Long-term Evolution of the Earth Radiation Belts during Solar Cycles 23 – 25

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Outline

- Motivation: mid-latitude aurora above Russia

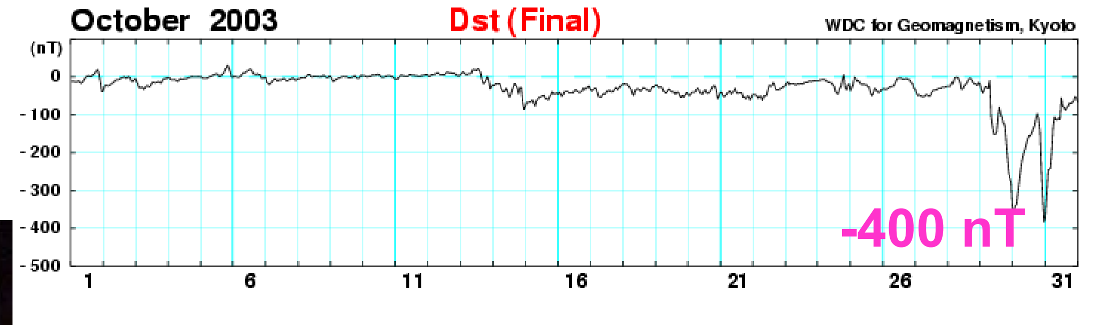
- Statistical analysis of ERB fluxes

- Quiet day technique for the outer ERB

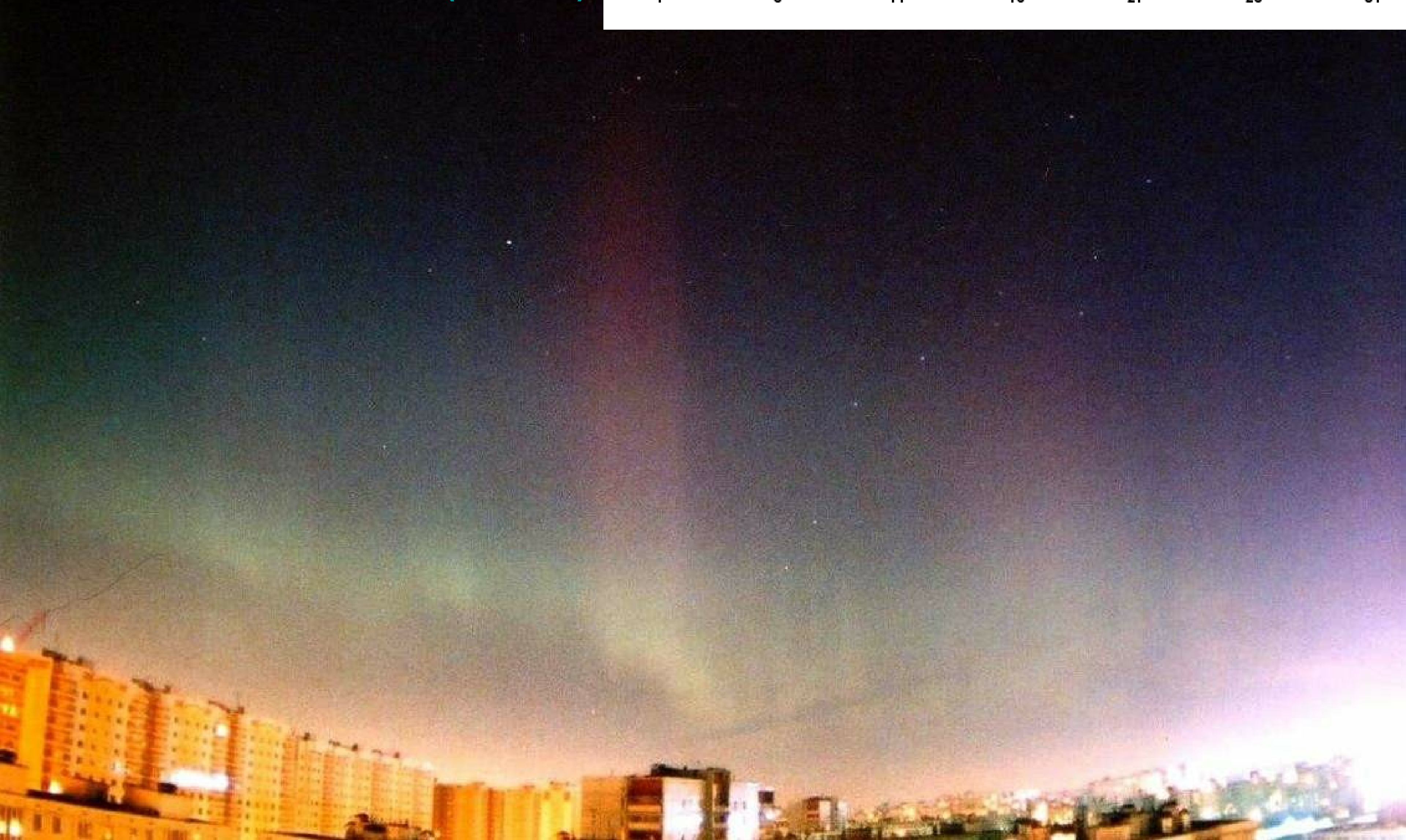
Dmitriev, A. V. (2019), On the radiation belt location during the 23rd and 24th solar cycles, *Ann. Geophys.*, 37, 719-732, DOI: https://doi.org/10.5194/angeo-37-719-2019.
Dmitriev A.V. (2021), Study on the Outer Radiation Belt Location in the 23-24 Solar Cycles, Challenging Issues on Environment and Earth Science, 6, 1-20. DOI: https://doi.org/10.9734/bpi/ciees/v6/10702D
Dmitriev, A.V., A.V. Suvorova, S. Ghosh, G.V. Golubkov, M.G. Golubkov (2022), Spatial Evolution of Energetic Electrons Affecting the Upper Atmosphere during the Last Two Solar Cycles, *Atmosphere*, 13, 322. https://doi.org/10.3390/atmos13020322

