Space Sci Rev (2018) 214:9
DOI 10.1007/s11214-017-0445-6

An Experiment in Radiation Measurement Using the Depron Instrument

Victor V. Benghin[1,2] · Oleg Y. Nechaev[2] · Ivan A. Zolotarev[2] · Alexander M. Amelyushkin[2] · Vasiliy L. Petrov[2] · Milhail I. Panasyuk[2,3] · Ivan V. Yashin[2]

Received: 6 February 2017 / Accepted: 15 November 2017

Abstract Most of the radiation measurements have been made onboard spacecraft flying along orbits with an inclination of up to 51.6 degrees. Due to the prospect of manned missions at orbits with larger inclinations, it is advisable to conduct preliminary detailed dosimetry measurements at a high-inclination orbit; due to its polar orbit, the Lomonosov satellite provides good opportunities for such study. We chose a method of cosmic radiation dosimetry based on semiconductor detectors. This method is widely used onboard spacecraft, including full-time radiation monitoring onboard the International Space Station (ISS). It should be noted that not only did the charged particles contribute significantly in the dose equivalent, but also did the neutrons. Semiconductor detectors have low sensitivity to neutron radiation and are not sufficient for detecting the expected flux of neutrons. We add a thermal neutron counter to the proposed device in order to provide an opportunity for estimation of neutron flux variations along the satellite trajectory.

Thus, the design of the instrument DEPRON (Dosimeter of Electrons, PROtons and Neutrons) was determined. DEPRON is intended for registration of the absorbed doses and linear energy transfer spectra for high-energy electrons, protons and nuclei of space radiation, as well as registration of thermal neutrons. The present paper provides a brief description of the DEPRON instrument. Its calibration results and the first mission results of background radiation measurements are also presented.

Keywords Space radiation measurements · Radiation belts · Dosimetry · Lomonosov satellite · Charged particle telescope · Neutron detector

The Lomonosov Mission
Edited by Yuri Shprits, Hans Bloemen and Jim Burch

✉ I.A. Zolotarev
brilkov@sinp.msu.ru

[1] State Scientific Center of Russian Federation, Institute of Biomedical Problems, Russian Academy of Sciences, Moscow, Russia

[2] Skobeltsyn Institute of Nuclear Physics (SINP MSU), Lomonosov Moscow State University, Moscow, Russia

[3] Physics Department, Lomonosov Moscow State University, Moscow, Russia

Published online: 30 November 2017

1 Introduction

It is commonly known (Bobkov et al. 1970; Grigoriev 1975; Shafirkin 2008), that cosmic radiation generates a negative impact on the human body during space flight. The structure of the radiation fields in the near-Earth space was studied during intensive research of recent decades (Van Allen and Frank 1959; Benton and Benton 2001; Lemaire et al. 1990; Panasyuk 2007). Huge number of dosimetry studies was conducted on manned and unmanned space vehicles in order to solve the problem of humans radiation safety during space flights (Apáthy et al. 2007; Badhwar et al. 1992, 1998; Balashov et al. 2003; Bottollier-Depois et al. 1996; Cleghorn et al. 2004; Gazenko 1986; Jurjatin et al. 1979). It should be noted that most of the measurements were made onboard spacecraft flying along orbits with an inclination of up to 51.6 degrees. Due to the prospect of manned missions at the orbits with a larger inclination, it seems advisable to conduct preliminary detailed dosimetry measurements at high-inclination orbit, for which the "Lomonosov" satellite provides good opportunities. We chose a method of cosmic radiation dosimetry based on semiconductor detectors. Proposed in the late 70's (Markelov and Red'ko 1978, 1982) this method is widely used onboard spacecraft (Benghin et al. 1992; Shurshakov et al. 1999; Semkova et al. 2014), including full-time radiation monitoring onboard the ISS (Ljagushin et al. 2002; Labrenz et al. 2015). Recently it has been improved, providing an opportunity to register not only the absorbed dose of charged particles radiation but also the range of their ionization losses. It allowed assessment of dose equivalent (Reitz et al. 2005; Semkova et al. 2010). An appropriate procedure based on using of a telescope consisting of two semiconductor detectors provided a basis of the developed unit.

