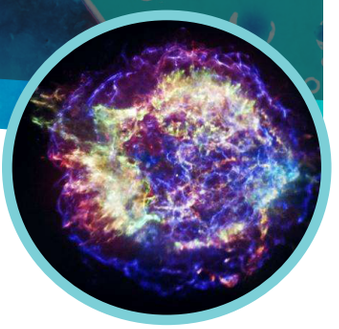
Humans + Space Radiation

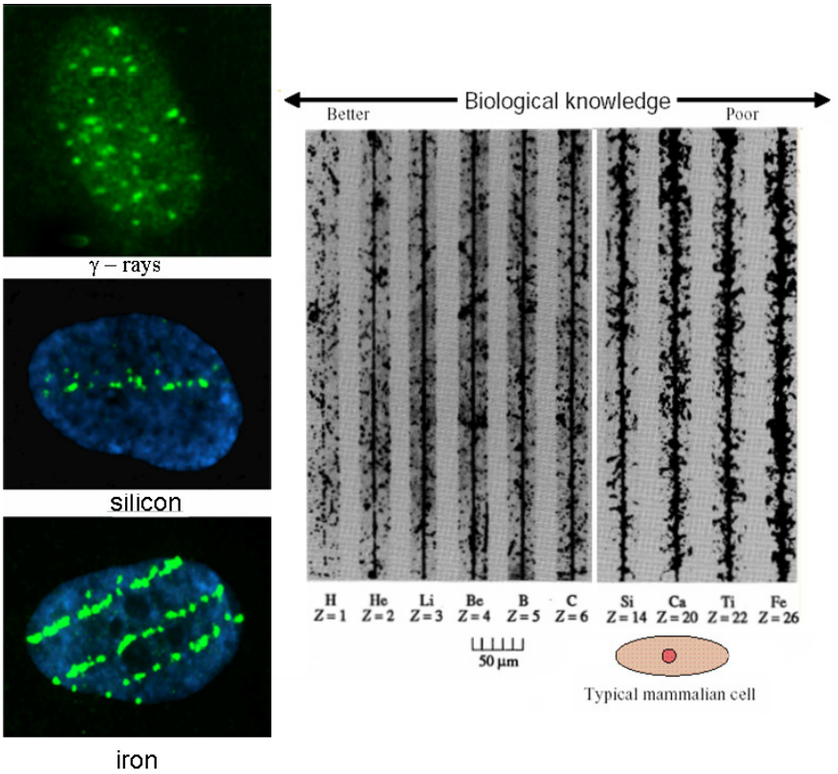
How USRA scientists helped assess the risks for humans who travel in space.



Credit: Shebeko/Shutterstock.com

During NASA's Apollo program, crew members of Apollo 11 reported seeing flashes of light while on their way to the Moon. Neil Armstrong and Edwin Aldrin Jr. reported seeing the flashes with their eyes either open or shut.[1]

Scientists soon realized that the flashes of light were the result of cosmic rays that had penetrated the cabin of the spacecraft and crossed through the retinas of the astronauts' eyes. Cosmic rays are charged particles, mostly protons, that travel near the speed of light and thus have very high energies. For human space travelers, the deadliest cosmic rays are those that come from sources in the Milky Way galaxy. Some of these "galactic cosmic rays" have high mass, high charge and so much energy that they easily penetrate the skin of a spacecraft. They are called HZE cosmic rays (the acronym derives from high (H) atomic number (Z) and energy (E)), with prominent examples including the nuclei of helium, carbon, oxygen or iron atoms.



A comparison of particle tracks in nuclear emulsions and human cells. From Figure 1.2 of Cucinotta and Durante., 2006.

When massive stars explode, shock waves caused by the fast-moving gas produced during the explosion continue to generate X-rays and, more importantly for the subject of humans in space, galactic cosmic rays. There are many supernova remnants in the Milky Way Galaxy, such as the supernova Cassiopeia A. The galactic cosmic rays produced by Cassiopeia A and similar explosions pervade our solar system.

