GALACTIC COSMIC RAYS IN SPACE: A REVIEW OF EXPOSURES AND HEALTH EFFECTS ON ASTRONAUTS

Hiten Pragji, Ayidah Barqawi, Okiemute Mughelli, Siyu Huang
University of Surrey
(Dated: May 26, 2020)

The radiation health risks to astronauts on multiple ISS missions, exploration missions and EVAs mainly arise from exposure to galactic cosmic rays and solar particle events. Long-term exposures to cosmic rays can induce stochastic effects such as cancer, and short-term exposures to highly energetic solar particles can induce radiation sickness. We need to know what the risks are, what the limitations are in predicting these risks, the biggest challenges in reducing the exposure to astronauts, and how we may protect astronauts from space radiation. We have found that at solar maximum, cosmic ray exposures are decreased by a factor of 3-4 compared to solar minimum. Cosmic ray models have been compared and we showed that the inclusion of new data reinforces the ability for these models to predict exposures. The health effects of acute radiation syndrome are reviewed and a countermeasure program is suggested. Shielding requirements vary between radiation types, and we discuss the implications of performing extravehicular activities. A thorough review of risk management efforts is given, and the linear no-threshold risk model is critiqued. The overall aim of this review was to summarise the space radiation literature thus far and recommend further improvements to research in this field.

I. INTRODUCTION

Space exploration missions present very unique challenges to astronauts due to the nature of the radiation permeating the space in which they travel. The main radiation health risks are from energetic solar particle events (SPEs) and long-term exposures to galactic cosmic rays (GCRs). Modern shielding materials can protect astronauts from photon radiation but cannot protect against the biological damage incurred by the body due to relativistic heavy ions, whose origins may lie elsewhere in the galaxy, such as in supernovae. These heavy charged particles interact with the spacecraft material, causing secondary ionisations that release δ-rays whose lateral diffusion can occur over many micrometres from the primary ion track.[1] Fragmentation of the heavy ion into particles of reduced atomic mass may have the potential to cause more biological damage than the primary particle.[2]

Exposures to high fluxes of low- to medium-energy protons emanating from the Sun during solar particle events (SPEs), such as solar flares or coronal mass ejections (CMEs), places the crew at a large risk of prodromal effects (nausea, vomiting), skin injury, immune system dysfunction and haematological changes.[3] Thus, appropriate measures must be taken to minimise the risk of biological damage from any duration or type of exposure. The first consideration might be to employ thicker shielding around the spacecraft, however, this is not practical due to current lift-mass capabilities of space launch systems; additionally, thicker shielding would only reduce the GCR effective dose by $\leq$25% using aluminium, or by $\leq$35% using polyethene.[1,2]

NASA has set a maximum permissible exposure limit to astronaut career exposures, a 3% risk of exposure-induced death (REID), and protects against uncertainties in the risk projection model by making estimates of the upper 95% confidence level (CL).[4] To achieve this target, risk projection models are combined with radiation transport codes to provide estimates of dose quantities pertaining to the radiobiological effects of ionising radiation. However, risk projection models are subject to very large uncertainties that are difficult to estimate and depend on the type of risk and the model used to predict the risk.[5] This review summarises and critiques the methods used to obtain dose estimates from various GCR models and observed measurements, and we compare the observed short- and long-term effects of exposure to space radiation. An overview of current spacecraft shielding is given. We also review the requirements for further research into the radiobiological effects of GCR radiation, medical countermeasures, and NASA's risk management procedure.

II. SPACE RADIATION ENVIRONMENT

The space radiation environment is a complex radiation field comprising of the full electromagnetic spectrum and a mixture of charged particles. Typical spacecraft shielding materials provide astronauts with sufficient protection against photon radiation but cannot effectively shield against the energetic charged particle (ion) species traversing the spacecraft. These energetic ions are relativistic and originate from both outside and inside the solar system. The four main sources of radiation in space are: galactic cosmic rays (GCRs), solar particle events (SPEs), the solar wind, and trapped radiation belts (Van Allen belts). Figure 1 shows the types and energies of radiation relevant in space; each source varies spatially and temporally. GCRs present a significant health risk to astronauts on deep-space exploration missions or extended periods in LEO and near-Earth interplanetary space.

III. GALACTIC COSMIC RAYS

A. COMPOSITION

The composition of GCR nuclei has been studied using data spanning several decades, obtained by both balloon-based missions and space-based missions (Pioneer, Voyager, Ulysses spacecraft) for LEO, near-Earth interplanetary space and deep space. Composition data for low-energy (50-500 MeV/u) heavy ions (Z>2) from the Cosmic Ray Isotope Spectrometer (CRIS) onboard NASA's Advanced Composition Explorer (ACE) spacecraft has been available since 1997, and we have recently obtained planetary surface measurements thanks to the Radiation Assessment Detector (RAD) onboard the Mars Science Laboratory's Curiosity rover. According to the literature thus far, GCRs are composed of 85-

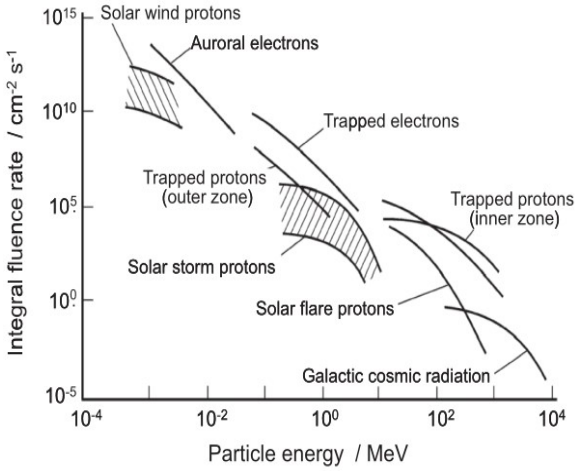

FIG. 1: Sources of ionising radiation in space and their corresponding energy ranges.[6]

