ANSWER TO REFEREE 1:

Anonymous Referee #1

Received and published: 20 February 2018

General comments

This paper investigates the location of the external boundary of the outer radiation belt (ORB) relative to the equatorward edge of the auroral oval during quiet or moderately unsettled geomagnetic conditions. The study is based on precipitating electron flux data from the METEOR-M No 1 satellite at auroral (0.03–16 keV) and > 100 keV energies, collected between between November 2009 and March 2010. Three types of situations are exemplified in the paper: (i) external ORB boundary inside the auroral oval during moderately disturbed conditions, (ii) external ORB boundary equatorward from the auroral oval during quiet conditions, and (iii) external ORB boundary inside the auroral oval during quiet conditions. This gives motivation to carry out a statistical study by looking at the distribution of the separation between the external ORB boundary and the equatorward auroral oval boundary, named d(lat) in the paper, as a function of geomagnetic activity. The distributions are plotted separately for quiet conditions (AE < 150 nT or PC < 1) and moderately disturbed conditions (AE > 150 nT or PC > 1). It is found that, during moderate geomagnetic activity, the ORB boundary is located within the auroral oval, whereas during quiet conditions its location can be either inside or outside the auroral oval.

We are grateful for the great work done by you with our article and for the list of useful comments and corrections! We hope that the new version of the paper become better and more understandable for readers.

1. *The title of the article is somewhat misleading, as it contains the word "relation" which leads one to expect to find an equation (be it empirical) linking the positions of the two studied boundaries. Since no such relation is obtained in the paper, the title should be modified to better reflect the conclusions of the study.*

Thank you, the new title is: "Relative locations of the polar boundary of the outer electron radiation belt and the equatorial boundary of the auroral oval"

2. *The caption of Figure 1 should be expanded to describe each panel in more detail. It is currently not easy for the reader to understand the data which are plotted, especially what the vertical dashed lines represent. I have not found in the text what the blue and red lines represent, for instance. Moreover, there are many of these lines which seem to be superposed on top of one another, but since the alignment is not perfect, I am not sure whether this is coincidental or done on purpose (same issue with Figure 3). Would it be possible to clarify this and improve the legibility of the figure? Also, it is not so clear why, in the lower panel, the flux energy is plotted, since (if I understood correctly) the criterion for determining the ORB boundary is the > 100 keV flux. Unless the blue curve is the integrated version of the fluxes displayed in the top panel? Please clarify this too, since I am not sure whether my guess is correct without additional information in the figure caption (or at the very least in the text describing the figure).*

We corrected the figures 1-3, trying to make them clearer and added the corresponding notation for all the curves. Also we added some additional comments to the text, see p. 4 l. 27-32

3. *I did not manage to understand the reasoning exposed on p. 3 l. 2–8 (and also mentioned on p. 8 l. 10–14). Why is it so that the energetic electron detector becomes less sensitive when it is outside of the auroral oval? Since we are here considering a same detector measuring fluxes in one given energy range (> 100 keV), why*

should it not be possible to compare the measurements when they are made inside or outside the auroral oval? To my mind, if such a comparison were not possible to make, this would question the validity of the entire study, since it would be difficult to conclude anything from the data analysis! Could you please explain in more detail or rephrase the idea behind your reasoning in this paragraph?

Thank you for the comment! We did not explain our idea sufficiently accurately in the text, which is now is corrected.
The sensitivity of the detector is naturally fixed, and does not depend on the location and time of the measurements. We mean the well-known effect of decreasing of the electron fluxes inside the ORB with decreasing level of geomagnetic activity; for example during the periods of minimum solar activity (see, for example, McIlwain C.E., Processes Acting Upon Outer Zone Electrons, Radiation Belts: Model and Standard, Geophysical Monograph, pp. 15-26, 1996.). The observations presented were obtained during such period (September 2009 - April 2010) and sometimes the electron flux in the ORB were very weak, close to the sensitivity limit of the detector. In these cases, we can only detect the beginning of the decline from the ORB maximum to the background level of the electron intensity. In such situations, the detected boundary can be shifted to the equator relative to the true boundary of this low intensity ORB, which could be observed by a detector with better sensitivity. That's why we believe that the discussed effects could be clearer in the period of solar maximum activity or if the sensitivity of the detector was better. We added some additional comments on p. 3 l.1-4 and l. 24-31

4. *On p. 8 l. 5–6: "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." I think this statement should be justified with numbers, since currently the "statistical scattering in the position of each boundary" is not quantified in the paper. This should be easy to add, as you already have made a statistical study of the boundary locations, and there are certainly many references in the literature that could be cited to support the said statement.*

   Thank you for the comment! We added some additional comments and statistical numbers at the end of the section 3 (p.8. l. 13-20 p.9 l.1-2) with corresponding references.

5. *The conclusions presented on p. 9 ("there [is] strong evidence that [the] trapping boundary of energetic electrons [...] is located inside the auroral oval") do not reflect the interpretation of Figures 4 and 5. One cannot neglect the relatively high number of events for which this trapping boundary is situated equatorwards from the auroral oval, so the quoted statement is misleading.*

   Thank you for the comment! You are right this statement is too categorical. We have corrected it and aligned with the discussed results (see p.10. l 31-33)

6. *Finally, I think it could be extremely interesting to go a bit further in the analysis before the final publication of the manuscript, by trying to determine why d(lat) changes with increasing geomagnetic activity (from totally quiet to moderate activity). Is it so that only the auroral oval equatorward boundary moves equatorwards, while the ORB external boundary does not change, or does the ORB boundary also migrate equatorwards/polewards when geomagnetic activity is enhanced? If such a result could be obtained, this*

would to my mind greatly increase the impact of the paper, and this would enable one to deepen the interpretation of the results.

Thank you for the comment! The increasing of geomagnetic activity affects first of all the position of the equator boundary of the auroral oval (see, for example, Feldstein et al. (2014, doi: doi:10.5194/hgss-5-81-2014). The position of the polar ORB boundary is more stable (see Kanekal et al. (1998)). The figures 1.1 below show the distributions of the position of both boundaries by Meteor-M1 measurements in McIlwain coordinates (separately for Northern Hemisphere, Sothern Hemisphere, for AE<150 nT and AE>150 nT). The distributions are rather wide, but you can clearly see that the maximum of distributions for polar boundary of ORB is rather stable and don't show any clear dependence on geomagnetic activity. On the other hand the maximum of distributions of equator boundary of auroral oval clearly moves toward the equator with increasing geomagnetic activity. Nevertheless, this is not a simple question because the distributions are rather wide and their widths increase with enhanced geomagnetic activity (for both boundaries). This means that the boundaries position (including polar ORB boundary) are unstable in these cases, and we cannot unequivocally confirm that the polar ORB boundary does not depend on geomagnetic activity. This question needs more thorough study and we don't want to add this discussion to the paper. The main aim of this paper is to show that the polar ORB boundary can be observed rather often inside the auroral oval. It is a very important point for the problem of the ORB formation. So, we introduce new figure (fig.6) and text in the paper with the discussion of the dependence of studied boundaries on geomagnetic activity (section 3 p.9 l. 3-9).

