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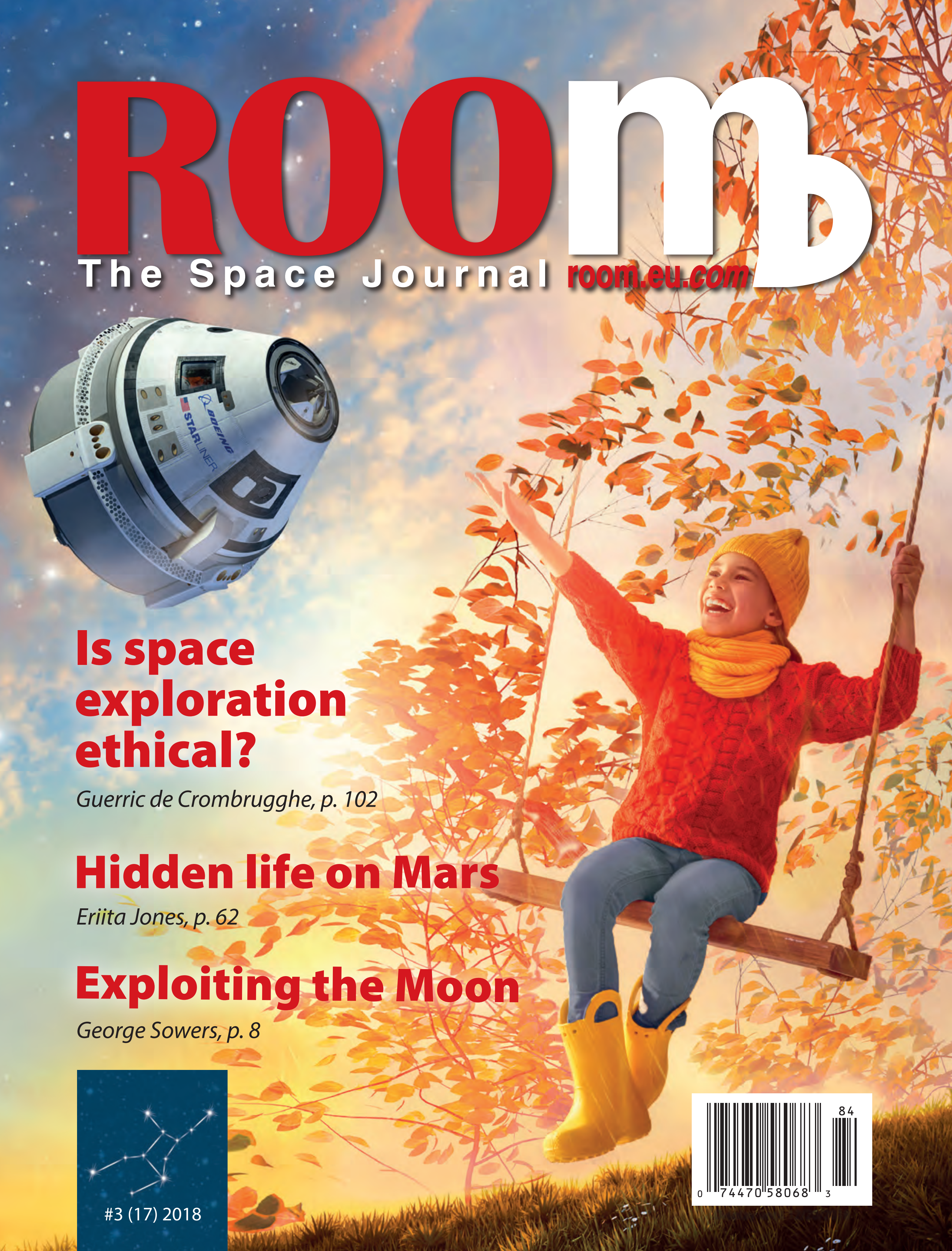

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Radiation study paves way for safe deep space exploration

Exposure to space radiation remains one of the greatest challenges for human space exploration beyond low Earth orbit (LEO) for long-duration missions to the Moon and Mars. The Matroshka AstroRad Radiation Experiment (MARE) will test newly developed personal protection equipment and close gaps in our understanding of the radiation field and its effects on crew beyond LEO. This article provides a detailed description of the MARE payload and its implications for enabling future human space exploration.