90% protons (hydrogen nuclei), 10-13% helium nuclei, about 1% electrons, and about 1% heavier nuclei.[7] The latter component is termed HZE – high (H) charge (Z) and energy (E); these ions are documented to have charges in the range $3 \leq Z \leq 28$.[2,3,8] Figure 2 shows the relative abundance of atomic

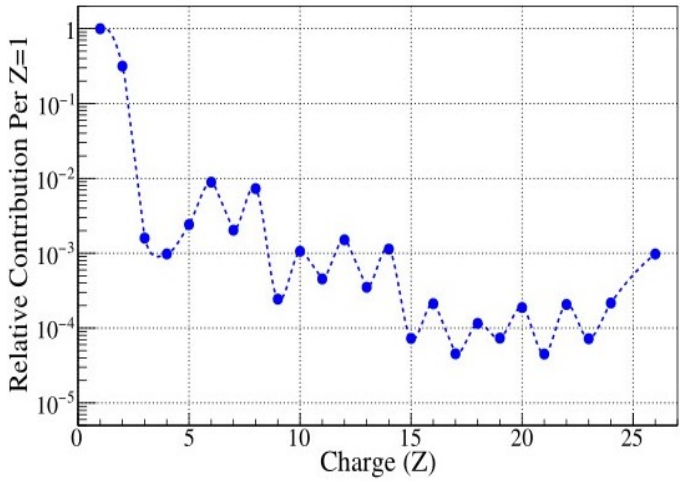

FIG. 2: Relative contribution of each of the nuclei components of the GCR spectrum for $1 \leq Z \leq 26$, normalised to Z=1 on the y-axis.[2]

species in the GCR spectrum; data was adapted from a study on model calculations of the distribution of the particle flux in deep-space and Martian orbit by CRIS and MARIE instruments, respectively.[9] This study compared the December 2002 particle spectrum of the CRIS instrument with calculations using NASA's high-charge-and-energy transport (HZETRN) computer code and the quantum fragmentation multiple-scattering model of heavy-ion fragmentation (QMSFRG). Results from this comparison showed that the model calculations are in agreement with CRIS/ACE observed particle fluxes by about 15% for low Z and about 5% for high Z.[9]

B. SPECTRA AND MODELS

GCR spectra are required to calculate radiation exposures to humans on deep-space missions. In descriptions of the GCR spectrum, it is usually sufficient to consider GCRs of energies within $10 \leq E \leq 10^5$ MeV/nucleon; though, energies below 30 MeV/u tend not to be included in descriptions of the radiation environment in space, because their ranges are very small.[7,8,10] GCR energies can extend to about 10^{21} eV.[11] GCR intensity is modulated by solar activity and fluctuates inversely with the solar cycle; this is a direct consequence of the reversal of the Sun's dipolar magnetic field once every ≈11 years, resulting in solar minima and maxima periods. The solar modulation parameter describes the attenuation of GCR particles depending on the state of the heliosphere (the bubble created by the solar wind).[12] At solar maximum, the increased outward flow of material from the Sun enhances the magnetic field of the heliosphere, which has the effect of blocking the inward flow of GCRs from outside the solar system. Therefore, GCR flux (particles per unit area, time, solid angle and energy) is reduced at solar maximum.[10] At solar maximum, however, the probability of occurrence of SPEs such as solar flares and CMEs is larger than at solar minimum and the relatively high energy and particle fluences pose a major threat to astronauts. Although many SPEs occur during the solar cycle, they are difficult to predict.[13] Forecasting and alert systems should be improved to allow for better prediction of SPEs.

The Badhwar-O'Neill GCR flux model (BO'96) was updated (now BO'10) to include GCR data collected by CRIS/ACE and all previous balloon and satellite data, spanning six solar cycles, with an improved method of calculating the solar modulation parameter. The BO'10 model was used to analyse the spatial and temporal variation in GCR flux over the period 1955 to 2010; the 2010 paper shows that the BON'10 model can accurately model the GCR spectrum using 55 years of GCR measurements, providing knowledge of worst-case scenarios in mission risk assessments. A more recent paper used the BON'10 model with the radiation transport code, GEANT4, to highlight discrepancies between different GCR models.[8] Figure 3 shows the effect of different solar conditions on absorbed dose and dose equivalent rates for two mission environments. Comparisons of the data with more recent papers confirms that GCR flux during solar maximum is reduced by a factor of 3 to 4 compared to solar minimum.[14,15] For the first time, it is possible to compare ground-based measurements on Earth with measurements of the radiation surface environment on Mars. RAD is the first instrument to continuously measure the surface radiation environment of Mars. Charged particle fluence spectra are used to validate radiation transport models currently used to model the radiation environments on Mars and elsewhere in space; RAD data was found to improve the choice of input parameters and physical models.[11,16]

IV. SPACE RADIATION EXPOSURES

Radiation exposures are typically provided by the principal dosimetric quantities absorbed dose, dose equivalent and effective dose. The dose equivalent H_T is used to provide information about the biological response to a specific type of radiation and is given by

