3

Radiation, Space Weather

Marco Durante

GSI Helmholtzzentrum für Schwerionenforschung and Technische Universität Darmstadt, Darmstadt, Germany

Space radiation has long been acknowledged as a major showstopper for long-term space missions, especially interplanetary, exploratory-class missions [1]. Space radiation is generally divided into three components: trapped radiation, solar particle events (SPEs), and galactic cosmic radiation (GCR). Trapped radiation is the main source of exposure in low Earth orbit (e.g., on the International Space Station), and SPEs are a cause of great concern because they may potentially cause acute radiation syndromes in unprotected crews. However, this type of radiation is mostly composed of protons at energies below 100–200 MeV, and it is therefore relatively easy to shield with conventional bulk materials. On the other hand, GCR contains high-charge and high-energy (HZE) nuclei.

These particles are very penetrating and have high relative biological effectiveness for several late effects. Therefore, energetic heavy ions from the GCR represent the major source of health risk in long-term manned space missions [2].

Cosmic radiation effects could be studied directly in space. This approach has the advantage of including all other space environment factors (microgravity, stress, vibration, etc.) in the experiment. Several radiobiological studies have been carried out during spaceflights [3], but most of the results gathered thus far have been inconclusive. Several factors contribute to the difficulties in interpretation of charged particle radiation effects from spaceflight experiments. The average dose rate in low Earth orbit, though substantially higher than that on Earth, is still fairly low ($\leq$1 mSv/day). The resultant biological effects are small and are often below the detection threshold of most assays, even for long-term missions on the International Space Station. For this reason, radiobiology experiments in space often include high-dose radiation exposure of the sample preflight or onboard, which further complicates the experiment and its interpretation. Second, flight experiments are expensive, difficult to control, restricted to limited sample sizes, and hard to repeat. Very few radiobiology experiments in flight have been repeated, and in the rare cases where this was possible, results were often not confirmed.

It can be safely stated that most of our current knowledge of the health effects of cosmic radiation exposures has been obtained from ground-based experiments at high-energy accelerators [4]. The evaluation of candidate materials for space radiation shielding as well as the effects on microelectronics is also commonly performed by accelerators [5]. Space radiation experimental programs were run at the BEVALAC at the Lawrence Berkeley National Laboratory in Berkeley, CA, USA; the SIS18 at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany (Figure 3.1) [6]; the HIMAC at the National Institute for Radiological Sciences in Chiba, Japan; and at the NASA Space Radiation Laboratory (NSRL) at the Brookhaven National Laboratory in Upton, NY, USA (Figure 3.2) [7]. Many other experiments relevant to extrapolate space radiation effects were performed in other accelerators around the world.

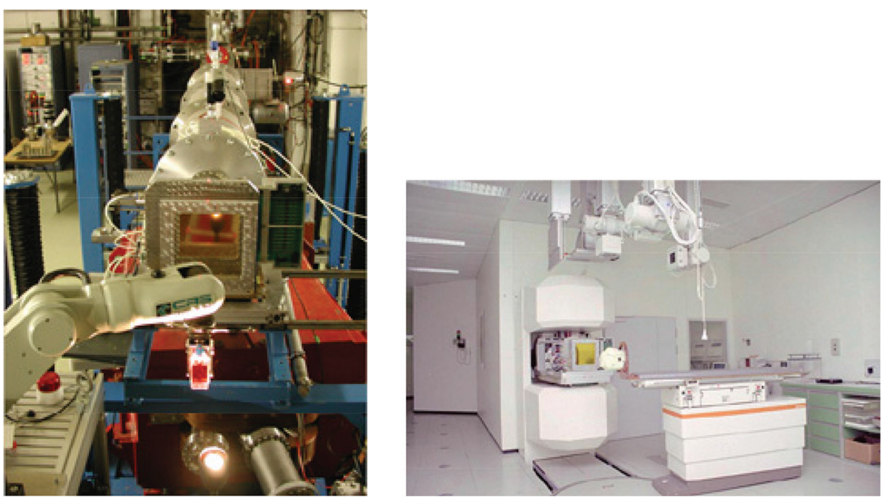

Figure 3.1 Irradiation facility in cave A (left) and cave M (right) from the SIS18 synchrotron of the GSI Helmholtz Center in Darmstadt, Germany. Cave A is equipped with a robotic arm for remote control of the samples. Cave M is equipped with a couch used in 1997–2008 for treatment of cancer patients with C-ions and is currently dedicated to experiments in animals or other 3D targets. Image from the GSI Web site [6].

