astronauts' skyrockets. This is a pressing issue that must be solved by 2026, when NASA plans to send the first crews to space as part of the mission to Mars.

The enormous risk of radiation poisoning is currently one of the main limiting factors in NASA's planning for the Orion mission to Mars, where astronauts will live and work on the Martian surface in the Ice Home[2]. The Ice Home is the permanent crew quarters and laboratory planned to be deployed on the Martian surface. The current techniques used to protect from radiation will not work for deep space travel, because they are designed for use within the Earth's protective magnetic shield. This review will discuss the different types of radiation that pose a risk to astronauts during a trip to Mars, the current techniques proposed for use in the Orion capsule and the Martian Ice Home to mitigate the effects of radiation, and the research being done on radiation shielding techniques to allow for long-duration human spaceflight.

RADIATION TYPES

UV radiation is one type of radiation from the sun that will affect astronauts on a long-term trip anywhere in space. On a trip to Mars, astronauts will be constantly exposed to the radiation from the sun, both while in flight to Mars and while on the Martian surface. The Earth has a geomagnetic shield that combines with the atmosphere to protect people on the surface from harmful radiation. Charged particles that constitute types of radiation like UV radiation are deflected by the geomagnetic shield or absorbed in the atmosphere [5]. Since the Earth's geomagnetic shield extends past the Earth to cover objects in Low Earth Orbit (LEO), this was not a problem for the Apollo missions or for astronauts on the ISS [4]. However, it does not extend far enough to protect astronauts on the trip from Earth to Mars. During the trip to Mars, astronauts will instead have to rely on the materials that make up the Orion capsule to provide a suitable level of radiation protection. Mars has a much weaker atmosphere and magnetic field, meaning that more harmful radiation gets through to the surface [9]. Astronauts will need a level of radiation protection on the Martian surface that would not be necessary on Earth's surface.

A second type of radiation called Galactic Cosmic Radiation, or GCR, is a significant issue for astronauts as well. GCRs are a type of radiation that comes from somewhere deep in space and is constantly all around, but the actual sources of GCRs are unknown. GCRs make it through to the surface of the Earth, but the magnetic shield and the atmosphere create enough of a barrier that by the time it reaches the surface, the GCR becomes secondary radiation and is much less harmful, as is shown in Figure 1[6]. As secondary radiation is an effect of the Earth's dense atmosphere, this type of radiation poses a serious problem for astronauts beyond the Earth's protection. Research has not been done directly on what effects GCRs have on humans because humans have not traveled into deep space, but some studies approach the topic by simulating the parts of GCRs that are known. A 2018 study performed at the NASA Space Radiation Laboratory showed that exposure to GCRs increases the likelihood of lung cancer [10]. This was done by simulating parts of GCR rays and using them to irradiate human lung cells, then comparing the cancer rate of the irradiated cells with that of cells not exposed to the simulated GCRs [10]. More research is needed to establish the effects of GCRs on other parts of the human body, but even with research only on the lungs, it is clear that GCR shielding is of the utmost importance if astronauts are to survive their missions beyond Earth.

GCRs have also created serious problems for electronic devices in deep space, as they tend to have much more immediate and serious effects on electronics than UV radiation [7]. Electronic devices in orbit need radiation shielding just like humans do, because any radiation or external magnetic field can render them inoperable, much like a cell phone deactivating a hotel room key [11]. For example, high levels of this type of radiation have been shown to create subatomic gaps in electronic devices like computer chips that leave the computer chips unable to function [12]. GCR levels would only reach such a height if there were an astronomical event that creates GCRs that hit our solar system during the flight. This is unlikely but impossible to predict, since we do not know how GCRs are created [6]. This means that the electronics will slowly deteriorate over time with slow exposure to GCRs, with the potential for a sudden and total malfunction at any given time. GCRs are expected to be a significant problem for humans in deep space travel beyond Earth's geomagnetic protection, both in terms of human health and in terms of computer malfunction. Both factors would clearly prove fatal to the mission in a programmed space launch vehicle. Shielding techniques are needed to protect astronauts from this type of radiation.

CURRENT MITIGATION TECHNIQUES

Water-based shielding is an effective but inefficient method for blocking all types of radiation. This technique involves simply surrounding an object with water, since water blocks radiation in the same way that lead blocks X-rays. About 2 meters of water on each side is needed to reduce radiation exposure by 50%, and increasing that amount to 3 meters reduces radiation exposure by 75% (with an increase in uncertainty)[13]. NASA has determined that safe levels of radiation for the expected mission duration are within the

50-75% range, making this an effective method of protecting astronauts on the Martian surface [2]. However, water production on Mars occurs by extracting water from the Martian surface at a rate of about 0.25 m^3 per day [2]. While water shielding would absolutely reduce radiation exposure on the Martian surface to an acceptable amount, getting 3 meters of water to surround the Ice Home is not the most practical solution. Water is too heavy to carry in such large quantities on the Orion capsule to Mars, so it cannot be used as the only shielding technique for the trip to the Martian surface [8].

Because of the slow production rate, it would take too long to get enough water in the Ice Home to use that as the sole shielding technique on the Martian surface as well. NASA's current approach to dealing with excess radiation on the surface of Mars is to place the Ice Home in the location on Mars with the lowest radiation amounts in the general area. There are certain locations on Mars that would work for a human habitat based on landing requirements, water accessibility, dust storms, and a wide range of other factors [2]. NASA is looking in these certain areas for the location with the lowest radiation levels. The Curiosity Rover on Mars gathered radiation information for several locations, taking into account different factors such as the Martian weather at the time of gathering the data [3]. That way, factors like dust storms that could temporarily lower the radiation levels in a certain spot wouldn't throw off the measurements. From this data, a radiation map of the Martian surface was created with detailed information on the radiation levels, including even the differences in radiation levels at different times during the Martian day, or sol [8]. This will be used to select the ideal deployment spot for the Ice Home to have the lowest possible radiation risk to astronauts from the start, before including any shielding techniques [2]. Combining this technique with water shielding, the risk to astronauts can be reduced but not eliminated.

