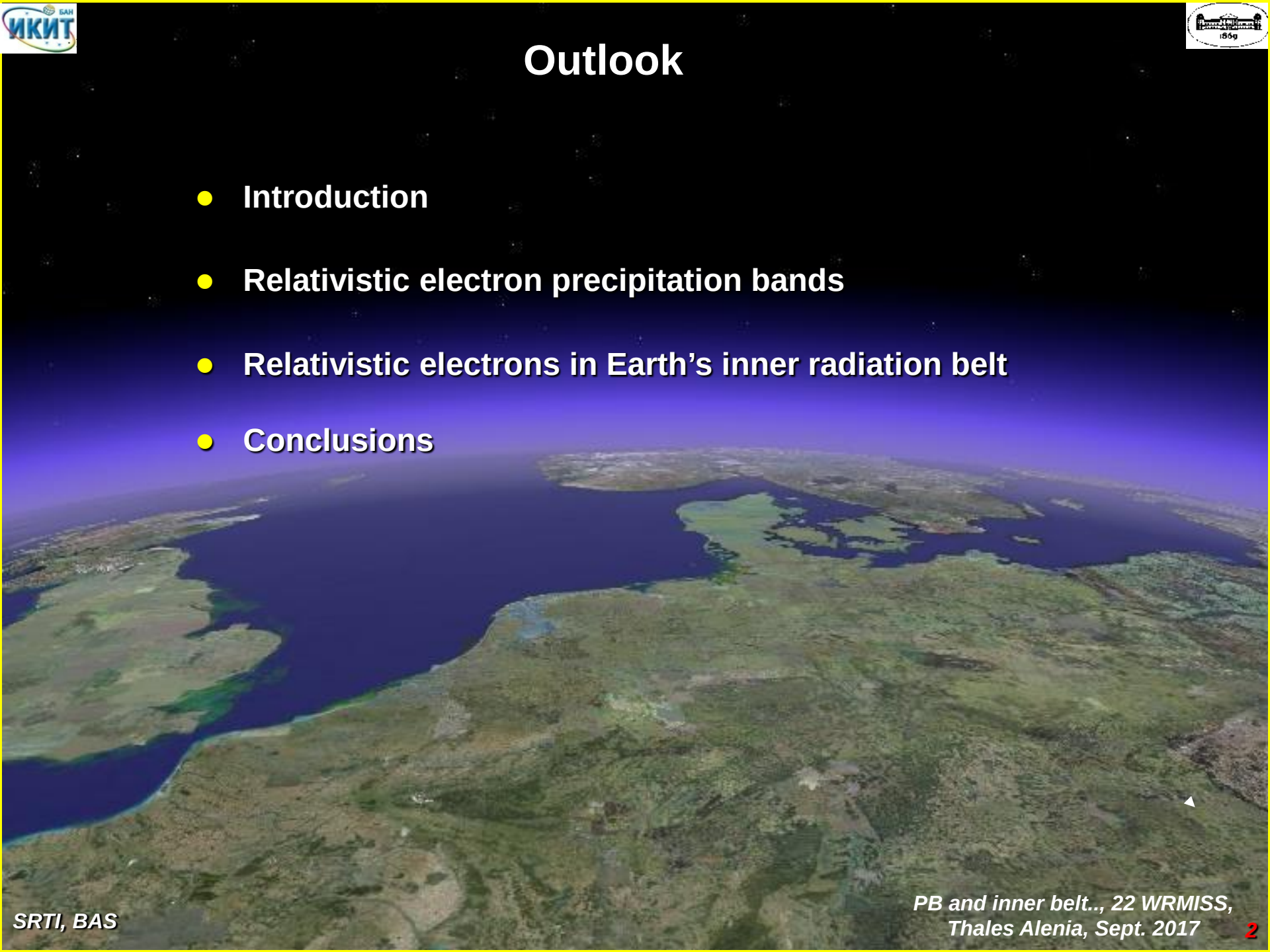
Relativistic electron precipitation bands and relativistic electrons in Earth's inner radiation belt

T.P. Dachev[a], B. T. Tomov[a], Yu. N. Matviichuk[a], Pl. G. Dimitrov[a]

[a]*Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria*

Outlook

- Introduction
- Relativistic electron precipitation bands
- Relativistic electrons in Earth's inner radiation belt
- Conclusions

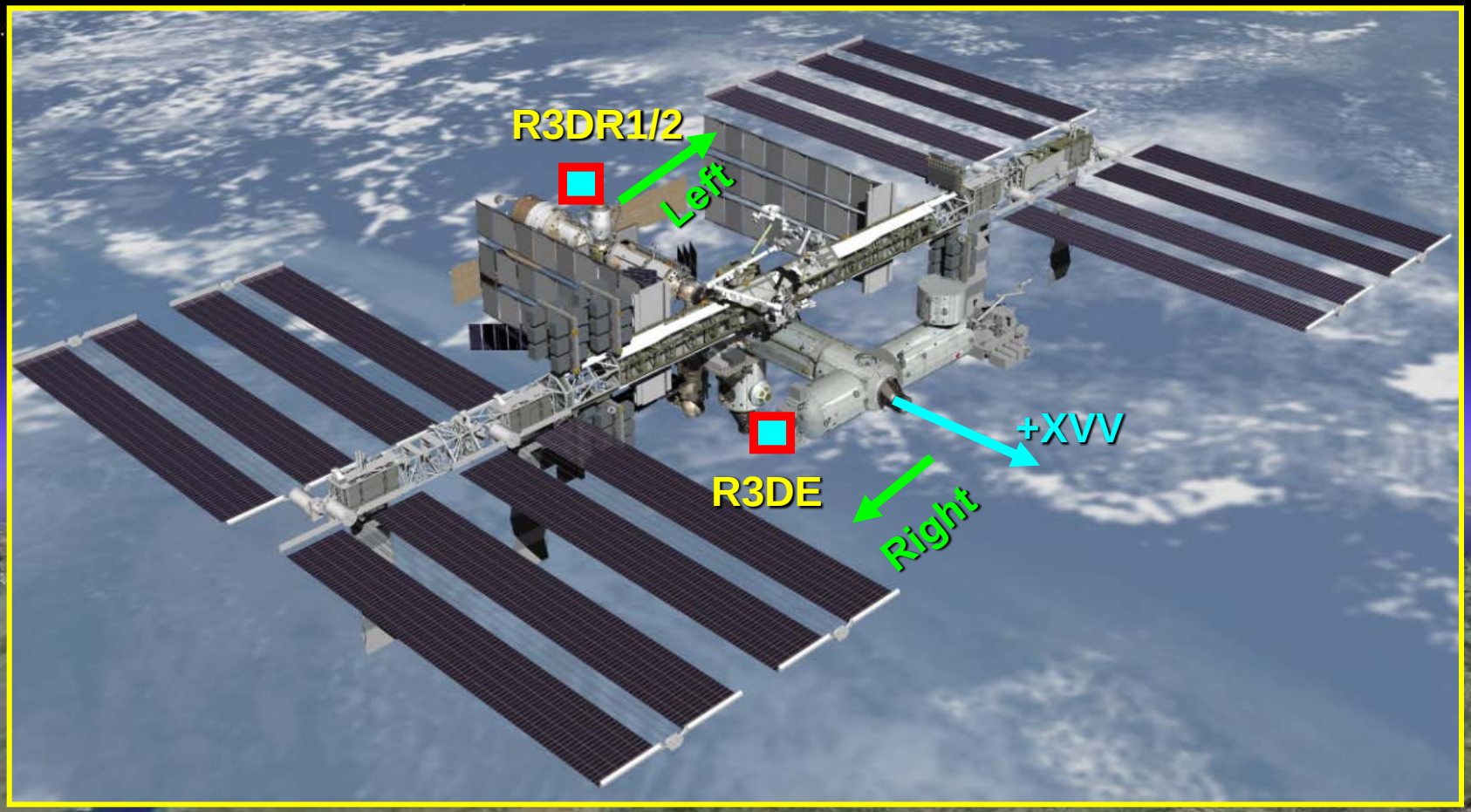


Introduction

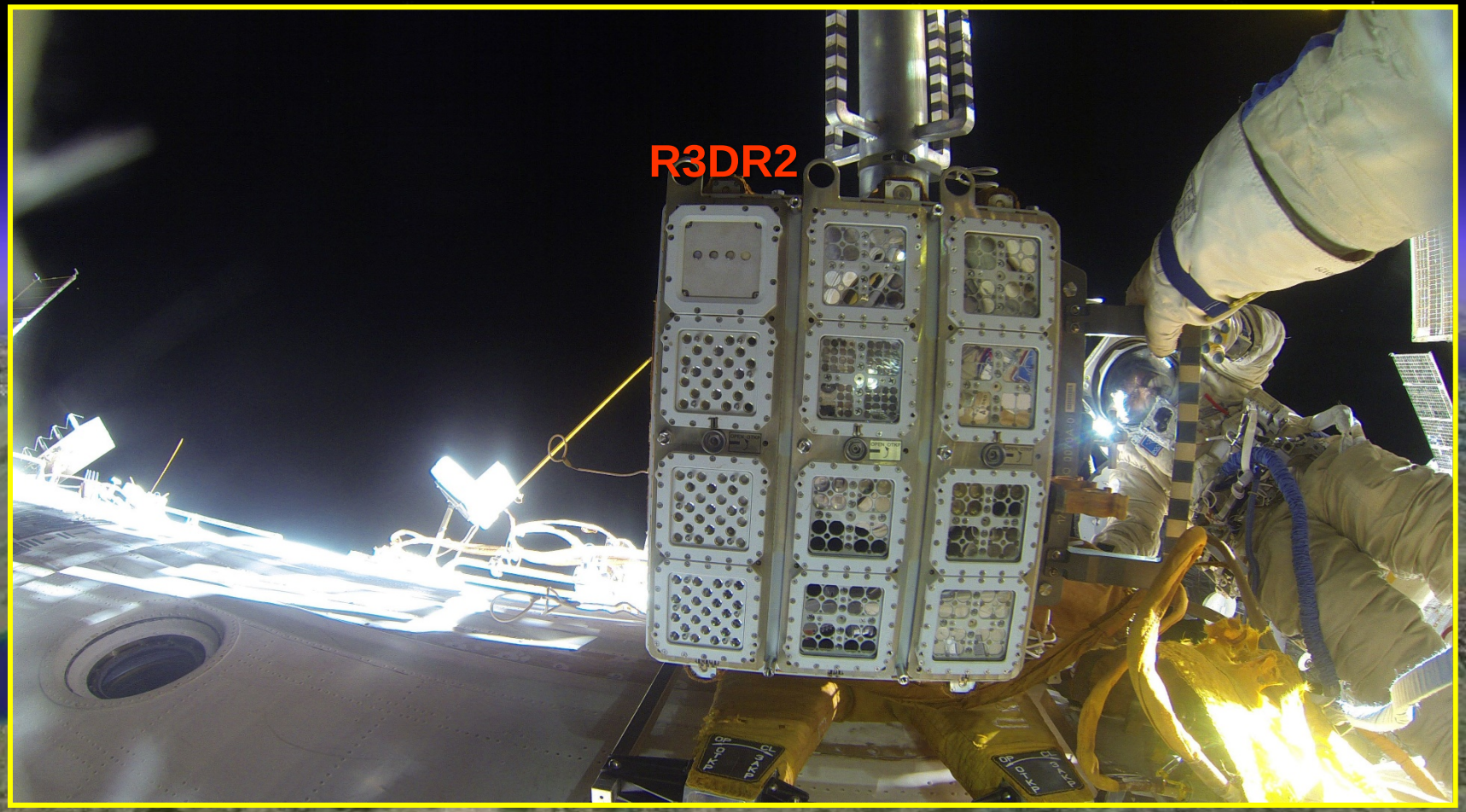
External view of R3DR2 instrument

(The current R3DR2 spectrometer-dosimeter onboard the ISS is the same instrument as flown in the EXPOSE-R facility from 2009-2010, but here is given the extension R2 to distinguish between the data from the previous EXPOSE-R mission.

General positions of the R3DE/R1/R2 instruments in the ISS coordinates



External view of R3DR2 instrument (in the red square) as mounted in the EXPOSE-R2 facility. (Picture taken by Russian cosmonaut G. Pedalka (only his arm is seen in the left-upper corner, while cosmonaut M. Kornienko is seen in the left middle plan) on 15 August 2015 during EVA for examination EXPOSE-R2 facility outside Russian “Zvezda” module.) (Picture credit of ESA/RKA).



The following four primary radiation sources were expected and recognized in the data obtained with the R3DR2 instrument:

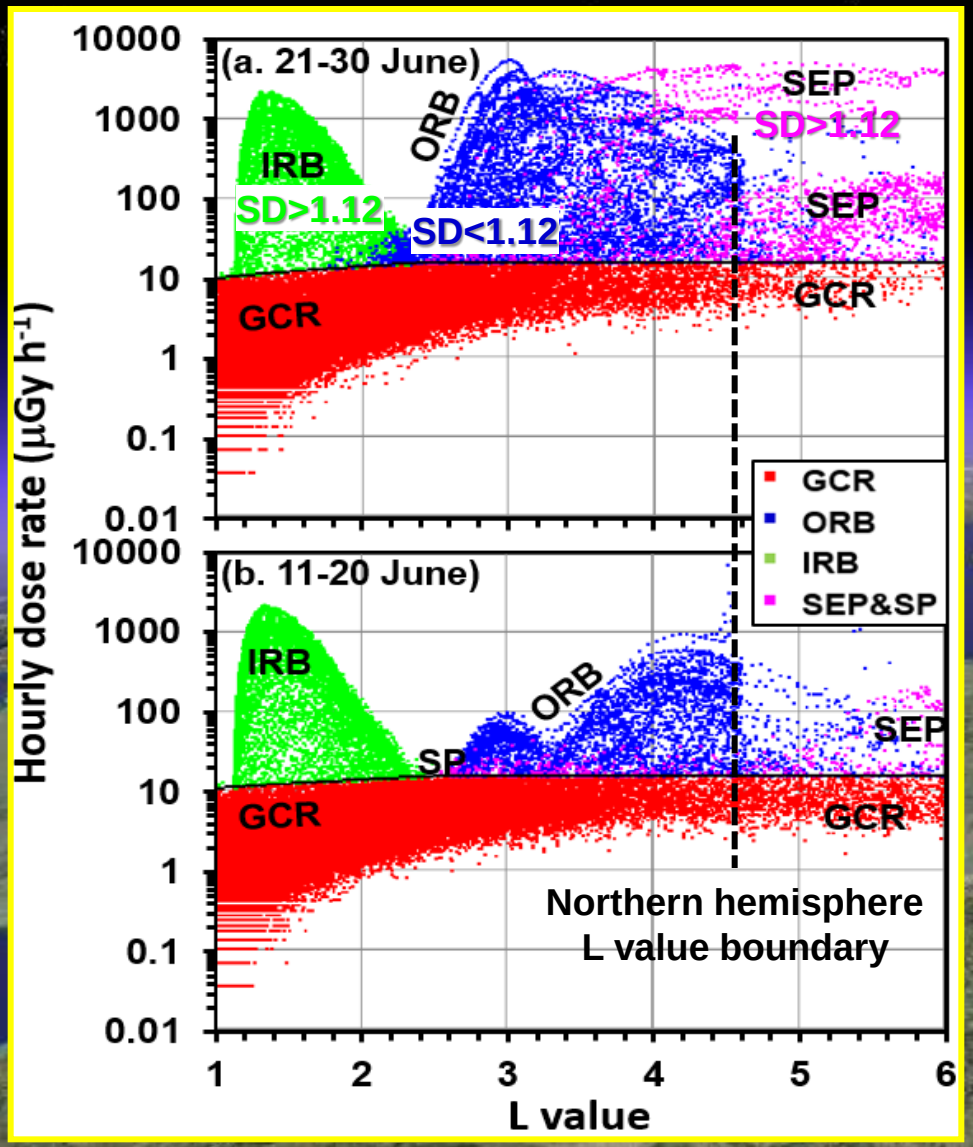
→ Globally distributed GCR particles and those derived from them;

→ Protons in the 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. Together with the real SEP particles, a low flux of what were likely to be mostly secondary protons (SP) were observed in the data.

