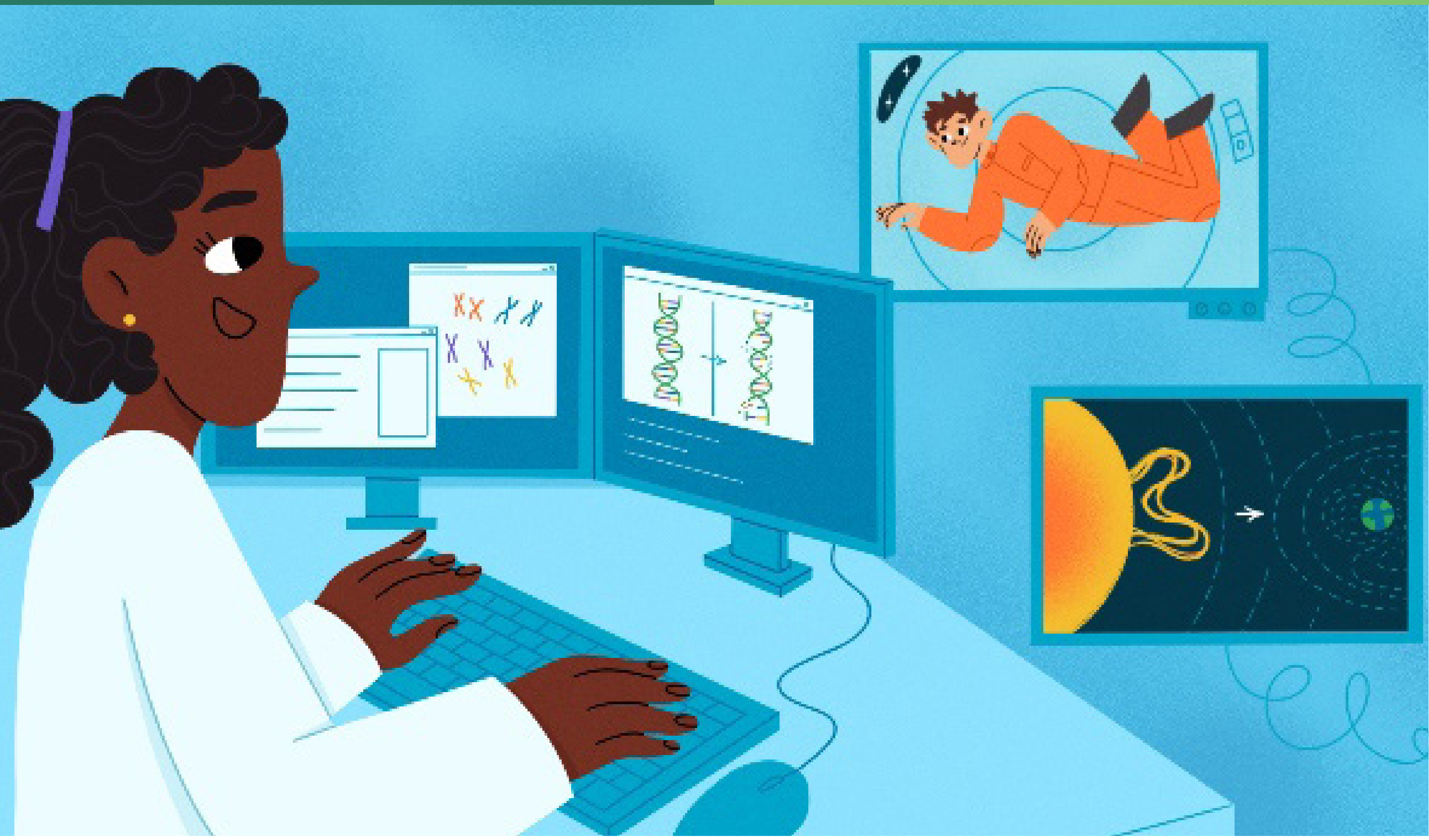
Frontiers for Young Minds

Traveling the cosmos – Risks, rewards, and radiation!

Edited by
Janice L. Huff, Eleanor Blakely and Polly Chang



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Traveling the cosmos – Risks, rewards, and radiation!

Collection editors
Janice L. Huff — Langley Research Center, National Aeronautics and Space Administration, United States
Eleanor Blakely — Berkeley Lab (DOE), United States
Polly Chang — SRI International, United States

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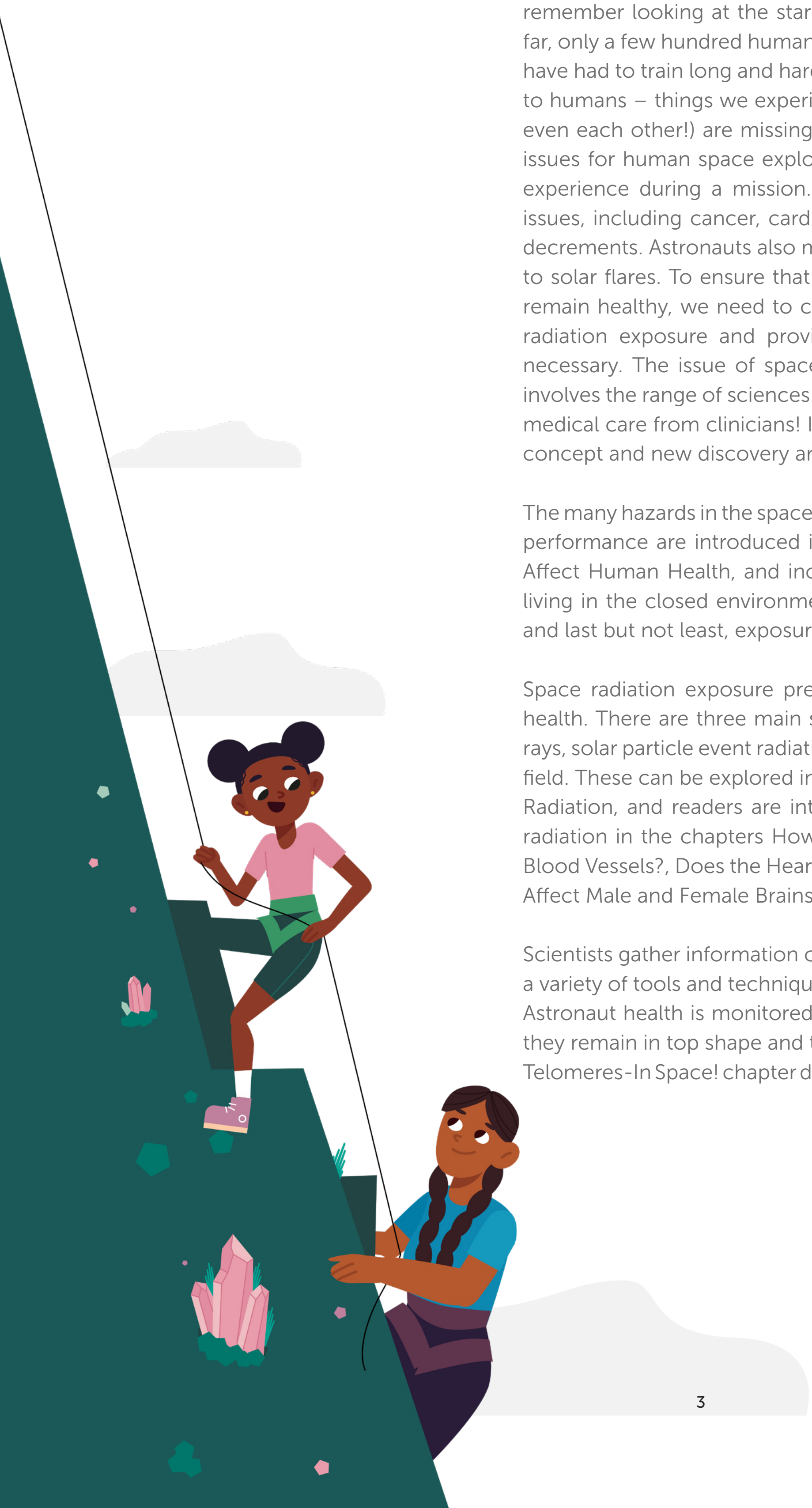

Welcome to the collection Traveling the Cosmos – Risks, Rewards and Radiation! Here we strive to introduce young readers to the excitement and wonder of human spaceflight and to describe the harsh reality of how living and working in space can negatively impact the health of human space travelers.

Space is known as the "final frontier" and for good reason! Many of us remember looking at the stars as a kid and dreaming about going there. So far, only a few hundred humans have ever been in space, and these astronauts have had to train long and hard for that chance. This is because space is harsh to humans – things we experience on Earth (like gravity, an atmosphere, and even each other!) are missing in the space environment. One of the biggest issues for human space exploration is the radiation exposure astronauts will experience during a mission. Radiation exposure can cause several health issues, including cancer, cardiovascular disease, and brain and performance decrements. Astronauts also must be protected from radiation when exposed to solar flares. To ensure that astronauts can safely explore the cosmos and remain healthy, we need to characterize the human health risks from space radiation exposure and provide prevention or protection strategies when necessary. The issue of space radiation is complex and multidisciplinary. It involves the range of sciences from understanding basic physics all the way to medical care from clinicians! In this collection, we present articles (both core concept and new discovery article types) that cover a wide range of topics.

The many hazards in the space environment that can impact human health and performance are introduced in the chapter Hazards During Spaceflight Can Affect Human Health, and include altered gravity, long distance from Earth, living in the closed environment of a spacecraft, isolation and confinement, and last but not least, exposure to space radiation.

Space radiation exposure presents one of the major challenges to human health. There are three main sources of radiation in space - galactic cosmic rays, solar particle event radiation and trapped particles in the Earth's magnetic field. These can be explored in the chapter Protecting Astronauts From Space Radiation, and readers are introduced to health risks associated with space radiation in the chapters How Does Space Exploration Affect the Heart and Blood Vessels?, Does the Heart Age Faster in Space?, and Space Radiation May Affect Male and Female Brains Differently.

Scientists gather information on the health effects of radiation exposure using a variety of tools and techniques both on Earth and in the space environment. Astronaut health is monitored before, during, and after spaceflight to ensure they remain in top shape and to detect any problems early on. The Twins And Telomeres-In Space! chapter describes a ground breaking study where identical twin astronauts were studied over the course of an entire year while one twin lived in space on the International Space Station and the other remained at home on Earth. Other scientists gather information using epidemiology to study radiation effects on human populations as introduced in Radiation Epidemiology: Keeping Space Travelers Safe. Scientists also perform biological research to understand how space radiation damages cells and tissues using research facilities on Earth (NASA's Galactic Cosmic Ray Simulator - Studying the Effects of Space Radiation on Earth), and also in space (Meet BioSentinel: The First Biological Experiment In Deep Space).

These articles are all reviewed by young minds like yourself, with the same shared interests and passion for getting those spacesuit boots back onto the Moon and then forward to Mars! We hope that this collection fuels that spark in you like it does in us.

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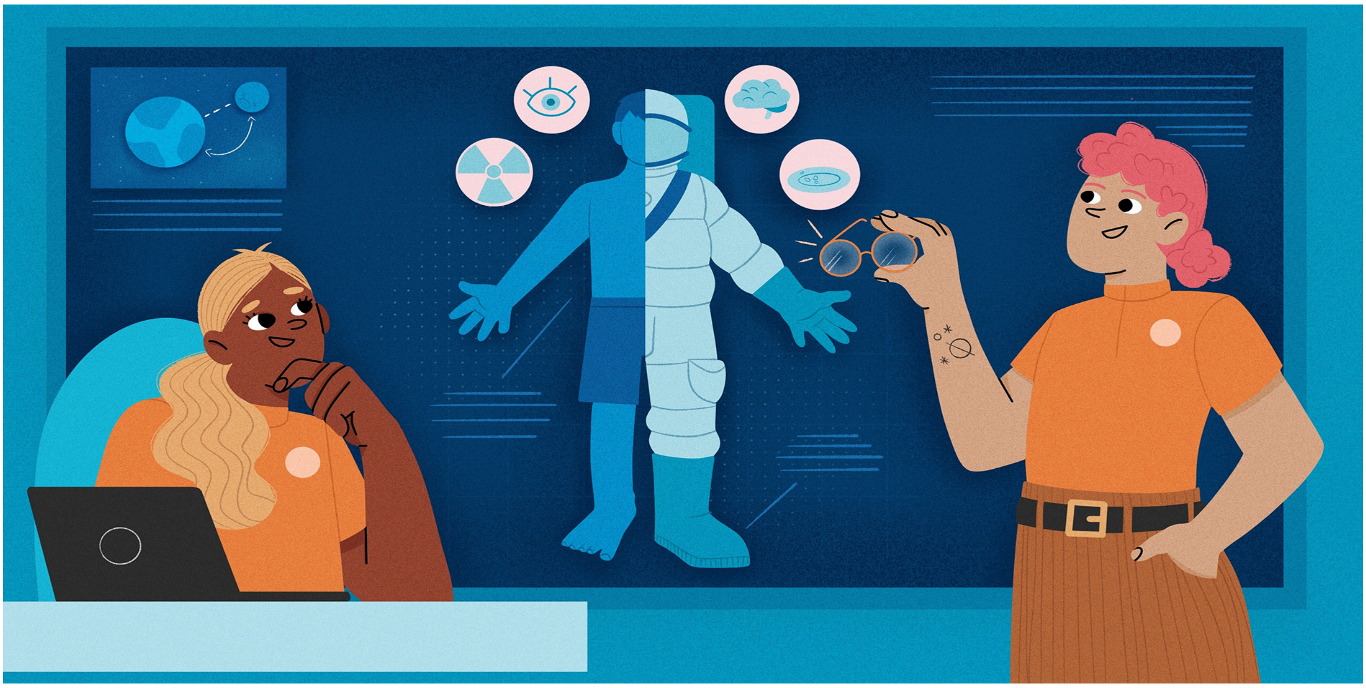

HAZARDS DURING SPACEFLIGHT CAN AFFECT HUMAN HEALTH

Kathleen B. Miller[1]*, Janice L. Huff[2] and Zarana S. Patel[3]

[1] Department of Health and Exercise Science, University of St. Thomas, St. Paul, MN, United States
[2] National Aeronautics and Space Administration Langley Research Center, Hampton, VA, United States
[3] Center for Scientific Review, National Institutes of Health, Bethesda, MD, United States

YOUNG REVIEWERS:


BRIAN
AGE: 13


MABEL
AGE: 14


SEAN
AGE: 11

Space missions present several unique challenges to human health and performance, including space radiation, unique gravity fields, living with just a small group of companions in a small space for a long time, limited resources like food and water, and being far away from Earth. Since our last visit to the Moon, scientists at the National Aeronautics and Space Administration (NASA) have identified over 20 categories of human health risks that are related to these spaceflight hazards. Identifying the human health risks posed by space travel allows new science experiments to be designed and new knowledge to be gained, so we can ensure the health and safety of astronauts on their journeys of space exploration. In this article, we will set off on our own exploration mission to discover and learn about some of the main hazards and related health risks that space travelers will encounter.

SPACE CAN BE RISKY

In late 2022, the successful launch and return of the Artemis I Moon mission marked the start of a new and exciting chapter in human space exploration. Humans will soon set foot on the Moon for the first time in over 50 years, with plans to establish outposts on the Moon surface and in lunar orbit. Going to Mars is next, and the trip to Mars may take up to 3 years in space! Ensuring that space travelers are safe and have healthy bodies and minds is important for the success of these missions. As space travelers go further away from planet Earth, staying healthy becomes more challenging. For example, during a stay on the **international space station** (ISS), an astronaut developed a blood clot in a large neck vein [1]. Normally our bodies make blood clots, which are clumps of blood cells, to stop bleeding if there is a cut or injury. However, if a clot forms in a blood vessel it can be very dangerous because it may block the natural flow of blood needed by tissues and organs. The astronaut took images of the blood clot using an ultrasound device and sent the images to doctors on Earth, so they could form a treatment plan. The treatment plan included medications already aboard the ISS that, luckily, would not run out before the ISS was resupplied. Because of this collaboration between doctors on Earth and the astronaut in space, the astronaut was treated effectively and arrived home safely after the mission. However, if a health event occurred during a longer mission further away from Earth, it would not be as easy to consult with doctors or get certain medications. This article will describe various health challenges astronauts will face, called **spaceflight hazards**, and will describe several of the most important **health risks** posed by the hazards faced during a long trip in space.

INTERNATIONAL SPACE STATION (ISS)

A large spacecraft in orbit around the Earth where astronauts can work and live.

SPACEFLIGHT HAZARDS

Hazards to human health and performance that are unique to space.

HEALTH RISKS

The risk of developing illnesses or unwanted changes in the body. Some health risks are important to think about for a long trip in space, like a trip to Mars.

SPACEFLIGHT HAZARDS AND ASSOCIATED HEALTH RISKS

The spaceflight environment has a unique set of health hazards that space travelers must deal with. Spaceflight hazards include **space radiation**, gravity that is different from that of Earth, long periods of isolation and confinement, living in a small, potentially uncomfortable living space within a closed environment or ecosystem, and being a long distance from home [2]. Importantly, space travelers will likely experience more than one spaceflight hazard at a time. It is important to understand how the combination of these hazards impacts the unique bodies and minds of every space traveler, as shown in Figure 1. Spaceflight hazards are linked to various human health risks, as shown in Figure 2. These include the risk of cancer or other diseases caused by space radiation, the risk of eye and vision problems, the risk of brain changes that negatively affect behavior, mood, and thinking abilities, and the risk of a poor diet [3].

SPACE RADIATION

Energetic charged particles originating from the sun and galactic supernovae remnants.

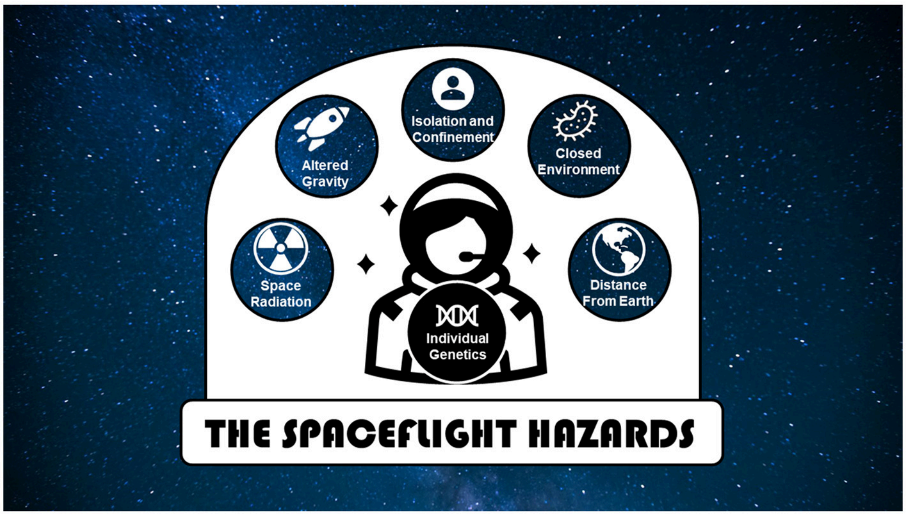

Figure 1

Figure 1

Spaceflight hazards are a unique set of hazards present during space travel. Scientists are working to understand how the combination of these hazards, along with individual genetic differences, impact the health of space travelers.

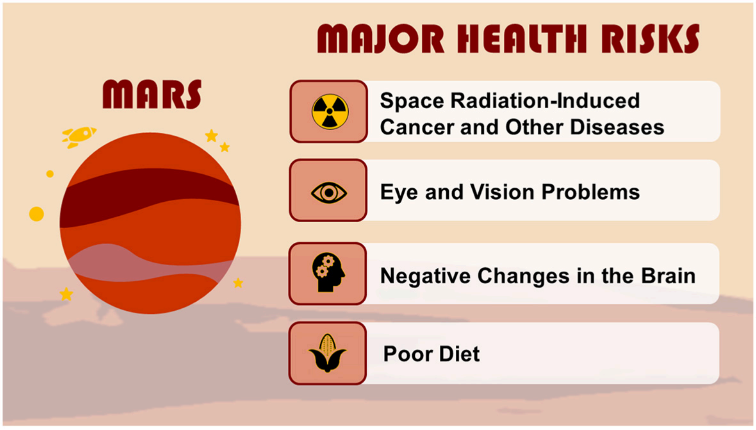

Figure 2

Figure 2

There are many health risks from space travel, especially during long trips like a mission to Mars. Important health risks include space radiation-induced cancer and other diseases, eye and vision problems, changes in the brain that negatively affect behavior, mood, and thinking abilities, and a poor diet. Studying these risks and figuring out how to combat them will enable space travelers to have healthy bodies and minds on their trips to the Moon, Mars, and beyond.

IONIZING RADIATION

Radiation with enough energy to break chemical bonds.

HEALTH RISK 1: CANCER AND OTHER DISEASES FROM SPACE RADIATION

Did you know there is radiation in space? Space radiation is **ionizing radiation**, meaning it has enough energy to break chemical bonds. Space radiation is unlike any radiation found on Earth. It includes solar particle event radiation coming from the sun, and energetic particles known as galactic cosmic rays that come from outside our solar system (For more information on space radiation, read more here). Unfortunately, space radiation can damage the cells and tissues of space travelers, leading to health problems like cancer or other diseases (To learn more about studying the human health on Earth, read more here and in space, read more here).

