NASA's Galactic Cosmic Ray Simulator – How we study the effects of space radiation on Earth

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ABSTRACT

Earth's atmosphere and natural magnetic field do a good job protecting us from space radiation. Space radiation is different from radiation on Earth, which mostly comes from isotopes found in rock and soil or from medical procedures like an Xray. Ionizing space radiation comes from particles ejected from the Sun, or solar particle events, and from supernovae outside our solar system making up a background of galactic cosmic radiation. These particles, representing the elements of the periodic table, have been stripped of their electrons as they are accelerated in interstellar space to almost the speed of light. One of NASA's biggest challenges is protecting astronauts from these high energy particles of galactic cosmic radiation which can cause cancer and other diseases. To understand the biological damage imparted to living systems and to develop protective countermeasures, NASA has built a galactic cosmic ray simulator on Earth.

I. What is Galactic Cosmic radiation?

Galactic cosmic rays (GCR) are the main radiation health hazard for humans embarking on long duration exploration missions. They originate outside our solar system and are likely formed by supernova when a star reaches the end of its life and explodes. While radiation sources on Earth generally include things like gamma and x-rays, GCR consist of the nuclei of the chemical elements, from hydrogen to uranium, which have been accelerated to extremely high energies. These energetic fully ionized particles come from all directions and form a continuous background of radiation in space. They are considered much more biologically damaging compared to terrestrial radiation (Figure 1) [1]. Understanding this difference is fundamental to quantifying health risks faced by our astronauts.

