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Overview of the Space Radiation Extreme Events Observed with Liulin Type Instruments

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1. Abstract The paper presents the space radiation extreme events observed with Liulin type instruments. The following events, characterized by fast increase of the dose rate were classified as extreme: solar energetic particles (SEP) events, relativistic electron enhancements (REE) and burst type REE in the outer radiation belt (ORB). We compare the dose rates data from 4 SEP events in 1989, 2012, 2015 and 2022, 2 REE events in 2010 and 2015 and 1 burst type REE in 2015. All data were selected to cover periods of 6 hours and 30 minutes that are the average continuation of the extra vehicle activities (EVA) on the ISS. The time intervals were chosen to coincide with the maximum of the observed dose rates during different events. Only the REE1 event data was chosen simultaneously with real EVA-1 of STS-131 astronauts on April 9 2010. The dose rates data in the inner and the outer radiation belt maxima measured by RADOM instrument in 2008 at about 3,000 and at about 20,000 km altitude, respectively, are compared with the extreme events data.

2. Introduction

In the other space two radiation sources are observed - galactic cosmic ray (GCR) and solar energetic particle (SEP). Both sources are populated mainly by high-energy protons. In the near Earth space environment two additional radiation sources exists-the inner (mainly energetic protons) (IRB) and other (mainly relativistic electrons (ORB) radiation belts. We study the fast enhancements in proton and electron sources and call them "Extreme".

The source selection procedure described by [Dachev et al. 2017] was used and the result of the separation of the four radiation sources is seen in Figure 1b. In the Figure 1a the variations of the disturbance storm-time (Dst) index (in nanotesla) are presented (https://wdc.kugi.kyoto-u.ac.jp/index.html). From Fig. 1b, is seen that the most stable are the daily dose rate variations in the GCR source with a heavy black dotted line in the bottom of Fig. 1b. The next relatively 'stable' source is the IRB source, seen with a moving average green line over two points in the lower part of Figure 1b. The most dynamic is the ORB source. Well seen anti correlation with the Dst index is observed because the ORB source is filled up by relativistic electrons during magnetic storms. Two of the fast enhancements "Extreme" in the ORB source named REE2 and Burst REE are object of study in the paper.

There are two major measurement systems developed by the Bulgarian team until this moment [Dachev et al., 2015]. The first one is based on one detector and is known as Liulin type Deposited Energy Spectrometer (DES) [Dachev et al., 2002, 2017, 2020], while the second one is dosimetric telescope (DT) by 2/3 detectors [Semkova et al., 2007, 2012, 2018]. The cited above papers are easy accessible that is why we will not go in details for the instrumentation description in this paper. The Liulin experiments names used here are LIULIN, Liulin-5, Liulin-MO, RADOM, R3DR1 and R3DR2.

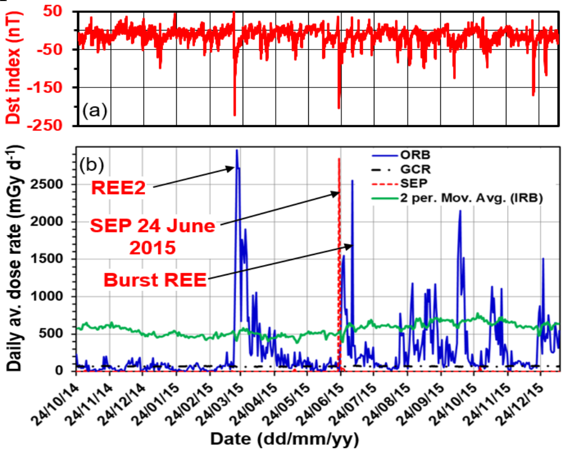
3. Overview of the extreme events observed with Liulin type instruments

3.1. SEP event observed by LIULIN instrument on MIR SS on 30 September 1989

The first observation of SEP event was made with the Bulgarian-Russian dosimeter-radiometer LIULIN (see Fig. 2), which was installed in the working compartment of the MIR space station [Dachev et al., 1989]. The detector unit (LIULIN-DU) is a miniature, portable, self-indicating device. The LIULIN-microcomputer unit (LIULIN-MCU) is an eight-bit microprocessor unit. (One of the first microcomputers in the Bulgarian space instrumentation practice.) The LIULIN-DU use a surface-barrier silicon detector in the form of a 0.3 mm thick disk with an area of 2-cm^2 and dose sensitivity of 10^{-9} Gy/pulse. LIULIN was in active operation on MIR space station from 1989 to 1994.