Cancer takes many years to develop, so it is unlikely to happen during a space mission. However, cancer could occur after a mission. Scientists are working to understand if cancer triggered by space radiation is more severe and more difficult to treat than cancer caused by ionizing radiation on Earth. They are also trying to figure out how to prevent it. Space radiation may cause health problems besides cancer, like problems with the heart, lungs, blood vessels, gut, or immune system (to learn more about heart health in space explorers, read more here and here). Space radiation may also have effects on the brain, causing problems with the ability to perform tasks, remember things, or learn new things (to learn more about how space radiation impacts the brain, read more here). To study the effects of space radiation, scientists use the National Aeronautics and Space Administration's (NASA) Space Radiation Laboratory, a special facility where space radiation can be mimicked (Figure 3A, to learn more about studying space radiation effects here on Earth, read more here and here). Importantly, most of the studies on the effects of space radiation have been done in cell cultures and rodent models, so scientists are still trying to understand if these effects would also happen in human bodies.

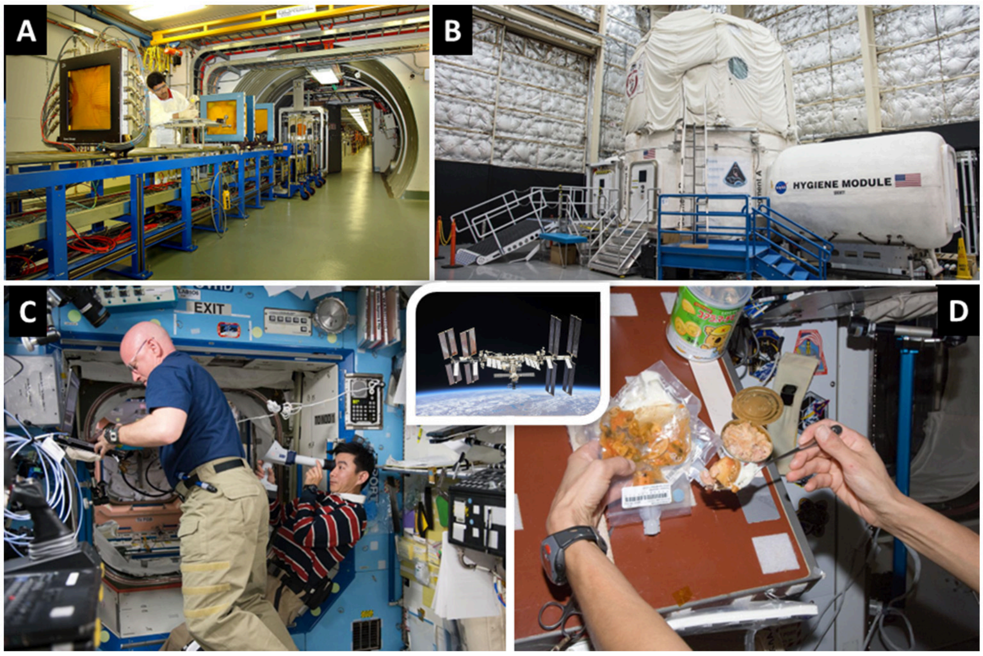

Figure 3

Figure 3

Health risks from spaceflight can be studied on Earth in space analogs like: **(A)** the NASA Space Radiation Laboratory, located at Brookhaven National Laboratory in New York; or **(B)** the Human Exploration Research Analog located at NASA Johnson Space Center. These risks are also studied in space onboard the International Space Station (ISS) **(middle)**. **(C)** ISS expedition NASA astronaut Scott Kelly (left) assists Japan Aerospace Exploration Agency astronaut Kimiya Yui (right) with eye and vision measurements. **(D)** An ISS crew member prepares a meal of various food items (Image credits: NASA).

HEALTH RISK 2: EYE AND VISION PROBLEMS

Do you or does someone in your family wear eyeglasses to see better? We have known for a long time that going into space can change an astronaut's vision, so we give them several pairs of eyeglasses of differing power to take with them. More recently, scientists have identified an eye disease that is specific to spaceflight, called **spaceflight associated neuro-ocular syndrome (SANS)**. SANS includes swelling of the eye nerve and folding of one of the tissue layers of the eye. Both of these issues can make it difficult to see clearly.

SPACEFLIGHT ASSOCIATED NEURO-OCULAR SYNDROME (SANS)

Eye and vision changes that may occur in astronauts during and after long-duration spaceflight missions.

So far, SANS has not impacted how well space travelers can see before or after a mission. However, scientists are studying how SANS may impact astronauts during and after a longer trip in space, like a trip to Mars. Scientists are also trying to understand what causes SANS. One theory is that the shifting of the fluids in the body that happens in **microgravity** is part of the problem, though more data are needed to support this theory. Scientists are also working on studying the eyes of both men and women space travelers, to understand if SANS affects them equally (Figure 3C) [3].

MICROGRAVITY

Conditions occurring when the pull of gravity is small, and objects seem weightless.

HEALTH RISK 3: CHANGES IN THE BRAIN THAT AFFECT BEHAVIOR, MOOD, AND THINKING ABILITIES

Going to space for a long time can be pretty stressful. On a mission to Mars, space travelers will experience long periods of isolation, will be confined in a small space, and may have to go long periods of time without talking to people on Earth. These issues may cause problems with making decisions, performing tasks well, working together in a team, and handling stress. In severe cases, space travelers may feel depressed, anxious, or angry. Luckily, scientists have shown that there are habits that can reduce the stress of going to space. On the ISS, a laboratory in space where astronauts work and live (Figures 3C, D), sleeping well, exercising, journaling, communicating with loved ones, and thinking positively has helped astronauts reduce stress.

However, a journey to Mars will be more challenging than a mission on the ISS. Space travelers will be gone for much longer periods of time and they may not be able to communicate with people on Earth for long stretches. To study these conditions, scientists use a **space analog**: something that mimics the experience of traveling in space, without actually going to space [3]. One example is the Human Exploration Research Analog (HERA) at NASA's Johnson Space Center (Figure 3B). Within HERA, teams can do mock space missions, where they complete mission objectives, live for long periods isolated in small spaces, experience delays in communication, and eat space food [3]. Remote locations on Earth, such as Antarctica, have also been used as a space analog. Space analogs help scientists understand which changes in behavior, mood, and thinking abilities may occur during space missions and what space travelers can do to reduce stress and keep their bodies and minds healthy.

SPACE ANALOG

Environments on Earth that are used to study conditions in space.

HEALTH RISK 4: A POOR DIET

A poor diet has always been a concern for explorers. For example, scurvy, a disease caused by a lack of vitamin C, killed many sailors between the sixteenth–eighteenth centuries. Like sailors, space travelers will also need to ensure they are eating enough healthy foods that contain the vitamins and nutrients they need to survive and thrive. However, unlike sailors, space travelers do not have the option to stop at a port city and refill their food supplies. On the ISS, scientists have been studying the importance of good nutrition and the consequences of poor nutrition, as NASA prepares for longer journeys to the Moon and Mars (Figure 3D) [3]. Poor nutrition can cause many health issues, like poor bone health, reduced ability to think clearly, reduced heart function, and vision problems. Good nutrition may also help fight some of the negative health effects caused by the other spaceflight hazards. Some health conditions on Earth may also be linked to poor nutrition, so studying how a poor diet impacts space travelers is not only useful for a trip to space—it could improve the health of people on Earth, too.

BACK TO THE MOON… AND BEYOND!

There are many hazards in the space environment that may impact the health of space travelers. These hazards may lead to a number of potential health problems. Research on space-related health risks will enable space travelers to have healthy bodies and minds on their trips to the Moon, Mars, and beyond! If you still want to learn more, and we hope you do, further information on these topics can be found on NASA's website.

AUTHOR DISCLAIMER

This work was prepared while ZP was employed at KBR/NASA Johnson Space Center. The opinions expressed in this work are the author's own and do not reflect the view of the National Institutes of Health, the Department of Health and Human Services, or the United States Government.

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the highest priority human health risks for a mission to Mars. *NPJ Microgravity* 6:33. doi: 10.1038/s41526-020-00124-6

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3. Patel, Z. S., Brunstetter, T. J., Tarver, W. J., Whitmire, A. M., Zwart, S. R., Smith, S. M., et al. 2020. Red risks for a journey to the red planet: the highest priority human health risks for a mission to mars. *NPJ Microgravity* 6:33. doi: 10.1038/s41526-020-00124-6

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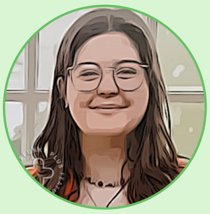
CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

BRIAN, AGE: 13
Brian is interested in aerospace engineering and astrophysics. He hopes to study space law or help write policy and contracts for space agencies. Brian is taking challenge courses through a local community college in advanced mathematics.



MABEL, AGE: 14

I have always been fascinated about how things work and this sparkled my passion for science. I read a book by Stephan Hawking and I was captivated by physics. I love the logic and also the complexity of it and how it expands out knowledge and understanding of the world. This is formed by subject choice at school and I am aiming to study physics in more depth at university.

SEAN, AGE: 11

Sean is interested in mechanical and aerospace engineering and astronomy. He loves to observe space through telescopes. Sean tutors students in math and volunteers at conferences as a helper. He has twice gone to the National Invention Convention.

AUTHORS

KATHLEEN B. MILLER

Dr. Kathleen B. Miller is an assistant professor at the University of St. Thomas in St. Paul, MN. She was formerly a research scientist and member of the Multi-Model Ensemble Risk Assessment project at NASA Langley Research Center. Her research aims to assess long-term health outcomes from space radiation exposure. Dr. Miller earned her Ph.D. in kinesiology with a minor in neuroscience from the University of Wisconsin-Madison. *mill4945@stthomas.edu

JANICE L. HUFF

Dr. Janice L. Huff works at the NASA Langley Research Center where she is the project scientist for the Multi-Model Ensemble Risk Assessment Project. She is a council member of the National Council on Radiation Protection and Measurements. Dr. Huff previously served as the space radiation deputy scientist within the Human Research Program at NASA. She earned her Ph.D. in microbiology from the University of Virginia, studying the cellular and molecular biology of cancer.

ZARANA S. PATEL

Dr. Zarana S. Patel earned her Ph.D. in bioengineering from Rice University and her Master of Public Health at UTHealth in the Environmental and Occupational Health Sciences department. She previously has served as a discipline lead for the Risk of Cardiovascular Disease from Radiation within the Human Research Program at NASA and as a senior bioengineer and project manager for the Cardiovascular Disease Risk Modeling project in the NASA Langley Research Center Space Radiation Group. Dr. Patel is currently a scientific review officer at the National Institutes of Health Center for Scientific Review.

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PROTECTING ASTRONAUTS FROM SPACE RADIATION

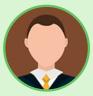
Charles M. Werneth *

Durability, Damage Tolerance, and Reliability Branch, NASA Langley Research Center, Hampton, VA, United States

YOUNG REVIEWERS:

BRIAN
AGE: 13

RYAN



SEAN
AGE: 11

Astronauts on missions to the International Space Station, the moon, and beyond are exposed to several hazards, one of which is space radiation. Space radiation is composed of tiny particles from various sources that spread out in all directions throughout the solar system. These particles have a wide range of energies, and some of them are a serious concern for the safety of space crews. Radiation that passes through the shielding on spacecraft and into the human body can damage cells and may lead to the development of cancer or other negative health effects. To protect astronauts, the National Aeronautics and Space Administration (NASA) is trying to better understand the space radiation environment so they can minimize the effects of radiation exposure on astronauts. This article describes the kinds of space radiation and the approaches that NASA is using or studying to keep astronauts as safe as possible.

In space, astronauts are exposed to several health risks, including a low-gravity environment, stress from being in a small space for a long time, and limited access to health care. One of the greatest risks astronauts face is space radiation [1]. Space radiation may have high enough energy to strip electrons away from the nuclei of atoms, so it can damage human tissue and lead to numerous health problems, including cancer. Space radiation comes from several sources. The Sun ejects charged particles (called ions) into space during violent eruptions known as **solar particle events** (SPEs). These events may be hazardous to crew members if a SPE storm shelter is not available. **Galactic cosmic rays** (GCRs) are formed when the shock waves from galactic **supernovae** (events in which stars explode) send particles like protons and heavier atomic nuclei into space at very high energies, which may cause those particles to penetrate deeply into the spacecraft and human tissue. In addition to these sources of radiation, energetic protons and electrons may also become trapped in Earth's magnetic field, in a region known as the Van Allen **radiation belts**. This article describes SPEs, GCRs, the Van Allen radiation belts, the potential health risks of radiation exposure, and methods that the National Aeronautics and Space Administration (NASA) uses to reduce radiation risks.

SOLAR PARTICLE EVENTS

Ejections of particles (radiation) from the sun that may be harmful to astronauts

GALACTIC COSMIC RAYS

Protons, helium nuclei, and other particles that move uniformly through the solar system and come from supernovae located in the Milky Way galaxy.

SUPERNOVAE

Events in which stars explode and accelerate high energy particles into space.

RADIATION BELTS

Radiation consisting of protons and electrons that have become trapped in the Earth's magnetic field

SOLAR PARTICLE EVENTS

Solar flares and **coronal mass ejections (CMEs)** are examples of SPEs where particles are ejected into space from the sun [2]. Space radiation is often described in terms of the number of particles with a specific energy passing through a specified unit of area. This is called **differential particle flux**. If a CME has a large flux, that means there are a large number of the particles (more radiation) passing through the area. Likewise, a small flux means a smaller number of particles (less radiation). Solar flares consist mostly of high fluxes of electrons but are usually short lived and do not cause significant health risks. In contrast, CMEs may last from a few hours to several days and consist of large plumes of plasma (hot ionized gas), mostly made up of protons. Compared to solar flares, the abundance of protons and the higher energies of CMEs can cause more damage to human tissue. Since CMEs can be predicted several hours to days before they reach a spacecraft, astronauts can protect themselves by setting up storm shelters. Solar conditions are monitored by spacecraft such as the Solar Dynamics Observatory, which can inform crew members of approaching CMEs.

SOLAR FLARES

Short-lived events of mostly electrons ejected from the sun that usually do not pose serious health risks for astronauts.

CORONAL MASS EJECTION

An ejection of charged particles (mostly protons) from the sun's outermost atmospheric layer.

DIFFERENTIAL PARTICLE FLUX

The number of particles per unit energy that pass through a specified unit of area.

You may have seen pictures of the sun on which darker areas, called **sunspots**, are visible. The Sun has been observed to have an 11-year solar cycle, where the solar activity transitions from a solar minimum, with few or no sunspots, to a solar maximum, with a larger number of sunspots [2]. CMEs occur most frequently during the relatively high activity of solar maximum, when more sunspots are seen. An example of a CME is shown in Figure 1. Have you heard of the northern or southern lights, also called auroras? These bright, colorful lights observed near the Arctic and Antarctic regions are

SUNSPOTS

Dark spots on the surface of the sun that are cooler than caused by CMEs, as ions stream into Earth's magnetic field and cause molecules in Earth's atmosphere to emit light. Large CMEs can even damage satellites.

the surrounding areas on the solar surface. Large numbers of the spots are associated with high solar activity and an increased likelihood for coronal mass ejections and solar flares to occur.

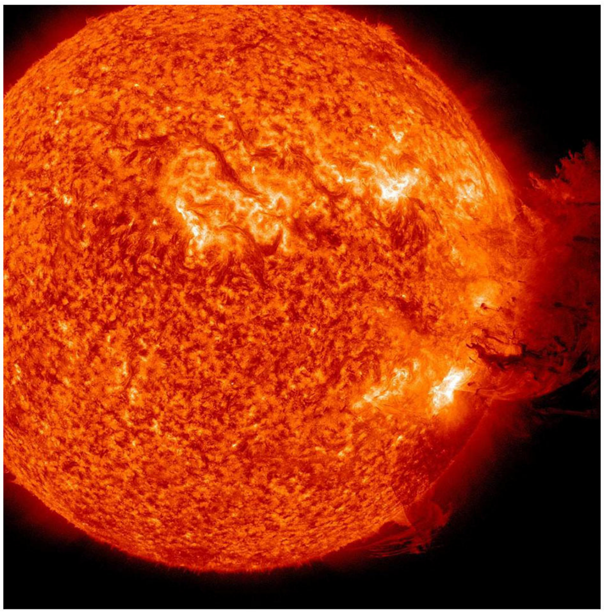


Figure 1

Figure 1

A CME captured by the Solar Dynamics Observatory on 7 June 2011. You can see the ejected plasma on the right side of the image, which was nearly half the diameter of the Sun! To put this into perspective, this CME was approximately 50 times the diameter of Earth (Image credit: Solar Dynamics Observatory and NASA).

GALACTIC COSMIC RAYS

GCRs are produced from the remains of supernovae (Figure 2) [3] and consist of protons, helium nuclei, and heavier ions that can move nearly at the speed of light [2]. Supernovae are grouped into two types. Type I supernovae occur when white dwarf stars (dense stellar cores that are nearly the size of Earth) accumulate mass from a nearby star. Once the mass of a white dwarf star exceeds 1.4 times the mass of the Sun, the white dwarf explodes violently [4]. Type II supernovae occur when massive stars use all of their nuclear fuel and explode, with light intensities that may be brighter than a galaxy for a short time.

GCRs vary with the solar cycle. During the solar maximum, the Sun's magnetic field is more intense, so it deflects a lot of the GCRs, meaning that differential particle flux is decreased. During the solar minimum, the Sun's magnetic field is less intense. There are fewer GCRs blocked, and this means there is larger differential particle flux when compared to solar maximum. The radiation risk is greater during solar minimum because astronauts receive more radiation exposure. Low energy GCR fluxes at solar minimum may be over 10 times greater than the fluxes at solar maximum. However, particles with very high energies are not as effectively blocked by the Sun's magnetic field. These high-energy GCRs can penetrate spacecrafts and may be harmful to humans. Unlike SPEs, which happen only periodically, GCRs are always present, which makes them a major challenge for long space missions,

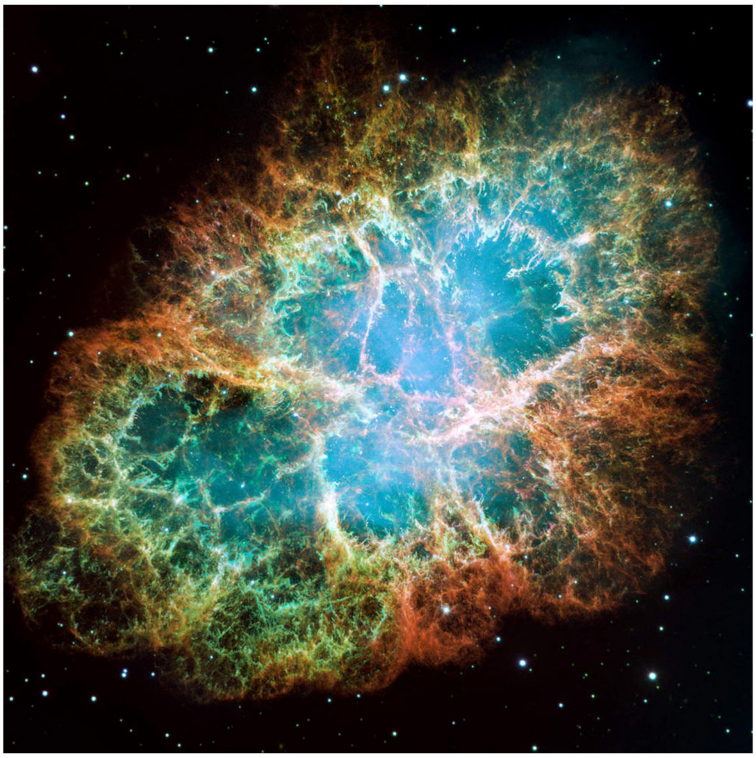


Figure 2

Figure 2

A supernova remnant known as the Crab Nebula. A supernova is an event in which a star explodes leaving behind mostly gases surrounded by a shockwave that accelerates protons, helium nuclei, and other particles into space at high speeds. The particles travel through space and eventually into the solar system, where astronauts may be exposed to the harmful radiation (Image credit: NASA).

such as a mission to Mars. During long spaceflights, astronauts could receive amounts of radiation greater than the career safety limit set by NASA.

VAN ALLEN RADIATION BELTS

The Earth's iron core creates a magnetic field around the planet that exerts a force on charged particles. In space, protons and electrons are charged particles that experience forces from the Earth's magnetic field and become trapped as radiation belts around the Earth. The Van Allen radiation belts (Figure 3) consist of inner and outer belts: the inner belt mostly contains protons and electrons, and the outer belt contains mostly electrons [2]. The flux of electrons in the outer belt is nearly 10 times greater than the electron flux in the inner belt; however, this radiation does not penetrate deeply into spacecraft materials. The protons are more energetic and pose a greater radiation risk. The International Space Station orbits Earth at an altitude that is beneath most of the trapped proton radiation, although there is a region known as the South Atlantic Anomaly, where changes in Earth's magnetic field increase radiation exposure from protons.