Examples of the selected 10 days latitudinal distribution profiles of the dose rates measured with the R3DR2 instrument against McIlwain's L values for the period 10-20 and 21-30 June 2015



- These 10 days plots were used for the selection of the all 441 days data;

- The selection curve is the black line in the middle of the plots;

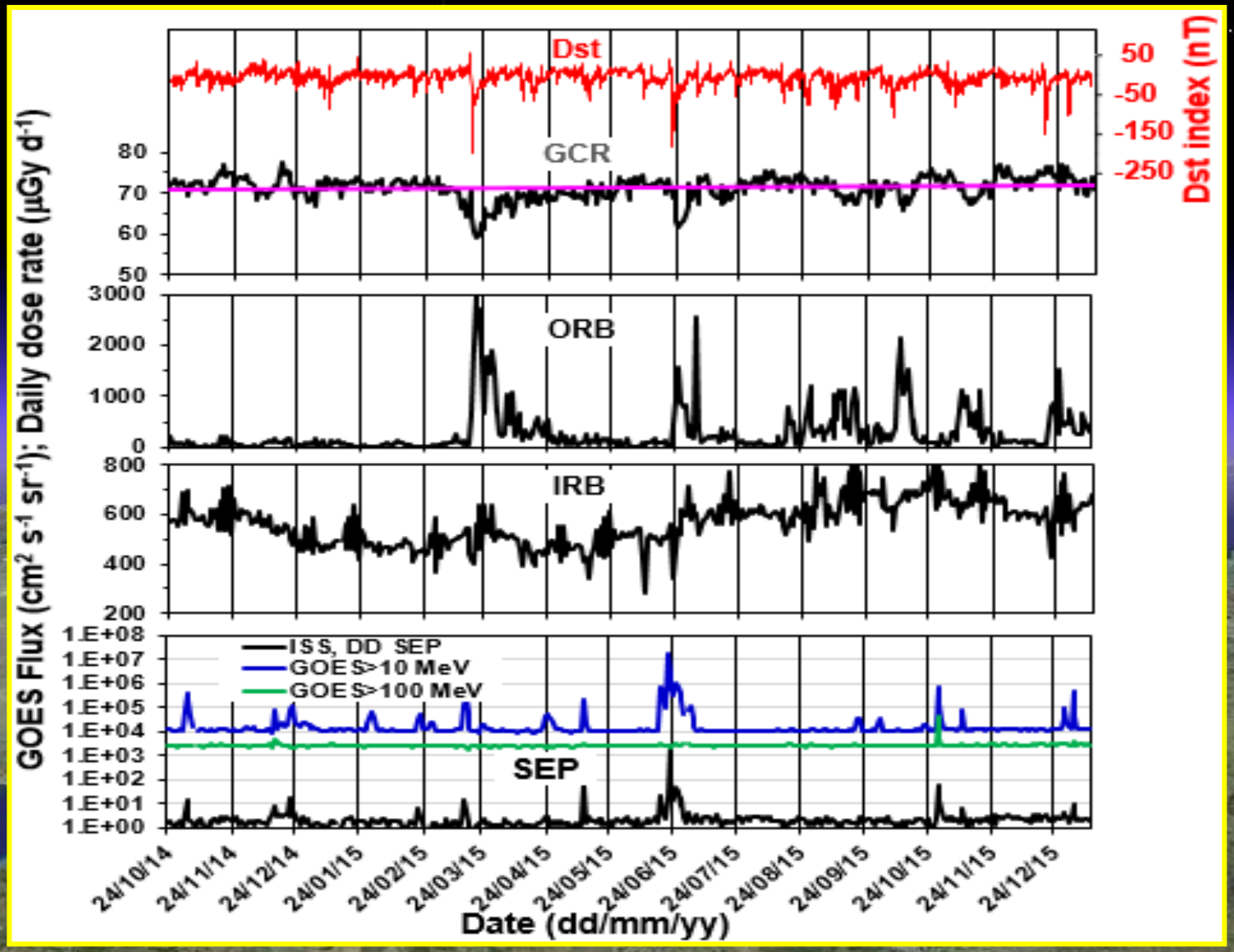
- Galactic cosmic rays (GCR) are situated by red points in the lower part of each figure;

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

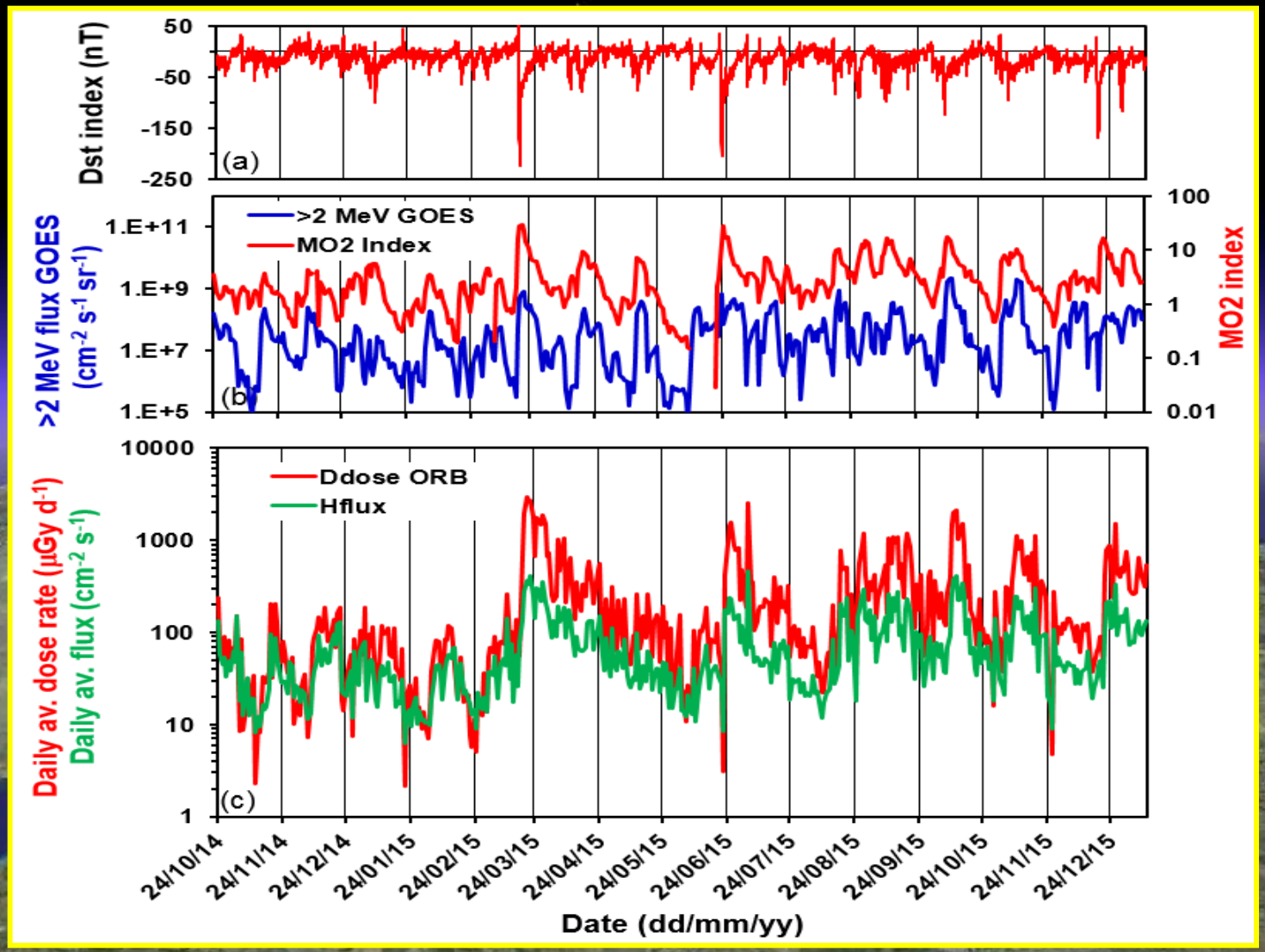
- The maximum in the upper left corner of the figure plotted by green points (IRB) is created by high-energy protons when the ISS crosses the region of the SAA;

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

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



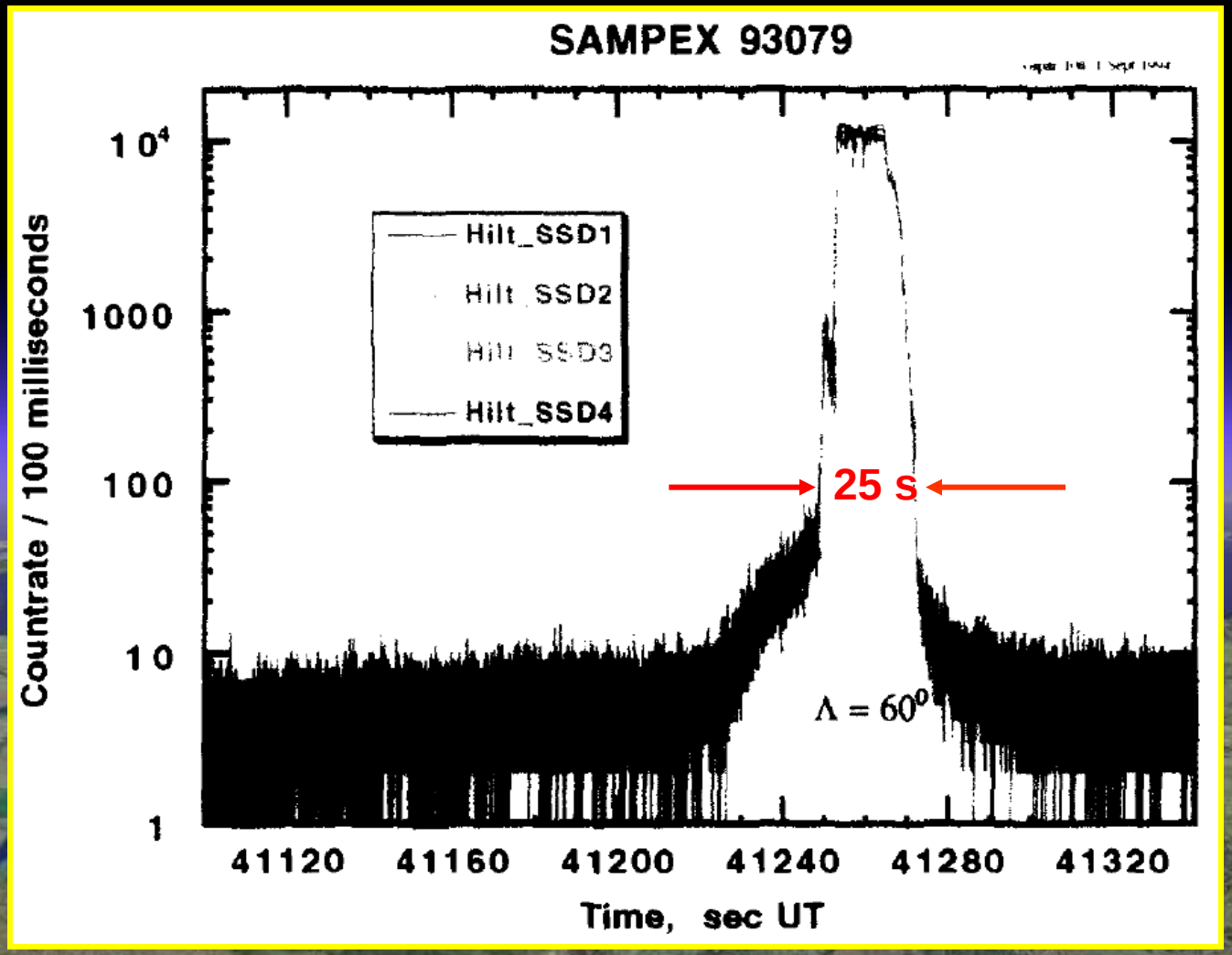
Comparison of the R3DR2 daily average dose rate and flux with the >2 MeV GOES electron flux and MO2 index obtained with NOAA SEM-2 instrument on MetOp-2 satellite



Relativistic electron precipitation bands

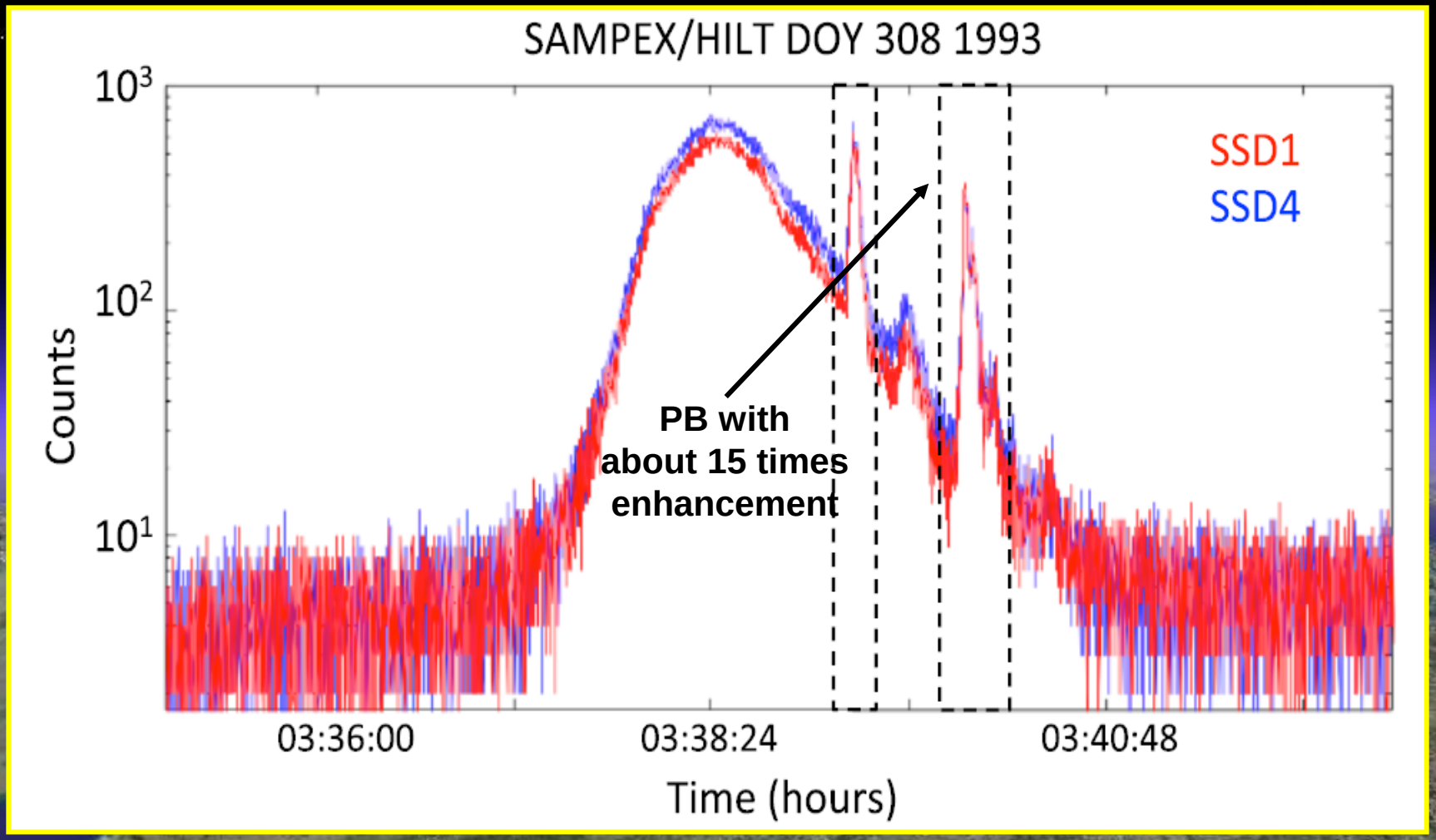
(The precipitation bands (PB) were first identified in the R3DR2 instrument data. Later they were confirmed in the R3DR(1) and R3DE data that is why the presentation begins with the PBs during the EXPOSE-R2 mission)

Intense precipitation band observed on Day 93079 when the SSDs were driven to saturation*



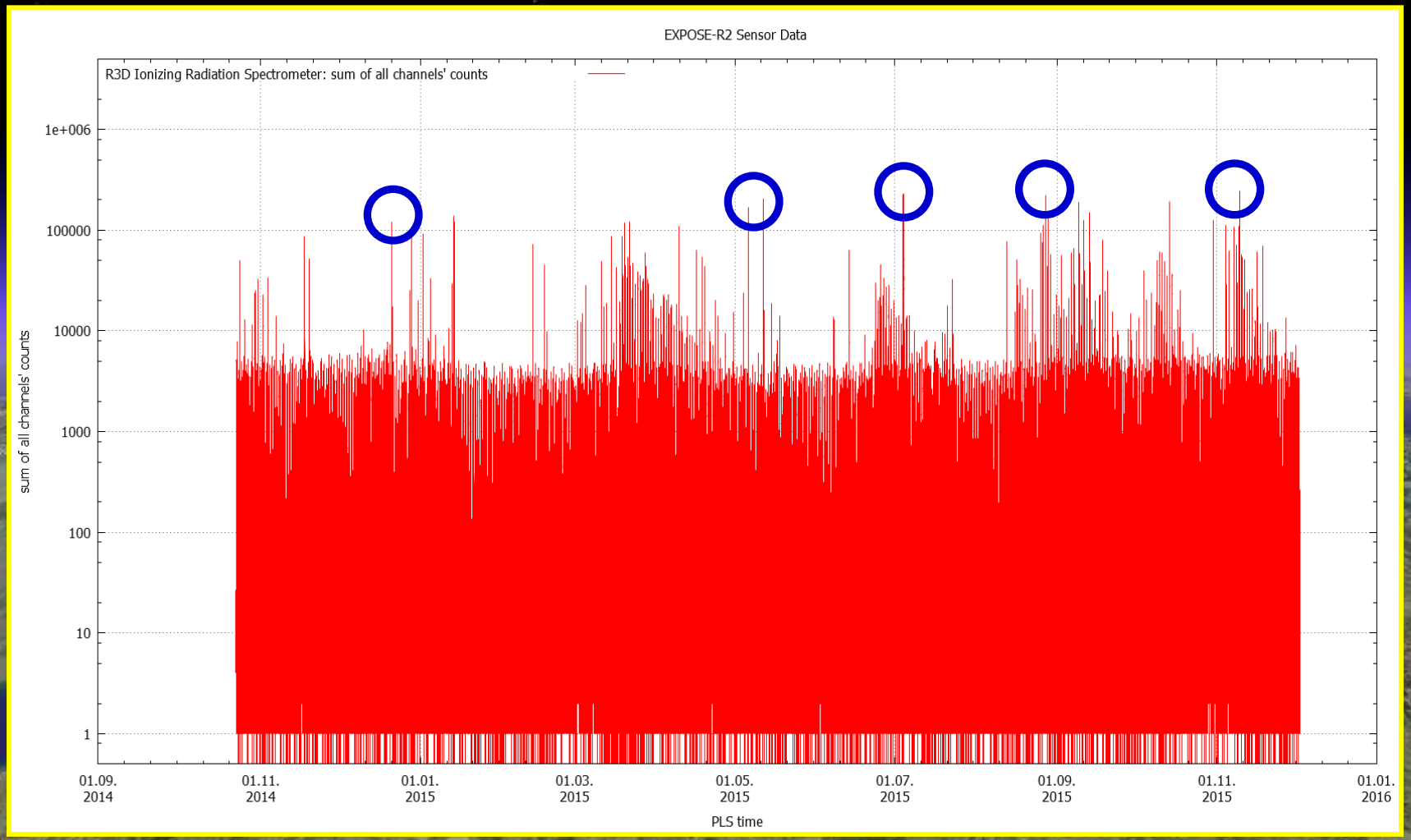
*Blake, J. B., Looper, M. D., Baker, D. N., Nakamura, R., Klecker, B., & Hovestadt, D., 1996. New high temporal and spatial resolution measurements by SAMPEX of the precipitation of relativistic electrons. Advances in Space Research, 18(8), 171-186.

