INTERNATIONAL SPACE STATION RADIATION FIELD MEASUREMENTS BY LIULIN-SET SPECTROMETER OF ARMAS FLIGHT MODULE 9 IN 2022

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Abstract: *Liulin-SET spectrometer-dosimeter is part of the Automated Radiation Measurements for Aerospace Safety (ARMAS) flight module number 9 (FM9).*

ARMAS FM9 was launched on February 19, 2022 and operated outside of the Japanese Experimental Module of the International Space Station for 216 days from March until December 2022, measuring the ionizing dose and LET spectrum.

The goal of this paper is to present, in brief, a preliminary analysis of the Liulin-SET data and to compare them with the data from another Liulin instrument, the R3DR2, that flew outside the Russian segment of the International Space Station inside the ESA EXPOSE-R2 module in 2014–2016.

ИЗМЕРВАНИЯ НА РАДИАЦИОННОТО ПОЛЕ НА МЕЖДУНАРОДНАТА КОСМИЧЕСКА СТАНЦИЯ НАБЛЮДАВАНО ОТ СПЕКТРОМЕТЪРА LIULIN-SET ОТ МОДУЛА ARMAS 9 ПРЕЗ 2022 Г.

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Резюме: ***С****пектрометърът дозиметър Люлин-СЕТ е част от полетния модул номер 9 (FM9) на автоматизираните системи за радиационни измервания за аерокосмическа безопасност (ARMAS).*

ARMAS FM9 беше изстрелян на 19 февруари 2022 г. и работи извън японския експериментален модул на Международната космическа станция в продължение на 216 дни от март до декември 2022 г., измервайки дозата и потока на космическата радиация.

Целта на тази статия е да представи накратко част от предварително обработените данни от Люлин-СЕТ и да ги сравни с данните от друг инструмент от серията Люлин, инструмента R3DR2, летял извън руския сегмент на Международната космическа станция вътре в модула на ESA EXPOSE-R2 през 2014–2016 г..

Introduction

The ionizing radiation field around the International Space Station (ISS) is very complex. It is composed of galactic cosmic rays (GCR), trapped radiation of the Earth’s radiation belts, solar energetic particles, albedo particles from the Earth’s atmosphere and secondary radiation, produced in the shielding materials of the spacecraft or space suits of the astronauts.

Both, the radiation field and the shielding of the surrounding material [1], affect the absorbed dose outside the spacecraft. In the low Earth orbit (LEO), the radiation dose also depends on other factors, such as the spacecraft orbit parameters, solar cycle phase and current helio- and geophysical parameters.

The dominant radiation component in the space environment near the Earth are the galactic cosmic rays (GCR), modulated by the solar activity. High-energy charged particles are trapped by the Earth’s magnetic field and form the two distinct belts of toroidal shapes surrounding the Earth: the Inner Radiation Belt (IRB) and the Outer Radiation Belt (ORB). The IRB is situated at an altitude from 0.2 to 2.0 Earth radii at the geomagnetic equator and consists of electrons, with energies of up to 10 MeV, and protons with energies of up to 700 MeV. The ORB is located in the altitudinal range from 3.4 to 10 Earth radii. The ORB energetic population are electrons with energies of a few MeV.

The first observations of the ORB relativistic electron fluxes in the ISS were made in 2001 with Liulin-E094 instrument on the American laboratory module [2, 3]. Later, ORB relativistic electron fluxes were observed with Liulin type instruments flying again on the ISS and on LEO satellites.

The Goal

The goal of this paper is to present, in brief, a preliminary analysis of Liulin-SET data and to compare them with the data from another Liulin instrument, the R3DR2 instrument [4]. The latter flew outside the Russian segment of the ISS inside the ESA EXPOSE-R2 module [5].

Material and Method

Liulin-SET spectrometer

Liulin-SET instrument was developed under request from Space Environment Technologies (SET) Limited Liability Corporation (LLC) Chief Scientist, Dr. K. Tobiska.