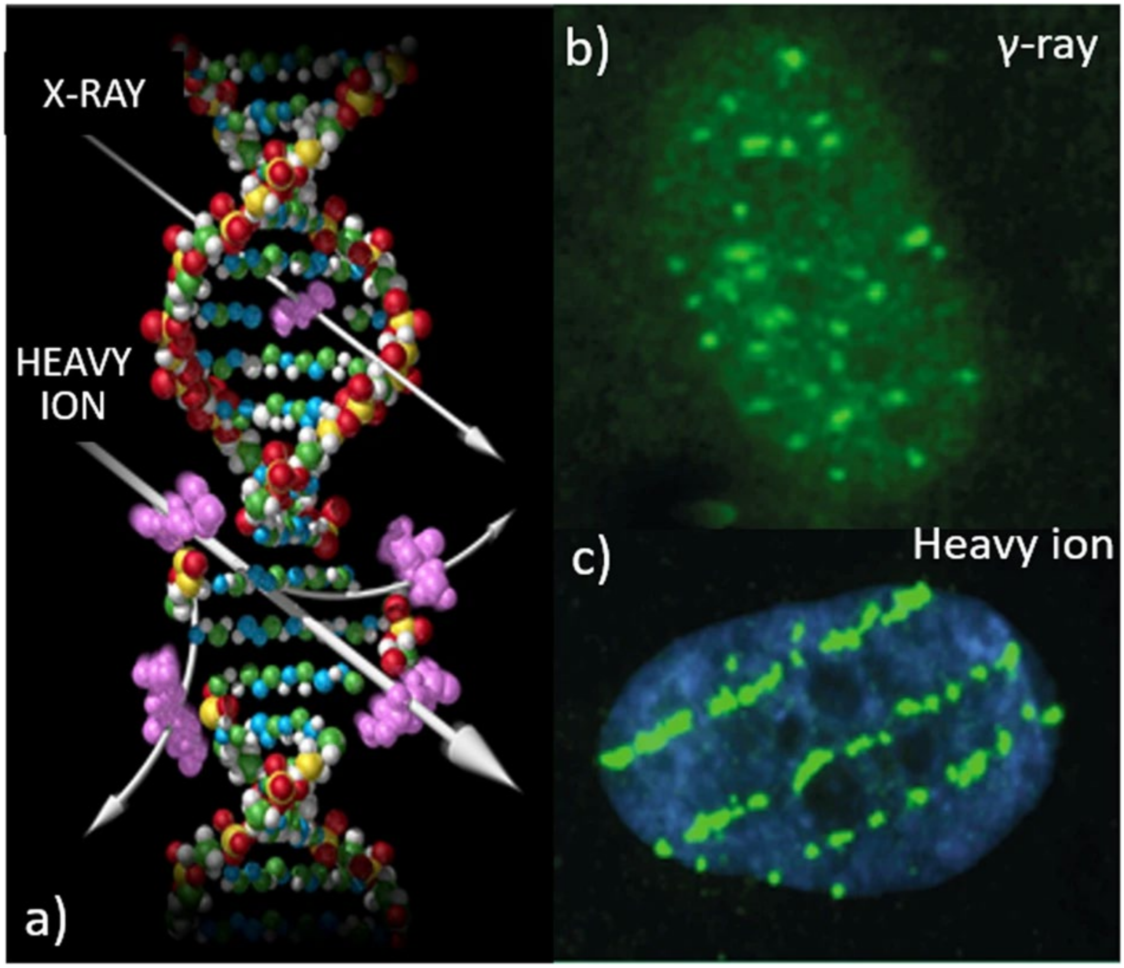

Figure 1. (**a**) High (H) charge (Z) and energy (E) ions, often referred to as HZE ions, produce dense ionization along the particle track as they traverse a tissue and impart distinct patterns of DNA damage compared to terrestrial radiation such as X-rays or gamma radiation. γH2AX foci (green) illuminate distinct patterns of DNA double-strand breaks in nuclei of human fibroblast cells after exposure to **(b)** gamma-rays, with diffuse damage, and (**c**) HZE ions with single tracks. Image credits: (a) NASA and (b and c) Cucinotta and Durante [1].

Hydrogen alone accounts for approximately 87% of the GCR particles; helium accounts for approximately 12%, and all particles heavier than helium account for the remaining 1% [2]. Although there are far fewer heavy ions compared to hydrogen and helium, they are biologically very damaging, and estimating the health risk they present is challenging. There is a broad range of energies associated with each of these particles. The lower energy GCR fall in the MeV range, where only a few centimeters of tissue or shielding can fully stop the particles. The higher energy GCR reach the GeV and TeV range, where many meters of shielding are still unable to fully stop the particles (these particles have velocities that approach the speed of light!). The energy range between a few hundred MeV to ~50 GeV is the primary focus for human space radiation protection.

This naturally occurring and highly complex GCR environment is modified as it encounters spacecraft shielding and human tissues. A mixture of atomic and nuclear interactions take place that can slow down primary GCR particles and initiate the production of new particles, referred to as secondary radiation. The secondary radiation includes particles such as neutrons that can penetrate further and cause greater biological damage than the incoming GCR. The radiation environment encountered by astronauts inside spacecraft is therefore a combination of primary GCR ions which penetrate through shielding and secondary radiation produced by the various physical interactions with matter.

II. How much radiation exposure does an astronaut receive?

An astronaut's daily exposure to GCR not only depends on the amount of shielding provided by their spacecraft but also mission duration and where they are in our solar system. In low Earth orbit, Earth's protective magnetic field extends far enough out in space to provide a significant amount of protection to astronauts on the International Space Station. For missions to the moon and Mars, the largest exposures will be in-transit beyond low Earth orbit – or what is referred to as free-space. Once on the surface, the mass of the celestial body will protect astronauts from half of the free-space particles. On Mars, the atmosphere although much thinner than Earth's provides some additional protection. In addition to shielding provided by the spacecraft, our own body's mass provides some additional protection to our critical organs.

To estimate astronaut radiation exposures, NASA uses a combination of nuclear transport codes, geometry models, and measurements to calculate the full spectrum of particles and energies reaching sensitive organs such as the lungs, heart, and brain. Dose or energy deposited (in units of Gray) and an estimate of dose equivalent or biological damage (in units of Sivertz) are then calculated. Exposures in our current astronaut corps range from ~20 mSv (short shuttle missions and like those expected for lunar Artemis sorties) to over 300 mSv for long durations on the International Space Station. Astronauts on a single 6-month International Space Station mission receive approximately 50 mSv to 100 mSv (30 to 60 mGy), while Mars exposures for missions of nearly 3 years are on the order of 1200 mSv (~500 mGy). Compared to workers on Earth with average exposures of < 3 mSv/year, astronauts receive the most radiation of any modern occupational workers.

To study health effects associated with exposure to the space environment, the GCR simulator is designed to approximate the mixed field of primary and secondary particles seen at critical organ locations within an astronaut in a shielded vehicle. Experimental exposures are delivered at mission relevant doses ranging from 250 to 750 mGy.

III. What are the radiation health risks to astronauts for long-duration missions?

Both in-mission and long-term health risks have been attributed to exposure levels expected for astronauts. The major risks include the possibility of changes in the brain resulting in poorer performance or behaviors during flight and post mission (5- 15 years after flight) blood cancers (e.g., leukemias), solid cancers (e.g., lung or gastrointestinal tumors), cardiovascular diseases, and the potential for neurodegenerative impairments later in life [3]. Characterization and mitigation of these risks requires a significant reduction in the large biological uncertainties of chronic (low-dose rate) heavy ion exposures and the validation of countermeasures in a relevant space environment. This continues to be a significant area of research for NASA.

