Studying the effects of galactic cosmic radiation on astro- and microbiological model systems

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MINIREVIEW - TEXT

In-depth knowledge regarding the biological effects of the radiation field in space is required for assessing the radiation risks in space (**Fig. 1 and 2**). Within the last 50 years, space technology has provided tools for transporting terrestrial life beyond this protective magnetic field in order to study in situ responses to selected conditions of space (reviewed in Horneck et al., 2010). From a biological perspective applicable to simple and complex organisms (ranging from biomolecules and microorganisms to humans) various influential physical modifications such as increased radiation exposure were experienced onboard an orbiting spacecraft in low Earth orbit (LEO), out- and inside the International Space Station (ISS), orbiting Moon or on the way to other astrobiological-interesting targets (Mars or icy moons of Saturn or Jupiter). The majority of experiments on microorganisms in space were performed using Earth-orbiting robotic spacecraft, e.g., the Russian Foton satellites (FOTON) and the European Retrievable Carrier (EURECA), or human-tended spacecraft, such as space shuttles and space stations, e.g., MIR and ISS (reviewed in Nicholson, 2009; Nicholson et al., 2009; Horneck et al., 2010).

Ionizing radiation is considered to be one of the major threats and hazards for astronauts (as well as for all other biological systems). The two cosmic sources of radiation that could impact a mission outside the Earth's magnetic field are solar particle events (SPE) and galactic cosmic rays (GCR) (**Fig. 1 and 2**). One of the major radiation sources in our solar system is the Sun itself (Hellweg and Baumstark-Khan, 2007; Reitz, 2008). Charged particles, mainly electrons and protons (hydrogen nuclei) are steadily ejected from the upper atmosphere of the Sun, creating the solar wind with a relatively low energy of about 1 keV (Ferrari and Szuszkiewicz, 2009; Dartnell, 2011). In addition, solar particle events (SPE), eruptions of high energy particles, occur sporadically and are more frequent during phases of solar maximum (McKenna-Lawlor et al., 2011). SPE originate from magnetically disturbed regions of the Sun and are composed primarily of protons (~90-95 %) with a minor component (~5-10 %) being helium nuclei (alpha particles) and an even smaller part (~1 %) heavy ions and electrons (Badhwar and O'Neill, 1994; Benton and Benton, 2001). SPEs can last for hours to days and can reach very high energies, in the worst cases up to tens of thousands of MeV. In contrast, GCR reaches our solar system from our Galaxy and even beyond and originates in cataclysmic astronomical events such as supernova explosions (**Fig. 1 and 2**).

GCR is a continuous radiation in space consisting of 98 % baryons and 2 % electrons (Hellweg and Baumstark-Khan, 2007). The baryonic component is composed of 85 % protons, with the remainder being alpha particles (14 %) and heavier nuclei (about 1%). These heavier particles, also called HZE particles (particles of high charge Z and high energy E) can reach very high energies, up to >1000 GeV (Dartnell, 2011). However, HZE particles are orders of magnitude less frequent than the solar radiation and the particles of the radiation belts surrounding Earth. The flux of the lower energy part of GCR, i.e. of energies below 10 000 MeV in our solar system, is modulated by the Sun's magnetic field; therefore it depends on the activity cycle of our Sun, i.e. reduced at solar maximum and increased at solar minimum (Pissarenko, 1994; Reitz, 2008). GCR constitute a variety of accelerated nuclei of different chemical elements with very high energies up to 10^{20} eV, most of the deleterious effects with regard to astronauts' health produced by GCR are associated with nuclei in the energy range from several hundred MeV/nucleon to a few GeV/nucleon (Badhwar and O'Neill, 1994; Nelson, 2003). The space ionizing radiation environment of our galaxy is dominated by highly energetic and penetrating ions and nuclei (**Fig. 2**). These particles constitute the primary radiation hazard for humans (and

all other biological systems) in space (Nelson, 2003; Ferrari and Szuszkiewicz, 2009; Dartnell, 2011). In the interplanetary space, the primary components of the radiation field (**Fig. 1**) are GCR and solar cosmic radiation (SCR). Studying the impact of cosmic rays may hold answers to a great number of fundamental questions, but they also shape our natural habitat and influence the radiation environment of our planet Earth as well as the radiation climate of astrobiological-relevant planetary objects (Ferrari and Szuszkiewicz, 2009; Dartnell, 2011).