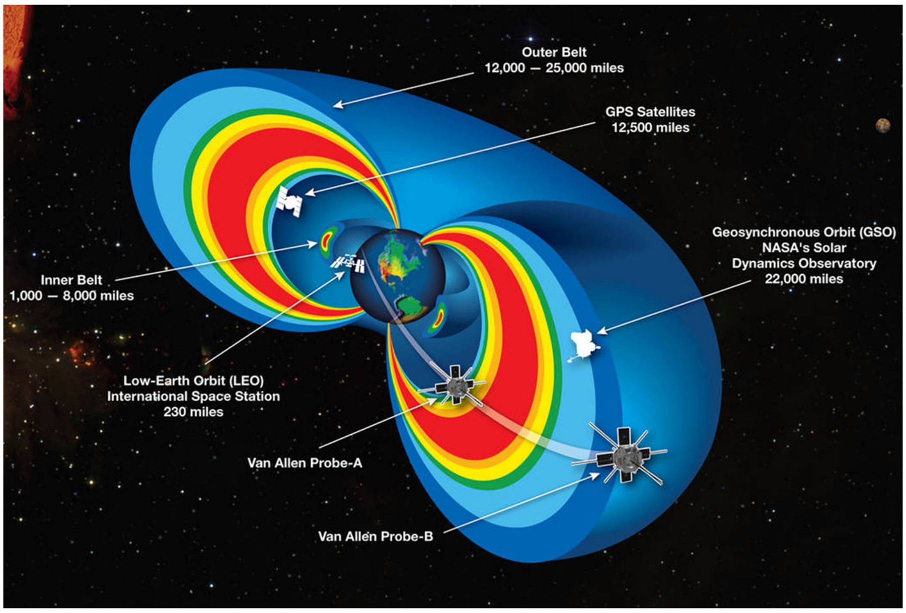


Figure 3

Figure 3

Earth's magnetic field traps protons and electrons in layers around the Earth known as Van Allen radiation belts. Here, you can see the belts and the approximate locations of the International Space Station in low-Earth-orbit, probes that measure the Van Allen radiation belt, and global positioning system satellites (Image credit: NASA).

PROTECTING ASTRONAUTS FROM RADIATION RISKS

Space radiation may lead to many health effects such as cancer, heart disease, stroke, problems with brain function, and diseases of the brain and spinal cord. NASA uses several strategies to minimize the risk of space radiation for astronauts. These include designing spacecraft shielding to reduce radiation exposure, providing storm shelters for use during SPEs, carefully planning space missions to avoid as much radiation as possible (including timing with the solar cycle), and selecting crew members that are best suited to perform NASA's missions. Even with these precautions, astronauts are likely to exceed their career radiation limits on long missions, such as a mission to Mars. So, NASA is also investigating whether medications can be used to reduce risk from radiation exposure. Studies have shown that some well-known medications, including aspirin and medicines to treat blood clots and diabetes, can reduce the chances of getting cancer or dying from cancer. NASA has recently shown that these medicines may also reduce the risk of cancer deaths caused by space radiation exposure [5].

CONCLUSION

Space contains a complex mixture of radiation, consisting of particles from SPEs, GCRs, and radiation belts, all of which can be dangerous to human health. Timing missions so that they happen during the safest part of the solar cycle is very important to keep radiation exposure to a minimum. GCRs are the hardest type of radiation to protect astronauts from; therefore, missions may be planned during solar maximum to minimize GCR exposure, even though SPEs are more likely to occur then. Crew members may decrease their radiation risks from SPEs by using storm shelters made from resources onboard the spacecraft. Astronauts onboard the International Space Station or other missions during which spacecraft stay relatively close to Earth are somewhat protected from GCRs, since Earth's magnetic field weakens the GCR flux. NASA is working to make spaceflight safer for astronauts by taking various steps to protect them from space radiation, including potential new medicines. The aim is to protect astronauts enough that long-distance missions, such as to Mars, will eventually be possible.

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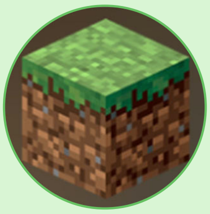
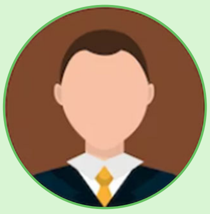
YOUNG REVIEWERS

BRIAN, AGE: 13
Brian is interested in aerospace engineering and astrophysics. He hopes to study space law or help write policy and contracts for space agencies. Brian is taking challenge courses through a local community college in advanced mathematics.



RYAN
I really enjoy coding and I love Rubik's cubes. I also really love playing Minecraft.



SEAN, AGE: 11
Sean is interested in mechanical and aerospace engineering and astronomy. He loves to observe space through telescopes. Sean tutors students in math and volunteers at conferences as a helper. He has twice gone to the National Invention Convention.

AUTHORS

CHARLES M. WERNETH
Dr. Werneth is a research physicist at the NASA Langley Research Center. His research interests include radiation risk, cancer risk modeling, and nuclear physics modeling. He earned a Ph.D. in computational science (physics), M.S. in Physics, and a B.S. in physics and mathematics. *charles.m.werneth@nasa.gov

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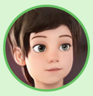
HOW DOES SPACE EXPLORATION AFFECT THE HEART AND BLOOD VESSELS?

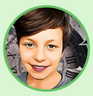
Ashley S. Nemec-Bakk and Marjan Boerma *

Division of Radiation Health, Department of Pharmaceutical Sciences, University of Arkansas for Medical Sciences, Little Rock, AR, United States

YOUNG REVIEWERS:


EDOARDO
AGE: 8


ILYAN
AGE: 8


LORYAN
AGE: 12


MATTIA
AGE: 9


REAGAN
AGE: 10


VITTORIA
AGE: 10

During missions in space, men and women are exposed to many factors that can alter the cardiovascular system, which consists of the heart and blood vessels. Both onboard the International Space Station and in space crafts in deeper space, people experience very little (micro) gravity. Because the human cardiovascular system is used to working against the gravity we have on Earth, living in microgravity can lead to unwanted changes. Moreover, exposure to space radiation, the diet onboard space missions, and the mental stress of long-term missions can all influence cardiovascular health. This article reviews the current knowledge of how the environment in space can alter the heart and blood vessels of space explorers, and it discusses some things that we still do not fully understand. The research in this area is ongoing and is very important to make future human missions into deep space possible.

FROM THE INTERNATIONAL SPACE STATION TO MISSIONS IN DEEP SPACE

INTERNATIONAL SPACE STATION (ISS)

A station built by several space agencies that circles about 400 km above Earth. It is a laboratory for space research and can hold space explorers for weeks to months.

The International Space Station (ISS), the largest object in space ever built by people, is a collaboration between the space agencies of many countries. The area within the ISS where people live is about 390 cubic meters in size—about the same size as a family home in the United States or Canada, or 1.5–2 homes in Europe. More than 200 men and women have lived aboard the ISS for various lengths of time, mostly between 3 months and a year per mission. Exciting plans have been made for manned missions that go much further than the ISS, deeper into our solar system. In the near future we may see multi-year missions to the Moon, other near-Earth objects such as asteroids, and even the planet Mars. During those deep-space missions, explorers will be exposed to an environment that is very different from that on Earth.

THE HEART AND BLOOD VESSELS OF SPACE EXPLORERS

CARDIOVASCULAR SYSTEM

The body system made up of the heart and blood vessels, which bring oxygen and other nutrients to all organs and tissues and remove carbon dioxide and other waste products.

MICROGRAVITY

The experience of very little gravity, so that people and objects appear to be weightless.

The human **cardiovascular system** is made up of the heart and all the blood vessels, including the tiny ones that reach into all the organs and tissues. It is important to have a healthy cardiovascular system, and we know that there are things people can choose to do on Earth that can reduce cardiovascular health, such as smoking or eating an unhealthy diet. The environment that deep-space explorers will be in also has several factors that could influence the health of the heart and blood vessels. This article focuses on four of the main factors: **microgravity**, psychological stress, space radiation, and diet (Figure 1). We will describe what we know and what we do not know about these factors of space, and we will tell you about some of the research that

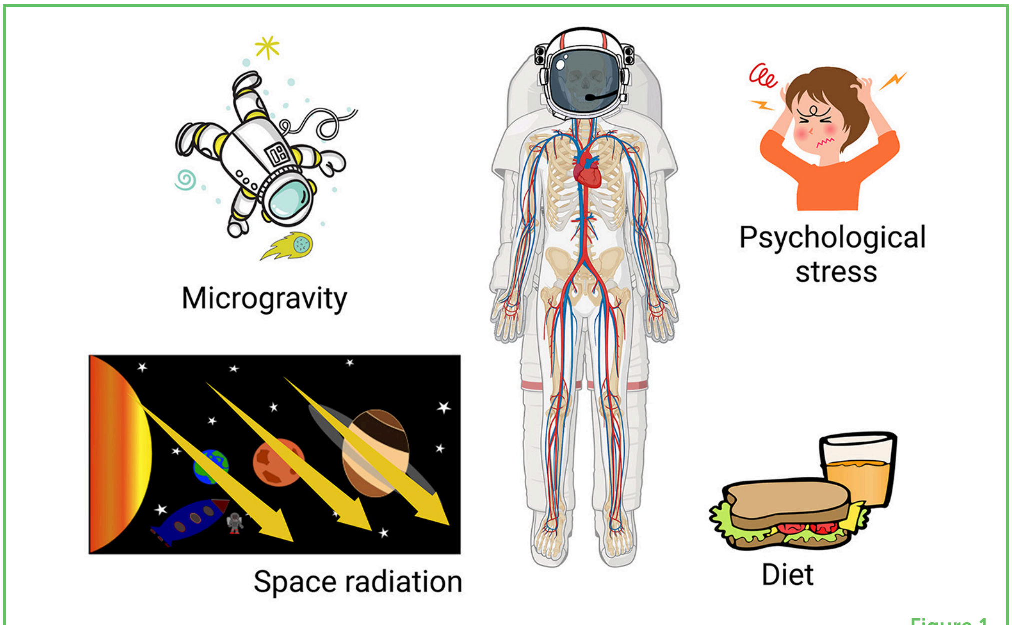


Figure 1

During missions in deep space, factors such as microgravity, psychological stress, space radiation, and diet may all effect the hearts and blood vessels of space explorers (Figure created with BioRender).

is being done to increase our understanding and find ways to make space travel safer for crew members.

MICROGRAVITY AND THE CARDIOVASCULAR SYSTEM

Because humans have evolved on Earth, the cardiovascular system is built to function in Earth's gravity. However, far from Earth, deep-space explorers will be living in a state of very little gravity, called microgravity. Even missions to other space objects will involve altered gravity, as gravity on the surface of the Moon is only about one sixth of that on Earth, and gravity on Mars is about one third. The ISS is close enough to the Earth that gravity still exists, keeping the station circling around our planet. However, people inside the ISS experience no forces on their bodies, so to them it feels the same as being in microgravity.

When people live in microgravity, more blood and fluids will be in the tissues of the chest and head compared to the lower parts of the body, because the pull from Earth's gravity is not there to draw those fluids downwards. That is why the faces of people traveling in space can look slightly puffy compared to when they are on Earth (Figure 2). When space travelers return to Earth, their appearances go back to normal.

Figure 2

Figure 2

Faces of people in space often look a little puffy because microgravity inhibits body fluids from moving to the lower parts of the body. **(A)** NASA astronaut and Expedition 68 Flight Engineer Nicole Mann on Earth, and **(B)** working on a physics experiment aboard the ISS. **(C)** NASA astronaut and Expedition 68 flight engineer Woody Hoburg in training on Earth, and **(D)** while preparing a spacesuit inside the ISS for an upcoming spacewalk (Photo source: NASA Image and Video Library).

In addition to the appearance of the face, several studies on people aboard the ISS have shown changes in the shape and rhythm of the heart. However, we do not yet understand the consequences of living in these conditions for many years.

RADIATION IN DEEP SPACE

Several types of radiation travel through our solar system at almost the speed of light. The types of radiation that are particularly harmful to the human body are composed of very small particles that have a positive charge and very high energy. These particles come from elements of the periodic table, from helium all the way up to iron, which is the largest charged particle in space. When these particles, also called **galactic cosmic rays (GCR)**, pass through the human body, they damage the body's cells. This could negatively affect many organ systems, including the heart and blood vessels. Earth's magnetic fields reflect a large portion of GCR, which is why Earth dwellers are protected from this type of radiation. The levels of GCR are also not very high aboard the ISS, because the ISS is close enough to the Earth that it has some protection from Earth's magnetic fields. However, exposures to GCR will be higher on deep-space missions, where there is no protection.

GALACTIC COSMIC RAYS (GCR)

High-energy, positively charged particles that move through space at almost the speed of light. They originate outside the Solar System in our own galaxy and from distant galaxies.

For many years, we have known that radiation exposure on Earth, such as from nuclear accidents or from certain types of work, increase cardiovascular diseases. Therefore, there is concern that the cardiovascular system may be impacted by radiation in deep space—although we must keep in mind that GCR is different from the types of radiation on Earth.

DIET OF EXPLORERS ON SPACE MISSIONS

Deep-space explorers will likely have to bring most of their food with them on the mission. So, their diets will be limited by the weight and volume that can be carried onboard. We know how important a healthy diet is for the cardiovascular system. Therefore, we must make sure that the most optimal food products will be brought aboard, and/or that space explorers will have the technology to grow their own crops during long missions.

PSYCHOLOGICAL STRESS OF DEEP-SPACE TRAVEL

Another concern of deep-space missions is the psychological stress that explorers will have to face, for instance from being far from family and friends, being confined in a small space, and the absence of days and nights as we have on Earth. Stress can become worse if crew members do not get enough sleep. Research on Earth is showing a connection between psychological stress and reduced cardiovascular health. Therefore, on deep-space missions, psychological stress may be one more risk factor that we should try to manage as much as we can.

WHAT RESEARCH CAN TEACH US

While we know all these factors can have negative effects on the cardiovascular system, we do not know the *exact* risks for cardiovascular disease in deep-space explorers. We do not always know exactly how each of these factors alters the heart and blood vessels. And we must still do more research to find ways to reduce the risks and make deep-space missions safer, such as through dietary changes or medications. To answer some of the questions we have described, research is being done on people aboard the ISS. Some scientists can also send living cells or small animals to the ISS for research purposes.

Since only a few people have traveled to the moon, we must rely on research performed here on Earth to determine the health risks of space travel. For instance, to simulate the effects of microgravity, research volunteers are asked to remain in bed for several days to weeks, with their heads slightly tilted down. These studies are safe and respectful of human rights and allow us to examine what happens when fluids shift to the head and chest, similar to microgravity.

Because the doses of GCR aboard the ISS are lower than what deep-space explorers will encounter, we must simulate GCR-like radiation on Earth to test its effects. Luckily, the technologies for such research are now available [1], and studies are being done in which small animals are exposed to simulated GCR while under the constant care of scientists and veterinary doctors. These studies have shown only small changes in the structure and function of the heart and the main arteries [2, 3]. However, we must keep in mind that the human body functions differently from the body of a small animal. Therefore, we must be careful when we make predictions about human health based on the results of animal studies.

Lastly, there is an exciting new development called human **organs-on-chip**, which uses human cells to grow mini-organs that are kept alive in the laboratory for research. The use of human organs-on-chip allows researchers to study the effects of the ISS environment as well the effects of simulated GCR on human organs on Earth—without using humans *or* research animals.

ORGAN-ON-CHIP

Various cell types grown on a device with simulated blood flow, so that tiny organs develop and can be tested in the lab.

METHODS FOR INTERVENTION

Research is being done to find ways that we might reduce the negative effects of space travel on the human body. For instance, crew members of the ISS are asked to exercise every day, because exercise is known to increase the health of the cardiovascular system, the muscles, and the bones [4]. Exercise reduces stress, too. In addition, researchers are testing dietary supplements and medications to protect the heart and other organs from the effects of space radiation. One strategy proposed to reduce psychological stress involves inviting artists to put their artwork on the ISS. Viewing or making art is thought to make people feel better and reduce stress.

In conclusion, we have exciting times ahead for deep-space travel. There is a lot of exciting research happening to make space travel safe for humans, but there are still many questions to be answered and discoveries to be made.

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SCIENCE MENTORS: Matteo Lorenzini and Jennifer Butler

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YOUNG REVIEWERS

EDOARDO, AGE: 8
Hi, my name is Edoardo and I really like Pokémon. I am 8 years old, I live in Monte Porzio Catone in the neighborhood of Rome and I have a very pretty little sister. I am interested in constellations, especially Sagittarius because it is my zodiac sign. I really like jumping, climbing, and running so I practice parkour.

ILYAN, AGE: 8
Hi, my name is Ilyan, I am 8 years old and I come from Borghesiana, a town close to Roma. My school is GermogliAmo. I like to play soccer, tap dance, piano, and love singing. I like gifts and surprises. My favorite animal is the gorilla. My best friends are Edoardo, Yuri, Leonardo, and Flavio.

LORYAN, AGE: 12
My name is Loryan and I am 12 years old. I live in Roma, I love football and music. I am very interested in all what concerns climate, pollution and planet Earth, and space environment.

MATTIA, AGE: 9
Hi! I am Mattia, I like skateboard, basketball, and draw comic strips. I think that scientific articles could be more interesting if they were written in cartoon bubbles. Maybe one day I will be a scientific cartoonist!

REAGAN, AGE: 10
Reagan is a ambitious 10 year old. She loves learning about space and is fascinated with NASA. She hopes to one day work at NASA. She loves to learn anything about science but also has a black belt in karate and is very disciplined and focus on achieving her goals. She lives with her mom, who is a retired Navy officer, and her chihuahua, Dax.

VITTORIA, AGE: 10

My name is Vittoria, I am 10 years old and I am in fifth grade at the GermogliAmo school. My favorite subjects are: history, geography, and science. I like to read and my favorite sagas are Fairy Oak and Harry Potter. My family is composed by me, my mom and dad, my little sister, and my dog Celeste. I like pop corn, drawing, playing chess, and attending school. I have been Young Reviewer for already 1 year and I enjoy doing it so much, reading articles is more and more interesting!

AUTHORS

ASHLEY S. NEMEC-BAKK

Ashley Nemec-Bakk received her PhD at Lakehead University in Thunder Bay, Ontario where she studied the effects of low dose radiation in the heart. In 2021 she became a postdoctoral fellow at the University of Arkansas for Medical Sciences in the United States. She has received a postdoctoral fellowship from the NASA Translational Research Institute for Space Health to test two new models of the space environment here on Earth. This research will help determine the effects of the space environment on the cardiovascular system and test a new dietary medicine to protect astronauts from the space environment.

MARJAN BOERMA

Marjan Boerma received her PhD in radiation biology from the University of Leiden, the Netherlands. In her thesis work, she used animal and cell culture models to investigate biological mechanisms of radiation-induced heart disease. Then, she moved to the United States for her postdoctoral training. She is now a professor in the department of Pharmaceutical Sciences at the University of Arkansas for Medical Sciences in the United States. Her research uses research models to understand cardiovascular effects from radiation such as in radiation therapy, radiation accidents, and space radiation. *mboerma@uams.edu

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DOES THE HEART AGE FASTER IN SPACE?

Emil Rehnberg [1,2*], ***Bjorn Baselet*** [2], ***Lorenzo Moroni*** [3], ***Sarah Baatout*** [1,2] ***and Kevin Tabury*** [2,4*]

[1] *Department of Molecular Biotechnology, Ghent University, Ghent, Belgium*

[2] *Radiobiology Unit, Nuclear Medical Applications Institute, Belgian Nuclear Research Center, Mol, Belgium*

[3] *Department of Complex Tissue Regeneration, MERLN Institute for Technology-Inspired Regenerative Medicine, Maastricht University, Maastricht, Netherlands*

[4] *College of Engineering and Computing, Biomedical Engineering Program, University of South Carolina, Columbia, SC, United States*

YOUNG REVIEWERS:

CLARA
AGE: 11

ELEANOR
AGE: 14

Living in space is not as simple as living on Earth. The environment in space is harmful for humans. Astronauts experience weightlessness and are exposed to dangerous radiation. On top of that, astronauts live in a tiny area, far from their loved ones. All our organs are harmed by these factors. The heart, for example, starts to age much quicker in space than on Earth. This means that astronauts have a higher risk of heart disease after going to space. It is therefore important that we investigate why this happens so that we can prevent it. In the past, these studies were based on experiments using animals or humans. Today, we can create mini-hearts in the lab for our experiments instead. In this article, we will explain how we make mini-hearts and how they help us understand and prevent the heart's aging in space.

SPACE AGES OUR HEARTS

Many people think it is exciting to go into space! Imagine swimming weightlessly on the International Space Station, cruising in a spaceship, or just seeing our home, planet Earth, from above. In the next few years, we will build a new space station around the moon and send the first humans to the moon since 1972. As if that was not enough, before 2040, the first human ever will set foot on Mars, and soon anyone who wants to go to space will be able to! But it is not risk free to stay in space. The deeper into space we go, the more dangerous it gets.

The heart is an important human organ. It is responsible for pumping the blood, which delivers energy to all the body's parts. Naturally, the older we become, the less efficient and weaker our hearts get, and the slower we become (Figure 1). You might have noticed this in your grandparents. In space, this phenomenon is accelerated, meaning that our hearts become weaker more quickly in space compared to on Earth. It seems that the heart ages quicker in space.