Motivation

Mid-latitude aurora

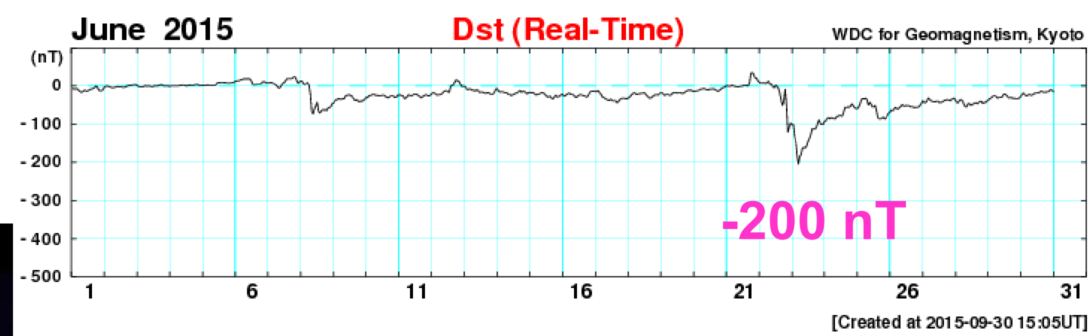


29 October 2003 Moscow (mlat 52)



Discrete aurora at

Middle latitudes



22 June 2015 Omsk (mlat 51)

http://geektimes.ru/post/252426/

Mid-latitude aurora above Russia in the 24-25 solar cycles

Date	minDst nT	Location	Geomagnetic	Reference
2015 March 17-18	-220	Moscow	51°16N 122°06E	Ref1
2015 June 22-23	-200	Moscow	51°16N 122°06E	Ref2
2015 August 16-17	-84	St. Petersburg	56°23N 117°36E	Ref3
2015 October 7-8	-120	St. Petersburg	56°23N 117°36E	Ref4
2016 February 17-18	-50	St. Petersburg	56°24N 117°37E	Ref5
2016 April 3-4	-50	St. Petersburg	56°24N 117°37E	Ref6
2016 August 24-25	-80	St. Petersburg	56°24N 117°37E	Ref7
2017 September 7-8	-124	Novosibirsk	45°56N 160°07E	Ref8
2017 November 7-8	-74	St. Petersburg	56°25N 117°38E	Ref9
2022 August 7-8	-59	Cheboksary	49°55N 129°48E	Ref10
2022 December 4-5	-44	Cheboksary	49°55N 129°48E	Ref11
2023 February 15-16	-72	Olkhon, Baikal	43°42N 179°58E	Ref12
2023 February 26-27	-132	Moscow	51°16N 122°06E	Ref13
2023 March 24-25	-200	Irkutsk	43°42N 179°58E	Ref14
2023 April 01-02	-30	Norilsk	51°16N 122°06E	Ref15
2023 April 23-24	-200	Europe Irkutsk	43°42N 179°58E	Ref16
2023 Sep 12	-79	Chelyabinsk	48°N 141°E	Ref17
2023 Sep 14-15	-31	St. Petersburg	56°58N 117°07E	Ref18
2023 Sep 18-19	-72	Moscow	51°16N 122°06E	Ref19
2023 Sep 25	-66	St. Petersburg	56°18N 38°E	Ref20
2023 Oct 20-21	-88	Sergiev Posad	51°7N 121°E	Ref21
2023 Nov 5-6	-122	St. Petersburg	56°18N 38°E	Ref22
2023 Nov 21-22	-59	St. Petersburg	56°18N 38°E	Ref23
2023 Nov 25	-90	Cheboksary	49°55N 129°48E	Ref24
2023 Dec 1	-108	Irkutsk	43°42N 179°58E	Ref25
2023 Dec 17	-77	St. Petersburg	56°18N 38°E	Ref26
2024 Jan 1	-27	St. Petersburg	56°18N 38°E	Ref27
2024 Mar 3-4	-112	Uliyanovsk	48°73N 148°35E	Ref28
2024 Mar 24-25	-128	Komi	56°82N 140°9E	Ref31
2024 Apr 19-20	-117	Novosibirsk	46°N 159°E	Ref32
2024 Apr 26-27	-51	Irkutsk	43°42N 179°6E	Ref33
2024 May 2-3	-96	Tver	53°N 120°7E	Ref34
2024 May 10-12	-412	SUPERSTORM		Ref35
2024 Aug 4	-116	Ekaterinburg	49.9°N 141.5°E	Ref38
2024 Aug 11	-203	Chelyabinsk	48°N 141°E	Ref39
2024 Aug 17-18	-36	St. Petersburg	56°18N 38°E	Ref40
2024 Aug 30-31	-88	St. Petersburg	56°18N 38°E	Ref41