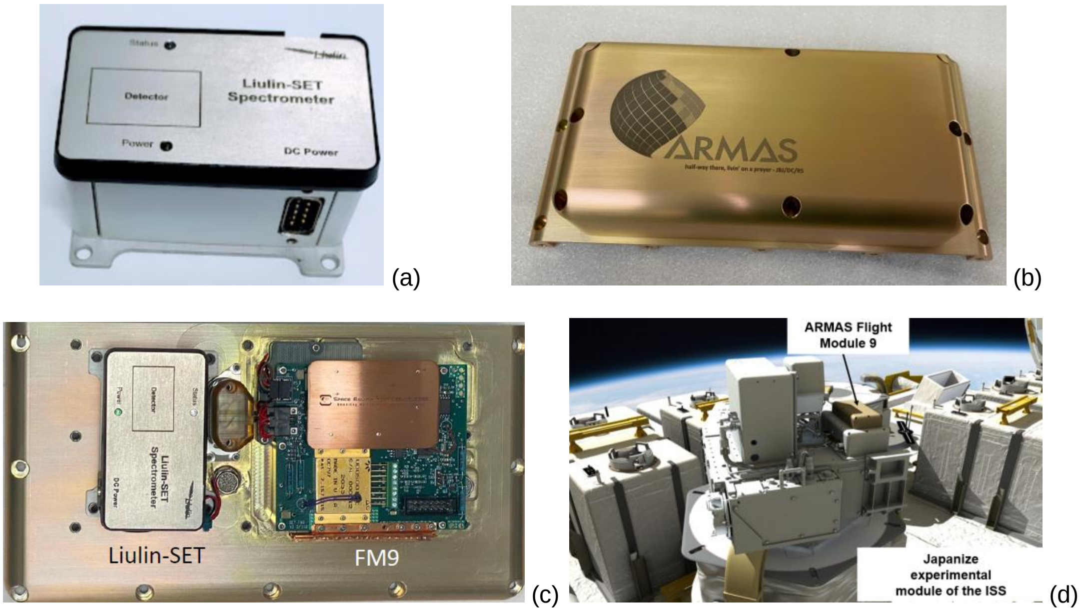


Fig. 1. Liulin SET (a) and ARMAS (b) – outside views, (c) inside the ARMAS – Liulin SET and FM9, (d) schematic presentation of the ARMAS position outside the Japanese experimental module

Liulin-SET is part of the Automated Radiation Measurements for Aerospace Safety (ARMAS) flight module number 9 (FM9). More information is available at https://spacewx.com/wp-content/uploads/2021/05/FM9-overview.pdf. ARMAS FM9 was launched on February 19, 2022. It operates outside of the Japanese Experimental Module (JEM) of the ISS from March until December 2022 for 216 days, measuring the ionizing dose and LET spectrum [6].

The design of the portable spectrometer Liulin-SET is not a new one. Various Liulin spectrometers flew in space since 1989 [7]. Three Liulin battery operated units took part in certification flight of the NASA Deep Space Test Bed (DSTB) balloon [8] on June 8, 2005. The NASA RaD-X mission [9] used a Liulin in September 2016, too. Similar to Liulin-SET instruments flew inside the ESA EXPOSE-E/R/R2 platforms [4].

Liulin-SET spectrometer-dosimeter contains one silicon-PIN diode of Hamamatsu S2744-08 type (2 cm^2 area and 0.3 mm thickness), one ultra-low noise charge-sensitive preamplifier of AMPTEK A225 type, 2 microcontrollers, 64 MB flash memory. After passing a charge-sensitive preamplifier, the signal is digitized by a 12-bit fast analogue to digital (A/D) converter.

