

Interactive comment on “On the radiation belt location in the 23–24 solar cycles” by Alexei V. Dmitriev

Anonymous Referee #2

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In their manuscript, “On the radiation belt location in the 23-24 solar cycles”, Dmitriev exploited long-term data on energetic electron fluxes available from the NOAA/POES satellites that cover the time period 2001-2018 to show a clear solar cycle variation. Furthermore, the outer Van Allen belt is shown to shift equatorward as a result of the latest changes observed in the geomagnetic field that could not be predicted by the 12th generation of the IGRF model. In particular, a more than 31° displacement in the geographic latitude of the maximum electron flux in the outer radiation belt over the longitudinal sector of Siberia centred around 80°W – higher than in the European and North American sector - was largely attributed to sudden geomagnetic field changes that were observed during solar cycle 24 and possibly originated in the Earth’s core.

The presented material offers insufficient evidence pointing towards an anomalous shift

C1

of the outer radiation belt equatorward over the last years although electron flux data analysed have been carefully chosen so that the influence of sources of variability in the solar wind or related to geomagnetic activity are minimal. However, the solar cycle variation has not been adequately addressed. If the author can address this concern such that their conclusions are clearly supported by the data presented and can improve the placement of this work in the context of previous literature, then this manuscript could become a useful addition to the literature. Specifically, I could recommend this manuscript for publication in Annales Geophysicae subject to the specific points detailed below:

Page 2

In lines 27 – 28, a brief description of the outer Van Allen radiation belt is provided where this population of charged particles is presented as part of the outer magnetosphere, contrary to what has been widely established and is presented in the following publications:

- Baker (1995), The inner magnetosphere: A review, *Surveys in Geophysics*, doi: 10.1007/BF01044572
- Ebihara & Miyoshi (2011), Dynamic inner magnetosphere: A tutorial and recent advances, in Liu W., Fujimoto M. (eds) *The dynamic magnetosphere*, doi: 10.1007/978-94-007-0501-2_9

Additional references on the long-term variations of the radiation belts’ structure that should be considered are the following:

- Fung et al. (2006), Long-term variations of the electron slot region and global radiation belt structure, *Geophysical Research Letters*, doi: 10.1029/2005GL024891
- Baker & Kanekal (2008), Solar cycle changes, geomagnetic variations, and energetic particle properties in the inner magnetosphere, *Journal of Atmospheric and Solar-Terrestrial Physics*, doi: 10.1016/j.jastp.2007.08.031

C2

- Glauert et al. (2018), A 30-year simulation of the outer electron radiation belt, *Space Weather*, doi: 10.1029/2018SW001981

On lines 30 and 35, the semi-annual variation of the outer radiation belt is mentioned. This seasonal and not annual change could be explained by the IMF-effect also known as Russell-McPherron effect which is described in:

- Russell & McPherron (1973), Semiannual variation of geomagnetic activity, *Journal of Geophysical Research*, doi: 10.1029/JA078i001p00092

- McPherron et al. (2009), Role of the Russell-McPherron effect in the acceleration of relativistic electrons, *Journal of Atmospheric and Solar-Terrestrial Physics*, doi: 10.1016/j.jastp.2008.11.002

and where origins of the seasonal variability in geomagnetic activity have been traced.

Page 3

There are minor issues with English language use and several typographical errors.

For example, on line 54, the term auroral electrojet is first introduced that should be one word. Since Smith et al. (2017) studied both current in the north and south hemisphere, it should also be plural (auroral electrojets – AEJs).

Further down on the same page, on line 72, the work of Kataoka et al. (2015) is listed among the references for the October-November 2003 superstorms although it is focused on the magnetic storm of 17 March 2015 which is mentioned further down, in lines 74-81. It should, therefore, be moved more appropriately further down after the brief description of the 2015 Saint Patrick's Day storm.

Page 4

On line 89, it is indicated that the satellite observations used for the study of the outer electron belt location cover the time period from 1998 to 2016. However, the dates listed in Table 2 are within the time period between 2001 and 2018 which is also the

C3

time period on which this study is focused as indicated throughout the manuscript.

Page 5

On line 119, it should read “geomagnetic activity was very weak” and not “very week”.

On line 135, it is indicated that Figure 2 shows POES observations from 3 June 2016, while the figure caption indicated that the observations shown are from 2 June 2016.

