Radiation Field Outside the ISS Observed by ARMAS Flight Module 9 March - December 2022

W. Kent Tobiska[1,2], Brad Gersey[1,3], Leonid Didkovsky[1], Kevin Judge[1], Seth Weiman[1], Dave Bouwer[1] , Justin Bailey[1]
Tsvetan Dachev[4], Borislav Tomov[4], Yury Matviichuk[4], Plamen Dimitrov[4]
Malina Jordanova[2], Mityo Mitev[2], Nikolay Bankov[2], Jordanka Semkova[4]

[1]Space Weather Division, Space Environment Technologies, Los Angeles, CA, USA
[2]Now at Space Environment Technologies, Los Angeles, CA, USA
[3]Department of Electrical Engineering, Prairie View A. & M. University, Prairie View, TX, USA
[4]Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria

Introduction

Abstract:

ARMAS Flight Module 9 instrument description

The design of the portable spectrometer Liulin-SET is not a new one. Similar devices have already flown on aircraft and stratospheric balloon and in space since 1988. Liulin-SET spectrometer contains one silicon-PIN diode of Hamamatsu with 0.3 mm thickness, one ultra-low noise charge-sensitive preamplifier of AMPTEK A225F type, two microcontrollers, a flash memory and an internal battery operated clock-calendar. Lillian-SET starts to work with the time from the clock-calendar at each switch ON of the external voltage of ±28 V. Sixty switch ONs were registered between March 17 and December 9, 2022. The available in the flash memory 60 files contain data starting from few minutes and finishing with more than 1.5 months.

The analysis of the data shows the existence of tree radiation sources: galactic cosmic rays (GCR), inner radiation belt (IRB) protons in the region of the South-Atlantic anomaly and outer radiation belt (ORB) electrons in the high latitude regions of the ISS orbit. The source selection is performed by the 1971 translations of J. W. Haffner's (1967, 1971) experimental formulation of the dependence between the incident energy of incoming protons and electrons and the dose to flux ratio. The variations of dose rates during quiet geomagnetic conditions are in the ranges: GCR from 0.4 mGy h^{-1} at geomagnetic equator to 25 mGy h^{-1} in the high latitude regions of the ISS orbit; IRB from 10 mGy h^{-1} to 2100 mGy h^{-1} and ORB from 10 mGy h^{-1} to 30 mGy h^{-1}. During the magnetic storm from 3 to 12 September 2022, the GCR and IRB dose rates remain almost the same as during the quiet conditions, while ORB doses rise up in an enhancement to 2100 mGy h^{-1}.

Outlook

Introduction

Liulin-SET description

Preliminary scientific results

- Methods for identification of radiation sources type

  Identification based on the Dose to Flux (D/F) ratio calculations. The method was developed experimentally by J. W. Haffner;

  Identification by the dose rate from flux and dose to flux (D/F) from flux dependencies;

  Identification by the shape of the deposited energy spectra.

- Outer Radiation Belt (ORB) enhancements observed in Liulin-SET 2022 data

Discussion and conclusions

Acknowledgements

Liulin-SET Description

17 Liulin space experiments of Space Research and Technology Institute at the Bulgarian Academy of Sciences

Main scientific goals:

1. Monitoring of the flux and dose rate variations from GCL, SCL, radiation belts around the Earth and in the interplanetary space.
2. Application of the data in the models validation.

8 experiments from 17

Around the Earth

On rocket

Around the Moon

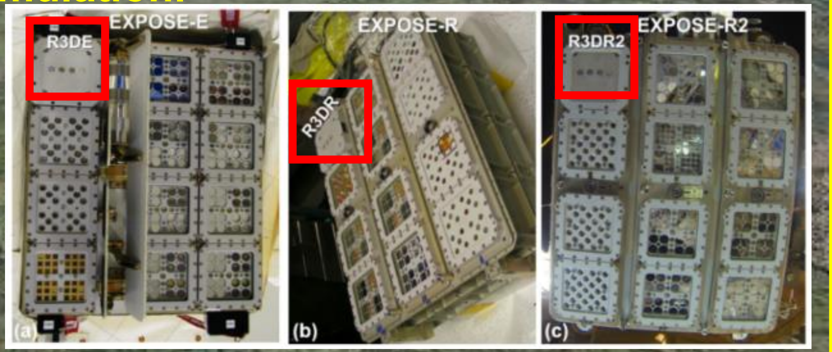
Around the Mars. Still operating!

9 experiments from 17

3. Support of biological and chemical experiments with up-to-date information on the history of dose accumulation.

Foton-M2/3, BION-M1, Foton-M4

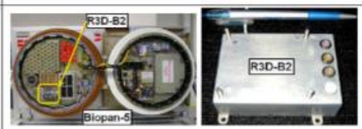
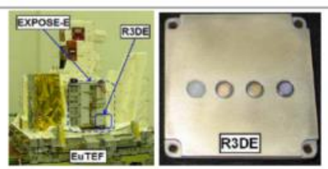
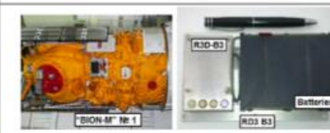
ISS, Liulin-5



ISS, EXPOSE-E/R/R2

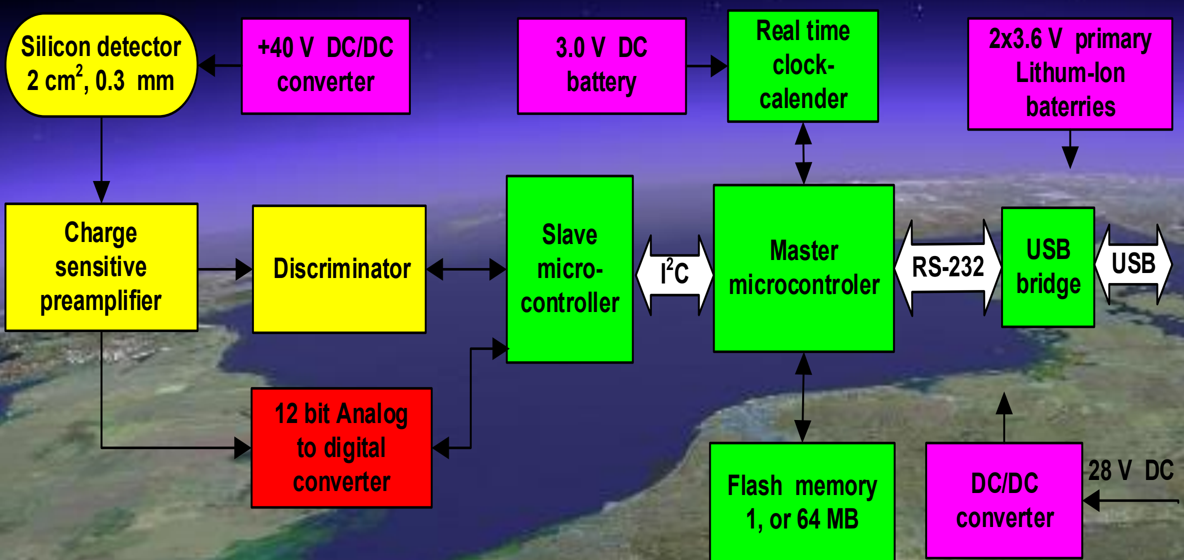
The data from 10 Liulin space experiments are available in online database at:

https://esa-pro.space.bas.bg/database

No	Satellite, Experiment name Begin-end of data Number of measurements and data sources Resolution [sec]/[min]	Cooperation PI, CoPI Main description reference	Instrument location image; External view of the instrument	Most remarkable scientific publications
1	**MIR SS, LIULIN** 01/01/1991-31/12/1991 1,500,034, 2 30 sec	Russia, Bulgaria Petrov, Dachev (Dachev et al., 1989, http://dx.doi.org/10.1016/0273-1177(89)90445-6)		Shurshakov, V.A., et al., New belt..., 1996. http://dx.doi.org/10.1016/1350-4487(96)00040-6 Shurshakov, V.A., et al., SEP events..., 1999. http://dx.doi.org/10.1016/S1350-4487(99)00058-X
2	**ISS, ESA, Dosimetric Mapping, Liulin-E094** 11/05/2001-25/07/2001/ 602,090, 2 2 30 sec	Germany, Bulgaria Reitz, Dachev (Dachev et al., 2002) http://dx.doi.org/10.1016/S0273-1177(02)00411-8		Reitz, G.R. et al., 2005. http://rpd.oxfordjournals.org/cgi/content/abstract/116/1-4/374 Nealy, J.E., et al., Spaceflight validation, 2007. http://dx.doi.org/10.1016/j.asr.2006.12.030
3	**Foton M2, ESA, Biopan 5, R3D-B2** 01/06/2005-12/06/2005 15,845, 1 1 60 s	Germany, Bulgaria Häder, Dachev (Häder et al., 2009) http://dx.doi.org/10.1016/j.asr.2009.01.021		Dachev, T.P., et al., Observation of the Earth Radiation Environment by R3D-B2 Instrument on Foton M2 Satellite, 2005. http://www.stil.bas.bg/11conf/Proc/171-174.pdf
4	**Foton M3, ESA, Biopan 6, R3D-B3** 14/09/2007-26/09/2007 16,801, 1 60 s	Germany, Bulgaria Häder, Dachev (Häder et al., 2009); http://dx.doi.org/10.1016/j.asr.2009.01.021		Dachev, Ts.P., et al., B.T. Tomov, Yu.N. Matviichuk, P.G. Dimitrov, N.G. Bankov, Relativistic Electrons High Doses at International Space Station and Foton M2/M3 Satellites, Adv. Space Res., 44, 1433-1440, 2009. http://dx.doi.org/10.1016/j.asr.2009.09.023
5	**ISS, Columbus module, ESA, EXPOSE-E, R3DE** 17/02/2008-03/09/2009 3,573,786, 57 10 s	Germany, Bulgaria Horneck, Häder, Dachev (Dachev et al., 2012). http://dx.doi.org/10.1089/ast.2011.0759 http://eea.spaceflight.esa.int/attachments/spacestations/ID501800a9c26c2.pdf		Dachev, T.P., et al., Space Shuttle drops down the SAA doses on ISS, 2011. http://dx.doi.org/10.1016/j.asr.2011.01.034 Dachev, T.P., Profile of the ionizing radiation exposure between the Earth surface and free space, 2013,. http://dx.doi.org/10.1016/j.jastp.2013.05.015
6	**ISS, Zvezda module ESA, EXPOSE-R, R3DR** 11/03/2009-20/08/2010 2,540,000, 31 10 s	Germany, Bulgaria Häder, Dachev (Dachev et al., 2015) http://dx.doi.org/10.1017/S1473550414000093		Dachev, T.P., et al., Relativistic Electron Fluxes and Dose Rate Variations during April-May 2010 Geomagnetic Disturbances in the R3DR Data on ISS, 2012. http://dx.doi.org/10.1016/j.asr.2012.03.028 Dachev T.P., Analysis of the space radiation doses obtained simultaneously at 2 different locations outside ISS, 2013. http://dx.doi.org/10.1016/j.asr.2013.08.011
7	**ISS, Matroshka-R, Liulin-5** 17/05/2007- 05/09/2015 2,200,000, 59 20 or 90 sec for dose rate and flux, 15 or 85 min for LET and dep. energy spectra	Russia, Bulgaria Shurshakov, Semkova Semkova et al., 2003 http://dx.doi.org/		Semkova, J.V., et al., Observation of radiation environment in the International Space Station in 2012–March 2013 by Liulin-5 particle telescope, 2014. http://dx.doi.org/10.1051/swsc/2014029
8	**"BION-M" №1, RD3-B3** **19/04/2013-13.05.2013** **34,391, 1** 60 s	Russia, Bulgaria Shurshakov, Dachev (Dachev et al., 2014) http://dx.doi.org/10.1016/j.jastp.2014.12.011		Dachev, T.P., et al., "BION-M" №1 spacecraft radiation environment as observed by the RD3-B3 radiometer-dosimeter in April-May 2013, 2015. http://dx.doi.org/10.1016/j.jastp.2014.12.011
9	**ISS, Zvezda module ESA, EXPOSE-R2, R3DR2** 24/10/2014-10/01/2016 3 836 286, 44 10* *Separated in 4 sources, GCR, IRB, ORB and SEP.	Germany, Bulgaria Häder, Dachev Dachev et al., (2017) https://doi.org/10.1002/2016SW001580 10		Dachev, T.P., et al., High dose rates obtained outside ISS in June 2015 during SEP event, 2016, http://dx.doi.org/10.1016/j.lssr.2016.03.004. Dachev, T. P., South-Atlantic Anomaly Magnetic Storms Effects as Observed outside the International Space Station in 2008-2016, 2018. (Under evaluation)
10	**ESA ExoMars 2016 satellite, FREND instrument, Liulin-MO dosimeter** Cruise to Mars: 22.04.2016–15/09/2016 Mars elliptic orbit: 01/11/2016-14/01/2017 Mars circular orbit 16/04/2018 -	Russia, Bulgaria Mitrofanov, Semkova (Semkova, J. et al. (2016) https://doi.org/10.1016/j.icarus.2017.12.034		Semkova, J.V., et al., 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, 2018.* *https://doi.org/10.1016/j.icarus.2017.12.034*