SAMPEX/HILT data from the SSD1 (red) and SSD4 (blue) detector rows during a pass through the outer radiation belt*

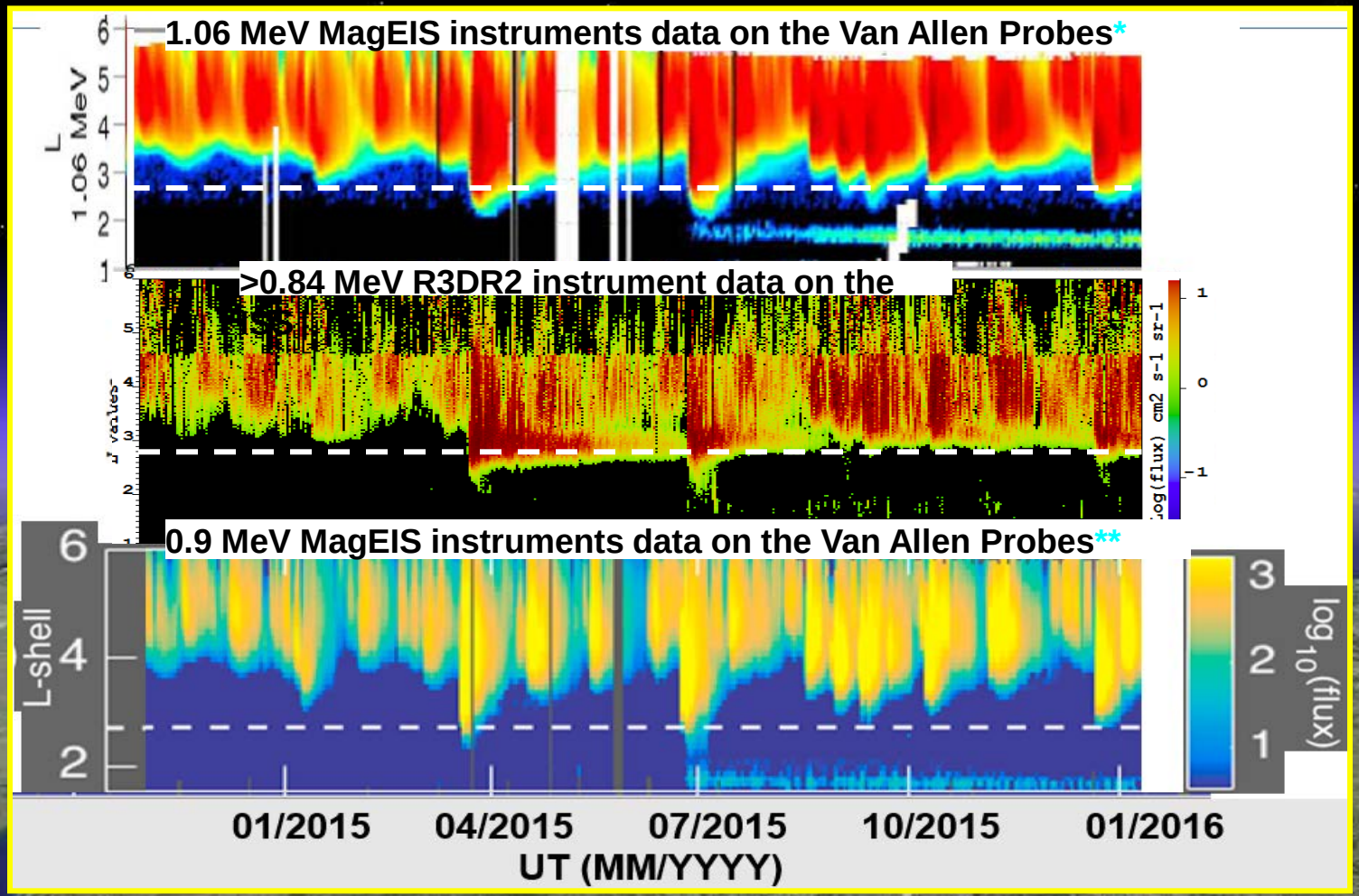


*Blum, L., X. Li, and M. Denton (2015), Rapid MeV electron precipitation as observed by SAMPEX/HILT during high-speed stream-driven storms, J. Geophys. Res. Space Physics, 120, doi:10.1002/2014JA020633.

The rapid flux enhancements was first presented in the grahics (as the shown below), prepared by Dr. W. Schulte and his colleagues from OHB System AG, München, Germany, during the EXPOSE-R2 mission support



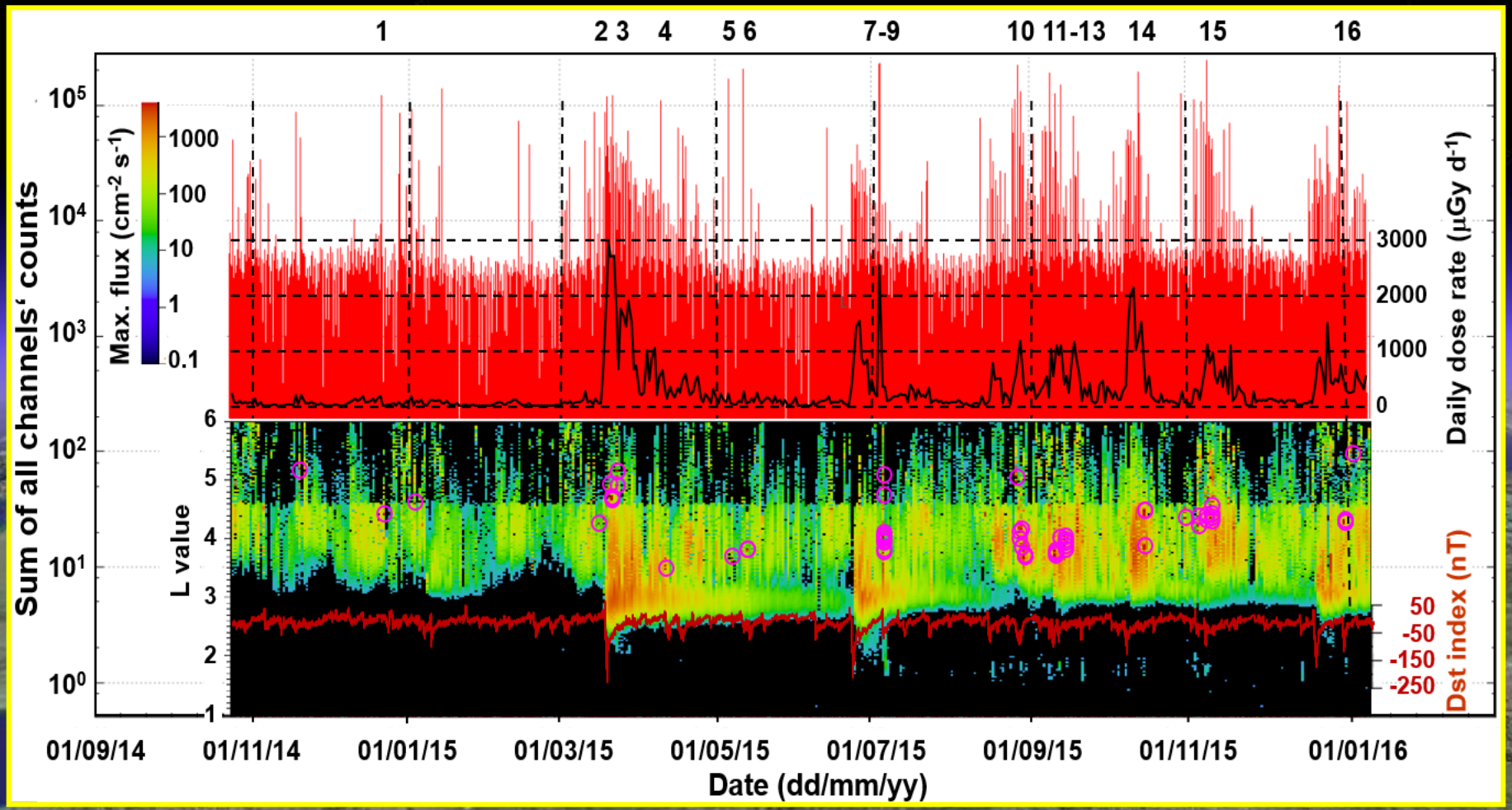
Comparison of daily-averaged electron fluxes plotted in L-versus-time format from R3DR2 instrument with about 1 MeV MagEIS-B instrument data on NASA's Van Allen Probes



*Claudepierre, S. G., et al. (2017), The hidden dynamics of relativistic electrons (0.7-1.5 MeV) in the inner zone and slot region, J. Geophys. Res. Space Physics, 122, 3127–3144,doi:10.1002/2016JA023719.

**Turner, D. L., et al. (2017), Investigating the source of near-relativistic and relativistic electrons in Earth's inner radiation belt, J. Geophys. Res. Space Physics, 122, 695–710, doi:10.1002/2016JA023600.

Variations of the measured with R3DR2 instrument: Sum of all channels' counts, maximal flux (L value versus time plot), daily average dose rate and Dst between 24 October 2014 and 11 January 2016



Identification of PB

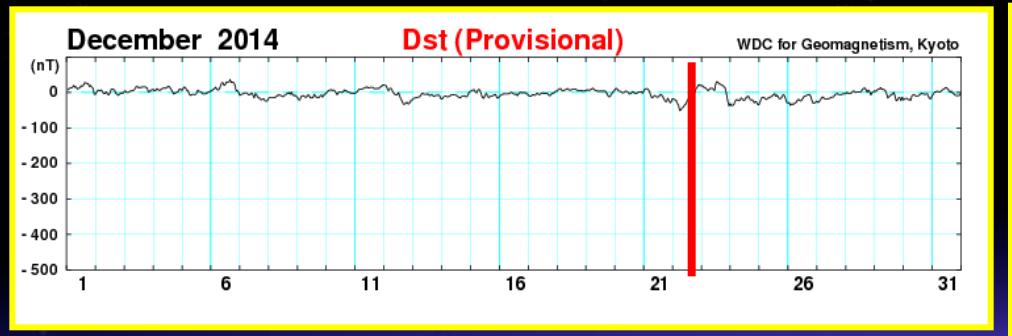
PB was identified as rapid enhancement from the usual (100-2000 mGy h^{-1}) ORB level and similar fast return to the same low level. Only rapid (in 10-20 s) enhancement in the time profile above 10,000 mGy h^{-1} and above ~ 4,000 cm^{-2} s^{-1} for 10 or more seconds were selected.

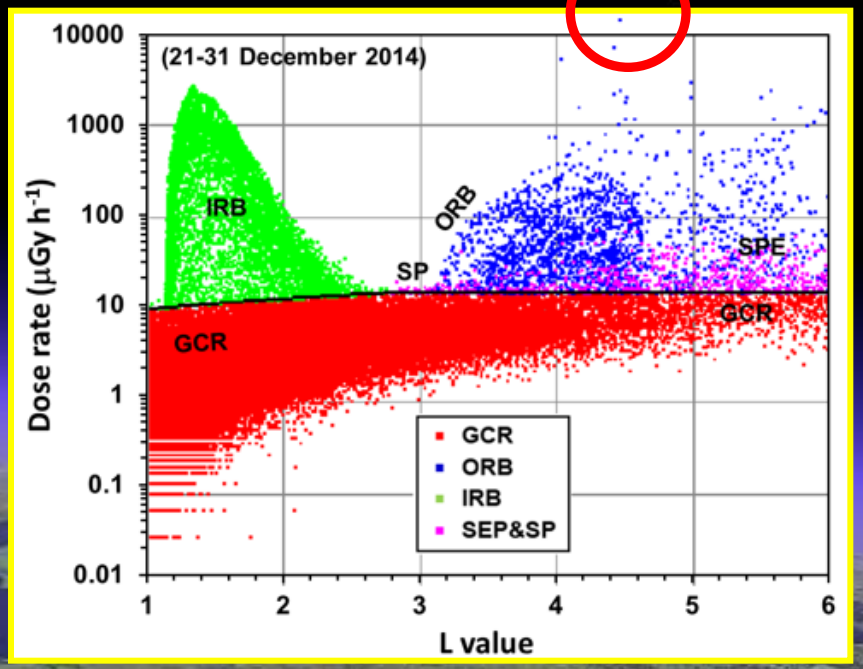
The R3DR2 data in EXPOSE-R2 mission covered the period between 24 October 2014 and 16 January 2016, which was the most geomagnetically disturbed in comparison with EXPOSE-E/R periods. That is why an maximum number of 61 points, which reflects the mentioned requirements were identified.

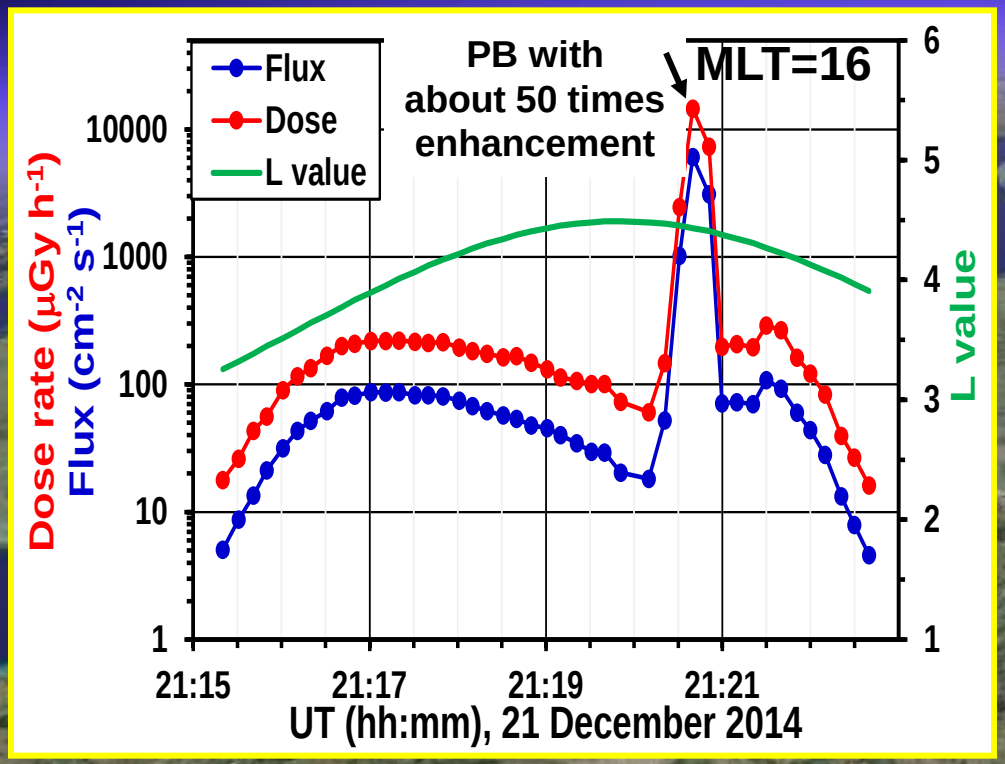
Results of the investigation of the potentially PB numbered from 1 to 16

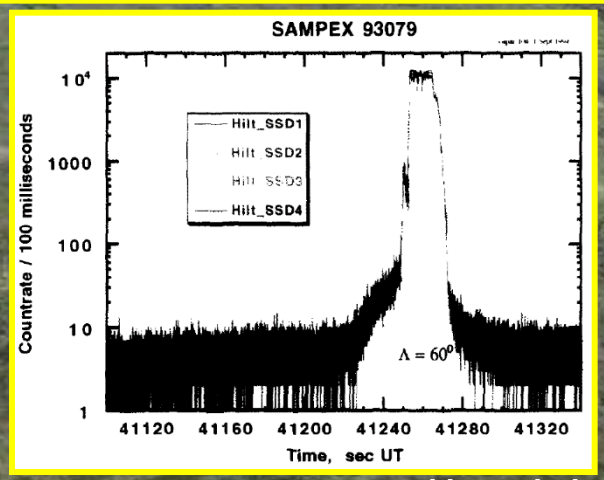
No	Date (dd/mm/yyyy)/ Time (hh:mm)/ Comment	Result	Dst value (nT)	Maximal dose rate (μGy h^{-1})/ Flux (cm^{-2} s^{-1})	Delivered dose (μGy)/ No of rel. electr.
1	21/12/2014 21:20 **See Fig 3**	10-s PB	-22	14,547/ 6,075	40 in 10-s. 121,480
2	20/03/2015 06:31	30-s PB	-58	13,623 5,888	101 in 30-s 315,540
3	22/03/2015 07:53	20-s PB	-43	14,003 6,035	70 in 20-s 220,500
4	10/042015 01:21	10-s PB	-33	12,722 5,413	35 in 10-s 108,260
5	06/05/2015 11:36	10-s PB	-18	19,481 8,326	54 in 10-s 166,520
6	12/05/2015	Not clearly seen PB at low L value.			
7 8 9	04/072015 12:47 14:24 18:59 **See Fig. 4**	10-s PB 10-s PB 70 s PB	15 32 -7	26,262 10,297 10,884 4,569 27,020 11,164	**73 in 10-s** 205,940 30 in 10 s 91,380 **464 in 70-s** 1,365,760
10	27/08/2015 18:21	10-s PB	-77	25,588 10,532	71 in 10-s 210,640
11	09/09/2015 08:40 **See Fig. 5**	30-s PB	-92	21,997 9,314	157 in 30-s 478,840
12	11/09/2015 08:23	10-s PB	-13	14,769 5,684	41 in 10-s 113,680
13	13/09/2015 13:45	50-s PB	-33	17,998 7,412	214 in 50-s 633,400
14	14/10/2015 01:12	20-s PB	-41	22,712 9,408	101 in 20-s 305,800
15	09/11/2015 15:12	30-s PB	-52	28,840 11,813	117 in 20-s 348,920
16	31/12/2015 11:52 31/12/2015 11:55 **See Fig. 6**	30-s PB 20-s PB	-5 -5	17,482 7,343 16,821 7,186	132 in 30-s 399,120 82 in 20-s 249,660

Single point PB on 21 December. 2014. 40 μGy was delivered in 10-s. PB occurred after a small magnetic storm with minimal Dst=-65 nT on 22 December 2014 at 05:40 UT.