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While astronauts on the International Space Station (ISS), at an altitude of about 400 km, are beyond the radiation protection of Earth's atmosphere, they still enjoy the benefits provided by the magnetic field of Earth. But when astronauts venture beyond LEO towards the Moon, Mars, or other celestial bodies, they leave the protection of both Earth's atmosphere and magnetosphere, thereby increasing their exposure to harmful space-borne radiation. Therefore, appropriate shielding and protective mechanisms are necessary in order to prevent acute exposures and reduce cumulative exposures to as low as reasonably achievable (ALARA). This need is amplified as missions get longer, especially when humans go to Mars in coming decades.

The next time a human-rated spacecraft departs LEO en route to the Moon, it will carry a payload specifically focused on protecting astronauts from space radiation. NASA's uncrewed Orion Exploration Mission 1 (EM-1) flight around the Moon in 2019 will carry the MARE payload to expand upon previous research done on the ISS as part of the Matroshka project to study space radiation and its impact on the human body, and to increase the scope of testing novel personal radiation protection equipment - specifically, the AstroRad radiation protection garment. MARE also has the distinction of being the first experiment

designed to assess the radiation dose deposition within the human body in the severe radiation environment beyond LEO.

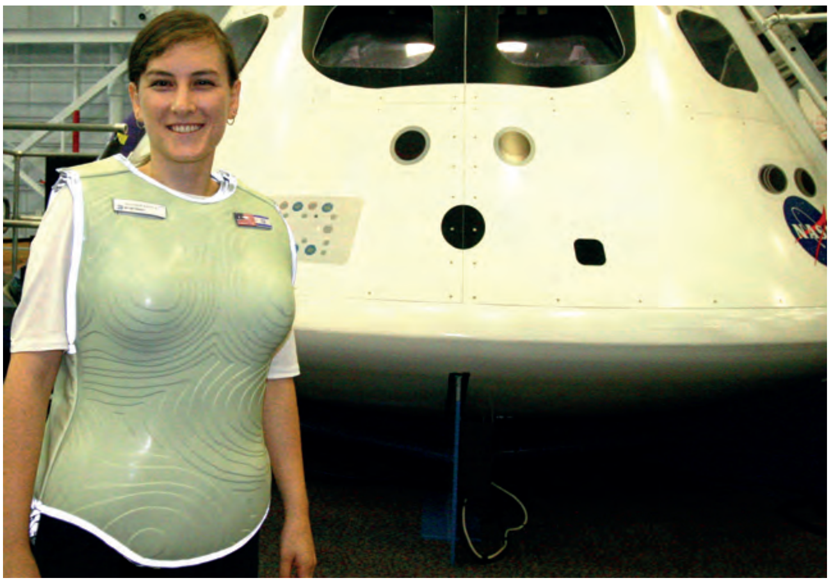
Radiation threats

Space crews travelling to the Moon or Mars face three sources of naturally occurring radiation which can threaten their health: galactic cosmic rays (GCR), solar particle events (SPE), and trapped radiation in the Van Allen belts. Depending on a variety of factors including the total radiation dose and exposure time, these ionizing radiation sources increase the lifetime risk of cancer, central nervous system (CNS) decrements, degenerative tissue effects or even acute radiation syndrome (ARS). The current standard is to limit the radiation exposure induced death (REID) probability to be less than three percent - which is not an easy challenge according to some risk assessments for Mars missions.

GCR are extremely high energy charged particles that originate from outside of our solar system. They can penetrate through spacecraft and the human body. Most GCR are lighter ions - protons and alpha particles - but approximately one percent are heavy ions with high charge and energy (HZE). Despite being a small fraction of GCR, HZE are considered especially important due to their high linear energy transfer making them more destructive to biological systems compared to other radiation sources.