In lines 123-126, the close link between increases in solar wind speed and enhancements in electron fluxes in the outer radiation belt is briefly described. Periodic oscillations in the Earth's magnetic field with frequencies in the range of a few millihertz (ultralow frequency waves) may indeed be an intermediary through which solar wind influences radiation belt dynamics due to their potential for resonant interactions with energetic electrons causing the radial migration of resonant electrons. It should, however, be corrected that electrons are accelerated and increase their energy when they are transported earthward to regions of stronger geomagnetic field. Recent, representative publications on this acceleration mechanism are the following:

- Mann et al. (2013), Discovery of the action of a geophysical synchrotron in the Earth's Van Allen radiation belts, *Nature Communications*, doi: 10.1038/ncomms3795

- Su et al. (2015), Ultra-low frequency wave-driven diffusion of radiation belt relativistic electrons, *Nature Communications*, doi: 10.1038/ncomms10096

Radial transport acts as a loss mechanism when particle drift outward and are lost to the magnetopause. The work of Horne et al. (2007) and Reeves et al. (2013), provided as reference, is centered on a different acceleration mechanism acting in the heart of the radiation belt (local acceleration) that involves whistler mode chorus waves rather than waves generated through the Kelvin-Helmholtz instability along the magnetopause.

Page 7

C4

In lines 187-188, the author notes that the inner edge of the outer radiation is defined as the “first high-latitude point of electron flux enhancements”. Could the latitude above which the flux enhancement was searched be indicated? In addition, which criterion was applied on flux measurements to determine which fluctuations in electron flux correspond to the enhancement observed at the inner edge of the outer electron belt?

Page 8

On line 203, the maximum of solar cycle 23 is indicated that it was observed in 2001 and that of solar cycle 24 in 2012-2013. It is not clear to me, and perhaps the reader, how this maximum was defined as both solar cycles were double-peaked according to the number of sunspots observed on the surface of the Sun that has been presented in Figures 4 and 5 with the solid grey line.

Further down, in the paragraph starting with line 208, an example of how the IGRF-12 model was used on the geographic coordinates of the outer radiation belt maximum flux to obtain the corresponding geomagnetic coordinates is provided. What height was selected as input to the model to determine the geomagnetic or geographic coordinates?

The choice of a simple linear fit over the set of outer radiation belt latitudes that have been calculated for the selected quiet days in the period 2001-2018 and are presented in Figures 4 and 5 puzzles me as it seems inadequate to support the main conclusion of the study. There is significant variability in the outer radiation belt location that is related to the solar activity variability that has not been accounted for – although it should – during linear regression. The difference in the variability observed in the location of the inner edge of the outer radiation belt or the location of the maximum electron flux has also not been quantified nor considered in the evaluation of the difference estimated between electron observations and magnetic field predictions from the IGRF-12.

Page 10

C5

On line 264, among the reference provided for the effect of the tilt angle variation on the location of the outer radiation belt, the study of Newell et al. (2006) is found. The specific study was centred on the cusp location as it is detailed in the next paragraph and should, therefore, be excluded from the reference list provided here.

In lines 269 and 270, the cusp location is suggested as a proxy of the outer radiation boundary. The author must imply the outer edge of the electron radiation belt or more correctly that a displacement of the cusp influences the location of the outer radiation belt but this is not clear from the text. It is also not substantiated by the findings of Newell et al. (2006). To date, the inner edge of the outer radiation belt has been suggested to be defined by the plasmopause, the outer boundary of the plasmasphere. Specifically, in the following publication:

- Baker et al. (2014), Impenetrable barrier to ultrarelativistic electrons in the Van Allen radiation belts, *Nature*, doi: 10.1038/nature13956

the authors analysed 20 months of electron flux data from the NASA/Van Allen Probes to identify a barrier in the inward transport of ultrarelativistic electron transport. Earlier,

- Darrouzet et al. (2013), Links between the plasmopause and the radiation belt boundaries as observed by the instruments CIS, RAPID and WHISPER onboard Cluster, *Journal of Geophysical Research*, doi: 10.1002/jgra.50239

had reached a different conclusion. The radiation belt location was found to be dependent on the energy range of particles examined but also that the plasmopause is more variable than the inner edge of the outer radiation belt. Namely, the inner or outer edge of the outer electron belt does not always coincide with the plasmopause.

In lines 274 and 275, the statement “Variations of the ORB location from cycle to cycle are not investigated yet” is not entirely correct. There are indeed significant limitations in such studies due to the lack of data covering several years that could be discussed at this point. Reference to studies such as Glauert et al. (2018) could also be provided.

C6

Page 11

On line 295, the findings of Finlay et al. (2015) suggesting rapid changes in the geomagnetic field in the past 15 years are briefly mentioned. Although the latest change observed in 2012-2013 seems to influence the location of the outer radiation belt, is there a signature of the change observed in 2006 and 2009 in the POES measurements from the same period analysed here?

Page 23

Individual graphs in Figure 2 are difficult to read because of the dark background colour. The font size selected for the x and y axis labels are so small that, even after blowing them up to 200%, labels are still difficult to read. On the other hand, titles over the two columns (2016 for the right column and 2006 for the left column) seem to be misplaced.

Pages 24-25

Fonts on plots in Figure 3 could also be enlarged if these are selected to be the final sizes of the graphs.

Interactive comment on Ann. Geophys. Discuss., <https://doi.org/10.5194/angeo-2018-118>, 2018.