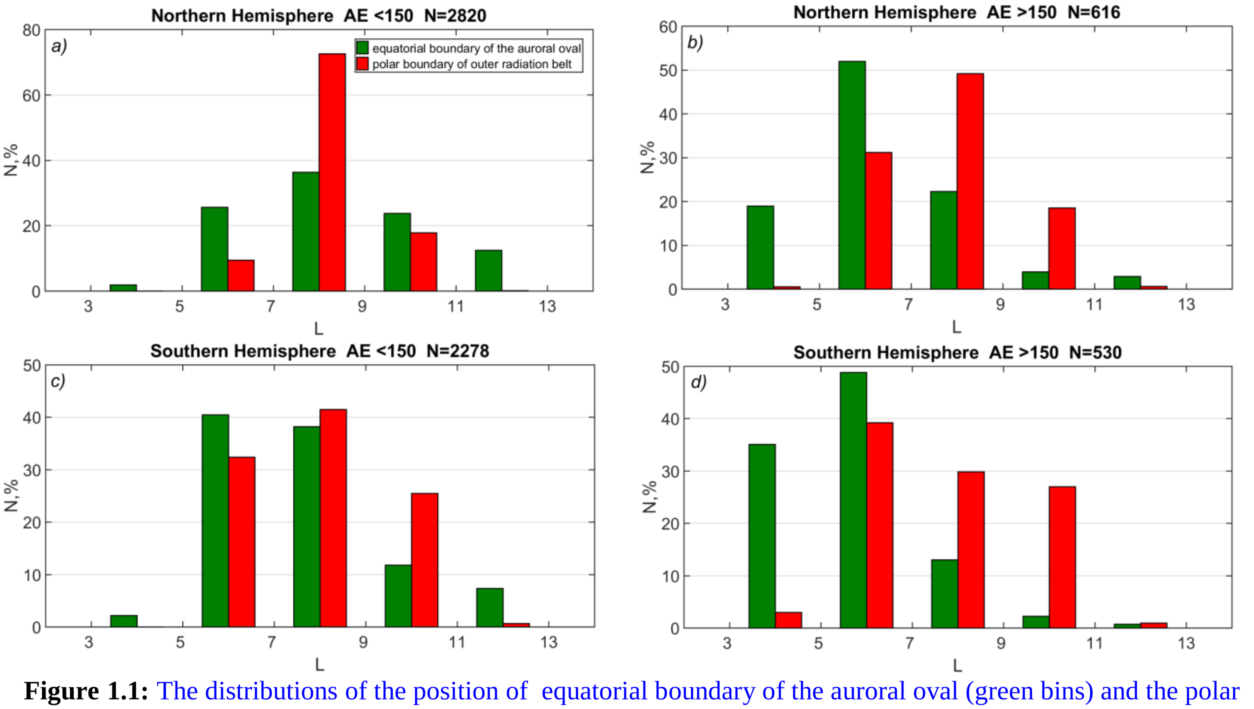

Figure 1.1: The distributions of the position of equatorial boundary of the auroral oval (green bins) and the polar ORB boundary (red bins) from the L (where L is the McIlwain parameter) for northern (a,b) and southern (c,d) hemispheres for AE <150 nT (a,c) and AE>150 nT (b,d).

Specific comments (minor)
– The acronym "ORB", which first appears on p. 2 l. 24 (and most probably stands for "outer radiation belt") should be defined in the introduction.

Thank you for the comment! We defined the acronym ORB in the Introduction (p.1 l.24)

– p. 2 l. 28: "After that we searched for the closest to the pole location of the ORB flux" does not sound very clear to the reader. This should be rephrased.

Thank you! We have tried to make this sentence clearer. (P.2 l. 2-3)

– p. 3 l. 14: I would suggest to add the reference to Davis and Sugiura (1966) on the AE index, since references are provided for the PC indices.
Davis, T. N., and M. Sugiura (1966), Auroral electrojet activity index AE and its universal time variations, J. Geophys. Res., 71, 785–801, doi:10.1029/JZ071i003p00785.

Thank you for the reference! We have added it at p.4 l. 19.

– p. 4 l. 22–23: "According to the (http://omniweb.gsfc.nasa.gov/)..." → There must be several words missing here!

Thank you for the comment! We mean "According to the omniweb database....". We corrected the corresponding phrase (p.5 l.1) .

– p. 7: Could you explain in a little more detail why you chose the value of 150 nT for the AE index to separate the events in the analysis? What would happen if you chose, say, AE = 100 nT instead? Would the trend for low geomagnetic activity become clearer? (cf l. 6)

Thank you for the comment! Unfortunately, geomagnetic activity was rather low during the observed period (November 2009 - March 2010), so we can't use traditional criteria for disturbed periods. AE~150 nT was selected as a compromise between the idea of separation of disturbed and quiet periods, and the volume of the statistic. If we change the selection criteria to AE = 100 nT, the results do not change significantly (see the figure 1.2 for AE>150 nT, AE<150 nT (a,b), and below for AE>100 nT, AE<100 nT (c,d)). If we changed the selection criteria significantly to make a strong difference between the geomagnetic conditions (for example to select AE>500 nT and AE<10nT (see the panel (e,f) on the figure 1.2)) we can see that the trapping boundary would always be located inside the auroral oval for AE>500 nT, but the statistic of such crossings is rather poor for the observed period.