Unfortunately, due to GCR's extremely high energy and penetration through matter, the ability to block them and the secondary radiation associated with them using passive shielding is limited in foreseeable

▼ AstroRad protective garment with the Orion capsule at NASA's Johnson Space Center.



Crew radiation protection is a design driver of the Orion spacecraft and it includes a storm shelter as a method to protect crew

spaceflight architectures. The dose rate from GCR is relatively low compared to SPE, but especially for longer missions the cumulative dose from GCR increases the risk of radiation-induced cancer, CNS effects and degenerative tissue effects.

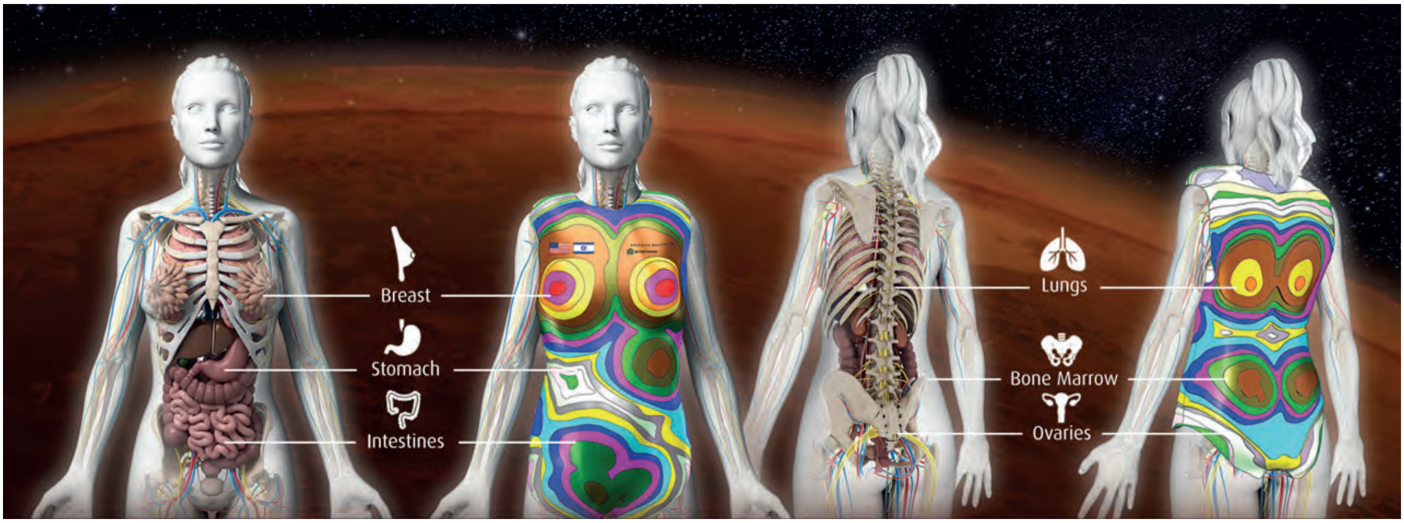
SPE, also called proton storms, occur when energetic particles are emitted by the Sun with high intensity making them capable of delivering acute doses of radiation. Most of the particles are high energy protons but are less energetic than GCR. Such storms occur intermittently and can last for hours to days. They are more likely during times of maximum solar activity but are ultimately unpredictable. Current detection methods allow for warning space crews in advance by about an hour to prepare for the incoming radiation. Since even modest amounts of shielding are beneficial for SPE protection, being inside the spacecraft and not on EVA during SPEs is very important.

Interestingly, there is an inverse relationship between the amount of GCR radiation and the SPE occurrence probability due to the Sun's 11-year solar cycle. During periods of maximum solar activity, SPE occurrence is more likely, but GCR radiation is deflected by the increased strength of the solar wind. The exact opposite effect is seen at solar minimum activity when SPE are less likely and GCR flux through the solar system is greater.