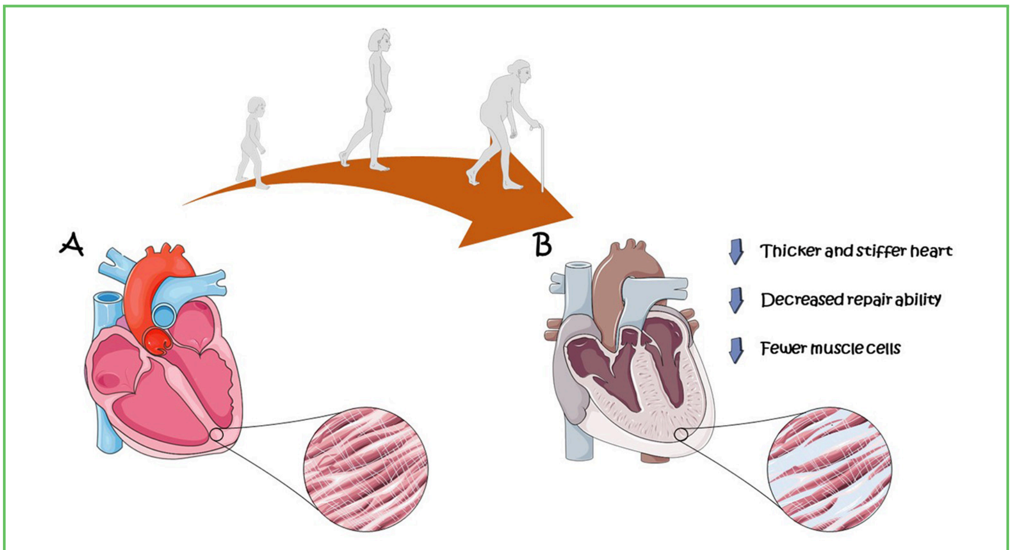

Figure 1

Figure 1

(A) A young heart compared with **(B)** an old heart. As we age, our hearts become less efficient. This is caused by several processes, such as the loss of muscle, stiffening of the heart, and a decreased ability to repair injuries. The circles show close ups of the cells of **(A)** a young human heart and **(B)** an old human heart. The red cells with stripes are heart muscle cells while the more blue cells are non-muscle cells (figure created using elements from Servier Medical Art; smart.servier.com).

RADIATION

Invisible particles or waves that transfer energy. Highly energetic radiation can cause damage to our bodies.

WHY DOES SPACE AGE THE HEART?

There are several ways that space causes the heart to age. The first and most important reason is **radiation**. Radiation is invisible to our eyes but can be very dangerous. While not all radiation is dangerous (we use radiation to connect to the internet or make phone calls, for example) radiation in space is quite harmful, making it dangerous to stay in space for even a short time. When our cells are exposed to space radiation, they become damaged—particularly their DNA. When heart cells are damaged in this way, the risk of many heart diseases increases. Because of this, astronauts exposed to space radiation suffer from more **cardiovascular diseases** [1].

CARDIOVASCULAR DISEASE

Diseases that affect the heart and/or vascular system

The second reason is weightlessness. While it might seem like a lot of fun to swim in the air or do effortless backflips, it is actually harmful to the body and organs. Being weightless means that the muscles do not need to work to support the body's weight. This causes the astronaut's muscles to slowly break down. The heart is also a muscle, so when gravity is not pulling the blood down toward the feet, the heart does not need to work as much to pump the blood around the body. This causes more blood to stay in the upper body compared to on Earth. Because of this, the heart's shape becomes rounder and more similar to a ball. Some parts of the heart also become smaller and lose muscle tone [2].

The third reason space ages the heart is the loneliness and stress. It is difficult to send help into space, so astronauts are lonely and can usually only get help from each other, which can make them stressed. On top of that, spacecrafts are usually very small, with little space to move around, which makes them very stressful environments to be in. Being stressed and lonely for a long time can cause astronauts to become less motivated, weaker, and worse at teamwork. Astronauts are carefully selected to ensure that they can handle this stressful environment as best as possible [2].

Together, these three reasons cause the heart to age quicker in space [3]. If we want to send more humans into space and explore further into the galaxy, we must know how to stop this sped-up aging. Unfortunately, we still know very little about what happens to the heart deep in space, so we need to do more research on this topic.

HOW CAN RESEARCHERS STUDY AGING IN SPACE?

One common way to study organs is to perform experiments on animals. You can, for example, test medicines on animals or study what happens to a mouse's heart when it goes into space. This does not work so well to study aging, for two main reasons. The first and most important reason is that animals' organs are different from human organs. As you can imagine, a mouse heart is not the same as a human heart. This means that much of the research done on animals does not match what happens in the human body. For example, a medicine that treats heart disease in rats may not work for humans or may even be dangerous. Secondly, animal experiments can sometimes cause the animals to suffer.

ORGANOID

A mini organ grown in the lab, often created from stem cells.

To fix this, researchers can now create miniature human organs in a lab. We call these mini-organs **organoids**. Organoids represent real human organs better than animal organs do. Because of that, we can be more certain that a medicine that works on an organoid also works for humans. Researchers can also make organoids personalized. Since all humans are different, each person might react differently to a certain medication or environment. With personalized organoids, we can customize medication specifically for you, or tell you exactly how much your heart will age in space [4].

HOW TO BUILD AN ORGANOID

To build an organoid, researchers start with the smallest building blocks of the body, cells. When building a mini-heart, either heart cells or **stem cells** can be used. Stem cells are special cells that can turn into the different cell types of the body, so researchers can "program" them to become all the cells necessary to build a mini-heart. By instructing the stem cells to become heart cells, researchers can eventually form a mini-heart that beats. These beating mini-hearts are also called heart organoids [5].

STEM CELLS

Cells that have the capability to develop into several different cell types.

The process of stem cells turning into other cells, such as brain cells or heart cells, is called **differentiation**. Differentiation is done in the lab by giving the stem cells specific nutrients and molecules. The specific combination they are given determines what type of cells the stem cells will turn into. So, researchers follow a very precise recipe of nutrients and molecules to form heart cells and mini-hearts [4].

DIFFERENTIATION

The process of a cell becoming more specialized. For example a stem cell turning into a heart cell.

First, researchers put stem cells together into a tiny ball. This ball is just a few hair strands wide but contains a few thousand stem cells. After the stem cell ball has formed, the very precise recipe of nutrients and molecules is followed. After a few days, hollow pockets form inside the ball and, at the same time, stem cells slowly turn into heart cells, which eventually start to beat. Within 1–2 weeks, a hollow beating ball of heart cells has formed. This is the mini-heart, and it is about 1–3 mm wide (Figure 2) [5].

Mini-hearts can also be created using 3D printing. Functional heart cells can be mixed into a liquid that can turn into a gel. The combination of cells and this liquid is called a **bioink**. By combining different cells with different liquids, different bioinks are created. Bioinks are then 3D printed in a specific shape and order to build a mini-heart [6].

BIOINK

The combination of cells and a 3D printable liquid material that can solidify. This material needs to be able to support the growth and survival of the cells.

The mini-hearts can also be placed into a training device that functions like a mini-gym. When mini-hearts are first formed, they are very weak. By putting pressure on the cells when they beat and giving them tiny electric shocks, the mini-heart can be trained to become stronger, just like our real hearts when we exercise. This is important if researchers want the mini-heart to mimic the human heart [7].

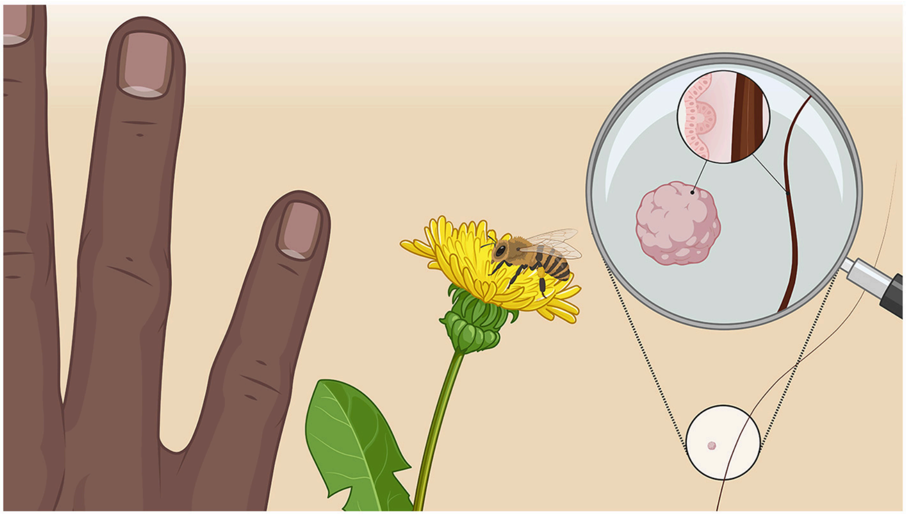

Figure 2

Figure 2

The size of a mini-heart compared to a hand, bee, and hair strand. The lower right circle shows the actual size of a mini-heart next to a human hair. In the magnification, you can see the mini-heart next to the human hair. The even closer magnification, above the mini-heart, shows the size of the cells of the mini-heart compared to the width of a human hair (figure created using Biorender; biorender.com).

HOW CAN MINI-HEARTS MAKE SPACE TRAVEL SAFER?

By sending mini-hearts into space, researchers can study how the space environment affects human hearts and why the heart ages quicker in space. They can study how and why the ability of the heart to beat changes in space. They can also simulate space conditions (weightlessness, radiation, and stress) using machines and drugs on Earth. Space missions are very expensive and not very common, so performing an experiment on Earth before performing it in space can give researchers a lot of additional information.

Today, there is no specific way to prevent the heart's quicker aging in space. With the help of organoids, mini-hearts in this case, researchers can study why our hearts age more quickly in space and how this aging might be prevented. With personalized mini-hearts, researchers will also be able to determine how much *each person's* heart will age in space and how to best treat each individual. This research will help to make space travel safer for everyone in the future!

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YOUNG REVIEWERS

CLARA, AGE: 11
Hello! My name is Clara and I live in Wales. I enjoy playing Minecraft and Animal Crossing. I also like reading. My favorite books are the Dragon Realm and Wizards of Once series. I love playing the violin, piano and two different recorders.

ELEANOR, AGE: 14

Eleanor is an avid reader, artist, violinist, guitarist, and soccer player.

AUTHORS

EMIL REHNBERG

Emil Rehnberg earned an M.Sc. in engineering nanoscience at the Faculty of Engineering, Lund University, Sweden. In 2018, he was nominated to go to the University of California, San Diego, where he studied techniques to manufacture microchips and engineering with living organisms. After graduating in 2020, Emil worked at the Lung Bioengineering and Regeneration Lab at Lund University, where he worked on the development of an organ-on-a-chip and other human 3D lung models. Currently, Emil works as a Ph.D. student on a joint collaborative effort between the Belgian Nuclear Research Center, Ghent University, and Maastricht University, developing 3D heart models to investigate heart aging in space. *emil.rehnberg@sckcen.be

BJORN BASELET

Bjorn Baselet obtained his Ph.D. at Université Catholique de Louvain and SCK CEN (Belgium) in the field of radiation-induced vascular disease. Currently, he is the leading space scientist at the Radiobiology Unit (SCK CEN), where he is involved in various space projects. His aim is to unravel the molecular mechanisms behind disease caused by space conditions, such as cosmic radiation and microgravity, on human health. He performs various types of space biology experiments, such as ground-based experiments using models for microgravity, cosmic radiation, and psychological stress, as well as space flight experiments on the International Space Station.

LORENZO MORONI

Lorenzo Moroni received his Ph.D. in 2006 from Twente University, working on materials for growing and regenerating bone and cartilage tissue. In 2014, he joined Maastricht University as a founding member of the MERLN Institute for Technology-Inspired Regenerative Medicine. In 2016, he became a full professor, working on design and manufacturing of materials and devices that mimic biology to help regenerate and heal diseased tissue and has now been chair of the Complex Tissue Regeneration Department since 2019 and director of MERLN since 2022. His research group aims at developing biology mimicking technologies that can control cell's identity and role in the body. His group works on applications for many different tissues, such as muscle, vascular and nerves.

SARAH BAATOUT

Sarah Baatout is deputy director of the Nuclear Medicine Applications Institute at the Belgian Nuclear Research Centre, Mol, Belgium. She is also a guest professor at UGent and KULeuven, Belgium. For more than 20 years, she has investigated the impact of radiation on health, through the development of better radiotherapy treatments for cancer patients, and the discovery of different molecules and measurements that help detect diseases for personalized medicine. Sarah is the head

of the Belgian delegation at the United Nations Scientific Committee on the Effects of Atomic Radiation, secretary-treasurer of the European Radiation Research Society, and chair of the Belgian Hadrontherapy Consortium.

KEVIN TABURY

Kevin Tabury obtained a M.Sc. in biochemical engineering at Katholieke Universiteit Leuven, Belgium, while working in the radiobiology unit of the Belgian Nuclear Research Center (since 2009). He then obtained a Ph.D. in biomedical engineering from the University of South Carolina, USA. Kevin is currently head of the Radiobiology Unit of the Belgian Nuclear Research Center, where he is working on several space- and hadron therapy-related projects. He leads the development of organ-on-chip with a focus on the cardiovascular system as well as cancer. *kevin.tabury@sckcen.be

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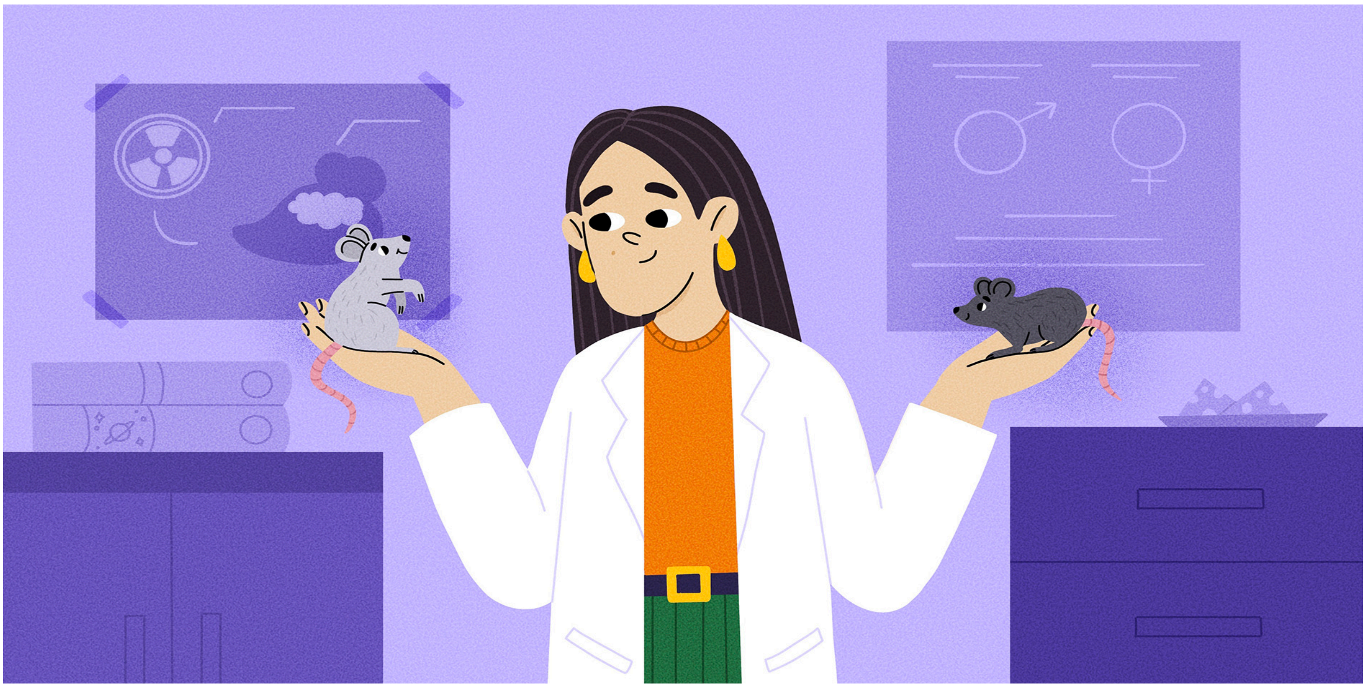

SPACE RADIATION MAY AFFECT MALE AND FEMALE BRAINS DIFFERENTLY

Robert G. Hinshaw * ***and Cynthia A. Lemere***

Brigham & Women's Hospital and Harvard Medical School, Boston, MA, United States

YOUNG REVIEWERS:

ABYAN
AGE: 13

REAGAN
AGE: 10

Radiation in outer space can be dangerous for astronauts who leave the protection of Earth's magnetic field. On long space missions to the moon and Mars, even small amounts of radiation will add up... but how will this affect the brain? Alzheimer's disease is a common brain disease in older people that damages brain cells and affects memory. Because both Alzheimer's disease and radiation can change the brain, we want to know if astronauts are more likely to get Alzheimer's disease when they get older. That way, we can work to better protect astronauts traveling into deep space. In this article, we will tell you about one of the first long-term studies in mice, describing how radiation and Alzheimer's disease affect each other. What is interesting is that the effect seems different in male mice and female mice. While female mice had more Alzheimer's brain disease than male mice in general, the brains of male mice were hurt more by radiation!

WHAT IS SPACE RADIATION AND WHY DO WE STUDY IT?

RADIATION

Energy carried through space by particles like light and atoms

Radiation is a form of energy carried by particles through space. There are many kinds of radiation. The light you can see and the signals that make Wi-Fi work are both types of radiation. Different kinds of radiation have different energies, and types with very high energy can be dangerous because they can stop the cells of your body from working properly [1]. Outer space is filled with exotic kinds of very-high-energy radiation that we do not have here on Earth [2]. Astronauts very close to earth, like on the International Space Station, are protected from most of this radiation by the Earth's magnetic field. But on a long trip to the moon or to Mars, astronauts will be exposed to much more space radiation than anyone ever has experienced before. Space radiation is especially good at damaging cells, so we want to learn more about it to help keep astronauts safe.

WHAT IS ALZHEIMER'S DISEASE AND WHY DOES IT MATTER FOR ASTRONAUTS?

ALZHEIMER'S DISEASE

A brain disease that causes problems with memory

Alzheimer's disease is a brain disease that kills nerve cells in the brain and damages memory, and it is very common in older people (Figure 1). In fact, it is so common that it is likely some astronauts will develop it when they get older. We do not know if the radiation from space travel will make Alzheimer's worse, but we think it is possible. The kinds of damage that radiation does to cells can last for a long time, and similar damage can also be found in the brains of people with Alzheimer's disease. Because of this link, we suspect that space radiation might make brains more likely to develop Alzheimer's disease later in life [3]. It might also make the disease worse or make it develop faster. In our experiments, we studied a special type of mouse that gets Alzheimer's disease as it ages so that we could learn more about how the Alzheimer's disease process is affected by radiation.

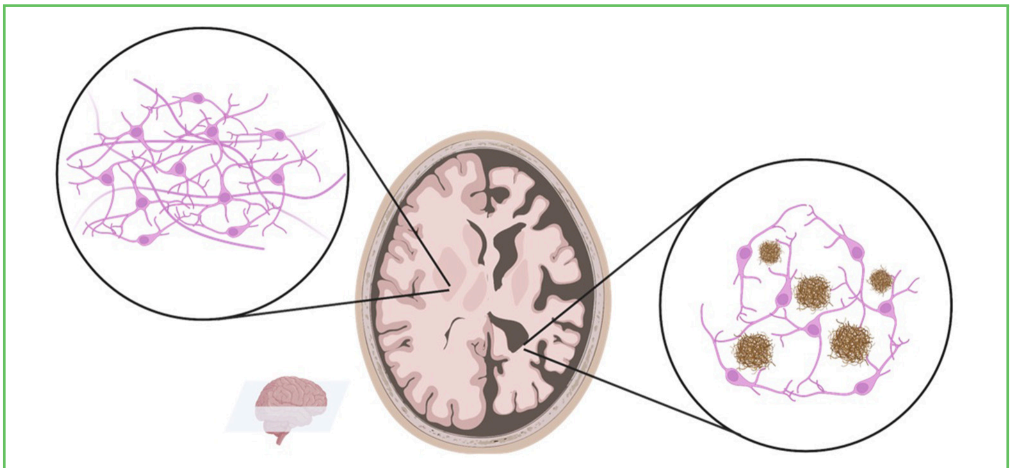

Figure 1

Figure 1

Here is an image of the brain, sliced as shown in the lower left. On the **left** side, you can see a healthy brain with no evidence of bad clumps of protein between the nerve cells. On the **right**, you can see a brain with Alzheimer's disease. Notice the Alzheimer's brain is smaller, with fewer nerve cells and bad clumps of protein between them (Created with Biorender.com).

HOW DID WE DO THIS EXPERIMENT?

To study the effects of radiation without putting people in danger, we tested male and female mice that were exposed to kinds of radiation similar to the radiation in space. This radiation is made in a **particle accelerator**, which is a large machine that pushes individual atoms with magnets until they are traveling at high speeds and have a large amount of energy. Remember that radiation is just energy carried by small particles like atoms. We exposed mice to this particle accelerator radiation to approximate the radiation exposure an astronaut would get over multiple years in outer space. We did this when the mice were young and then waited for them to get old. It only takes mice a little over a year to get very old, which makes studying aging easier in mice than in humans. Mice do not normally get Alzheimer's disease, so we used a special strain of mice **genetically engineered** to get the disease. When the mice were old, we studied their behavior with multiple tests, like solving mazes, and we also looked at their brains for signs of Alzheimer's disease. As a comparison, we also looked at the behavior and brains of mice that were *not* exposed to radiation. Figure 2 diagrams the structure of the experiment.