It should be noted that not only the charged particles contribute significantly in the dose equivalent, but also neutrons do (Armstrong and Colborn 2001; Dudkin et al. 1990; Sevast'janov et al. 1997). Semiconductor detectors have low sensitivity to neutron radiation and are not sufficient for detecting the expected flux of neutrons. It was therefore decided to add thermal neutrons counter to the developed device in order to provide an opportunity of estimation of neutron flux variations along the satellite trajectory. A gas-discharge counter SI-13N, operated in a mode of corona discharge was chosen as a neutron detector. This method of neutron detection is well-proven and used many times in Skobeltsyn Institute of Nuclear Physics (SINP) experiments (Bratoljubova-Celukidze et al. 1995; Panasjuk et al. 1990; Shavrin et al. 2002) and some other space missions, such as PAMELA (Goryacheva et al. 2017).

Thus, the appearance of the instrument DEPRON (Dosimeter of Electrons, PROtons and Neutrons) was determined. DEPRON is intended for registration of the absorbed doses for high-energy electrons, protons and nuclei of space radiation, as well as registration of thermal neutrons. The experiment based on DEPRON instrument is aimed at the studies of the distribution of space radiation dose rate at high latitude paths in order to study the flight paths of perspective-manned spacecraft. Present paper provides a brief description of the DEPRON instrument, its calibration results and the structure of the output data.

2 Materials and Methods

2.1 DEPRON Description

Device DEPRON intended for dosimetry measurements consists of ionizing radiation detector, analog and digital processing circuits of the signals from detectors, circuits for data transmission to the Block of Information (BI) of the scientific instruments complex and the power unit.

The DEPRON consists of two nodes with semiconductor detectors and two nodes with gas-discharge helium neutron counters.

The units with semiconductor detectors are used for registration of the absorbed dose from charged particles. Information on the absorbed dose value is obtained based on the principle of registration of the charge in the semiconductor, that is proportional to the energy release in a given volume.

Both semiconductors detector are packed into a cassette and arranged one above the other, forming a telescope of detectors. Thickness of the rectangular detectors is 300 microns, and their area is 1 cm^2. Using two detectors and the corresponding analog signal processing schemes are aimed at the improving of the reliability of the registration of the absorbed dose of radiation and at the same time allows us to get additional information on the energy deposition spectra of the particles passed both detectors simultaneously. The signals from the detectors come to charge-sensitive preamps based on a hybrid chip A225F produced by the Amptec company. Chip A225F provides two output signals. One is proportional to the charge generated in the detector comes to an analog-to-digital converter (ADC) and then to digital processing. There was used a 12-bit ADC AD7495 from Analog Devices with speed of 1 MSPS. Second, fast signal comes to a shaping amplifier and then to the processor interrupt register, wherein it is used to start the ADC and for the counting of registered particles number.

The neutron detector is based on the slow neutrons counter "SI-13H", which is a gas-discharge counter operating in corona discharge mode. In order to improve reliability of the system two counters of this type were used. The second detector is surrounded with a moderating shell produced of polycarbonate, which expands the energy range of recorded neutrons. Passing through He-3 gas filling the counter the neutrons cause nuclear reaction $\mathrm{n} + {}^3\mathrm{He} = \mathrm{p} + \mathrm{T} + 764$ keV. The reaction products cause ionization of the gas in the counter producing electric discharge in gas and pulse on counter's electrode. The pulse is input to amplifier shaper and then supplied to microcontroller interrupt register, which is used for counting the detected neutrons number. It should be noted that DEPRON device does not measure the dose of neutrons, it registers only the flux of thermal neutrons.

Digital signal processing is performed by microprocessor AT91SAM7X512. Hardware-software DEPRON is operated on a single microprocessor board SSD234 which is based on microcontroller AT91SAM7X512 manufactured by ATMEL and includes a processor ARM7 TDMI® ARM® Thumb® 32-bit RISC-architecture.