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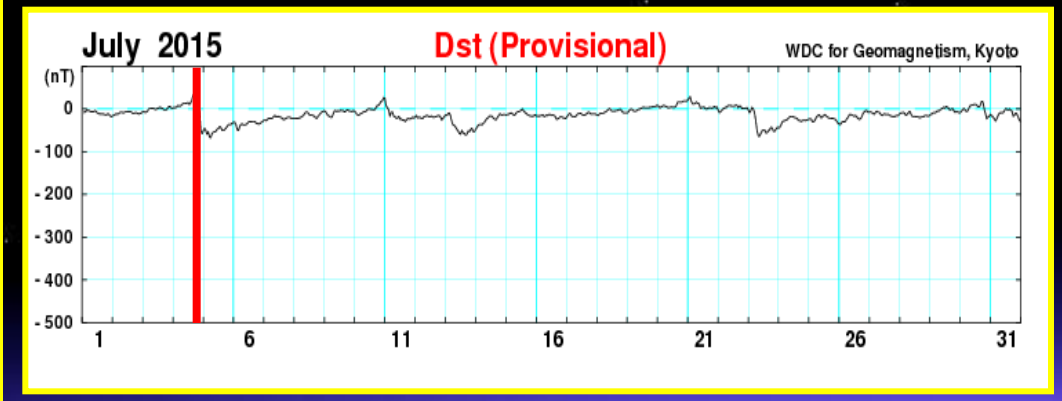
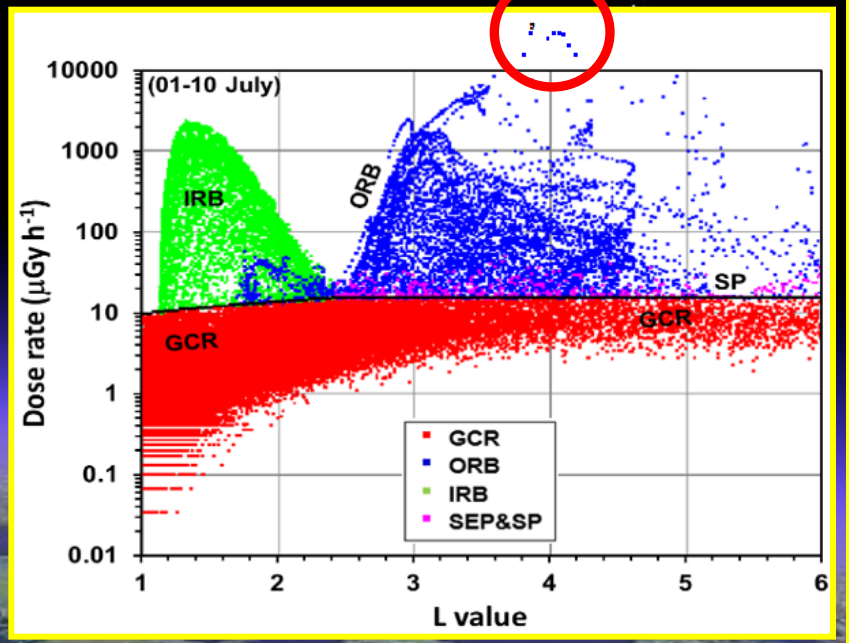
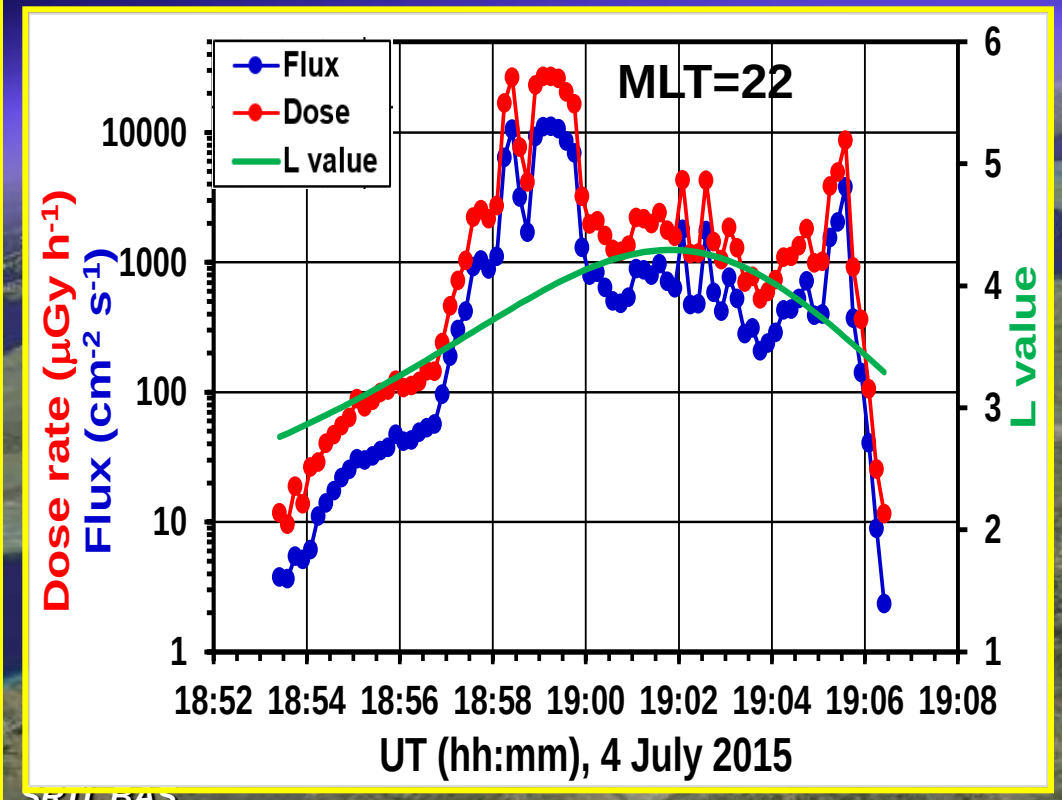
PB and inner belt.., 22 WRMISS, Thales Alenia, Sept. 2017

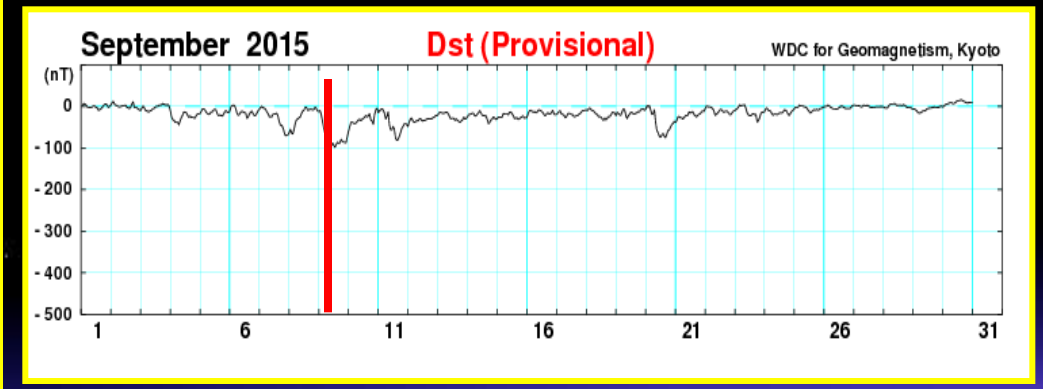
The left side maximum, which contains 7 points above 10,000 μGy h^{-1} was identified as PB on 4 July 2015.
464 μGy was delivered in 70-s. This is the largest PB in our data!

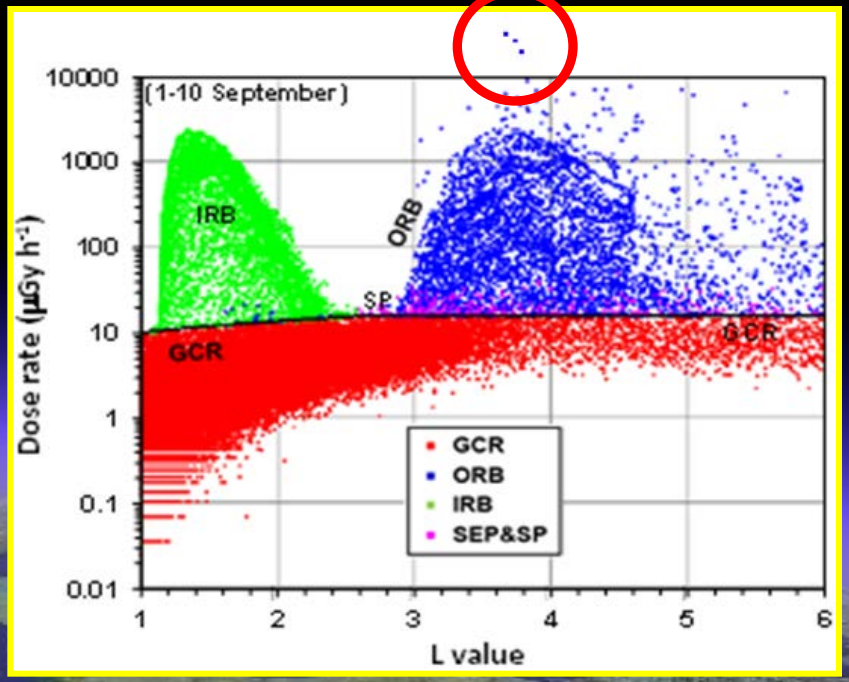


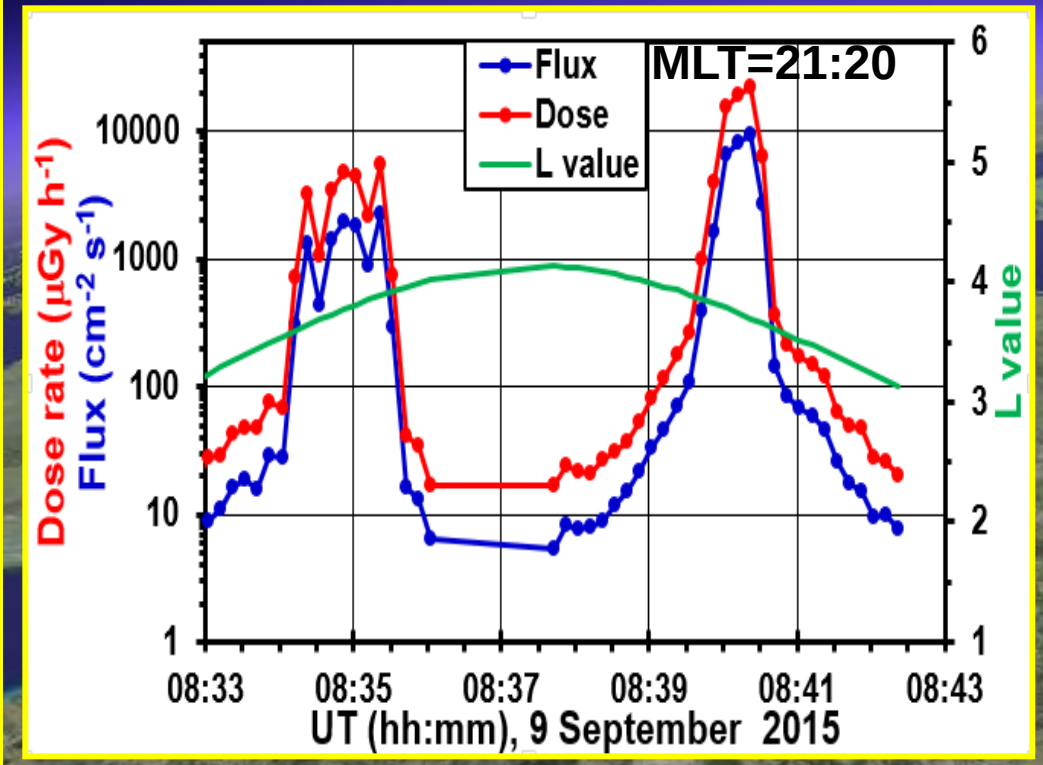




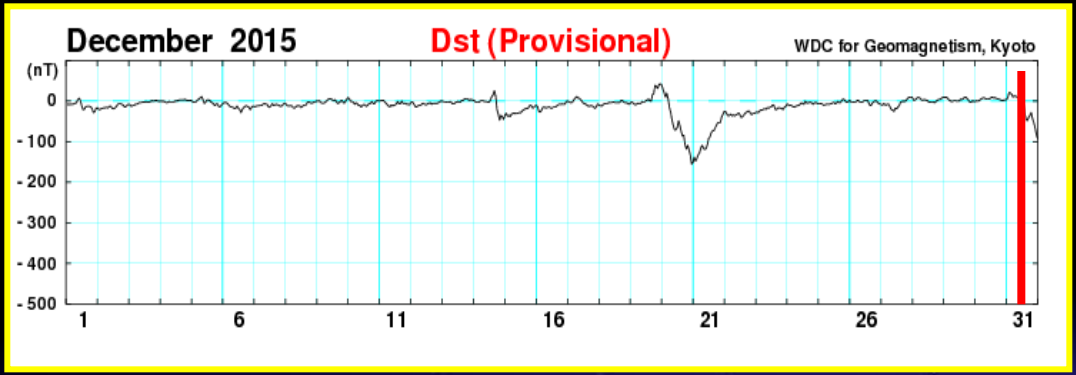
The right side maximum, which contains 3 points above 10,000 μGy h-1 was identified as PB on 9 September 2015. 157 μGy was delivered in 30-s