The Van Allen belts consist of high energy electrons and protons, mostly originating from the solar wind, which are captured and trapped in Earth's magnetic field. The risk to astronauts from the Van Allen belts is limited by designing mission trajectories that avoid long durations of exposure. The energy range of trapped protons is comparable to that of solar energetic particles encountered during SPEs. Therefore, MARE real-time radiation measurements performed on board Orion during Van Allen belt transit will be indicative of the shielding capability of AstroRad in the SPE environment even if no SPE occurs during the mission.

Orion Exploration Mission 1

The Orion Multi-Purpose Crew Vehicle is NASA's newest spacecraft designed to transport human crew farther from Earth than ever before, with plans for



▲ AstroRad Selective Shielding - proprietary smart shielding that focuses protection on the most vulnerable organs.

cis lunar flights and eventually round-trips to Mars. It is the first human-rated spacecraft for beyond-LEO space exploration since the Apollo programme.

Crew radiation protection is a design driver of the Orion spacecraft and it includes a storm shelter as a method to protect crew from intense SPE. The storm shelter is an internal area in the spacecraft where astronauts huddle together to be as protected as possible during the SPE by the structure of Orion and available on-board mass. While the storm shelter is effective in reducing astronaut radiation exposure during SPEs, it has the operational disadvantage of restricting astronauts to a confined space away from Orion control systems - potentially for days in cases of long or sequential SPEs.

Orion's first test flight, Exploration Flight Test 1 (EFT-1), was successfully completed in 2014. EM-1 is Orion's next test flight scheduled for 2019. The EM-1 launch will be the first use of the Space Launch System (SLS), the largest rocket launched since Saturn V carried Apollo astronauts to the Moon. During EM-1, Orion will fly without a crew beyond Earth's magnetosphere, orbit the Moon and conclude the return trip by splashing down in the Pacific Ocean. This trajectory will expose Orion to the Van Allen belt trapped radiation, GCR and SPEs if any occur during the mission.

Wearable protection is much more mass efficient than shielding the entire spacecraft

Wearable radiation protection

The AstroRad is personal protective equipment for astronauts to wear beyond LEO that is intended to provide significant reduction in REID while eliminating the possibility of ARS. It was co-developed by Israeli-based start-up company, StemRad, and Lockheed Martin to mitigate SPE effects, with initial research and development support coming from the Space Florida-Israel Innovation Partnership programme.

The AstroRad equipment follows previous advancements in wearable radiation protection developed by StemRad - namely the 360 Gamma equipment which protects first responders and military personnel on Earth from gamma radiation for nuclear and radiological response. Wearable protection is much more mass efficient than shielding the entire spacecraft and since the energy of SPE radiation is considerably less than GCR, the shielding provided by the AstroRad is very effective at mitigating SPE exposure - even from the most intense events.

The AstroRad uses a proprietary smart shielding design to selectively protect those organs and tissues which are most sensitive to radiation in terms of REID probability, to provide the greatest biological impact of protection with the least amount of mass. Tissue weighting factors are assigned to organs and tissues in the body to reflect the variance in radiation sensitivity, with organs like the lungs, bone marrow, colon, stomach, breasts and ovaries being among the most sensitive. Selective protection of these organs and tissue resident stem cell concentrations within them was accomplished by designing the variable shielding, thickness to compliment the body's own shielding resulting in an intriguing, functional topographic structure.

Selectively shielding stem cells enables regeneration of damaged tissue, thereby facilitating recovery from acute effects of radiation exposure. At the same time, shielding stem cells and progenitor cells also provides a disproportionate advantage in reducing the probability of radiation-induced cancer. This is due to the exponential progeny size of a stem or progenitor cell compared with a differentiated cell. Thus, a stem cell harbouring a mutation will pass this mutation on to a large number of daughter cells, increasing the frequency of mutated cells in an organ and the probability of malignancy in that organ.