Ref1 - www.dp.ru/a/2015/03/18/Severnoe_sijanie_uvideli_zh/
Ref2 - www.dp.ru/a/2015/06/23/Severnoe_sijanie_uvideli_v/
Ref3 - http://47news.ru/articles/92419/
Ref4 - www.dp.ru/a/2015/10/08/Severnoe_sijanie_v_Peterbu/
Ref5 - www.fontanka.ru/2016/02/17/058/
Ref6 - www.dp.ru/a/2016/04/03/ZHiteli_Peterburga_deljatsja/
Ref7 - www.fontanka.ru/2016/08/24/035/ & www.tonnews.ru/news_id_92986.html
Ref8 - http://www.ntv.ru/video/1515160/
Ref9 - https://www.fontanka.ru/2017/11/07/134/
Ref10 - https://chatrk.ru/novosti/ekologiya-i-priroda/cheboksarec-zasnyal-v-kozlovke-unikalnoe-dlya-nashih-shirot-severnoe-siyanie/
https://youtu.be/cnV9msewrO
Ref11 - https://pg21.ru/news/83510, https://vk.com/video-23951627_456256604
Ref12 - https://ircity.ru/text/science/2023/03/10/72121520/?utm_source=newsletter&utm_medium=email&utm_campaign=pochta_daily&utm_content=2023-03-10&from=pelkines_41%40mail.ru&utm_term=title_6
Ref13 - https://www.mk.ru/science/2023/02/28/polyarnoe-siyanie-dotyanulos-do-moskvy-uchenye-obyasnili-prichinu-yavleniya.html
Moscow https://t.me/weather_from_chief/6040
Tver https://tvtver.ru/lenta/27-fevralya-zhiteli-tverskoi-oblasti-uvideli-polyarnoe-siyanie/
Kaliningrad https://rugrad.ru/news/129681/
Germany https://www.dw.com/ru/unikalnyj-fenomen-severnoe-sijanie-nad-germaniej/a-64828986
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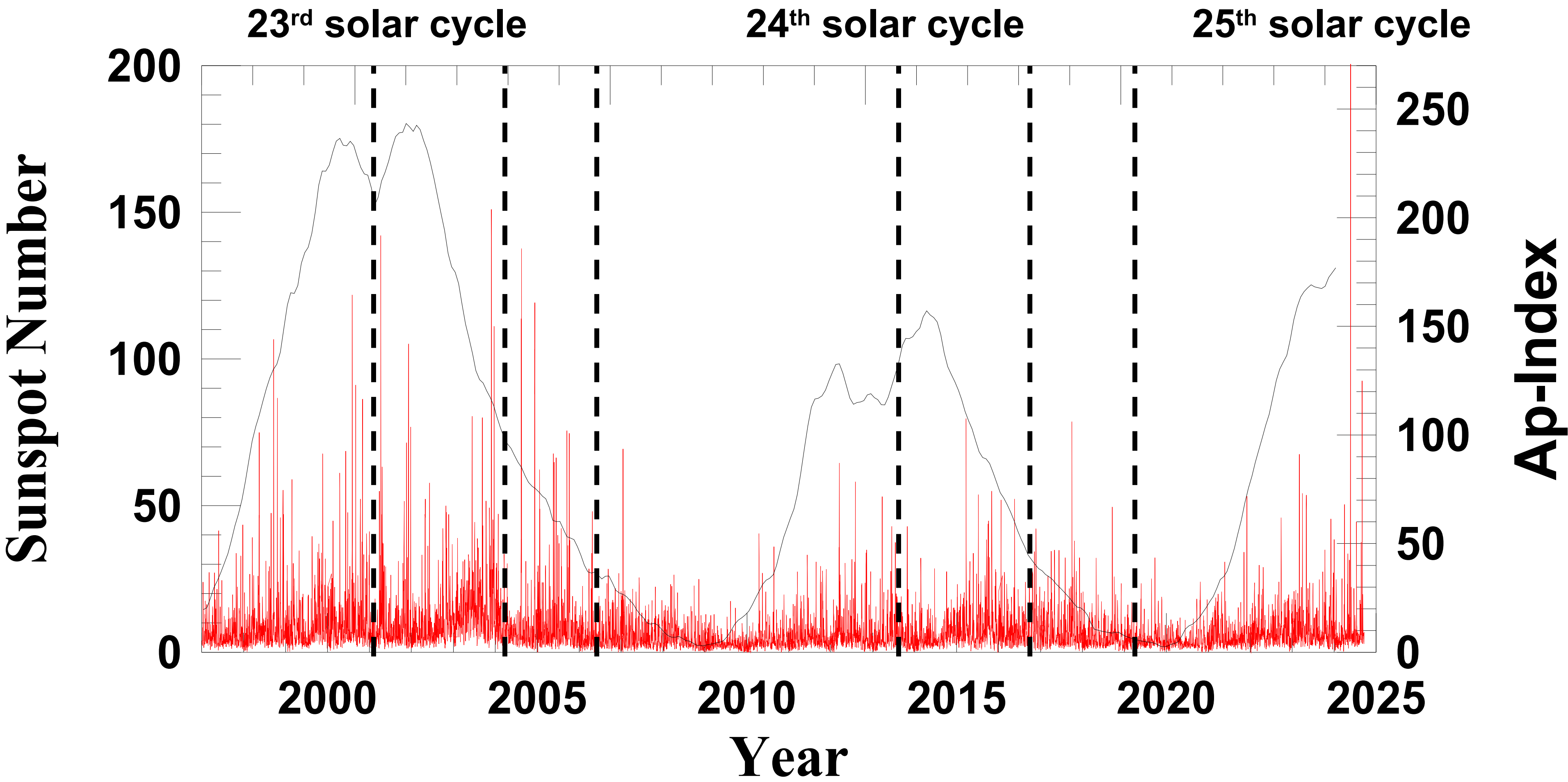
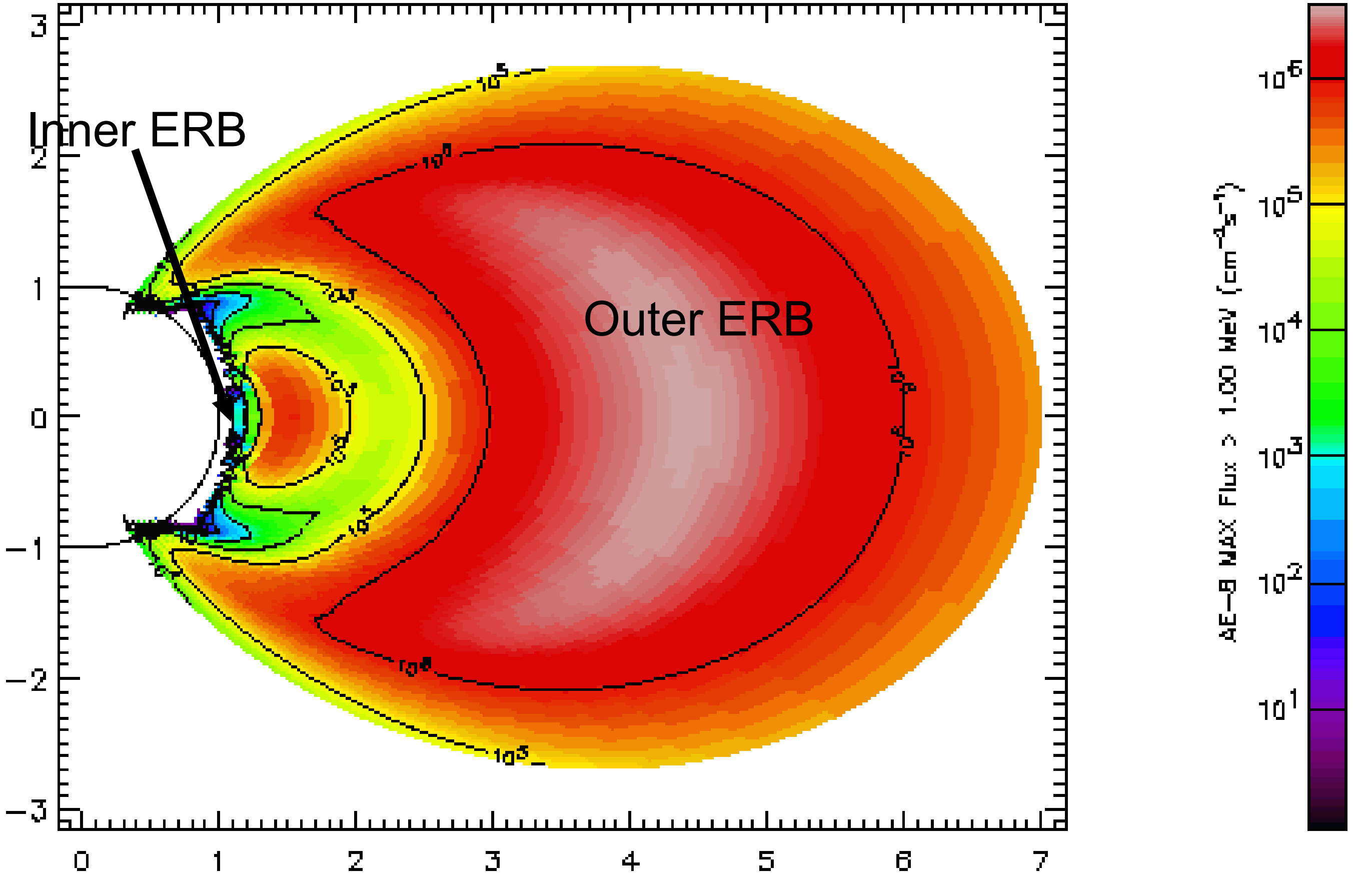
https://ircity.ru/text/society/2023/03/24/72159149/?utm_source=newsletter&utm_medium=email&utm_campaign=pochta_daily&utm_content=2023-03-24&from=pelkines_41%40mail.ru&utm_term=title_2
Ref15 - https://ngs24.ru/text/gorod/2023/04/04/72189218/
Ref16 -
https://i38.ru/nauka-obichnie/v-noch-s-23-na-24-aprelya-zhiteli-irkutskoy-oblasti-mogli-nablyudat-polyarnoe-siyanie
Ref17 - https://ozersk.bezformata.com/listnews/podelilis-snimkami-severnogo-siyaniya/121447972/
Ref18 - https://sanktpeterburg.bezformata.com/listnews/seriya-polyarnogo-siyaniya-razgorelos/121500459/
Ref19 - https://msk1.ru/text/gorod/2023/09/19/72720401/
Ref20 - https://www.dp.ru/a/2023/09/26/inogorodnim-zeteljam-stalo
Ref21 -
https://spb.mk.ru/social/2023/10/21/nad-peterburgom-v-noch-na-21-oktyabrya-nablyudali-prodolzhitelnoe-severnoe-siyanie.html
Ref22 - https://vk.com/wall17073439_18616
Ref23 -
https://peterburg2.ru/news/na-finskim-zalivom-nochyu-22-noyabrya-peterburzhcy-nablyudali-severnoe-siyanie-145030.html
Ref24 - https://pg21.ru/news/91563
Ref25 - https://www.irk.ru/news/20231202/shine/
Ref26 - https://vk.com/wall17073439_18748
Ref27 - @astrophotoboloto
Ref28 -
https://ulpressa.ru/2024/03/04/nad-ulyanovskoi-oblastyu-vnov-zametili-polyarnoe-siyanie-iz-za-silnoi-magnitnoi-buri/
Ref31 - https://vk.com/auroralights_ru?w=wall-165240816_3834
Ref32 - https://ngs.ru/text/entertainment/2024/04/20/73486256/
Ref33 - https://www.irk.ru/news/20240427/polarlights/
Ref34 -
https://moskvichmag.ru/gorod/v-moskve-i-oblasti-segodnya-mozhno-bylo-uvidet-severnoe-siyanie-iz-za-silnoi-magnitnoi-buri/
Ref35 –
Ref36 –
Ref37 –
Ref38 – https://ura.news/news/1052801155
Ref39 – https://m.ura.news/news/1052804771
Ref40 - https://vk.com/acat?z=photo17073439_457250046%2Fphoto_feed17073439
Ref41 - https://vk.com/acat?z=photo17073439_457250131%2Fphoto_feed17073439



Solar activity represented in sunspot number (left axis) and geomagnetic activity represented by daily Ap index (right axis) during the 23 - 25 solar cycles.