The Liulin-SET dimensions are 78x60x37 mm. The total mass is 0.16 kg. The black plastic bezel is made by polycarbonate, which is widely used in space applications. The front panel is lightweight from the backside down to 0.7 mm aluminum. This allowed registration of relativistic electrons from outer radiation belt (ORB) [10].

The Liulin-SET uses 28 VDC and has an insulated DC/DC converter for transforming 18–36 V DC input to 12 V DC internal. A 3.0 V DC battery supplies power to the internal real time clock-calendar and is independent of the external power supply after the first initialization.

The Liulin-SET spectrometer is situated inside of the ARMAS FM9 module (Fig. 1), which is developed by the Space Environment Technologies LLC. The FM9 module provides to Liulin-SET 28 V, 10 mA voltage from the Japanese experimental module.

The spectrum together with information for the real time is saved in the flash memory of the instrument. The capacity of the memory of Liulin-SET is sufficient for the storage of 390 days non-stop compressed spectra with 10 sec exposition time.

Determination of the dose

The doses (deposited energies) are determined by a pulse height analysis technique and then passed to a discriminator.

According to AMPTEK A225 specifications the pulse amplitudes, A[V] are proportional by a factor of 240 mV/MeV to the energy loss in the detector and respectively to the dose. The amplitude of each signal from the incoming particles and quanta are transformed into digital signals that are sorted into 256 channels by a multichannel analyzer. For every exposure interval, a single 256 channels energy deposition spectrum is collected. The energy channel number 256 accumulates all pulses with amplitudes exceeding the maximal level of the spectrometer of 20.83 MeV. All pulses in the 256^{th} channel are considered equal to the minimum energy level for this channel and were added to the dose calculation. Using a statistics of about 2.5 million 10-s data points from the R3DE instrument that flew on the ISS in 2008–2009, 1 event in the 256^{th} channel occurred, on average, once per 6.2 h of measurements.

The Data

Lillian-SET starts to work with the time from the clock-calendar at each switch ON of the external voltage of ±28 V.

In the period March 17 - December 9, 2022, sixty switch ONs were registered. The available in the flash memory 60 files contain data with different length of the registrations - from several minutes to over 1.5 months.

Results and Discussion

Verification of the Radiation Sources Selection Procedure for Liulin-SET

The following four primary radiation sources were expected to be registered in the data of Liulin-SET:

(i) Globally distributed primary GCR particles and their secondary products,

(ii) Protons in the South Atlantic Anomaly (SAA) region of the IRB;

(iii) Relativistic electrons and/or bremsstrahlung in the high latitudes of the ISS orbit where the ORB is situated, and

(iv) Solar energetic particles (SEP) in the high latitudes of the ISS orbit.

The first three sources were registered. Unfortunately, SEP events were not observed in the Liulin-SET data.

While analyzing Liulin space data, we use three methods for separation of the radiation sources.

The first method is the separation based on the dose to flux (D/F) ratio calculations. It was developed experimentally by J. W. Haffner [11], Dachev et al. 2017 [4] recently described the method that is why we will not go into details here. According to the formulae, published in [4, 11] the data can be simply split into two parts by using the dose to flux ratio (D/F). When the D/F is less than 1.12 nGy cm^2 particle^{-1}, the expected predominant type of radiation in the time interval are relativistic ORB electrons. When the D/F is greater than 1.12 nGy cm^2 particle^{-1}, the expected type of radiation are IRB or SEP protons. The GCR source spans the two ranges. The GCR source was identified also by the requirements that their dose rates to be less than 15 μGy h^{-1}.