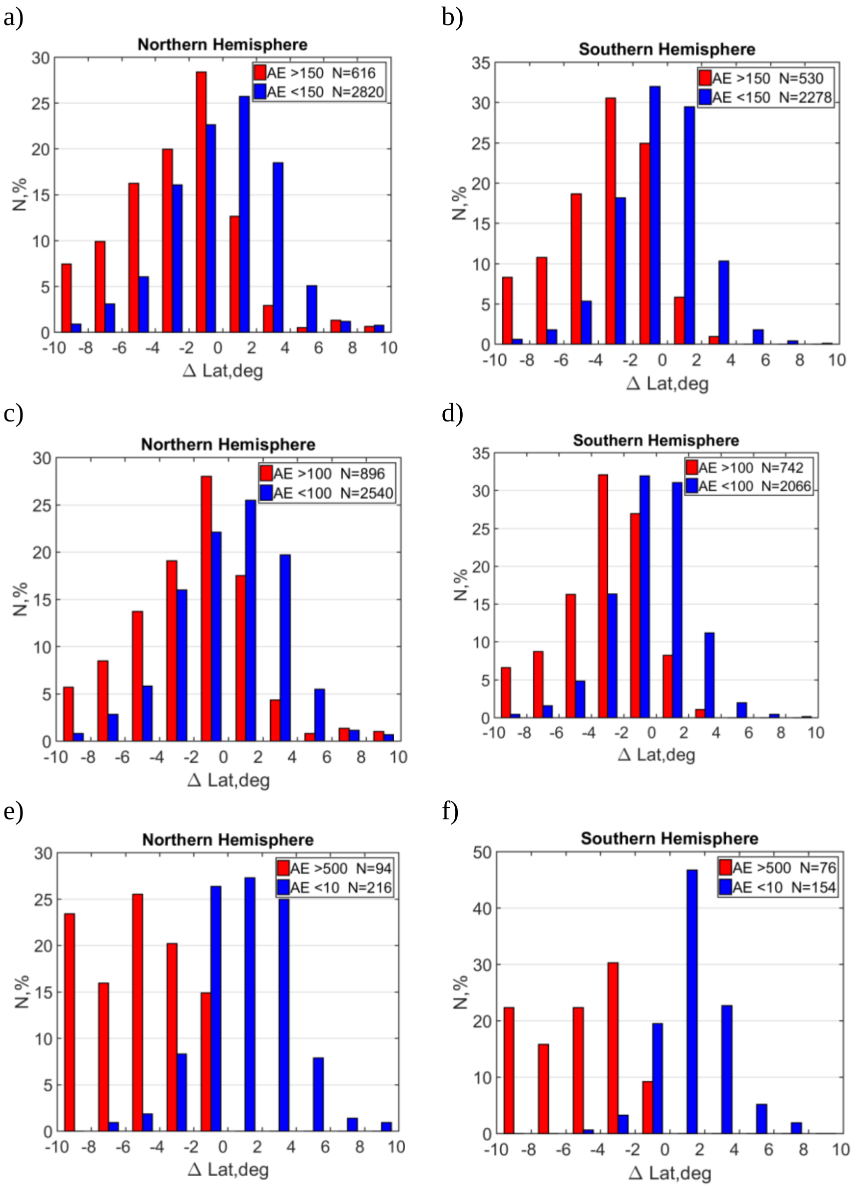

Figure 1.2: The distribution of Δ Lat for AE>150 nT and <150 nT (a,b) for AE>100 nT and <100 nT (c,d) and for AE>500 nT and <10 nT (e,f) for northern (a,c,e) and southern (b,d,f) hemispheres

– p. 7 l. 14–15: "using the AE and PC ind[ices] as a measure of geomagnetic activity by separately" –> there must be words missing here too

Thank you! I have changed slightly this sentence (p.8 l.11-12)

– "indexes" → "indices" (p. 1 l. 22; p. 3 l. 13–16; p. 4 l. 18–19; p. 7 l. 2–11–14)
*– p. 1 l. 16: "at the absence of" → "**in** the absence of"*

– p. 1 l. 18–19: “to the equator from” → “equatorward from” (same p. 2 l. 3) C4 ANGEOD Interactive comment Printer-friendly version Discussion paper
– p. 1 l. 19, l. 22: “auroral precipitations” → “auroral precipitation” (“precipitation” is uncountable)
– p. 1 l. 24: “is discussed” → “are discussed”
*– p. 1 l. 25: “the position of the trapping boundary **for** energetic electrons”*
– p. 1 l. 26: “sing” → “using”
– p. 1 l. 26: “low orbiting and high apogee” → “low-orbiting and high-apogee” (same l. 28, p. 2 l. 4)
– p. 2 l. 32: remove comma after “it is well known”
– p. 3 l. 9: “location” → “locations” (or change “have” into “has” on l. 11; same l. 11)
– p. 3 l. 17: “high latitude” → “high-latitude”
*– p. 3 l. 20: “of GGAK-M set” → “**of the** GGAK-M set”*
– p. 3 l. 22: “with the energies from...” → “with energies from...” (twice on this line)
*– p. 3 l. 29: “as a polar boundary” → “as **the** polar boundary”*
– p. 4 l. 2–3: correct the location of parentheses for the citations
*– p. 4 l. 6: “the visual inspection” → “**a** visual inspection”*
– p. 4 l. 18–19: remove capitalisation of “Northern” and “Southern” (see guidelines: https://www.annales-geophysicae.net/for_authors/manuscript_preparation.html)
– p. 6 l. 13: “trapping boundary d(lat)” → “trapping boundary, d(lat)” (add comma)
– p. 7 l. 14: “behaviour” → “behavior” (to remain consistent with p. 9 l. 1 and the use of American English spelling throughout the paper)
– p. 7 l. 16: I think “1.2 Subsection (as Heading 2).” should be deleted.
– p. 8 l. 5: “using the data from” → “using data from”
– p. 8 l. 23: “quite time” → “quiet time”
– p. 8 l. 27: “with another pitch angles” → “with other pitch angles”
– p. 8 l. 29: “can be also” → “can also be”
– p. 9 l. 3: “there are strong evidences” → “there is strong evidence” (“evidence” is uncountable)
*– p. 9 l. 3: “that trapping boundary” → “that **the** trapping boundary”*

Thank you for careful reading of our paper! The text was corrected according to your comments and corrections!

ANSWER TO REFEREE 2:

Anonymous Referee #2

Received and published: 8 March 2018

This paper presents potentially interesting results and interpretations. With a little more detail within the manuscript, and slightly more interaction between the introduction and the conclusions sections it will provide a useful scientific step forward. Some comments regarding the text and figures are presented below:

We are grateful for your careful reading of our paper! We try to improve the paper taking into account all your comments.

