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RADIATION RISK IN SPACE EXPLORATION

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Abstract

Humans living and working in space are exposed to energetic charged particle radiation due to galactic cosmic rays and solar particle emissions. In order to keep the risk due to radiation exposure of astronauts below acceptable levels, the physical interaction of these particles with space structures and the biological consequences for crew members need to be understood. Such knowledge is, to a large extent, very sparse when it is available at all. Radiation limits established for space radiation protection purposes are based on extrapolation of risk from Japanese survivor data, and have been found to have large uncertainties. In space, attempting to account for large uncertainties by worst-case design results in excessive costs and accurate risk prediction is essential. It is best developed at ground-based laboratories, using particle accelerator beams to simulate individual components of space radiation. Development of mechanistic models of the action of space radiation is expected to lead to the required improvements in the accuracy of predictions, to optimization of space structures for radiation protection and, eventually, to the development of biological methods of prevention and intervention against radiation injury.

1. SPACE ENVIRONMENT

Human crews engaged in exploration of space will be exposed to weightlessness and to space radiation. The effects of radiation exposure thus need to be considered in the context of weightlessness. Removal of the force of gravity results in structural and functional changes, especially in weight-bearing muscle, bone, and connective tissue. Changes also occur during space flight in endocrine, hematological, immunological, metabolic, nutritional and gastrointestinal, renal, sleep, biological rhythms, and temperature regulation; changes in pharmacokinetics and pharmacodynamics may further confound crew health care. Changes in immune function may be related to living in a "closed environment" -- the space habitat, the effect of stress during launch or landing, inhibition of white cell maturation due to microgravity or other factors.

Outside the protection afforded by the Earth magnetic field and atmosphere, the main penetrating components of ionizing space radiation are protons (and some heavier particles) emitted in the course of solar energetic particle (SEP) events, and protons and the energetic nuclei of other elements (HZE – high atomic number Z and energy E – particles) that constitute galactic cosmic rays (GCR). The SEP protons have energies up to several hundred MeV and intensities that can increase by four or five orders of magnitude within a few hours during a solar disturbance. In an unshielded environment, SEP particle fluxes have the potential to cause acute radiation effects, but several techniques, such as seeking refuge in a well shielded "storm shelter", can be used to keep the dose from SEP particles within acceptable limits. The important open questions related to SEP events deal with the solar physics of their origin. While some biological questions remain about the radiation risk induced by protons, the physical aspects of their interaction with matter are relatively well-known. Thus, from the point of view of radiation protection, given adequate monitoring and warning, the risk can be predicted fairly accurately and managed using operational procedures.

This is not the case for HZE particles, which present new and significant problems for radiation protection, that have not yet been resolved. The relative abundances of GCR particles between protons and iron, and typical energy spectra, are shown in Fig. 1. Such heavy particles, with energies of several hundred MeV per nucleon, will suffer nuclear interactions in spacecraft materials that result in fragmentation of the projectile into lighter nuclei proceeding roughly in the direction of the incident nucleus.

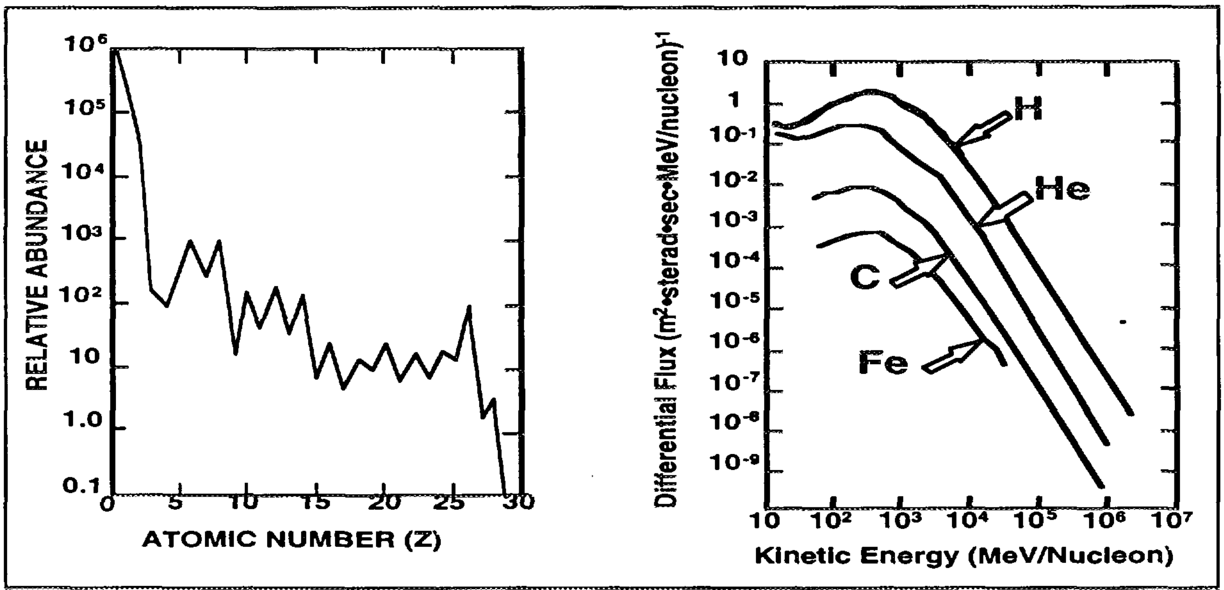

Figure 1. Relative abundances, redrawn after Mewaldt [1] and selected energy spectra, redrawn after Simpson [2], for galactic cosmic ray nuclei.