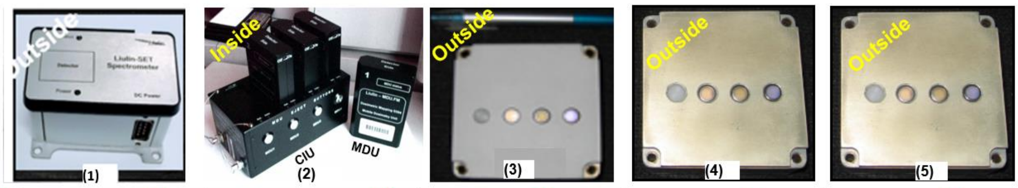
Radiation sources selection by the dose rate from flux and dose to flux (D/F) from flux dependencies

The second method is the separation by the dose rate from flux and dose to flux (D/F) from flux dependencies. To verify this method for Liulin-SET, we have presented the data from Liulin-SET together with data from another four Liulin type instruments, flown between 2001 and 2015 on the ISS.

The Mobile Radiation Exposure Control System Liulin-E094 was part of the experiment Dosimetric Mapping E094. It was placed in the US Laboratory module as a part of the Human Research Facility of Expedition Two Mission 5A.1, STS-102 Space Shuttle Flight [2]. The system consists of four Mobile Dosimetry Units (MDU) and one Control and Interface Unit (CIU). MDU number two (MDU-2) data are used in this study.

The European Space Agency (ESA) EXPOSE-E, EXPOSE-R and EXPOSE-R2 facilities [4, 5], accommodated three Bulgarian-German Radiation Risk Radiometer-Dosimeters (R3D). R3DE instrument was used at the EXPOSE-E facility on the Columbus module of ISS in 2008–2009. R3DR spectrometer [7] worked at the EXPOSE-R facility of ISS from 2009 to 2010. R3DR2 is the same instrument. It was part of EXPOSE-R2 facility on the ISS from 2014 until 2016 [4]. The extension "R2", the same as for the EXPOSE-R2 facilities, is used to distinguish its data from the results of the previous mission with R3DR instrument.

On Fig. 2 Liulin-SET data are compared with data registered at the ISS by the above mentioned instruments. There are three rows of figures and one table in Fig. 2. The first row visualizes the external views of the instruments, i.e. Liulin-SET, Liulin-E094, R3DE, R3DR and R3DR2.



Name, Resol. [sec]	Liulin-SET, 300	Liulin-E094, MDU-2, 30	R3DE, 10	R3DR, 10	R3DR2, 10
Position	Outside Jap. Exp. Module of ISS	Inside Amer. Lab. Module and NODE-1 of ISS	In ESA EXPOSE-E facility outside Russian Seg. of ISS	In ESA EXPOSE-R facility outside Rus. Seg. of ISS	In ESA EXPOSE-R2 facility outside Rus. Seg. of ISS
Time, Aver alt. Aver. F10.7	2 Sept.-17 Oct. 400 km 137	11 May - 25 July 2001, 400 km 154	12 -20 March 2008, 347 km 72	1-10 April 2010, 352 km 76	21-30 June 2015, 407 km 120

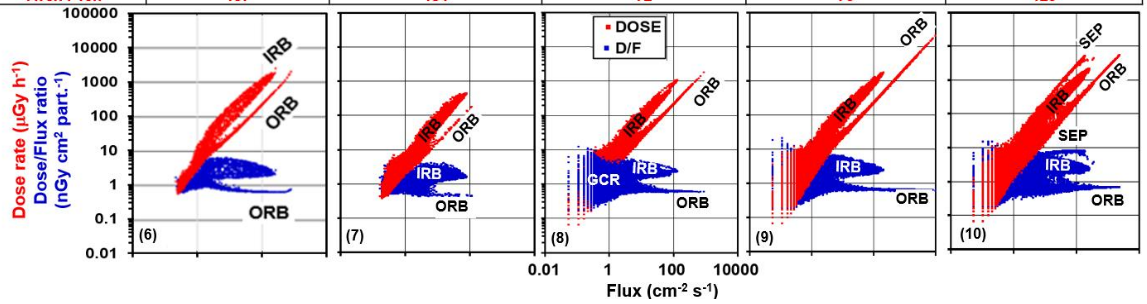


Fig. 2. Comparison of analogical data registered by five experiments on the ISS in the period July 2002-October 2022

The second row is a table providing information for the position of the instrument, its resolution in seconds, the time interval in which the measurements were performed and average for this interval F10.7 cm Radio Flux in solar flux units.