IV. How can we simulate space radiation on Earth?

Large particle accelerator facilities are required to generate and deliver ions at energies high enough to mimic the space environment. In 2003, NASA commissioned the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) with a dedicated beamline to conduct its ground-based, heavy-ion research [Figure 2] (https://www.bnl.gov/nsrl/). The facility is capable of supplying particles from protons to gold. Available beam energies range from 50 to 2,500 MeV for protons and 50 to 1,500 MeV/n for ions between helium and iron. Heavier ions from charge Z = 27 to 79 are limited to approximately 350 to 500 MeV/n [4]. To date, only the NSRL can deliver the range of GCR particles and energies encountered by astronauts while in their spacecraft. Over the last decade, facility investments in ion source and control system technologies enabled the fast switching of ion-energy beam combinations to more closely approximate the mixed field exposures found in space. Only NSRL can generate and switch between the different particle beams fast enough to make this type of simulator possible [Figure 3].

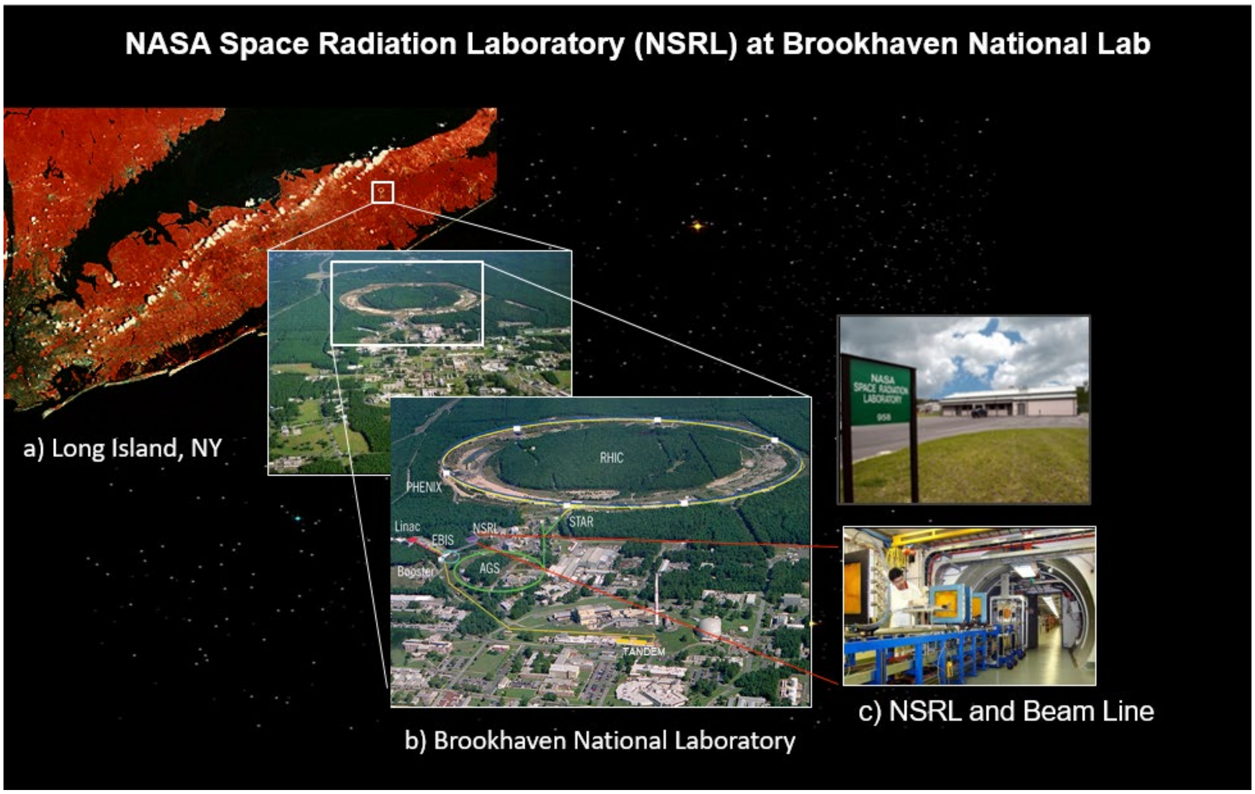

Figure 2. (a) Satellite image of Long Island, New York where Brookhaven National Laboratory is located. (b) Areal photo showing large accelerator complex needed to create high energy ions. For scale, the top "RHIC" ring is 2.4 miles in circumference. NSRL uses the "Booster" ring which is ~286 feet in circumference and lined with powerful magnets to accelerate ions. (c) Inside the NSRL target room where experiments are performed. *Images courtesy of BNL.*