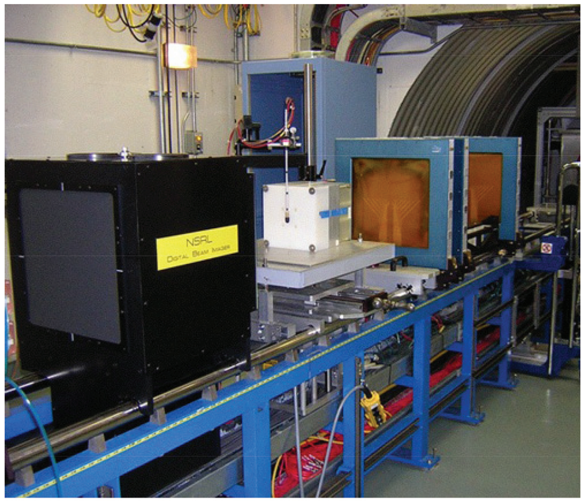

Figure 3.2 Irradiation facility at NSRL in Upton, NY, USA. The facility is dedicated to the NASA Space Radiation Health Program, the largest research program in the field of simulation of cosmic radiation effects. The photograph showing three large monitor chambers, a plastic target, the egg chamber used for dose measurements, and the digital beam analyzer to check beam position and uniformity. Image from the NSRL Web site [7].

3.1 Facilities for Space Radiation Simulation

Protons are by far the most abundant component in the space radiation environment (see later). In addition, secondary neutrons are produced in space and they can contribute an important fraction of the equivalent dose in shielded areas. Finally, HZE at very high energy can only be properly simulated in large-scale accelerator facilities. It is important to stress that having an accelerator and a cave is not enough to define a "facility" for space radiation research. Specialized infrastructure is necessary—from target handling to beam dosimetry, and including large and expensive tissue culture and animal laboratories for radiobiology experiments.

Accelerators can hardly reproduce the complex space radiation field in space. Generally, only one particle at one defined energy is accelerated.

Often protons around 200 MeV (typical in trapped radiation or SPE) or Fe at 1 GeV/n (representative of the HZE component in the GCR) are used. Moreover, experiments are generally conducted at high dose rate (around 1 Gy/min) and relatively high doses ($>$0.1 Gy) in most biology experiments. At NSRL (Figure 3.2), an SPE simulator is available that provides protons at different energies simulating energy spectra of past, very intense SPE.

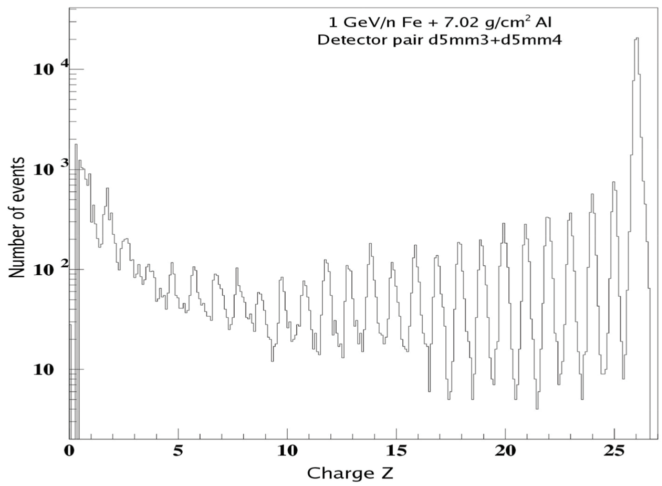

Figure 3.3 Measured spectra of fragments produced by a beam of 1 GeV/n Fe-ions on a target of 26 mm Al. Fragments at 0 degree are measured by a Si-telescope. Each peak correspond to a fragment of a different atomic number Z. Measurement performed at the Brookhaven National Laboratory (NY, USA), courtesy of Jack Miller and Cary Zeitlin, Lawrence Berkeley National Laboratory, CA, USA.

An incubator can also be used on the beamline, thus allowing low-dose rate exposures, even though these experiments are obviously expensive because they burn extended beamtime. Finally, the new electron beam ion source (EBIS) at NSRL allows fast switching between different species and therefore a realistic simulation of the GCR spectrum. Fast energy change is also possible at GSI (Figure 3.1), where a beamline microscope for live microscopy is also available. It should also be noted that a simple simulation of a GCR-like spectrum can be easily obtained using shielding. Using very heavy ions at high energy on a thick target, a fragmentation spectrum is produced which can be modified changing projectile mass and velocity or target material and thickness. An example is shown in Figure 3.3.