2. RADIATION RISK

The HZE particles are highly penetrating, with ranges comparable to body dimensions. The linear energy transfers (LET) are in the range of 10 to several thousand keV/μm. The relative biological effectiveness (RBE) of high-energy heavy ions has been measured for various end-points. It increases non-linearly from ~ 30 to ~ 200 keV/μm, with a peak around 100 keV/μm. A plot of LET vs. range is shown in Figure 2(a), and the maximum RBE region has been shaded, showing that HZE particles fall in the region of maximally effective radiation. The quality factor, Q, used in radiation protection, is correlated conceptually with RBE. Average quality factors, Q, for the GCR component, evaluated using measured distributions of LET and internationally recognized assumptions regarding the dependence of Q on LET [3,4] are between 2.3 and 3.4 [5].

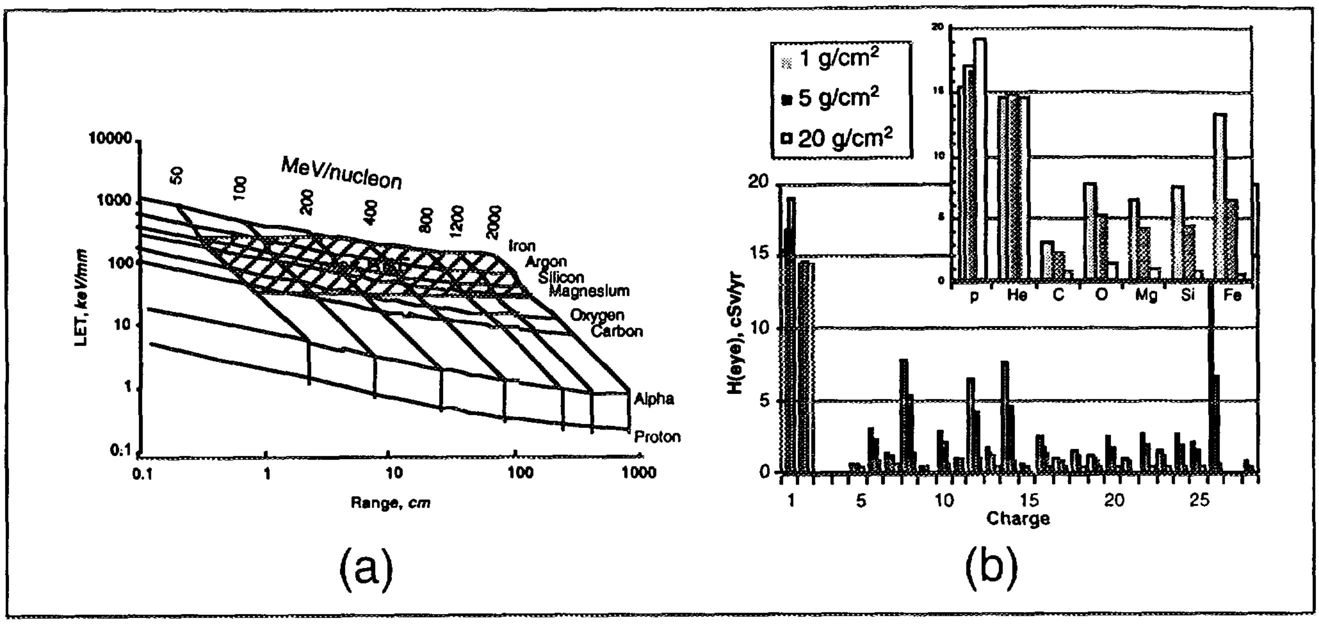

Figure 2. (a) Linear energy transfer (LET) as a function of range in water for selected HZE particles. Lines of constant velocity (expressed as energy per nucleon) have been indicated for each particle. The region corresponding to particles of maximum relative biological effectiveness (RBE) has been shaded. (b) The most significant components of space radiation, according to the dose equivalent to the eye behind 1, 5, and 20 g/cm^2 of polyethylene (approximately tissue-equivalent).

Current radiation limits (Table I) apply only to low Earth orbit activities, such as the International Space Station. Short-term radiation limits for astronauts are intended to ensure

TABLE I. Low Earth orbit radiation limits [3]

	Blood-forming organs (5 cm depth) Sv	Eye (0.3 cm depth) Sv	Skin (0.01 cm depth) Sv
30-day	0.25	1.0	1.5
Annual	0.5	2.0	3.0
Career	2.0 + 0.075 x (age - 30) for males 2.0 + 0.075 x (age - 38) for females		

that exposure to space radiation does not result in acute effects. Annual and career limits are intended to limit the risk to be less than an "acceptable risk" [6]. The acceptable risk is currently defined as a 3 per cent excess probability of fatal cancer above the background rate for the working US population.

The uncertainties associated with estimation of the risk from long-term exposure to HZE [7] are sufficiently large to prevent a meaningful definition of this risk at the present time. The conventional prediction of risk due to HZE particles for a given mission proceeds by evaluating the interplanetary space radiation environment during the mission. For a given spacecraft mass distribution and assumptions about the geometry of crew member bodies, radiation transport calculations [7] are used to calculate the radiation field inside the spacecraft and at crew organs. The cancer risk associated with the physical dose is estimated based on extrapolation of the risk obtained from atomic bomb survivor studies, corrected for dose rate effects and for the different biological effectiveness of HZE particles. A Task Group of the US National Academy of Sciences recently estimated [8] the resulting uncertainties to be within a factor of 4-15.

A substantive research program is currently sponsored by NASA, with collaboration of other national and international agencies, using ground-based simulation of space radiation to develop the radiobiological knowledge required to predict risk from HZE particles accurately enough to define radiation limits for the human exploration of space.

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