1) In the paragraph starting page 2, Line 19 two mechanisms are put forward for the relative locations of the equatorial boundary of the auroral oval and the outer radiation belt trapping boundary. The rest of the paper is about determining which mechanism is supported by the analysis of satellite data as presented. However, the opening sentence of page 8, line 18 indicates that the results agree with Anotonova et al. 2017. This work was not mentioned in the Introduction section and therefore is not expected. The new work should be discussed in section 1 to give the reader the background to the research mentioned in that paper.

The main idea presented in this study rose once it became clear that the main part of the auroral oval is not mapped onto the plasma sheet, as it used to be widely accepted. According to our previous studies, the oval is mapped onto the surrounding-the-Earth plasma ring. The existence of such ring, which exhibits characteristics similar to the plasma sheet, was known from the first satellite plasma measurements (see, for example, (Frank, 1971, doi:10.1029/JA076i010p02265). Transverse currents in this ring are closed inside the magnetosphere. So we added a discussion of the results by Anotonova et al.(2017) in the Introduction p.2 .l.24-25

2) The first paragraph of section 1 discusses the L-shell variations of the boundaries, particularly the outer radiation belt trapping boundary. Given the use of 100 keV in this study to determine the boundary location rather than 40 keV or 35 keV as previously used, it would be beneficial to the paper if the distributions in L-shell of the boundaries were plotted for the whole dataset - similar to Figures 4 and 5. These new figure(s) would provide clarity for the reader and confirm that the algorithm is producing results that are consistent with the previous work cited in paragraph 1&2, section 1.

Thank you for your comment! We use the lowest channel of energetic electrons (>100 keV) available on Meteor-M1 satellite to determine the trapping boundary. Below we show plots (figure 2.1) of the probability distributions of finding the obtained boundaries for each L value (where L is McIlwain parameter). For quiet geomagnetic condition the average value of the polar boundary of the ORB ≈8±1, the average value of the equatorial auroral oval boundary is almost the same ≈8±2. For perturbed geomagnetic condition AE>150 nT the average value of the polar boundary of the ORB is also ≈8±1, whereas the average value of the equatorial auroral oval boundary is much less ≈6±2 . The average position of the polar boundary of the ORB agrees with the position of the trapping boundary published by Vernov et al. (2009). We added figures and comments in section 3 p.9. l.3-9

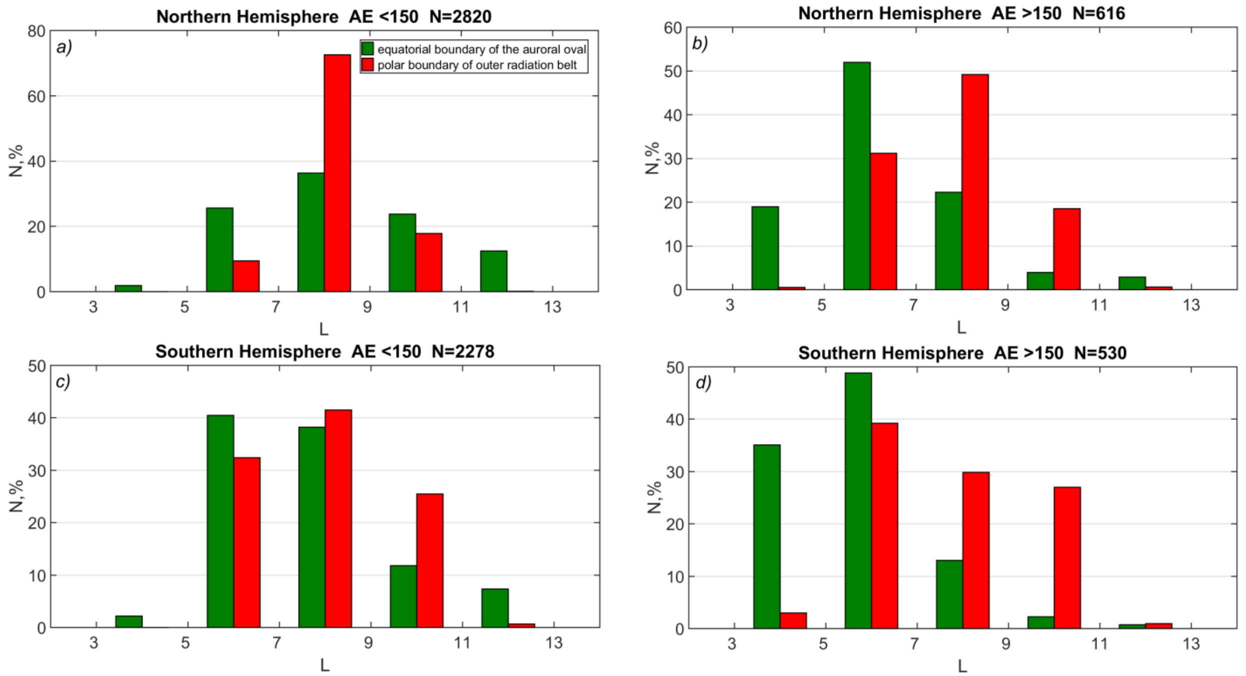

Figure 2.1: The distributions of the position of equatorial boundary of the auroral oval (green bins) and the polar ORB boundary (red bins) from the L (where L is the McIlwain parameter) for northern (a,b) and southern (c,d) hemispheres for AE <150 nT (a,c) and AE>150 nT (b,d).

3) Figures 4 and 5 show the distributions of the boundaries for northern and southern hemispheres. However, no obvious follow-up of this separation is undertaken, and it is unclear why it is done. It is reasonable to use the PCS index for the southern hemisphere analysis, but it is unclear why the data continue to be separated hemispherically after that. Just having one plot for each activity index would clarify the presentation and aid the discussion of the main result, i.e., that there is a latitudinal difference in the distributions for quiet and active conditions.

The maximums of distributions of Δ Lat for northern and southern hemispheres (see the figure 2.2 below) are slightly different (in adjacent bins). The combined distribution, for both hemispheres, exhibits a smeared maximum, and the effect is less clear. During the data analysis we found important differences using the AE and the PC indexes. The AE index is produced only due to magnetic measurements in the northern hemisphere. At the same time, the PC index exists separately for northern and southern hemispheres. We obtain slightly different pictures of Δ Lat for both hemispheres. We do not know whether this effect is connected to the difference in magnetic field between both hemispheres (IGRF effect) or some kind of seasonal effect (our measurements were made on September 2009 - April 2010). It could be very interesting to clarify this subject in the future. This is why we prefer to publish our figures without averaging both hemispheres.

