Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2018-6
Manuscript under review for journal Ann. Geophys.
Discussion started: 19 January 2018

Annales Geophysicae
Discussions
Open Access

A relation between the locations of the polar boundary of outer electron radiation belt and the equatorial boundary of the auroral oval

Maria O. Riazanteseva[1], Elizaveta E. Antonova[2,1], Marina V. Stepanova[3], Boris V. Marjin[2], Ilia A. Rubinshtein[2], Vera O. Barinova[2] , Nikita V. Sotnikov[2]

[1]Space Research Institute (IKI) Russian Academy of Science, Moscow, Russia
[2]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[3]Physics Department, Universidad de Santiago de Chile (USACH)

Correspondence to: Maria O. Riazantseva (orearm@gmail.com), Marina V. Stepanova (marina.stepanova@usach.cl)

Abstract. Finding the position of the external boundary of the outer electron radiation belt, relative to the position of the auroral oval, is a long-standing problem. Here we analyze it using data of the METEOR-M №1 auroral satellite for the period from 11 November 2009 to 27 March 2010. The geomagnetic conditions during the analyzed period were comparatively quiet. METEOR-M №1 has a polar solar-synchronous circular orbit with an altitude of ~832 km, a period of 101.3 min, and an inclination of 98°. We analyze flux observations of auroral electrons with energies between 0.03 and 16 keV, and electrons with energies >100 keV, measured simultaneously by the GGAK-M set of instruments, composed by semiconductors, scintillator detectors, and electrostatic analyzers. We assume that at the absence of geomagnetic storms the external boundary of the outer radiation belt can be identified as a decrease in the count rate of precipitating energetic electrons to the background level. It was found that this boundary can be located both inside the auroral oval or to the equator from the equatorial boundary of the auroral precipitations. It was also found that for disturbed geomagnetic conditions the external boundary of the outer radiation belt is almost always located inside the auroral oval. We observe that the difference between the position of the outer boundary of the outer radiation belt and the position of the equatorial boundary of auroral precipitations depends on the AE and PC indexes of geomagnetic activity. The implications of these results in the analysis of the formation of the outer radiation belt is discussed.

1 Introduction

The position of the trapping boundary energetic electrons in the outer radiation belt contains information about the topology of the magnetic field lines of the Earth. For a long time this has been analyzed sing the data from both low orbiting and high apogee satellites (Frank et al., 1964; Frank, 1971; Fritz, 1968, 1970, McDiarmid and Burrows, 1968; Vernov et al., 1969; Imhof et al., 1990, 1991, 1992, 1993; Kanekal et al., 1998 etc.). Using the data of high apogee satellites, Vernov et al. (1969) showed that the boundary of the outer radiation belt is located near to ~9R_E in the dayside sector and near to ~7-8 R_E close to midnight. These results were further supported by Imhof et al. (1993) using data from the CRRES and SCATHA satellites, and covering distances from ~6 to ~8.3 R_E (CRRES) and from ~7 to ~8.5 R_E (SCATHA). Results obtained by Fritz (1968, 1970), Imhof et al. (1997), and Yahnin et al. (1997) show that the isotropic boundary of energetic particles (i.e. the boundary where pitch-angle of particles becomes isotropic) is located to the equator from the trapping boundary. This allows us to determine the trapping boundary position using data from low orbiting satellites.

A good understanding of the relative location of the trapping boundary and the equatorial edge of the auroral oval is important for the analysis of the structure of magnetospheric plasma domains and the topology of the geomagnetic field. Comparison of the relative position of the trapping boundary and the auroral oval was statistically done using ground-based auroral observations and satellite observations of the trapping boundary. Akasofu (1968) compared the position of Feldstein's auroral oval with the trapping boundary of the 40 keV electrons obtained by Frank (1964) and statistically showed that the trapping boundary is located inside the auroral oval. However, later Feldstein and Starkov (1970) compared the position of the auroral oval with the results of Alouette-2 observations and concluded that the auroral oval is situated just on the polar border of the trapped radiation region of electrons with energy > 35 keV. Rezhenov et al. (1975) analyzed particle fluxes with energies 0.27, 11, 28 and 63 keV, from the COSMOS-424 satellite, and showed that the trapping boundary is located to the pole of the region of low energy electron precipitations. However, this study was done using the data obtained for only 21 orbits, and was not widely known. Feldstein and Vorobjev (2014) stressed (p. 120 in their paper), that poleward (high-latitude) boundary of the diffuse auroral belt without any discrete auroral forms “constitutes the equatorward boundary of the auroral oval and at the same time it is the high-latitude boundary of the radiation belt (RB) of electrons with energies from a few tens to hundreds of kiloelectronvolts (STB – stable trapping boundary for radiation belt electrons)”.