$$H_T = \sum_R w_R D_T, \tag{1}$$

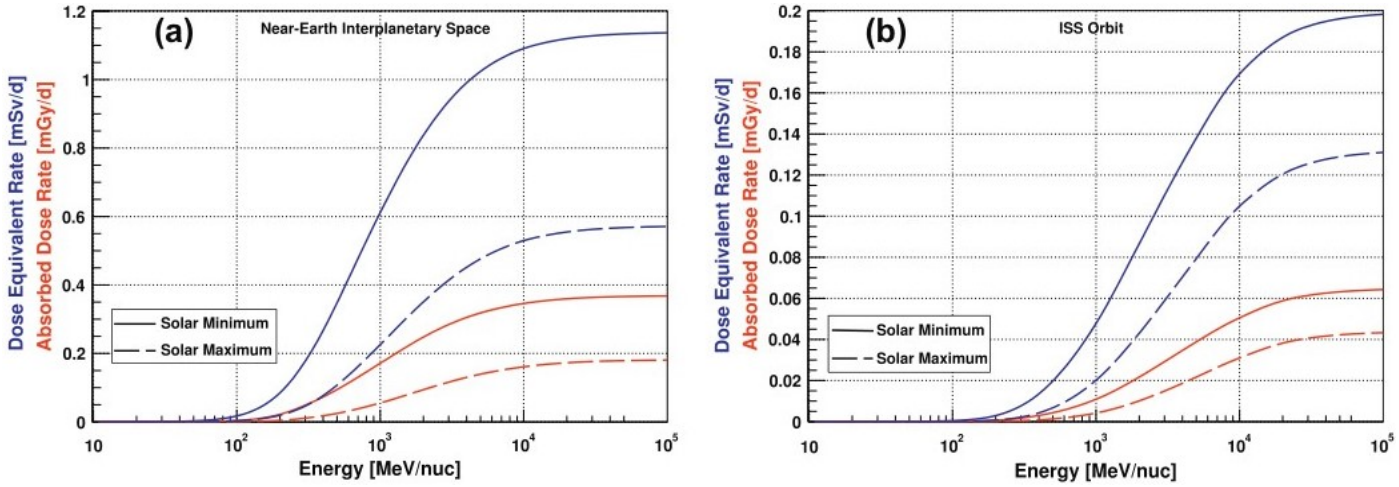

FIG. 3: The relationship between dose rates and GCR energies for solar minimum (straight line) and maximum (dotted line) at (a) near-Earth interplanetary orbit and (b) ISS orbit.[8]

where w_R is the radiation weighting factor and the absorbed dose $D_T = \epsilon_T/m_T$ is the total energy deposited in a mass m_T of tissue. The effective dose E is the sum of H_T to different tissues each weighted by the tissue weighting factor w_T: $E = \sum_T H_T$. Figure 4 was obtained from GCR models using HZETRN code and compares the effective doses for GCR nuclei for the interior of a spherical spacecraft shielded by 5 g cm^{-2} of aluminium (Al), on different mission scenarios and durations. According to the International Commission on

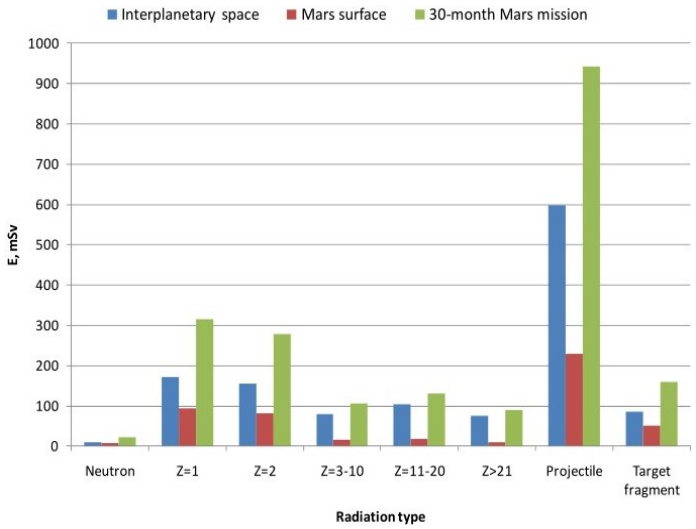

FIG. 4: The contribution of different charge groups to the annual GCR exposure in interplanetary space and on the Martian surface, and for a 30-month Mars mission, inside a spherical spacecraft shielded with 5 g cm^{-2} Al.[6,14]

Radiological Protection (ICRP), the recommended method of evaluating the risk of stochastic effects such as cancer, regardless of whether the irradiation is uniform or not, involves the use of an age- and gender-independent effective dose.[4] However, the radiation risk depends on both age and gender to a large extent. Also, ICRP w_R values are not used by NASA; in space, heavy charged particles contribute significantly to the total dose, therefore, a single w_R value of 20 for heavy charged particles is a conservative estimate at best.[14] Furthermore, w_R is defined in the context of external radiation fields incident on superficial body structures and lacks the ability to describe the complex nature of space radiation fields. Instead of Equation (1), the National Council on Radiation Protection and Measurements (NCRP) recommends that the organ dose equivalent H_T be defined as a mass average m over the tissue:

$$H_T = \frac{1}{m}\int_m dm \int Q(L)F_T(L)LdL, \qquad (2)$$

where m is the mass of the organ, L is the linear energy transfer (LET $= dE/dx$), $F_T(L)$ is the particle fluence through the tissue and $Q(L)$ is the radiation quality factor (QF) which is a function of LET. The dependence of Q on LET in Equation (2) is an oversimplification that has been acknowledged by the ICRP and NCRP.[4] NASA updated its strategy for calculating dose equivalents by defining a different approach for situations in which the QF may be dependent on particle type and energy rather than LET alone.[17] The NASA QF has two components, $Q_{\mathrm{NASA,solid}}$ and $Q_{\mathrm{NASA,leukaemia}}$, to distinguish between cellular growths in solid organs (solid cancer) and blood cancers (leukaemia). Figure 5 compares the body-averaged NASA QF values with the ICRP Q(L) relationship, as functions of the charge Z of the primary incident particle, for two shielding conditions. All curves in Figure 5 exhibit a similar behaviour. However, the major differences in average Q values are observed for low- and high-Z particles.

V. RADIATION HEALTH EFFECTS

Outside LEO, the nucleus of every cell in an astronaut's body would be traversed by a proton once every few days and an HZE ion once every few months.[1,2,10] Despite their infrequency and relatively low contribution to GCR composition, HZE ions contribute a significant amount to the dose received by an astronaut. The high ionisation power of HZE ions is explained by the mechanism of interaction of heavy charged particles with matter, which is well known. In general, high-LET radiation produces more irreparable damage than a similar dose of low-LET radiation. It has been shown that energy deposition by high-LET radiation can cause different DNA lesions, such as complex DNA breaks, and that complex biological damage is associated with an increased relative biological effectiveness (RBE) of densely ionising ra-

diation such as HZE.[1] The health and performance of crew members in space might be impacted by a major SPE, multiple SPEs or the cumulative effect of SPEs and GCRs. High particle and energy fluence rates during an energetic SPE can increase the risk of short-term and long-term side effects.