If a high-energy, charged particle passes through the nucleus of a living cell in an astronaut, it can disrupt individual molecules, including deoxyribonucleic acid (DNA) molecules that are essential for life. The biological effect of HZE ions is qualitatively different from the cell damage caused by terrestrial sources of radiation such as x-rays and γ-rays. For example, the left panel of the accompanying figure shows three nuclei of human fibroblasts that have

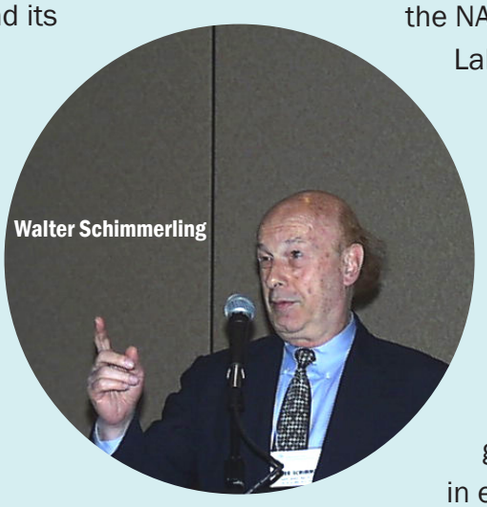
Inset image above: A photograph of Cas A from NASA's Chandra X-ray Observatory. In this representative-color image low-energy X-rays are red, medium-energy ones are green, and the highest-energy X-rays detected by Chandra are colored blue. (Credit: NASA/CXC/SAO)

Essay by W. David Cummings. Design by Erin Senoz.

been exposed to γ-rays, high-energy silicon ions, or high-energy iron ions. Each green dot corresponds to a DNA double-strand break. Cells that are exposed to HZE particles show DNA damage along tracks (one Si- and three Fe-particles, respectively), and the spacing between DNA double-strand breaks is reduced for more massive HZE ions. The graph on the right shows how increasing the charge Z increases the ionization density along the particle track.[2]

Earth's magnetosphere and atmosphere shield life on the planet from galactic cosmic rays. In near-Earth space, such as the environment of the International Space Station, the Earth's magnetic field provides some protection from galactic cosmic rays, as the field deflects the incoming charged particles. Away from Earth, in interplanetary space or on the surface of planetary bodies with little or no atmospheric or magnetic shielding, galactic cosmic rays pose a substantial hazard for astronauts. During the 1970's, NASA was focused on human space flights of short duration and had not yet studied in detail the medical implications of long-duration space flights. In a 1975 report on the biomedical results of the Apollo program, J. Vernon Bailey of NASA's Johnson Space Center noted, "the effect of high-energy cosmic rays on humans is unknown but is considered by most authorities not to be of serious concern for exposures of less than a few years."[3]

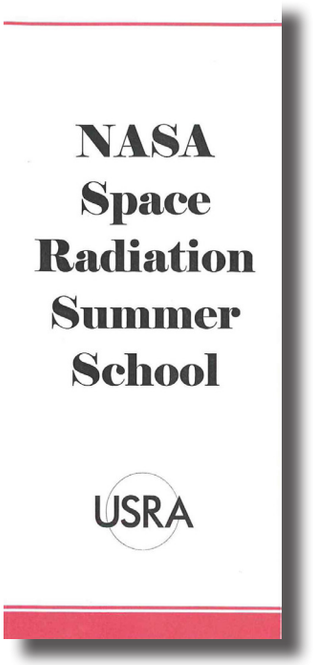
USRA's Division of Space Life Sciences (DSLS) was created in 1983 (originally as the Division of Space Biomedicine, or DSB) to work with NASA and other research organizations to find and develop countermeasures for the various hazards to which astronauts are exposed during space missions. Throughout the remainder of the 1980s, NASA conducted flights of the Space Shuttle that were of short duration, and exposure to galactic cosmic rays was minimal because of the shielding provided by the Earth and its magnetic field. Aside from occasional workshops on the topic of the effects of space radiation on astronauts, the DSB concentrated on countermeasures for other hazards of space missions.


Walter Schimmerling

In 1992, Dr. Walter Schimmerling joined USRA and was assigned to NASA Headquarters. Schimmerling is a nuclear physicist who had worked at Princeton University and the Lawrence Berkeley National Laboratory at the University of California, Berkeley, in high-energy, heavy-ion physics and its application to cancer therapy and space. Later in his tenure with USRA, Schimmerling was detailed to NASA through an Intergovernmental Personnel Act agreement between USRA and NASA so that he could serve as Director and Program Scientist for NASA's Space Radiation Program. For his work there, Schimmerling received the Astronaut's Silver Snoopy Personal Achievement Award and the Administrator's Flag Award for outstanding direction in research. He also received a NASA award for, "championing the need for an expanded knowledge of space radiation effects that support human exploration of space and for unwavering efforts to create the NASA Space Radiation Laboratory."[4]