According to the traditional point of view (see, for example, Pashman et al. (2002)), the auroral oval is mapped to the plasma sheet. In this case the trapping boundary should be located to the equator or at the equatorial boundary of the auroral oval. However, Antonova et al. (2014, 2015), and Kirpichev et al. (2016) showed that most part of the auroral oval does not map to the plasma sheet. It is mapped to the plasma ring that surrounds the Earth at geocentric distances from ~ 7 R_E to the magnetopause, near noon, and to 10-13 R_E near midnight. They suggested that the plasma in the magnetosphere is in magnetostatic equilibrium, and used the value of plasma pressure as a natural tracer of magnetic field lines, comparing the pressure at low latitudes and at the equatorial plane. Results obtained by Antonova et al. (2014, 2015), and Kirpichev et al. (2016) showed that the auroral oval is mapped to the region of quasitrapping, where drift trajectories of energetic electrons with pitch-angles smaller than 90° surround the Earth (Delcourt and Sauvaud, 1999; Öztürk and Wolf, 2007; Ukhorskiy et al., 2011; Antonova et al., 2011a) due to drift shell splitting effect (Shabansky effect). Such mapping suggests that the trapping boundary should be located to the pole from the equatorial boundary of the auroral oval.

Therefore, it is very important to establish the true location of the trapping boundary with respect to the equatorial auroral oval boundary. This can be done using simultaneous observations of both auroral electron precipitations and fluxes of energetic electrons. It is well known, that the location of the auroral oval and the location of the trapping boundary are strongly affected by geomagnetic activity. Therefore, it is necessary to compare these relative locations using simultaneous measurements of the auroral oval and trapping boundary on the same satellite. However, there are some difficulties related to the sensitivity of the instruments used for the detection of the auroral electron precipitations and energetic electron fluxes. While the location of the auroral boundary is almost the same for different electrostatic analyzers, the location of the trapped boundary depends on the electron energy established as a threshold, and the detector sensitivity. Therefore, even when it was found that the trapping boundary was located to the equator of the equatorial boundary of the oval, it does not necessarily mean that this boundary is truly located outside the oval, it could just mean that the sensitivity of the detector of energetic particles is not enough to continue measuring the energetic particle precipitations inside the auroral oval. In contrast, when the trapping boundary is observed to the pole of the equatorial boundary of the oval, it really means that this boundary is located inside the oval.

Despite the significant amount of particle measurements carried out by low-orbiting satellites, the relative location of the trapping boundary and the equatorial boundary of the auroral oval, and how they could be affected by geomagnetic activity, have not been properly studied yet. In this work, we use data of the satellite METEOR-M №1 to establish the location of the trapping boundary and of the auroral oval for different levels of geomagnetic activity, which were quantified using the AE and PC geomagnetic indexes. The paper is organized as follows. First, we describe the METEOR-M №1 satellite instrumentation and the data analysis, including important caveats. Then we obtain the position of the trapping boundary of electrons with energies >100 keV relative to the equatorial boundary of the auroral oval, and how it varies for small and large values of the AE and PC indexes of geomagnetic activity. At the end, we shall discuss the role that our results might play on the determination of features of the high latitude magnetospheric topology.

2 Instrumentation and data analysis

We used the data from the METEOR-M №1 satellite launched 17 September 2009 into a polar solar-synchronous circular orbit with an altitude of ~830 km, a period of ~100 min, and an inclination of 98°. We used the data of GGAK-M set of instruments, composed by semiconductor and scintillator detectors, and electrostatic analyzers. In particular, it measured energetic electrons with the energies from 0.1 to 13 MeV, and low energy electrons with the energies from 0.032 to 16.64 keV (see more details and available data in http://smdc.sinp.msu.ru/index.py?nav=meteor_m1).

For automatic detection of the outer boundary of the ORB and the equatorial boundary of the auroral oval we compared the corresponding fluxes with a background reference flux, calculated for each orbit. For energetic particles we calculated the average flux in the polar cap and its standard deviation. We assumed that the measured flux can be classified as ORB electron flux if the difference between this flux and the background flux was greater than five standard deviations. After that we searched for the closest to the pole location of the ORB flux, obtained according to the described criteria, and took that point as a polar boundary of the ORB. These selection criteria might shift the obtained boundary toward the equator with respect to the true boundary. This means that we could underestimate the number of events for which the outer boundary of the ORB is observed inside the auroral oval.

The automatic detection of the outer boundary of ORB, also known as the trapping boundary, might be affected by the sharp local increases in the energetic electron fluxes sometimes observed at the trapping boundary (see (Imhof et al., 1990, 1991, 1992, 1993)) or just to the pole of it. Such fluxes are usually much smaller than the maximum fluxes of the ORB precipitating electrons. Nevertheless, they can be observed during a few hours at the same location in a few consecutive polar satellite orbits (Myagkova et al., 2011, Antonova et al., 2011b; Riazantseva et al., 2012), and alter the automatic detection of the boundary. It was one of the reasons to do the visual inspection of all events.