To obtain this knowledge, microorganisms, plants, and animals have been studied as radiobiological model systems in space and at heavy ion accelerators on the ground (reviewed in Horneck et al., 2010). Radiation interacts with matter primarily through ionization and excitation of electrons in atoms and molecules (Nelson, 2003). Biological effects are induced either through direct energy absorption by key biomolecules, such as proteins and nucleic acids, or indirectly via interactions of those molecules with radiation-induced radicals which are produced, for example, by radiolysis of cellular water as well as with other secondary particles (such as secondary electrons; *Bremsstrahlung*) (Hutchinson, 1985; Goodhead, 1994; 1999) (**Fig. 3**).

Both low and high LET radiation produce a wide range of damage types (SSB, DSB) but also clustered DNA damage, a variety of different lesions, for example, strand breaks, abasic sites, or oxidized bases in short regions (i.e., one or two helical turns of the DNA); however, not all damage types have the same biological significance (Hutchinson, 1985; Goodhead, 1994, 1999; Yokoya et al., 2008). Furthermore, it is known that clustered DNA damage in local regions of the DNA are known to act as critical lesions for increased mutagenicity and high lethality (Sutherland et al., 2000; Lomax et al., 2002; Moeller et al., 2010) (**Fig. 3**).

In a variety of space experiments, several microorganisms have been used as biological dosimeters to characterize the biological efficiency of different parts of the galactic cosmic radiation (reviewed in Horneck et al., 2010). Since the advent of space flight, the ability of microorganisms to survive exposure to outer space conditions e.g. parts of the GCR has been investigated to examine the following questions: To which extent could microbial life respond or survive the exposure to simulated space radiation? Which biochemical cellular changes can be determined in different astrobiological model systems? What is the contribution of the GCR in interplanetary transport of microorganisms by natural processes (meteorite-mediated lithopanspermia) or man-made processes (microorganisms-contaminated spacecraft with regard to planetary protection)?

In 2012, we established a consortium (called STARLIFE ("Intercomparison study of astrobiological model systems in their response to major components of the galactic cosmic radiation")) of various international laboratories and research groups in order to determine and investigate a selection of previously, present and intended use of astrobiological model systems for the ionizing radiation experiments at HIMAC (Heavy Ion Medial Accelerator at the National Institute of Radiological Sciences (NIRS & QST) in Chiba, Japan) (Moeller et al., 2017). Because exposure to cosmic radiation damages living cells leading to mutagenesis or cell death, it is an important parameter in consideration of astronaut safety and performance (Petrov, 2002). It is also a highly relevant parameter in the study of interplanetary transport of microorganisms either by natural impact processes (i.e., lithopanspermia) or as a consequence of human spaceflight activities (i.e., planetary protection) (see COSPAR, 2015; Hassler et al., 2014). In both cases, cosmic radiation constitutes the environmental space parameter that may limit microbial survival over long periods (Tuleta et al., 2005; Nicholson, 2009). In STARLIFE, all samples were exposed under identical conditions to same dose and qualities of ionizing radiation allowing (i) a direct comparison between the tested specimens and (ii) providing information on

the impact of the space radiation environment on currently used astro- and microbiological model organisms.

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Figure legend

Figure 1 Space radiation sources of our solar system: sun, Earth, Moon, Mars and Jupiter. Of special concern for astro-/microbiology-relevant missions are GCR and the electrons, protons and heavy ions of SCR (modified from reference (Hellweg and Baumstark-Khan, 2007).

Figure 2 Space radiation sources of our solar system: sun and Earth.

Figure 3. Radiobiological chain of events that starts in a microbial cell after exposure to ionizing radiation, with two alternative pathways of interaction, resulting in either direct or indirect radiation damage (see Horneck et al., 2010 (Figure 4)).