PARTICLE ACCELERATOR

A very specialized machine that uses electricity and magnets to shoot small particles like atoms at very high speeds

GENETICALLY ENGINEERED

Artificial changes were made to the DNA

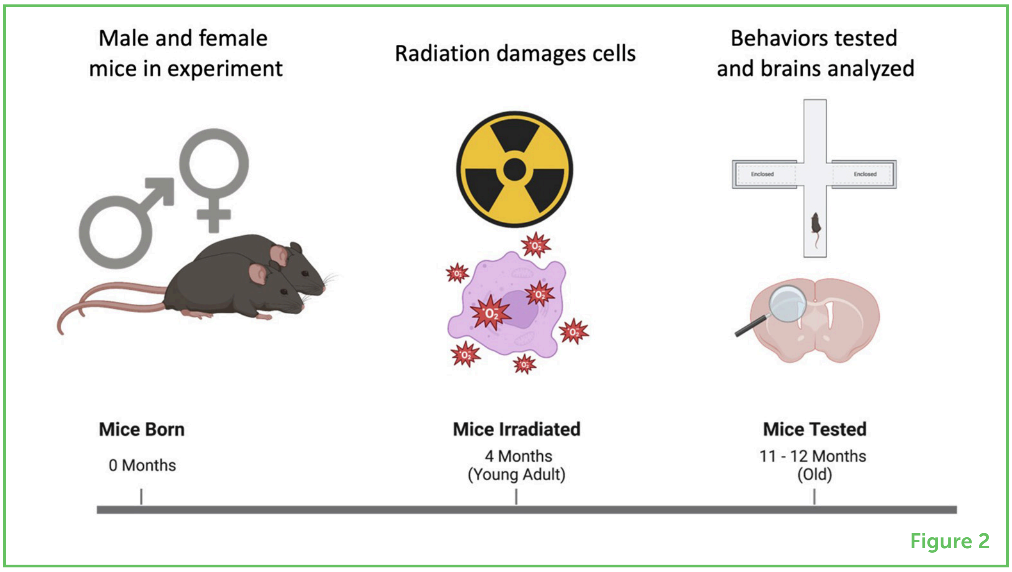

Figure 2

Experiment timeline. Male and female mice were exposed to radiation (irradiated) at 4 months old. This damaged their cells, including their brain cells. After the mice aged to 11–12 months old, we tested their behaviors and analyzed their brains for Alzheimer's disease. We compared these results to mice that were not exposed to radiation (Created with Biorender.com).

We measured the amount of Alzheimer's disease by looking at thin slices of the mouse brains under a microscope. The thin slices made it easier to detect the clumping of a particular kind of protein that builds up in Alzheimer's disease. Proteins, in addition to fats and sugars, are a very common type of molecule made by all cells. However, in Alzheimer's disease, very specific kinds of protein that brain cells make tend to clump together outside of the cells. This clumping can interrupt the normal function of cells and eventually cause them to die. Measuring the amount of bad clumps of protein can tell us how far the disease has progressed in the mice.

HOW DOES SPACE RADIATION AFFECT ALZHEIMER'S DISEASE?

When we looked at the brains of these mice with Alzheimer's disease, we noticed a couple different patterns. First, we observed that the female mice had worse Alzheimer's disease than the male mice, regardless of whether they were exposed to radiation. Second, we observed that the radiation *did* make Alzheimer's disease worse in some mice but not in others. It turns out that radiation made the disease worse in male mice but not in female mice (Figure 3). Even though the female mice had worse Alzheimer's disease, they did not appear to get worse with radiation like the male mice did. We do not know why this difference between males and females happens, but we are excited to keep doing our research to find out.

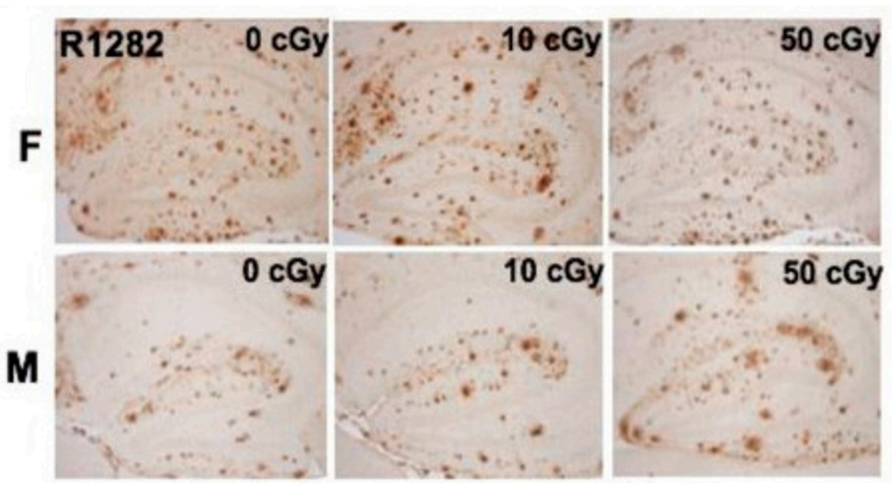

Figure 3

Figure 3

We examined thin sections of mouse brains and saw clumps of protein like those found in the brains of people with Alzheimer's disease. R1282 is the name of the molecule we used to detect these proteins. The top row of images are from female (F) mice, and the bottom images are from male (M) mice. The leftmost images are from mice that received no radiation (0 Centigray, cGy), and dose increases to the right. You can see that higher dose corresponded with more clumps in male but not female mice (Figure from original publication).

HOW DOES SPACE RADIATION CHANGE MOUSE BEHAVIOR?

The clumping of protein is one part of Alzheimer's disease, but what we really care about is whether the memory and other behaviors of the mice got worse after radiation. We tested the mice on 10 different behaviors, including various kinds of memory. We saw changes in mice exposed to radiation. In general, the behaviors of male mice were more likely to be affected by radiation exposure than those of female mice. In particular, radiation appeared to make the male mice move around less and do worse in tests of their memory. This matches with the observation that the radiation made Alzheimer's disease worse in the male mice brains but not in the female mice brains. The good news is that these changes were small, and in many tests, we did not see any difference between radiation-exposed mice and normal mice.

SUMMARY

Space radiation can threaten the health of astronauts traveling in outer space. We want to understand if this radiation could worsen Alzheimer's disease later in life. To test this, we exposed mice to radiation when they were young and looked at their behavior and brains much later, when they were old. The long-term changes caused by radiation were small but still observable. To begin with, female mice had worse Alzheimer's disease than male mice regardless of radiation. We saw that radiation worsened Alzheimer's disease in the brains of only the male mice and not in the female mice. We also saw that the radiation changed the behaviors of the male mice more than it did to the female mice. We still do not know how space radiation will affect humans, but this experiment with mice can give us clues. We can now guess that space radiation could worsen Alzheimer's disease as astronauts get older. We also suspect that these changes might vary greatly from person to person, depending on things like whether they are male or female. As astronauts return to the moon and then venture out toward Mars, scientists and doctors will have to watch their health carefully, even after they get back to Earth. Space is a dangerous place! In addition to radiation, altered gravity levels, confined spaces, high carbon dioxide levels, and poor sleep all add stress to the brain during spaceflight. But by studying and understanding the risks of traveling in space, we can help make it safer for people to explore.

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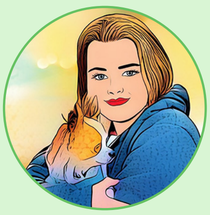
YOUNG REVIEWERS

ABYAN, AGE: 13

Hi, I am Abyan! I like Science, specifically space related Science, and Physics! I also like Mathematics and English. I would say that I am an independent person who loves new challenges. An example would be that I just recently started playing competitive tennis. I have a pet cat named Astro and I love spending time with him! In my free time, I play and interact with my friends and read about new space discoveries.



REAGAN, AGE: 10

I love science, astronomy, volleyball, swimming, and taekwondo. I am learning to play the violin. This past summer, I had fun at space camp learning a computer program to send the Mars Rover to the moon. I want to be an officer in the U.S. Space Force and be an astronaut when I grow up.

AUTHORS

ROBERT G. HINSHAW

Dr. Robert Hinshaw, Ph.D., is 30 years old and a scientist at NASA Ames Research Center in California, working to improve biology research in space. Before that, he trained as a graduate student under Professor Cynthia Lemere at the Brigham & Women's hospital in Boston, Massachusetts, where together they studied the effects of radiation on Alzheimer's disease. He graduated with his Ph.D. from the Massachusetts Institute of Technology in September 2022. Robert likes to spend his free time hiking and rock climbing with his friends as well as playing games online and reading science fiction. *rghinshaw@gmail.com

CYNTHIA A. LEMERE

Dr. Cynthia Lemere, Ph.D., is 65 years old and a professor of neurology at Brigham and Women's Hospital and Harvard Medical School in Boston, MA, where she has worked for 33 years—mostly to understand what causes Alzheimer's disease and how to prevent or treat it. She also works on a NASA-funded project to determine if astronauts on long-term missions to deep space will be more likely to get Alzheimer's disease later in life. She had the pleasure of mentoring Rob for his Ph.D. on this project. Cindy likes to spend her free time at the beach, kayaking, and traveling the world.

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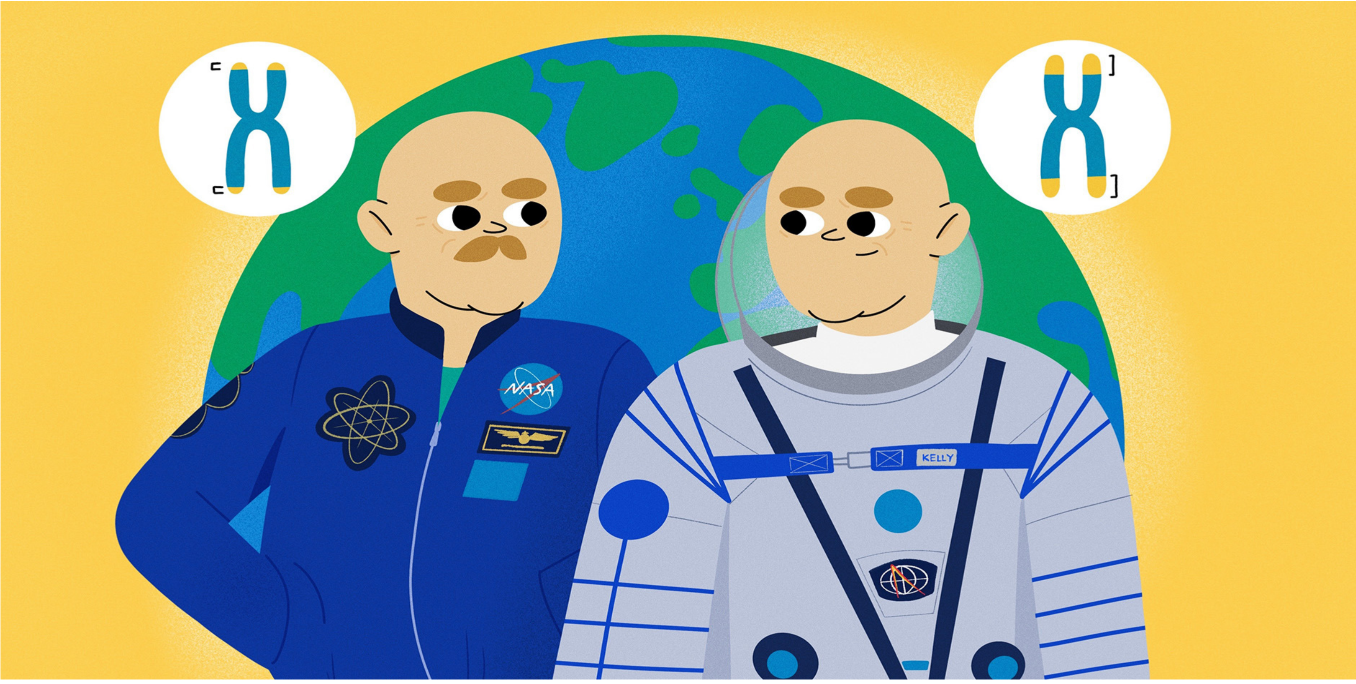


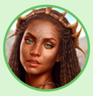
TWINS AND TELOMERES-IN SPACE!

Susan M. Bailey *

Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, CO, United States

YOUNG REVIEWERS:


BRAYDON
AGE: 13


ELLOUISE
AGE: 12


KAJ
AGE: 10

As part of the NASA Twins Study, our investigations related to telomeres and DNA damage responses (genome stability) during long-duration spaceflight have important implications for the health and performance of astronauts participating in exploration missions, as well as for long-term aging and disease risk outcomes. Together with the other Twins Study investigations, results will guide future studies and development of personalized medicine approaches for evaluating health effects for individual astronauts as we make our way back to the moon and beyond. Particularly as the number and diversity of space travelers and even space tourists increases over the coming years, identifying individual differences in response to the extreme environment, experiences and chronic exposures associated with space travel, exploration, and eventual habitation of other planets, represents a critical next step for ensuring future astronaut performance and health during, and improving disease and aging courses following, such missions. *Ad astra*!

SPACE IS HARD!

In the summer of 1969, Apollo 11 rocketed American astronauts to the Moon, and on July 20th the world stood still and watched as Neil Armstrong took those first small steps on the surface. Fast forward almost 50 years and NASA astronauts Scott Kelly and Christina Koch each spend nearly a year in space aboard the International Space Station (ISS). In 2020, and marking a new era of human space exploration, the first commercial rocket SpaceX Falcon 9, launched NASA astronauts from U.S. soil in the Crew Dragon spacecraft Endeavor to the ISS. NASA and its commercial partners are rapidly advancing innovative space technologies, and with the Artemis (twin sister of Apollo) program and astronauts, plans are to send the first woman and next man back to the moon before the end of the decade. Humankind will then be poised to take the next giant leap—pioneering human exploration of Mars.

For more than 20 years now, the ISS has supported continuous human presence in low Earth orbit (LEO). While living onboard the ISS is exciting and gives astronauts an "out-of-this-world" view and a life-changing perspective of our own home planet that few of us ever personally experience (see video: Down to Earth: The Astronaut's Perspective), life on the ISS is also extraordinarily challenging and stressful. Their "home" in space travels at a speed of over 17,000 mph, approximately 250 miles (~400 km) above the Earth, and astronauts experience microgravity, **space radiation** exposure, and 16 light/dark cycles every 24 h—all while isolated from family and friends and floating around in a confined spacecraft the size of a football field, with a handful of folks they depend on for everyday survival. If this sounds hard, it is! With NASA's first one-year mission on the ISS (2015–2016), they have been interested in better understanding how long-duration space travel can affect human health and the way that people age in space.

SPACE RADIATION

Once outside of the Earth's protective atmosphere, astronauts are exposed to higher levels of more harmful radiations, energetic particles from the sun and cosmos that damage DNA.

NASA TWINS STUDY—A FIRST FOR ASTRONAUTS

Simply by chance and good fortune, the astronaut selected for NASA's first 1-year mission, Scott Kelly, had an identical twin brother, Mark Kelly, who was also an astronaut and former Navy test pilot. This remarkable coincidence set the stage for the perfect experiment—identical twin sons of similar nature and nurture, one spending a year in space ("space twin"), while the other remained on Earth ("Earth twin"). This launched the most in-depth study of the human body's response to spaceflight ever conducted. Ten investigations from around the country were selected for what became known as the NASA Twins Study (Figure 1). The Twins Study represented many firsts for the space program, including an assortment of "genomics-based" studies [e.g., genomics (**DNA**), transcriptomics (RNA), proteomics (proteins), metabolomics

DNA

Deoxyribonucleic acid, is the hereditary material that carries genetic information or the code for life – it is what makes you, you.

(metabolites)], the first test of a vaccine (a flu vaccine) in space, as well as the first assessments of the space microbiome and a biological marker of aging—**telomeres**.

TELOMERES

Protective "caps" on the ends of chromosomes, much like the plastic aglet on the end of a shoestring, that shorten with cell division and provide an indicator of aging.

Figure 1

Figure 1

The NASA Twins Study patch showing the space- and Earth-twins holding on to a DNA molecule, which represents the genomic focus of the study—a first for astronauts.

The Twins Study sparked a great deal of global attention and renewed interest in space. One of the questions often asked of Scott was whether he would return from space younger than his brother Mark, usually in the context of the movie "Interstellar" or Einstein's "Twin Paradox" thought experiment. Although a year onboard the orbiting space station would produce an age difference of only ∼ millisecond (one thousandth of a second), the question of aging associated with long-duration spaceflight, and possible increased risk of developing age-related diseases like frailty, dementias, heart disease and cancer—is an important one, and one we aimed to address as our part of the Twins Study. Here, I highlight findings from our investigations and propose potential mechanistic roles for chronic space radiation exposure underlying changes in telomere length dynamics (changes over time) and persistent **DNA damage responses (DDRs)** associated with long-duration spaceflight.

DNA DAMAGE RESPONSE (DDR)

Complex signaling pathways in cells that detect and repair damaged DNA in order to preserve DNA integrity and maintain genome stability.

Telomeres are protective "caps" at the physical ends of our **chromosomes** that serve to shield them from damage and keep them from "fraying"—much like an aglet at the end of a shoestring (Figure 2). Functional telomeres are therefore important for maintaining genome integrity and stability. However, telomeres shorten as we age (due to normal cell division), as well as with a variety of lifestyle factors (nutritional, physical, psychological stresses) and environmental exposures (air pollution, ultraviolet, and space radiations).

CHROMOSOME

Long, tightly coiled DNA molecules in the nucleus of most living cells that carry genetic information in the form of genes.

Figure 2

Telomeres are the "end-parts" of linear chromosomes that protect them from damage and loss, as well as from fusing to other telomeres or actual broken DNA ends. Available online at: https://www.genome.gov/genetics-glossary/Telomere.

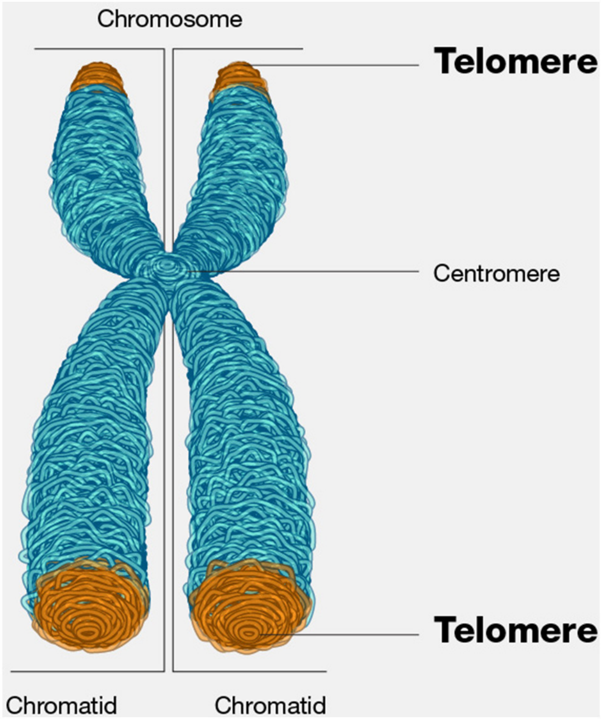


Figure 2

We hypothesized that the unique stresses and chronic exposures experienced by astronauts living in space would speed up telomere shortening during spaceflight (they would shorten more quickly in space). That is, an astronaut's genetics, exposure to the extreme conditions of space (e.g., microgravity, space radiations, altered atmospheres), as well as a many other stressors (e.g., confinement and isolation, biologically hostile and closed environment) [1], are all captured as changes in telomere length over time. To test this, we evaluated telomere length in blood samples collected from both Scott and Mark Kelly before, during, and after the one-year mission onboard the ISS [2] (Figure 3).

UNEXPECTED RESULTS!

While Earth twin's telomere lengths remained relatively stable during the study, much to our surprise space twin's telomeres were *longer* at every time point tested during spaceflight—exactly the opposite of what we thought we would see! Similar results were also observed in a separate study involving 10 unrelated astronauts on other, shorter ISS missions (∼6 months), compared to healthy age- and sex-matched subjects on Earth [3, 4]. Another unexpected result was that astronaut telomere length shortened very quickly upon return to earth, and astronauts in general had many more short telomeres *after* spaceflight than they had before. Consistent with chronic (every day, every hour) exposure to space radiation, we also observed DNA damage in the

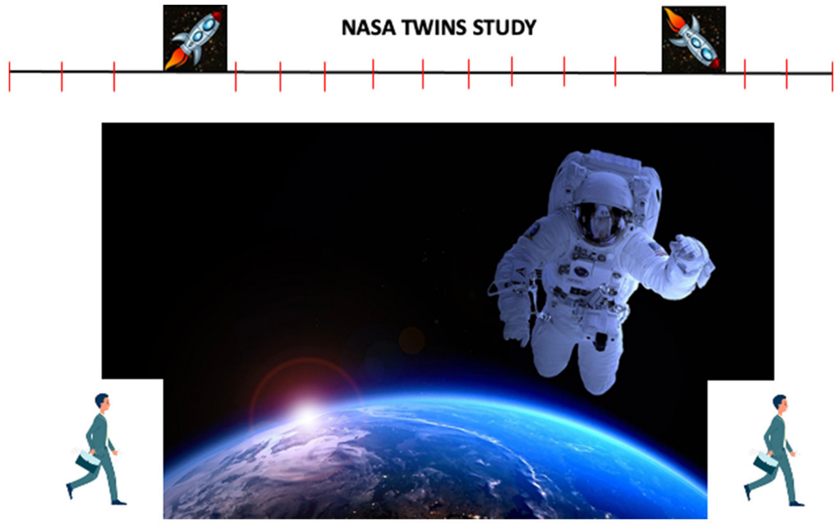


Figure 3

Figure 3

For the NASA Twins Study, blood samples were collected from "space-twin" and "Earth-twin" at various timepoints (red bars on the timeline) before, during and after the 1-year mission onboard the ISS.

form of chromosome rearrangements. Together with other findings from the Twins Study, we have important clues that will guide future studies, as well as evidence of differences in individual responses to investigate further [5].