On the ground, it is not feasible to deliver every particle and energy combination found in the space environment. That would include every ion on the Periodic Table! The amount of time required and the number of solid and gas sources available for ion generation makes this impractical. In addition, particle accelerators cannot produce energies as high as those found in free space. Therefore, the simulator is designed to deliver representative ions spanning the particle types and energies seen by astronauts in a shielded spacecraft - where the free space ions have been slowed down to lower energies.

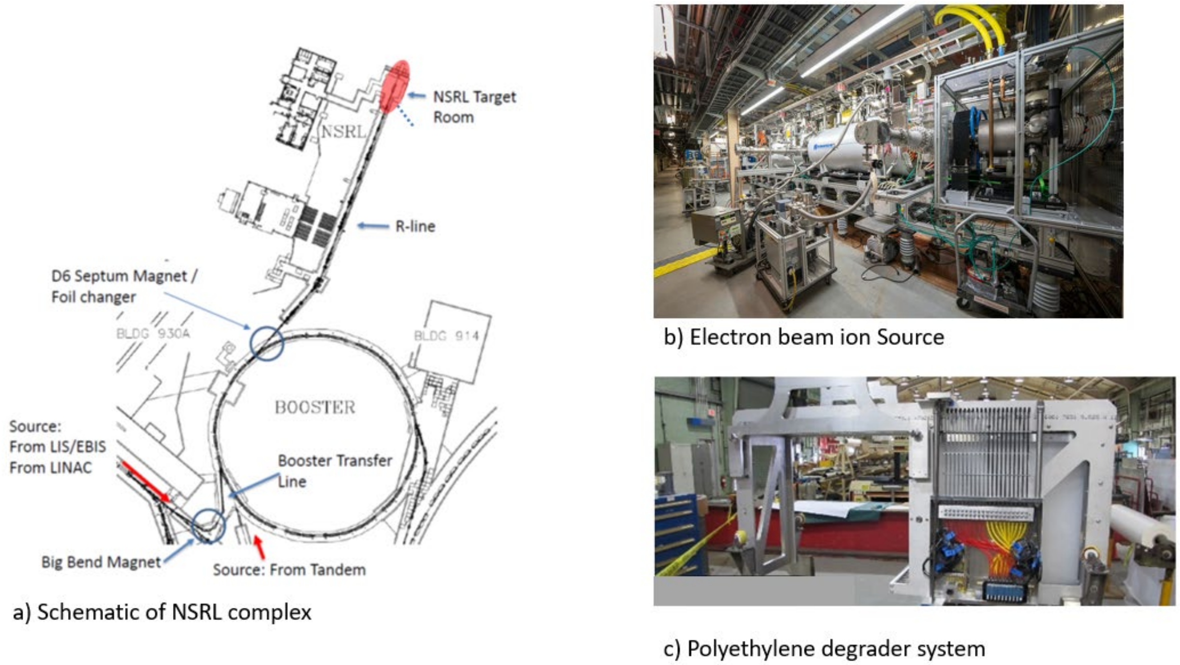

Figure 3. (a) The simulator uses ions from three sources: the Linear Accelerator (LINAC), the Tandem Van de Graaff, and the Electron Beam Ion Source (EBIS). GCR simulator ion beams are accelerated to high energies in the Booster synchrotron and transported to the target room via a series of powerful magnets. (b) A laser ion source (LIS) produces ions from many different solid targets and has the capability to rapidly switch between solid-source targets through automated controls software. (C) A polyethylene degrader system is used in the in beam line to generate the lower energy beams for the simulator. *Images courtesey of BNL.*

The GCR Simulator delivers most of its dose from protons (~65%–75%) and helium ions (~10%–20%) with the remainder of the dose delivered from heavier ions ($Z \geq 3$). Representative ion-energy beam combinations include 33 beams of 14 proton energies, 14 helium energies, and the 5 heavy ions of C, O, Si, Ti, and Fe. A polyethylene degrader system is used in the beam line to slow down hydrogen and helium to provide a nearly continuous distribution of low-energy particles. Each GCR simulation requires 21 switches of unique ion-energy beam combinations to the target room with the 12 additional hydrogen and helium beams generated using the degrader system. New system controls were developed to deliver beams reliably and rapidly. Switch times range between approximately 2 to 4 minutes. A 500 mGy exposure requires approximately 75 minutes to deliver. To more closely simulate the low-dose rates found in space, sequential field exposures can be divided into daily fractions over 2 to 6 weeks. Using ground-based accelerator facilities to simulate the low GCR dose rates found in space remains one of our greatest challenges.