Software CPU registers the signals coming from the conversion circuits of detectors pulses, they do conversion and storage data, transfer results via communication path to the BI of spacecraft. Software of the device DEPRON consists of a program for the controller unit, written in C++ (C) using the IAR Workbench® package for ARM® microcontroller architecture. Total data volume generated by the instrument does not exceed 1 MByte/day. Communication with BI is implemented via Controller Area Network (CAN) channel. Along with the processing and transfer of data from the radiation detectors, DEPRON unit transmits information received from the device IMISS-1 via RS232 (USART) to the BI via CAN. Information from device IMISS-1 is transmitted unchanged.

Power supply of the DEPRON's circuits is realized by means of DC/DC converters. The supply voltage of the on-board power system of 27 V is supplied to two converters 28/12 V. From the first converter voltage comes to the voltage regulator and then form the following voltages: +6 V power supply for the amplifier, pulse shaping circuits and microprocessor. The second converter supply power to the +70 V power supply converter for semiconductor detectors and 1200 V converter for the supply of gas discharge counters.

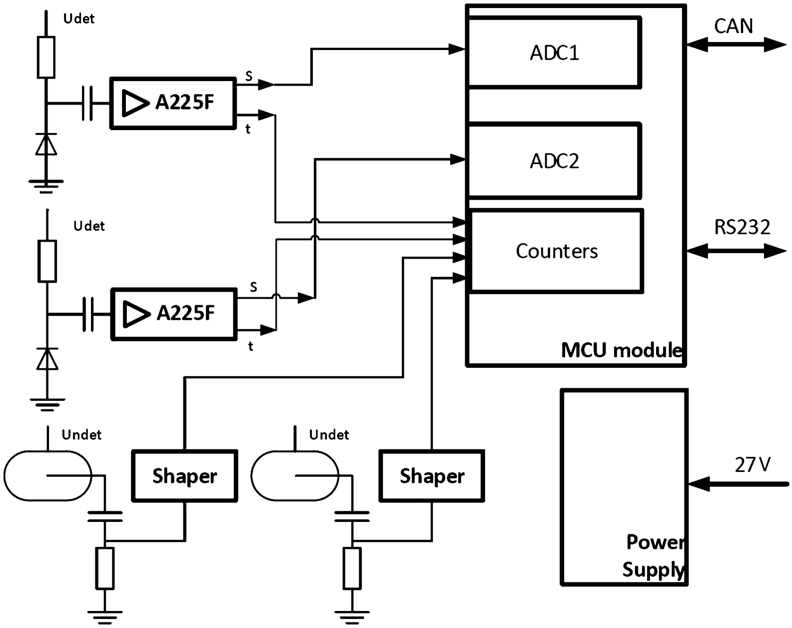

Fig. 1 The block diagram of the DEPRON device. All sensitive elements and amplifying circuits are doubled for better reliability and to enlarge range of registered energy deposition

The block diagram of the device is shown in Fig. 1.

2.2 Calibration of the Instrument

During the manufacture of instrument tuning of the parameters of its units was performed by means of simulation of the detector signals by electrical pulses from the generator. At the final stage functional test of the device measuring paths using radioactive sources ^{226}Ra and ^{60}Co was made. Examples of spectrum of energy release in the first semiconductor detector obtained under the influence radioactive sources are presented in Fig. 2 (^{226}Ra) and in Fig. 3 (^{60}Co).

The peaks in the spectrum obtained under the influence of the ^{226}Ra source were associated with energies of alpha particles produced by radioactive decay of radium and thorium. After the appropriate processing the ADC (used for semiconductor detector signals conversion) step calibration value was determined. Further, basing on this value the boundary energy release spectrum of Compton electrons recorded by the detector under the influence of the source ^{60}Co was estimated. The resulting value −714 keV is much smaller than Compton spectrum boundary known to be 1118 keV for gammas with energy of 1332 keV. It caused by the fact that the 300 microns thickness of the detector does not provide full absorption of high-energy electrons. The value of the boundary spectrum energy of Compton electrons recorded by the detector under the influence of the source ^{60}Co taken equal to 714 keV was used for subsequent evaluation of the energy equivalent of ADC step. Later on the sensitivity of the instrument amplifier channel was reduced by 2.6 times in order to provide higher upper limit of the recorded energy release values. The spectra obtained under the influence of ^{60}Co allowed to estimates ADC step of 36 keV/channel for the first detector and 42 keV/channel—for the second.