All 10 datasets contain, in addition to the data from the instruments, data on the geographic and magnetic coordinates and time of the carrier. There are a total of 256 columns in Excel files.

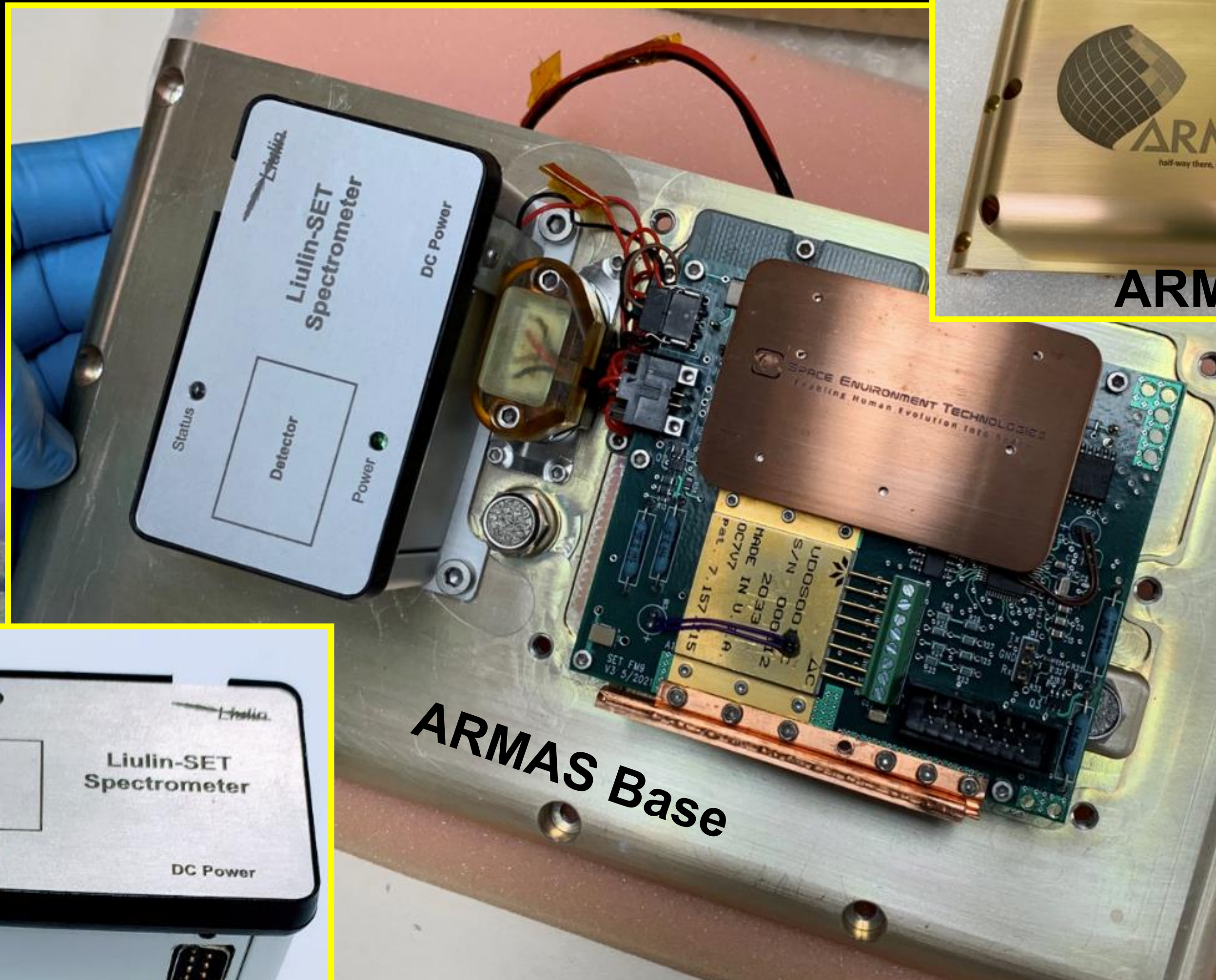
The Liulin-SET is an active, low mass (140 g), small consumption (150 mW) spectrometer, measuring the deposited energy in 256 channels. The measurements have 300 seconds time resolution.



Two independent hardware channels transmit the measured from the detector deposited energy (dose) and counts (flux). The D/F ratio is used for the identification of the radiation sources type.

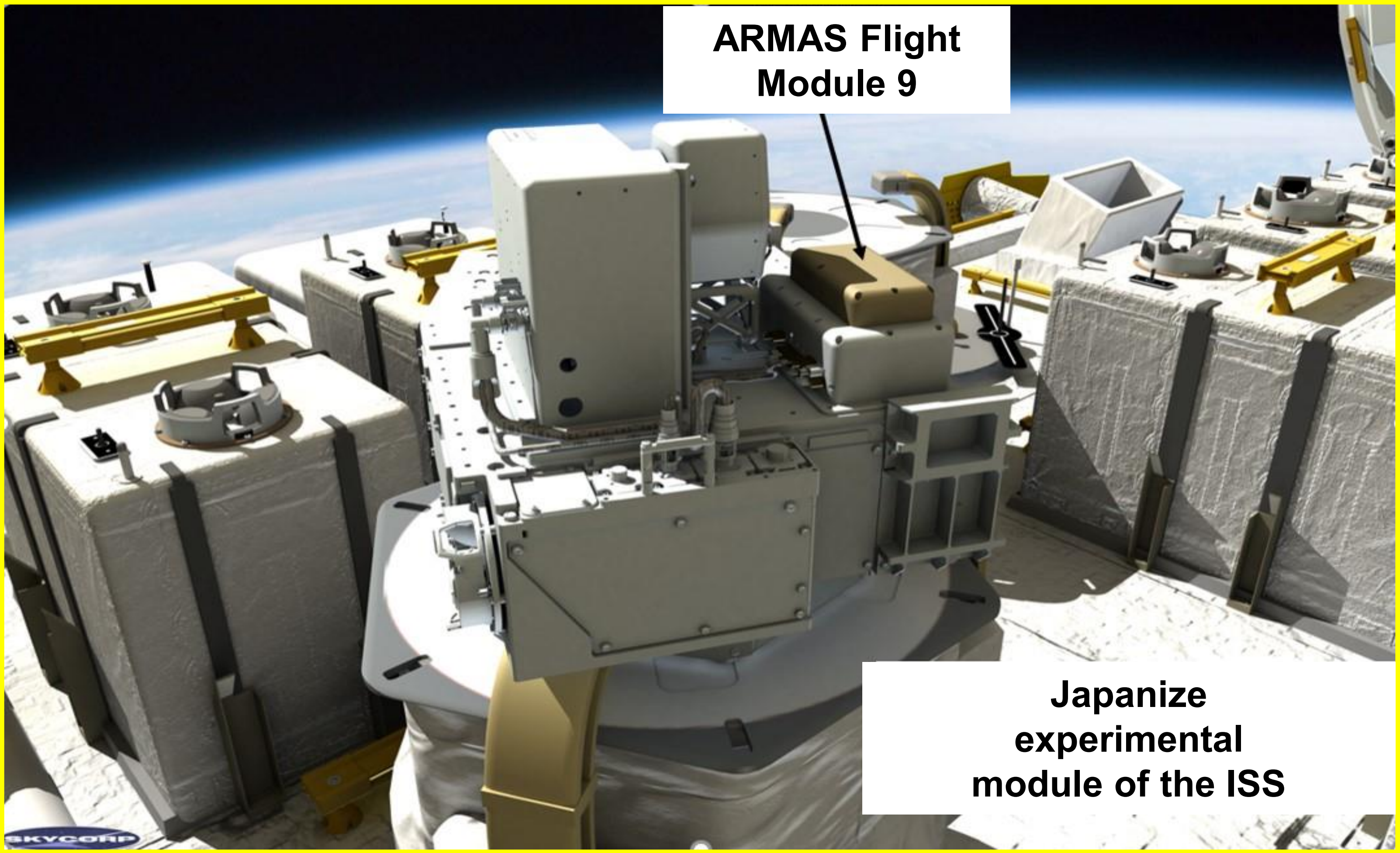
Block schema of Liulin-SET

Liulin-SET is arranged in the enclosure of ARMAS Flight Module 9



https://spacewx.com/armas-instruments/

The ARMAS Flight Module 9 was outside the Japanize experimental module of the ISS



Preliminary Scientific Results

Study of the radiation sources around the ISS

The following four primary radiation sources were expected and recognized in the data obtained with the Liulin instruments:

→ Globally distributed Galactic cosmic rays (GCR) particles and those derived from them;

→ Protons in the South Atlantic Anomaly (SAA) region of the inner radiation belt (IRB);