A comprehensive review of the facilities for space radiation research was published by the IBER Study Group and supported by the European Space Agency in 2006 [8]. Here, updated information on this topic is summarized.

3.2 Protons

Virtually all electrostatic accelerators and cyclotrons can produce protons at energies below 30 MeV. Moving to the range of 150–250 MeV, there are a number of facilities specialized for proton therapy in oncology which can be used for space radiation research as well. In fact, this is the energy range typical for trapped radiation and SPEs.

Protons are nowadays widely used in cancer treatment [9], thanks to their favorable depth–dose distribution compared to X-rays which can lead to a reduced exposure of the normal tissue with the same conformal coverage of the target. Protons are often used for pediatric tumors, prostate cancers, and head-and-neck tumors. Recently, their use is rapidly increasing also for breast and lung cancers. In June 2014, a total of 105,743 patients had been treated with protons in different facilities in USA, Europe, and Asia [10]. Proton therapy facilities are perfectly equipped with beam delivery and dosimetry systems and often have biology laboratories available, used for preclinical studies. However, availability of beamtime for research is sometimes difficult, because the facilities are very busy treating patients. Currently, very little space-related research has been conducted in clinical proton therapy centers, with the possible exception of Loma Linda in California, where several NASA-supported experiments have been completed. The geographical distribution of the current facilities and those planned or under construction is given in Table 3.1. Facilities for simulation of galactic protons require high-energy machines described in Section 3.4.

3.3 Neutrons

While thermal and fission spectrum neutrons have been studied for many years for radiation protection on Earth, fast neutrons are less characterized and the facilities able to provide reference quasi-monoenergetic neutron fields at energies >20 MeV are only a few.

A recent EURADOS report [11] identified six quasi-monoenergetic neutron facilities in operation worldwide (Table 3.2). These operate in less-than-optimal conditions, especially when seen from the viewpoint of dosimetry. All six facilities make use of the 7Li(p,n) reaction for neutron production. The resulting neutron energy distributions consist of a peak close to the energy of the incoming proton and a broad and roughly even distribution down to zero energy. Each of these components generally contains about half the neutron intensity. A new facility (Neutron for Science (NFS)) is currently under construction in GANIL, France, and is expected to produce quasi-monoenergetic high-energy neutrons from 2014.

Table 3.1 Medical facilities for deep proton therapy (energy >200 MeV) worldwide in operation (at April 2015) and planned or under construction [10]

Location	In Operation	Planned
USA	15	13
Europe	9	16
Russia	3	1
Japan	6	3
China	2	2
South Africa	1	–
Taiwan	–	1
Saudi Arabia	–	1
Australia	–	1

Table 3.2 High-energy quasi-monoenergetic neutron facilities in operation [11]

Name	Country	Energy Range (MeV)
iThemba	South Africa	35–197
TSL	Sweden	11–175
TIARA	Japan	40–90
CYRIC	Japan	14–80
RCNP	Japan	100–400
NPI	Czech Republic	18–36

3.4 Heavy Ions

For the simulation of protons and HZE ions in the GCR, large accelerator facilities are necessary. These facilities are generally synchrotrons, and their main use is either nuclear physics or heavy ion therapy. We will only consider here accelerator facilities capable of providing HZE ions at energies >200 MeV/n. Iron ions are often chosen by space radiation investigators because they are the most abundant specie among the HZE nuclei. The contribution in dose equivalent of Fe alone in deep space is comparable to that of protons.

At March 2013, three facilities deliver both protons and carbon ions in the energy range 200–400 MeV/n for cancer therapy: HIT (Heidelberg, Germany), CNAO (Pavia, Italy), and HIBMC (Hyogo, Japan). These centers, however, are not presently involved in space radiation experiments, even though they have the capability to run this program. On the other hand, the National Institute for Radiological Sciences in Chiba (Japan) and the Institute of Modern Physics of the Chinese Academy of Sciences in Lanzhou (China) treat patients with deep tumors using C-ions and also run extensive space radiation research programs. Both facilities can deliver Fe-ions at energies around 500 MeV/n, and have strong local research groups dedicated to space radiation biology and physics research.