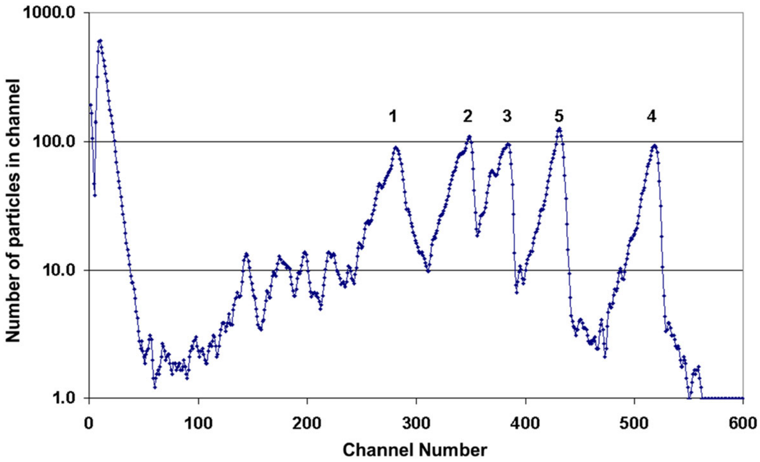

Fig. 2 Spectrum recorded in the first semiconductor detector, obtained under the influence of the ^{226}Ra source. *Four peaks numbered from 1 to 4 on diagram* refers to alpha particle peaks of ^{226}Ra: 4.781 MeV, 5.486 MeV, 6.000 MeV, 7.688 MeV. *Peak 5* refers to 6.555 MeV alpha particle product of ^{226}Tr decay

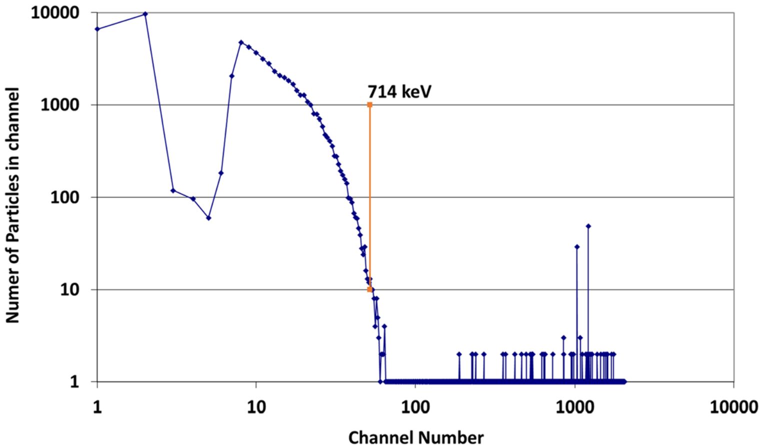

Fig. 3 Spectrum recorded in the first semiconductor detector, obtained under the influence of the ^{60}Co source. *Orange line* shows measured Compton edge at 52 channel, with corresponding energy 714 keV

The resulting estimates form the basis for calculating of the DEPRON dosimetry characteristics.

2.3 Measured Parameters and Structure of the Information Produced by DEPRON Device

The list of passed parameters:

- The counting rate and dose rate from the 1st and 2nd semiconductor detectors with second resolution;
- The counting rate of SI13N counter with one-second resolution;

Table 1 The list of array types produced by DEPRON device

No.	Passed information	Array code
1	Counting rate and dose rate with second resolution	A
2	Energy release spectra of semiconductor detectors	S
3	Time profile of neutron signals series	N
4	Receipt for the command from BI	T

Table 2 The general structure of messages

Start of message (DLE,STX)	Category (CAT)	Length (LEN)	Data(RECORD)
Marker 1	Marker 2		
2 bytes	2 bytes		508 bytes

- Energy deposition spectra in semiconductor detectors in the absence and presence of coincidences, 1 time every 5 minutes;
- The time profile of neutron signals series (for up to 2 s) with millisecond resolution.