The period of September-October 1989 was marked by a series of 3 SEP events, which were the most significant over the period of observations since the known SEP of August 1972 [Shurshakov et al., 1999]. The most powerful was the SEP on 19 October 1989. Unfortunately, there are LIULIN data only fort the first part of this SEP. That is why here we analyze the data obtained on 30 September 1989. Also, the SEP maxima on 24 June 2015.

Fig. 2 presents 10-sec resolution data obtained in the time interval between 00:30 and 07:00 hour UT on 30 September 1989 when the maximal SEP dose rate was observed [Dachev et al. 1972]. The vertical axes covers seven orders of magnitude and is same for all figures in the paper to allow easier comparison among them. Two correlating parameters are plotted in the figure – the measured dose rate and the L-value of the point of observation. The dose rate data are selected to be larger than 20-μGy h^{-1} that is why eight coinciding maxima are seen in both parameters.



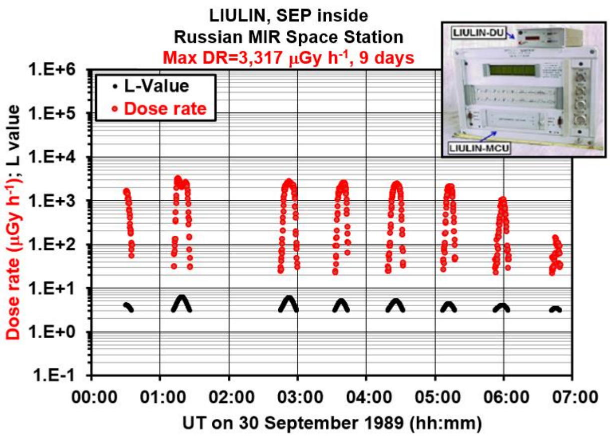


Fig. 1. *Fig. 2.*

***Figure 1a.** Daily Dst index variations; **Figure 1b.** Daily GCR, IRB, ORB and SEP dose rate variations as measured by R3DR2 instrument on Russian segment of ISS. Some of the extreme events studied in the paper are marked. **Figure 2.** External view of the LIULIN dosimeter radiometer and dose rate data dynamics during the SEP on 30 September 1989.*

The reason for the reduction of the SEP dose rates, toward lower L values is the geomagnetic shielding, measured by the vertical cutoff rigidity [Smart & Shea, 2005]. The vertical cutoff rigidity decreases at the higher L values. As a result, large amount of SEP protons, including the low-energy protons, penetrates to the MIR orbit altitude and produces the high latitude maximum in the absorbed SEP dose rate. In the region of lower L-values due to the large magnetic field and respectively vertical cutoff rigidity, the low-energy SEP particles are deflected by the magnetic field outside the magnetosphere and dose rate is decreased.

3.2. SEP event observed by Liulin-5 DT instrument on ISS on 12 March 2012

Liulin-5 DT instrument (see Fig. 3) [Semkova et al., 2007, 2012] was launched to the Russian segment of ISS in May 2007. Measurements with Liulin-5 were conducted in the spherical tissue equivalent phantom of Matroshka- R experiment located in the PIRS-1 module of the Russian segment of ISS.

During the SEP events of 7-12 March 2012 at L>3 the particle flux and dose rates increased in all three detectors of Liulin-5 charged particle telescope located at 40, 60 and 165 mm depths along the radius of the tissue-equivalent spherical phantom in MIM1 module of Russian segment of ISS.