To calculate the position of the auroral oval boundary, we first calculated the average value and standard deviation of the electron fluxes measured at L<3 Re, where L is the McIlwain parameter. In the next step we considered the fluxes that exceed the background flux seven standard deviations. If the obtained boundary was located at L>3 Re, we repeated this procedure but calculating the average flux and its standard deviation up to the boundary, determined in the first step. Based on the Vorobjev et al., (2013) definition of the auroral oval, we also imposed additional criterion to the value of the total energy electron flux: it should be greater than 0.2 erg/cm^{2}s. The results obtained were also confirmed by the visual inspection.

We used the AE index, that represents the dynamics of the auroral electrojet, to identify the intervals of substorm activity. We also used the Polar Cap (PC) index (Troshichev and Andrezen, 1985; Troshichev and Janzhura, 2012), which was created as a proxy of dawn-dusk electric field in the polar cap and Region 1 currents of Iijima and Potemra (1976) intensity. We took for the analysis the one minute values of the AE and PC indices when the spacecraft was at the equatorward boundary of the auroral oval. Taking into account that there are two PC indexes, obtained for the Northern (PCN) and Southern (PCS) hemispheres, we used the corresponding PCN (PCS) indexes for Northern (Southern) crossings of the auroral oval.

Figure 1 shows an example of two crossings of the auroral oval in the morning and evening MLT sectors on 01 February 2010, when the trapping boundary was located inside the auroral oval. According to the (http://omniweb.gsfc.nasa.gov/), the solar wind number density (Nsw) and velocity (Vsw), and of three components of the interplanetary magnetic field (IMF) for both equatorial borders were very common: Bx≈2 nT, By≈-4 nT, Bz≈-1 nT, Nsw≈6 cm^{-3}, and Vsw≈450 km/s. This event took place in the absence of geomagnetic storms (Dst≈-7 nT), and during moderate auroral activity (150 nT<AE<300 nT, and AL>-300 nT). The values of PC index were also moderate (PCS<3) (see http://pcindex.org). As it can be seen, for this event the trapping boundary of energetic electrons, shown by green dashed lines, is located inside the auroral oval. The differences between the latitudes of the equatorial boundary of the oval and the trapping boundary (d(lat)) are equal to -5.8° for the dawn and -1.7° for the dusk boundaries.

Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2018-6
Manuscript under review for journal Ann. Geophys.
Discussion started: 19 January 2018

Annales Geophysicae
Discussions
Open Access

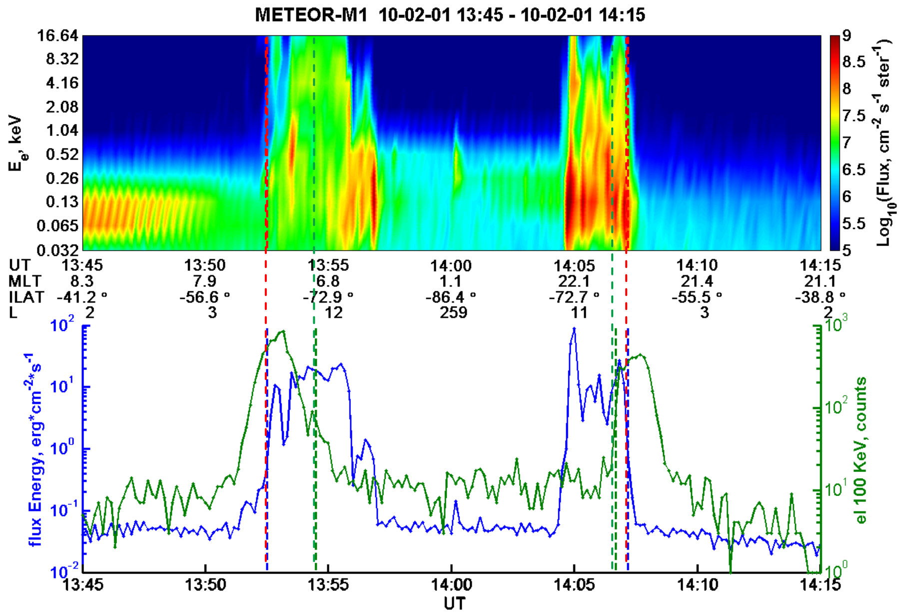

Figure 1: An example of the location of the polar boundary of outer radiation belt inside the auroral oval at AE>150 nT.