Schimmerling, among others at NASA and elsewhere, recognized the challenge of reducing the great uncertainties in establishing the health risks for astronauts who would be exposed to galactic cosmic rays on interplanetary missions. A particular problem was the development of risk statistics for galactic cosmic rays based on an extrapolation of data obtained from the exposure of humans to gamma rays and X-rays, primarily from data obtained from survivors of the atomic bombs dropped on Hiroshima and Nagasaki. Schimmerling advocated for the establishment of the NASA Space Radiation Laboratory (NSRL) at the Brookhaven National Laboratory (BNL) because the particle accelerators at BNL can produce

beams of protons and other atomic nuclei to simulate galactic cosmic rays. The NSRL was commissioned in 2003, and scientists began to use the particle accelerators at BNL to determine the biological effects of exposure to HZE ions and the effectiveness of shielding materials, among other things.



The following year, USRA's DSLS began to manage a NASA Space Radiation Summer School at BNL in collaboration with NASA, BNL, the U.S. Department of Energy, Loma Linda University, and Lawrence Berkeley National Laboratory. At this writing, the Summer School continues as a three-week course for young researchers from the fields of molecular biology and genetics. The course is taught by leading university and national laboratory biologists and physicists who are actively engaged in NASA's space radiation research, and by BNL experts in heavy ion experimentation and methods. Following successful completion of the course, participants are qualified to submit experimental proposals and perform research at the NSRL.

Among the findings of the panel was the conclusion that long-duration missions to the Moon or to Mars should be delayed until uncertainties in risk prediction have been reduced.

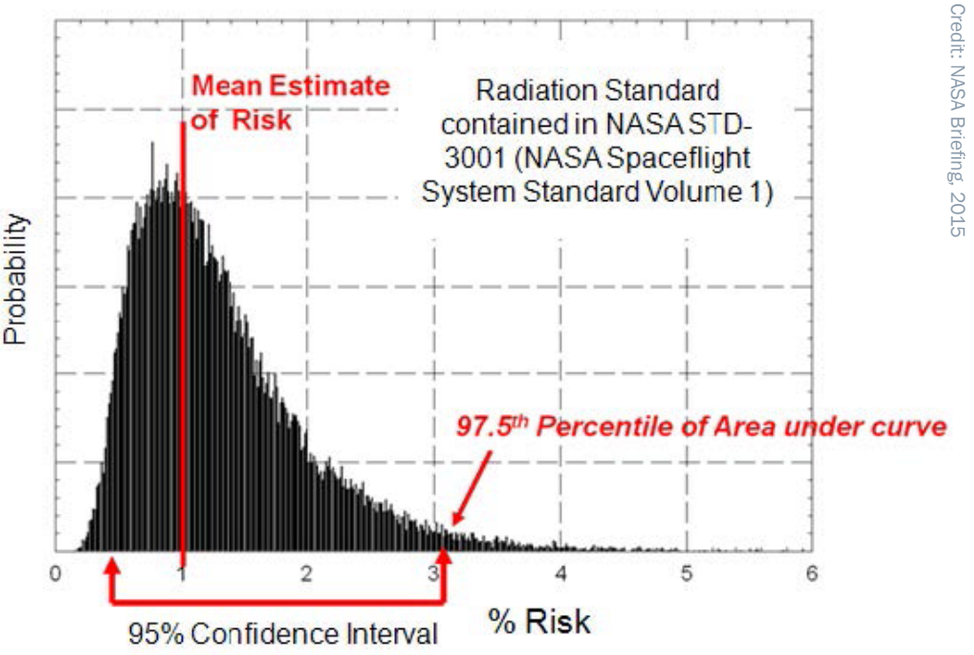
In 2008, the National Research Council of the National Academies of Science formed a panel of experts, including Walter Schimmerling, to examine space radiation risks. Among the findings of the panel was the conclusion that long-duration missions to the Moon or to Mars should be delayed until uncertainties in risk prediction have been reduced.[5]

The reason for the finding was elaborated upon in an article by Drs. Marco Durante of Germany's Helmholtz Center for Heavy-Ion Research and Francis A. Cucinotta, who at the time was NASA's Program Scientist for space radiation research at NASA's Johnson Space Center. Durante and Cucinotta explained:

Among the various health risks, carcinogenesis caused by exposure to space radiation is now generally considered the main hindrance to interplanetary travel for the following reasons: large uncertainties are associated with the projected cancer risk estimates, no simple and effective countermeasures are available, and the large uncertainties prevent determining the effectiveness of countermeasures. Optimizing operational parameters such as the length of space missions and crew selection for age and gender, or applying mitigation measures, such as radiation shielding or use of biological countermeasures, can reduce risk, but these approaches are clouded by uncertainties.[6]