Fig. 3 presents 30-sec resolution data obtained in the time interval between 12:59 and 19:29 hour UT on 7 March 2012 when the maximal SEP dose rate was observed [Semkova et al., 2012]. The dose rate data are presented in the same way as in Fig. 2. Simple comparison show that the dose rates in the 2012 SEP event are about 1 and half order of magnitude smaller than the 1989 dose rates, independently that the GOES 6 and GOES 16 proton fluxes for energies larger than 10 MeV are similar (pls. see first column of Table 1).

3.3. SEP event observed by R3DR2 instrument in ESA EXPOSE-R2 platform outside Russian segment of ISS on 22 June 2015

Fig. 4 presents 10-sec resolution data obtained by R3DR2 instrument in the time interval between 16:57 and 22:27 hour UT on 22 June 2015 [Dachev et al., 2016]. The green line in Fig. 3 presents the measured on GOES-16 >10 MeV proton flux when the maximal SEP dose rate was observed.

The studied SEP event is remarkable by the low energy proton fluxes. The method for estimation of the proton energy [Haffner, 1971, Dachev et al., 2017] allowed to be calculated the energy of the SEP protons at the surface of the R3DR2 instrument detector. The blue points in Fig. 4 shows that close to the SEP maxima the proton energy have a local minimum with mean energies of 7-8 MeV. The small energy of the SEP protons in June 22 event is confirmed by Prof. Semkova. She mentioned in a private communication that the Liulin-5 DT inside RS of ISS do not observe enhanced proton flux during the time of the event.

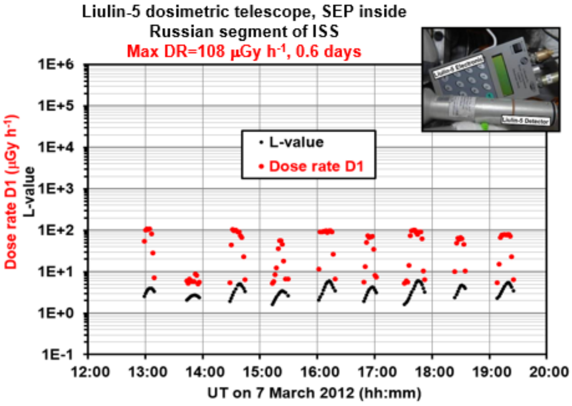


Fig. 3.

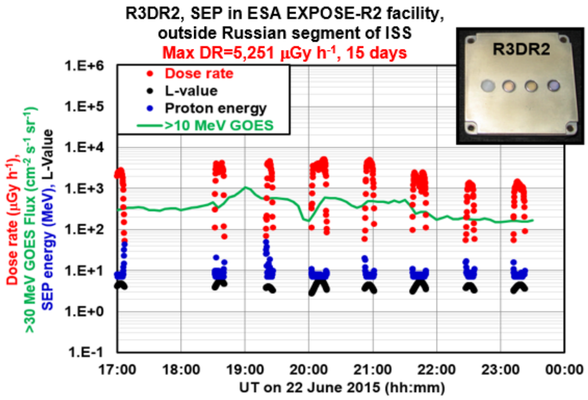


Fig. 4.

Figure 3. *External view of the Liulin-5 dosimetric telescope and dose r1te data dynamics during the SEP on 7 March 2012.* ***Figure 4.*** *External view of the R3DR2 dosimeter and dose rate data dynamics during the SEP on 22 June 2015;*

3.4. SEP event observed by Liulin-MO dosimetric telescope in 400 km Mars circular orbit outside ESA-Roscosmos ExoMars TGO satellite in February 2022

Solar prominence was seen by the Full Sun Imager of the Extreme Ultraviolet Imager on board the ESA/NASA Solar Orbiter spacecraft at about 22:00 UT on 15 February 2022 (https://www.esa.int/ESA_Multimedia/Images/2022/02/Solar_Orbiter_captures_giant_solar_eruption). This is the largest solar prominence eruption ever observed in a single image together with the full solar disc. The coronal mass eruption (CME) propagated in northeast direction, includes the ecliptic. Its speed was about 1000 km s^{-1} and the consequent shock wave accelerated the SEP that reached Mars orbit where Liulin-MO instrument worked outside ESA-Roscosmos ExoMars TGO satellite.