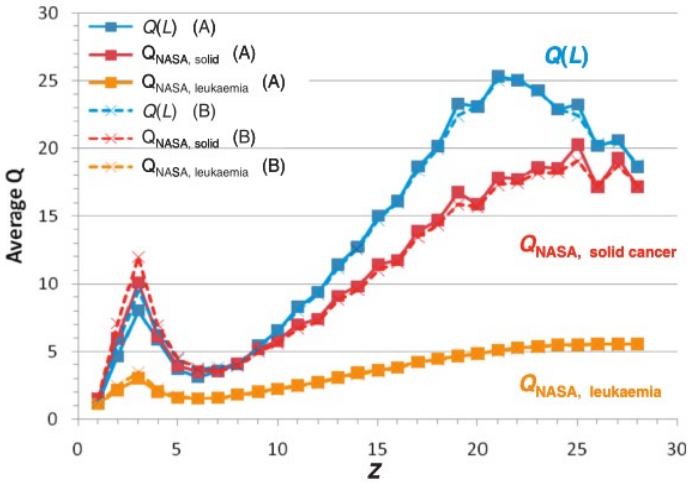

FIG. 5: Body-averaged quality factor values as a function of primary incident particle charge Z for NASA QFs and the ICRP Q(L) function, for (A) thin, 5 g cm^{-2} Al and (B) thick, 20 g cm^{-2} Al shielding conditions.[6]

A. SHORT-TERM EFFECTS

Short-term effects arise from direct damage to cells, caused by ionisation, which can lead to decreased blood function, skin erythema, hair loss, and reproductive dysfunction. The damage to the blood system depends largely on the damage of radiation to the bone marrow and lymphatic tissue; the main reasons for this is that normal cell division is inhibited, leading to cell death. The risk of crew members suffering from acute radiation syndrome (ARS) has been identified as a major threat during future exploration-grade missions. There are two main ways in which space radiation can damage cells and tissues: via direct action, which damages the active material through the ionisation and excitation of radiation, and via indirect action, where other molecules or atoms in the active material are irradiated to produce free radicals that cause damage to active substances. The severity of radiation damage is related to the radiation dose. If the exposure is relatively mild, symptoms will include nausea, vomiting, a decreased blood count and increased susceptibility to infection. The harsh radiation environment of space can destroy the nucleus and causes mutations, leading to a series of radiation diseases. Astronauts exposed to space radiation may suffer profound fatal symptoms because the cells are degraded due to the destruction of DNA and other cellular structures.

ARS is a systemic disease caused by high dose (>1Gy) ionising radiation in a short period. ARS is divided into three syndromes: hematopoietic syndrome, gastrointestinal syndrome and neurovascular syndrome. Hematopoietic syndrome results from radiation doses that may be encountered during exposure to an SPE.[18,19] It damages the hematopoietic blood system and is mainly caused by pancytopenia, deficiency in red blood cells, white blood cells and platelets (the three cellular components of blood) and for doses between 3.5 and 5.5 Gy, 50% to 99% of untreated individuals will display severe symptoms such as bleeding and infections.[13]

Gastrointestinal syndrome damages the gastrointestinal tract and the mucosa of the gastrointestinal tract will fall off in a large area. Crews absorbing 6-30 Gy of radiation will suffer from high fever, vomiting and repeated diarrhoea. Neurovascular syndrome occurs for exposures larger than 30 Gy.[20] The symptoms of neurovascular syndrome are cerebellar granule cells and brain stem cells with large-area contraction and necrosis, cerebral circulation disorders, and oedema. Its clinical manifestations are ataxia, increased muscle tone and tremor, spasm, lethargy, and nystagmus.

The stages of ARS include prodromal, latent, critical and recover stages. During the prodromal stage, the main symptoms experienced by patients post-exposure are gastrointestinal dysfunction, hematopoietic dysfunction and metabolic disorders. During the latent stage, symptoms will alleviate or disappear and the mental state has improved significantly, but the hematopoietic function will rapidly decline. The critical stage is marked by symptoms of increased body temperature, vomiting and diarrhoea, systemic failure, obvious infection and bleeding, and severe hematopoietic dysfunction. The recover stage is where the patient's body gradually improves after being exposed for 35-60 days.

In crew members who have suffered high levels of ionising radiation, stem cell or bone marrow transplantation will be the only option.[21] However, if medical technology onboard the spacecraft is incapable of stem cell transplantation or bone marrow transplantation, palliative care will be the only option. Treatment is partly determined by the Andrews curves in Figure 6, which show lymphocyte depletion kinetics. During the early stages of exposure, anti-radiation and

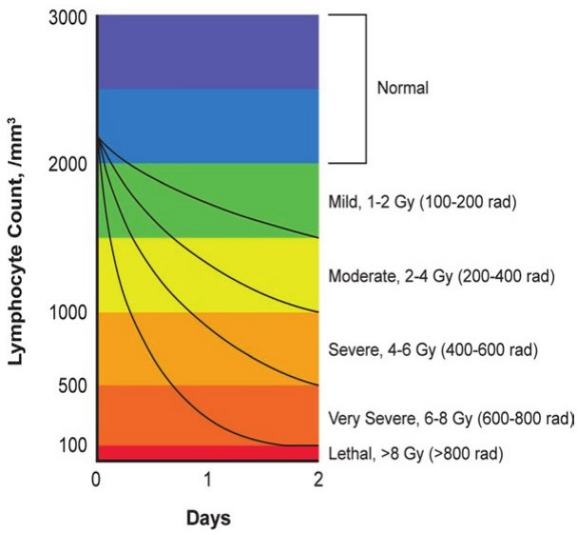

FIG. 6: Andrews curves describing the pattern of lymphocyte response in relation to dose.[22]

microcirculation-improving drugs such as cysteine (Cys) and mercaptoethylamine (MEA) can be used, and MEA is five times more effective than Cys. In addition, estrogen can also be used to stimulate the proliferation and differentiation of hematopoietic stem cells. Antibiotic and anti-bleeding drugs can be used as a combination. Sometimes it is also possible to use internal nutrition and proton pump inhibitors.