Figure 2 shows an event of the trapping boundary located outside the auroral oval observed on 17 January 2010. The satellite crossed twice the auroral oval during very quiet geomagnetic conditions (Bx≈2 nT, By≈-1 nT, Bz≈2.5 nT, Nsw≈6 cm^{-3}, Vsw≈350 km/s, Dst≈-2 nT, AE≈15 nT, AL≈-15 nT, PCN<1). The observed difference was comparatively small: d(lat)=1° for the dawn and 3.3° for the dusk boundaries.

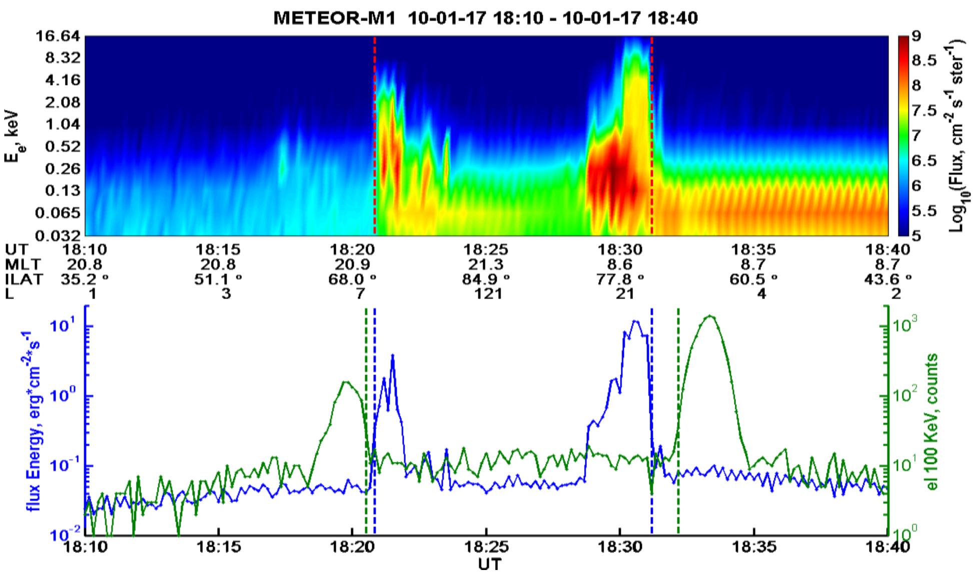

Figure 2: An example of observation of the polar boundary of outer radiation belt outside the auroral oval at AE<150 nT.

Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2018-6
Manuscript under review for journal Ann. Geophys.
Discussion started: 19 January 2018

Annales Geophysicae Discussions

Comparison of events shown in Fig. 1 and 2 could bring to a conclusion that the relative location of the trapping boundary and the equatorial boundary of the auroral oval might be affected by the shift of the oval to higher latitudes with the decrease of the geomagnetic activity. However, there are many other events observed for low activity for which the trapping boundary was observed inside the oval. One of examples of such kind of events is shown in Fig. 3.

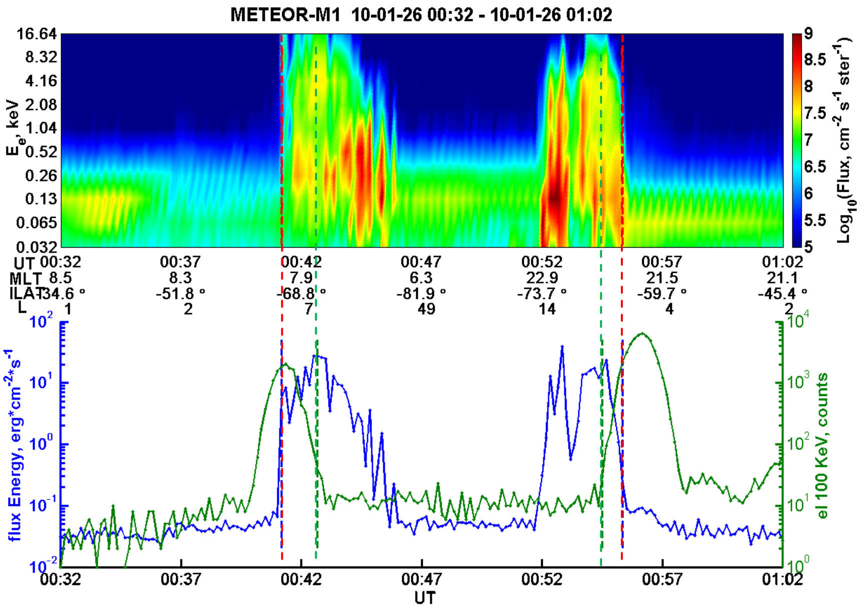

Figure 3: An example of observation of polar boundary of outer radiation belt inside the auroral oval at AE<150 nT

It took place on 26 January 2010 during quiet geomagnetic conditions (IMF Bx≈-2.2 nT, By≈-4.0 nT, Bz≈-1.5 nT, Nsw≈3.5 cm^{-3}, Vsw≈370 km/s, Dst≈-17 nT, AE≈50 nT AL≈-30 nT, and PCS<1). For this event, d(lat)=-5.1° for the dawn and -2.2° for the dusk sectors.