Fig. 5 presents 60-sec resolution SEP dose rate data in the Liulin-MO dosimetric telescope (DB direction of the telescope) [Semkova et al., 2018]. The data was obtained at 400 km Mars circular orbit outside ESA-Roscosmos ExoMars TGO satellite. All data set between 12 UT on 15 February and 12 UT on 17 February is shown with heavy black line, while the 6 hours and

30 minutes similar to EVA time interval close to the maximum of the SEP event with heavy red line.

In the left part of Fig. 5, the small dose rate data present the GCR conditions, which is characterized by average dose rate value of 15.8-μGy h^{-1}. Further, the dose rate increase in result of registration of solar energetic protons, reach maximal value of 1,355-μGy h^{-1} and slowly decrease toward GCR levels out of the time shown in Fig. 5.

3.5. Inner and other Radiation belts observation by RADOM instrument outside Indian Moon satellite Chandrayaan-1 on 22 October 2008

The Indian Moon Chandrayaan-1 spacecraft was launched on 22 October 2008 and injected into a 255-22,860 km preliminary orbit. The **RAD**iati**O**n **M**onitor (RADOM) is a miniature (110x40x20 mm, 0.1 kg) dosimeter-spectrometer (pl. see fig 6), which was switched "ON" two hours after the launch. In Fig. 6 dose rate, dose to flux and altitude data are presented in the UT time interval 18:00-00:30 on 22 and 23 October 2008.

The analysis shows that in the left part of Fig. 6 are observed high doses and fluxes with time resolution of 10-sec. We interpret these dose rates as generated by predominating relativistic electrons in the ORB at altitude above 20,000 km, because the specific doses are less than one nGy cm^2 particle^{-1} [Haffner, 1971]. The doses here reach maximum values of 43,568-μGy h^{-1}. Gradually from left to right in Fig. 6 when the satellite moves toward the slot region and next reached the IRB maximum where high-energy protons are observed. The dose rate here reaches 125,699-μGy h^{-1}, while the dose to flux is few nGy cm^2 particle^{-1}.

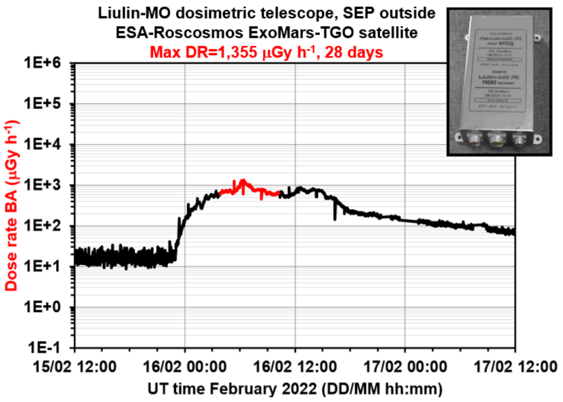


Fig. 5.

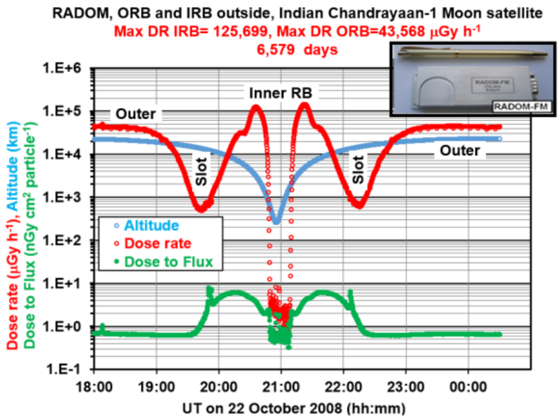


Fig. 6.