→ Relativistic electrons and/or bremsstrahlung in the high latitudes of the ISS orbit where the outer radiation belt (ORB) is situated;

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

Methods for Identification of The Radiation Sources Type

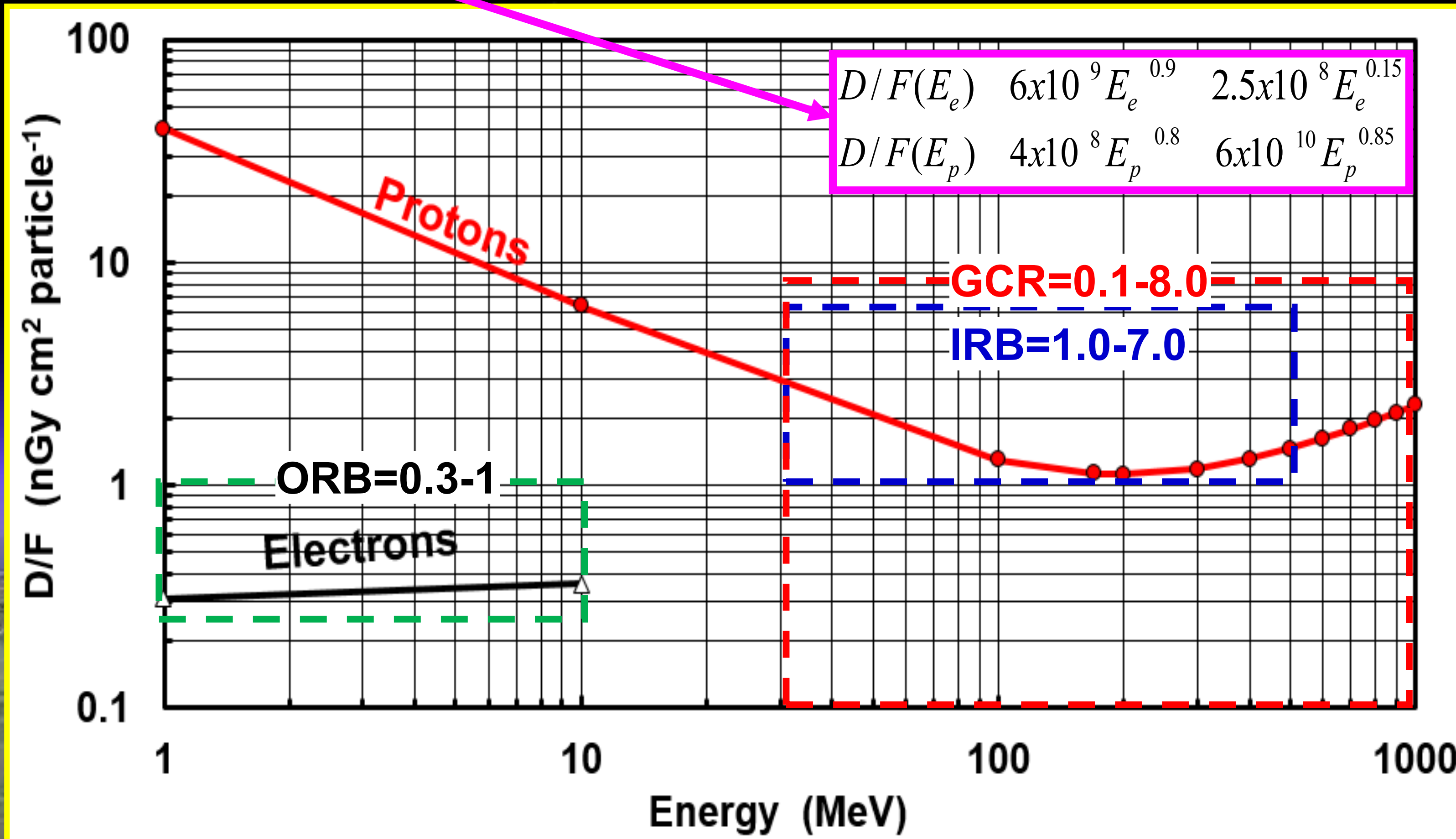
We use three methods for the identification of the radiation sources type during the experiment on the ISS

- Identification, based on the Dose to Flux (D/F) ratio calculations. The methodic was developed experimentally by J. W. Haffner;

- Identification by the dose rate from flux and dose to flux (D/F) dependencies;

- Identification by the shape of the deposited energy spectra.

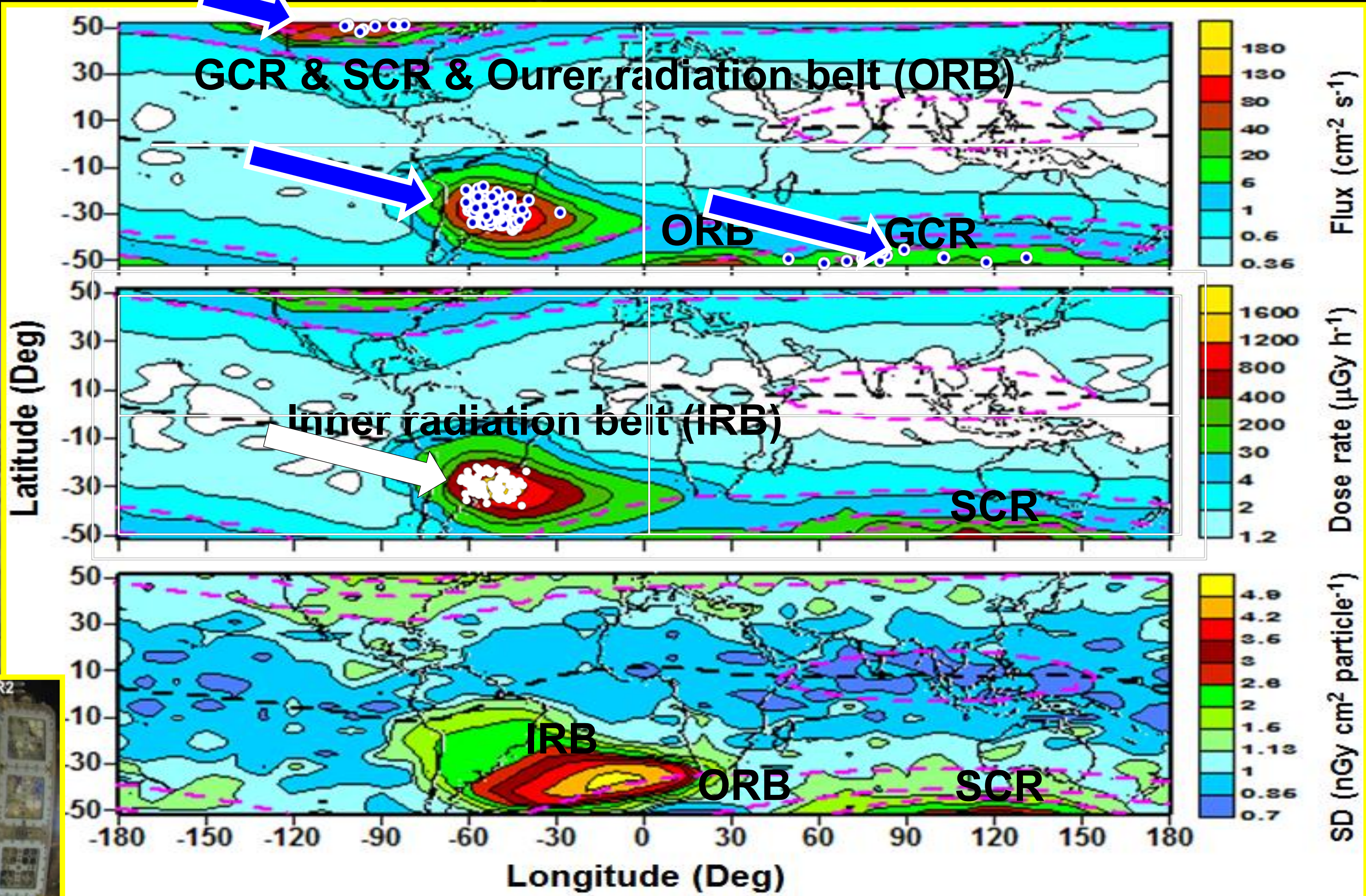
Identification, based to the Dose to Flux (D/F) Formulae, experimentally developed by J. W. Haffner*



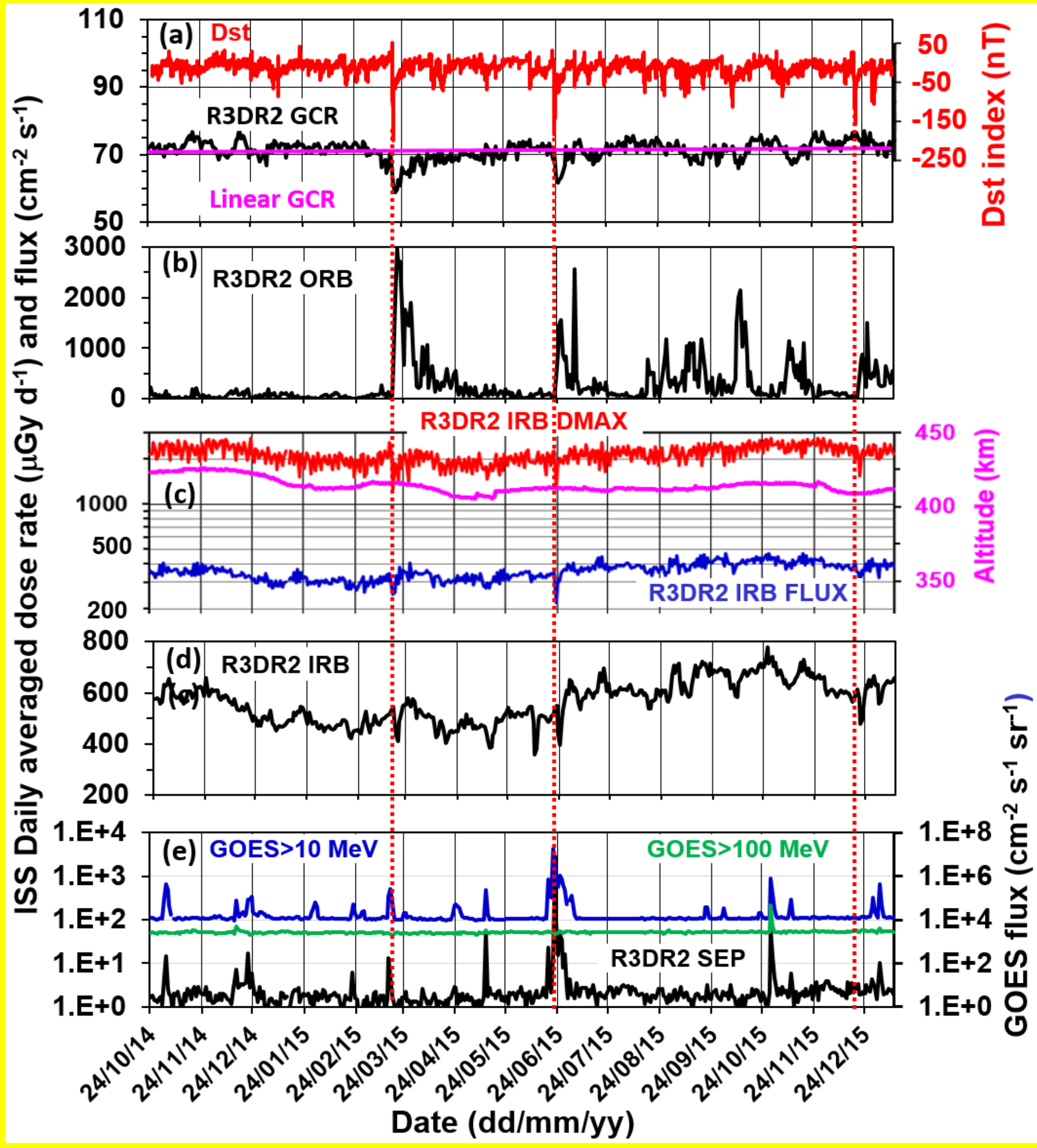
The valid ranges for D/F(Ee) and D/F(Ep) are 1-10 MeV, and 1-1000 MeV, respectively.