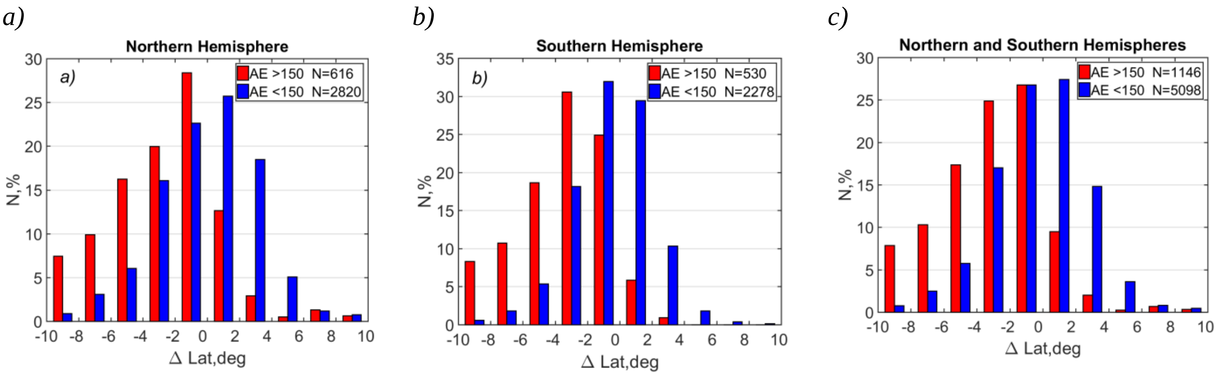

Figure 2.2: The distribution of Δ Lat for AE>150 nT (red bins) and <150 nT (blue bins) for northern (a) and southern (b) and combined northern and southern (c) hemispheres

Some small points:

4) 'to the equator of' should be replaced by 'equatorward of'. 'to the pole of' should be replaced by 'poleward of'.

Thank you! We have corrected the terms everywhere.

5) Page 2, line 4-5. The sentence is unclear. I think it says that the outer radiation belt trapping boundary is clearly identifiable in low orbiting satellite data.

Thank you! We have corrected this sentence. (p. 2 l.2-3.)

6) It would be useful to the reader to state whether the electron detector was measuring spin averaged electrons or was omni-directional etc.

Unfortunately, we have no information on the pitch-angle distribution of both auroral electrons and energetic electrons. METEOR-1 satellites were spin stabilized. The detectors of GGAK-M instrument look within the loss cone and mostly observe precipitating particles. However, because of the large fields of view and particle scattering, some amount of the trapped population is also seen. We used early published information about the isotropy of the observed fluxes of energetic electrons near the ORB from Imhof et al. (1990, 1991, 1992, 1993). Auroral oval was identified by precipitating low energy electrons.

7) Page 4, line 7-8. What energy did you use to calculate the average value and std of the electron fluxes? Same question for the total energy electron flux. If all of the auroral electron energy data in the range from 0.032-16.64 keV was used, how was it combined?

The polar boundary of ORB was determined using the average flux of electrons with energy>100 keV. The equator boundary of the auroral oval was determined using the value of the total energy flux of low energy electrons. Each spectra was approximated in the range 0.032-16.64 keV with an energy step dε=0.01 keV, and the energy flux was calculated as a numerical integral $Flux_{\varepsilon} = 2\pi \int (j(\varepsilon) \cdot \varepsilon \, d\varepsilon$ (j(ε) - flux for current value of energy ε). We have added the corresponding explanations in the text (p. 4 l.10-13).

8) Figure 1. The caption should describe the lines added to the plot. What does the red vertical dashed line represent. The caption should say - the text doesn't. Why are there two green vertical lines at 14:06 UT. Why is there a red vertical line in Figure 1 and a blue vertical line in Figure 2?

We are sorry. I. The new version contains corrected and improved figures 1-3.

All relevant changes made in the manuscript are shown by blue colour in the marked-up manuscript version below. Also in response to the reviews we show the pages and lines of all major changes in the each corresponding answer item.

Relative locations of the polar boundary of the 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 polar 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 in the absence of geomagnetic storms the polar 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 equatorward of the equatorial boundary of the auroral precipitation. It was also found that for disturbed geomagnetic conditions the polar boundary of the outer radiation belt is almost always located inside the auroral oval. We observe that the difference between the position of the polar boundary of the outer radiation belt and the position of the equatorial boundary of the auroral precipitation depends on the AE and PC indices of geomagnetic activity. The implications of these results in the analysis of the formation of the outer radiation belt are discussed.

1 Introduction

The position of the trapping boundary for energetic electrons in the outer radiation belt (ORB) contains information about the topology of the magnetic field lines of the Earth. For a long time this has been analyzed using 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 ORB 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 equatorward of the trapping boundary. It means that the ORB trapping boundary can be clearly identifiable using low orbiting satellites measurements.

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 poleward of the region of low energy electron precipitation. 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 equatorward 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. Antonova et al. (2017) showed that the outer boundary of this ring in the night sector coincides with the external boundary of the ring current. Results obtained by Antonova et al. (2014, 2015,2017), 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 poleward of 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 precipitation 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 detection of the trapping boundaries during the periods of low geomagnetic activity (for example during the solar minimum). In these cases the level of electron fluxes inside the ORB can be rather low, close to the limit of sensitivity of the instrument. Thus the detected trapping boundary can be located closer equatorward with respect to the true trapping boundary.

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, has 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 indices. 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 indices 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 the GGAK-M set of instruments, composed by semiconductor and scintillator detectors, and electrostatic analyzers. In particular, it measured energetic electrons with energies from 0.1 to 13 MeV, and low energy electrons with 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 polar 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 of electrons with energies >100 keV 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 during the continuous time interval of at least 1 minute duration (the separate single points spikes are not taken into account). The nearest poleward point that satisfies the described criterion is selected as the polar boundary of the ORB. These selection criteria show stable results of the ORB detection but as a rule they define the boundary at the end of the decline of electron intensity from ORB maximum to the background level. This means that electron fluxes lower than the established criteria, and belonging to the ORB, could be missed. This is why it might shift slightly the obtained boundary equatorward with respect to the true boundary especially in the case of low intensity ORB crossing (see the introduction). This means that we could underestimate the number of events for which the polar boundary of the ORB is observed inside the auroral oval. Such underestimation changes slightly the results of the statistical analysis.