DEPRON device forms several types of information blocks corresponding to different parameters passed. The list of array types is presented in Table 1.

The size of each array of information is 512 bytes.

Each message consists of the following fields:

- Start of message;
- Category;
- Message length;
- Data.

The general structure of messages is presented in Table 2.

The field "start of message" consists of 2 bytes.

The field "category" contains one byte (CAT), which value depends on the type of the corresponding array and corresponds to the value specified in the 3rd column of Table 1.

The field "message length" contains 1 byte (LEN) transmitted default '0', which means that the total length of packet is 512 bytes.

The field "data" (RECORD) contains the data which structure is determined by the type of the array.

2.4 Specifications

Overall dimensions—280 mm × 160 mm × 78 mm. Weight of the device—3 kg. Power consumption—5 W. The range of measured parameters: absorbed dose 10^{-5} Gy–10^{+1} Gy; absorbed dose rate 10^{-6} Gy/h–10^{-1} Gy/h; particles flux 1–10^4 particles/(cm^2 s); neutron flux with energy from 0.03 to 100 eV 0.1–10^2 neutrons/(cm^2 s). Dose equivalent rate range and deposited energy range are the subjects for further work and publication.

3 Results and Discussion

Educational satellite Lomonosov with the DEPRON instrument onboard was launched on April 28, 2016 from the Vostochnyi into sun-synchronous orbit about 480 km altitude, the main objective of the mission is to study the transient phenomena in the Earth's atmosphere. After the in-flight tests DEPRON instrument operates in permanent mode as primary radiation monitoring device of mission. For the early 2017 it has more than half of the year power up time. Figure 4 shows an example timeline data received in August 2016.

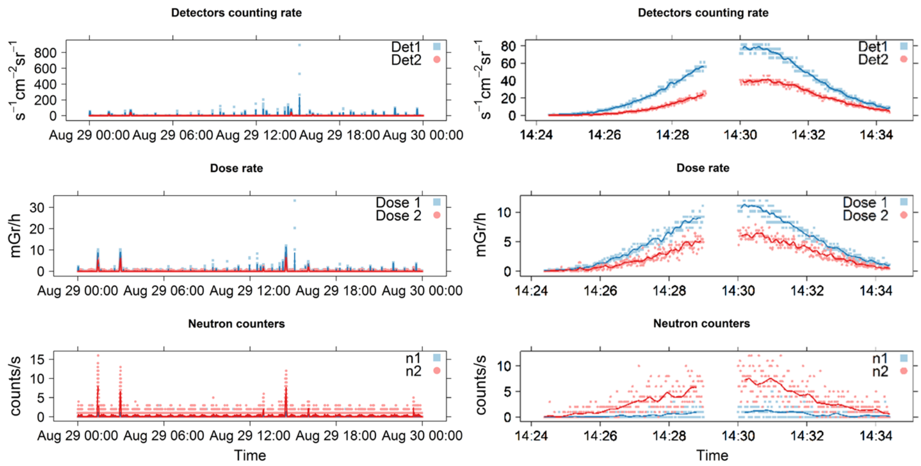

Fig. 4 Depron data time series of count rates and dose rates for 29 August 2016. *Right figure* give us closer look of the moment of South Atlantic Anomaly crossing at 14:30 UT. Actual measurements shown by dots and lines shows a smoothed data with a triangle filter. It is seen that are missing data for one minute interval of measurements 14:29, the reason for this is the high load of the data transmission channel