Electron Radiation Belt (ERB) of energetic electrons (above tens of keV) is governed by geomagnetic field.

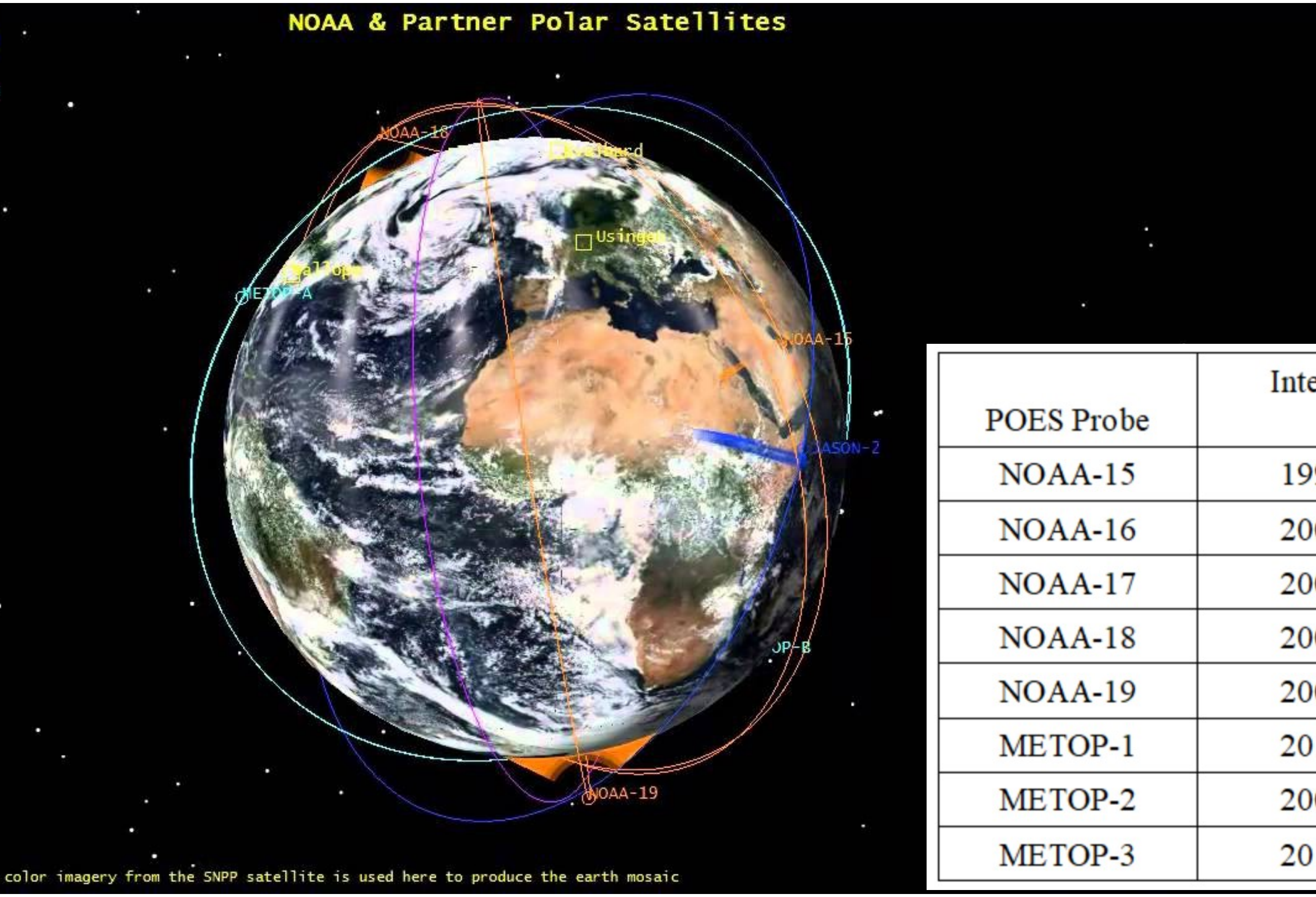
ERB topology traces the geomagnetic field.



ERB consists of the inner and outer zones.

- Electrons from the outer ERB precipitate into the atmosphere at high and middle latitudes due to pitch-angular scattering into the loss cone.
- Electrons from the inner ERB penetrate into the atmosphere in the region of South Atlantic Anomaly (SAA) during eastward azimuthal drift and due to anomalous ExB radial transport

At LEO orbit, electrons from ERB are monitored for several decades by NOAA/Polar-orbiting Operational Environmental Satellites (POES). They have Sun-synchronous orbits at altitudes of ~800-850 km in different local time sectors.