Existence of different types of events requires to make a statistical analysis to clarify how the geomagnetic conditions could affect the relative location of both boundaries.

3 Statistical analysis

We analyzed the data from METEOR-M №1, obtained for more than 6200 auroral oval crossings. For each crossing, we determined the difference between the geomagnetic latitudes of the equatorial boundary of the auroral oval and of the trapping boundary d(lat). The negative difference d(lat) <0 means that the trapping boundary is located inside the auroral oval while the positive difference d(lat) >0 indicates that the trapping boundary is located to the equator of the auroral oval. The METEOR-M №1 satellite has a sun-synchronous orbit. That is why we obtained d(lat) only for a limited range of MLTs.

Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2018-6
Manuscript under review for journal Ann. Geophys.
Discussion started: 19 January 2018

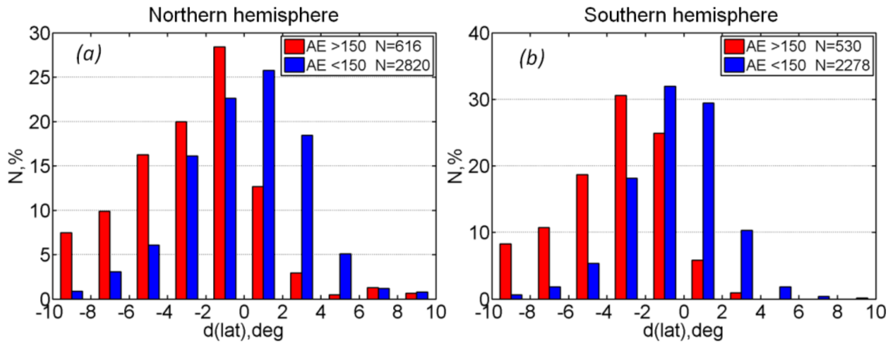

Figure 4: The distribution of d(lat) for AE>150 nT and <150 nT for northern (a) and southern (b) hemispheres.

To analyze how these differences could be affected by geomagnetic activity, we divided all data into two data sets according to the AE or PC indexes. Figure 4 shows the distribution of the latitude differences d(lat) for AE>150 nT and AE <150 nT for the Northern (a) and Southern (b) hemispheres. As it can be seen, the number of events for which the trapping boundary is observed inside the auroral oval increases significantly with the increase of geomagnetic activity, quantified through the AE index. For AE>150 nT the trapping boundary is located inside the auroral oval for the majority of events for both hemispheres, while for AE<150 the trend is not so clear. However, for both sets there are a comparatively large number of events, for which this difference is comparatively small.

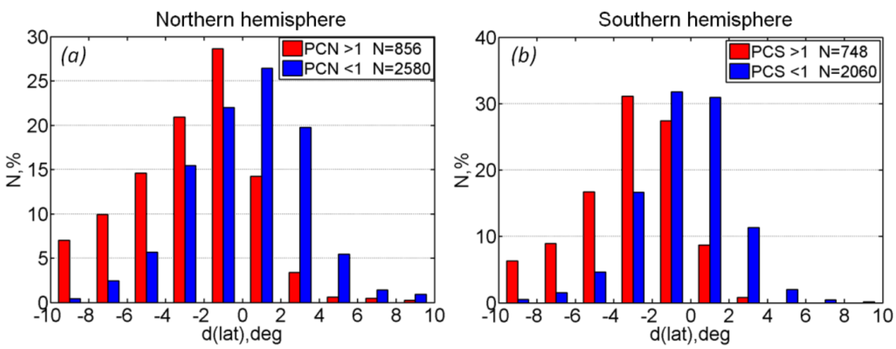

Figure 5: The distribution of d(lat) for PC>1 and <1 for northern (a) and southern (b) hemispheres.

Figure 5 shows the distribution of the latitude differences d(lat) for PC>1 and <1 and for the northern (a) and southern (b) hemispheres, respectively. Comparing Fig. 4 and 5, we can see that both distributions are very similar, which can be explained by high correlation between the AE and PC indexes obtained by Vennerstrøm et al. (1991). This correlation is related to the formation of ionospheric current systems as a result of the magnetosphere-ionosphere interactions, and the dominant role of the Region 1 currents of Iijima and Potemra (1976) in the formation of the PC index (Troshichev and Janzhura, 2012). However, the obtained similarity in the behaviour of the boundaries, using the AE and PC indexes as a measure of geomagnetic activity by separately, was not evident at the beginning of this study. This supports the picture obtained by Akasofu (1968) in which the trapping boundary is located inside the auroral oval.1.2 Subsection (as Heading 2).