Cucinotta and Durante provided a stark illustration of the risks associated with interplanetary travel, arguing in NASA's Evidence Book that, "in travelling to Mars, every cell nucleus within an astronaut would be traversed by a proton or secondary electron every few days, and by an HZE ion every few months."[7]

The challenge posed by galactic cosmic rays for interplanetary space is daunting, but Walter Schimmerling insisted that the way forward for space biomedical researchers is to continue efforts to better understand and characterize the risk.



Credit: NASA Briefing, 2015

To this end, NASA seeks to characterize the risk to astronauts from exposure to space radiation by developing a model that contains the various conditions and processes associated with the Risk of Exposure Induced Death (REID) to astronauts. The model is interdisciplinary and comprehensive. It includes basic cancer risk data from a given population; models of exposure obtained from astrophysics and space physics, including the interaction of penetrating radiation with spacecraft shielding, spacecraft internal structure (or the surface of a planetary body), and the astronauts' bodies; the biological effect of a given dose rate; and the biological effect related to the nature of the radiation. All these factors have uncertainties and ranges of uncertainties. The risk probability distribution function is developed using a so-called Monte-Carlo simulation. The cancer risk is calculated for a large number of "runs," randomly varying the individual risk factors within their uncertainty ranges for each run and then binning the results to form an overall probability distribution function for REID.

Using this process, NASA has developed a policy to manage career exposures for astronauts by setting a limit that shall not exceed 3% REID for cancer mortality, adjusted for age and sex. The risk limit must be met at a 95% confidence level. The accompanying figure illustrates a risk distribution in which the risk at the upper 95% confidence level is approximately 3%.

In 2012, NASA's lifetime risk assessment for a 940-day mission to Mars was 6.52% at the upper 95% confidence limit for a 45-year-old male astronaut who had never smoked. The risk for a 45-year-old female astronaut who had never smoked was calculated as 8.87% at the upper 95% confidence level.[8]

NASA's Space Cancer Risk (NSCR) model has been developed and revised through the collaborative efforts of DSLS and NASA scientists. In 2012, members of the DSLS team included Drs. Myung-Hee Y. Kim, Lori J. Chappell, Hatem Nounu, Shaowen Hu, Zarana Patel, Janapriya Saha, Minli Wang, Artem Ponomarev, Ianik Plante, Megumi Hada, and Janice Huff. Drs. Kim and Chappell were co-authors with the NASA Program Scientist for space radiation, Dr. Francis A. Cucinotta, on the 2010 and 2012 versions of the NSCR.