The AstroRad shielding itself is composed of a polymer structure with high abundance of hydrogen, which is advantageous for shielding against space radiation because it minimises the generation of secondary radiation. Individual, solid shielding elements are organised into a scale-like architecture to allow for flexible, comfortable movement of the astronauts while wearing the AstroRad. StemRad is currently exploring the use of recycled plastics materials generated on-board future spacecraft for use in the shielding elements which would dramatically decrease the payload mass associated with the equipment.

According to simulation studies, the AstroRad provides protection on par with the on-board storm shelter of Orion, while enabling crew to exit the storm shelter to perform important activities even in the midst of a proton storm. Also, consistent with the ALARA radiation protection principle, the AstroRad is compatible for use even within the spacecraft's storm shelter so crew can combine both protection tools simultaneously to minimise long-term health risks.

ISS Matroshka heritage

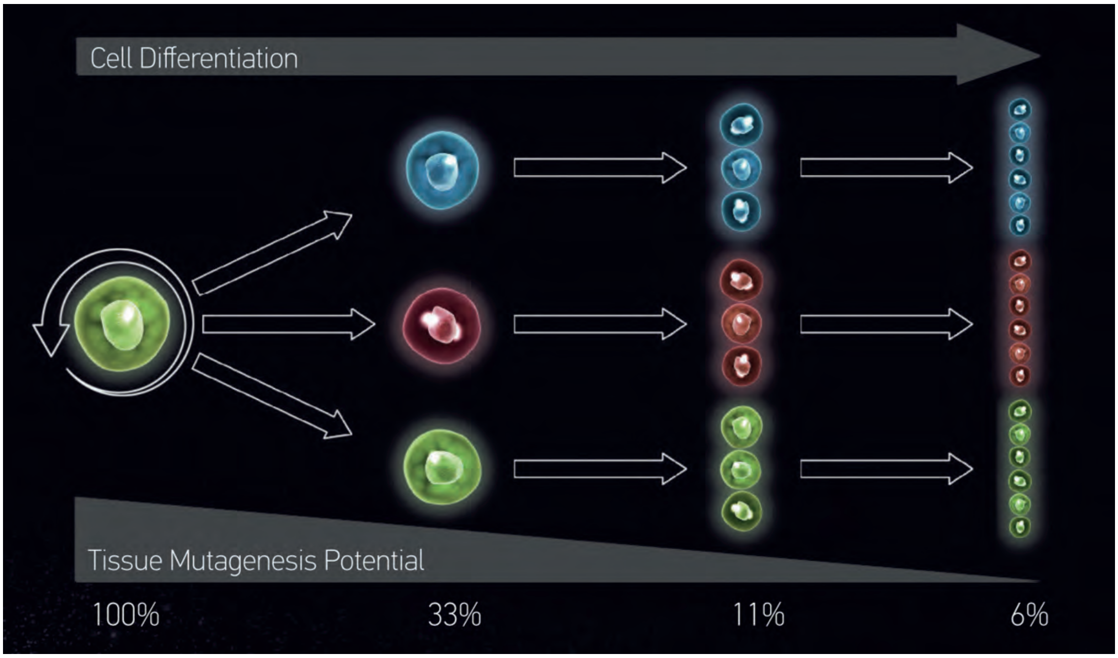
The German Aerospace Center (DLR) led the Matroshka project on the Space Station beginning in 2004 with the goal of delivering basic radiation dose deposition data for the calculation of health risks for astronauts. The Matroshka experiments were named after the popular Russian doll but, instead of containing ever-smaller dolls fitting within each other, the Matroshka was a human mannequin used for radiation measurements called an anthropomorphic phantom.

This phantom consisted of a real human skeleton cast into a polymer formulation which is radiologically equivalent to soft tissue, with lower density material simulating the lung volumes. The Matroshka phantom was filled with thousands of passive radiation detectors in a grid pattern to measure the three-dimensional absorbed dose deposition throughout the phantom's body and to measure radiation in two environments in LEO: outside ISS (simulating a space-walk) on Matroshka-1 and inside ISS on Matroshka-2.

