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Radiation impacts on human health during spaceflight beyond Low Earth Orbit

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ABSTRACT

Many features of the space environment cause physical ailments for human explorers, some which are truly unique. For example, the long-term health effects of living and working in a microgravity environment can currently only be experienced in an orbiting spacecraft. Radiation exposure, however, is a significant concern in space but is also an issue in certain terrestrial environments. Despite similarities with terrestrial radiation, space-based radiation is rarely encountered in an Earth environment. In fact, there are only a few locations around the world where space radiation can even be produced for research purposes. Although many long-term studies on the health effects of terrestrial radiation have been performed, there remain significant uncertainties as to whether or not Earth-based radiation can be used as a model for space-based radiation. Some of this uncertainty rests with the limited human-applicable radiation data acquired in space environments beyond Low Earth Orbit. Recent publications documenting radiation measurements from NASA's Mars Science Laboratory have significantly added to the understanding of estimated total radiation exposure doses during a human Mars mission. Despite the uncertainties regarding these estimates and the use of Earth-based radiation as a model, it is known that there are unquestionable health risks associated with long-term exposure to space radiation including tissue damage, increased cancer risk, acute radiation syndrome, central nervous system defects, and many others. This paper will discuss these health risks, the differences between terrestrial and space radiation, recent knowledge developments regarding space radiation, and also potential countermeasures for protecting future human spaceflight explorers.

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1. Radiation background

Typical space radiation is significantly different from that most commonly experienced under terrestrial conditions, due to shielding from the Earth's atmosphere and magnetic field. Radiation on Earth is most often electromagnetic in nature. The most common radiation forms are referred to as alpha (α), beta (β), and gamma (γ) radiation. These are helium nuclei, electrons, and gamma rays, respectively. Alpha particles are observed in terrestrial conditions, but are typically associated only with radioactive decay. Gamma rays, along with their less energetic cousin, X-rays, are forms of high-energy electromagnetic radiation, and have the potential to cause severe damage to biological tissue. Electromagnetic radiation, along with electrons and muons (similar to electrons), can be classified in general as low linear energy transfer (LET) radiation. LET refers to the energy deposited into the matter that has been struck by radiation. Low-LET radiation is the predominant concern for terrestrial activities [1].

High-LET radiation, which includes protons and high mass, high-energy (HZE) ions, is mostly a concern reserved for space exploration. Neutrons make up a significant portion of the effective radiation dose during high altitude flights. All other high-LET energetic particles are typically stopped by the atmosphere, and their interactions in the atmosphere are what form high altitude neutrons [2]. The primary particles of concern to humans in space are protons and HZE ions. These particles are thought to originate from Solar Particle Events (SPEs) and Galactic Cosmic Rays (GCRs) [2].

SPEs are singular events in which the Sun ejects greater than normal amounts of protons, alpha particles, and HZE ions. Protons comprise the vast majority of the matter in an SPE. Due to the fact that they are singular events, SPEs vary widely in intensity, duration, and direction. SPE duration can range in length from a few hours to weeks, and the intensity range is even broader. SPEs are highly focused in their directionality from the Sun, as one can erupt from any point on the solar sphere. Those that are directed away from astronauts pose virtually no risk. In the case that an SPE is directed towards astronauts in Low Earth Orbit (LEO), the Earth's magnetic field provides significant protection. This effective shielding, however, is limited to low orbital inclinations. Near the Earth's magnetic poles, the protection drops significantly, and these energetic particles are able to reach deep down into the Earth's atmosphere. This can visually be seen in the form of the Auroras. Very large SPEs can dramatically increase ground radiation, and tend to occur during the Solar Maximum, which happens once every 11 years with the Solar Cycle [1]. The Solar Maximum lasts for months and takes place when the average sunspot numbers reach their highest point in the Solar Cycle [3].

Unlike SPEs, GCRs are essentially omnidirectional, as their point of origin is from the galaxy at large, as their name implies. Despite this, their relative occurrence is also tied to the Solar Cycle. The flux rate of GCRs tends to increase during the Solar Minimum, whereas SPEs tend to peak during Solar Maximum. This increase in radiation from GCRs during the Solar Minimum is due to the weakened solar magnetic field, which is generally protective [1]. GCRs are composed of approximately 85 percent protons, 14 percent alpha particles, and 1 percent HZE ions. Although the overall amount of GCRs is quite low, even at Solar Minimum, the extremely high energy associated with them still poses a large potential risk [2].

For the purposes of quantifying dose equivalents, or the total effective radiation exposure, the unit Sievert (Sv) is used when biological effects are of concern. The calculation of dose equivalent is based upon the directly absorbed dose of particles, with the addition of weighting factors applied for the type of particle and the organs/tissues in which the dose was absorbed [1]. In some cases, it is more convenient to discuss absorbed dose in terms of the pure physical meaning, without any weighting factors. For this purpose, the unit Gray (Gy) is used. For this paper, when discussing small doses, the Sievert will be used, and when discussing large doses, the Gray will be used. In the United States, the Federal Aviation Administration (FAA) has set maximum effective dose limits for civilian aviation crewmembers, which provide information as to theoretically safe doses for humans. For non-pregnant crewmembers, the FAA has set a recommended limit of a 5-year average of 20 milli-Sv (mSv) per year, with no more than 50 mSv in a single year [4].

Space agencies around the world set radiation exposure limits for their astronauts. For example, the National Aeronautics and Space Administration (NASA) sets exposure limits for its astronauts based on specific parts of the body and time spans. Table 1 shows the limit for blood forming organs over a career, depending on the astronaut's chronological age. The European Space Agency (ESA) and the Roscosmos State Corporation for Space Activities (Roscosmos) have set a career limit of 1 Sv; this limit is not age or gender dependent [5]. Limits for the eye and skin are set at higher levels. The highest skin dose recorded on a Space Shuttle flight was 79 mSv, and 178 mSv on Skylab 4 [6].

To assess the potential impact of radiation on human spaceflights beyond LEO, recent NASA spacecraft have included radiation instruments to assess the doses that future astronauts might receive. The Odyssey spacecraft, which has been orbiting Mars since 2001, contains a detector that investigated the types of radiation on the Martian surface [8]. The Curiosity rover that landed on the Martian surface in August 2012 carried an instrument called the Radiation Assessment Detector (RAD). While RAD has been monitoring the surface radiation environment since the landing, it was also recording the radiation environment during the spacecraft's approximately six-month transit from Earth to Mars. The instrument observed multiple SPEs as well as the more general background radiation that included GCRs. The observed data suggest that a human crew on a Mars mission would receive a total dose of 662 ± 108 mSv during the round trip transit time. This estimate does not include either the potential time on the Martian surface or the possibility of high intensity SPEs [9]. This level of exposure is four times higher than the highest level observed on the Skylab 4 mission, and would even exceed the current one-year limit set by NASA.

In its HUMEX study, ESA described the limits of and requirements for potential exploratory missions to the moon and Mars [10,11]. For these missions, the total radiation exposure from each scenario was estimated. Factors such as shielding, solar distance, solar cycle, and mission duration were considered in these estimates. The results of this study are show in Table 2. In this research, the "worst case" SPE was based on 1989 SPE data

Table 1
NASA Astronaut Career Exposure Limits for Blood Forming Organs by Age and Gender [7].

Career Exposure Limits for NASA Astronauts by Age and Gender				
Age (Years)	25	35	45	55
Male	1.50 Sv	2.50 Sv	3.25 Sv	4.00 Sv
Female	1.00 Sv	1.75 Sv	2.50 Sv	3.00 Sv