When performing long-term missions in space, the crew is indeed in danger of being exposed to the radiation dose that

causes ARS. To prepare for space missions, agencies must have the ability to accurately predict radiation exposure and be able to deal with the corresponding consequences.[18,23,24] One method is to implement a radiation medical countermeasures program. This might involve: choosing a time when there is no strong solar activity for spaceflight, shortening travel time, choosing older male astronauts that are resistant to radiation, improving spacecraft shielding and taking medicines and foods that can reduce radiation syndrome and harm. At the same time, some drugs that can be used to treat or prevent radiation. Superoxide dismutase (SOD) has a certain protective effect on radiation damage.

Many astronauts have complained about bright flashes that streak across their vision as they are trying to sleep, which is thought to be caused by high-energy cosmic radiation.[25] Decompression may lead to an embolism due to the reduced pressure in the environment, which can lower the boiling temperature of body fluids and introduce a transition of liquid water around the bloodstream and soft tissues into water vapour. The slightest ebullism can cause tissue swelling and the skin can be bruised as water vapour is formed under it; at worst, this can give rise to embolism, or blood vessel obstruction due to gas effervesces in the bloodstream. The muscular waste experienced by astronauts is closely related to that of bedridden patients, and as they return to Earth, some of the astronauts have difficulties maintaining an upright posture.

B. LONG-TERM EFFECTS

The long-term effects of the space radiation environment on the human body include cancer, genetic effects and cataracts. High-energy radiation penetrates human cells and causes damage to DNA. If DNA cannot be repaired, chromosomal abnormalities will occur. When radiation causes clusters of DNA damage, base pairs cannot be formed due to loss of nucleobases, which will cause damage to the main chain of genetic structure.[26] When the normal function of the cell is damaged, there will be erroneous repair or incomplete repair of the cell's DNA, which will cause the cell to mutate and invade the surrounding tissue or transfer to the far away site, which will lead to cell cancer. The probability of radiation carcinogenicity increases as the received dose increases.

C. HUMAN RESEARCH ROADMAP

NASA's Human Research Roadmap investigates and mitigates all of the significant risks to human health and performance due to hazards such as ionising radiation, altered gravity and hostile environments. Health risks from exposure to ionising radiation include carcinogenesis, acute and late central nervous system (CNS) risks, chronic and degenerative tissue risks, and acute radiation risks. Research on the various biological mechanisms is being conducted; these include DNA damage, oxidative damage, cell loss, changes in the extra-cellular matrix, cytokine activation, and many more.[25] This knowledge can assist in the production of appropriate countermeasures. Scientists have developed space radiobiology experiments to study the effects of space radiation exposure on organisms.[27] These organisms are sent to space where they are allowed to grow and develop; this is the flight experiment. The same experiment has also been repeated on the Earth, and this is called ground control.

VI. SHIELDING

The Earth is well protected from cosmic rays by a thick layer of atmospheric gases that prevent the harmful effects of cosmic rays. That nature of protecting the Earth suggests how one might shield astronauts in interplanetary space. This could be done by surrounding the astronaut with multiple layers of materials. A 2003 study estimated that the mass required to shield a spacecraft from GCRs is 400 tonnes which, in comparison with the usual weight of a fully-loaded spacecraft (200 tonnes), would be impractical for deep-space missions due to the lift-mass capabilities of planned space launch systems. In 2002, a study was carried out to design lighter and safer alternatives for spacecraft shielding. This study involved altering the configuration of electromagnetic fields, which cannot be used as a shielding method for deep space missions.[28] We present a summary of the use of magnetic field shielding against GCRs and propose some methods for shielding against GCR in deep space missions. Some recommendations and limitations of the deep space radiation environment for future research are made. Demonstrations

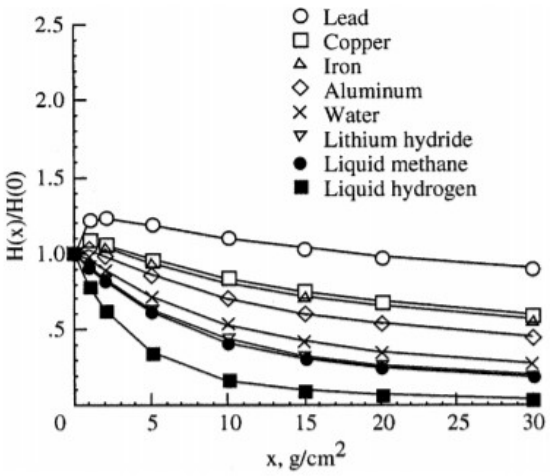

FIG. 7: Attenuation of the dose equivalent for a year of GCR exposure for shield materials.[29]

of magnetic shielding as an effective barrier against solar flare protons have been discussed, however this technique cannot be applied for the more energetic GCRs.[30] The idea of magnetic shielding was taken from the nature of the geomagnetic field of the Earth near the equator, which relies on the sheltering effect of the main dipole (north-south component). However, the geomagnetic field cannot adequately protect astronauts during their deep space missions due to the complexity and the presence of heavy ions in deep space.