The main research facilities involved in high-energy cosmic ray simulation experiments are NSRL in USA (Figure 3.2) and GSI in Germany (Figure 3.1). The maximum energy available in these facilities is 1–2 GeV/n, depending on the particle mass. Ions up to Au and U have been accelerated at NSRL and GSI, respectively. Most of the space radiation simulation experiments in these facilities, supported by NASA (Space Radiation Health Program) or ESA (IBER program), were however performed with Fe 1 GeV/n. Some space-related studies were also performed at the RIKEN cyclotron in Japan (Z 6, E 135 MeV/n) and at the Joint Institute for Nuclear Research in Dubna, Russia (mass up to Fe, and maximum energy for protons around 6 GeV).

3.5 Facilities Planned

In addition to the new proton therapy centers planned or under construction (Table 3.1), a few new medical centers designed to treat cancer patients with heavy ions are planned or under construction (e.g., MedAustron in Austria: SAGA-HIMAT in Japan, and the Shanghai Proton and Heavy Ion Therapy Hospital in China). However, as noted above, it is unclear how much beamtime can be allocated in these medical facilities to space research.

At least two research facilities are planned in Europe where space radiation research is part of the plans. GSI is now building the facility and antiproton and ion source (FAIR), a double synchrotron with magnetic rigidities of 100 and 300 Tm which will use the current SIS18 as injector [12]. FAIR, which should start operations in 2018, is planning extensive cosmic radiation simulated, extending the ESA support to the current GSI facility. CERN (Geneva, Switzerland) is also considering an experimental biomedical facility based at the low energy ion ring (LEIR) accelerator [13]. Such a new facility could provide beams of light ions (from protons to neon ions) for both cancer therapy and space radiation research projects.

3.6 Conclusions

Ground-based space radiation simulation facilities require large accelerators and dedicated infrastructures. The two main research programs in the field are run at NSRL (NY, USA) with NASA support and GSI (Darmstadt, Germany) with ESA support. Both facilities have limitations in beamtime and suffer by financial problems in the laboratories (possible RHIC shutdown in Brookhaven; the construction of FAIR in Darmstadt). Particle therapy centers could be used, but access to beamtime is limited in facilities dedicated to patient treatment. New facilities (such as FAIR, NFS, and LEIR in Europe) or more beamtime at therapy centers is needed to run physics, electronics, and biology experiments relevant for space exploration, that is, energetic protons, neutrons, and heavy ions.

References

[1] Radiation Hazards to Crews of Interplanetary Missions. Washington, D.C.: NationalAcademyPress, 1996.
[2] Durante, M., and F.A. Cucinotta, " Heavy Ion Carcinogenesis and Human Space Exploration." *Nature Reviews Cancer* 8, no. 6 (2008): 465–472.
[3] Horneck, G. "Impact of Microgravity on Radiobiological Processes and Efficiency of DNA Repair." *Mutation Research* 430, (1999): 221–222
[4] Durante, M., and A. Kronenberg. "Ground-Based Research with Heavy Ions for Space Radiation Protection." *Advances in Space Research* 35, no. 2 (2005): 180/184.
[5] Durante, M., and F.A. Cucinotta. "Physical Basis of Radiation Protection in Space Travel." *Reviews of Modern Physics* 83, no.4 (2011): 1245–1281.
[6] GSI webpage-http://www.gsi.de/biophysik
[7] NSRL webpage-http://www.bnl.gov/medical/NASA/
[8] Investigation on Biological Effects of Radiation (IBER). Final report. ESA Publication CR(P)-4585, 2006.
[9] Loeffler, J.S., and M. Durante, "Charged Particle Therapy-Optimization, Challenges and Future Directions." *Nature Reviews Clinical Oncology* 10, no.7 (2013): 411–424.
[10] PTCOG webpage-http://http://ptcog.web.psi.ch/
[11] High-Energy Quasi-Monoenergetic Neutron Fields: Existing Facilities and Futureneeds. EURADOS Report 2013–02, Braunschweig, May 2013.
[12] FAIR webpage–http://www.fair-center.eu/
[13] Abler, D., A. Garonna, C. Carli, M. Dosanjh, and K. Peach. "Feasibility Study for a Biomedical Experimental Facility Based on LEIR at CERN." *Journal of Radiation Research* 54, Suppl. 1 (2013): i162–i167.