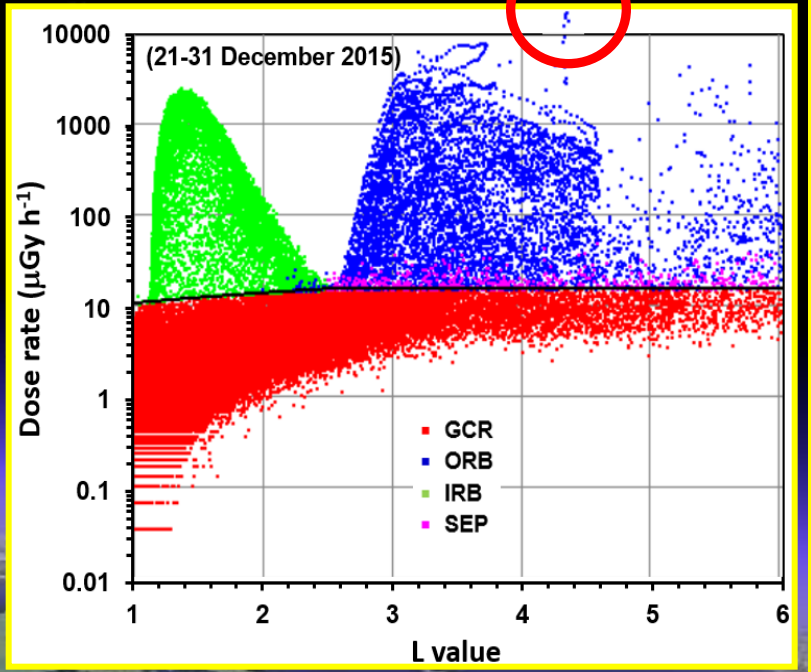


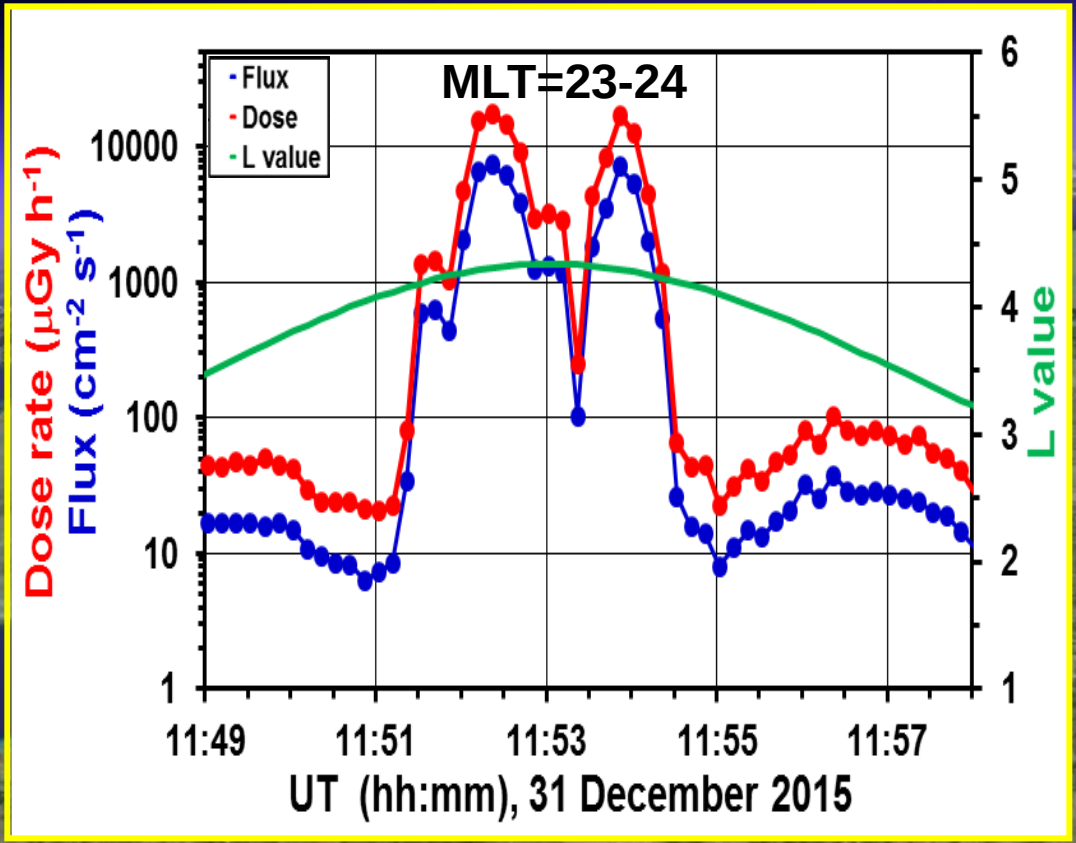




Two large PB on 31 December 2015. Totally 214 μGy was deliver in 50-s

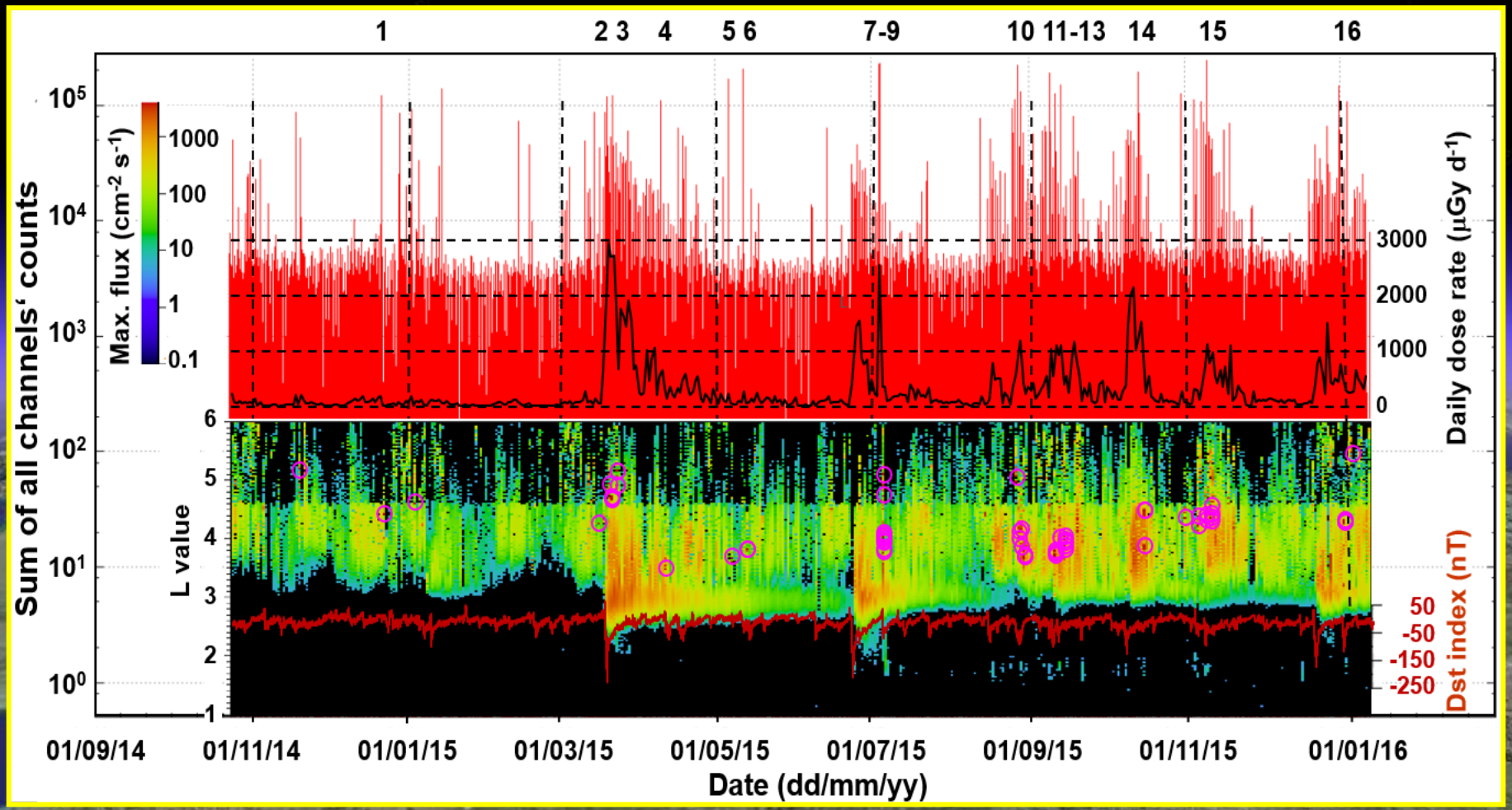




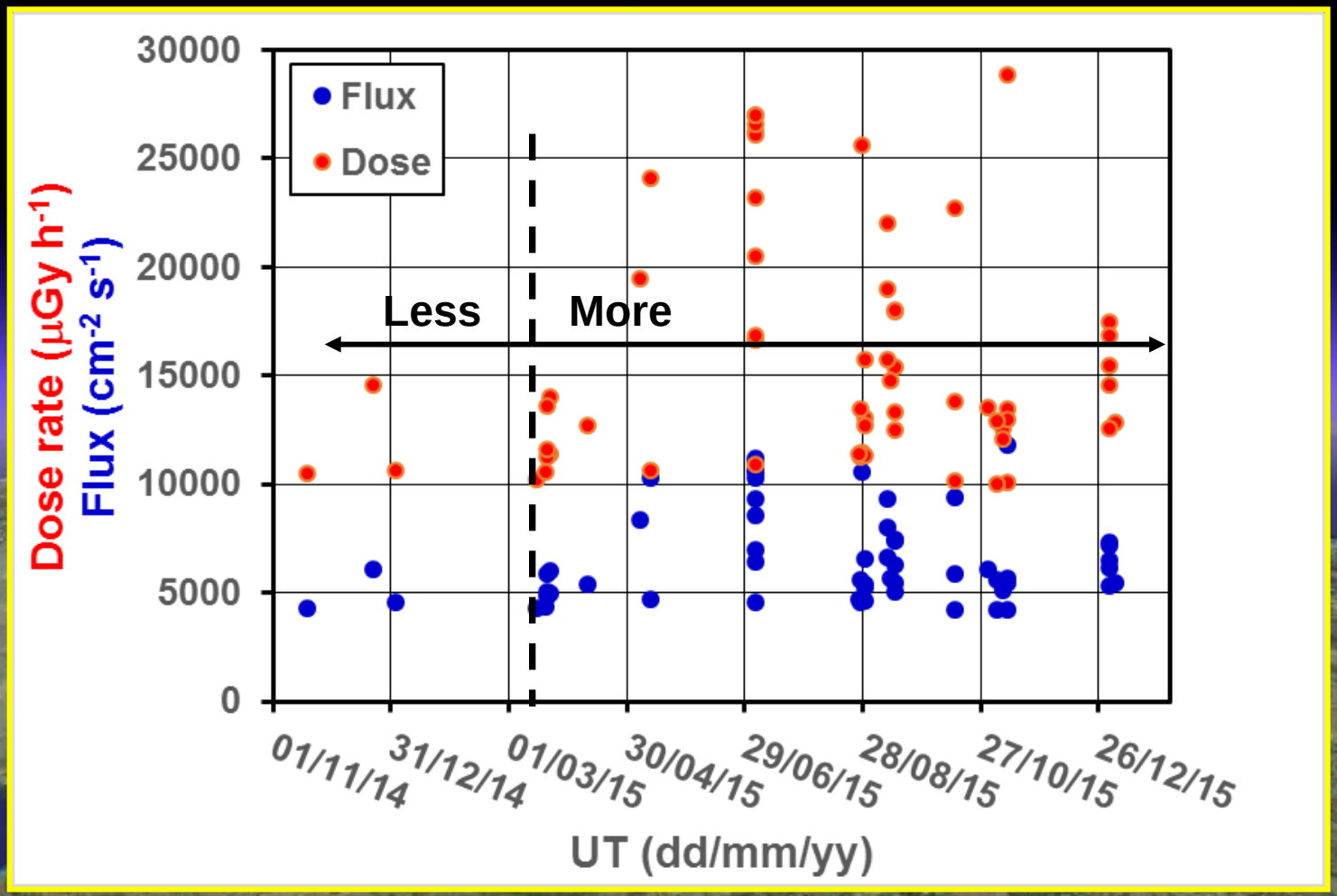


PB and inner belt.., 22 WRMISS, Thales Alenia, Sept. 2017

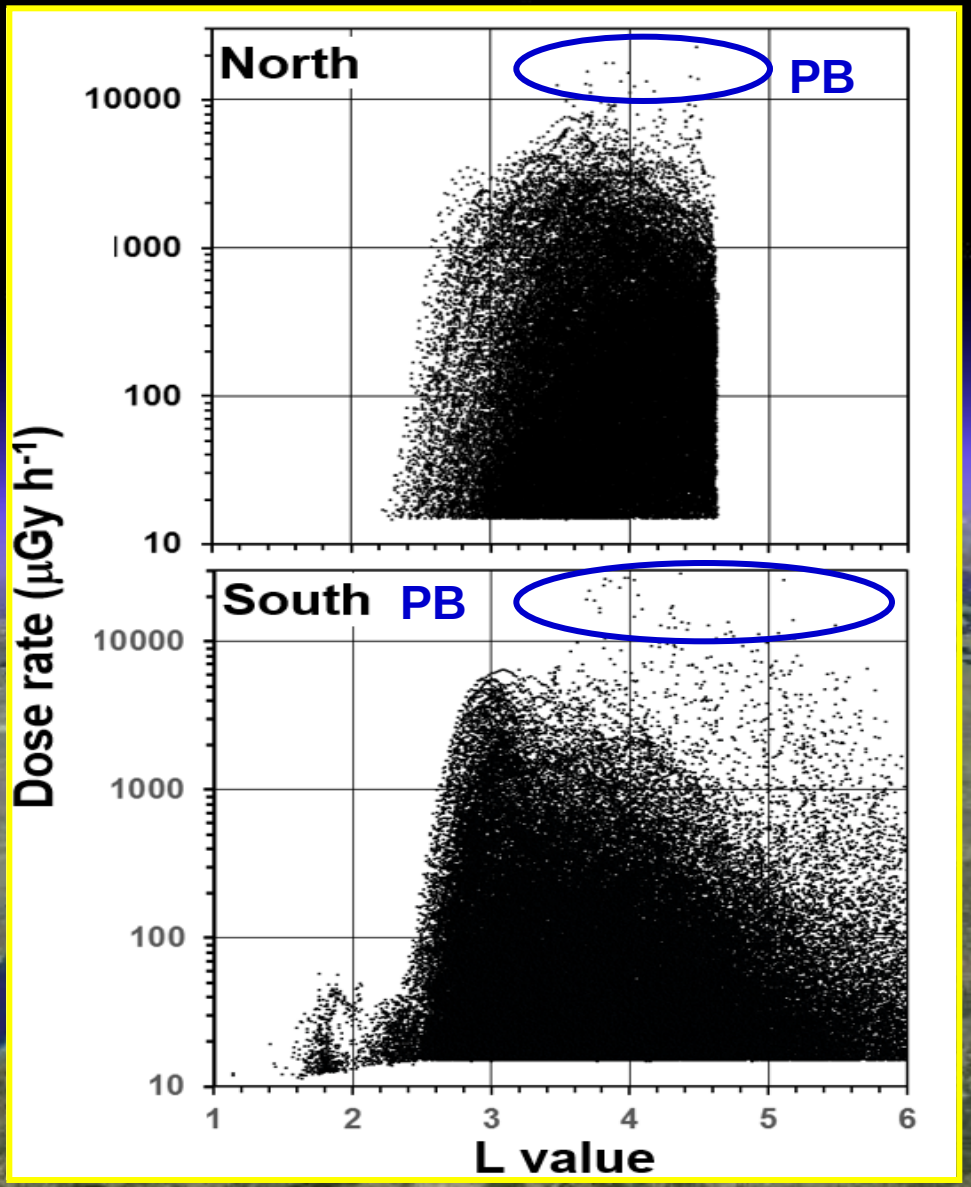
Statistical analysis of the 61 measurements (magenta circles in the figure belov) with dose rate higher than 10,000 μGy h^{-1} (flux higher than 4,000 cm^{-2} s^{-1})



Only 3 PB were observed in the less disturbed period till middle of March 2015. The PB flux and dose rate values were higher for more disturbed period

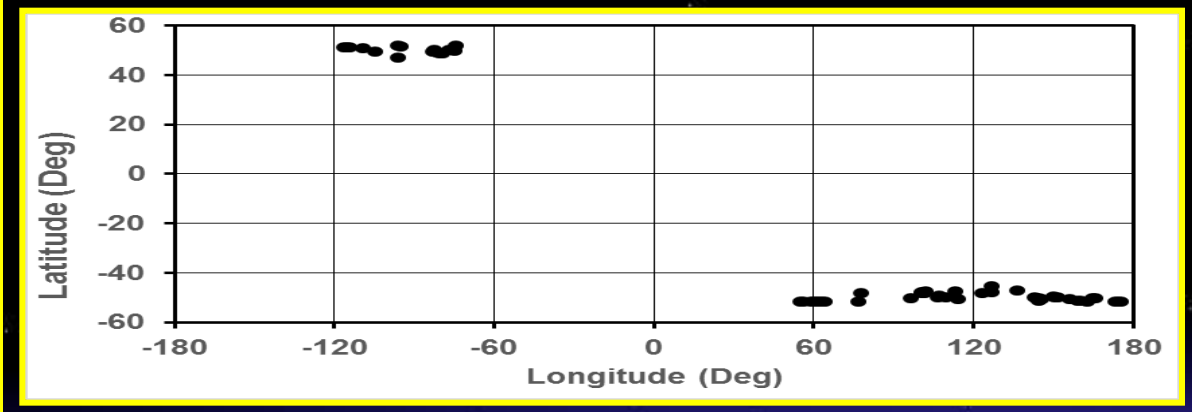


Differences in the ORB dose rates L value distribution for North and South magnetic hemispheres



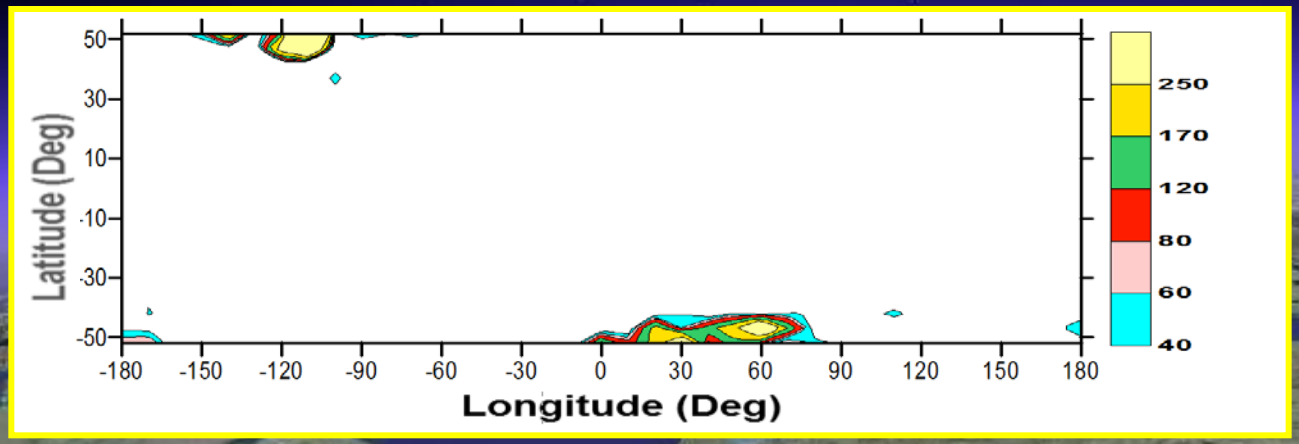
PB occurred more frequently in Southern hemisphere (44 occurrences out of 61)

Global distribution of the ORB dose rate and PB

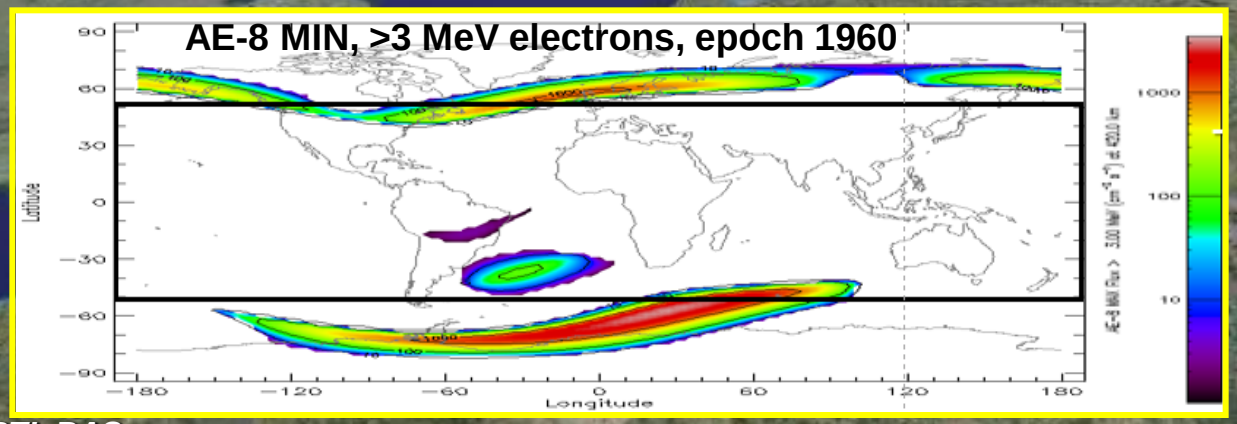


PB occurred:

- More frequently in Southern hemisphere (44 occurrences from 61;

