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Profile of the ionizing radiation exposure between the Earth surface and free space

Tsvetan P. Dachev*

Space Research and Technology Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. Block 1, 1113 Sofia, Bulgaria

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ABSTRACT

Since 2000 scientists from the former Solar-Terrestrial Influences Institute at the Bulgarian Academy of Sciences contributed Bulgarian-build instruments to a number of experiments for measurements of the incoming space radiation fluxes and dose rates from the Earth surface up to the free space and 100 km Moon orbit. The purpose of this paper is to summarize the data obtained by different instruments on the ground and in aircraft, balloon, rocket, and on spacecraft. Dose rate, flux and specific dose (SD) data are analyzed, compared and plotted. The result is a unified picture how the different ionizing radiation sources contribute and build the space exposure altitudinal profile from the Earth surface to the free space.

1. Introduction

Humans are exposed to ionizing radiation all the time at all altitudes above the Earth surface, and it is known that it can induce a variety of harmful biological effects. Consequently, it is necessary to quantitatively assess the level of exposure to this radiation as the basis for estimating risks due to ionization radiation.

The radiation field around the Earth is complex, composed of galactic cosmic rays (GCR), trapped radiation of the Earth radiation belts, solar energetic particles, albedo particles from the Earth's atmosphere and secondary radiation produced in the shielding materials of the aircraft and spacecraft and in biological objects.

1.1. Galactic cosmic rays

The dominant radiation component in the near Earth and free space environment are the galactic cosmic rays (GCR). The GCR are charged particles that originate from sources beyond our solar system. They are thought be accelerated at the highly energetic sources like neutron stars and supernovae within our Galaxy. GCR are the most penetrating of the major types of ionizing radiation. The distribution of GCR is believed to be isotropic throughout interstellar space. The energies of GCR particles range from several tens up to 10^{12} MeV nucleon^{-1}. The GCR spectrum consists of 98% protons and heavier ions (baryon component) and 2% electrons and positrons (lepton component). The baryon component is composed of 87% protons, 12% helium ions (alpha particles) and 1% heavy ions (Simpson, 1983). Highly energetic particles in the heavy ion component, typically referred to as high Z and energy (HZE) particles, play a particularly important role in space dosimetry (Benton and Benton, 2001). HZE particles, especially iron, possess high-LET (Linear energy transfer) and are highly penetrating, giving them a large potential for radiobiological damage (Kim et al., 2010). Up to 1 GeV, the flux and spectra of GCR particles are strongly influenced by the solar activity and hence show modulation which is anti-correlated with solar activity.

1.2. Trapped radiation belts

Radiation belts are the regions of high concentration of the energetic electrons and protons trapped within the Earth's magnetosphere. There are two distinct belts of toroidal shape surrounding the Earth where the high energy charged particles get trapped in the Earth's magnetic field. Energetic ions and electrons within the Earth's radiation belts pose a hazard to both astronauts and spacecraft. The inner radiation belt (IRB), located between about 0.1 to 2 Earth radii, consists of both electrons with energies up to 10 MeV and protons with energies up to ~700 MeV. The outer radiation belt (ORB) starts from about 4 Earth radii and extends to about 9–10 Earth radii in the anti-sun direction. The outer belt mostly consists of electrons whose energy is not larger than 10 MeV. The electron flux may cause problems for components located outside a spacecraft (e.g. solar cell degradation). They do not have enough energy to penetrate a heavily shielded spacecraft such as the International space station (ISS) wall, but may deliver large additional doses to astronauts during extra vehicular activity (Dachev et al., 2009a, 2012a). The

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* Tel.: +359 878366225.
E-mail addresses: tdachev@bas.bg, tdachev59@gmail.com

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South-Atlantic Anomaly (SAA) is an area where the radiation belt comes closer to the Earth surface due to a displacement of the magnetic dipole axes from the Earth's center. The daily average SAA doses reported by Reitz et al. (2005) inside of the ISS vary in the range 74–215 μGy d^{-1} for the absorbed dose rates and in the range 130–258 μSv d^{-1} for the averaged equivalent daily dose rates.

1.3. *Solar energetic particles (SEP)*

The SEP are mainly produced by solar flares, sudden sporadic eruptions of the chromosphere of the Sun. High fluxes of charged particles (mostly protons, some electrons and helium and heavier ions) with energies up to several GeV are emitted by processes of acceleration outside the Sun. It is now generally understood that SEP events arise from coronal mass ejections (CME) from active regions of the solar surface. The CME propagates through interplanetary space carrying along with it the local surface magnetic field frozen into the ejected mass. There is a transition (shock) region between the normal sectored magnetic structure of interplanetary space and the fields frozen into the ejected mass, which forms a transition region (shock) where the interplanetary gas is accelerated forming the SEP. As the accelerated region passes an observation point, the flux intensity is observed to increase dramatically (Mertens et al., 2007). The time profile of a typical SEP starts off with a rapid exponential increase in flux, reaching a peak in minutes to hours. The energy emitted lies between 15 and 500 MeV $nucleon^{-1}$ and the intensity can reach 10^4 cm^{-2} s^{-1} sr^{-1}. Electrons with energies of ~0.5 to 1 MeV arrive at the Earth, usually traveling along interplanetary field lines, within tens of minutes to tens of hours. Protons with energies of 20 to 80 MeV arrive within a few to ~10 h, although some high energy protons can arrive in as early as 20 min. SEP are relatively rare and occur most often during the solar maximum phase of the 11-year solar cycle. In the years of maximum solar activity up to 10 flares can occur, during the years of minimum solar activity only one event can be observed on average (Lantos, 1993).