Research regarding the best shielding materials as protection against GCRs has been carried out. The protection standards applied to the International Space Station (ISS) are for minimal exposure to GCR in a low orbit. These standards are for mainly low energy radiations where ion tracks have very limited lateral extents and biological responses are mainly characterized by LET. Each heavy charged particle has a characteristic response function to the human body, therefore, any shielding material chosen to attenuate these ions must be chosen carefully to prevent any future harmful effects. The curves in Figure 7 represent the relation-

ship between dose equivalents and shielding thickness for various shielding materials. There is not enough knowledge about the exposure and response of specific astronaut tissues to GCR ions, which limits researchers from making further progress in their work.[29]

Astronauts performing extravehicular activities (EVAs) are not well protected from external trapped electrons and protons especially during extremely poor weather condition. The high flux of external electrons can penetrate the extravehicular mobility unit (EMU) spacesuit and irradiate shallow tissues.[31] The dose gradient of the electron near the body surface is extremely steep and decreases by as much as three orders of magnitude within the first centimetre of depth (Figure 8). In bad weather conditions, the background radiation

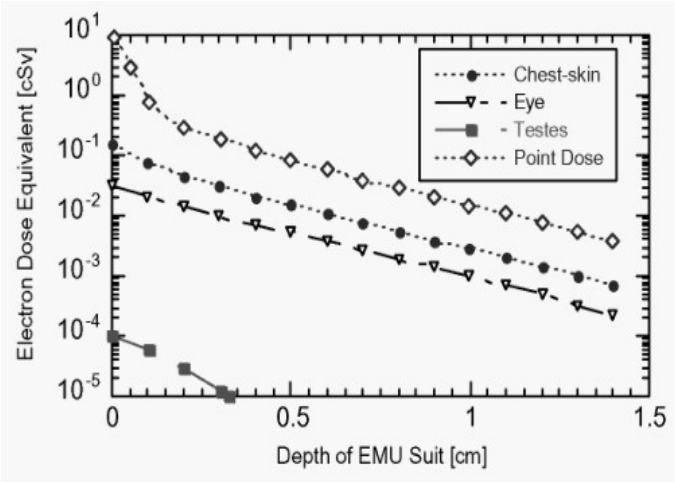

FIG. 8: Trapped electron dose equivalent as a function of EMU suit thickness for a 6-hour EVA at ISS orbit.[31]

environment changes and shielding materials and space components are repositioned. As a result, spacesuits should be designed to minimise the impact of trapped electrons and protons for future EVAs. Currently, the most effective way to avoid trapped proton belts and electrons at high latitude is by following dose-reduction strategies, including scheduling EVAs during benign weather conditions, monitoring and responding to environmental conditions, and limiting EVA duration.[31]

VII. RISK MANAGEMENT

A. TYPES OF RISK

Exposure to GCRs and, in particular, HZE ions, gives rise to two main types of risk: short-term risk and long-term risk. Short-term risks may be experienced by astronauts during SPEs, when exposure to highly energetic solar particles results in high superficial (skin) doses but relatively low doses to internal organs, potentially endangering the health and performance of crews during a mission. Long-term risks arise from exposure to normal levels of solar and GCR radiation; this leads to an increased likelihood of developing cancers and changes in brain cells, reproductive organs and other tissue.[5] Risk predictions are subject to very large uncertainties and estimating the magnitude of these uncertainties is a difficult process because uncertainties depend on the risk prediction models used, and the type of risk. The complete elimination of risk is not possible, therefore, efforts are focused on reducing the risk to manageable/relatively safe levels.

B. RISK PROJECTION MODELS

NASA's Technical Report on cancer risk projections and uncertainties compares newer projections and uncertainties with earlier ones made by the NCRP; some of the most important additions to the literature are results from radiobiology experiments conducted at NSRL, which provide new data on solid cancer and leukaemia risks from heavy charged particles. Figure 9 shows the relationship between the accumulated exposure and the probability of risk of exposure-induced death (REID). Age- and gender-specific exposure limits are based on the 3% REID criteria and estimates of the upper 95% CL protect against uncertainties in the risk projection model. The curves in Figure 9 are displaced to account for uncertainties in the model.

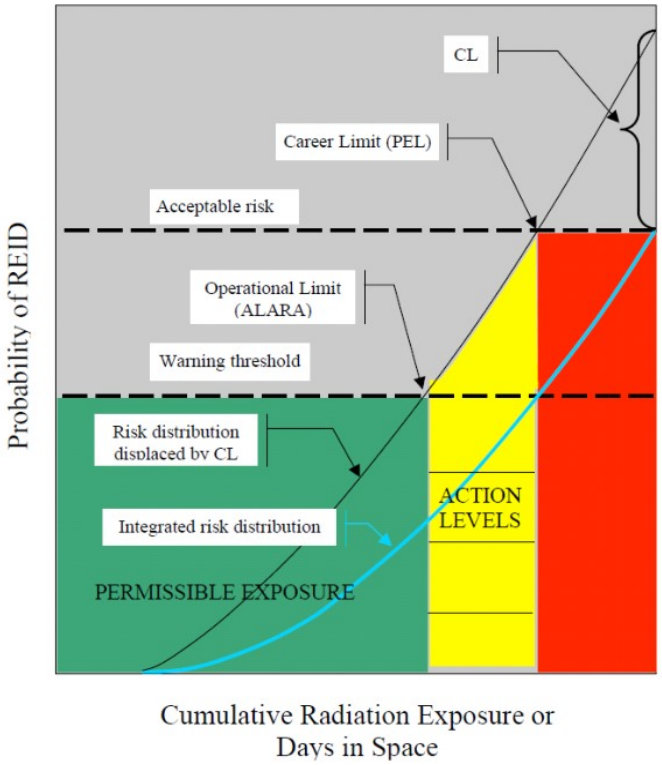

FIG. 9: The integrated risk distribution is displaced by CL to account for uncertainties in the risk projection model. The ALARA principle and action levels are fitted depending on the degree of uncertainty.[4]

The As Low As Reasonably Achievable (ALARA) principle is often used in radiation protection, but exposures in space can be so high that for deep-space missions, another method may be required; an example of a reasonable substitution is the As High As Relatively Safe (AHARS) principle.[22] However, justifying such a change in principle would require many discussions to be had within the scientific community, especially regarding the controversial linear no-threshold risk model (LNT). LNT is used to estimate stochastic health effects such as cancer, by assuming a linear relationship (proportionality) between the risk of detrimental stochastic effects and the radiation dose; the model assumes that there is no threshold below which linearity in the response ceases to exist.[1] In contrast, deterministic effects such as ARS occur beyond a threshold dose. LNT

suggests that even for an extremely low dose of radiation (one electron traversing a cell), there is a corresponding risk of carcinogenesis.[32] The controversy around LNT lies in its methodology - that the risk of stochastic health effects from low doses of radiation can be estimated by extrapolating from the risk assessed at high doses. This extrapolation is based on epidemiological data from atomic bomb survivors which models the risk of cancer mortality due to very high doses of low-LET radiation, but we know that the radiation environment of space is complex, so simple extrapolation from high dose and dose-rate to low dose and dose-rate is unlikely to provide accurate estimates of risk.