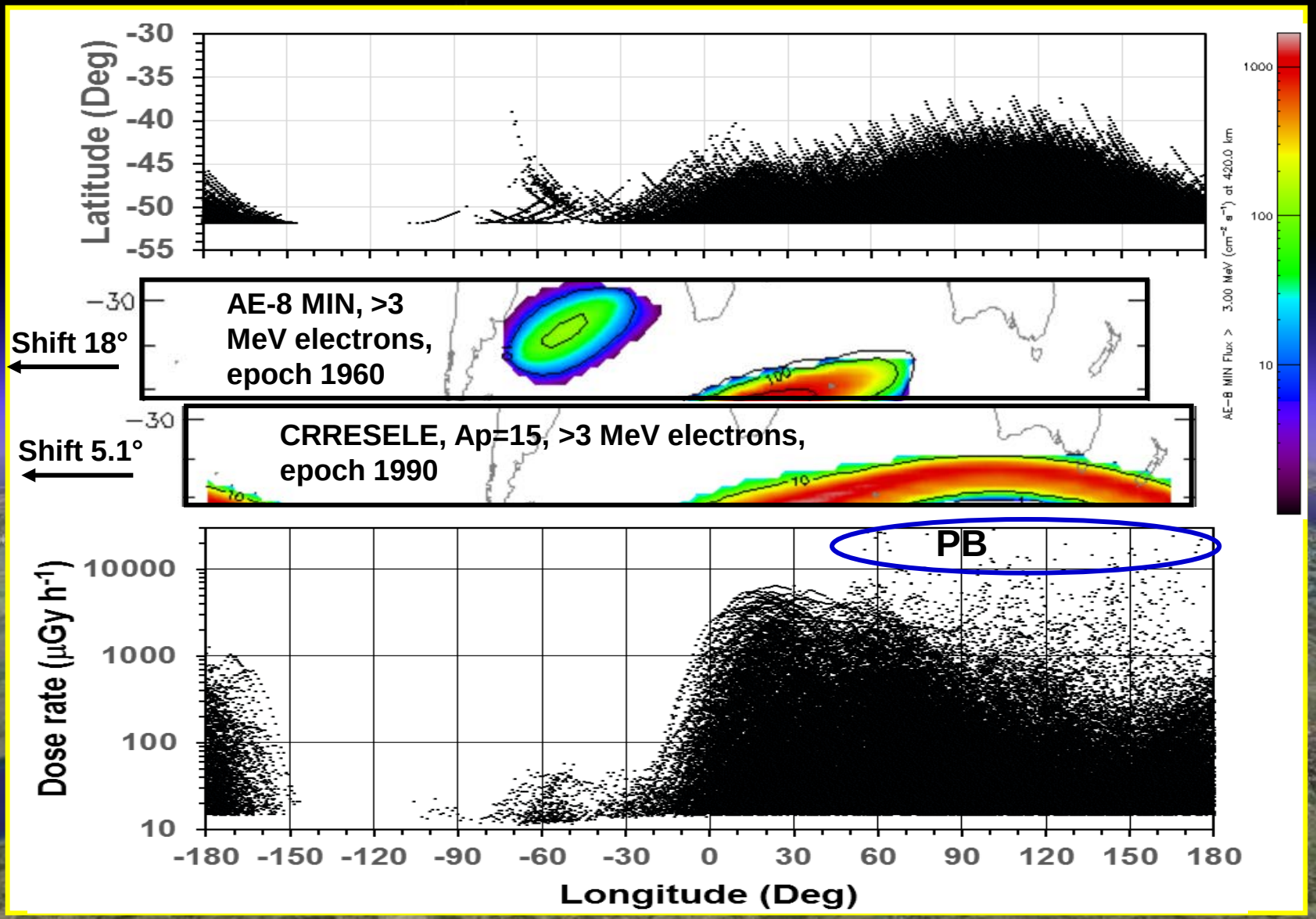


- Mainly out of the ORB maximum location,

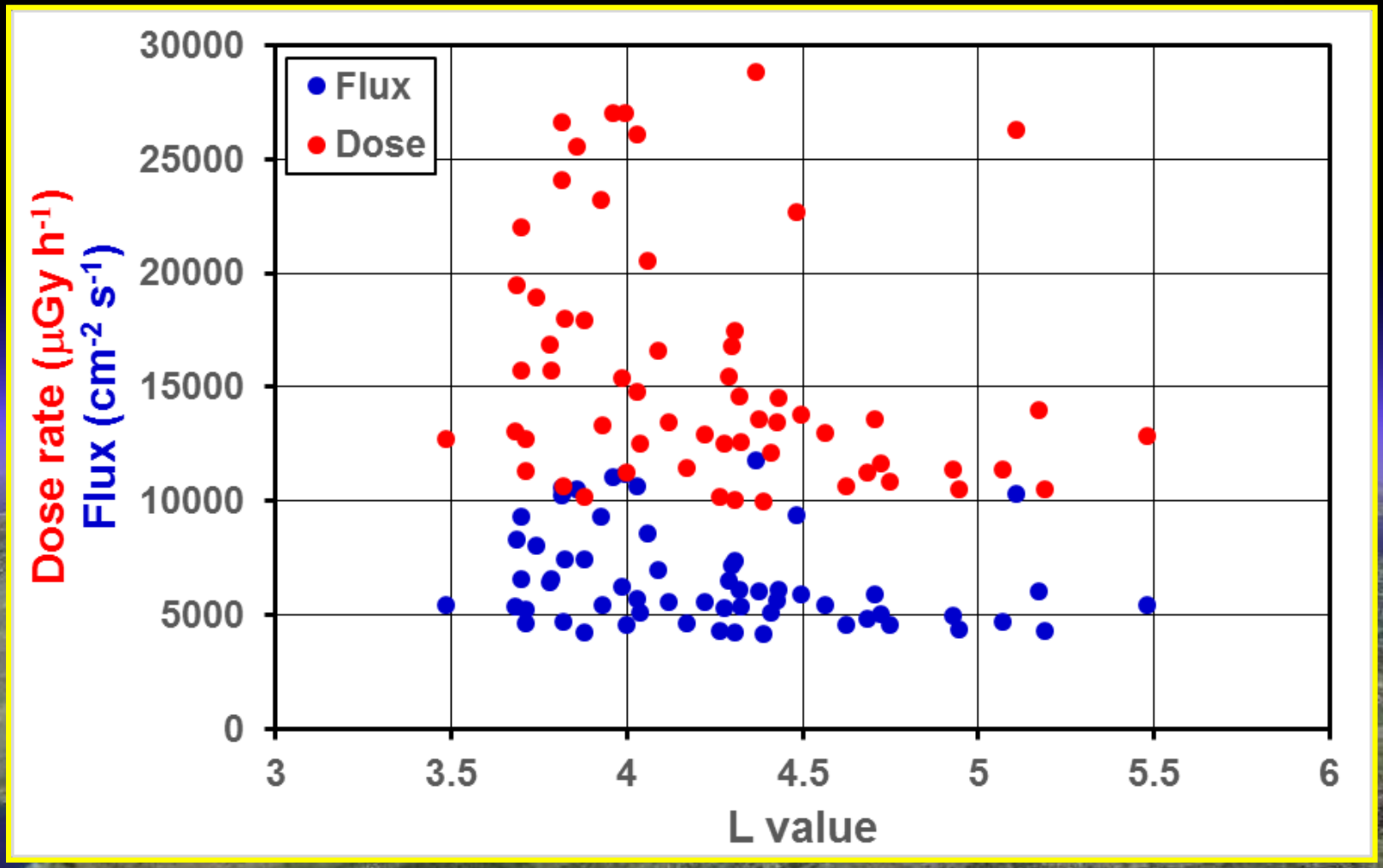


- In places mainly out of the maximum of >3 MeV AE-8 MAX model at 420 km altitude ;

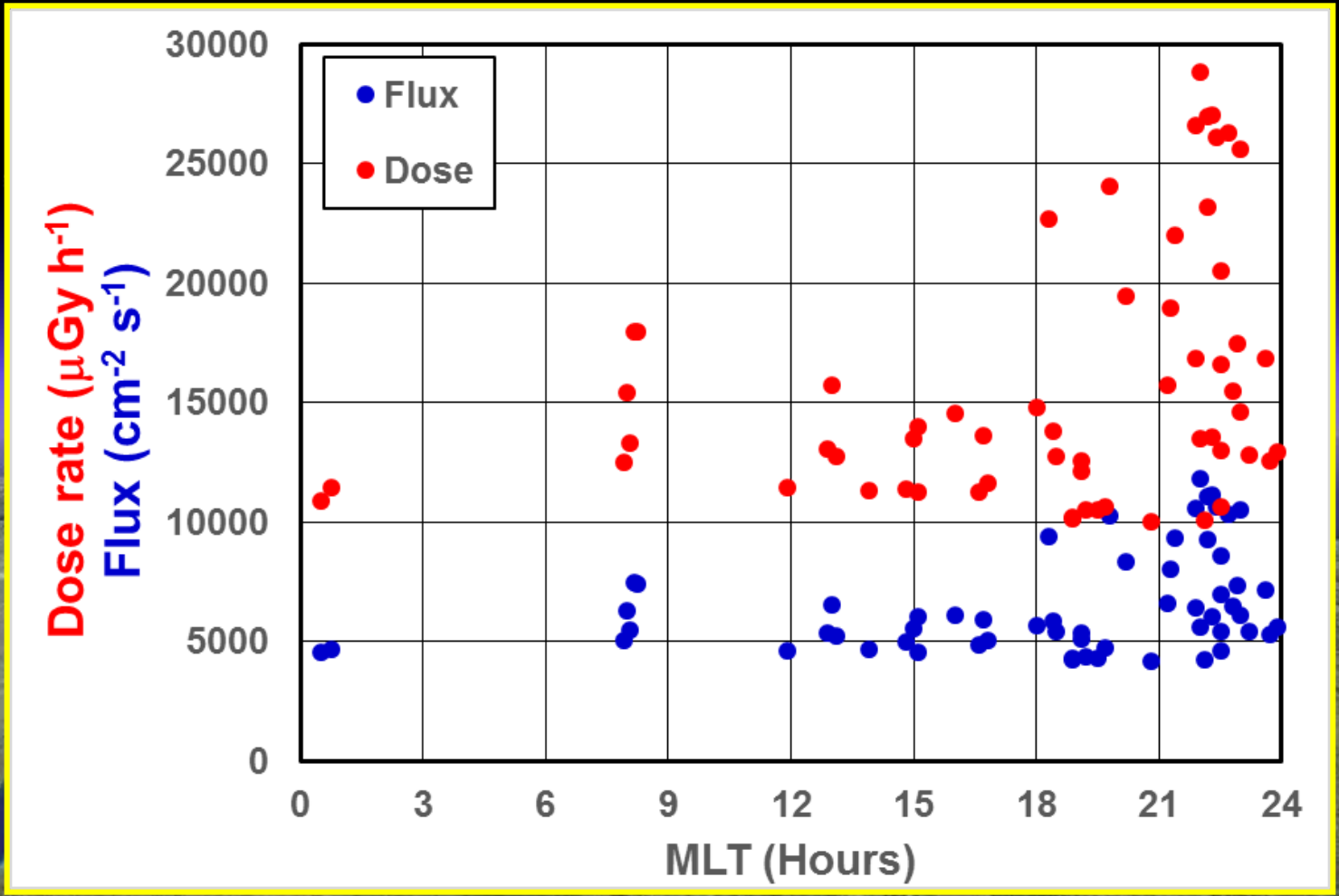
Longitudinal distribution of the R3DR2 ORB dose rate in Southern hemisphere compared with shifted models data



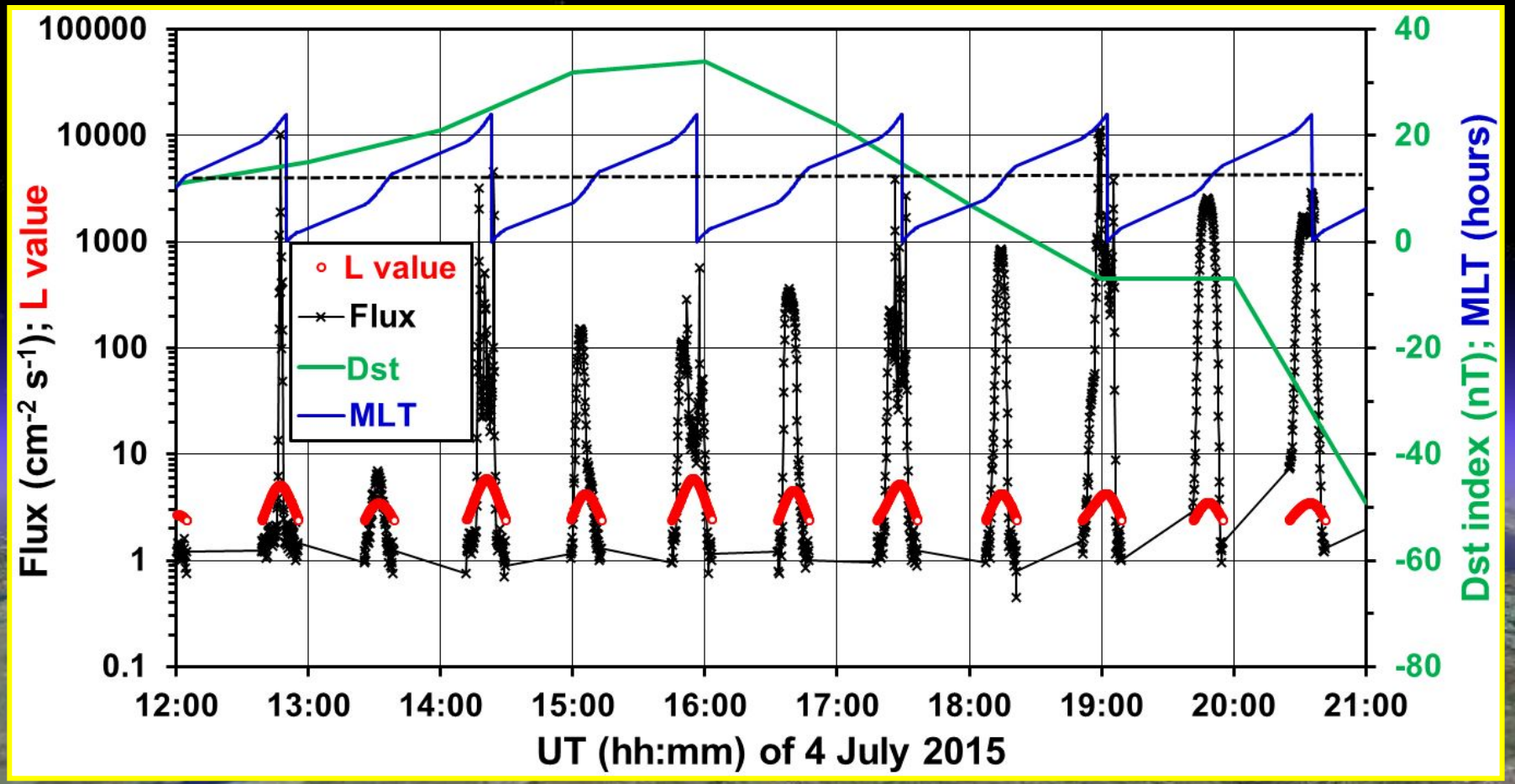
PB covered L coordinates from 3.5 to 5.5 with well seen tendency of maximum at L=4



PB were observed more frequently in the dusk local magnetic times and the values were larger for the same period also



Magnetic local time plays very important role in the formation of PB

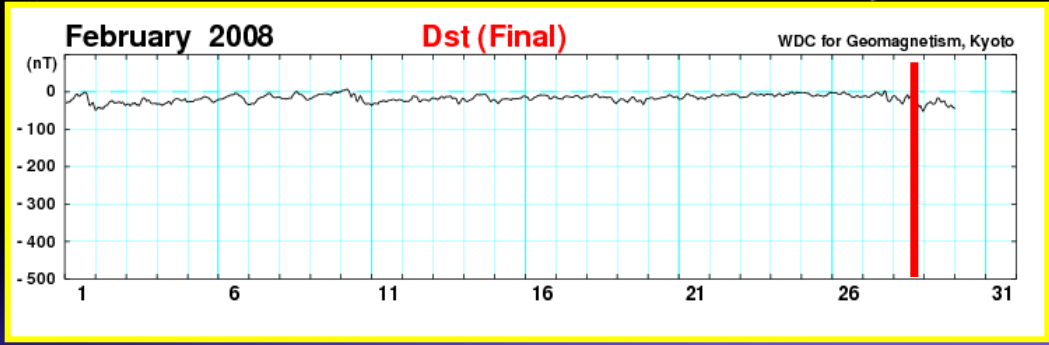


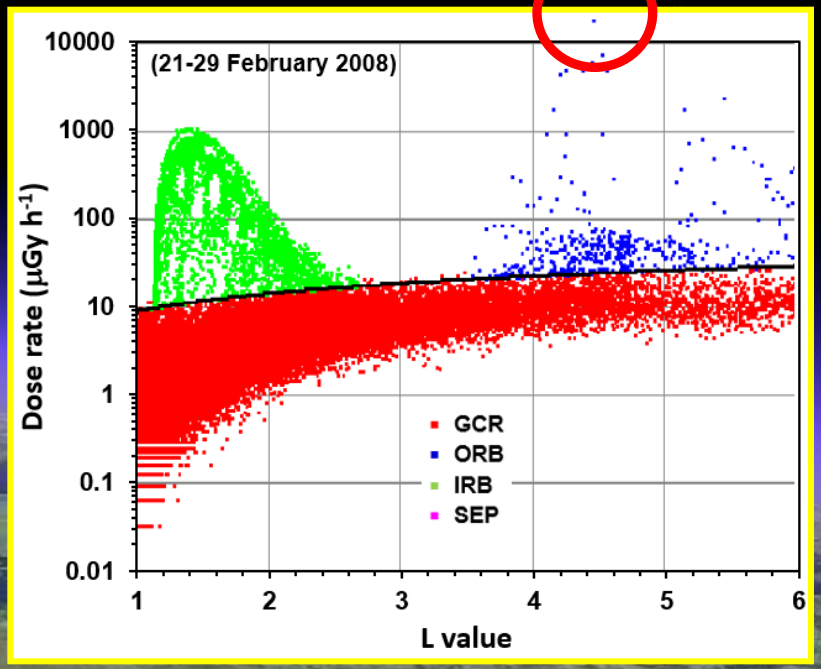
According to literature analysis made by Blum et al., (2015): "the PB during more active times may be induced by electromagnetic ion cyclotron (EMIC) waves… In the inner magnetosphere, these waves are observed primarily in the afternoon sector, where anisotropic ring current ions overlap cool, dense plasmaspheric plumes."

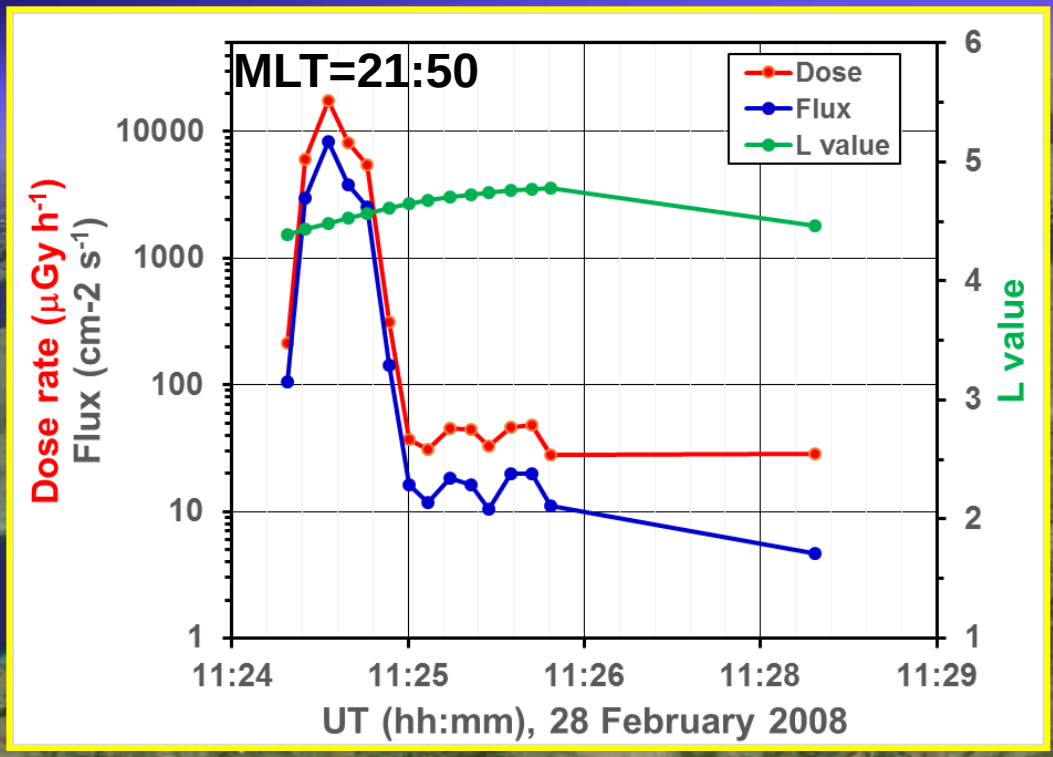
EXPOSE-E* mission in the period 17 February 2008 - 3 September 2009 was the quietest mission from geomagnetic activity point of view that is why only 1 PB with dose rate above 10,000 μGy h^{-1} was observed on 28 February 2008 at 11:24 UT.

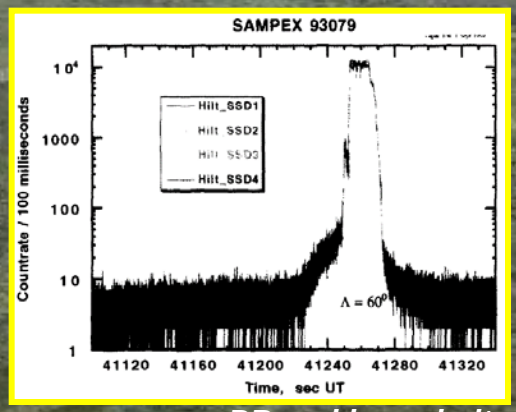
*Dachev, Ts., Horneck, G., Häder, D.-P., Lebert, M., Richter, P., Schuster, M., Demets, R., 2012. Time profile of cosmic radiation exposure during the EXPOSE-E mission: the R3D instrument. Journal of Astrobiology, 12, 5, 403-411, http://eea.spaceflight.esa.int/attachments/spacestations/ID501800a9c26c2.pdf.