The third row of Fig. 2 presents five graphics of the dose rate from flux and dose to flux (D/F) from flux dependencies. On the horizontal axis is the flux in cm^{-2} s^{-1}, while on the vertical axes are two parameters: the dose rate in μGy h^{-1} (red points) and the dose to flux ratio in nGy cm^2 particle^{-1} (blue points). These graphics are an easy way of visualizing the four different radiation sources components expected at the stations altitudes.

In the first four graphics, the following radiation sources are observed: (1) GCR particles, (2) protons with more than 15.8 MeV energy in the SAA region of the IRB and (3) relativistic electrons with energies above 0.78 MeV. The dose rates (red points) from IRB and the IRB sources are seen as two maxima in the diagonal of each of the first four pictures. An additional maximum from SEP particles is seen in the last column picture, presenting data from the R3DR2 instrument.

The dose to flux maxima (blue points) are situated horizontally in the pictures. The ORB D/F maxima being narrower and below the IRB maxima lies almost in all flux values below 1.12 nGy cm^2 particle^{-1}, which according to Haffner's formulation shows that the predominant amount of particles there are the relativistic electrons. On the opposite, the IRB D/F maxima lies in all flux values above 1.12 nGy cm^2 particle^{-1}, which shows that the predominant amount of particles there are energetic protons. The SEP D/F maximum in the fifth column shows D/F values larger than IRB maximum values and reveal that the protons there are with smaller energies than in the IRB maxima.

When we have analyzed the maxima distribution in the first column with Liulin-SET data, we may conclude that they have very similar shape as other three R3D data sets outside the ISS without SEP particles observation. This verifies the correctness of the dose and flux measurements with Liulin-SET.

Radiation sources selection by the shape of the deposited energy spectra

This is the third method for the separation of the radiation sources.

Fig. 3 compares the deposited energy spectra shapes visualized by Liulin-SET software (the two figures on the left) with data from R3DR2 instrument outside the ISS in 2015.

The leftmost graphic presents 40 Liulin-SET spectra obtained between 13:41 and 16:56 UTC on September 7th, 2022. ORB and GCR spectra predominate. The red points are divided in two branches. The first branch contains points distributed in five orders of the count rates (proportional to the dose rate) against the vertical axes and up to twentieth channel. This shape of spectra reveals ORB spectra with high-count rate and small-deposited energy (as from electrons), which is

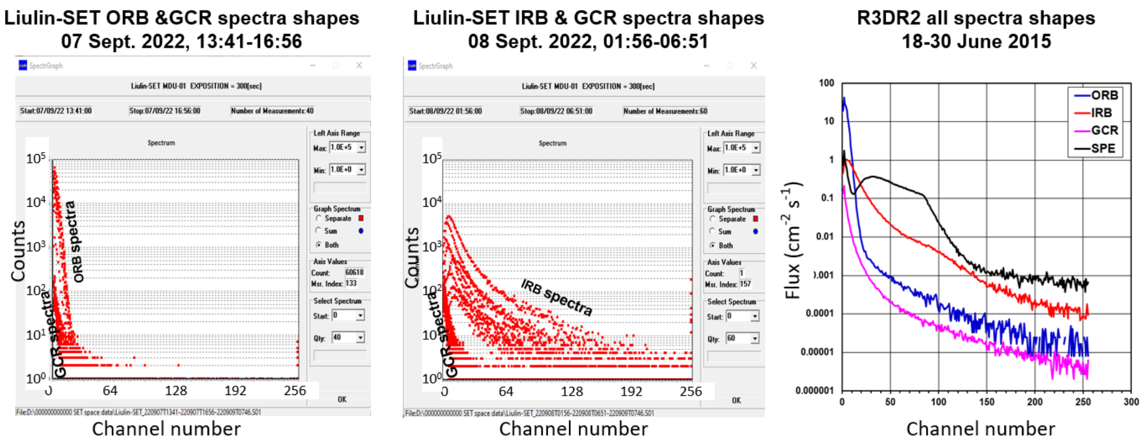


Fig. 3. Comparison of deposited energy spectra shapes of Liulin-SET (the two figures in the left) and data from R3DR2 outside the ISS in 2015