TO THE STARS!

It is an exciting time for the space program, with NASA and its commercial partners developing and advancing innovative space technologies at a faster pace than ever before. The decade began with the dawn of a new era of human space exploration, as the first commercial rocket, SpaceX Falcon 9 launched NASA astronauts Robert Behnken and Douglas Hurley from U.S. soil in the Crew Dragon spacecraft to the ISS. We have also witnessed the first all-civilian crew to orbit Earth (for ∼3 days) as part of the SpaceX Inspiration4 mission. That crew included the youngest astronaut—a childhood cancer survivor in her early 20s. We saw William Shatner blasting off on a Blue Origin Rocket—the 90-year-old "Captain Kirk" from *Star Trek* setting a record as the oldest person to fly in space (for ∼3 min). The successful uncrewed Artemis 1 mission (late 2022) represented the first step in returning to the moon, and a crewed Artemis 2 mission that will circle the moon is scheduled for late 2024. Plans are to send humans back to the moon to stay before the end of the decade—maybe you will be going!

As the number and diversity of space travelers—and even space tourists—increases in the coming years, we will gain a better understanding of how long-duration spaceflight affects human health. It is certain that people will respond to spaceflight differently, and such knowledge is essential for informing personalized medicine strategies and ensuring future astronaut performance and health during, and improving disease and aging courses following, future exploration missions.

ACKNOWLEDGMENTS

It has been a pleasure and a privilege to be a part of these pioneering studies. The efforts and contributions of all participants and funding from NASA are gratefully acknowledged (NNX14AB02G, NNX14AH51G, and 80NSSC19K0434).

ORIGINAL SOURCE ARTICLE

Garrett-Bakelman, F. E., Darshi, M., Green, S. J., Gur, R. C., Lin, L., Macias, B. R., et al. 2019. The NASA twins study: a multidimensional analysis of a year-long human spaceflight. *Science* 364:eaau8650. doi: 10.1126/science.aau8650

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

BRAYDON, AGE: 13

Braydon is an honor middle school student and his favorite subject is math. Braydon enjoys spending time with his family and friends, serving in his church, and participating in athletics. Braydon plays soccer and basketball and runs cross country for his school's junior varsity teams.

ELLOUISE, AGE: 12

Ellouise plays volleyball, chess, and is an avid reader & writer. Conversations are also very important to her. She loves music a lot and appreciates different genres. She particularly enjoys lasagna, despite being lactose intolerant.

KAJ, AGE: 10

A playful boy who plays chess and football. He loves video games and his favorite actor is Kevin Hart. He also enjoys food quite a lot and cooks.

AUTHORS

SUSAN M. BAILEY

Susan M. Bailey, Ph.D., is a Professor of Radiation and Cancer Biology in the Department of Environmental & Radiological Health Sciences at Colorado State University in Fort Collins, Colorado. Dr. Bailey is a Fellow and Past President of the Radiation Research Society, and she serves on numerous National and International committees. As one of the investigators selected for NASA's Twins Study, her research program seeks to better understand the influence of long-duration spaceflight on human health and aging, and ultimately how such information can serve to improve healthspan for astronauts and those on Earth as well. For example, see https://www.allure.com/story/astronaut-health-problems-space-body-skin-effects. *Susan.Bailey@ColoState.EDU

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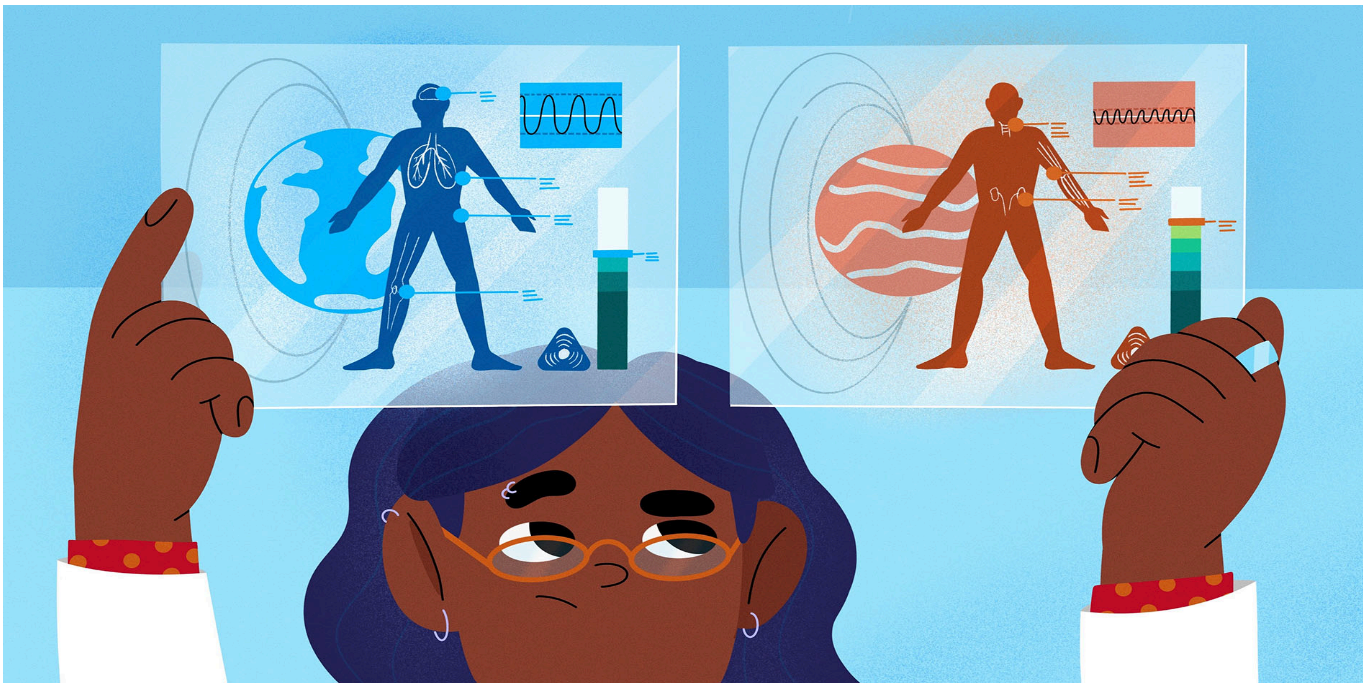
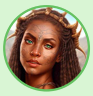


RADIATION EPIDEMIOLOGY: KEEPING SPACE TRAVELERS SAFE

Jennifer Butler[1*], Kathleen B. Miller[2] and Lawrence T. Dauer[3]

[1] *United States Army Training and Doctrine Command (TRADOC), Ft Eustis, VA, United States*
[2] *University of St. Thomas, St. Paul, MN, United States*
[3] *Memorial Sloan Kettering Cancer Center, New York, NY, United States*

YOUNG REVIEWERS:


ELLOUISE
AGE: 12


KAJ
AGE: 10


STANFORD ONLINE HIGH SCHOOL
AGES: 13–18

Did you know that millions of people are exposed to radiation on Earth as part of their jobs or during helpful medical procedures? The branch of medicine that studies the health effects of radiation exposure on large groups of people is called radiation epidemiology. Radiation also exists in space! But how do we study the ways that radiation impacts the body in space when there are so few space travelers? In this article, we will define radiation epidemiology, give some examples of studies that evaluate how radiation on Earth effects people's health, and explain how we use the information from studies on Earth to better understand the health effects of radiation in space.

Radiation epidemiology is a branch of medicine that studies the health effects of radiation exposure on large groups of people. Millions of people are exposed to radiation on Earth as part of their jobs or during certain medical procedures. Radiation also exists in space. As space travelers go on longer missions further away from Earth, they will be exposed to increasing amounts of radiation. To understand how radiation impacts the body *in space*, it is important to understand how radiation impacts the body *on Earth*. In this article, we will define radiation epidemiology, give some examples of studies that evaluate how radiation on Earth effects people's health, and tell you how the information from Earth-based studies is used to better understand the health effects of radiation in space.

WHAT IS IONIZING RADIATION?

Radiation is energy that can travel through space or a material. It can be in the form of energy waves or energized particles. We cannot feel, see, or smell radiation. Sometimes radiation can have so much energy that it can excite molecules and break their chemical bonds. When radiation breaks the chemical bonds of molecules, it is called **ionizing radiation**. Ionizing radiation can damage DNA, the molecules that contain the instructions to build our cells and bodies and to help them function properly (Figure 1). Normally, our bodies can repair broken DNA. However, sometimes the DNA cannot be repaired or is not repaired correctly. This can lead to health problems. A small amount of ionizing radiation exposure is not harmful but too much ionizing radiation exposure may lead to health effects such as cancer and changes to heart tissues.

IONIZING RADIATION

A form of energy that acts by removing electrons from atoms and molecules of materials that include air, water, and living tissue.

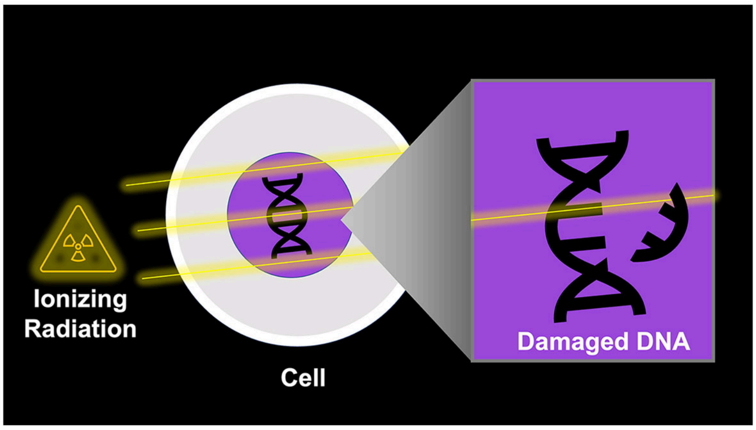


Figure 1

Figure 1

Ionizing radiation can damage DNA within cells. The body can repair damaged DNA. However, if there is too much damage or if the damage is not repaired correctly, health effects like cancer can result.

Ionizing radiation is present on Earth and in space. On Earth, people can be exposed to ionizing radiation for their jobs (nuclear energy workers or some medical technicians) or during medical procedures (X-rays, CT scans, or some cancer treatments). There is also ionizing radiation in space. **Space radiation** comes from the sun and from distant galaxies. Various types of shields made of many different materials can be used on spacecraft to block some of the ionizing radiation from the sun, for example, but not all types of space radiation can be blocked by a shield. For example, radiation coming from

SPACE RADIATION

The spread of energy through space or matter in the form of waves or particles.

distant galaxies, called **galactic cosmic rays**, cannot be blocked by a shield.

GALACTIC COSMIC RAYS

A type of ionizing radiation found in space that comes from distant galaxies. They cannot be blocked by a shield.

WHAT DO RADIATION EPIDEMIOLOGISTS STUDY?

Epidemiology is a branch of medicine that studies patterns of diseases in groups of people. Radiation epidemiology examines the health of groups of people who have been exposed to ionizing radiation. It also examines actions that can be taken to help reduce risks of getting injured or sick from radiation. Understanding the health impacts of ionizing radiation is important so that policy makers can create laws and regulations that set limits of ionizing radiation exposure, to keep workers and the public safe.

Through their research, radiation epidemiologists have learned about the health risks of large doses of ionizing radiation that happen all at once. These studies have shown that large amounts of ionizing radiation can cause cancer and other tissue damage. However, researchers still have some questions. For example, what are the long-term impacts of radiation exposure, both on Earth and in space? What are the impacts of a little bit of radiation exposure over a long period of time? Does ionizing radiation exposure increase the risk of heart or brain disease? Does exposure to ionizing radiation affect a person's unborn children or grandchildren? Radiation epidemiologists are still working hard to answer these questions.

WHAT MAKES A HIGH-QUALITY RADIATION EPIDEMIOLOGY RESEARCH STUDY?

There are several types of epidemiology studies. To study radiation effects on the human body, **cohort studies** are generally the best. A cohort study starts with a group of people who share some things in common, such as their occupation or where they live, and follows them for the rest of their lives. These studies measure the types of diseases or cancers that develop in the group over time, and determine which diseases are from ionizing radiation exposure. High-quality radiation epidemiology research includes many components such as: (1) having good measurements of the amount of radiation each individual received; (2) including as many relevant people in the research study as possible; (3) working to reduce any biases, or unfair judgments that may not be accurate; (4) minimizing other factors that may have caused the disease, such as smoking; and (5) following the people in the study for as long as possible, preferably over their lifespan [1].

COHORT STUDY

A study that follows a group of people over time. The people in the group share something in common such as their occupation or where they live.

EXAMPLE OF EPIDEMIOLOGY RESEARCH ON RADIATION

One example of epidemiological research on radiation is the Life Span Study (LSS) [2]. The LSS investigates life-long health effects of Japanese atomic bomb survivors, to understand long-term radiation effects, including death and cancer. Since 1950, 94,000 atomic bomb survivors and 27,000 unexposed individuals have been followed in a cohort study. A periodic check of people who have died from cancer, which is called a **mortality rate**, and those who have been diagnosed with cancers, called an **incidence rate**, is conducted to continuously update the data. The results of this study suggest that individuals who were exposed to the ionizing radiation have a greater risk for developing some cancers and other deteriorating diseases. There have also been studies on their children and grandchildren, and there is currently no evidence of radiation effects on that are passed down through the genes. This cohort of individuals will continue to be evaluated throughout their lives.

MORTALITY RATE

The measure of the frequency of death in a defined population during a specified timeframe.

INCIDENCE RATE

The occurrence, rate, or frequency of a disease.

Another large-scale study that examines the health effects of ionizing radiation is the Million Person Study (MPS) [3]. The MPS includes about 30 cohorts of American workers and Veterans from the 20th century who were exposed to radiation through a variety of environments and jobs. By including one million or more people, researchers can more accurately assess risks of radiation exposure, to keep workers and veterans safe.

WHY IS RADIATION EPIDEMIOLOGY IMPORTANT FOR SPACE TRAVELERS?

People who have been to space received some ionizing radiation exposure. It is difficult to measure the health effects of space radiation. Most people who have traveled in space have not gone very far away from the Earth and have been shielded from radiation by the Earth's **magnetosphere**. Therefore, they have been exposed to only small amounts of space radiation. In addition, there are many factors in space that can be hard on the body, including changes in the gravitational. Because of these factors, researchers must study many more people to understand the effects of ionizing space radiation on human health. That is where studies on Earth come in.

MAGNETOSPHERE

A magnetic field around Earth that protects against ionizing radiation.

Eventually humans want to travel to Mars and beyond. Longer missions further out into space will expose space travelers to greater amounts of ionizing radiation (Figure 2). These people will be outside of the protection of Earth's magnetosphere and will be exposed to more galactic cosmic rays, which cannot be blocked with a shield. Therefore, planning these missions in ways that will keep space travelers safe—both during and after their missions—will require understanding the risks of ionizing radiation on the human body. Even though radiation in space is different than radiation on Earth, agencies interested in radiation studies, such as the National Aeronautics and Space Administration (NASA), periodically review the effects of ionizing radiation on human health to help them create their radiation policies. Someday, after many people have traveled in space, there may be a branch of radiation epidemiology that specifically studies space radiation cohorts. But for now, researchers use data from both Earth and space to understand potential risks and health consequences of space radiation exposure.

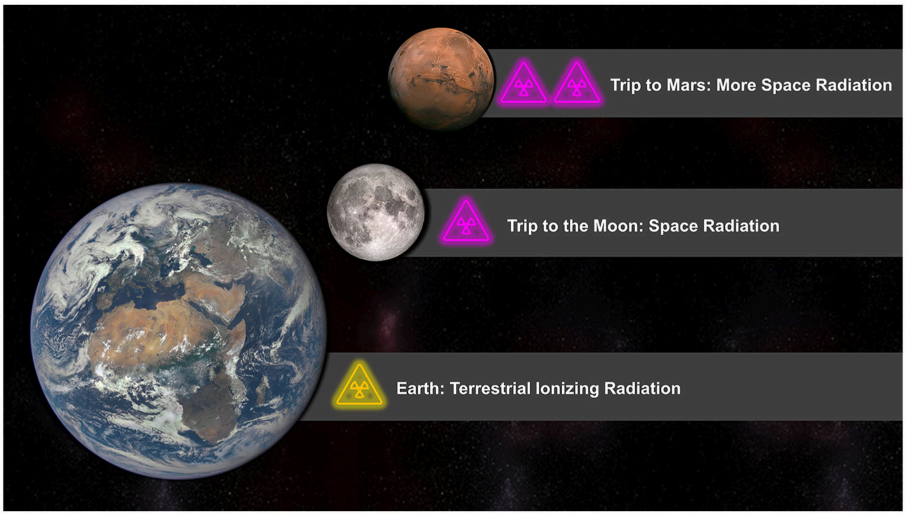


Figure 2

Figure 2

Ionizing radiation exists both on Earth and in space. A long trip to Mars will expose space travelers to more space radiation than will a trip to the Moon. This is because of the longer time spent in space and the greater exposure to galactic cosmic rays, which cannot be blocked by a shield.

CONCLUSION

Radiation epidemiology is the study of how radiation exposure impacts human health. Exposure to ionizing radiation, which is radiation with enough energy to break the chemical bonds of molecules, can occur from a person's occupation, from the environment, from certain helpful medical procedures, and from space travel. Researchers are working to understand the health effects of exposure to ionizing radiation, and they know that large doses of ionizing radiation can increase the risk of developing cancer. However, the consequences of low doses are still being studied. As space travelers go further into space for longer missions, understanding the impact of ionizing radiation on human health is critical, so that scientists and policy makers can ensure safe space travel to Mars and beyond.

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YOUNG REVIEWERS

ELLOUISE, AGE: 12
She plays volleyball, chess, and is an avid reader & writer. Conversations are also very important to her. She loves music a lot and appreciates different genres. She particularly enjoys lasagna, despite being lactose intolerant.

KAJ, AGE: 10

A black playful boy who plays chess and football. He loves video games and his favorite actor is Kevin Hart. He also enjoys food quite a lot and cooks.

STANFORD ONLINE HIGH SCHOOL, AGES: 13–18

The Stanford Online High School Astrobiology class is a collection of young citizen scientists all over the world. Our Avatar is a picture of our school mascot (the pixel) on one of the high altitude balloons that we launched.

AUTHORS

JENNIFER BUTLER

Dr. Jennifer Butler is a clinical staff specialist in the Surgeon's Office for the U.S. Army Training and Doctrine Command (Ft. Eustis, VA, USA). She is a former research scientist and member of the NASA Langley Research Center Multi-Model Ensemble Risk Assessment (MERA) team within the Space Radiation Group, where she is working on a radiobiology project to model combined spaceflight risks. She earned her doctorate in public health, with a specialization in epidemiology, from Capella University in Minneapolis, MN. *jennifer.l.butler12.civ@army.mil

KATHLEEN B. MILLER

Dr. Kathleen B. Miller is an assistant professor at the University of St. Thomas in St. Paul, MN. She was formerly a research scientist and member of the Multi-Model Ensemble Risk Assessment project at NASA Langley Research Center. Her research aims to assess long-term health outcomes from space radiation exposure. Dr. Miller earned her Ph.D. in kinesiology with a minor in neuroscience from the University of Wisconsin-Madison.

LAWRENCE T. DAUER

Dr. Lawrence T. Dauer is an attending physicist specializing in radiation protection at Memorial Sloan Kettering Cancer Center in the Departments of Medical Physics and Radiology. He is a council and former board member of the National Council of Radiation Protection, served as a member of the International Commission on Radiological Protection Committee 3, Protection in Medicine, and serves the National Council of Radiological Protection as the Scientific Director for the Million Person Study.

