

Interactive comment on “Earth’s radiation belts ions: Patterns of the spatial-energy structure and its solar-cyclic variations” by Alexander S. Kovtyukh

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Reply to Interactive comment by Anonymous Referee #1 on the manuscript “Earth’s radiation belts ions: patterns of the spatialenergy structure and its solar-cyclic variations” by Alexander S. Kovtyukh The manuscript addresses the scientific topic of understanding the spatial distributions of protons, Helium nuclei and CNO-group ions in the Earth Radiation Belts together with their variations during various solar minima and maxima. Even if it does not contain new data (it analyzes a wide range of older data from satellites), it offers a new interpretation of the mechanisms behind the different distributions of particle populations inside the magnetosphere. The exposition is fairly linear and

C1

the theoretical approach is sufficiently explained by the author, even if the description of the 3 sections seems rather repetitive, but it is something due to the very nature of the manuscript. The abstract reflects the content of the manuscript very well. Overall, it appears a little too long and with quite a few grammatical errors that make reading pretty hard and not fluent. Nevertheless, the topic is interesting, figures are simple but explanatory and the conclusions are satisfactory; thus, in my opinion, could be published after some fairly substantial grammar revision. I have a few more comments, then I will provide a table with some suggestions on how to correct some grammatical mistakes.

1. lines 96-97: what does “averaged” means here? And what does it mean that “All values of differential fluxes reduced to one dimension”? I think that this sentence should be rewritten more clearly. AC: These sentences reflect only the ordinary practice of working with experimental data. Apparently, they are surplus here and I removed them.

2. lines 144-147: this whole sentence, in my opinion, is not suitable for a scientific paper. The method used is the result, I believe, of your careful reasoning. Therefore the scientific community will evaluate and judge it on its own. You do not have to show any doubts about your choice. You can just address the fact that the uncertainties are linked to the errors of the experimental points shown in the various Figures. AC: I fully agree with you. The sentences removed from the text. A note about errors of the experimental points added.

3. Ines 148-157: in my opinion, describing in too much detail a procedure or a method that has not been used in the paper, does not help the linearity of the text and distracts the reader. This whole paragraph could be restricted to just two sentences. For example “[...] Representing plots in a different space of variables would lead only to more significant methodological errors and uncertainties, because of the natural differences in the instrumentation of the experiments taken into account; thus, a series of approximations or interpolation/extrapolation techniques would become inevitable.”. AC: I agree with you. The sentences have been replaced by your sentence.

C2

4. lines 179-180: I would remove this sentence because it does not add much to the description of the Figures. AC: I agree with you. The sentence is removed from the text.
5. line 184: the function $f(\mu, K, L)$ is not previously cited nor defined. I guess it is a reference to line 30 and to the curves in the $\{E, L\}$ plane, but maybe this implicit formula could be at least introduced earlier in the text. AC: I changed this sentence.
6. line 201: What is α ? I can infer it is the slope of the flux (spectral index) but maybe in this occasion, it could be useful to, at least, describe (with a couple of words) what it means explicitly in these plots. AC: I made this addition.

Line Comment

1. I think that after ":" the P in "Pattern" should be lowercase AC: I agree. Text corrected.
6. In my opinion the word "ions" appears two times in too little space. I would write "[...] protons, helium and ions of [...]" AC: I agree. Text corrected.
- 8-9. "[...] considered here using data from satellites in the period 1961–2017" AC: I agree. Text corrected.
- 9-10 "It has been found that the results of these measurements line up [...] following some regular patterns" AC: I agree. Text corrected.
- 10-11 see line 6 AC: I agree. Text corrected.
- 11-14 This sentence is a little bit convoluted and it may result difficult for the reader to understand. I would suggest: "[...] It has been observed that in the inner regions of the ERB, ion fluxes decrease with increasing solar activity and that the solar-cyclic variations of fluxes of $Z = 2$ ions are much greater than for protons; moreover, it seems that they increase with increasing atomic number Z ." AC: I agree. Text corrected.
- 14 "Finally, the possible physical [...]" AC: I agree. Text corrected.
- 20-21 "The ERB consist mainly of [...]" AC: I agree. Text corrected.