C. CHALLENGES IN ESTIMATING RISK

There are many obstacles in the way of predicting the biological risk of space radiation exposures, most important of which include modelling the transfer of energy and inadequacy of the terrestrial analogues used to study and predict the effects of space radiation on biological tissues. Most of the uncertainty in risk projection models is due to insufficient knowledge of heavy ion radiobiology. The GCR simulator at NSRL is now capable of simulating a broad spectrum of heavy ion energies, allowing us to study the passage of three to five consecutive mono-energetic beams of heavy ions through shielded biological targets.[2] A 2018 paper, detailing the limitations in predicting the health risks due to space radiation, stated that NSRL's GCR simulator cannot emulate the full GCR environment due to energy constraints; current energies are 2.5 GeV for protons and 1.0 GeV/u for heavier ions, but planned upgrades will see an increase to 4.0 GeV and 1.5 GeV/u, respectively.[33] Nevertheless, there are some inherent problems - for example, the simulator cannot generate particles that follow spallation reactions (pions, neutrons), even though this would constitute 15-20% of the intravehicular dose.[2]

Animal studies have demonstrated that the risk of radiation-induced carcinogenesis is larger for HZE exposures, as compared with low-LET radiation. However, not many studies using HZE nuclei have been conducted to fully understand their carcinogenic effectiveness.[4] The use of animal models as terrestrial analogues in ground-based radiobiology experiments introduces large uncertainties in risk projection because different animals have different responses and sensitivities to radiation, which is unlikely to reflect human responses to similar exposures. These experiments are usually carried out using rapid and sequential doses delivered to experimental animals, however these dose rates are much higher than those delivered in actual space radiation environments.[2] Thus, the process of extrapolation of cancer risk from experimental animal studies to humans is an important challenge.[5]

D. RISK MITIGATION

NASA has outlined five possible approaches to reduce risk; currently, only the first two are practical. The Strategic Plan highlights the following approaches.

1. Operational: Limit the time and duration of exposure by selecting older crew members, avoiding EVAs during SPEs, minimising the time spent travelling through interplanetary space by using spacecraft transfer trajectories.

2. Shielding: Improve upon existing computational tools, for example, radiation transport codes to more accurately describe the modification of incident radiation fields at any depth in materials. Shielding is currently the most effective countermeasure available.

3. Screening: Individuals may have genetic predispositions that place them at a higher risk of cancer than normal. Screening for radiation susceptibility could be implemented on a person-by-person basis, and the obtained data could be used for individual consent. These individuals may require aggressive surveillance if they continue to work in space.

4. Prevention: Current knowledge of radioprotective agents is limited, however, there is much doubt on the effectiveness of these substances against HZE particles. In the distant future, genetic enhancement of the body's ability to repair against radiation damage (for example, a radiation vaccine) may be possible.

5. Intervention: In the future, it may be possible for biomolecular intervention methods, such as gene therapy, to enhance cell repair by analysing damaged cells and inducing cell death within them. This would be particularly beneficial for scenarios in which radiation levels are heightened due to solar disturbances.

VIII. CONCLUSIONS

This review summarises the nature of the space radiation environment, GCR models used to calculate space radiation exposures, the health effects of space radiation on biological systems and relevant shielding requirements. The health effects of radiation sickness (ARS) due to SPEs are reviewed. The treatment of ARS is based on the CMO's observation of typical symptoms and estimation of the radiation dose, however the treatment may be limited if the spacecraft has limited medical facilities. Relevant countermeasures should be taken to reduce the danger that crew members face from exposure to acute and long-term doses. Appropriate spacecraft shielding is required to manage the intra-vehicular radiation environment. Limited knowledge of the radiobiological effects of HZE particles means that novel shielding materials may be required. Previous reviews have shown that the complex mixture of ions in space affects the choice of shielding material. NASA's Human Research Roadmap is a work in progress, and data from radiobiology experiments at NSRL should assist our understanding of the interaction of GCR nuclei with shielded biological targets. It is hoped that improvements in the output capabilities of the NSRL GCR simulator can shed light on the most complex interactions of radiation with matter. Furthermore, risk projection models should continuously be improved and reinforced using newer data. The 3% REID limit has been emphasised many times through the literature, however, new data could warrant some deviations from this limit. NASA's Strategic Plan aims to accomplish the objectives set forth by the Space Radiation Health Program, to gain the knowledge required to predict and manage radiation risk; to accomplish this, it is imperative for scientists across all relevant backgrounds to be involved in advancing space radiobiology research.

ACKNOWLEDGMENTS

We would like to thank Professor Paul Sellin for his guidance throughout the literature review process and NASA for public access to the Technical Reports Server.

[1] F. A. Cucinotta and M. Durante, Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings, The lancet oncology **7**, 431 (2006).

[2] J. C. Chancellor, R. S. Blue, K. A. Cengel, S. M. Auñón-Chancellor, K. H. Rubins, H. G. Katzgraber, and A. R. Kennedy, Limitations in predicting the space radiation health risk for exploration astronauts, npj Microgravity **4**, 1 (2018).

[3] J. C. Chancellor, G. B. Scott, and J. P. Sutton, Space radiation: the number one risk to astronaut health beyond low earth orbit, Life **4**, 491 (2014).

[4] F. A. Cucinotta, M.-H. Y. Kim, and L. J. Chappell, Space radiation cancer risk projections and uncertainties-2010, (2011).

[5] W. Schimmerling, F. Cucinotta, and J. Wilson, Radiation risk and human space exploration, Advances in Space Research **31**, 27 (2003).