The Matroshka experiments were successful in developing a space radiation dose-distribution model in the human body and serving as a benchmark against which radiation transport codes can be used to model space radiation - something extremely important for projecting risks and planning future missions. MARE is taking a very similar approach but with two very important distinctions: MARE uses two phantoms instead of one to allow for one to wear the AstroRad protective equipment with the other serving as a baseline for comparison; and the radiation exposure will be inside the Orion spacecraft in the harsher beyond-LEO radiation environment.

Other researchers from around the world with heritage participation in the Dose Distribution Inside the International Space Station - 3D

Selectively shielding stem cells enables regeneration of damaged tissue, thereby facilitating recovery from acute effects of radiation exposure



◀ Preventing cancer through enhanced protection of stem cells - a mutated stem cell produces thousands of mutated daughter cells, exponentially increasing the likelihood of cancer. StemRad's smart shielding spares stem cells of radiation, dramatically reducing the number of mutated cells in an organ.

▲ Anthropomorphic phantom installation within Orion for MARE on EM-1; AstroRad-protected phantom on right.

(DOSIS-3D) experiments associated with the Matroshka project will also be contributing passive radiation detectors for MARE.

International collaboration

The DLR research team is drawing on its experience from the Matroshka experiments to prepare the two female phantoms for MARE and the mounting mechanism required for vehicle integration. This includes the calibration, positioning, read-out and analysis of thousands of passive radiation detectors to obtain the three-dimensional map of radiation absorption in the human body, thus allowing scientists to determine which organs and tissues are most impacted.

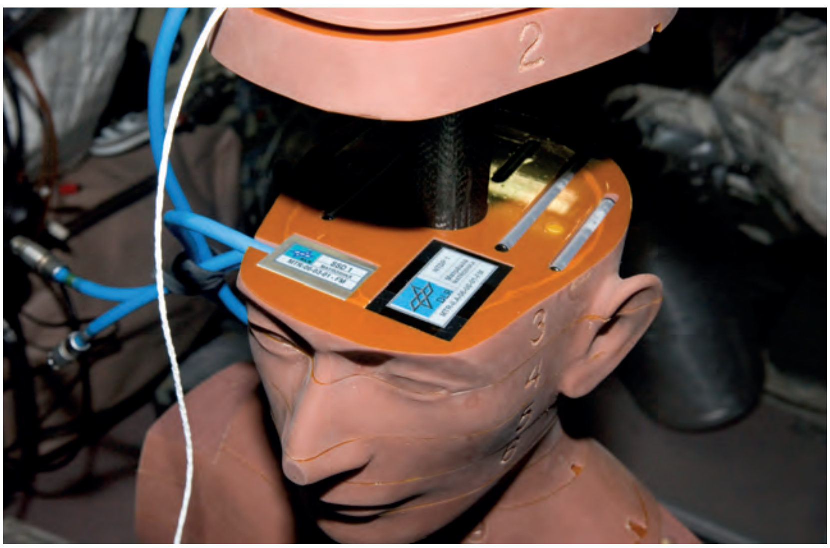
DLR is also developing customised active detectors for use within the MARE phantoms. These active detectors are battery powered with the ability to record not only how much radiation was absorbed at designated positions, but also when the exposures occurred - a necessary capability for discriminating between Van Allen belt, GCR and SPE exposures during the EM-1 flight. Since SPE occurrence is unpredictable and not guaranteed to occur during EM-1, proton exposure from the Van Allen belts, which are similar to SPE radiation, will serve as a proxy to assess AstroRad protection factors for SPE.