Francis A. Cucinotta

Myung-Hee Y. Kim

Lori J. Chappell

Hatem Nounu

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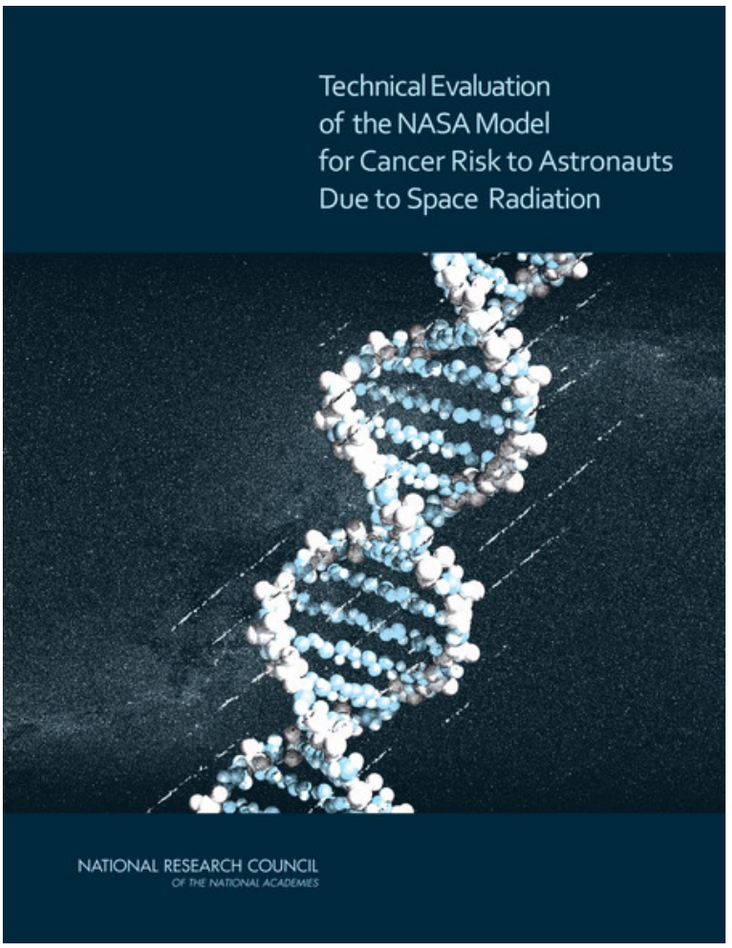
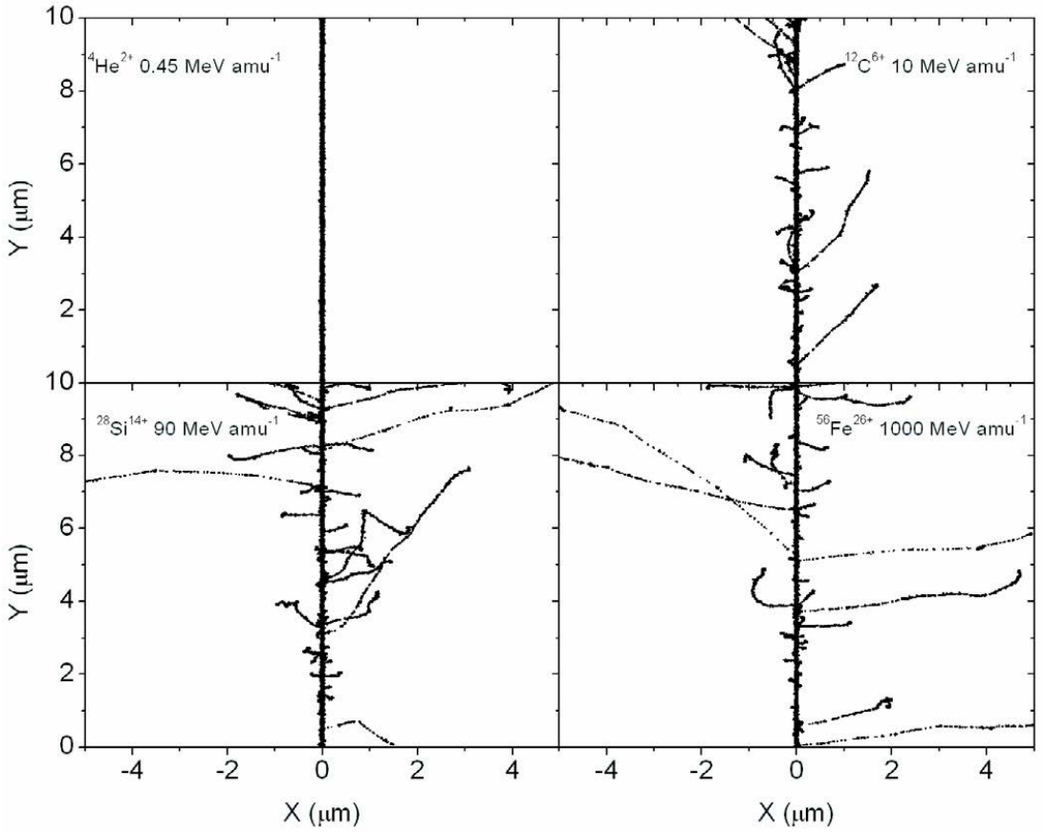


In their 2013 report, the DSLS/NASA team explained how the NSCR model is subject to continual refinements.[9] Improved knowledge of the space radiation environment has yielded better measurements and models that in turn produce advances in transport models used to describe how radiation at the location of a spacecraft makes its way to the tissue and various organs of an astronaut. For example, we now understand that the fluences of galactic cosmic rays and high-energy particles from the Sun vary as a function of distance from the Sun and are affected by the solar cycle. At a minimum in the solar cycle, galactic cosmic rays more easily penetrate the solar system to a given distance from the Sun, while, on average, there are fewer energetic particles coming from the Sun at the same distance. At solar maximum, the reverse is true.