However, it cannot change the answer to the main question: whether is the trapping boundary is located inside the oval or coincides with its equatorial boundary.

The automatic detection of the polar 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 poleward 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 a visual inspection of all events.

To calculate the position of the auroral oval boundary, we use the value of the total energy flux. We produce the spectra approximation from 0.032 till 16.64 keV with energy step dε=0.01 keV. Energy flux was calculated as the integral characteristic of low energy electron spectrum $Flux_{\varepsilon} = 2\pi \int (j(\varepsilon) \cdot \varepsilon \, d\varepsilon)$ (j(ε) is the flux for current value of energy ε). We first calculated the average value and standard deviation of the electron energy flux 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 a visual inspection.

We used the AE index (Davis and Sugiura, 1966), 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 equatorial boundary of the auroral oval. Taking into account that there are two PC indices, obtained for the northern (PCN) and southern (PCS) hemispheres, we used the corresponding PCN (PCS) indices 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. The top panel shows the spectrogram of low energy electrons, the bottom panel shows total energy flux, calculated from the electron spectra presented on the top (red solid line) and counts of electrons with energy ≥ 100 KeV (green solid line). Dashed red lines in both panels indicate the position of the equatorial boundaries of the auroral oval and dashed green lines show the position of the polar boundaries of ORB. It is clearly seen that the curves of total energy flux and counts of electrons with energy ≥ 100 KeV show the position of the trapping boundary poleward of the equatorial boundary of the auroral oval.

According to the omniweb database (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, ΔLat are equal to -5.8° for the dawn and -1.7° for the dusk boundaries.

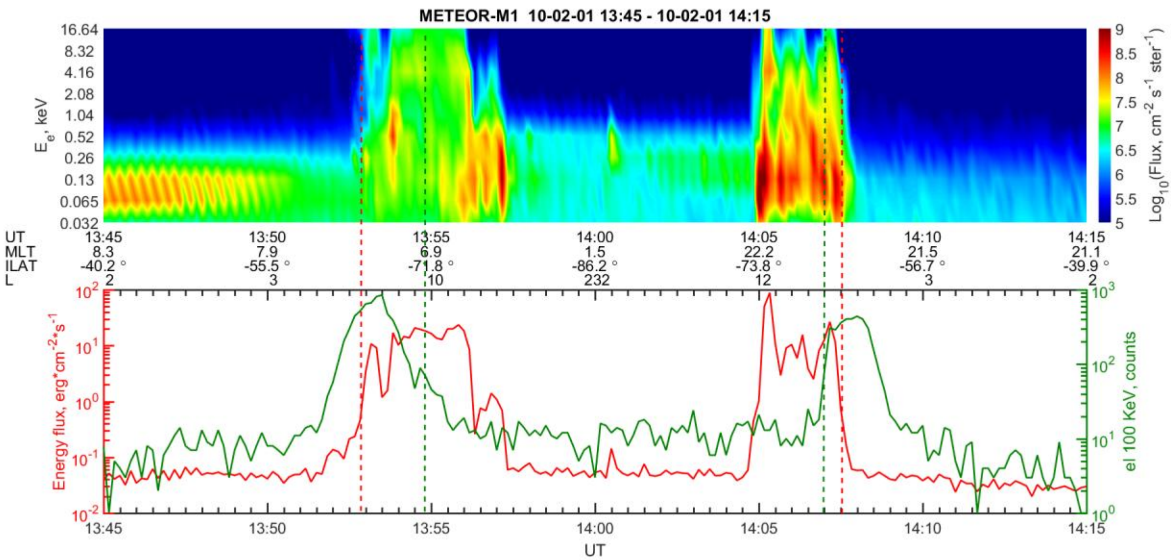

Figure 1: An example of the location of the polar boundary of ORB inside the auroral oval at AE>150 nT. Top panel -spectrogram of low energy electrons, bottom panel: red solid line - total energy flux, calculated from the electron spectra presented on the top; green solid line - counts of electrons with energy ≥ 100 KeV; dashed red lines mark the position of the equatorial boundaries of the auroral oval; dashed green lines - the position of the polar boundaries of ORB.

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: Δ Lat =1° for the dawn and 3.3° for the dusk boundaries.

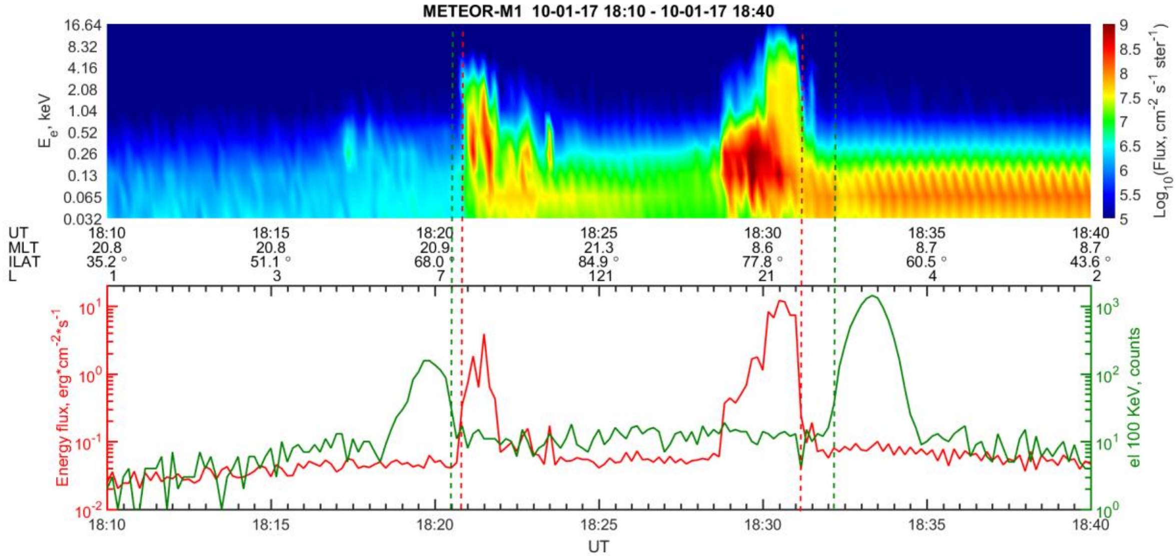

Figure 2: An example of observation of the polar boundary of ORB outside the auroral oval at AE<150 nT. The notations are the same as in Fig.1

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.