- Haffner, J. W. (1967). Radiation and shielding in space. NY: Academic Press.
- Haffner, J. W. (1971). Yadernoe izluchenie i zashchita v kosmose (Nuclear Radiation and Protection in Space), pp 115, Atomizdat, Moscow, (book in Russian).

Comparison of the global distribution of IRB and ORB doses between 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. Liulin-SET: the white points are data from the IRB dose rate >1200 nGy h^{-1} and ORB flux >80 cm^{-2} s^{-1} (blue points). The ORB points position in the Sothern hemisphere is shifted toward higher longitudes because of the smaller magnetic activity in 2022



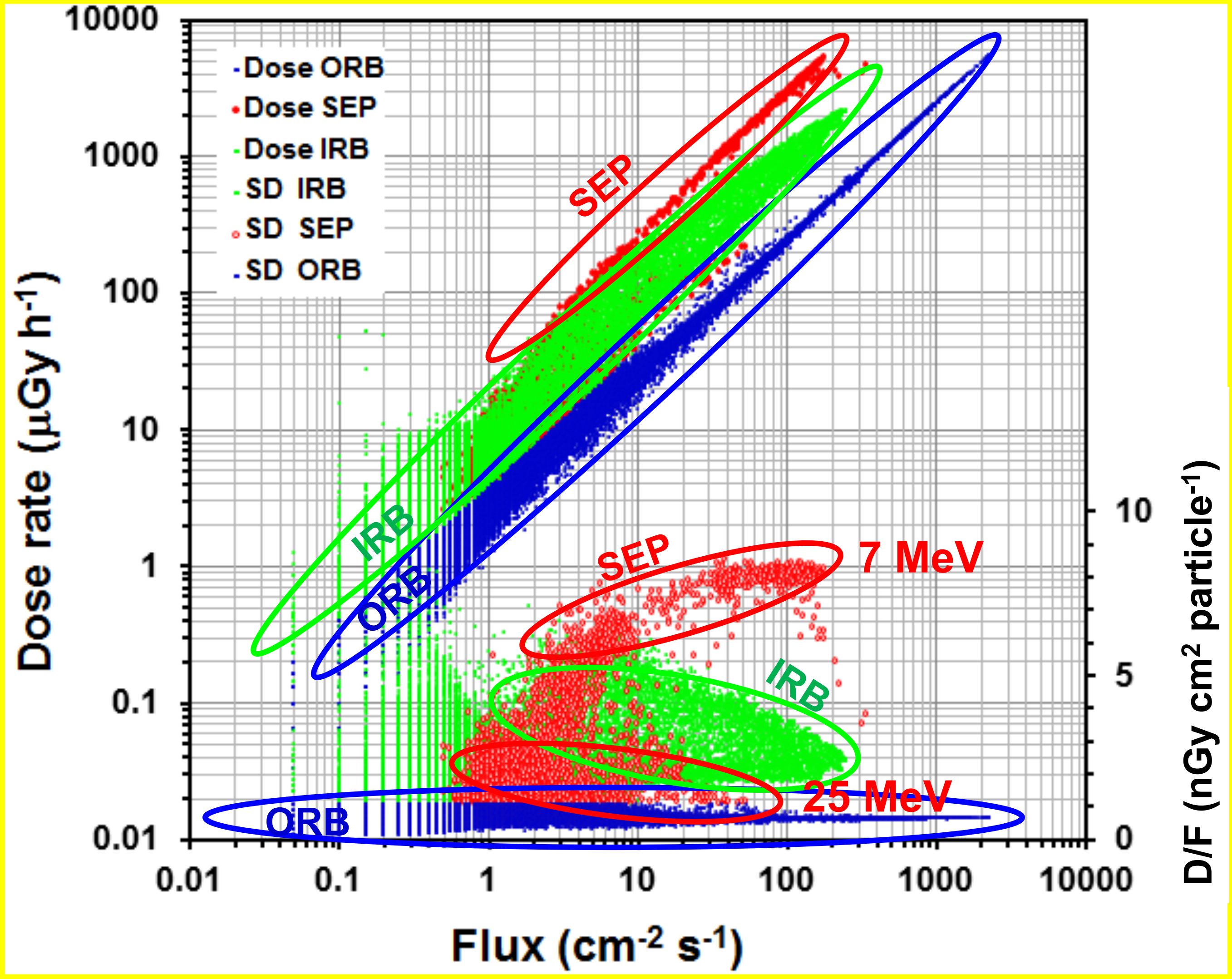
Final result of the separation of the R3DR2 instrument data for the period 24 October 2014-11 January 2016 in four radiation sources



Identification of the radiation sources by the dose rate from flux and dose to flux (D/F) from flux dependencies

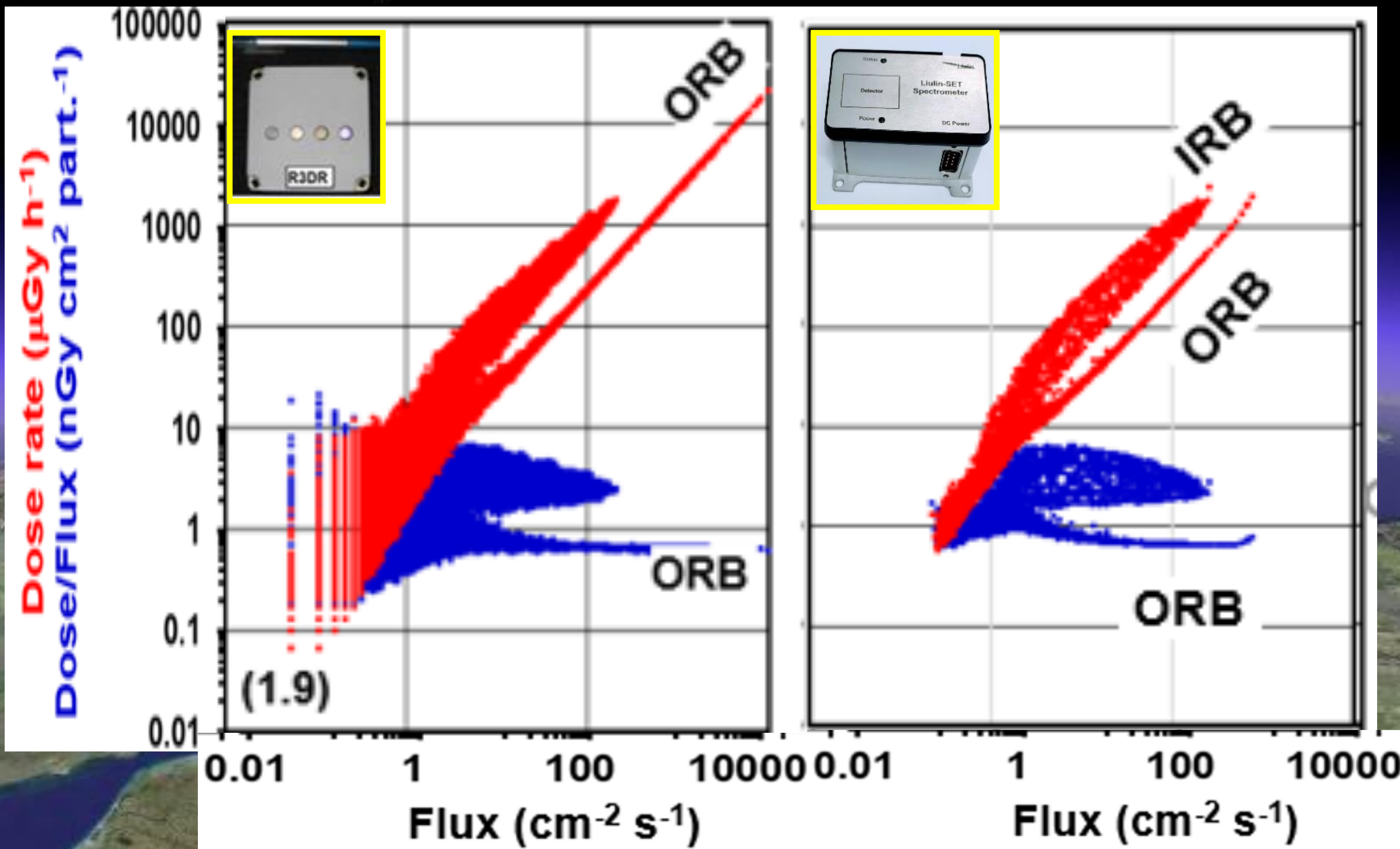
Identification of the radiation sources in R3DR2 data by the dose rate from flux and dose to flux (D/F) from flux dependencies.