V. How is the simulator being used by NASA?

NASA is using the GCR simulator to develop protection strategies to mitigate impacts to crew health and maintain high levels of human performance on future long duration missions. Large biological uncertainties exist in quantifying radiogenic health risks faced by astronauts - with a significant knowledge gap between our ISS experience and exposures anticipated during a Mars mission. Historically, most research on understanding space radiation-induced health risks has been performed using acute exposures of monoenergetic single-ion beams. Given the complexity of the space radiation environment, numerous studies spanning relevant ions and energies across multiple model systems and endpoints were required. Major scientific questions on the additivity of biological responses from single-ion data and the effect of dose rate remain. The simulator provides researchers the ability to conduct mixed field radiation studies on the ground under controlled conditions.

Now, research teams are using cellular and animal model systems as well as advanced tissues-on-a-chip to quantify mixed-field radiation quality effects, dose, and dose-rate effects compared with gamma (or Earth-like) irradiated controls. NASA will use these results to improve and validate risk models and update radiation exposure limits if needed. The GCR Simulator also provides a ground-based analog to test the efficacy of medical countermeasures to mitigate the health risks faced by astronauts. Multiple research teams are currently testing the effectiveness of a variety of pharmaceuticals and dietary supplements such as antioxidants and anti-inflammatory drugs to protect sensitive tissues from radiation damage.

VI. What key simulation challenges remain?

Key simulation challenges remain in determining whether the delivered field of mixed ion species adequately approximates the GCR environment for radiobiology endpoints of interest, in understanding how best to implement dose-rate studies to better simulate chronic deep-space exposures, and in the selection of appropriate animal and cell models supporting translation to humans. Research results are forthcoming and will inform future modifications to reference field specifications and implementation strategy for improved ground based GCR simulations at the NSRL.

Key Words:

Space Exploration Missions

Galactic Cosmic Radiation

NASA Space Radiation Research Laboratory

GCR Simulator

Glossary

1. **Fully ionized particles** – An atom that has been stripped of all its electrons.
2. **Gray, Gy** – Dose, or amount of energy deposited per unit mass, measured in the SI units of Gray.
3. **Sievert, Sv** – Unit of measure to reflect biological damage from a given dose (Gy) of radiation. This is referred to as the dose equivalent and the SI unit of measure is Sv.
4. **Radiation quality** – Describes the biological effect from a given dose (Gy) of radiation usually relative to gamma radiation. Understanding the quality of space radiation is fundamental to quantifying health risks faced by astronauts.
5. **Polyethylene degrader system.** A machine that remotely inserts defined thicknesses of polyethylene sheets into the beamline to slow down incoming particles. The GCR simulator uses between ~1 to 77 mm of polyethylene.

Conflict of Interest

The authors declare no conflict of interest.

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Original Source article

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Citation

An author biography and photo for each author

Dr. Lisa Simonsen is a senior scientist for Space Radiation Systems Integration at NASA Headquarters in Washington DC. She provides scientific and technical assessments to guide Agency strategic technology planning and investment strategies for radiation protection systems. In addition, Dr. Simonsen provides NASA senior technical leadership to maintain the NASA Space Radiation Laboratory (at DOE Brookhaven National Laboratory) as world-class facility to meet NASA objectives and U.S. national interests to mitigate risk and optimize engineering designs. Dr. Simonsen received her PhD in Nuclear Engineering and Health Physics from the University of Virginia, Charlottesville, VA in 1997.

Dr. Tony Slaba is a research physicist at NASA Langley Research Center. He is the primary developer for NASA's space radiation transport code, HZETRN. Starting in ~2015, Dr. Slaba and colleagues developed new techniques for simulating the space radiation environment at ground-based accelerator facilities for radiobiology experiments. More recently, he has extended NASA's model for projecting lifetime cancer risk for astronauts to an ensemble framework. Dr. Slaba received his PhD in computational and applied mathematics from Old Dominion University in 2007 and has authored or contributed to over 60 peer reviewed journal articles since 2010.