[6] G. Dietze, D. Bartlett, D. Cool, F. Cucinotta, X. Jia, I. McAulay, M. Pelliccioni, V. Petrov, G. Reitz, T. Sato, *et al.*, Icrp publication 123: Assessment of radiation exposure of astronauts in space, Annals of the ICRP **42**, 1 (2013).

[7] D. M. Hassler, C. Zeitlin, R. F. Wimmer-Schweingruber, B. Ehresmann, S. Rafkin, J. L. Eigenbrode, D. E. Brinza, G. Weigle, S. Böttcher, E. Böhm, *et al.*, Mars' surface radiation environment measured with the mars science laboratory's curiosity rover, science **343**, 1244797 (2014).

[8] A. I. Mrigakshi, D. Matthiä, T. Berger, G. Reitz, and R. F. Wimmer-Schweingruber, How galactic cosmic ray models affect the estimation of radiation exposure in space, Advances in Space Research **51**, 825 (2013).

[9] P. B. Saganti, F. A. Cucinotta, J. W. Wilson, T. F. Cleghorn, and C. J. Zeitlin, Model calculations of the particle spectrum of the galactic cosmic ray (gcr) environment: Assessment with ace/cris and marie measurements, Radiation measurements **41**, 1152 (2006).

[10] G. A. Nelson, Space radiation and human exposures, a primer, Radiation research **185**, 349 (2016).

[11] B. Ehresmann, C. Zeitlin, D. M. Hassler, R. F. Wimmer-Schweingruber, E. Böhm, S. Böttcher, D. E. Brinza, S. Burmeister, J. Guo, J. Köhler, *et al.*, Charged particle spectra obtained with the mars science laboratory radiation assessment detector (msl/rad) on the surface of mars, Journal of Geophysical Research: Planets **119**, 468 (2014).

[12] P. M. O'Neill, Badhwar–o'neill 2010 galactic cosmic ray flux model—revised, IEEE Transactions on Nuclear Science **57**, 3148 (2010).

[13] L. Carnell, S. Blattnig, S. Hu, J. Huff, M.-H. Kim, R. Norman, Z. Patel, L. Simonsen, and H. Wu, Evidence report: Risk of acute radiation syndromes due to solar particle events, (2016).

[14] M. Durante and F. A. Cucinotta, Physical basis of radiation protection in space travel, Reviews of Modern Physics **83**, 1245 (2011).

[15] L. C. Simonsen, T. C. Slaba, P. Guida, and A. Rusek, Nasa's first ground-based galactic cosmic ray simulator: Enabling a new era in space radiobiology research, PLOS Biology **18**, e3000669 (2020).

[16] D. Matthiä, B. Ehresmann, H. Lohf, J. Köhler, C. Zeitlin, J. Appel, T. Sato, T. Slaba, C. Martin, T. Berger, *et al.*, The martian surface radiation environment–a comparison of models and msl/rad measurements, Journal of Space Weather and Space Climate **6**, A13 (2016).

[17] F. A. Cucinotta, Review of nasa approach to space radiation risk assessments for mars exploration, Health physics **108**, 131 (2015).

[18] L. Heslet, C. Bay, and S. Nepper-Christensen, Acute radiation syndrome (ars)–treatment of the reduced host defense, International journal of general medicine **5**, 105 (2012).

[19] R. C. Ricks, M. E. Berger, and F. M. O'Hara Jr, *The medical basis for radiation-accident preparedness: the clinical care of victims* (CRC Press, 2002).

[20] I. Gusev, A. Guskova, and F. A. Mettler, *Medical management of radiation accidents* (CRC Press, 2001).

[21] E. Chernykh, E. Y. Shevela, S. Morozov, and A. Ostanin, Immunopathogenetic aspects of ischemic stroke, Meditsinskaya Immunologiya **20**, 19 (2018).

[22] E. Seedhouse, *Space Radiation and Astronaut Safety* (Springer, 2018).

[23] J. K. Waselenko, T. J. MacVittie, W. F. Blakely, N. Pesik, A. L. Wiley, W. E. Dickerson, H. Tsu, D. L. Confer, C. N. Coleman, T. Seed, *et al.*, Medical management of the acute radiation syndrome: recommendations of the strategic national stockpile radiation working group, Annals of internal medicine **140**, 1037 (2004).

[24] F. A. Cucinotta, W. Schimmerling, J. W. Wilson, L. E. Peterson, G. D. Badhwar, P. B. Saganti, and J. F. Dicello, Space radiation cancer risks and uncertainties for mars missions, Radiation research **156**, 682 (2001).

[25] S. Hu, M.-H. Y. Kim, G. E. McClellan, and F. A. Cucinotta, Modeling the acute health effects of astronauts from exposure to large solar particle events, Health physics **96**, 465 (2009).

[26] L. W. Townsend, Implications of the space radiation environment for human exploration in deep space, Radiation protection dosimetry **115**, 44 (2005).

[27] P. D. McCormack, C. E. Swenberg, and H. Bucker, *Terrestrial space radiation and its biological effects*, Vol. 154 (Springer Science & Business Media, 2012).

[28] L. Townsend, Overview of active methods for shielding spacecraft from energetic space radiation, Physica Medica **17**, 84 (2001).

[29] J. Wilson, F. Cucinotta, J. Miller, J. Shinn, S. Thibeault, R. Singleterry, L. Simonsen, and M. Kim, Approach and issues relating to shield material design to protect astronauts from space radiation, Materials & design **22**, 541 (2001).

[30] L. W. Townsend, J. W. Wilson, J. L. Shinn, J. E. Nealy, and L. C. Simonsen, Radiation protection effectiveness of a proposed magnetic shielding concept for manned mars missions, SAE transactions , 965 (1990).

[31] F. A. Cucinotta, M. R. Shavers, P. B. Saganti, and J. Miller, Radiation protection studies of international space station extravehicular activity space suits, (2003).

[32] M. Tubiana, L. E. Feinendegen, C. Yang, and J. M. Kaminski, The linear no-threshold relationship is inconsistent with radiation biologic and experimental data, Radiology **251**, 13 (2009).

[33] T. C. Slaba, Galactic cosmic ray simulator design at nsrl, (2015).