First PB in R3D data was observed on 28 February 2008 with single point PB, which delivered 49 μGy. PB occurred in the pre-phase of a small magnetic storm with minimal Dst=-52 nT on 28 February at 23:00 UT









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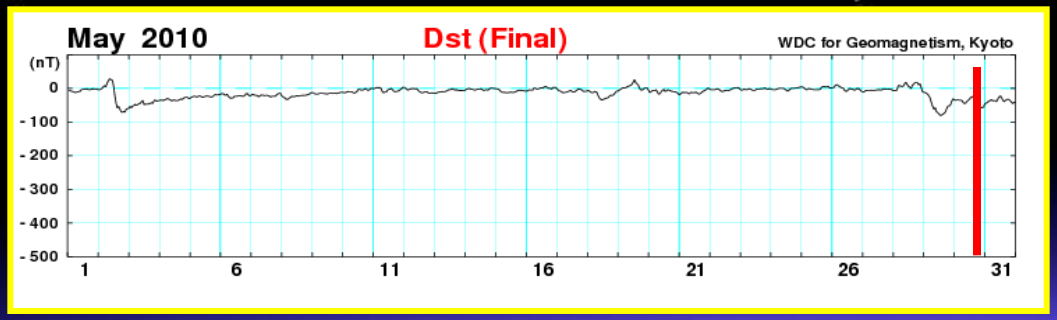
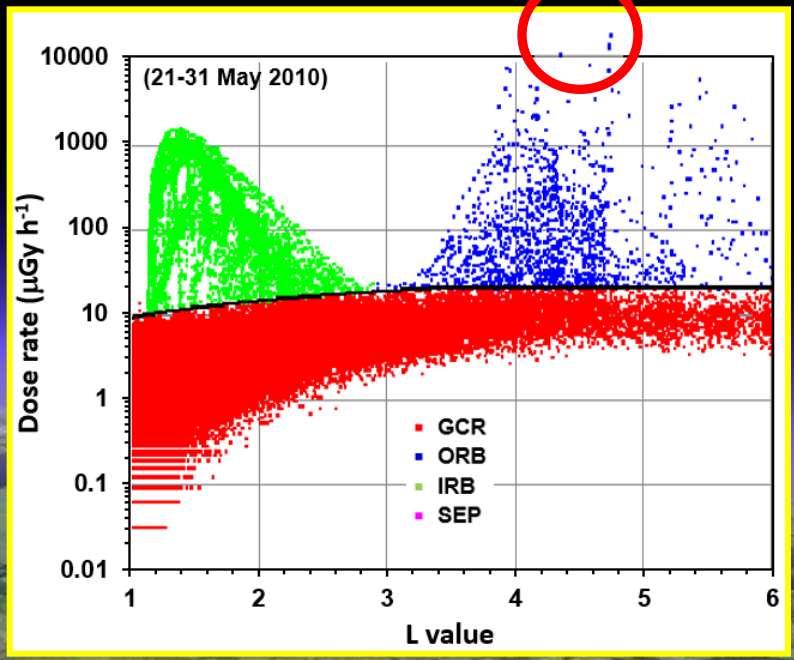
EXPOSE-R(1) mission was performed in the period 11 March 2009 - 20 August 2010;

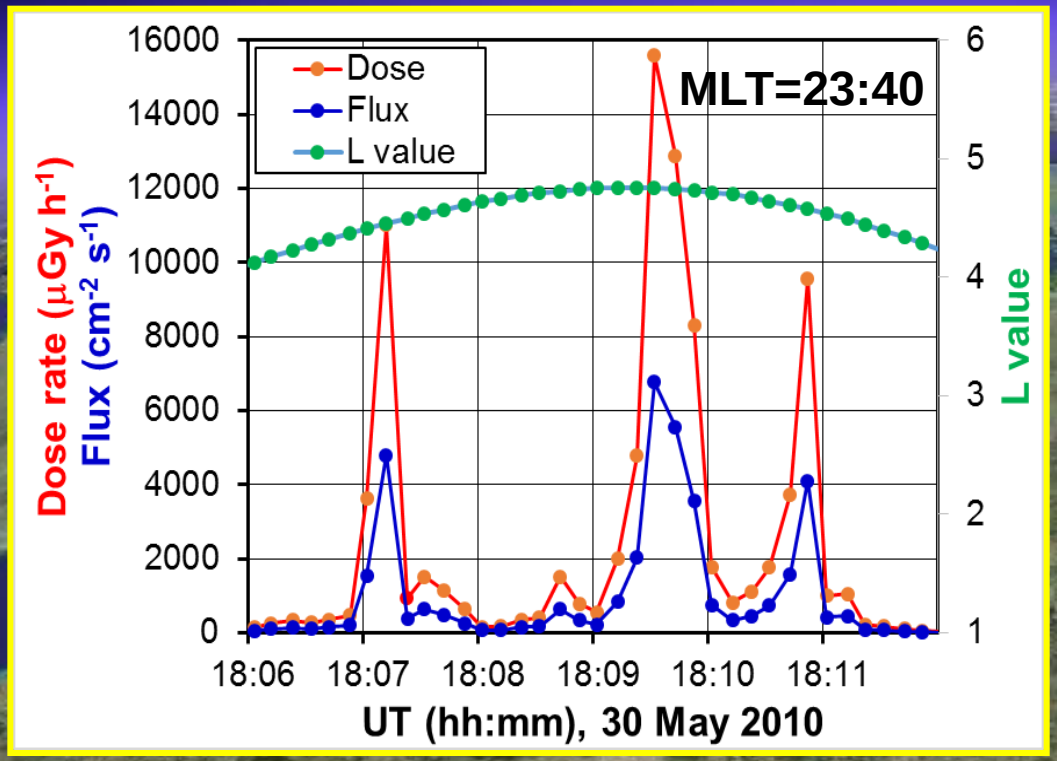
The period between 1 March 2009 and 1 March 2010 was characterized by low solar and magnetic activity, which was the main reason for the low ORB activity and lack of PB;

6 PB were observed during the mission on 6 March, 6 April and 29 May 2010.

Two PB were observed in R3DR data on 30 May 2010, which delivered 66 μGy. They occurred in response to moderate geomagnetic storm with minimal Dst=-80 nT about noon on 29 May.







Relativistic electrons in Earth's inner radiation belt

Earth's inner electron radiation belt has long been considered a very stable population compared to the highly variable outer belt…

Proton contamination muddled results from the inner electron belt until NASA's Van Allen Probes mission was launched in 2012…

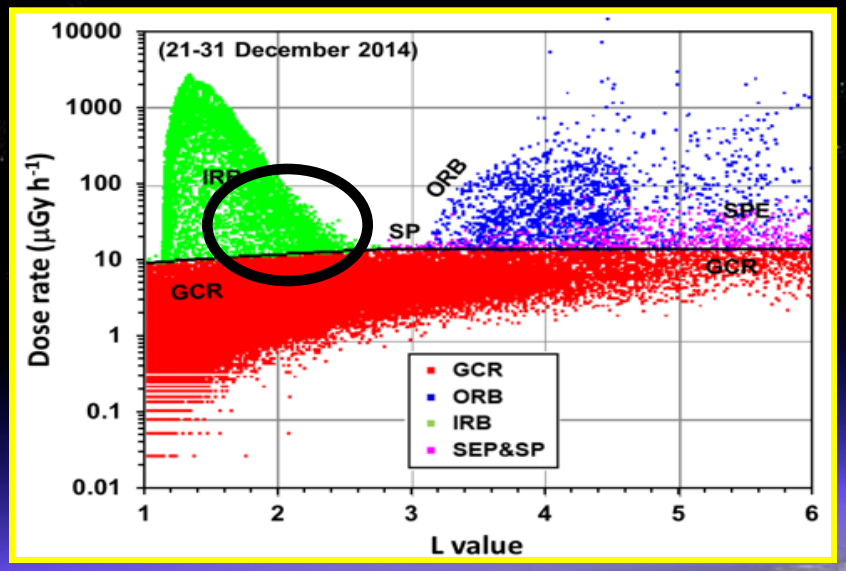
Since then, reliable observations (described below) have enabled a series of new discoveries concerning Earth's inner belt electrons…*

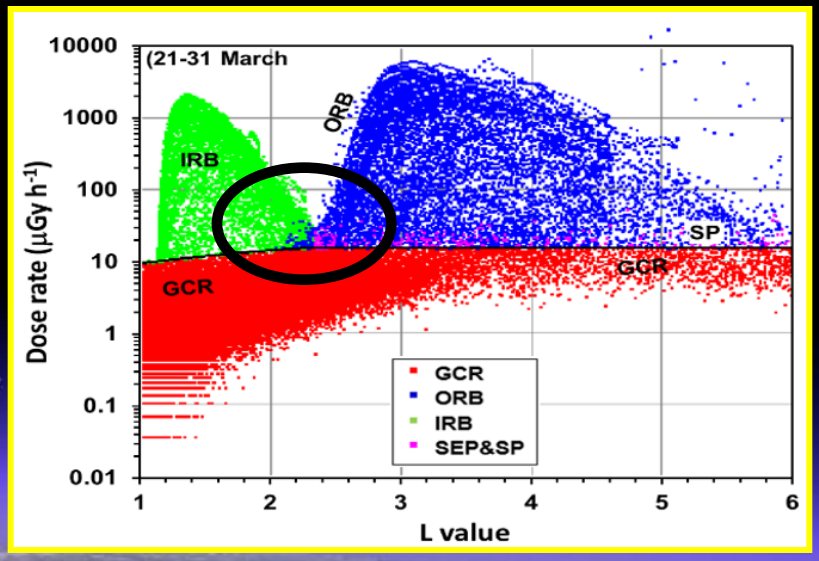
…we did not investigate the physical processes that lead to the observed differences in the rapid slot region decays, when compared with the slower, more gradual decays observed in the inner zone. Such analyses are reserved for future work.**

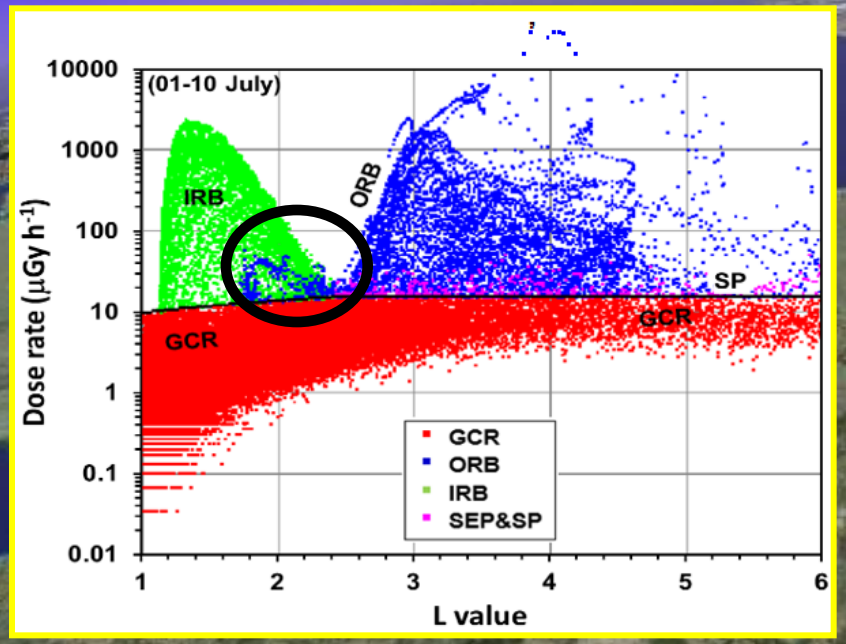
*Turner, D. L., et al. (2017), Investigating the source of near-relativistic and relativistic electrons in Earth's inner radiation belt, J. Geophys. Res. Space Physics, 122, 695–710, doi:10.1002/2016JA023600.

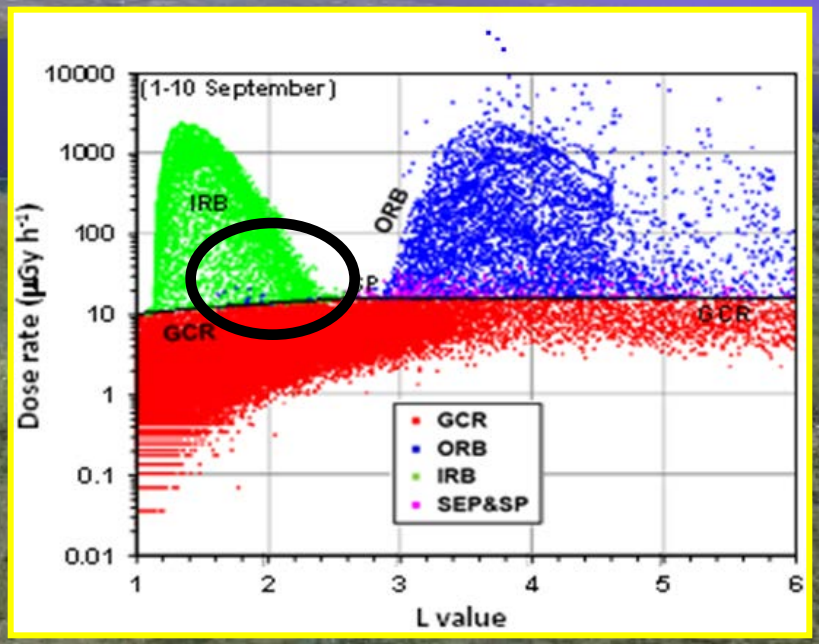
**Claudepierre, S. G., et al. (2017), The hidden dynamics of relativistic electrons (0.7-1.5 MeV) in the inner zone and slot region, J. Geophys. Res. Space Physics, 122, 3127–3144,doi:10.1002/2016JA023719.

Different examples of the slot region dynamics

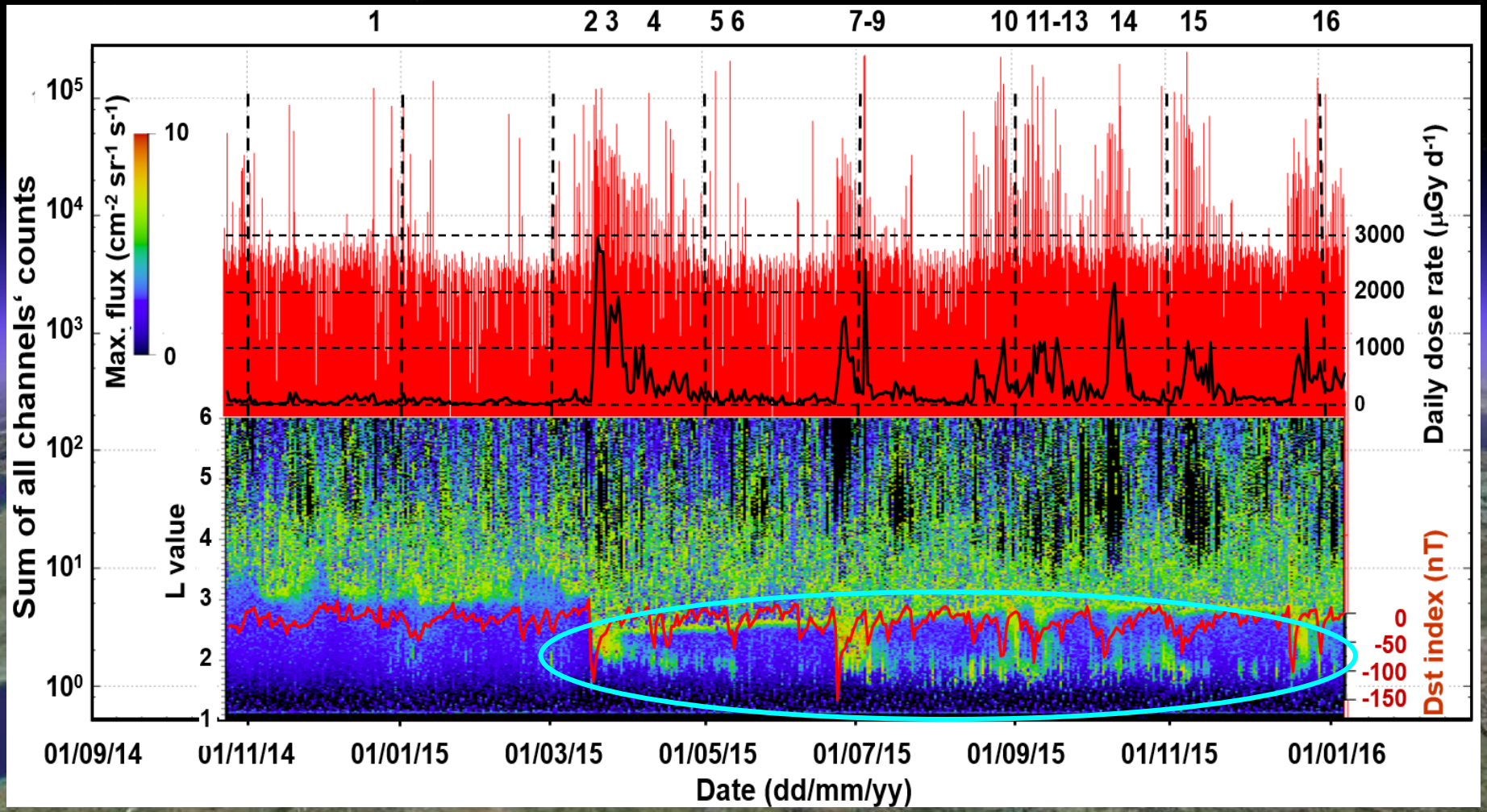




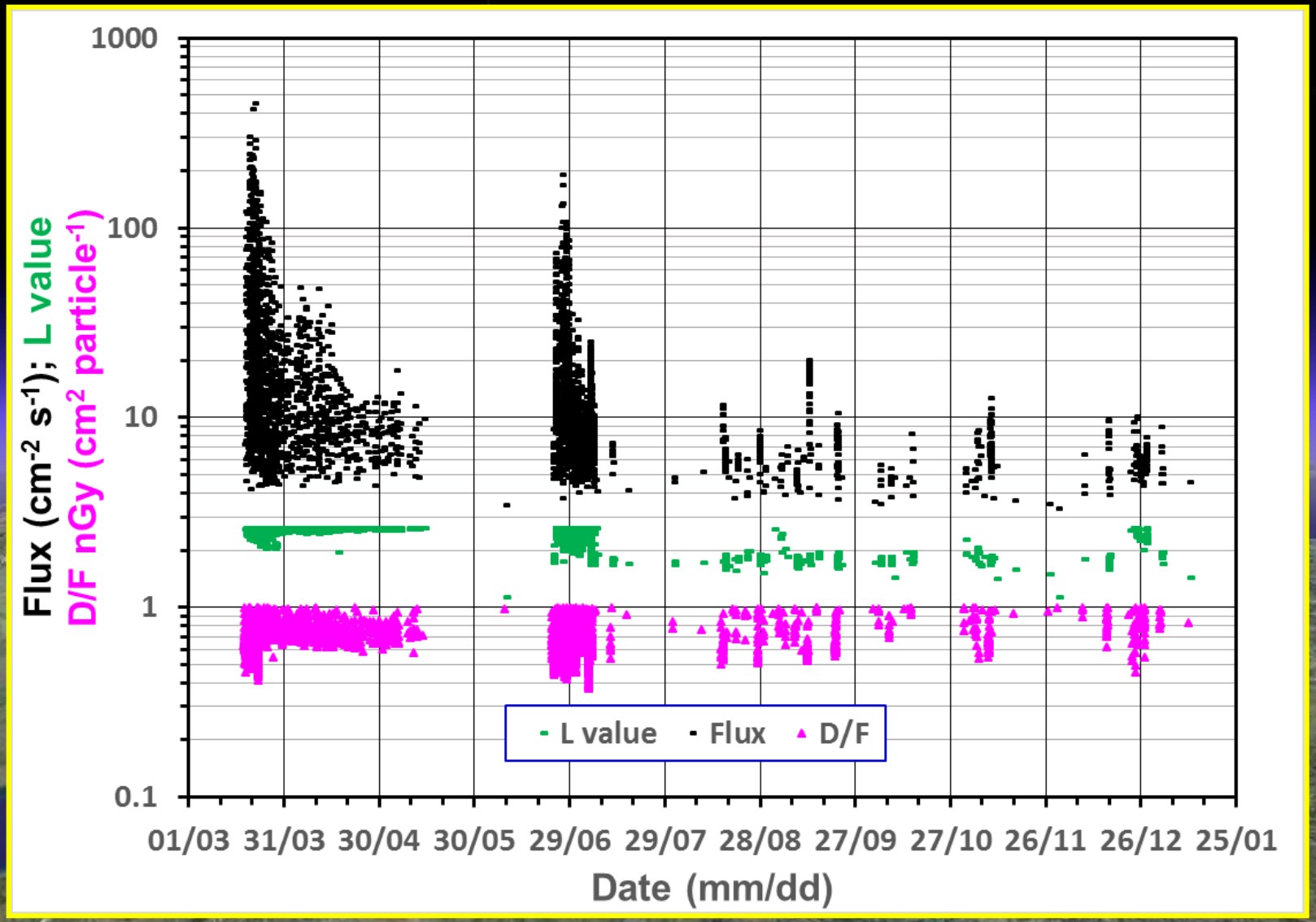




Locations of the relativistic electrons in the inner radiation belt (Data are presented in an appropriate scale)



Detailed analysis of the inner belt and slot region relativistic electrons existence in the R3DR2 data



Discussion and conclusions

- The most important achievement of the paper is the discovery and proof of the existence of precipitation bands in the relativistic electrons dose rates outside ISS during the EXPOSE missions in the period 2008-2016;
- PB was identified as rapid enhancement from the usual (100-2000 $\mu Gy\ h^{-1}$) ORB dose rate level and similar fast return to the same low level;
- Only rapid (in 10-20 s) enhancement in the time profile above 10,000 $\mu Gy\ h^{-1}$ and above ~ 4,000 $cm^{-2}\ s^{-1}$ for 10 or more seconds were selected;
- 1 PB was identified in the EXPOSE-E data in the quietest from geomagnetic activity point of view period in 2008-2009.
- 6 PB were observed in April-May 2010 during EXPOSE-R mission;
- 16 PB were selected in the ExposeR2 mission data because the maximal magnetic activity during the observations;

- Second important achievement of the paper is the discovery and proof of the existence of relativistic electrons in the slot and inner radiation belt region of the ISS outside radiation environment.