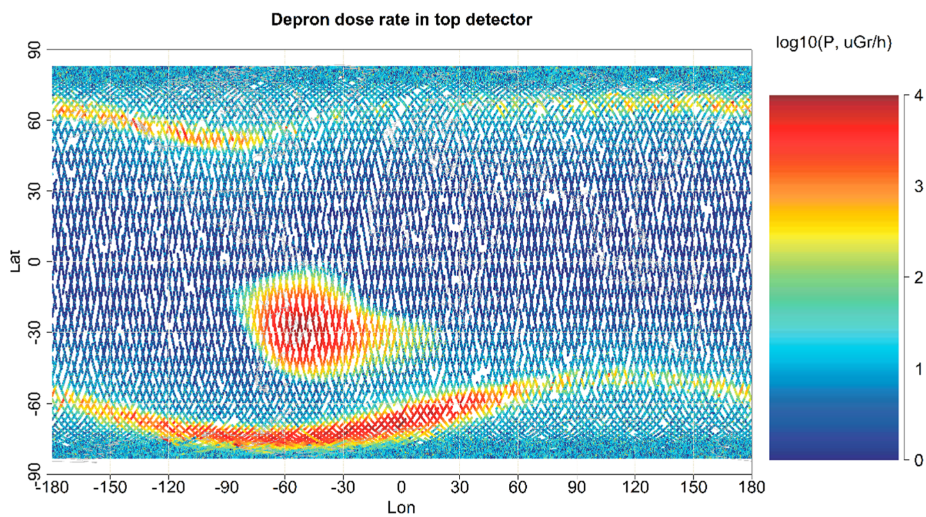

Fig. 5 Global map of radiation conditions onboard the Lomonosov satellite obtained for one week of measurements in August 2016

As a result of the radiation monitoring experiment in space we get a map of charged particles flux measured with semiconductor detectors and dose rates maps (Fig. 5). Datasets of the experiment and additional materials are available on the mission site at http://lomonosov.sinp.msu.ru.

4 Conclusion

DEPRON instrument was successfully developed, manufactured and submitted for further development as a part of the satellite's scientific equipment. Its specifications allow sufficiently detailed measurements of dosimetry parameters of the radiation environment along the path of the satellite. DEPRON experiment provides a high time-resolution data of cosmic radiation protons and electrons absorbed dose accumulation, as well as the thermal neutrons count rates.

References

I. Apáthy, Y.A. Akatov, V.V. Arkhangelsky, L. Bodnár, S. Deme, I. Fehér, A. Kaleri, I. Padalka, T. Pázmándi, G. Reitz, S. Sharipov, Acta Astronaut. **60**, 322 (2007)

T.W. Armstrong, B.L. Colborn, Radiat. Meas. **33**, 229 (2001)

G.D. Badhwar, A. Kondradi, A. Hardy, L.A. Braby, Int. J. Radiat. Appl. Instrum., Part D, Nucl. Tracks Radiat. Meas. **20**, 13 (1992)

G.D. Badhwar, W. Atwell, B. Cash, V.M. Petrov, A. YuA, I.V. Tchernykh, V. a Shurshakov, V. a Arkhangelsky, Adv. Space Res. **22**, 501 (1998)

S.V. Balashov, V.V. Ivanov, I.A. Maksimov, V.V. Hartov, N.A. Vlasova, I.V. Gecelev, T.A. Ivanova, N.N. Pavlov, S.J. Rejzman, I.A. Rubinshtejn, J.N. Sosnovec, L.V. Tverskaja, M.V. Tel'cov, Cosmonaut. Rocket Eng. **30**, 95 (2003)

V.V. Benghin, T.A. Kostereva, J.V. Semkova et al., Cosm. Res. **30**, 700 (1992)

E.R. Benton, E.V. Benton, Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms **184**, 255 (2001)

V.G. Bobkov, V.P. Permin, I.B. Keirim-Markus, Radiobiology **11**, 766 (1970)

J.F. Bottollier-Depois, L. Lebaron-Jacobs, M. Siegrist, E. Duvivier, B. Almarcha, T.P. Dachev, J.V. Semkova, Y.N. Matviichuk, R.T. Koleva, B.T. Tomov, P.T. Baynov, V.M. Petrov, V.V. Shurshakov, V. Bengin, S.B. Koslova, Adv. Space Res. **18**, 171 (1996)