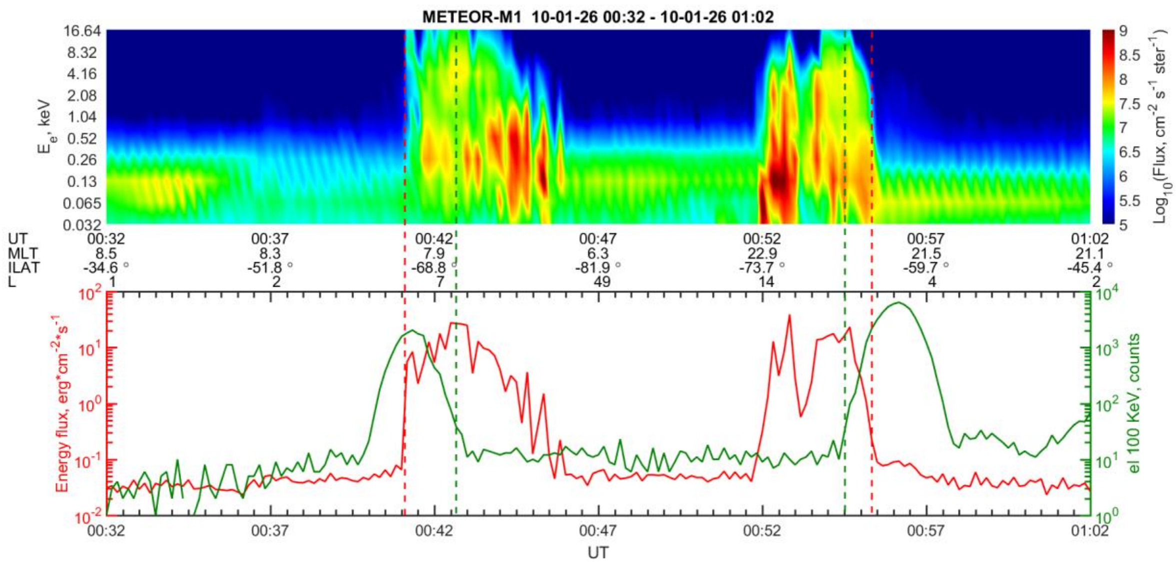

Figure 3: An example of observation of polar boundary of ORB inside the auroral oval at AE<150 nT. The notations are the same as in Fig.1

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, Δ 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, Δ Lat. The negative difference Δ Lat <0 means that the trapping boundary is located inside the auroral oval while the positive difference Δ Lat >0 indicates that the trapping boundary is located equatorward of the auroral oval. The METEOR-M №1 satellite has a sun-synchronous orbit. That is why we obtained Δ Lat only for a limited range of MLTs.

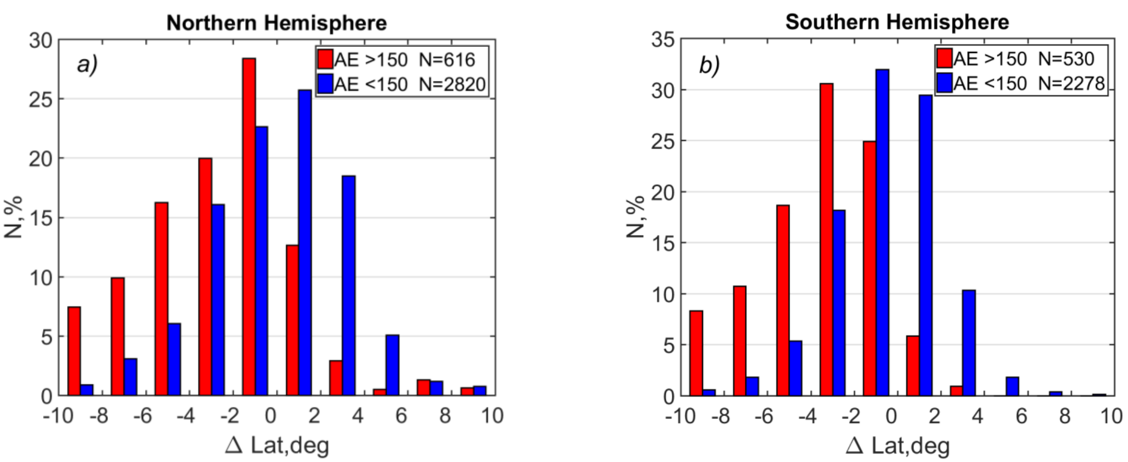

Figure 4: The distribution of Δ Lat for AE>150 nT (red bins) and <150 nT (blue bins) for northern (a) and southern (b) hemispheres. N show the number of events under described criteria.

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 indices. Figure 4 shows the distribution of the latitude differences Δ 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 - the number of events where the trapping boundary is located inside and outside of the auroral oval is nearly the same. However, for both sets there are a comparatively large number of events, for which this difference is comparatively small.

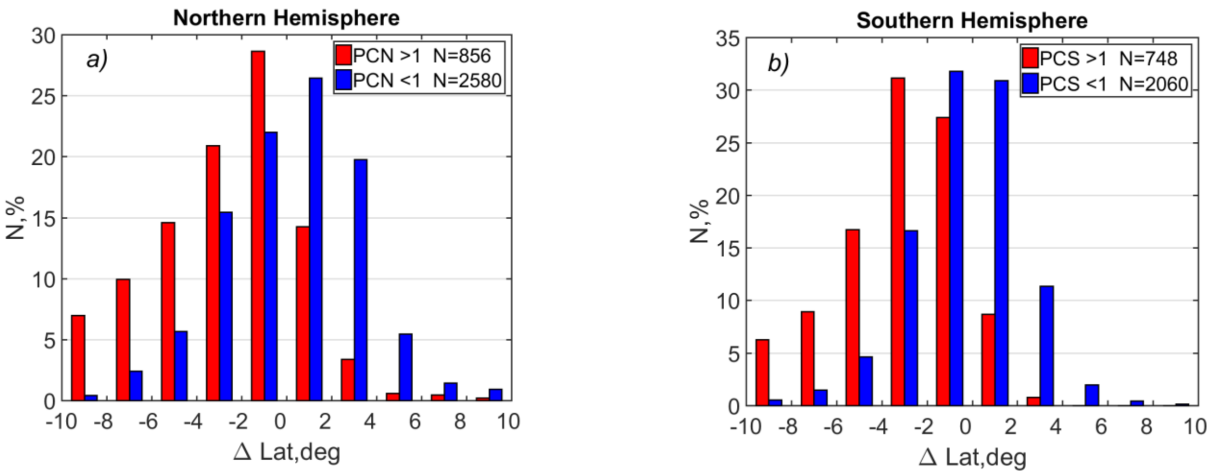

Figure 5: The distribution of Δ Lat for PC>1 (red bins) and <1 (blue bins) for northern (a) and southern (b) hemispheres. N show the number of events under described criteria.