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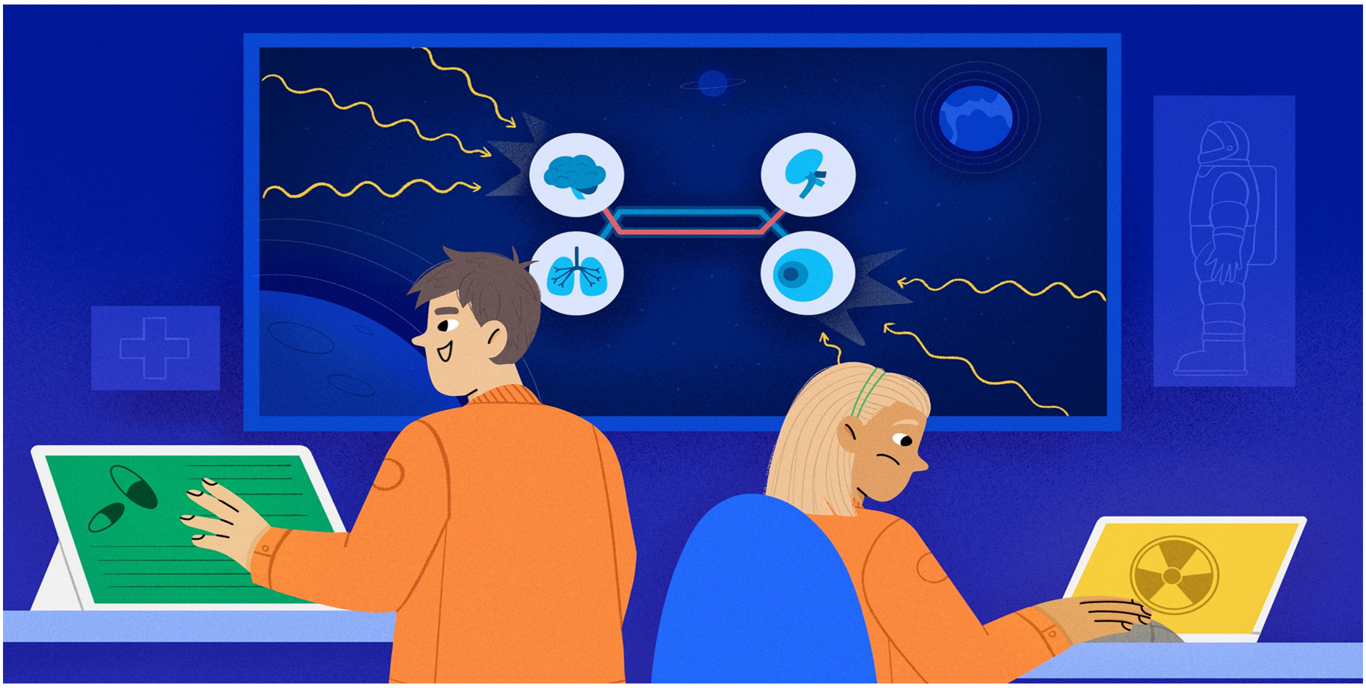

NASA'S GALACTIC COSMIC RAY SIMULATOR - STUDYING THE EFFECTS OF SPACE RADIATION ON EARTH

Lisa Simonsen [1*] ***and Tony Slaba*** [2]

[1] *NASA Headquarters, Washington, DC, United States*
[2] *NASA Langley Research Center, Hampton, VA, United States*

YOUNG REVIEWERS:

CLARA, MADELEINE, AND ORLAITH
AGES: 11–12

JIARUI
AGE: 15

Earth's atmosphere and natural magnetic field do a good job of protecting us from space radiation. Space radiation is different from radiation on Earth, which mostly comes from sources found in rocks and soil or from medical procedures like X-rays. Space radiation comes from particles ejected from the Sun, or from the explosions of dying stars (called supernovae) outside our solar system. These particles have been stripped of their electrons as they are accelerated in space to almost the speed of light. One of NASA's biggest challenges is protecting astronauts from these high-energy particles, called galactic cosmic rays (GCRs), because they can cause cancer and other diseases. To understand the biological damage caused by GCRs and to develop ways to protect astronauts, NASA has built a galactic cosmic ray simulator on Earth.

WHAT IS GALACTIC COSMIC RADIATION?

Galactic cosmic rays (GCRs) are the main radiation health hazard for humans traveling on long missions through space. GCRs come from outside our solar system and are likely formed by supernovae—major explosions that happen when a star reaches the end of its life. While radiation sources on Earth generally include things like **gamma radiation** and X-rays (like the ones you get at the doctor or dentist), GCRs consist of the nuclei of the elements in the periodic table, including hydrogen through uranium. When all of an atom's electrons have been stripped off, they are called **fully ionized particles**. GCRs move extremely fast—some of the particles approach the speed of light. Space radiation is called mixed-field radiation, which means it contains a variety of particles, all moving at different speeds. These energetic particles come from all directions in space, and they are much more damaging to living things compared to the types of radiation found on Earth (Figure 1). Understanding this difference is fundamental to estimating health risks faced by our astronauts [1].

Hydrogen alone accounts for ~87% of the GCR particles; helium accounts for ~12%, and all particles heavier than helium (called **heavy ions**) account for the remaining 1% [2]. Although there are far fewer heavy ions compared to hydrogen and helium, they are very damaging to living things, and estimating the health risk they present is challenging. There is a broad range of energies associated with each of the particles found in GCRs. For lower-energy GCRs, a few centimeters of living tissue or spacecraft shielding can fully stop the particles. For higher-energy GCRs, many meters of shielding still cannot fully stop the particles—these particles are moving at nearly the speed of light! Scientists are focused on testing radiation damage across this entire energy range.

To make things even more complex, GCRs can be changed as they interact with spacecraft shielding and human tissues. These interactions can slow down GCR particles and cause the production of new particles, which are referred to as **secondary radiation**. The secondary radiation includes atomic particles such as neutrons, which can penetrate further into living things and cause even more damage than the incoming GCR. The radiation environment encountered by astronauts inside their spacecraft is therefore a combination of primary GCR particles that penetrate through shielding and secondary radiation produced by the interactions of GCR with matter.

HOW MUCH RADIATION EXPOSURE DOES AN ASTRONAUT RECEIVE?

An astronaut's daily exposure to GCRs not only depends on the amount of shielding provided by their spacecraft, but also the length

GALACTIC COSMIC RAYS

High energy particles, including protons and heavy ions, that move through space at nearly the speed of light.

GAMMA RADIATION

A high energy form of electromagnetic radiation with a short wavelength arising from the radioactive decay of atomic nuclei.

FULLY IONIZED PARTICLES

Atoms that have been stripped of all their electrons.

HEAVY IONS

Nuclei of the elements with charge number >3 such as oxygen, carbon, or iron that are positively charged because some or all (fully ionized) of their planetary electrons have been stripped.

SECONDARY RADIATION

Radiation, including neutrons, produced by interaction between the primary space radiation and matter such as shielding.

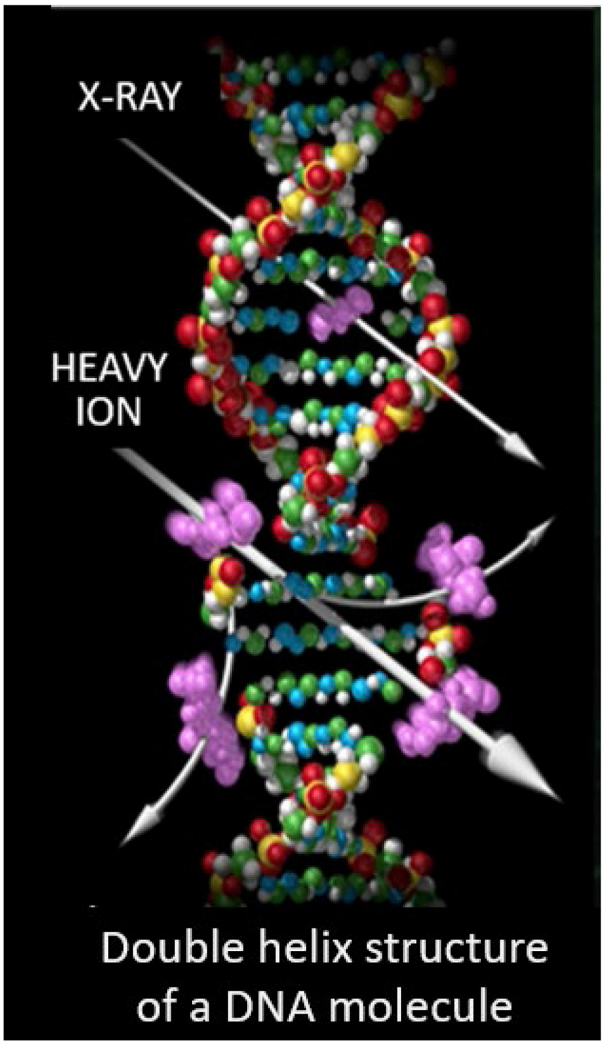

Figure 1

Figure 1

Galactic cosmic rays contain heavy ions that can pass through human cells and cause DNA damage (purple) that is much more difficult for the body to repair compared to radiation found on Earth, such as x-rays or gamma radiation (image courtesy of NASA).

of the mission and where they are in our solar system. Close to home, Earth's protective magnetic field can provide a significant amount of protection to astronauts on the International Space Station (ISS), for example. For missions to the moon and Mars, the largest exposures happen further out in space. Once on the surface, the mass of the moon or planet will protect astronauts from half of the GCRs. On Mars, the atmosphere provides some additional protection. In addition to the shielding provided by the spacecraft, the tissues of the human body itself provide some protection to critical organs.

To estimate astronaut radiation exposures, NASA uses a combination of tools and measurements to calculate the amount of radiation reaching sensitive organs such as the lungs, heart, and brain. Next, an estimate of the amount of biological damage can be calculated based on the dose and type of radiation received. Biological damage is described using a unit called **Sieverts (Sv)**. Astronaut exposures range from ∼20 mSv ("milli"Sv, or 10^{-3} Sv) for short space shuttle-type missions to over 300 mSv for long stays on the ISS. Astronauts on a

SIEVERT (SV)

Unit of measure to reflect biological damage from a given dose of radiation.

short 30-day lunar mission will receive ∼40 mSv, while exposures for a Mars missions, which would last nearly 3 years, are on the order of 1,200 mSv. Compared to workers on Earth, with average exposures of <3 mSv per year, astronauts receive the most radiation of any modern radiation worker.

WHAT ARE THE RADIATION HEALTH RISKS TO ASTRONAUTS FOR LONG-DURATION MISSIONS?

Astronauts face risks from exposure to GCRs both while they are on space missions and long after their missions are complete. During missions with high exposures like a Mars mission, the major risks are possible changes in the brain, resulting in poorer performance during flight. After spaceflight, astronauts face increased risks of blood cancers (e.g., leukemias), solid cancers (e.g., lung or gastrointestinal tumors), heart-related diseases, and the potential for worsening brain-related problems later in life (for more details about the health risks faced by astronauts, see this Frontiers for Young Minds article). NASA is working hard to increase understanding of both in-flight and long-term health risks, so that they can better protect astronauts from them.

HOW CAN WE SIMULATE SPACE RADIATION ON EARTH?

One way to learn about the radiation threats astronauts face is to study them here on Earth. But, as we mentioned earlier, the radiation on Earth is different from the radiation in space. So first, we must find a way to reproduce space-like radiation on Earth. Large **particle accelerator** facilities are needed to speed up particles to energies high enough to mimic the space environment. However, these facilities can only produce one type of particles at a time—and, as we mentioned, space radiation is a mixed-field of radiation containing essentially all of the elements in the Periodic Table! This makes mimicking space radiation on Earth quite a challenge.

PARTICLE ACCELERATOR

Is a machine that uses electromagnetic fields to propel charged particles to very high speeds and energies.

In 2003, NASA began using the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory to perform its ground-based, heavy-ion research (Figure 2). Here and around the world, most research on understanding health risks from exposure to space radiation has been performed using exposures to one type of particle at one energy. Over the last decade, upgrades made to the NSRL have helped the facility to more closely approximate the radiation exposures found in space. Today, the facility can supply many types of particles with a variety of energies during a single radiation experiment by switching from one type of particle to another every 2–4 min [3]. While particle energies are still much lower than the GCR field outside the spacecraft, the NSRL can simulate the range of GCR particles and energies encountered by astronauts while *inside* their spacecraft, which have slowed down considerably while moving through the spacecraft's shielding.

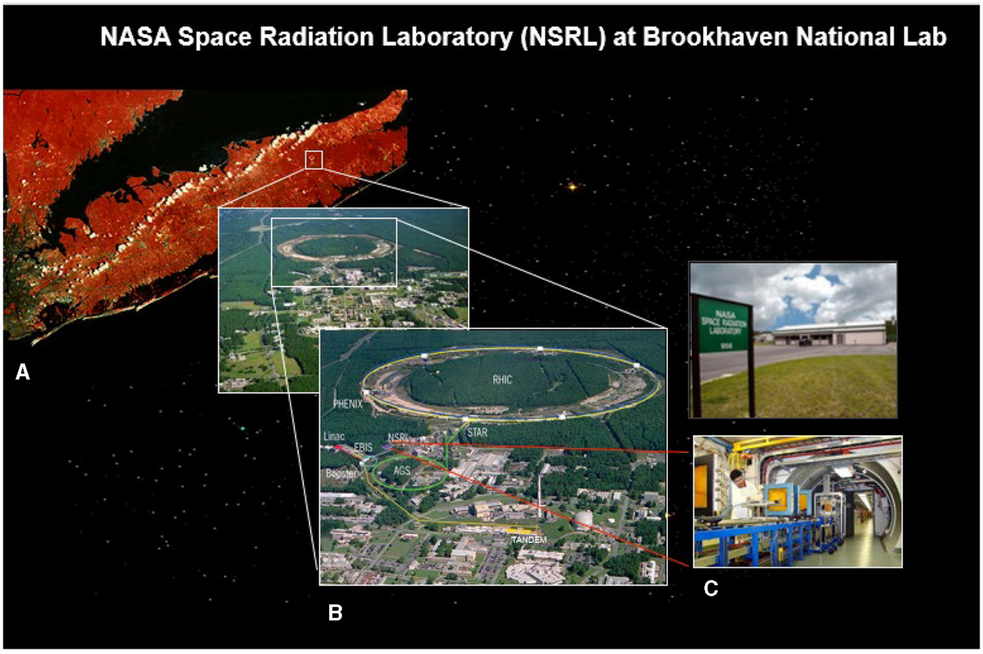

Figure 2

Figure 2

(A) Satellite image of Long Island, New York, where Brookhaven National Laboratory is located. **(B)** Aerial photo showing the large accelerator facility needed to create high-energy ions. For scale, the top "RHIC" ring is 2.4 miles in circumference. NSRL uses a "booster" ring, which is ∼286 feet in circumference and lined with powerful magnets to accelerate ions. **(C)** Inside the NSRL target room where experiments are performed (images courtesy of BNL).

NSRL is the only facility that can closely simulate space radiation. NSRL systems and controls software have been optimized to deliver beams of particles reliably and rapidly (Figure 3). Each GCR simulation utilizes 21 switches of unique energy-ion beam combinations. A typical exposure requires ∼75 min to deliver. To simulate lower dose rates more closely, several smaller exposures can be given daily over 2–6 weeks. Simulating the low GCR dose rates found in space remains one of NASA's greatest challenges.

HOW IS THE SIMULATOR BEING USED BY NASA?

NASA is using the GCR simulator to develop protection strategies to reduce impacts to astronauts' health and to keep astronauts performing at their best on future long-duration missions. While we have learned a lot from astronauts living on the ISS, many details remain unknown about the radiation health risks faced by astronauts—especially from the large radiation exposures that will be experienced during a Mars mission. The GCR simulator provides researchers the ability to conduct mixed-field radiation studies on Earth, under controlled conditions. Research teams are using cells and experimental animal systems, as well as advanced tissues-on-a-chip technologies, to study the effects of mixed-field radiation. NASA will use these results to better estimate radiation health risks and to update radiation exposure limits if needed. The GCR simulator

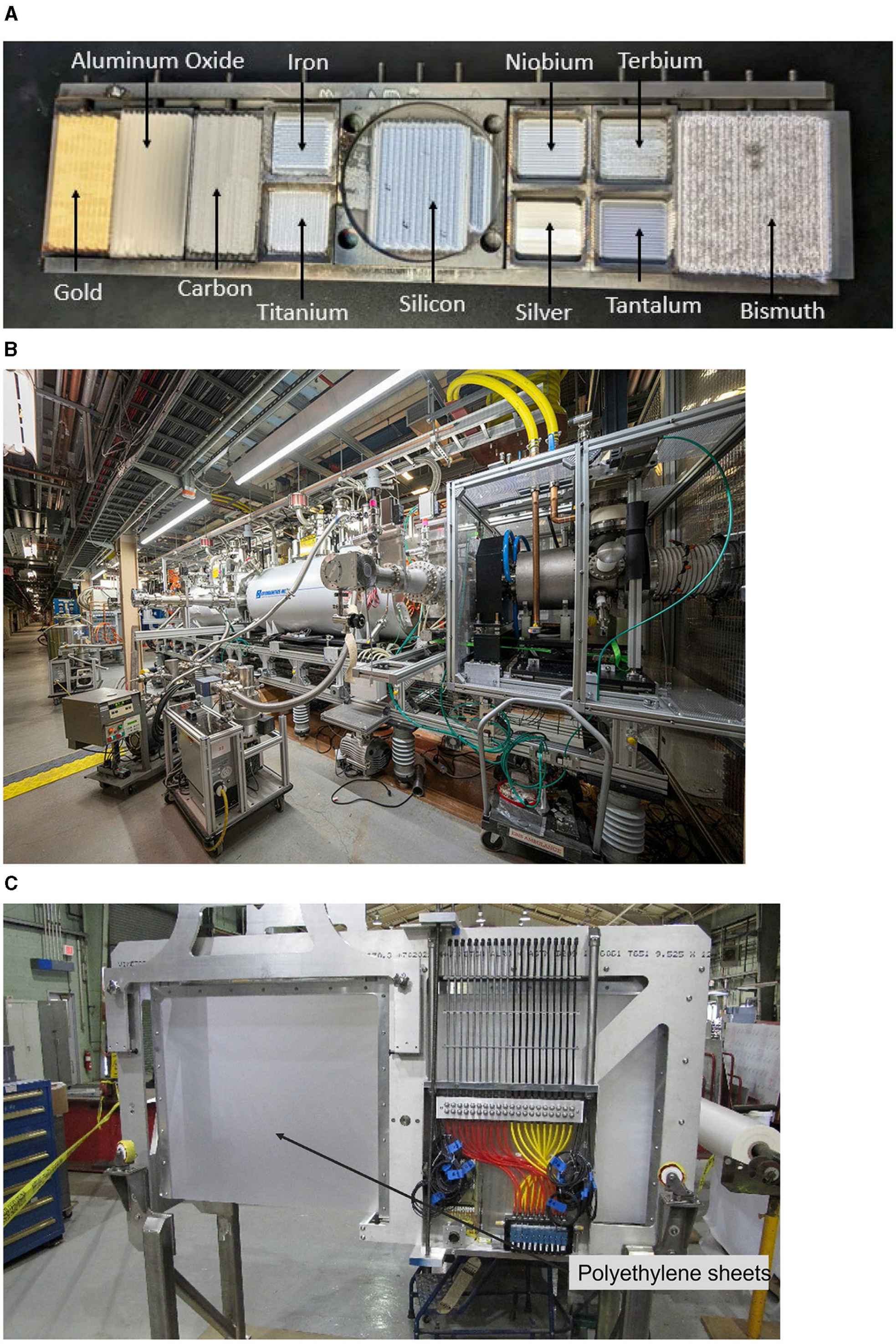

Figure 3

Figure 3

Complex systems and machinery create and accelerate ions from solid and gas sources. **(A)** A laser is used to evaporate high-purity solid targets to produce ions needed for the simulation. The target holder is 25 cm by 6 cm. The iron target is roughly the size of a US quarter. **(B)** The Electron Beam Ion Source further strips these ions of their electrons before delivery to the "booster ring" which accelerates ion beams to high energies. **(C)** To produce the lowest energy beams, some ions are slowed down by inserting sheets of polyethylene into the beamline (images courtesey of BNL).

ANTIOXIDANTS

Man-made or natural substances that may prevent or delay some types of cell damage caused by free radicals or unstable molecules.

also allows scientists to test the methods that could be used to protect our astronauts. Multiple research teams are currently testing the effectiveness of a variety of medicines and dietary supplements, such as **antioxidants** and anti-inflammatory drugs, to reduce radiation damage to sensitive tissues.

WHAT KEY SIMULATION CHALLENGES REMAIN?

Scientists still have major questions to answer about space radiation. Key challenges remain in determining whether the GCR simulator mimics the radiation environment in space closely enough to accurately predict health effects for humans. Scientists are still learning how to run these tests properly and are working to better simulate deep-space radiation exposures, including figuring out which animals and cell types provide the best information for how humans respond to space radiation. Research results are expected soon and will help NASA to protect the brave individuals doing the important and exciting job of exploring space.

ORIGINAL SOURCE ARTICLE

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YOUNG REVIEWERS

CLARA, MADELEINE, AND ORLAITH, AGES: 11–12

Hello—we all live in Cardiff, Wales, and enjoy doing science, reading books, and playing musical instruments. Our favorite series is Harry Potter. Between us we play the violin, French horn, piano, flute, recorder, euphonium, trumpet, and cornet! Our favorite lessons are performing arts, math's, and music.

JIARUI, AGE: 15

My name is Jiarui, and I am a 9th grader at a middle school in China. I won national prizes in English speech contests and state awards for coding. I like piano, and have gotten the Grade 8 Certificate of ABRSM with a distinction score. I am very excited about physics. I like baking and cooking. I love dogs and have two poodles.

AUTHORS

LISA SIMONSEN

Dr. Lisa Simonsen is a senior scientist for Space Radiation Systems Integration at NASA Headquarters in Washington, DC. She works to identify research and technology development efforts needed to reduce crew radiation exposures and minimize health risks while advancing NASA mission objectives. In addition, Dr. Simonsen provides technical leadership within NASA's Space Radiation Research Laboratory in Upton, New York where biological research and electronics testing is performed. Dr. Simonsen received her Ph. D. in nuclear engineering and health physics from the University of Virginia, Charlottesville, VA in 1997. *lisa.c.simonsen@nasa.gov

TONY SLABA

Dr. Tony Slaba is a research physicist at NASA Langley Research Center in Hampton, Virginia. He is the primary developer for NASA's space radiation transport code used to evaluate spacecraft shielding and crew protection. Dr. Slaba and colleagues developed new techniques for simulating the space radiation environment at NASA's ground-based accelerator facility for radiobiology experiments. Dr. Slaba also works on improving and updating NASA's model for projecting lifetime cancer risk for astronauts from exposure to space radiation. Dr. Slaba received his Ph. D. in computational and applied mathematics from Old Dominion University in 2007.