The GCR data were excluded by selection of dose rate larger than 20 nGy h^{-1}. Note: All ORB D/F data are <1 nGy cm^2 $particle^{-1}$ as expected

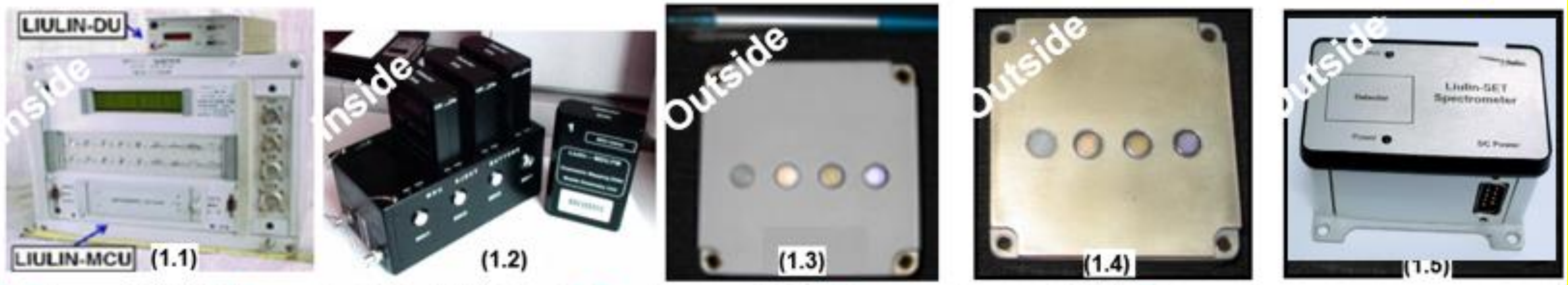


Comparison of the identification of the Liulin-SET and R3DR predominant radiation sources by the dose rate from flux and dose to flux (D/F) dependencies

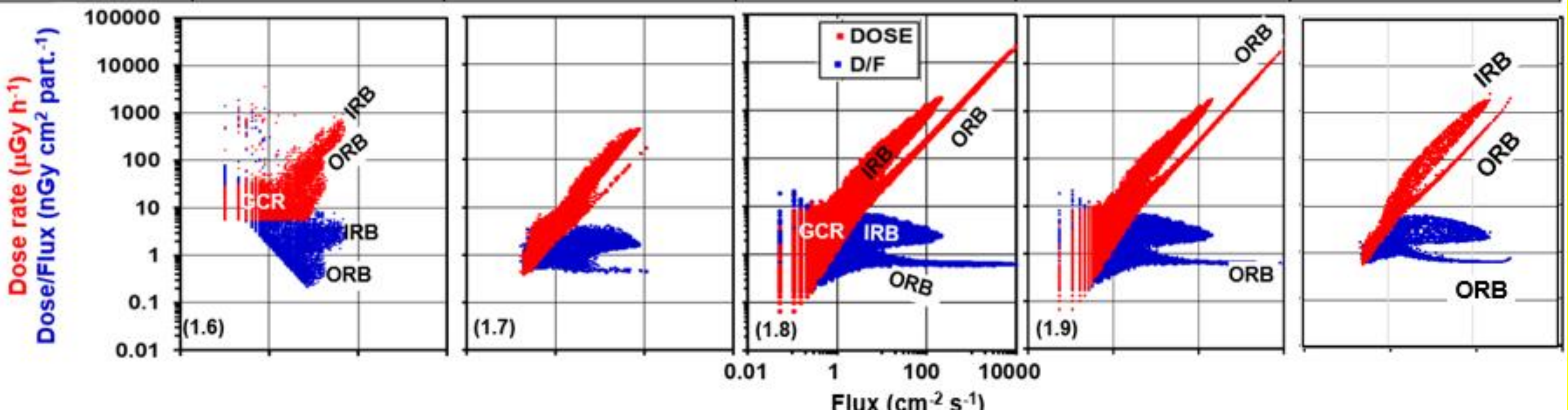
R3DR data **Liulin-SET data**



Comparison of data from four , , p l v , the period July 1991 - January 2015 with Liulin-SET data 2 September 27 October 2022

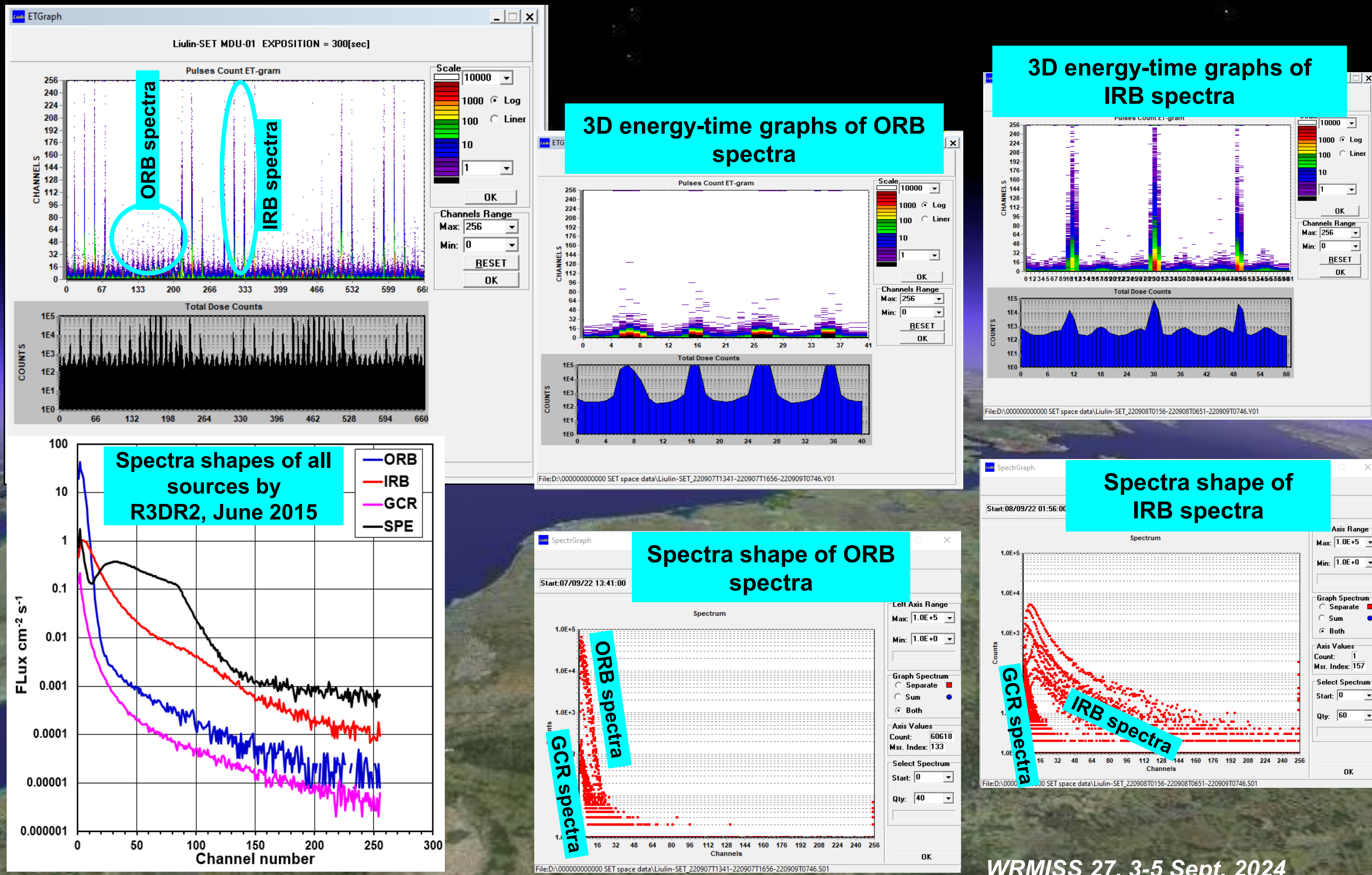


LTS name, Res. [sec]	LIULIN, 10	Liulin-E094, MDU-2, 30	R3DE, 10	R3DR, 10	Liulin-SET, 300
Position	Inside "MIR" Space St.	Inside Amer. module of ISS	Outside Rus. module of ISS	Outside Rus. module of ISS	Outside Jap. exp. mod.
Time, Aver. F10.7	1 - 30 July 1991, 205	11 May - 25 July 2001, 154	12 -20 March 2008, 72	1-10 April 2010, 76	2 Sep.-17 Oct. 2022



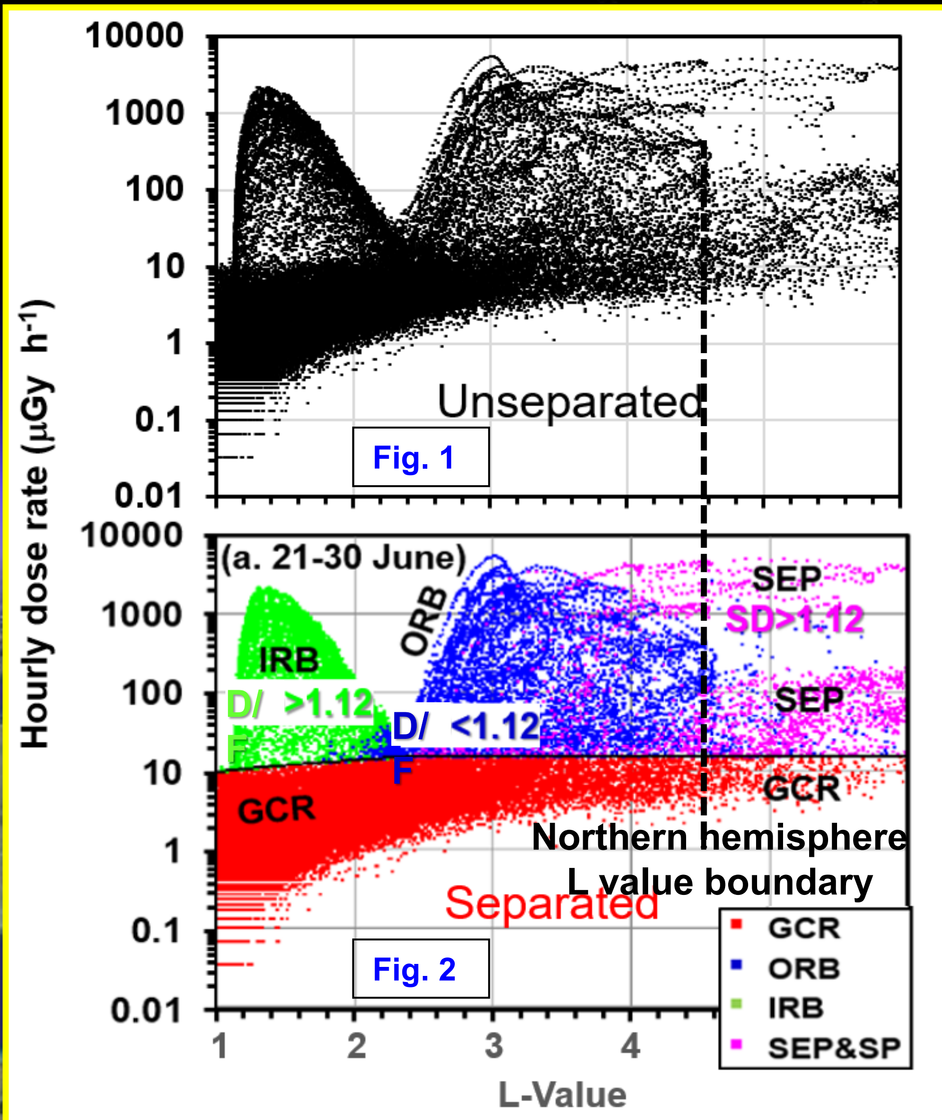
Identification of the radiation sources by the shape of the deposited energy spectra

3D energy-time graphs and deposited energy spectra, Liulin-SET, September-October 2022



Outer radiation belt enhancements in Liulin-SET 2022 data

10 days latitudinal distribution profiles of dose rates measured with the *v F e v E ,* ,-values for the period 21-30 June 2015



- Fig. 1 presents the unseparated radiation sources. Fig. 2 shows the separated sources;