4 Discussion and conclusions

We analyzed the relative position of the trapping boundary and the equatorial boundary of the auroral oval using simultaneous measurements of the energetic electrons with energy >100 keV and the auroral electrons made at the same METEOR-M №1 satellite. Previous comparisons of the relative position of these boundaries were made mostly statistically using the data from different satellites. Our analysis shows that the differences in the positions of both boundaries are typically smaller than the statistical scattering in the position of each boundary. This fact explains why previous statistical studies led to different conclusions, and why the use of statistical results about the location of each boundary cannot answer the question about the relative position of trapping boundary and equatorial boundary of the auroral oval.

Our study shows the trapping boundary is often located inside the auroral oval. For a number of cases it is located to the equator of the oval. However, it is necessary to remember that the trapping boundary is defined as the boundary where particle fluxes become lower than a threshold determined by the sensitivity of a detector. This means that there are no doubts about the relative location of both boundaries when the trapping boundary is located inside the auroral oval, meanwhile the location of the trapping boundary equatorward from the oval might be attributed to the low sensitivity of the detector which is not able to register the low fluxes of energetic electrons. This statement is indirectly supported by the analysis of the latitudinal difference in the position of both boundaries for AE more or less than 150 nT, and for PC more or less than 1. The number of events when the trapping boundary is observed inside the auroral oval significantly increases with both AE and PC indexes.

The location of the trapping boundary inside the auroral oval agrees with new results on the auroral oval mapping discussed by Antonova et al. (2017). They argue that the auroral oval has a form of a comparatively thick ring for all MLTs. Mapping of the plasma sheet to the ionospheric altitudes cannot produce the structure with non-zero thickness near noon. Therefore, it seems natural to map the auroral oval into the plasma ring, that surrounds the Earth, as selected by Antonova et al. (2013, 2014a), and filled with plasma similar to the plasma in the plasma sheet. Results of Antonova et al. (2014b, 2015) and Kirpichev et al. (2016) also support such conclusion and locate the quite time equatorial boundary of the auroral oval at R~7 R_E near midnight and polar boundary at R~10-13 R_E. It is also important to remember that starting from Vernov et al. (1969) this magnetospheric region is classified as the region of quasitrapping for energetic particles. It contains the closed magnetic field lines, and only particles with near to 90° pitch-angles have the drift trajectories crossing the magnetopause. The drift trajectories of particles with another pitch angles are closed inside the magnetosphere. Therefore, the registration of trapping boundary of energetic electrons with nearly zero pitch angles inside the auroral oval seems quite natural.

The observation of the trapping boundary of energetic electrons inside the oval can be also important for the solution of the problem of acceleration of electrons in the outer radiation belt, taking into account that the injection of seed population of relativistic electrons during magnetic storms takes place at the equatorial boundary of the auroral oval (Antonova and Stepanova, 2015). Electrons of such seed population must be trapped inside the magnetosphere and further accelerated to relativistic energies during the recovery phase of storm, forming a new outer radiation belt. Our current studies were done for comparatively quiet geomagnetic conditions. The behavior of the trapping boundary during magnetic storms is almost unknown and requires additional analysis.

In summary, there are strong evidences that trapping boundary of energetic electrons which coincide with the outer boundary of the outer radiation belt is located inside the auroral oval, that might help to re-analyse a relation between the dynamics of radiation belts and auroral phenomena.

Acknowledgments

The work of E.E.A., was supported by the Russian Foundation for Basic Research (RFBR, project no. 15-05-04965). The work of M.S. was supported by Chilean FONDECYT No 1161356 grant, and CONICYT PIA Project Anillo de Investigacin en Ciencia y Tecnologa ACT1405, and AFORS 695 FA9559-14-1-0139.

References

Akasofu, S. I.: Polar and magnetospheric substorms. D. Reidel publishing company, Dordrecht-Holland, 1968.

Antonova, E. E, Kirpichev, I. P., Ovchinnikov, I. L., Pulinets, M. S., Znatkova, S. S., Orlova, K. G., and Stepanova, M. V.: Topology of High-Latitude Magnetospheric Currents, IAGA Special Sopron Book Series, The Dynamic Magnetosphere, Editors William Liu and Masaki Fujimoto, Springer, 3, 2001-2010, 2011a.

Antonova, E. E., Myagkova, I. M., Stepanova, M. V., Riazantseva, M. O., Ovchinnikov, I. L., Marjin, B. V., and Karavaev, M. V.: Local particle traps in the high latitude magnetosphere and the acceleration of relativistic electrons, J ATMOS SOL-TERR PHY, 73, 1465–1471, doi:10.1016/j.jastp.2010.11.020, 2011b.