Figure 5. *External view of the Liulin-MO dosimetric telescope and dose rate data dynamics during the SEP on 16 February 2022.* ***Figure 6.*** *External view of the RADOM dosimeter and dose rate data dynamics during the crossings of the inner and outer radiation belts on Indian Chandrayaan-1 Moon satellite on 22 June 2015.*

When the satellite crosses the altitudes of about 2000 km, a drastic decrease of doses and fluxes occur because it moves below the ORB maximum. Further motion of the satellite toward the perigee brings the minimal observed dose rate values of about 12-μGy h^{-1} corresponding to the usual GCR dose rates. After the crossing of the perigee region at about 250 km, altitude the satellite starts to move back to the proton and electron belts where the dose rates rise again to the values observed at the left part of Fig. 6.

3.6. Relativistic electron enhancements observation by R3DR1/R2 instruments in ESA EXPOSE-R1/R2 facilities outside Russian segment of ISS

Fig. 7 presents 10-sec resolution data obtained by R3DR1 instrument in the time interval between 05:31 and 11:58 hour UT on 9 April 2010. It is seen that the maxima in the dose rate correlate well with the L-value and anticorrelate by the Dose to Flux value, showing minima less than 1 nGy cm^2 particle^{-1}. This according to Heffner's formulae [Heffner, 1971] confirm that the predominate particle population in the dose rate maxima are relativistic electrons. The

REE in April 2010 collected data simultaneously with real EVA-1 of STS-131, April 9 2010 between 05:31 and 11:58 UT (https://www.nasa.gov/pdf/440897main_sts_131_press_kit.pdf).

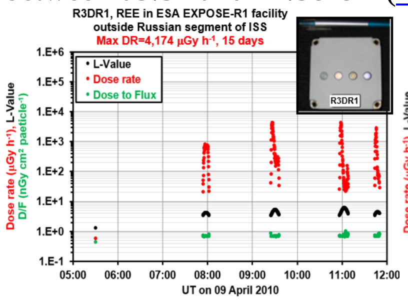


Fig. 7.

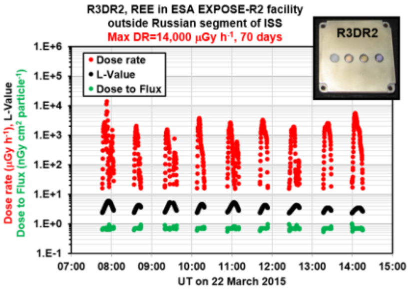


Fig. 8.

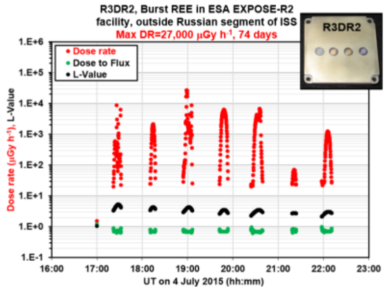


Fig.9.

Figure 7. *External view of the R3DR1 dosimeter and dose rate data dynamics during the REE1 on 9 April 2009;* ***Figure 8.*** *External view of the R3DR2 dosimeter and dose rate data dynamics during the burst REE2 on 4 July 2015;* ***Figure 9.*** *External view of the R3DR2 dosimeter and dose rate data dynamics during the REE2 on 22 March 2015.*

Table 1. Summarized data for SEP (red) and REE (blue) events. The ISS daily averaged dose of 177-µGy h^{-1} in the last column is averaged value from data in Table 2 of Reitz et al., 2005.