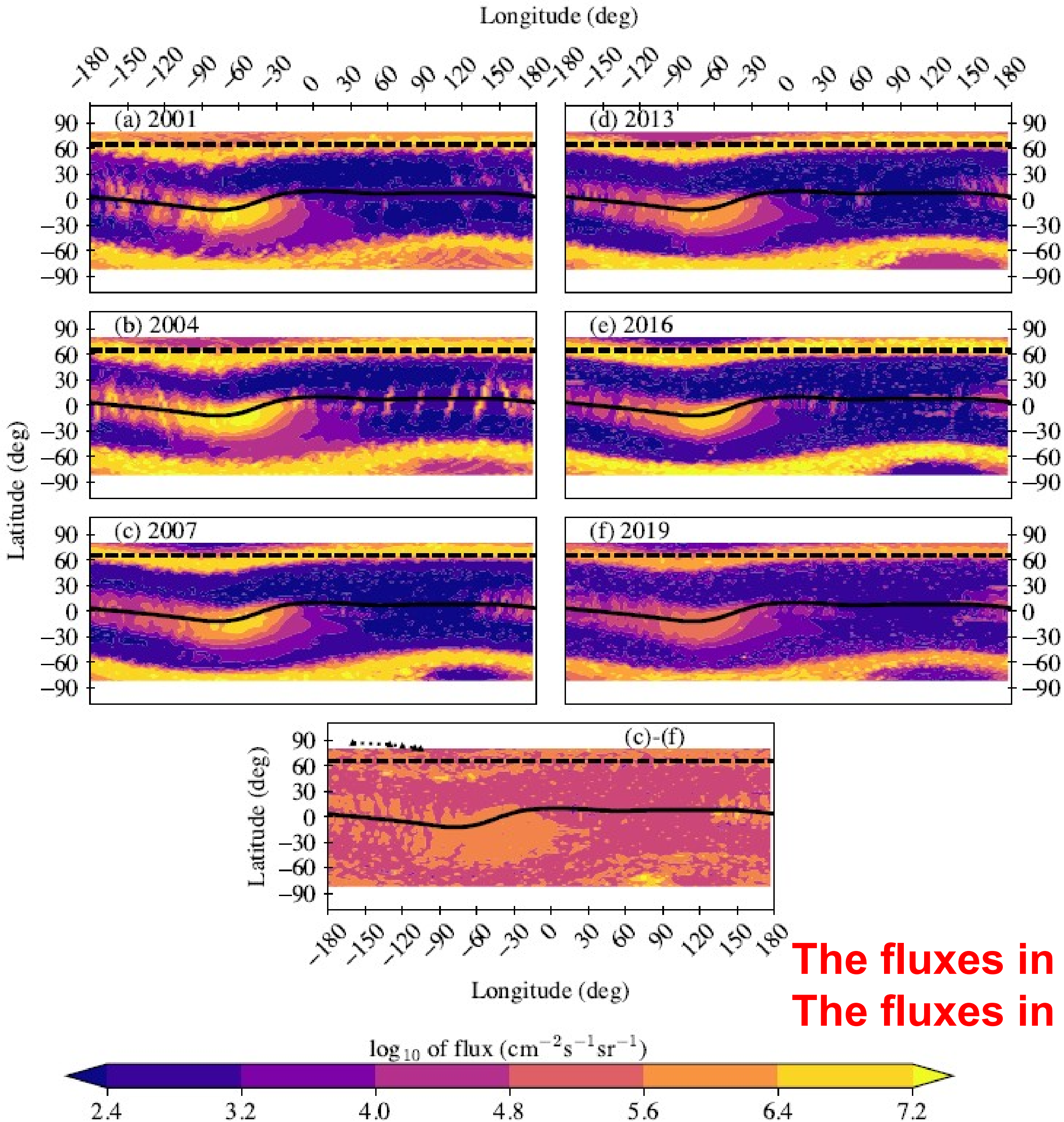


POES Probe	Interval, years	Local time at equator
NOAA-15	1998 – 2024	6 – 18
NOAA-16	2001 – 2014	6 – 18
NOAA-17	2002 – 2013	9 – 21
NOAA-18	2005 – 2024	2 – 14
NOAA-19	2009 – 2024	2 – 14
METOP-1	2014 – 2024	9 – 21
METOP-2	2006 – 2022	9 – 21
METOP-3	2018 – 2024	9 – 21

Medium Energy Proton and Electron Detector (MEPED) instruments on board POES satellites allow measuring electrons with energies >30, >100, and >300 keV in vertical and horizontal directions. That makes it possible to observe:

- electrons precipitating vertically to the atmosphere from the outer ERB
- trapped and quasi-trapped electrons in the SAA region and in a forbidden zone

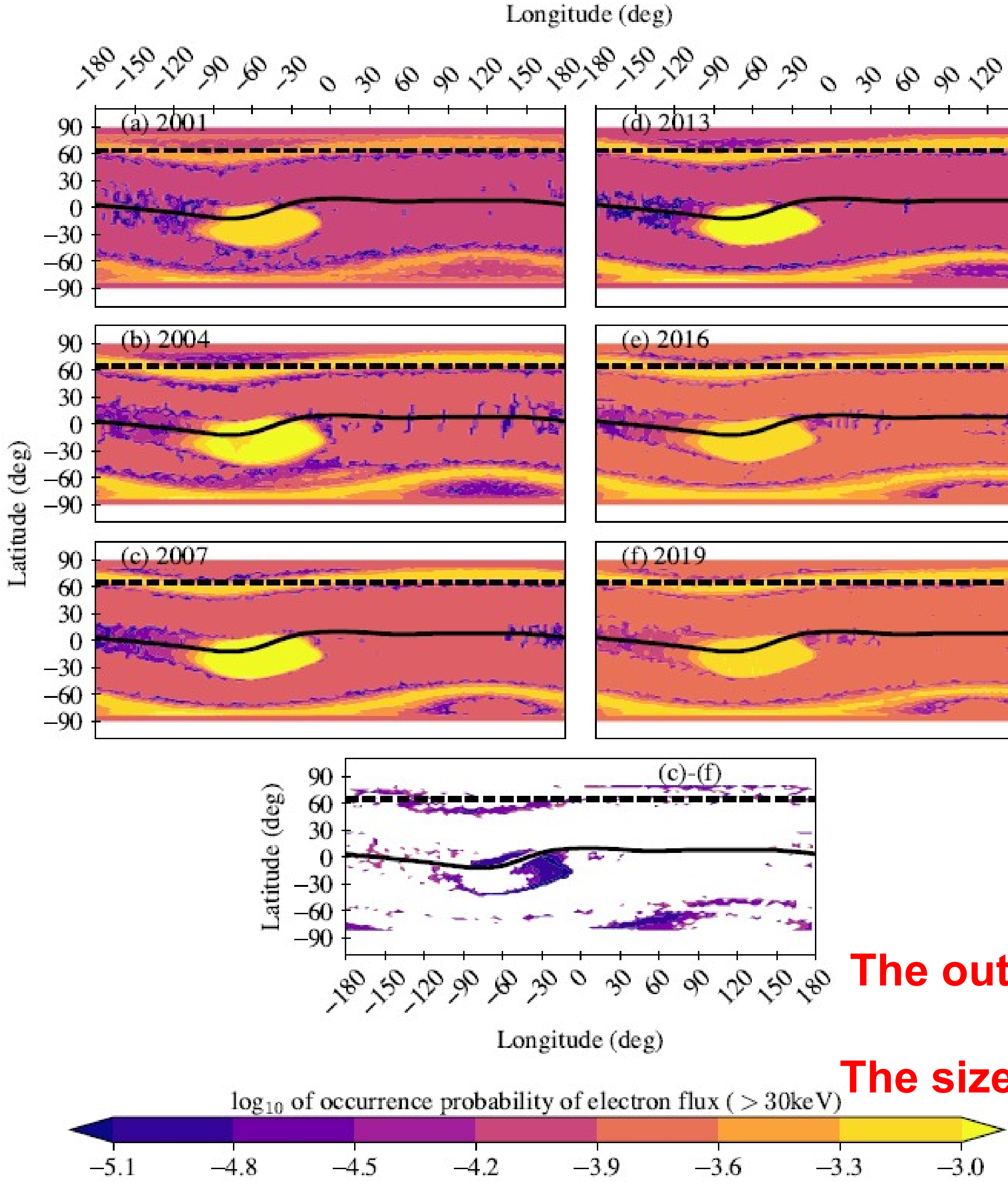
Dynamic of electron fluxes in ERB



Geographic maps of >30 keV electron fluxes measured by NOAA/POES satellites during different levels of the solar activity in the 23rd solar cycle (left column) and in the 24th solar cycle (right column): upper panels - solar maximum (the years of 2001 and 2013, respectively); middle panels - declining phase (the years of 2004 and 2016, respectively); and near the solar minimum (the years of 2007 and 2019, respectively). Geomagnetic equator is shown by the black curve. The horizontal dashed lines depict the latitude of 65°. The bottom panel represents the difference in the electron flux maps between 2019 and 2007. The trace of the northern magnetic dip-pole from 1995 to 2015 is indicated with a black dotted line with triangular nodes at every five years (from right to left) in the bottom panel.