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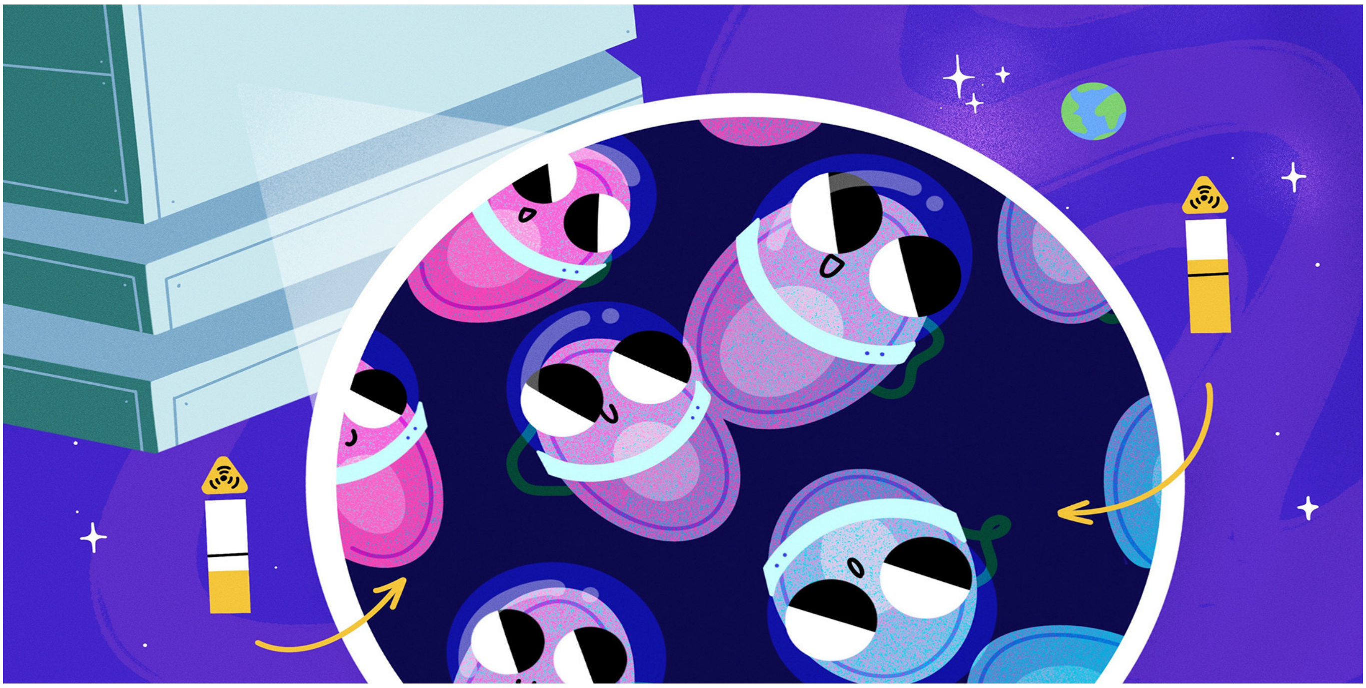

MEET BIOSENTINEL: THE FIRST BIOLOGICAL EXPERIMENT IN DEEP SPACE

Shirin Rahmanian [1*], ***Tony Slaba*** [2], ***Tore Straume*** [3†], ***Sharmila Bhattacharya*** [4] ***and Sergio R. Santa Maria*** [3]

[1] *Durability, Damage Tolerance, and Reliability Branch, National Institute of Aerospace, Hampton, VA, United States*
[2] *Durability, Damage Tolerance, and Reliability Branch, NASA Langley Research Center, Hampton, VA, United States*
[3] *Space Biosciences Division, NASA Ames Research Center, Moffett Field, CA, United States*
[4] *NASA Biological and Physical Sciences Division, NASA Headquarters, Washington, DC, United States*

[†] *Retired, Rocklin, CA, United States*

YOUNG REVIEWERS:


ABYAN
AGE: 13


BAIRON
AGE: 10


RANJAI
AGE: 14


RANVIR
AGE: 14

Recently, NASA launched a rocket called Artemis-I toward the Moon! The mission objective was to test the safety of the Space Launch System for future human travel into deep space. But vehicle safety is not the only concern for space travelers. Space radiation is an invisible danger to astronauts because it can damage the body's cells and potentially lead to serious health problems. How do we study the effects of space radiation on cells? Meet BioSentinel! BioSentinel is a small satellite deployed from Artemis-I that carries yeast cells and a sensor to measure space radiation. The job of BioSentinel is to transmit data from the cells in deep space back to Earth. In this article, we will explore the BioSentinel mission, discuss how the data are obtained and transmitted, and give examples of how the data from BioSentinel will help scientists better understand the effects of space radiation on living things.

Did you know that scientists are sending living organisms into space, to study how space **radiation** affects life forms [1]? It is true! Recently, the National Aeronautics and Space Administration (NASA) deployed a small **satellite**, called BioSentinel, from the Artemis-I rocket. BioSentinel carried yeast cells into space, to help scientists learn more about the effects of space radiation. This article will explore the BioSentinel mission and why it is important for space travel.

RADIATION

Transmission of energy through waves or traveling fast particles.

SATELLITE

An object that goes around (orbits) a planet.

WHAT IS THE BIOSENTINEL MISSION?

The Artemis-I rocket (Figure 1A) started its journey to the Moon on November 16, 2022. The aim of the mission was to test the safety of the Space Launch System for future human journeys into deep space. Vehicle safety, however, is not the only risk for space travelers. Astronauts are exposed to radiation while they are in space, which can lead to serious health effects. Therefore, alongside the primary launch objectives of Artemis-I, small satellites were also deployed to test other risks of space travel, with BioSentinel being one of them. The BioSentinel satellite consists of a shoe box-sized unit (Figures 1B, C) that holds yeast cells and the necessary electronics and solar panels to power the satellite in space.

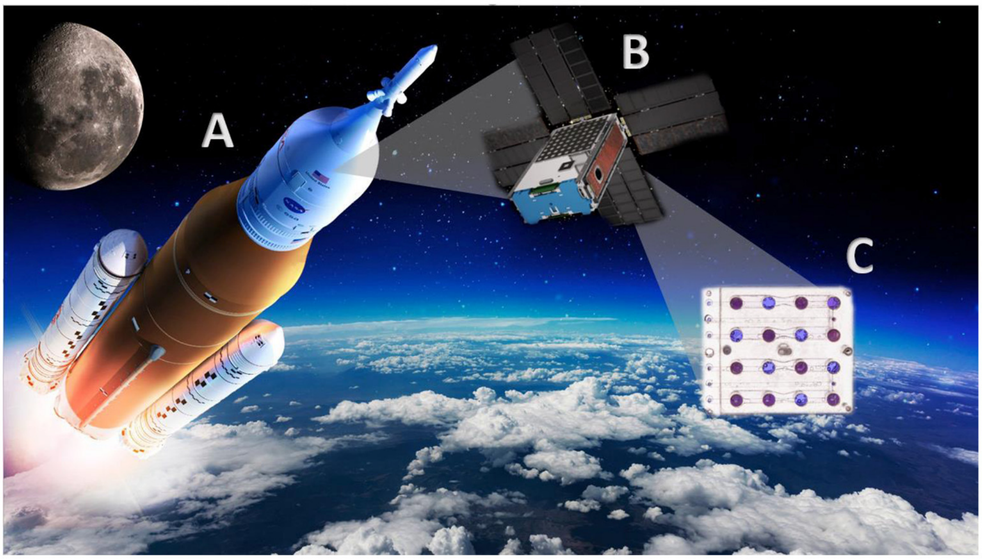

Figure 1

Figure 1

(A) The Artemis-I rocket was sent to space with the main mission of testing the safety of the Space Launch System. **(B)** Artemis-I also deployed BioSentinel, a shoe box-sized satellite. **(C)** BioSentinel was loaded with yeast cells, to study the effects of space radiation on living things in deep space. BioSentinel also has solar panels for power and contains the electronics necessary to send information back to Earth (Image Credit: adapted from NASA.gov).

WHY STUDY SPACE RADIATION?

Space radiation consists of **solar particles** originating from the Sun and **galactic cosmic rays** originating outside our solar system. (For more information on space radiation, see this Frontiers for Young Minds article.) Space radiation includes high-energy particles that travel through space at very high speeds and can pass through things like

SOLAR PARTICLES

Energetic particles released from the Sun into space.

GALACTIC COSMIC RAYS

High energy particles of different types originating from outside of our solar system that travel through space at very fast speeds.

spacecrafts and the spacesuits of astronauts [2]. Space radiation can harm humans and other living things if they are exposed to it for too long, because it can damage **DNA** and other important cell parts. (To learn more about space flight health risks see this Frontiers for Young Minds article.) DNA damage can lead to serious health problems like cancer. Most of the time, cells fix damage correctly; but in some cases, damage is too complex for the cell to repair. In these cases, the cell might die or repair itself incorrectly, leading to **mutations** in its DNA. Cells with mutations can start multiplying uncontrollably, and that is how cancer forms over time. Many of the health problems caused by space radiation, like cancer, are delayed effects—so astronauts would not get sick until later in their lifetimes, after they have returned to Earth. By studying space radiation, scientists hope to learn more about how it affects living things and how to protect astronauts.

DNA

A molecule found in the nucleus of living organisms that contains genetic information (genes) telling living organisms how to look and function.

MUTATION

Changes in the DNA of organisms that can make the cells function differently.

HOW DOES BIOSENTINEL STUDY SPACE RADIATION?

BioSentinel uses yeast cells (Figure 2D) to study how living things respond to space radiation [3]. Yeast cells are single-celled organisms commonly used to help bread dough rise or in the fermentation process used to make beer. The type of yeast used in BioSentinel is frequently used in research in many types of labs around the world. It was the first organism to have its DNA fully sequenced, for example. Yeast cells are important in scientific experiments because they share many similarities with human cells, and therefore the results obtained from yeast cells can give us clues about human health. Yeast cells can withstand the rigors of space travel, especially since they can be dried out and only activated by liquid when they are needed. Yeast cells can also be modified to make them either more sensitive or more

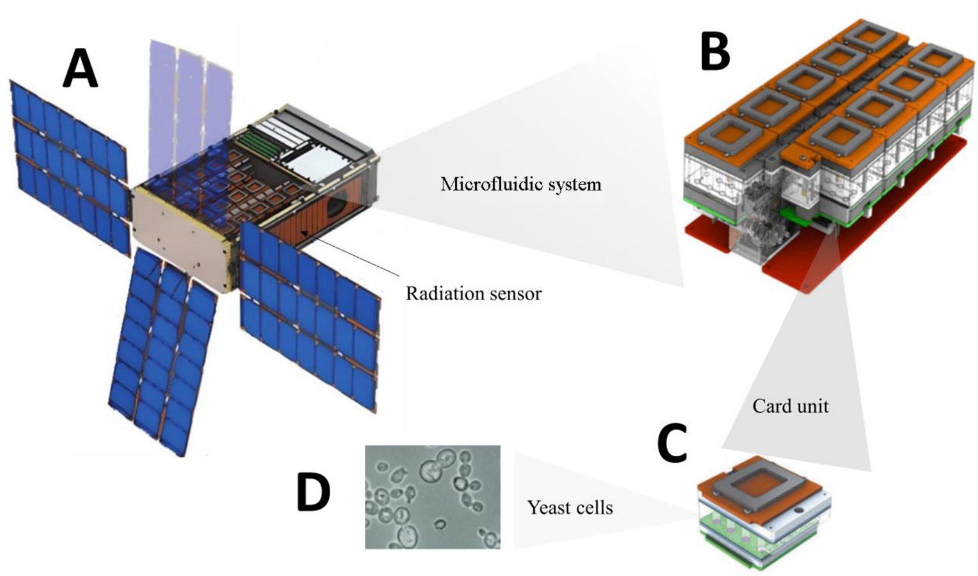

Figure 2

Figure 2

(A) BioSentinel contains a radiation sensor, to measure space radiation, and microfluidic cards containing yeast cells, to monitor the effects of space radiation on living cells. **(B, C)** The microfluidic system is made up of multiple smaller card units, and it can deliver nutrient-containing fluids to the yeast cells to help them survive. The microfluidic system also delivers the dye used for measuring DNA damage in response to space radiation. **(D)** Yeast cells (Image Credit: Adapted from NASA.gov).

resistant to space radiation, to better understand how human cells might respond to space missions.

In BioSentinel, the yeast cells are placed in special containers called **microfluidic cards**, where the cells receive the nutrients needed to stay alive (Figures 2B, C). As discussed earlier, space radiation can damage DNA. Damage to yeast DNA can change their **metabolic activity**, meaning how they change nutrients into energy. A special dye is delivered to the microfluidic cards, which changes color based on the metabolic activity of the yeast cells [1, 3]. Monitoring the change in metabolic activity allows scientists to see how space radiation affects the yeast cells (Figure 3). Additionally, there is a radiation sensor inside BioSentinel that measures the space radiation (Figure 2A). Data from the microfluidic cards and the radiation sensor are sent back to Earth, where scientists can analyze those data to see how radiation causes DNA damage and how the yeast cells respond.

MICROFLUIDIC CARD

Container in the BioSentinel that provides fluid and nutrients to keep the yeast cells alive.

METABOLIC ACTIVITY

The chemical reactions in cells that help to convert nutrients into energy for survival.

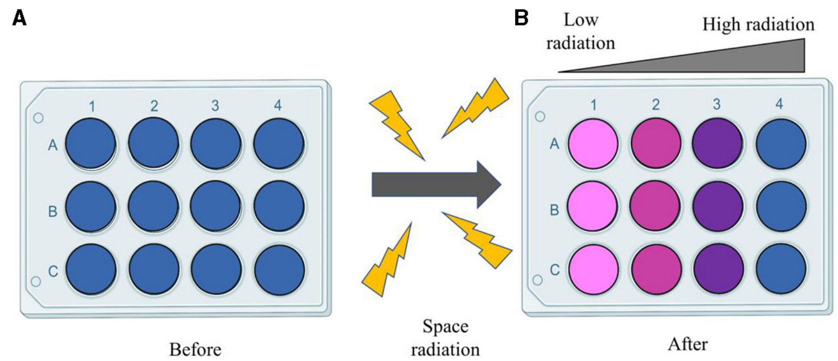

Figure 3

Figure 3

(A) To monitor the response of yeast cells to radiation during the BioSentinel mission, a special blue dye is added to the microfluidic cards. **(B)** When yeast cells are healthy and metabolically active (using nutrients to survive and grow), the dye changes from blue to pink. **(B)** However, if radiation damages yeast DNA, the rate of metabolic activity can change. The cells with damage remain blue longer, while the cells not affected by radiation turn pink faster.

WHAT HAPPENS AFTER THE BIOSENTINEL MISSION?

The Artemis-I spacecraft has safely returned to Earth, but BioSentinel will remain in space collecting data. The mission is set for 6 months, during which data from the radiation sensor and microfluidic cards are periodically transmitted to Earth. After the mission is complete, scientists will analyze all the data to learn more about how space radiation affects living things. Furthermore, the data will be compared to experiments on Earth and on the International Space Station, and also compared with computer simulations of the radiation-containing space environment. These data, together with information from other space studies, could be used to develop new ways to protect astronauts from radiation during long space missions—to the Moon, Mars, and beyond! Data could also have important implications for cancer research and other areas of human health related to space travel.

CONCLUSION

The BioSentinel mission is an exciting project that aims to study the effects of space radiation on living organisms. By sending yeast cells into deep space, scientists hope to learn more about how radiation affects cells and how to protect astronauts on long-duration space missions, as NASA prepares astronauts to return to the Moon and eventually travel to Mars and beyond. The results of the BioSentinel mission could have important implications for human health, and we cannot wait to see what scientists learn from this groundbreaking mission.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ABYAN, AGE: 13

Hi, I am Abyan! I like science, specifically space related science, and physics! I also like mathematics and English. I would say that I am an independent person who loves new challenges. An example would be that I just recently started playing competitive tennis. I have a pet cat named Astro and I love spending time with him! In my free time, I play and interact with my friends and read about new space discoveries.

BAIRON, AGE: 10

I am from Beaverton, Oregon. I love learning different fun facts about science. In my leisure time, I like playing tennis and coding. I also love to participate in events outside the science field. I participated in the event called "Oregon Battle of the Books" last year, 2023, and our team represented our elementary school in the regional contest. I also submitted an essay for the essay competition held by the Oregon government and my essay was selected to publish in the Oregon Blue Book 2023. I was also invited to the Capital of Oregon for a ceremony and saw lots of Senates.

RANJAI, AGE: 14

Ranjai loves math, chess, and physics and is especially a big fan of the NASA labs and space explorations.

RANVIR, AGE: 14

Ranvir loves origami models, reptiles, insects, and every specimen in his biology lab.

AUTHORS

SHIRIN RAHMANIAN

Dr. Shirin Rahmanian is a research scientist and member of the Multi-Model Ensemble Risk Assessment project at NASA Langley Research Center. Her research focuses on space radiation and modeling the associated risks for long-duration space missions. Dr. Rahmanian earned her Ph.D. in Medical Physics from University of Heidelberg, Germany. *shirin.rahmanian@nasa.gov

TONY SLABA

Dr. Tony Slaba is a research physicist at NASA Langley Research Center, working in the areas of space radiation physics, particle transport, experimental radiobiology, and risk assessment. He received his Ph.D. in computational and applied mathematics from Old Dominion University in 2007, and he has authored or contributed to over 60 peer reviewed journal articles since 2010. He currently serves as a council member for the National Council for Radiation Protection and Measurements.

TORE STRAUME

Dr. Tore Straume recently retired from NASA, where he served as senior scientist for the Space Biosciences Division at the NASA Ames Research Center in Mountain View, CA. During his almost 50-year career in science, Dr. Straume served in various senior scientist positions at the Lawrence Livermore National Lab and also as a university professor. Dr. Straume holds an M.S. in radiological sciences from the University of Washington and a Ph.D. in radiation biophysics from the University of California.

SHARMILA BHATTACHARYA

Dr. Sharmila Bhattacharya was originally the principal investigator for the BioSentinel mission, and she now serves as the program scientist for space biology in the Biological and Physical Science Division at NASA Headquarters. Dr. Bhattacharya has served as the space policy advisor to the U.S. Senate Committee for Commerce, Science, and Transportation. She has been a principal investigator and senior scientist at NASA, conducting research on the space shuttle, the International Space Station, and small satellites journeying beyond low-Earth orbit. Dr. Bhattacharya conducted her post-doctoral research in neurobiology at Stanford University and earned her Ph.D. in molecular biology at Princeton University.

SERGIO R. SANTA MARIA

Dr. Sergio Santa Maria is a research scientist at the Space Biosciences Division, NASA Ames Research Center. He is currently the principal investigator for the BioSentinel mission in addition to other NASA Space Biology projects. He is also a co-principal investigator in an upcoming mission to the Moon named LEIA, which will use similar technologies originally developed for BioSentinel to investigate the response of living organisms to the reduced gravity and radiation environment of the lunar surface. Dr. Santa Maria is originally from Lima, Peru, and earned his Ph.D. in molecular genetics from the University of Texas Medical Branch, Galveston, Texas.

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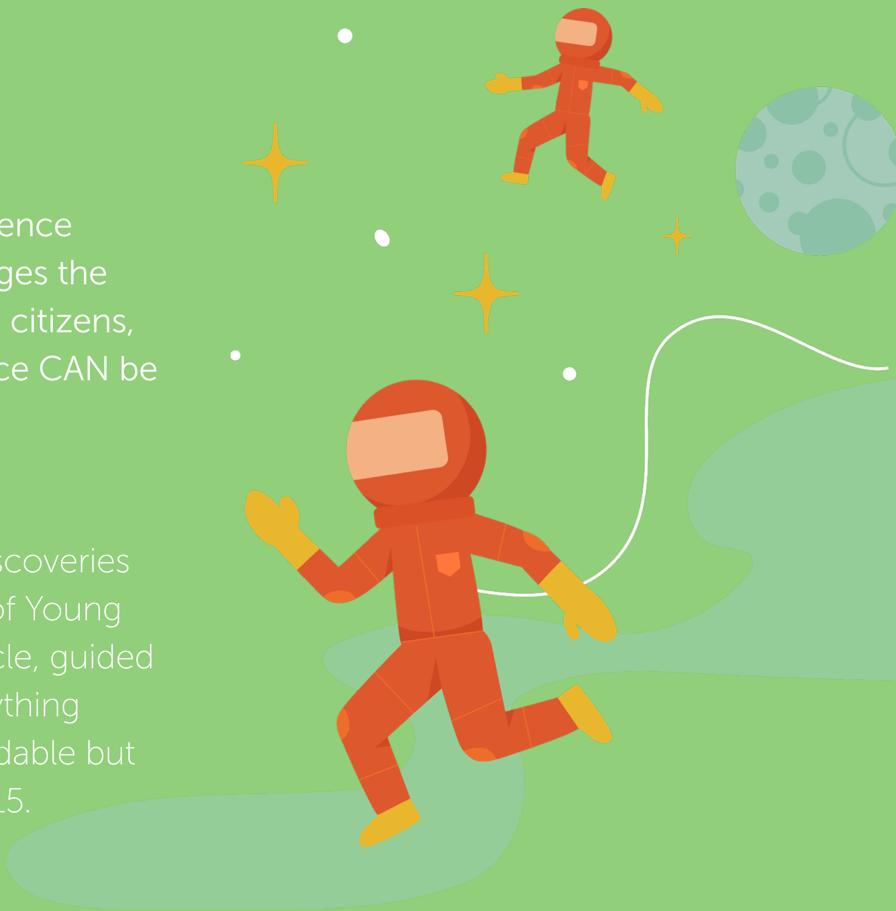

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