proportional to the channel number. The second branch contains points with small count rates (dose rates) distributed up to 128th channel. This shape of spectra reveals GCR spectra with small-count rate and high deposited energy.

The central graphic presents 60 Liulin-SET spectra obtained between 01:56 and 06:51 UTC on September 8th, 2022. The predomination of IRB and GCR spectra is visible. As in the most left graphic, two branches exists. Well seen is a branch similar to the GCR spectra with small count rates and high channel number. The branch with high-count rates (dose rates) and high channel number (deposited energy) can be associated with the IRB spectra.

The rightest graphic illustrates the energy deposition spectra from four radiation sources registered by R3DR2 instrument outside the ISS between 18 and 30th of June 2015 during an intensive SEP [4]. The magenta spectrum is the GCR spectrum. It has similar characteristics as the GCR spectra in the left side graphic. The same is true for the IRB (red) and ORB (blue) spectra.

Comparison of the global distribution of the IRB and ORB doses and fluxes measured with R3DR2 and Liulin-SET

Figure 4 compares the global distribution of the IRB and ORB doses recorded with R3DR2 instrument, 18–30 June 2015, outside the ISS, ESA EXPOSE-R2 platform and Liulin-SET, 2 September – 27 October 2022, outside the ISS, Japanese module.

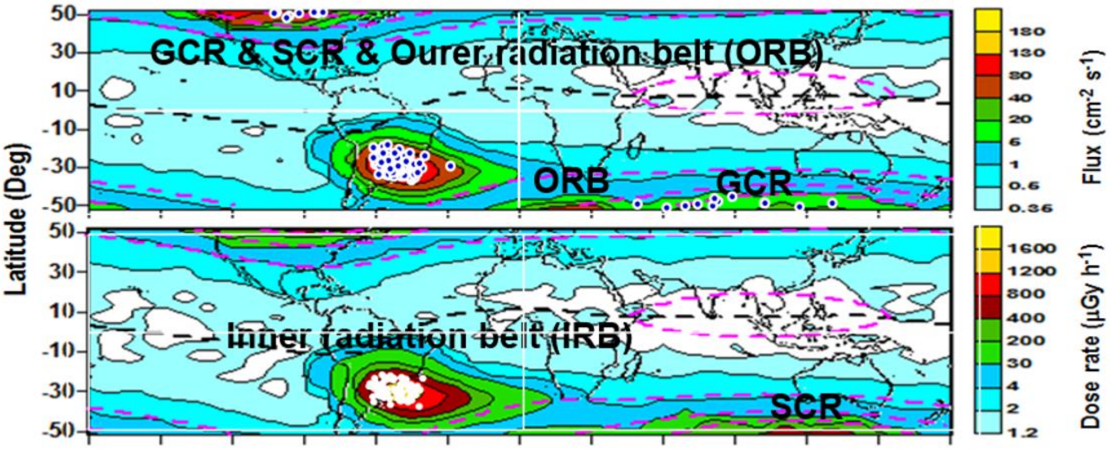


Fig. 4. Global distribution of the IRB and ORB doses and fluxes measured with R3DR2 and Liulin-SET

The basic figure is obtained by R3DR2 data in the ESA EXPOSE-R2 platform and presents in two panels the global 3D distribution of flux (upper panel) and dose rate (lover panel). The R3DR2 data are plotted according to the color bars in the right sides of the panels. The main features in the panels are the complex maxima of GCR, solar cosmic rate (SCR) or SEP and ORB radiation sources in the high latitudes of both hemispheres as well as the IRB maximum in the South Atlantic anomaly region.