1.4. *Atmospheric ionizing radiation*

The natural radiation level at cruising aircraft altitudes is much higher than it is at ground level. The radiation field arises as a result of the interaction of primary GCR particles with the Earth's atmosphere. An additional flux of albedo secondary GCR is observed at altitudes below 3 km, which contributes to the forming of the flux minimum around 1.6 km altitude (Bazilevskaya et al., 2013). The intensity of the atmospheric radiations, composed of GCR primary and secondary particles and their energy distribution vary with altitude, location in the geomagnetic field, and the time in the sun's magnetic activity (solar) cycle (Mertens et al., 2007). The atmosphere provides shielding, which depends on the overhead atmospheric depth. The geomagnetic field provides a different kind of shielding, by deflecting low-momentum charged particles back to space. Because of the orientation of the geomagnetic field, which is predominately dipolar in nature, the Polar Regions are susceptible to penetrating GCR (and SEP) particles. At each geographic location, the minimum momentum per unit charge (magnetic rigidity) a vertically incident particle can have and still reach a given 3 location above the Earth is called the geomagnetic vertical cutoff rigidity (Shea and Smart, 2001). The local flux of incident GCR at a given time varies widely with geomagnetic location and the solar modulation level. When the solar activity is high, the GCR flux is low, and vice versa. The dynamic balance between the outward convective flux of solar wind and the inward diffusive flux of GCR is responsible for the anti-correlation between the incident GCR and the level of solar activity (Mertens et al., 2007).

1.5. *Natural radioactivity*

The larger fraction of the Earth's surface where people live and work has as natural soil cover resulting from weathering processes. The lower atmospheric radiation and the associated external exposure are mainly from gamma rays emitted from the top 25 cm of the surface layer of the Earth and the construction materials of the buildings (Wilson et al., 2003). At ground level the space radiation (originating from outside the Earth's atmosphere, including solar radiation) generate about 11% of the effective dose which the average US population, is exposed to, while the terrestrial one (radiation emitted by radionuclides in soil and rocks) is 7%. The major amount of the effective dose is produced by inhaled Radon and ingested Potassium, Thorium and Uranium (Wahl, 2010).

2. Material and methods

The main purpose of the Liulin type Deposited Energy Spectrometer (DES) is to measure the spectrum (in 256 channels) of the deposited energy in a silicon detector from primary and secondary particles at the aircraft altitudes, at low Earth orbits, outside of the Earth magnetosphere on the route and on the surface of the planets of the solar system. The DES is a Liulin type (Dachev et al., 2002, 2011a) miniature spectrometer-dosimeter containing one semiconductor detector (Hamamatsu S2744-08) PIN diode, 2 cm^2 area, 0.3 mm thick), one charge-sensitive preamplifier, 2 or more microcontrollers and flash memory or telemetry. Pulse analysis technique is used to obtain the deposited energy spectrum, which is further used for the calculation of the absorbed dose and flux in the silicon detector. The unit is managed by the microcontrollers through specially developed firmware. Plug-in links provide the transmission of the data stored on the flash memory via standard interfaces (parallel, serial or USB) of a personal computer or to the telemetry system of the carrier.

For the analysis of altitudinal profiles of space exposure since 2000 the following DES were used in near Earth and free space radiation environments on different carriers:

- A mobile dosimetry unit (MDU) MDU-5 of Liulin-4C instrument (100 × 110 × 45 mm, 410 g including 2 × 80 g Li-Ion D size batteries) was used for more than 12,000 flight hours between 2001 and 2008 on Czech Airlines (CSA) aircraft on different routes with 10 min resolution. In this paper the data between March 22 and May 7 2001 are used (Spurny and Dachev, 2009).
- Mobile dosimetry unit MDU#1 of Liulin-4U instrunent (100 × 64 × 24 mm, 210 g including 80 g Li-Ion rechrgeable battery pack) was used on the Deep Space Test Bed (DSTB) balloon during the 8 June 2005 certification flight from Ft. Sumner, New Mexico, USA up to 37.3 km altitude with 60-s resolution (Benton, 2005). It was part of the NASA Space Radiation Shielding Program, Marshall Space Flight Center (Adams et al., 2007).
- Radiation Risks Radiometer-Dosimeter (R3D) (82 × 57 × 25, 129 g.) for Biopan (R3D-B) with 256 channels ionizing radiation monitoring spectrometer and 4 channels visible and UV spectrometer known as R3D-B2 which was successfully flown 31 May–16 June 2005 inside of the ESA Biopan 5 facilities on a Foton M2 satellite. The operation time of the instrument started on 24 April for about 20 days filling the total 1.0 MB flash memory with 60-s resolution (Häder et al., 2009).
- Liulin-R spectrometer-dosimeter (110 × 40 × 20 mm, 92 g) was successfully launched on the HotPay2 rocket from Andoya Rocket Range (ARR), Norway, on 31 January 2008, rising to an