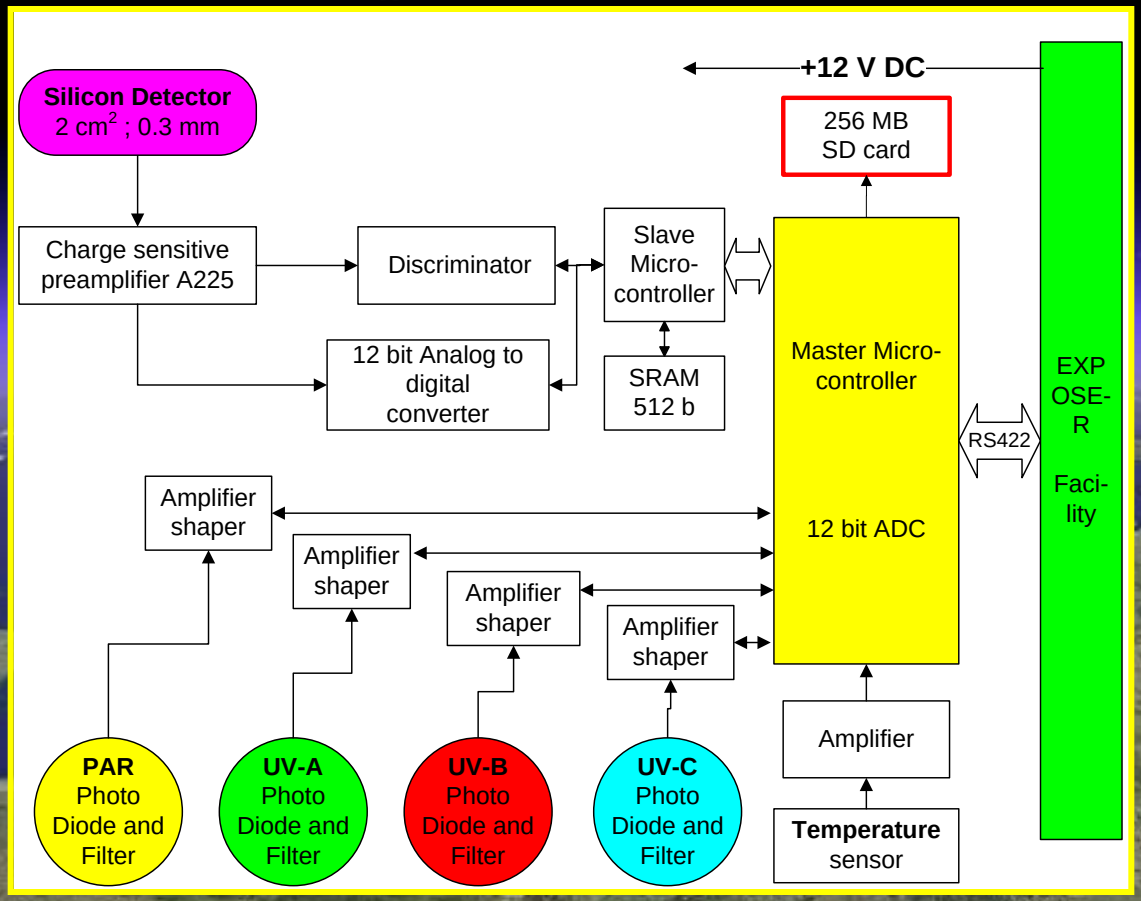
Acknowledgements and data availability

This work was partially supported by Contract No. 4000117692/16/NL/NDe funded by the Government of Bulgaria through an ESA Contract under the Plan for European Cooperating States (PECS).

The R3DR2 data used in this paper are part of the above mentioned contract entitled: “DOSIMETRY: Dosimetry science payloads for ExoMars TGO & surface platform; Unified web-based database with Liulin-type instruments’ cosmic radiation data”. This is the reason why the R2DR2 dose rate and flux data and some time-spatial coordinates of the ISS are currently available online at the following URL: http://esa-pro.space.bas.bg/node/23. Later they will be part of the database.

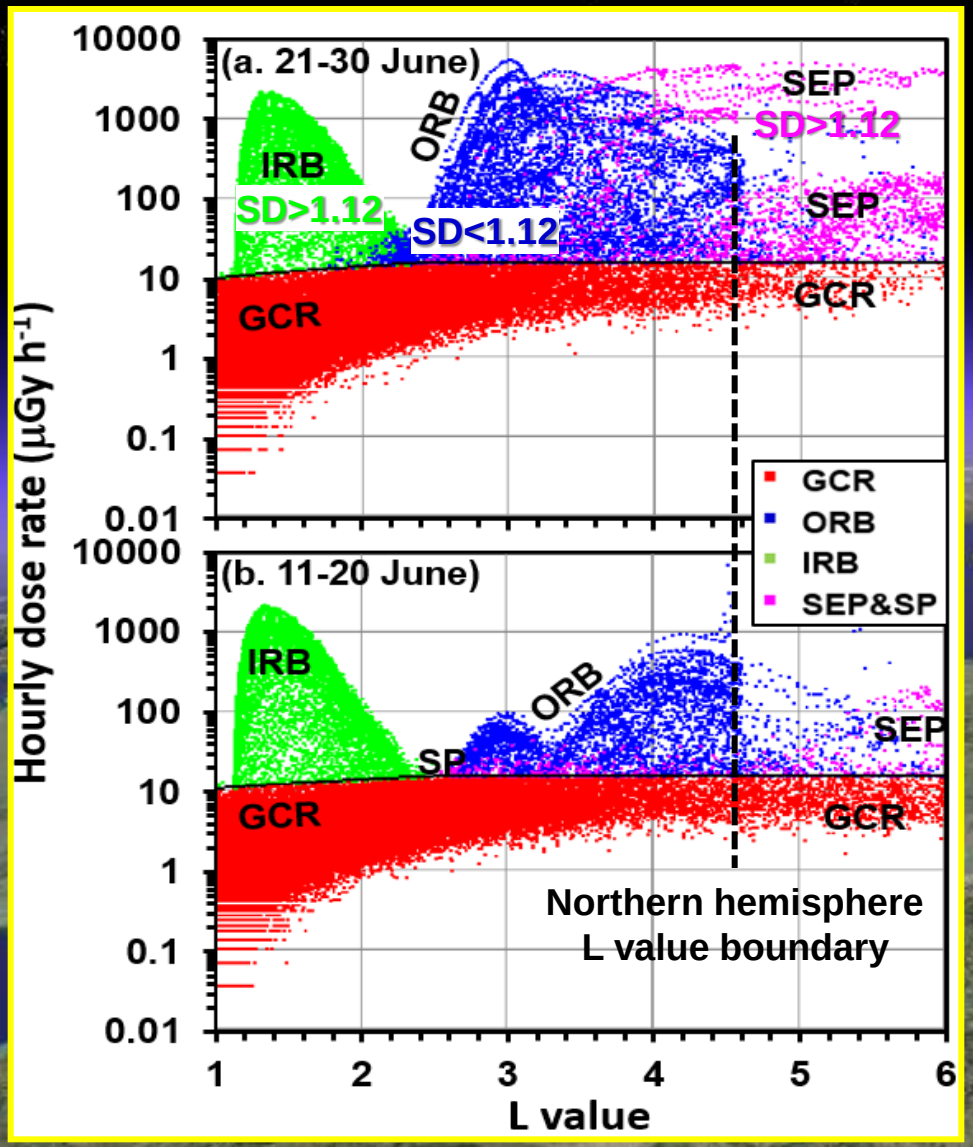

Thank you for your attention

The R3DER2 instrument is active, low mass (170 g) and small consumption (150 mW) device, which measure solar radiation in 4 channels and space ionizing radiation in 256 channels. Measurements have 10 s. time resolution. The spectrometers were mutually developed with University of Erlangen, Germany



Block schema of the R3DE/R/R2 devices

Examples of the selected 10 days latitudinal distribution profiles of the dose rates measured with the R3DR2 instrument against McIlwain's L values for the period 10-20 and 21-30 June 2015



- These 10 days plots were used for the selection of the all 441 days data;

- The selection curve is the black line in the middle of the plots;

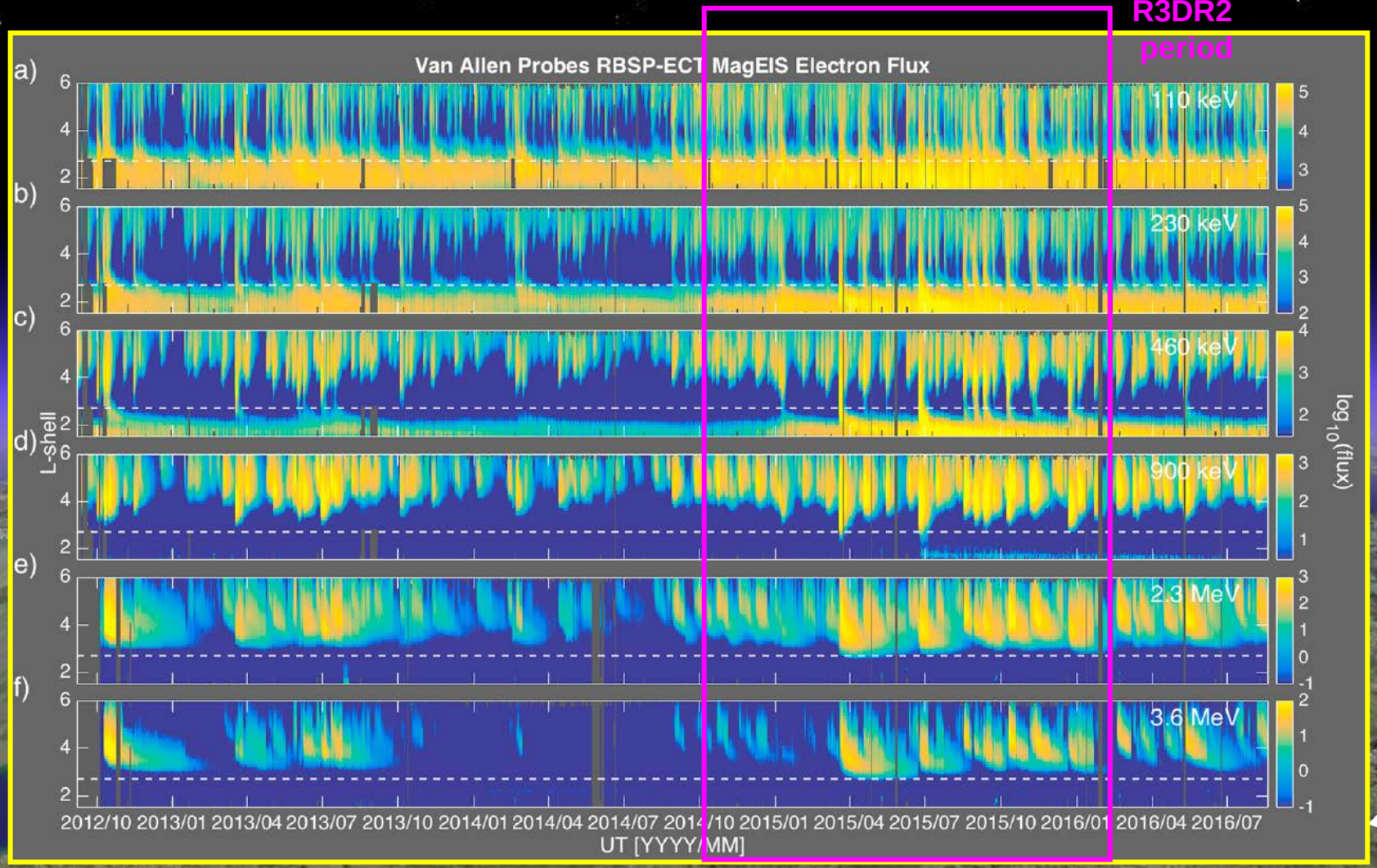
- Galactic cosmic rays (GCR) are situated by red points in the lower part of each figure;

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

- The maximum in the upper left corner of the 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 right side visualize the distribution of the SEP high energy protons.

Electron differential fluxes from the MagEIS instruments on the Van Allen Probes spacecraft. Data are shown in color binned in time and L shell September 2012 through February 2016*



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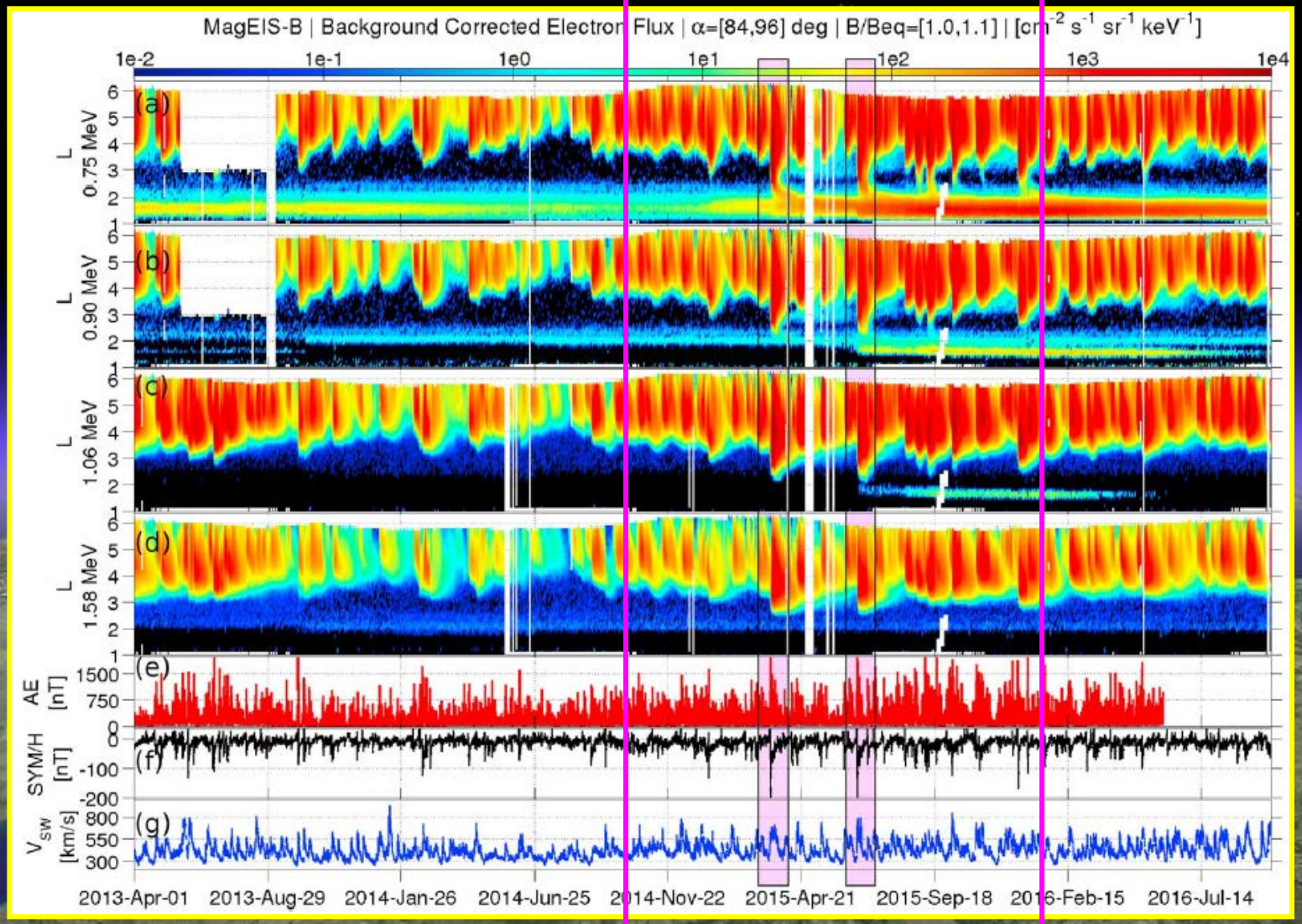
MagEIS-B daily-averaged electron fluxes plotted in L-versus-time format*

R3DR2 period



*Claudepierre, S. G., et al. (2017), The hidden dynamics of relativistic electrons (0.7-1.5 MeV) in the inner zone and slot region, J. Geophys. Res. Space Physics, 122, 3127–3144,doi:10.1002/2016JA023719.

Comparison of daily-averaged electron fluxes plotted in L-versus-time format from R3DR2 instrument with 1.58 and 2.3 MeV MagEIS-B instrument data