- The black line in the middle of the lower plot is the selection curve, based on the selection software;

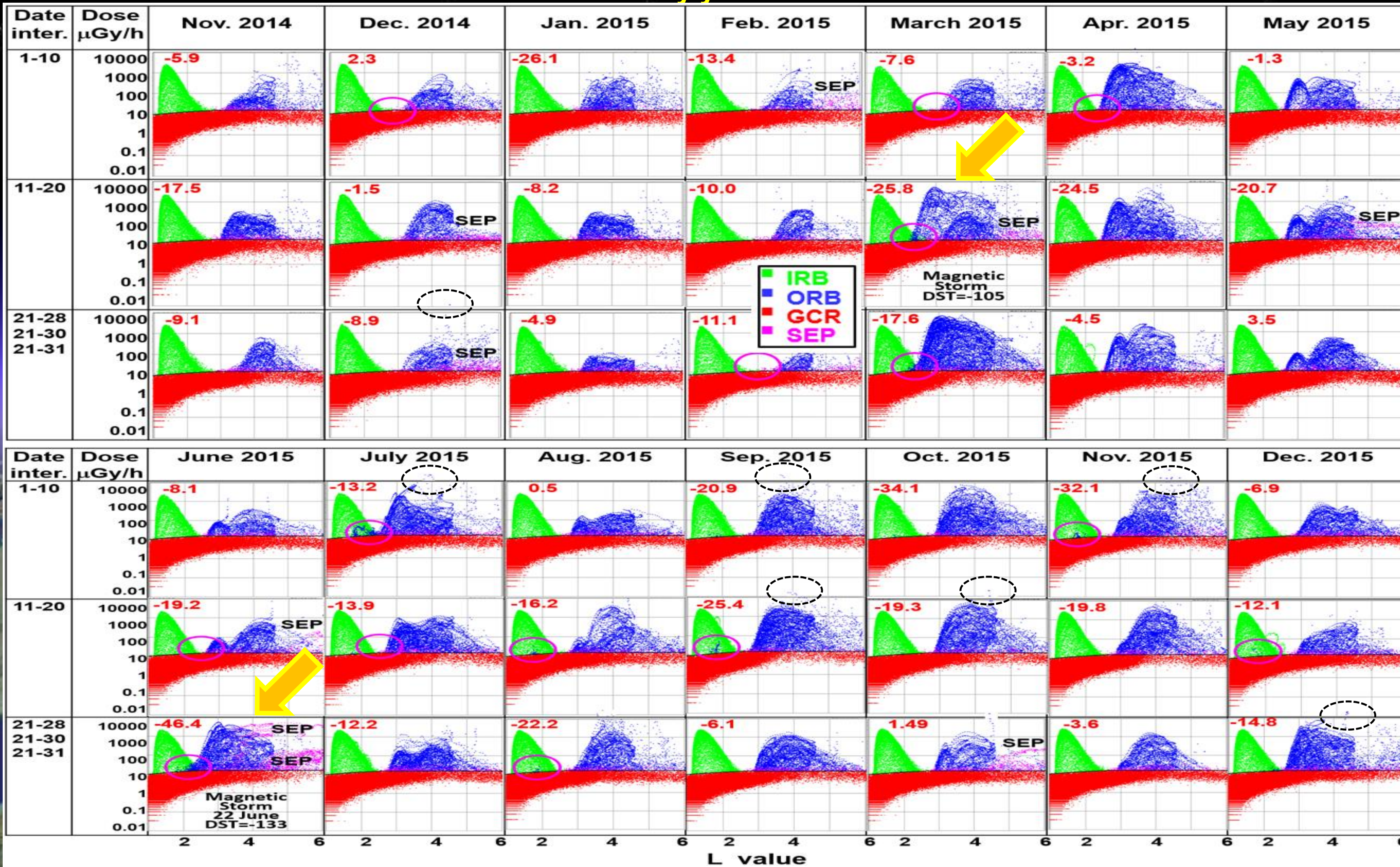
- The galactic cosmic rays are plotted by red points in the lower figure;

- The maximum in the centrum, plotted with blue points, is generated by high-energy electrons in the ORB enhancement, created after the magnetic storm on 17th of June 2015;

- The maximum in the upper left corner of the lower figure, plotted by green points (IRB), is created by high-energy protons, when the ISS crosses the region of the SAA;

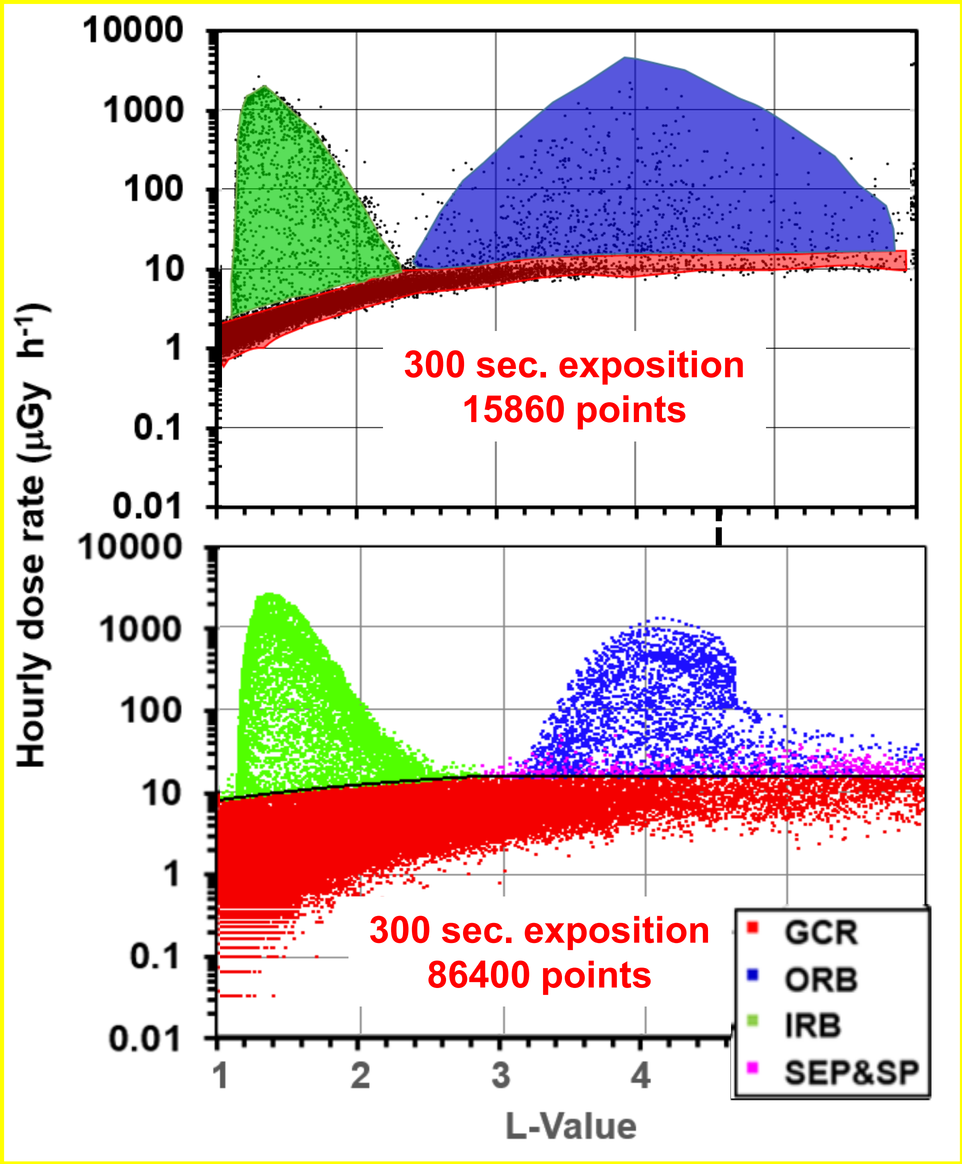
- The magenta points, spread from the center toward the right side of the lower figure, visualize the distribution of the SEP high energy protons.

L-profile dynamics of the four space radiation sources: galactic cosmic rays (GCR), inner radiation belt protons (IRB), outer radiation belt (ORB) relativistic electrons and solar energetic particles (SEP) between 11-20 December 2014 observed outside the ISS by the R3DR2. Note: During magnetic storms the blue points maxima is enhanced. They are indicated by yellow arrows



Red labels show the averaged per 10 days Dst index. Black dashed ovals-the precipitation bands.
Magenta ovals-places of the penetrations of the relativistic electrons from ORB into the IRB.

Comparison of the separated latitudinal distribution profiles of the dose rates measured with the R3DR2 for the period 21-30 June 2014 and Liulin-SET for the period 2 September-27 October 2022

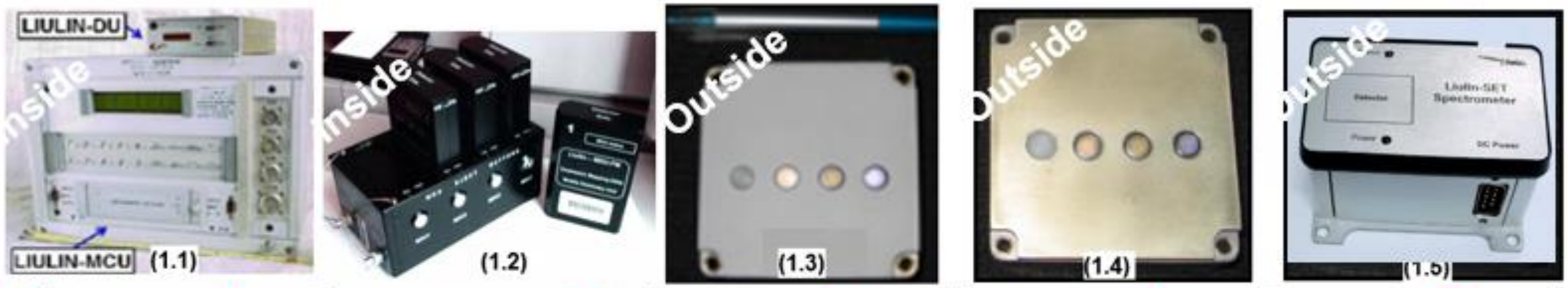


- Galactic cosmic rays (GCR) are shown by red points in the lower part of each figure;