The fluxes in the outer ERB are increasing
The fluxes in the inner ERB are decreasing

Dynamic of the spatial scales of ERB

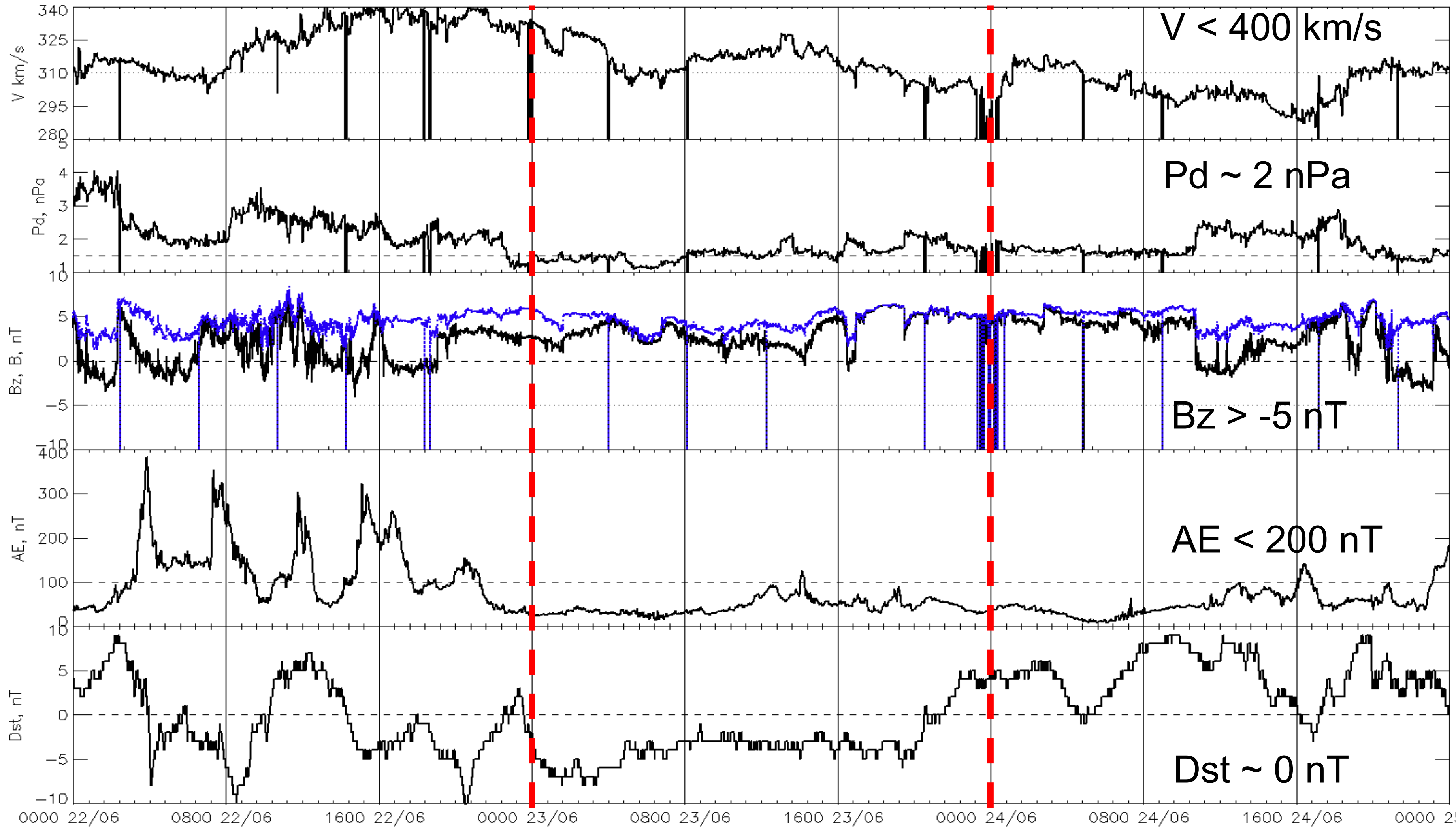


Geographic maps of normalized occurrence probability to detect >30 keV electron fluxes with intensity > 1E4 $(cm^2 s sr)^{-1}$ within one year during different levels of solar activity in the 23rd solar cycle (left column) and in the 24th solar cycle (right column): upper panels—solar maximum (the years of 2001 and 2013, respectively); middle panels—declining phase (the years of 2004 and 2016, respectively); and near the solar minimum (the years of 2007 and 2019, respectively). Geomagnetic equator is shown by the black curve. The bottom panel represents the difference between 2019 and 2007.

The outer ERB moves equatorward over Siberia

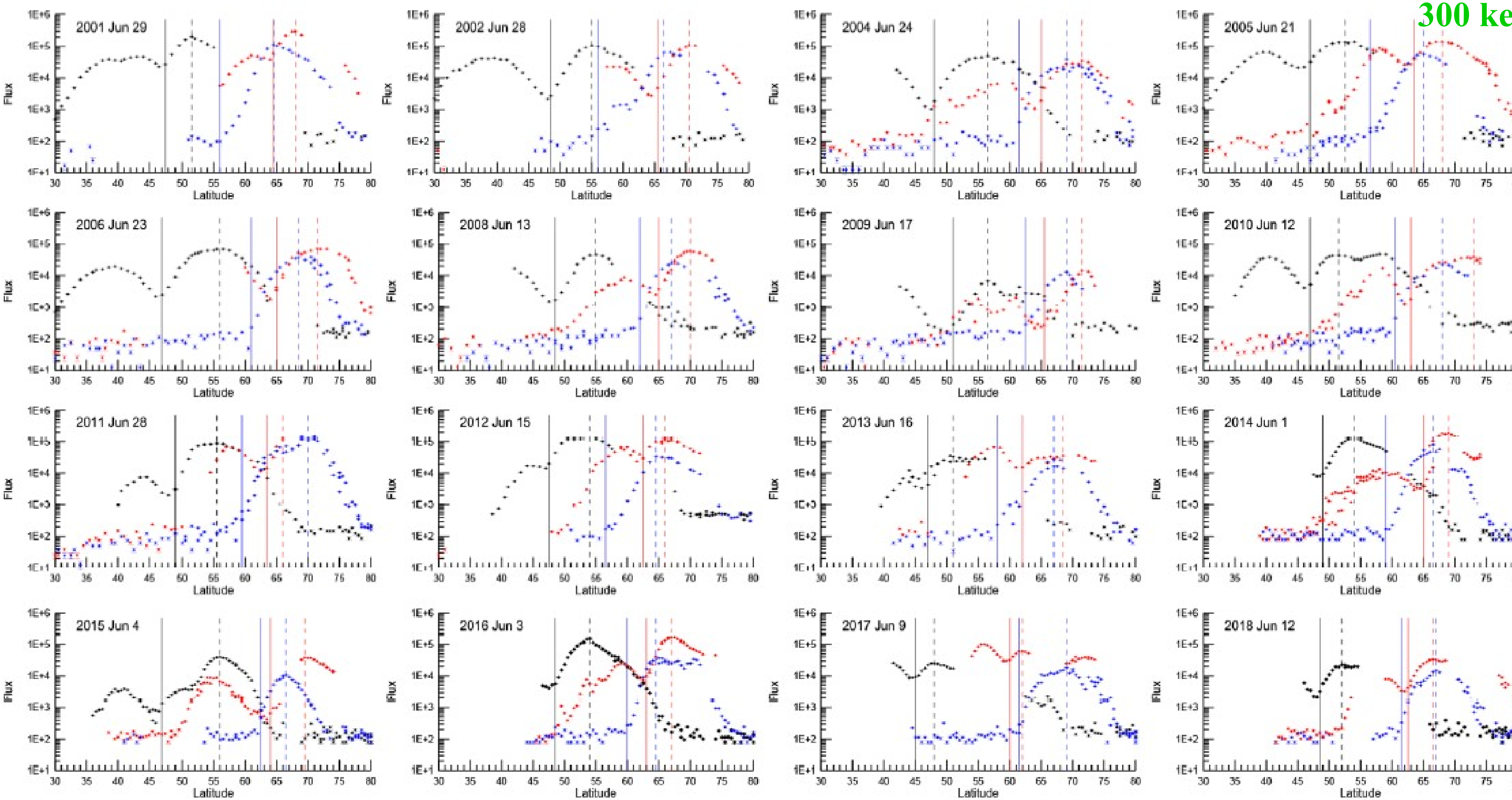
The size of the inner ERB has decreased dramatically!