Likewise, better understanding of cancer and human exposure to γ- and X radiations has led to improvements in (1) cancer risk projections (taking into account that 90% of astronauts are “never-smokers” and have a significantly reduced risk for lung cancer than the average US population), (2) the uncertainty factors of the cancer risk model (e.g., whether transfer models of Japanese nuclear survivor data apply to a US population), and (3) estimates that involve the factor of “radiation quality” (i.e., the relative biological effectiveness of the actual radiation striking an astronaut compared to γ- and X radiation).

DSLS team members helped NASA make a significant change in the way it determines radiation quality factors. Prior to their work, NASA had been determining radiation quality factors based on Linear Energy Transfer (LET), which is the amount of energy lost by a given charged particle per unit of length as it goes through a given material. In a 2008 paper, Ianik Plante of the DSLS and Francis Cucinotta of NASA demonstrated that for a given LET, ions of different



Projections over the XY -plane of simulated tracks segments (calculated at ~10^{-12} s) for the following impact ions: $^{4}He^{2+}$ (0.45 MeV amu^{-1}), $^{12}C^{6+}$ (10 MeV amu^{-1}), $^{28}Si^{14+}$ (90 MeV amu^{-1}) and $^{56}Fe^{26+}$ (1 GeV amu^{-1}). Ions are generated at the origin along the Y -axis in liquid water at 25 °C under identical LET conditions (~150 keV μm^{-1}). Each dot represents a radiolytic species. (From Figure 6 in Plante and Cucinotta, 2008. p. 11)

charge and energy give rise to significantly different ionization track structures as they go through matter. Cucinotta and the DSLS team determined that a parameter defined as the square of the effective charge of the ion, divided by the square of its velocity in units of the speed of light (Z^{*2}/β^2), could be used to better model the track-structure of ions and thus better model cancer-related biological endpoints, e.g., mutations and chromosomal aberrations, than models based on LET.

As a result, in their 2012 report on space radiation cancer risks, NASA proposed changing to a "track-structure-based" model of radiation quality factors. The National Academy of Sciences reviewed NASA's 2012 report and concluded that:

> *NASA's proposal to use Z^{*2}/β^2, rather than LET, and risk cross sections based on Z^{*2}/β^2 is reasonable and, hence, the committee judges that this change to the model is appropriate.*[10]

Improving the NASA cancer risk model might not result in lowering the estimated risk for astronauts on space missions that involve interplanetary travel. Further, the cancer risk model does not treat the risk for other potentially damaging effects of space radiation, e.g., the effect of radiation on the central nervous system. Nevertheless, the advice of Walter Schimmerling remains cogent, namely that the first step toward interplanetary travel for humans must be to thoroughly understand the risks. In this effort USRA researchers have made substantial contributions.

[1] Osborne, W. Z., Pinsky, L. S., and Bailey, J. V. (1975). Apollo light flash investigations. In R. S. Johnston, L. F. Dietlein, and C. A. Berry (Eds.), Biomedical Results of Apollo (NASA SP-368), (pp. 355-365). Washington, DC: National Aeronautics and Space Administration; p. 355.

[2] Cucinotta, F. A., and Durante, M. (2006). Cancer risk from exposure to galactic cosmic rays: Implications for space exploration by human beings. *Lancet Oncology 7*(5), pp. 431-435.

[3] Bailey, J. V. (1975). Radiation protection and instrumentation. In R. S. Johnston, L. F. Dietlein, and C. A. Berry (Eds.), Biomedical Results of Apollo (NASA SP-368), (pp. 105-113). Washington, DC: National Aeronautics and Space Administration; p. 108.

[4] NCRP (2014). NCRP commentary no. 23 - Radiation protection for space activities: Supplement to previous recommendations. Bethesda, MD: National Council on Radiation Protection and Measurements; p. 85.

[5] Van Hoften, J. D. A. (2008). Managing space radiation risk in the new era of space exploration. Washington, DC: National Academies Press; p. 97.

[6] Durante, M., and Cucinotta, F. A. (2008). Heavy ion carcinogenesis and human space exploration. Nature Reviews Cancer, *8*(6), pp. 465-472; p. 465.

[7] Cucinotta, F. A., and Durante, M. (2008). Risk of radiation carcinogenesis. In NASA's Evidence Book, Human Research Program, Human Health Countermeasures Element, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas; p. 121.

[8] NCRP (2014); p. 15.

[9] Cucinotta, F. A., Kim, M.-H. Y., and Chappell, J. J. (2013). Space radiation cancer risk projections and uncertainties – 2012 (NASA/TP-2013-217375), Washington, DC: National Aeronautics and Space Administration; pp. vi – xii.

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