Antonova, E. E., Kirpichev, I. P., Vovchenko, V. V., Stepanova, M. V., Riazantseva, M. O., Pulinets, M. S., Ovchinnikov, I. L., and Znatkova, S. S.: Characteristics of plasma ring, surrounding the Earth at geocentric distances ~7–10R_E, and magnetospheric current systems, J ATMOS SOL-TERR PHY, 99, 85–91, doi:10.1016/j.jastp.2012.08.013, 2013.

Antonova, E. E., Kirpichev, I. P., and Stepanova, M. V.: Plasma pressure distribution in the surrounding the Earth plasma ring and its role in the magnetospheric dynamics, J ATMOS SOL-TERR PHY, 115, 32–40, doi:10.1016/j.jastp.2013.12.005, 2014a.

Antonova, E. E., Vorobjev, V. G., Kirpichev, I. P., and Yagodkina, O. I.: Comparison of the plasma pressure distributions over the equatorial plane and at low altitudes under magnetically quiet conditions, GEOMAGN AERON+, 54, 278–281, doi:10.1134/S0016793214030025, 2014b.

Antonova, E. E., Vorobjev, V. G., Kirpichev, I. P., Yagodkina, O. I., and Stepanova, M. V.: Problems with mapping the auroral oval and magnetospheric substorms, EARTH PLANETS SPACE, 67, doi:10.1186/s40623-015-0336-6, 2015.

Antonova, E. E., Stepanova, M. V.: The problem of the acceleration of electrons of the outer radiation belt and magnetospheric substorms, EARTH PLANETS SPACE, 67, 148, doi:10.1186/750 s40623-015-0319-7, 2015.

Antonova, E. E., Stepanova, M., Kirpichev, I. P., Ovchinnikov, I. L., Vorobjev, V. G., Yagodkina, O. I., Riazanseva, M. O., Vovchenko, V. V., Pulinets, M. S., Znatkova, S. S., Sotnikov, N. V.: Structure of magnetospheric current systems and mapping of high latitude magnetospheric regions to the ionosphere, J ATMOS SOL-TERR PHY, 10.1016/j.jastp.2017.10.013, 2017.

Delcourt, D.C., and Sauvaud, J.-A.: Populating of the cusp and boundary layers by energetic (hundreds of keV) equatorial particles, J GEOPHYS RES, 104, 22635–22648, doi:10.1029/1999JA900251, 1999.

Feldstein, Y. I., and Starkov, G. V.: The auroral oval and the boundary of closed field lines of geomagnetic field, PLANET SPACE SCI, 18, 501–508, doi:10.1016/0032-0633(70)90127-3, 1970.

Feldstein, Y. I., Vorobjev, V. G., Zverev, V. L., and Förster, M., Investigations of the auroral luminosity distribution and the dynamics of discrete auroral forms in a historical retrospective, HIST GEO- SPACE SCI, 5, 81–134, doi:10.5194/hgss-5-81-2014, 2014.

Frank, L. A., Van Allen, J. A., and Craven, J. D.: Large diurnal variation of geomagnatically trapped and precipitated electrons observed at low altitudes, J GEOPHYS RES, 69, 3155–3167, doi:10.1029/JZ069i015p03155, 1964.

Frank, L. A.: Relationship of the plasma sheet, ring current, trapping boundary, and plasmapause near the magnetic equator and local midnight, J GEOPHYS RES, 76, 2265-2274, doi:10.1029/JA076i010p02265, 1971.

Fritz, T.A.: High-latitude outer-zone boundary region for ≥40-key electrons during geomagnetically quiet periods, J GEOPHYS RES, 73, 7245-7255, doi:10.1029/JA073i023p072457, 1968.

Fritz, T. A.: Study of the high-latitude, outer-zone boundary region for ≥40-kev electrons with satellite Injun 3, J GEOPHYS RES, 75, 5387-5400, doi:10.1029/JA075i028p05387, 1970.

Imhof, W. L., Mobilia, J., Datlowe, D. W., Voss, H. D., and Gaines, E.E.: Longitude and temporal variations of energetic electron precipitation near the trapping boundary, J GEOPHYS RES, 95, 3829-3839, doi:10.1029/JA095iA04p03829, 1990.

Imhof, W. L., Voss, H. D., Mobilia, J., Datlowe, D. W., and Gaines, E.E.: The precipitation of relativistic electrons near the trapping boundary, J GEOPHYS RES, 96, 619-5629, doi:10.1029/90JA02343 , 1991.