Determination of a quiet day



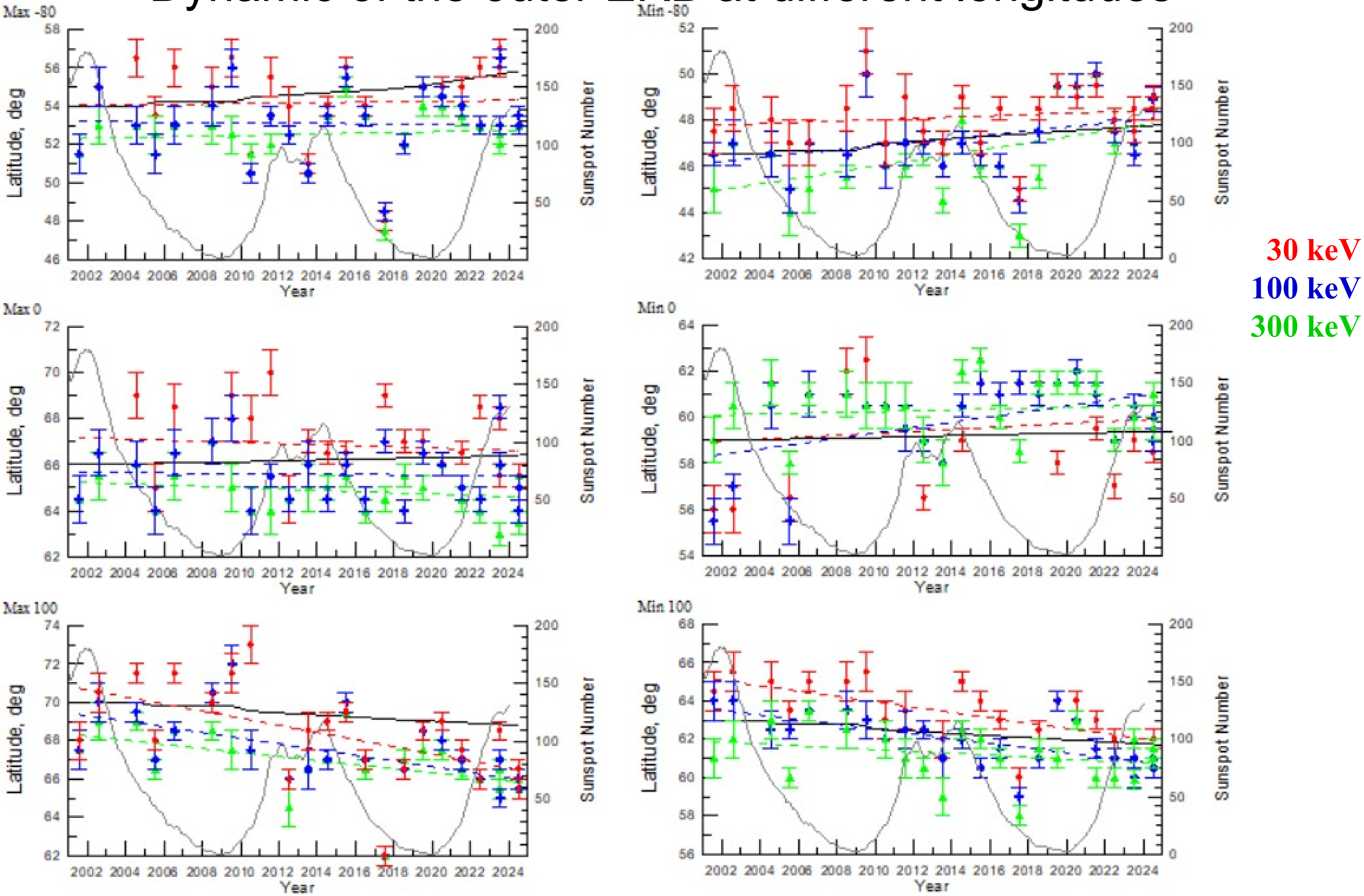
Dynamic of the outer ERB at different longitudes

30 keV
100 keV
300 keV



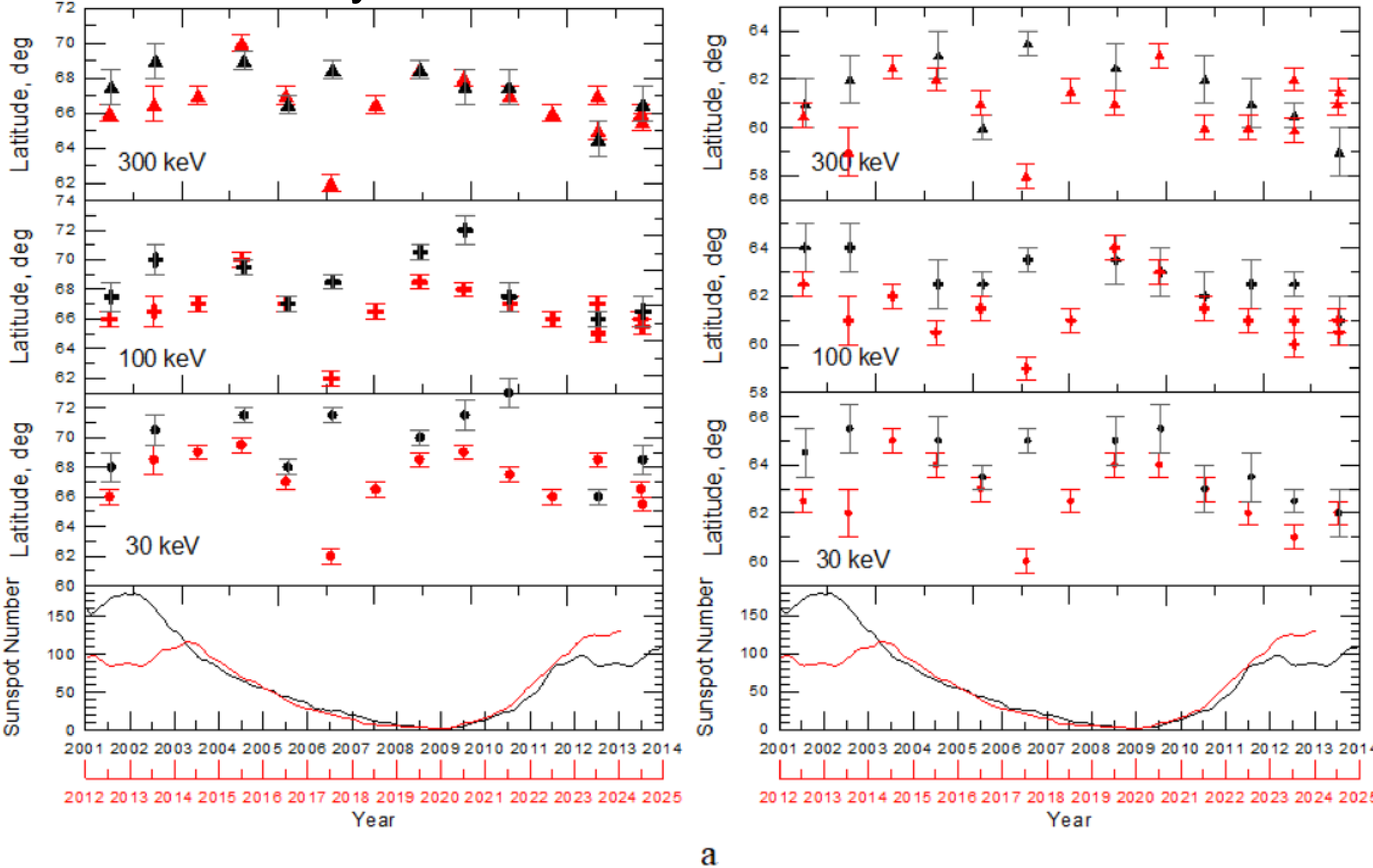
Latitudinal profiles of >30 keV electron fluxes with pitch angles of 90° observed by POES satellites during quiet days in different years in the 2-hour vicinity of local noon at longitudes around 100E (red circles), 0E (blue crosses) and 80W (black diamonds). Vertical dashed and solid lines indicate latitudes of the maximum and inner edge of the outer radiation belt, respectively.