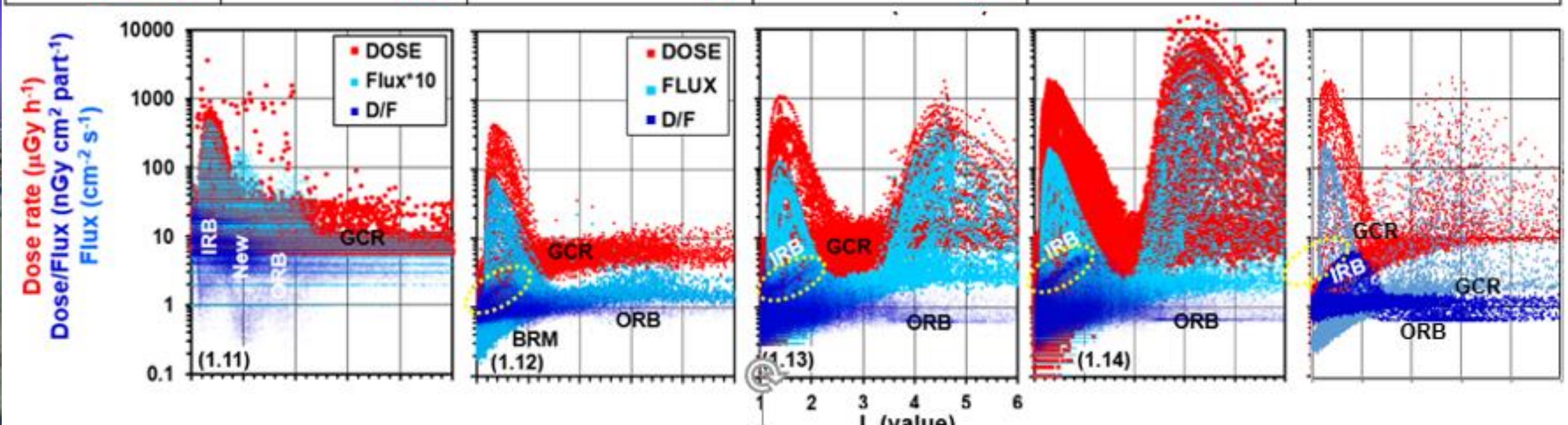
- The maximum in the centrum plotted with blue points (ORB) is generated by high-energy electrons;

- The maximum in the upper left corner, plotted by green points (IRB), is created by high-energy protons when the ISS crosses the region of the SAA.

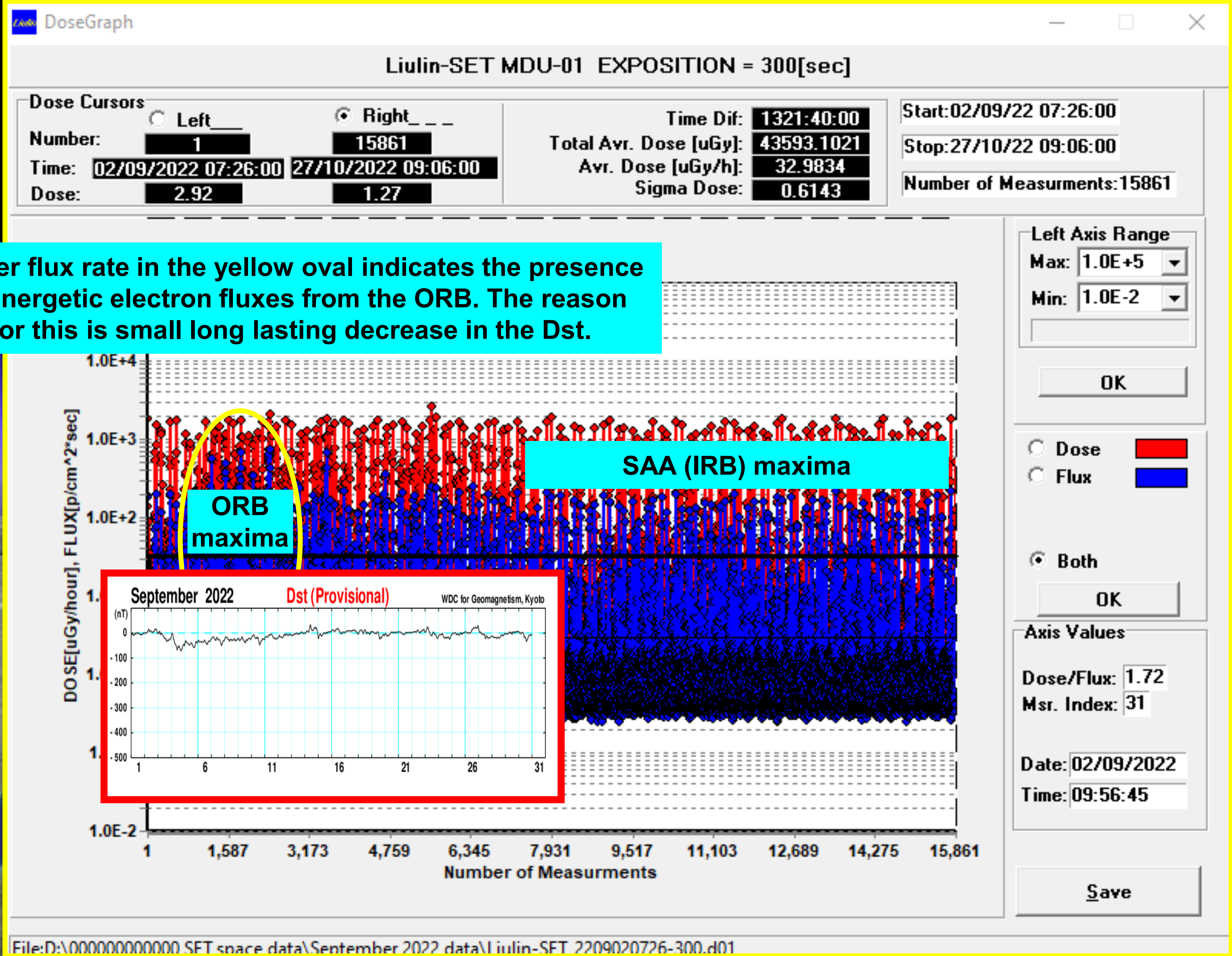
d , , , , ,
ISS in the period July 1991 - October 2022



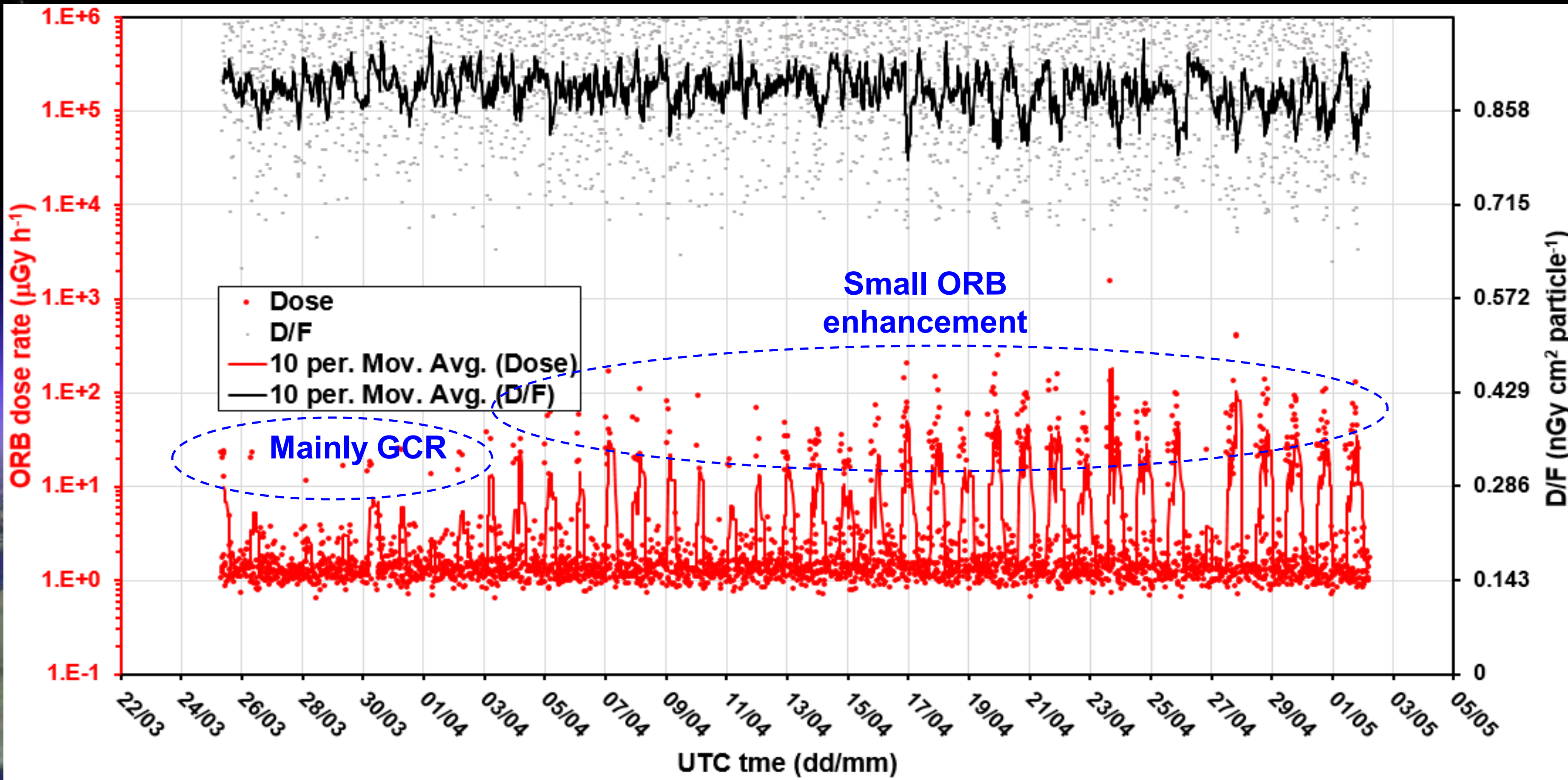
LTS name, Res. [sec]	LIULIN, 10	Liulin-E094, MDU-2, 30	R3DE, 10	R3DR, 10	Liulin-SET, 300
Position	Inside "MIR" Space St.	Inside Amer. module of ISS	Outside Rus. module of ISS	Outside Rus. module of ISS	Outside Jap. exp. mod.
Time, Aver. F10.7	1 - 30 July 1991, 205	11 May - 25 July 2001, 154	12 -20 March 2008, 72	1-10 April 2010, 76	2 Sep.-17 Oct. 2022