Liulin-SET data are plotted by white points for the IRB dose rate >1200 μGy h^{-1} in the lower panel, while the ORB flux >80 cm^{-2} s^{-1} are marked with blue points. The Liulin-SET ORB points position in the Sothern hemisphere is shifted toward higher longitudes because of the smaller magnetic activity in 2022.

Comparison of the L-value distributions of radiation sources doses between R3DR2 and Liulin-SET

Figure 5 compares the McIlwain's L values distributions of the three radiation sources doses (GCR, IRB and ORB) between R3DR2 and Liulin-SET.

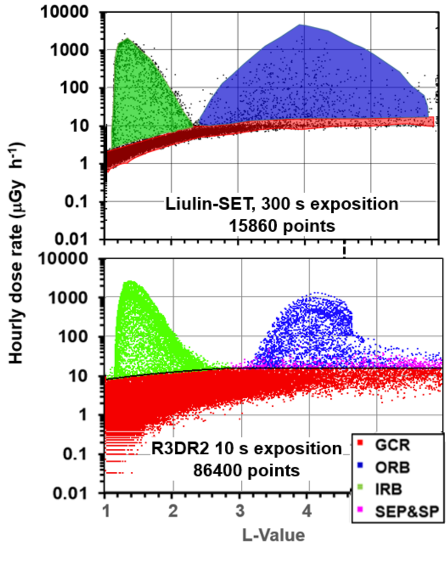


Fig. 5. Comparison of the L-value distributions of radiation sources doses between R3DR2 and Liulin-SET

The upper panel contains data from Liulin-SET in the period 2 September – 27 October 2022, outside the ISS, Japanese module, while the lower panel shows data from R3DR2 instrument in the period 11–20 December 2014, outside the ISS, inside of the ESA EXPOSE-R2 facility. R3DR2 points being almost 5 times more than Liulin-SET do not need additional color fields to separate the different radiation sources, while for Liulin-SET data we use such a fields.

The following radiation sources are seen in Fig. 5: Galactic cosmic rays (with dose rates typically <15-μGy h^{-1}) are plotted with red points in the lower part of each panel. Green points in the upper left corner of the panels are associated with high-energy protons detected when the ISS crosses the SAA region of the IRB. They are characterized by dose rate > 15 μGy h^{-1} and D/F > 1.12 nGy cm^2 $particle^{-1}$. The blue points in the center are associated with high-energy electrons from the ORB. They are characterized by dose rate > 15 μGy h^{-1} and D/F < 1.12 nGy cm^2 $particle^{-1}$ and flux >7 cm^{-2} s^{-1}. The magenta points in the lower panel visualize the distribution of the SEP high-energy protons and secondary protons with doses <20 μGy h^{-1}. In the case of Fig. 5 the magenta points are secondary protons [4].

The good coincidence between dose rates and shapes of the radiation sources in both panels of Fig. 5 allows concluding that Liulin-SET radiation sources distribution data in L-values are well separated and that the calculated values of the ISS orbit parameters are correct.

Conclusions

The preliminary analysis of the Liulin-SET data shows that the instrument is working as expected. The comparison of the Liulin-SET data with data from other instruments flown on ISS confirm that: (1) The radiation sources selection by the dose rate from flux and dose to flux (D/F) from flux dependencies is looking exactly as the selections by other four instruments; (2) Liulin-SET energy depositions spectra have the same shapes as the R3DR2 instrument shapes; (3) The positions of Liulin-SET IRB dose rate and ORB flux coincide with R3DR2 instrument positions; (4) The Liulin-SET L-value sources distributions are well separated and similar to R3DR2 instrument distributions.

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