Imhof, W. L., Voss, H. D., Mobilia, J., Datlowe, D. W., Gaines, E. E., McGlennon, J. P. and Inan, U. S.: Relativistic electron microbursts, J GEOPHYS RES, 97, 13829-13837, doi: 10.1029/92JA01138 , 1992.

Imhof, W. L., Robinson, R. M., Nightingale, R. W., Gaines, E. E., and Vondrak, R.R.: The outer boundary of the Earth's electron radiation belt. Dependence upon L, energy, and equatorial pitch angle, J GEOPHYS RES, 98, 5925-5934, doi:10.1029/92JA02553, 1993.

Imhof, W. L., Chenette, D. L., Gaines, E. E., and Winningham, J. D.: Characteristics of electrons at the trapping boundary of the radiation belt, J GEOPHYS RES, 102, 95-104, doi:10.1029/96JA02797, 1997.

Kanekal, S. G., Baker, D. N., Blake, J. B., Klecker, B., Cumming, J. R., Mewaldt, R. A., Mason, G. M., and Mazur, J. E.: High-latitude energetic particle boundaries and the polar cap: A statistical study, J GEOPHYS RES, 103, 9367-9372, doi:10.1029/97JA03669, 1998.

McDiarmid, I. B., and Burrows J. R.: Local time asymmetries in the high-latitude boundary of the outer radiation zone for different electron energies, CAN J PHYS, 46, 49-57, doi:10.1139/p68-007, 1968.

Myagkova, I. M., Ryazantseva, M. O., Antonova, E. E. and B. V. Marjin: Enhancements in the fluxes of precipitating energetic electrons on the boundary of the outer radiation belt of the Earth and position of the auroral oval boundaries, COSMIC RES+, 48, 165–173, doi:10.1134/S0010952510020061, 2010.

Öztürk, M. K., and Wolf, R. A.: Bifurcation of drift shells near the dayside magnetopause, J GEOPHYS RES, 112, A07207, doi:10.1029/2006JA012102, 2007.

Paschmann, G., Haaland S., and Treumann, R.: Auroral plasma physics, SPACE SCI REV, 103, 1–485, doi:10.1023/A:1023030716698, 2002.

Rezhenov, B. V., Vorobev, V. G., Tsirs, V. E., Liatskii, V. B., Pervaia, T. I., and Savin, B. I.: Distribution of intrusive low-energy electrons in the evening-premidnight sector from Cosmos-426 data, Kosmicheskie Issledovaniia, 13, 521-527. In Russian.

Riazantseva M. O., Myagkova, I. N., Karavaev, M. V., Antonova, E. E., Ovchinnikov, I. L., Marjin, B. V., Saveliev, M. A., Feigin, V. M., and Stepanova, M.V.: Enhanced energetic electron fluxes at the region of the auroral oval during quiet geomagnetic conditions November 2009, ADV SPACE RES, 50, 623–631, doi: 10.1016/j.asr.2012.05.015 , 2012.

Troshichev, O. A., and Andrezen, V. G.: The relationship between interplanetary quantities and magnetic activity in the southern polar cap, PLANET SPACE SCI, 33, 415– 419, doi: 10.1016/0032-0633(85)90086-8, 1985.

Troshichev, O., and Janzhura, A.: Space weather monitoring by ground-based means. PC index. Springer. 2012.

Ukhorskiy, A. Y., Sitnov, M. I., Millan, R. M., and Kress, B. T.: The role of drift orbit bifurcations in energization and loss of electrons in the outer radiation belt, J GEOPHYS RES, 116, A09208, doi:10.1029/2011JA016623, 2011.

Vernov, S. N., Gorchakov, E. V., Kuznetsov, S. N., Logachev, Yu. I., Sosnovets, E. N., and Stolpovsky, V. G.: Particle fluxes in the outer geomagnetic field, REV GEOPHYS SPACE GE, 7, 257-280, doi:10.1029/RG007i001p00257, 1969.

Vorobjev, V. G., Yagodkina, O. I., and Katkalov, Yu.V.: Auroral precipitation model and its applications to ionospheric and magnetospheric studies, J ATMOS SOL-TERR PHY, 102, 157-171, doi:10.1016/j.jstp.2013.05.007. 2013.

Yahnin, A. G., Sergeev, V. A., Gvozdevsky, B. B., and Vennerstrùm, S.: Magnetospheric source region of discrete auroras inferred from their relationship with isotropy boundaries of energetic particles, ANN GEOPHYS, 15, 943-958, doi: 10.1007/s00585-997-0943-z, 1997.

Vennerstrøm, S., Friis-Christensen, E., Troshichev, O.A., and Anderson, V.G.: Comparison between the polar cap index, PC, and the auroral electrojet indices AE, AL, and A U, J GEOPHYS RES, 96, 101-113, doi:10.1029/90JA01975, 1991.