ADVANCES IN RESEARCH

A major breakthrough in radiation shielding came in the form of synthetic nanomaterials. Traditional materials like metals can shield radiation, but each pound of a payload costs about $10,000 to just get into orbit, without even taking into account the cost for the rest of the trip to Mars [5]. The increase in cost associated with sending extra metal material to Mars far outweighs the benefits of the shielding effects. Less massive materials like plastics work for very short-term shielding, but GCRs tend to break down plastics very quickly and the shielding effect would not last the length of the trip to Mars[9]. Synthetic materials that are lightweight like plastics but have the tenacity of traditional metal and the load-bearing capacity needed to support spaceflight are vital to human space exploration. One promising synthetic material is boron-nitride nanotubes, or

BNNTs. BNNTs are equally as effective at shielding yet significantly less massive than traditional metals due to their nanoscale [14]. BNNTs can be integrated into traditionally lightweight spacecraft materials without a high mass tradeoff. However, these materials are historically not cheap or easy to make. New breakthroughs in 3D-printing plastics with BNNTs embedded in them show promise in using BNNTs for construction of space launch vehicles [15]. More research is needed to verify the structural integrity of 3D-printed BNNTs, since the load requirements are so extreme for spaceflight. However, this is a promising advance in a field that has been stagnant for some time.

CONCLUSION

There is a lot of work left to do to protect astronauts throughout their missions before reaching NASA's 2026 launch date. Radiation is a huge risk to astronauts, especially as they travel beyond the International Space Station and lose the natural protection of Earth's geomagnetic sphere. For any long-duration manned space mission, a complete overhaul of the current radiation shielding techniques are needed in order to keep astronauts safe in space. Current techniques like using water to block radiation is impractical on a longer mission, since the amount of water needed to effectively block radiation would be too heavy for a long flight [13]. The materials used to protect against GCR for space travel today will be exposed to more radiation than they can handle and will break down, rendering them ineffective by the time astronauts return to Earth [15]. More research is needed to determine the safety of recent advances in BNNTs, and to identify other possible shielding techniques [14]. New materials are needed for radiation shielding to allow astronauts to safely venture into the solar system.

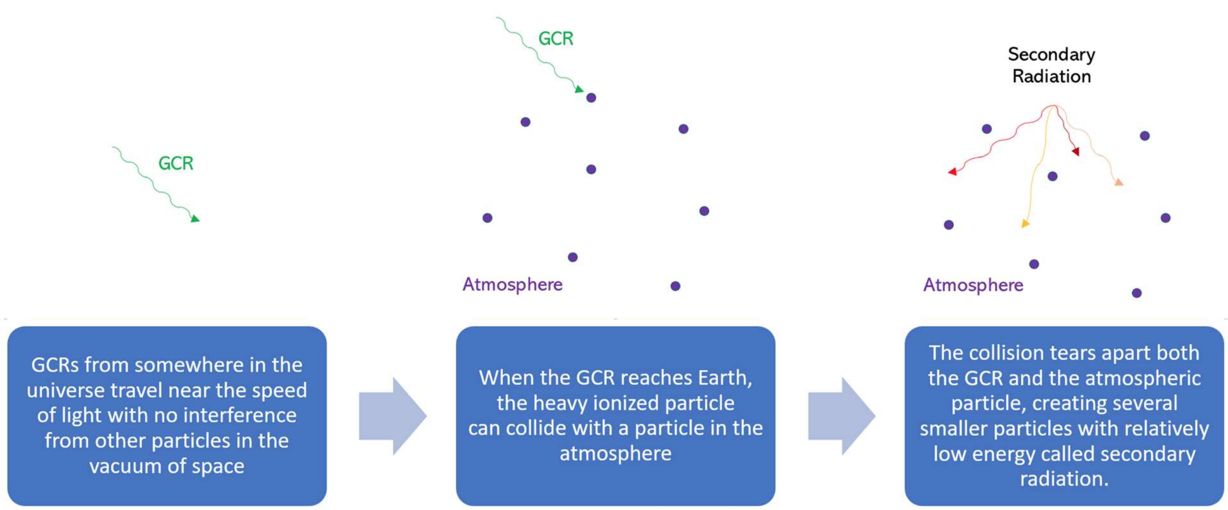

Figure 1 Secondary radiation formation from GCRs in Earth's atmosphere. When a galactic cosmic ray (GCR) reaches Earth's atmosphere, there is an extremely high probability that the GCR will collide with another particle long before it reaches the surface and become secondary radiation [5]. This is because the atmosphere is dense, so there are many chances for collisions. The secondary radiation that is formed has lower energy than the initial GCR [7]. This makes it less likely to penetrate human skin and cause damage to DNA [1]. The colors of the arrows above represent different frequencies, which is proportional to energy. This shows that the GCR has a different initial energy than the secondary radiation it creates, and that the secondary radiation created does not necessarily have an equal distribution of energy in the new particles. One particle can have higher energy than another while both being secondary radiation from the same GCR, but all of the particles have lower energy than the GCR and therefore are less of a threat to human health. Secondary radiation is different from UV radiation, which does not have enough energy to tear apart atmospheric particles on collision.

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