Instrument name and its shielding. GOES >10 MeV proton or >2 MeV electron flux (cm^2 s^{-1} sr^{-1})	Event type, Date UT from-to	Max. Observed dose rate/Min. allow. (µGy h^{-1}) Remark	Accumulated dose (mGy) for 6h and 30m	Calculated number of days inside ISS
Inside "MIR" SS; >15 g cm^2; "LIULIN" GOES-6: >10 MeV proton flux=1000-2000 >100 MeV proton flux=300-400	SEP, 30/09/1989 00:30-07:00	3,317/20 The largest dose rate on MIR.	1.72	10
Inside RS of ISS; >20 g cm^2; "Liulin-5" (First detector). GOES-15: >10 MeV proton flux=1000-2000 > 100 MeV proton flux=30-40	SEP, 07/03/2012 12:59-19:29 6 h 30 m	108/5	0.114	0.6
Outside ISS ESA, inside EXPOSE-R2 0.25-0.5 g cm^2; R3DR2 GOES-15: >10 MeV proton flux=200-500 >100 MeV proton flux=0.01-0.02	SEP 22/06/2015 16:57-22:27	5,251 The largest observed on ISS proton dose rate	2.84	16
Outside ESA-Roscosmos ExoMars 0.5-1 g cm^2; Liulin-MO	SEP, 16/02/2022	DB=1,355 DC=1,375	5.07	28
Outside Indian Moon Chandrayaan-1 0.5-1 g cm^2; RADOM	IRB & ORB, 22-23/10/2008 18:00:00:30	125,699 43,568	1,184	6,690
Outside ISS, inside ESA EXPOSE-R1 0.25-0.5 g cm^2; R3DR1 GOES-15 electron flux=10^4-10^5	REE1, 09/04/2010 05:31-11:58 (in the time of STS-131 EVA-1)	4,174	2.66	15
Outside ISS, inside R3DR2 in ESA EXPOSE-R2, 0.25-0.5 g cm^2; GOES-15 electron flux=10^2-10^3	Burst type REE 04/07/2015 17:00-23:30	27,020 The largest observed on ISS electron dose!	13.3	75
Outside ISS, inside ESA EXPOSE-R2 0.25-0.5 g cm²; R3DR2	REE2, 22/03/2015 07:46-13:46	14,000	12.6	71

Fig. 8 and Fig. 9 looks very similarly to Fig. 7 because similar REE events are observed. It is necessary to mention that the Burst REE on 4 July (Fig. 8) is the only one seen in the Liulin data. It is formed by seven maxima, classified as "Precipitation bands" [Dachev, 2018]. The PB were identified as rapid (10-40-sec) dose rate enhancement from the normal (20–200 µGy h^{-1}) ORB level and similar fast return to the same low level. Only PB that have in the time profile dose rates larger than 10,000-µGy h^{-1}, identical to flux larger than 4000 cm^{-2} s^{-1}, for 10 or more seconds were selected. 23 PB were found in the R3DR1/R2 data sets.

Conclusions

The main conclusion of the presented data is that the REE events bring more accumulated dose in 6 hour and 30 minutes. The maximal SEP accumulated dose of 15 mGy outside ISS is equal to the minimal REE1 accumulated dose. The fact that the new phenomena of burst REE brings the maximal accumulated dose of 74 mGy was unexpected. From other hand, the much smaller penetration of the relativistic electrons in the bodies of astronauts brings much smaller health effects.

Although the obtained relativistic electron doses do not pose extreme risks for the astronauts, being on EVA, they have to be considered as a permanently detected radiation source, which requires additional comprehensive investigations.

The accumulated doses during all studied extreme events on the MIR, ISS and in Mars orbit are incomparable with the doses during the crossings of the IRB and ORB maxima at 3,000 and 22,000 km respectively. This explain why the manned missions at low earth orbit are kept at altitudes below 500 km.

Acknowledgements

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References

Dachev, T.P., Matviichuk, Y.N., Bankov, N.G., Semkova … Machmutov, V.S., 1992. MIR Radiation dosimetry results during the solar proton events in September–October 1989. Advances in Space Research, 12(2-3), pp.321-324. https://doi.org/10.1016/0273-1177(92)90122-E

Dachev T.P., Tomov… F., Spurny, (2002). Calibration Results Obtained With Liulin-4 Type Dosimeters. Adv. Space Res. 30, No 4, 917-925. http://dx.doi.org/10.1016/S0273-1177(02)00411-8.

