note technique

Risk from relativistic heavy ions on manned space missions*

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(Manuscrit reçu le 28 novembre 1992)

The risk from exposure to radiation posed to space travelers outside the magnetic shielding provided by the geomagnetosphere will come from two sources : the slowly varying but low intensity high-energy galactic cosmic rays and the more intense predominantly low-energy protons from large solar particle events associated with magnetic disturbances originating sporadically on or within the solar surface during the active period of the 11-year solar cycle. The energy spectra of the protons in solar particle events are quite soft, with large numbers of low-energy protons and a rather steep decrease of the energy spectra with increasing energy. This allows for the possibility to provide, within the space vehicle or habitat, a well-shielded area sometimes called a "storm shelter" or "safe haven" where the travelers could gather during the largest particle events. Intensity risetimes on the order of half an hour or more and overall event durations of 1 to 2 days would make actively seeking a well-shielded shelter for the duration a distinct possibility. The high-energy and penetrating nature and relative constancy of the galactic cosmic rays, on the other hand, do not allow the use of highly shielded areas as a means of protection against them. The first question to answer becomes : what is the risk to human health from the galactic cosmic rays ? We need to have a good idea of the answer to this question before we can address the problem of how to best protect human health or, indeed, whether any specific measures need to be taken.

Considerable information is available on the intensities, energy spectra, composition and time-variation of the galactic cosmic rays. They comprise all the ions in the periodic table, 87 % are protons, 12 % are helium ions, with the rest being heavier particles. There is a preponderance of even over odd charge number and there is a peak at iron (Z = 26), presumably reflecting large abundances of iron in the galactic source (or sources). They permeate near-earth space isotropically and their intensities vary on the order of a factor of 2 over the 11-year period of increasing and decreasing solar activity. The intensities are at a maximum during the time solar

* Communication présentée aux journées internationales "Biological applications of relativistic heavy nuclei" (BARN 92), Clermont-Ferrand, 14-16 octobre 1992.

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activity is at its minimum, and are at a minimum when solar activity is at its maximum. The variation is due to the modulating effects of the solar magnetosphere which screens out the galactic particles more effectively during highly active solar periods. In addition, it is now known that, for every second solar cycle, the solar magnetic field changes its direction by 180 degrees. This causes a 22-year periodicity that is also reflected in the galactic cosmic ray intensities. Every second solar minimum is associated with higher cosmic ray intensities. Thus, the intensities in the solar minimum periods of 1954 and 1976-77 were larger than in 1965. It has been estimated that the galactic cosmic ray intensities can now be estimated to within 10-13 % accuracy throughout the solar cycle.

The next problem is the modulation of the primary radiation by the spacecraft or habitat shielding and body self-shielding of the space travellers themselves. An extensive effort has been going on at NASA Langley research center, among other places, to develop a computer code to calculate the radiation transport through spacecraft shielding and human tissue of the galactic cosmic rays. Nuclear interactions of all the primary and secondary particles, including neutrons, are propagated through the total shielding to body organs of interest. The approximations used are that the secondary projectile fragments from the nuclear interactions emerge straight ahead, *i.e.*, at zero degrees to the incident primary direction and with the same velocity as the primary. These calculations produce curves that have heen estimated to have uncertainties of less than 35 % due to our lack of knowledge of the nuclear cross sections.

The final aspect in the evaluation of the risk is the determination of the effects of the radiation on the tissues being exposed. Unfortunately, we know very little indeed about the hazards of human exposure to galactic cosmic ray particles. There is no counterpart to this kind of radiation on earth, except, of course, for the individual components at very well-defined energies in beams accelerated in a small and dwindling number of high-energy accelerators. There is, of course, no experience of exposure of humans to these beams. It is believed that the light flashes seen on Apollo missions, the joint American-Soviet orbital mission (ASTP), as well as on other low earth-orbital missions, were caused by direct optical stimulation from the passage of galactic cosmic rays (for the Apollo mission) and trapped protons (for the earth-orbital missions). It is not expected that these flashes caused permanent damage to the eye, but they provide dramatic testament that single-particle effects are detectable by the human body.

The only risk that is presently thought to be well-established from the galactic cosmic radiation is the risk of cancer. It is believed that cancer arises from single transformed cells, and radiation-induced cancer is a well-established end point in many different species of animals, and excess cancers have been found over background levels in radiation-exposed human populations such as the atomic-bomb survivors of Hiroshima and Nagasaki. Most of the human data, which include the Japanese data, however, have been gathered from populations exposed to gamma radia-

tion, a sparsely ionizing (low-LET) radiation. Although there is much cellular and animal experimental evidence to show that highly ionizing (high-LET) radiation such as found in the galactic cosmic rays are more efficient per unit of absorbed dose in producing biological effects, very little data are available from the high-energy heavy-ion beams directly relevant to galactic cosmic ray risk assessment. The conventional method of determining risk from a mixed environment of low-LET and high-LET radiation is to multiply the absorbed dose distribution by a *quality factor*, which is a weighting factor that is a function of LET and was designed to account for the higher efficiency of the high-LET components, and then integrating to obtain what is called the dose equivalent. The dose equivalent can be thought of as the amount of gamma radiation necessary to produce the same amount of damage (or risk) as the radiation in question. At present, we lack values of the relative efficiency of the heavy-ion component to cause molecular damage relevant to the carcinogenic process.

Finally, other risks that need to be evaluated are cataractogenesis and the effects of neural damage that might accumulate in the central nervous system over long exposure times. The question that should be answered regarding cataractogenesis is whether the total fluences of particles accumulated over a 2- or 3- years mission outside the geomagnetosphere is high enough to be above the threshold for human cataractogenesis. The question of irreparable damage accumulating in neural networks by the passage of high-energy heavy ions is at present just a conjecture. Such damage could cause degradation of brain function and/or neuroreceptor function elsewhere in the body. Well-designed animal experiments should be performed to measure end points related to the slow degradation of central nervous system functioning over long exposure times.

In sum, it is not established that all the human risks from galactic cosmic radiation have been identified. In view of this, and because the relative biological effectiveness of high-energy heavy ions beams (particularly iron) have been obtained on only a few biological systems to date, some of them of questionable relevance to cells and tissues in the human, it is clear that our uncertainty in risk assessment on extended missions back to the moon or on to Mars is predominantly due to our lack of understanding about the biological effects of the heavy components of the galactic cosmic rays. A somewhat subjective but, I hope, not unrealistic guess is that our uncertainty in the biological effects result in an uncertainty in risk estimation of a factor of between 2 and 5. Regardless of what the true numerical uncertainty in our risk estimates is, it is clearly dominated by our uncertainty in the biological effects. Much work needs to be done on high-energy heavy-ion accelerators using representative beams of iron and other particles with energies in the 0.5-2.0 GeV/nucleon range in order to evaluate adequately the risks from this unique type of radiation. ■

Acknowledgements *: This work is supported by the National aeronautics and space administration under order No.T-9310R, and by The NASA Specialized center of research and training (NSCORT) awarded to the Lawrence Berkeley laboratory/ Colorado State University consortium.*