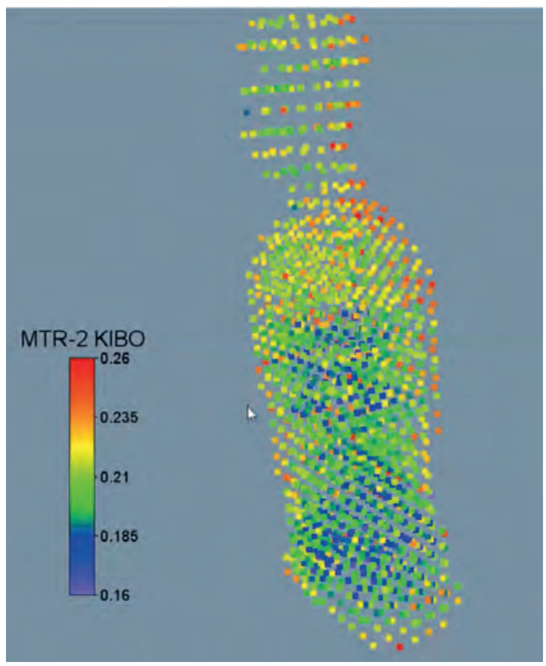
The Israel Space Agency (ISA) is supporting MARE by providing the AstroRad radiation personal protective equipment, the female phantom which will wear the AstroRad, and the associated detectors during the EM-1 flight. StemRad personnel are acting on ISA's behalf to design and manufacture the customised AstroRad for MARE and to conduct comparison analysis using data from both the protected and unprotected phantoms to assess the efficacy of the AstroRad and provide the best radiation protection equipment for spaceflight crewmembers.

NASA's contribution to MARE includes supporting the integration of the payload, providing both sets of active radiation detectors in the form of Crew Personal Active Dosimeters (CPADs), which will measure radiation on the surface of the phantoms, and the expertise of NASA's Space Radiation Analysis Group (SRAG), which monitors space weather to ensure astronaut safety on the ISS. Lockheed Martin

▼ Radiation dosimeters within the head of the anthropomorphic phantom used for the Matroshka study on ISS.

Right: Three-dimensional dose deposition results from Matroshka study on ISS.





◀ Orion future exploration mission.

personnel are also playing a central role in the development of MARE science objectives and assisting in the integration aboard Orion.

All three space agencies have been cooperating to plan MARE and will continue their support after the payload is returned to Earth to analyse the valuable collected data and publish the findings of the research.

Impact on the future

In 2006, the National Council on Radiation Protection and Measurements (NCRP) issued a report: 'Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit'. Recommendations in this report included improvement of the characterisation of the space radiation environment for GCR and SPE, assessment of SPE biological effects and shielding requirements, validation of space radiation physics and transport codes, and improved space dosimetry - all areas in which MARE is sure to have significant impact.

These findings will shed light on the safest ways to manage radiation risk to astronauts for future deep space missions. For example, if the SPE protection methods are found to be exceptionally effective, the inclusion of those measures and planning Mars flights during solar maximum (when GCR doses are lower) may be the safest radiation mitigating strategy for future crew.

MARE is a perfect example of an international collaboration coming together to build upon science and technology used on Earth and in LEO on the ISS, and advancing and testing them in the proving ground of lunar flights to help to achieve long-term exploration goals including human exploration of Mars. ■

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About the author

John Charles is a long-time NASA life scientist and manager fascinated with spaceflight history. He retired from NASA in February 2018 after nearly 33 years in a career that started as a cardiovascular investigator on Space Shuttle flights, spanned the NASA missions to the Russian space station Mir, the Shuttle flight of John Glenn, and Columbia's last mission, and included developing and overseeing the joint US/Russian one-year mission on ISS and the Twins Study. He was the Chief Scientist of NASA's Human Research Program, guiding NASA biomedical research on the ISS in preparation for sending astronauts to Mars. He is now the first scientist-in-residence at Space Center Houston, the official visitors center of NASA's Johnson Space Center, has one of the few emeritus positions at Johnson, and is also Adjunct Professor of Kinesiology at Texas A&M University. He and his wife Kathy own a private outreach, education, research and consulting business.

Acknowledgment

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