Figure 5 shows the distribution of the latitude differences Δ 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 indices 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 behavior of the boundaries, using the AE and PC indices as a separate measures of geomagnetic activity, 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. We underline that the described effect can be clearly seen only in case of simultaneous measurements of plasma and energetic electrons on board of the same satellite, which allow to observe the trapping boundary inside the auroral oval directly during the local measurements. The statistical comparison of boundaries masks this effect, because the scattering of the position of the discussed boundaries in different crossings can be rather large (the standard deviation in the statistical position of the boundaries ≈ ±2° for the trapping boundaries and ≈ ±3° for the equatorial boundaries of the auroral oval) whereas the main part of ΔLat distributions in Fig.4 and 5 show the difference between boundaries within the limits ±2° in case of low geomagnetic activity. The observed scattering in positions of the boundaries are in agreement with early established scattering of the auroral oval boundaries (see Vorobjev et al. (2013) and references therein) and the outer ORB boundary (Kanekal et al., 1998, Kalegaev et al., 2018).

The analysis of the shifts of the studied boundaries with the increase of geomagnetic activity requires special attention and it is far from the main subject of our research. Figure 6 shows the L (McIlwain parameter) – distribution of both boundaries for AE<150 nT and AE>150 nT in both hemispheres. It is possible to see the real shift of the equatorial boundary of the auroral oval equatorward with the increase of AE, which is well known due to multiple auroral oval observations. At the same time the position of the trapping boundary practically does not change with the increase of AE. This result is in agreement with Kanecal et al. [1998], in that, in comparison with plasma boundaries, the energetic particle boundaries show a lower degree of correlation with solar wind Bz, VBz, and Kp index of geomagnetic activity.

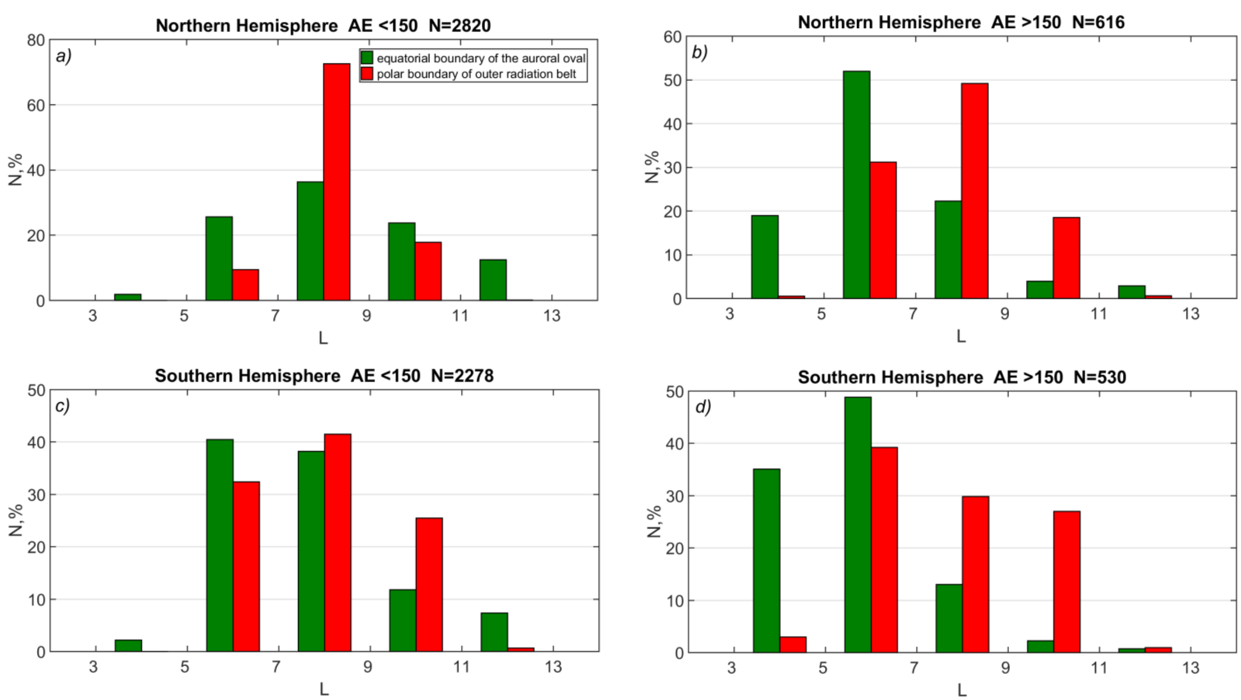

Figure 6: The distributions of the position of the equatorial boundary of the auroral oval (green bins) and the polar ORB boundary (red bins) from the L (where L is the McIlwain parameter) for northern (a,b) and southern (c,d) hemispheres for AE <150 nT (a,c) and AE>150 nT (b,d).

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 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 the trapping boundary and the equatorial boundary of the auroral oval.

Our study shows the trapping boundary is often located inside the auroral oval. The number of such events would be enhanced if instruments of better sensitivity were used. This is because the trapping boundary is defined as the boundary where particle fluxes become lower than a threshold determined by the sensitivity of a detector in case of low level of electron flux inside the ORB, so the increasing of the sensitivity would move the detected trapping boundary poleward, i.e. deeper inside the auroral oval. 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 shows that the number of events when the trapping boundary is observed inside the auroral oval significantly increases with both AE and PC indices.

The location of the trapping boundary inside the auroral oval agrees with latest 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 quiet time equatorial boundary of the auroral oval at $R \sim 7\ R_E$ near midnight and polar boundary at $R \sim 10$-$13\ R_E$. 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 other 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 also be important for the solution of the problem of acceleration of electrons in the ORB, 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 ORB. 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, we can conclude that the trapping boundary of energetic electrons, which coincides with the polar boundary of the ORB, is often located inside the auroral oval. This applies almost always to high geomagnetic activity times and also, though less often, to low geomagnetic activity times. All this that might help to re-analyse the relation between the dynamics of radiation belts and auroral phenomena.

Acknowledgments

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