Figures

Figure 1. ***Fujimori et al.***

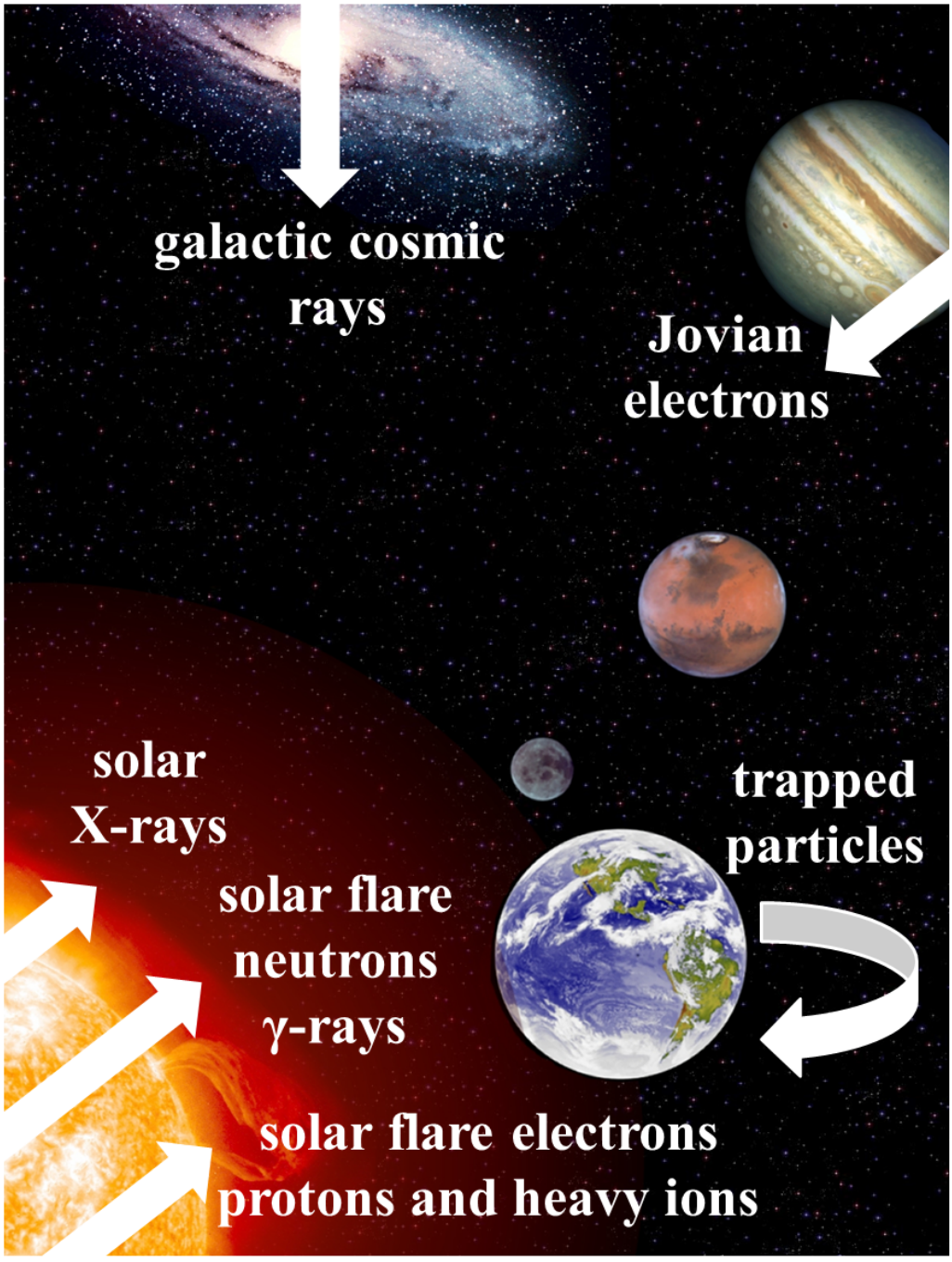


Figure 2. ***Fujimori et al.***

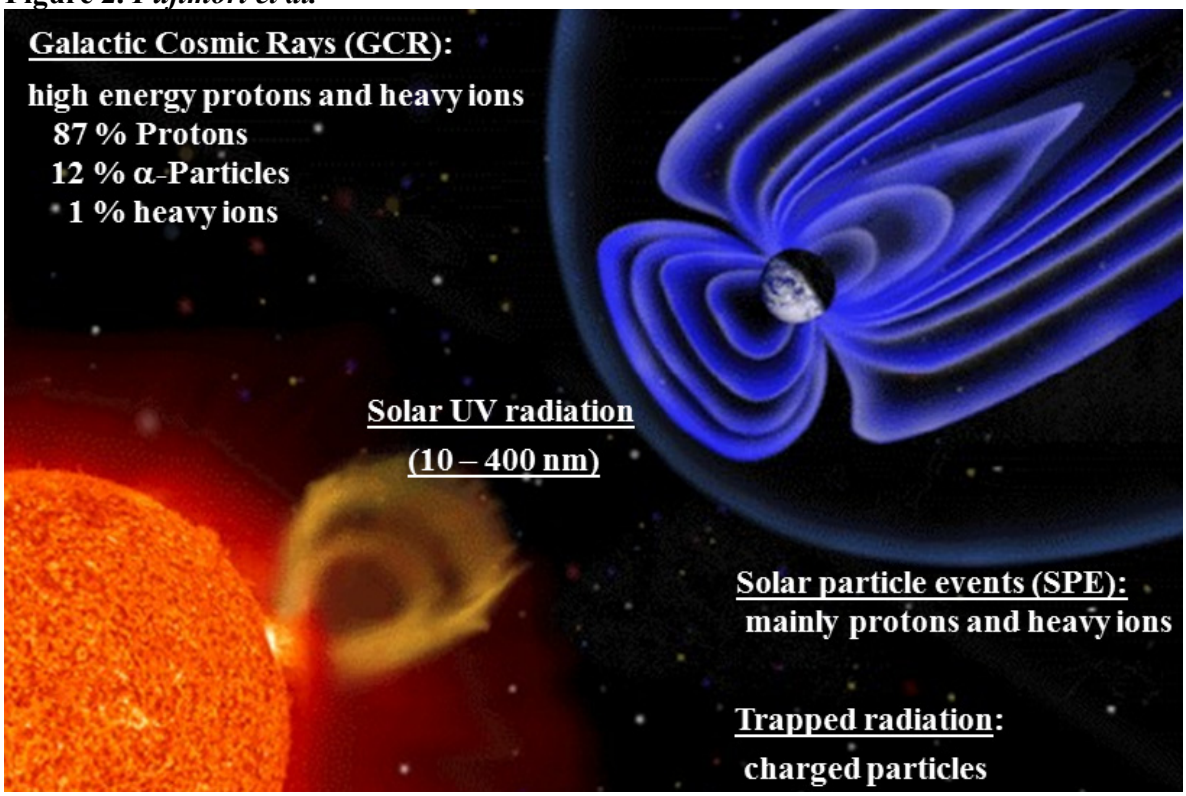