Dachev, T.P., Tomov, B.T., Matviichuk … Angelis G.De, (2011). An overview of RADOM results for Earth and Moon Radiation Environment on Chandrayyan-1 Satellite, Adv. Space Res., 48, 5, 779-791. http://dx.doi.org/10.1016/j.asr.2011.05.009

Dachev, T.P., Semkova…Kubancak, I. N. (2015). Overview of the Liulin type instruments for space radiation measurement and their scientific results. Life Sciences and Space Research, 4, 92–114. https://doi.org/10.1016/j.lssr.2015.01.005.

Dachev, T. P., Tomov, B.T., Matviichuk, Y.N., Dimitrov, P.G., & Bankov, N.G., (2016). High dose rates obtained outside ISS in June 2015 during SEP event, Life Sciences in Space Research, 9, 84-92. http://dx.doi.org/10.1016/j.lssr.2016.03.004.

Dachev, T.P., Bankov, N.G., Tomov, B.T., Matviichuk, Y.N., Dimitrov, P.G., Häder, D.-P, Horneck, G., (2017). Overview of the ISS radiation environment observed during the ESA EXPOSE-R2 mission in 2014–2016. Space Weather, **15**, 1475–1489. https://doi.org/10.1002/2016SW001580.

Dachev, T.P., (2018). Relativistic electron precipitation bands in the outside radiation environment of the international space station. Journal of Atmospheric and Solar-Terrestrial Physics, 177, pp.247-256. https://doi.org/10.1016/j.jastp.2017.11.008

Dachev, T.P., Tomov, B.T., Matviichuk, Y.N., Dimitrov, P.G., Semkova, J.V., Koleva, R.T., Jordanova, M.M., Bankov, N.G., Shurshakov, V.A. and Benghin, V.V., (2020). Solar modulation of the GCR flux and dose rate, observed in space between 1991 and 2019. Life Sciences in Space Research, 26, 114-124, 2020. https://doi.org/10.1016/j.lssr.2020.06.002.

Haffner, J.W., (1971). Yadernoe izluchenie i zashchita v kosmose, pp 115, Atomizdat, Moscow.

Reitz, G., Beaujean, R., Benton, E., Burmeister, S., Dachev, T., Deme, S., Olko, P., (2005). Space radiation measurements on-board ISS-the DOSMAP experiment. Radiat Prot. Dosimetry 116, 374–379. https://doi.org/10.1093/rpd/nci262.

Semkova, J., R. Koleva… I. Chernykh, Status and calibration results of Liulin-5 charged particle telescope designed for radiation measurements in a human phantom onboard the ISS, Advances in Space Research, 40, 2007, 1586–1592. http://dx.doi.org/doi:10.1016/j.asr.2007.01.008.

Semkova, J., Koleva, R., Maltchev, St., Bankov, N., Benghin, V., et al., (2012). Depth dose measurements with the Liulin-5 experiment inside the spherical phantom of the Matroshka-R project onboard the International Space Station, Adv. Space Res., 49, 471–478. http://dx.doi.org/10.1016/j.asr.2011.10.005.

Semkova, J., Koleva, … Malakhov, A., (2018). Charged particles radiation measurements with Liulin-MO dosimeter of FREND instrument aboard ExoMars Trace Gas Orbiter during the transit and in high elliptic Mars orbit, Icarus, 303, pp.53-66. https://doi.org/10.1016/j.icarus.2017.12.034.

Shurshakov, V.A., Petrov, V.M., Ivanov, Y., Bondarenko, V.A., Tzetlin, V.V., Makhmutov, V.S., Dachev, T.P. and Semkova, J.V., (1999). Solar particle events observed on MIR station. Radiation measurements, 30(3), 317-325. https://doi.org/10.1016/S1350-4487(99)00058-X

Smart, D.F. and Shea, M.A., (2005). A review of geomagnetic cutoff rigidities for earth-orbiting spacecraft. Advances in Space Research, 36(10), 2012-2020.