L.S. Bratoljubova-Celukidze, B.M. Kuzhevskij, S. Kuznecov, V.I. Ljagushin, O.J. Nechaev, M.G. Nikiforova, M.I. Panasjuk, P.I. Shavrin, Izv. Akad. Nauk SSSR, Ser. Fiz. **59**, 109 (1995)

T.F. Cleghorn, P.B. Saganti, C.J. Zeitlin, F.a. Cucinotta, Adv. Space Res. **33**, 2215 (2004)

V.E. Dudkin, P. YuV, A.B. Akopova, L.V. Melkumyan, E.V. Benton, A.L. Frank, Int. J. Radiat. Appl. Instrum., Part D, Nucl. Tracks Radiat. Meas. **17**, 87 (1990)

O.G. Gazenko, in *Obespechenie Radiac. Bezop.*, ed. by O.G. Gazenko (Nauka, Moscow, 1986), pp. 54–76

V.S. Goryacheva, S.A. Voronov, V.V. Mikhailov, J. Phys. Conf. Ser. **798**, 12039 (2017)

Y.G. Grigoriev, *Radiation Safety of Space Flights* (Atomizdat, Moscow, 1975)

E.I. Jurjatin, V.I. Shumshurov, V.A. Fominyh, M.V. Tel'cov, Meas. Tech. **3**, 48 (1979)

J. Labrenz, S. Burmeister, T. Berger, B. Heber, G. Reitz, J. Space Weather Space Clim. **5**, A38 (2015)

J. Lemaire, E.J. Daly, J.I. Vette, C.E. McIlwain, S. McKenna-Lawlor, in *Proc. ESA Work. Sp. Environ. Anal* (1990)

V.I. Ljagushin, A.N. Volkov, A.P. Aleksandrin et al., Vopr. At. Nauk. I Teh. Ser. Fiz. Radiac. Vozdejstv. Radioelektron. Appar. **4**, 22 (2002)

V.V. Markelov, V.I. Red'ko, USSR patent No. 766289, 1978

V.V. Markelov, V.I. Red'ko, Cosm. Res. **19**, 316 (1982)

M.I. Panasjuk, P.I. Shavrin, O.J. Nechaev, L.S. Bratoljubova-Celukidze, T.R. Markelova, M.A. Sergeeva, Preprint 90-13/159 SINP MSU, 1990

M.I. Panasyuk, in *Model Kosmosa. Tom 1. Fizicheskie Uslovija v Kosmicheskom Prostranstve*, (KDU, Moscow, 2007) (in Russian)

G. Reitz, R. Beaujean, E. Benton, S. Burmeister, T. Dachev, S. Deme, M. Luszik-Bhadra, P. Olko, Radiat. Prot. Dosim. **116**, 374 (2005)

J. Semkova, R. Koleva, S. Maltchev, N. Kanchev, V. Benghin, I. Chernykh, V. Shurshakov, V. Petrov, E. Yarmanova, N. Bankov, V. Lyagushin, M. Goranova, Adv. Space Res. **45**, 858 (2010)

J. Semkova, T. Dachev, R. Koleva, N. Bankov, S. Maltchev, V. Benghin, V. Shurshakov, V. Petrov, J. Space Weather Space Clim. **32**, 4 (2014)

V.D. Sevast'janov, G.B. Tarnovskij, V.I. Ljagushin, Cosm. Res. **35**, 216 (1997)

A.V. Shafirkin, *Biological Effects of Space Radiation and Radiation Safety of Space Flight* (SINP MSU, Moscow, 2008)

P.I. Shavrin, B.M. Kuzhevskij, S.N. Kuznetsov, O.Y. Nechaev, M.I. Panasyuk, S.P. Ryumin, B.Y. Yushkov, L.S. Bratolyubova-Tsulukidze, V.I. Lyagushin, Y.L. Germantsev, Radiat. Meas. **35**, 531 (2002)

V.A. Shurshakov, V.M. Petrov, Y.V. Ivanov, V.A. Bondarenko, V.V. Tzetlin, V.S. Makhmutov, T.P. Dachev, J.V. Semkova, Radiat. Meas. **30**, 317 (1999)

J.A. Van Allen, L.A. Frank, Nature **184**, 219 (1959)