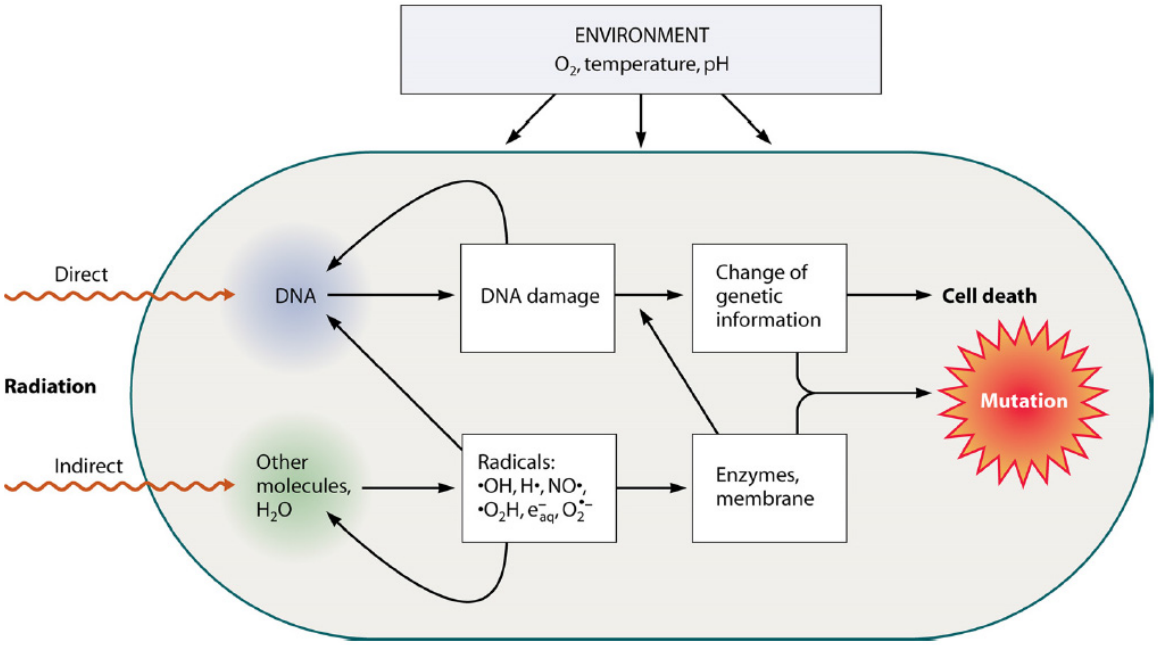


Figure 3 ***Fujimori et al.***



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