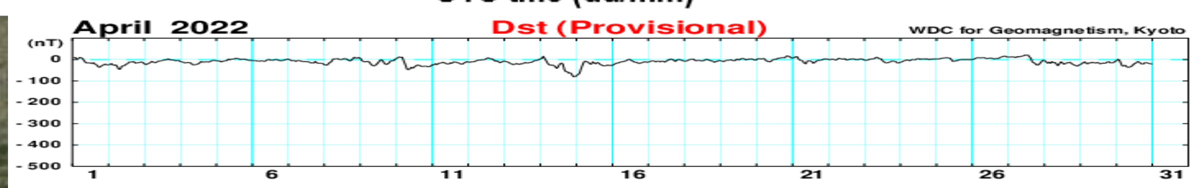


Liulin-SET software DoseGraph

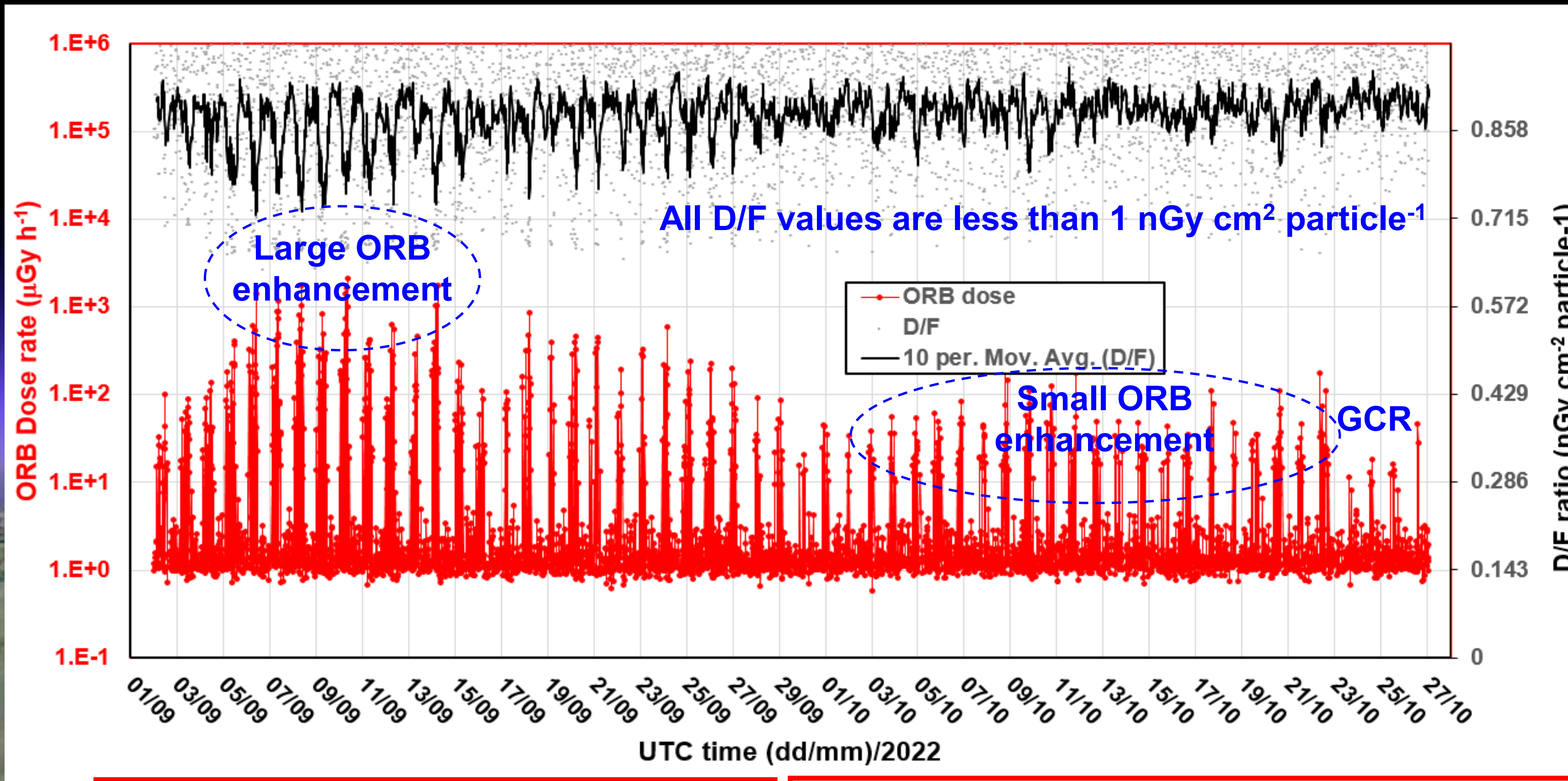


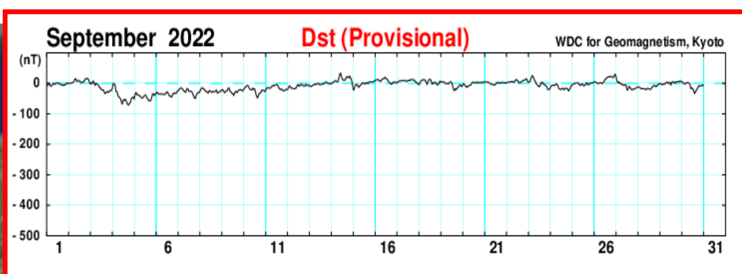
Comparison of the variations of the ORB dose rate and D/F ratio from 25th of March till 2nd of May 2022 with the Dst variations. It is seen that the low Dst values on 15-30 April are connected with a moderate enhancement of the ORB dose rates up to 100-200 μGy h^{-1}

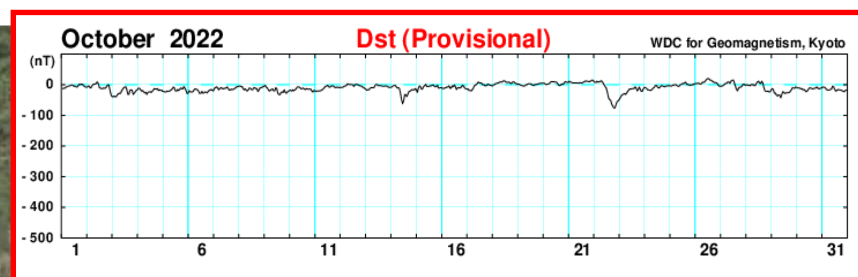




Comparison of the variations of the ORB dose rate and D/F ratio from 2nd September till 27th October 2022 with the Dst variations.
It is seen that low Dst values on 3-15 September are connected with a strong enhancement of the ORB dose rates up to >2000 nGy h^{-1}



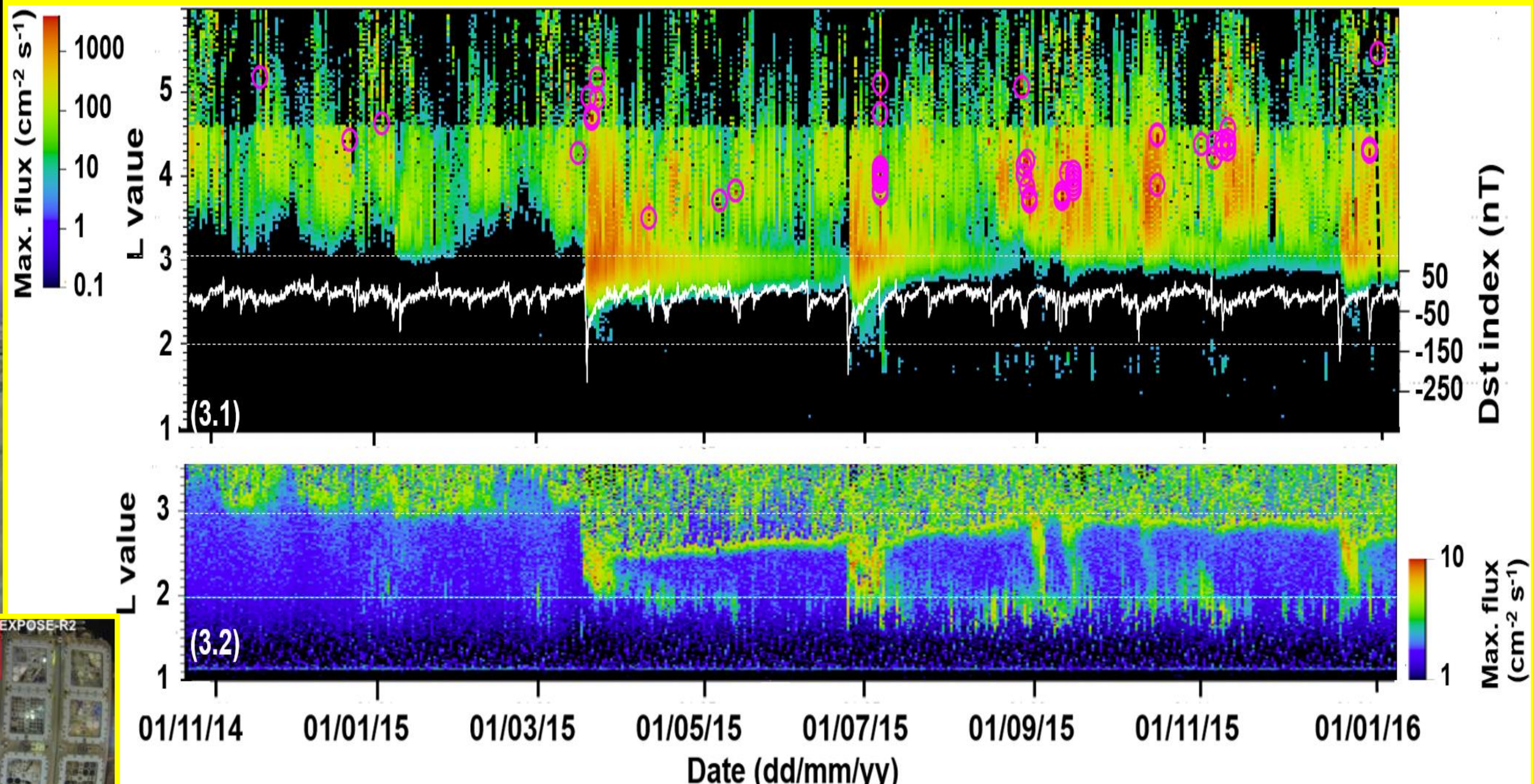




The two panels present the long-term variations in the ISS ORB features:
Panel (3.1) illustrates: 1) The ORB enhancements in dependence of the Dst index. The strong storms in March and June-July 2015 are connected with strong ORB enhancements.

Not every small minimum in Dst is connected with ORB enhancements.

2) The precipitation bands are marked with magenta circles;
Panel (3.2) shows the penetration of relativistic electrons in the low L-values and in the IRB.



Discussion and conclusions

The most important achievement is the preliminary analysis of the ISS radiation environment in the period March-October 2022;

Good results were obtained for the proofing of the three Liulin-SET radiation sources GCR, IRB and ORB against three methods of identification;

The comparison of the Liulin-SET radiation sources GCR, IRB and ORB values and positions with analogical measurements on the ISS in 2015 are performed. The coincidences are good;

The analysis of the outer radiation belt (ORB) relativistic electrons enhancements observed in Liulin-SET 2022 data just started;

The relativistic electrons fluxes do not pose a real health concerns for the astronauts being on extravehicular activities. It is important to study this phenomena further.

Acknowledgements

The authors thank:

To all Bulgarian and foreign specialists and organizations that participated in the development of the Liulin instruments and in conducting interpreting the data;

BAS, NSFI, PECS and our international partners for the financing of projects related to the creation and use in space of Liulin type instruments;

To the astronauts and cosmonauts aboard the manned space stations Mir and ISS for conducting experiments with Liulin equipment;

To Dr. Victor Benghin from the State Scientific Center of Russian Federation, Institute of Biomedical Problems, Russian Academy of Sciences, Russia for the help with the obtaining of the osculation elements of the ISS, necessary for calculation of the ISS orbit.

Thank you!