Dynamic of the outer ERB at different longitudes



Geographic latitude of the maximum (left) and inner edge (right) of the outer ERB projection at height of ~850 km and around 100°E during magnetic quiet days. Dashed curves show a latitudinal shift predicted by IGRF model of corresponding epochs.

Dynamic of the outer ERB at 100°E



Geographic latitude of the maximum (a) and inner edge (b) of the outer ERB measured during geomagnetic quiet days at longitude of 100 E for electrons with energies of > 30 keV. Bottom panels show the sunspot number in the 23rd-24th solar cycles (2001–20014, black curves) and in the 24th- 25th solar cycle (2012–2024, red curves). The outer ERB location is shown using black and red symbols, respectively. It can be seen that the outer ERB is systematically located at lower latitudes during the the 24th & 25th solar cycles compared with its location during the 23rd solar cycle.

Conclusions:

- The intensity of energetic electron fluxes in the SAA and forbidden regions, as well as their area, significantly decreased in the 24th solar cycle compared to the 23rd cycle. This was caused mainly by prominent changes in the geomagnetic field at low latitudes such that the magnetic field strength increased in the SAA region, which resulted in elevation of the inner ERB.

- The area of electron precipitation from the outer ERB shifted over eastern longitudes (Siberia) toward the equator. This is in good agreement with the latest data on the dynamics of the geomagnetic North Pole.

- The changes in projections of the ERB at low latitudes are related with changes of the magnetic field of the Earth and thus the ERB technique can be used for tracing the long-term variation of the geomagnetic field.

Variation of the secular acceleration power of the geomagnetic field

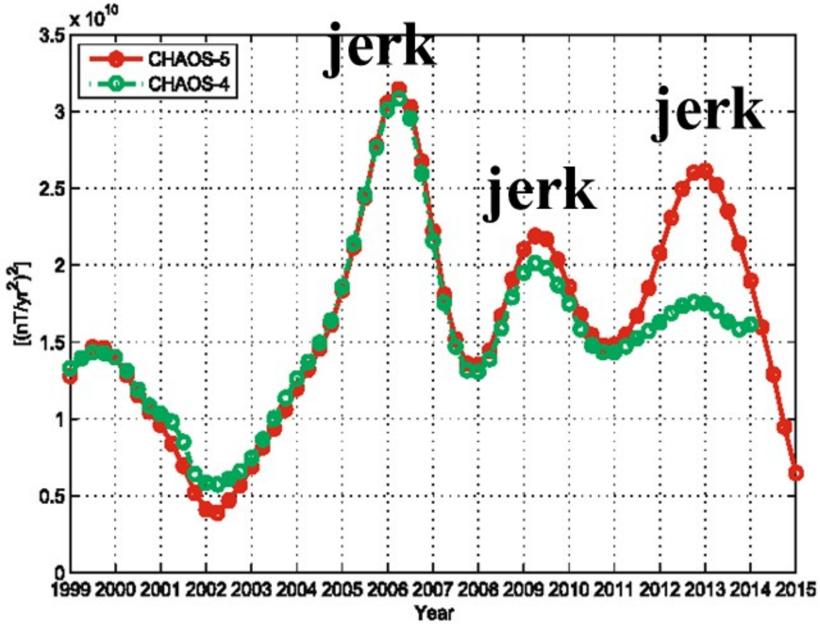


Fig. 10 Time evolution of the mean square secular acceleration power S_A (see Eq. 5 evaluated at the core surface, up to spherical harmonic degree 8) from CHAOS-4 (*green*) and CHAOS-5 (*red*)

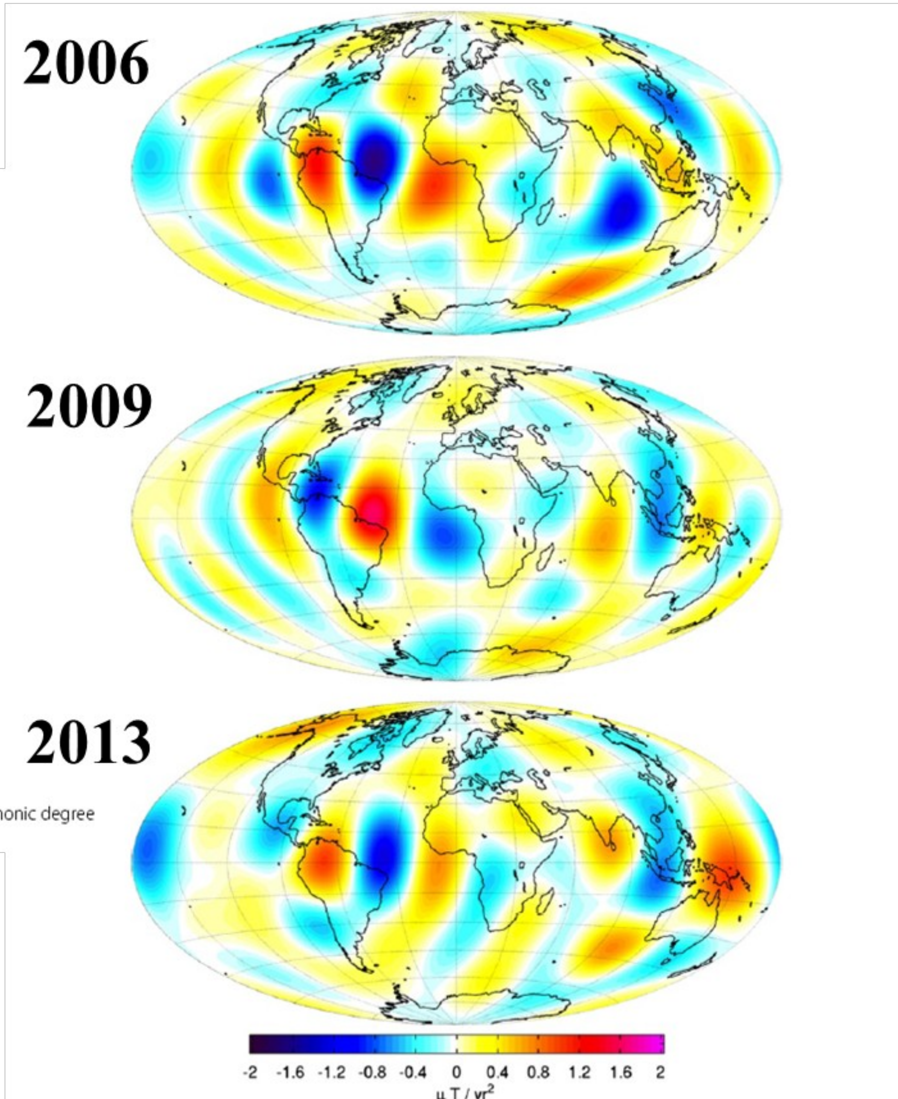


Fig. 11 Secular acceleration (SA) at the core surface (degrees 1 to 8 only) in 2006.2 (*top*), 2009.2 (*middle*) and 2012.9 (*bottom*). Maps are in Hammer-Aitoff projection, units are microtesla per year^2 ($\mu T/year^2$)

Finlay, et al. (2015), DTU candidate field models for IGRF-12 and the CHAOS-5 geomagnetic field model, Earth, Planets and Space, 67:114, 1-17, DOI 10.1186/s40623-015-0274-3