C3

- 23-24 The use of $Z = 2$ here is redundant, in my opinion. Helium and Oxygen are already ions with $Z = 2$ so I think that you can modify the sentence as "In ERB there are also helium nuclei and other $Z > 2$ ions (like Oxygen etc) [...]" AC: I agree. Text corrected.
- 25 "[...] disturbances, ion fluxes, and their distributions are changed" AC: I agree. Text corrected.
- 28 I think that "[...] between a local vector [...]" should be "[...] between the local vector [...]" because in a well-determined region you can have only one specific vector of the magnetic field. Moreover, I would put a "the" also in front of "vector of a particle velocity" AC: I agree. Text corrected.
- 29 "which are injected [...]" AC: I agree. Text corrected.
- 30 "[...] drifted conserving [...]" AC: I agree. Text corrected.
- 31 "This layer is called the drift shell" AC: I agree. Text corrected.
- 32-33 I will suggest adjusting the following sentence as follows, to maintain the text more easily readable: "Therefore, experimental data on the ERB are often represented in coordinates $\{L, B\}$, where L is the drift shell parameter and B is the local induction of the magnetic field [...]" AC: I agree. Text corrected.
- 35 "center of the dipole itself (in Earth's radii R_E)" AC: I agree. Text corrected.
- 36 In my opinion, the use of the passive form here should be avoided: "fluxes [...] decrease [...]" AC: I agree. Text corrected.
- 37 "[...] to higher latitudes [...]" AC: I agree. Text corrected.
- 41 I would add a "respectively" at the end of the sentence, to better distinguish between B and B_0 AC: I agree. Text corrected.
- 42-43 "Outer and inner regions of the ERB are maintained in dynamic equilibrium with

C4

the environment by different mechanisms" AC: I agree. Text corrected.

44-46 I would suggest to slightly modify this sentence as follows: "The outer belt [...] is formed mainly by the mechanisms of radial diffusion of such ions towards the Earth under the action of fluctuations of both electric and magnetic fields resonating with their drift periods" AC: I agree. Text corrected.

46-48 I would avoid the repetition of the word "ions" here. Moreover, I would rewrite these parts: "This transport is accompanied [...]" and "as a result of their interactions [...]" AC: I agree. Text corrected.

49-53 I think that there is a temporal mismatch between "[...] protons with $E > 10$ MeV is formed [...]" and "The inner belt of ions with $Z > 4$ was formed [...]" AC: I agree. Text corrected.

54-55 "[...] the mechanism of ion capture from Solar Cosmic Rays takes place [...]" AC: I agree. Text corrected.

57 "[...] ERB, together with the sources of injection and losses of ions, are known" AC: I agree. Text corrected.

58-61 The sentence here is very important, in my opinion, because it introduces the problem that this paper tries to solve, so it should be written more clearly. "However, for comprehensive verification of the physical models and to identify the mathematical models and their parameters, the formulation of complete and reliable empirical models of the ERB for each of the ion components, is necessary; it is also necessary for ensuring the safety of space flights [...]" AC: I agree. Text corrected.

62-67 "These models can be created only using experimental data, obtained over many years and decades; such models [...] were already created for protons (AP8/AP9) and they are widely used in space research. On the contrary, measurements of $Z = 2$ ion fluxes suffer from technical problems due to small statistics and high background of protons and electrons. For this reasons, empirical and semi-empirical models for $Z = 2$

C5

particles, are applicable [...]" AC: I agree. Text corrected.

68-72 I think that the first part of this sentence is just a repetition of what already said in lines 62-67; therefore I would leave only the part "One of the main problems of this work is to consider the possibility to create a sufficiently complete and reliable [...]" AC: I agree. Text corrected.

73-76 "In the following sections, the spatial-energy structure [...] (Sect. 2) together with the possible physical [...] are considered [...], and the main [...] are given (Sect. 4)" AC: I agree. Text corrected.

78-79 The sentence here is a bit confused. I would suggest to change it as "There can be ions trapped in drift shells only with energies less than some maximum values, determined by [...]" AC: I agree. Text corrected.

79 gyroradius AC: I agree. Text corrected.

83 "[...] The green line in Figs 1-6 represents this very boundary [...]" AC: I agree. Text corrected.

87-88 I would remove the second "satellites" here and just leave the phrase as: "[...] with the differences in their trajectories [...]" AC: I agree. Text corrected.

89 "[...] sets of energy channels [...]" AC: I agree. Text corrected. 90 I would substitute "Solar" with "Sun" AC: I agree. Text corrected.

91 "[...] of the Earth during various periods of data-taking [...]" AC: I agree. Text corrected.

91-92 "[...] influence the fluxes of [...] with respect to proton fluxes [...]" AC: I agree. Text corrected.

94-95 "[...] In this section, experimental data of various [...] 90_ have been used." AC: I agree. Text corrected.

C6

97-98 "[...] L shells, where these data were obtained, the ion fluxes are not distorted by the background [...]" AC: I agree. Text corrected.

99-103 "In many important experiments, the instruments were not able to separate fluxes of ions by their charge. Moreover, for the ions of the CNO group, the separation by mass are not usually performed. For heavier species, for example for Fe ions, we have very small data-sets. Therefore, this work presents data on helium ions (without any charge separation) and CNO ions (without any mass or charge separation)." AC: I agree. Text corrected.

104-108 "To solve the aforementioned problems, it is important to choose the form of representation (space of variables), in which the results of the single experiments can be compared to each other. In our case, the space {E, L} has been used; this choice is very efficient to better organize fragmentary experimental data obtained in different ranges of E and L." AC: I agree. Text corrected.

112-113 "Experimental points on these figures are connected by lines [...]" AC: I agree. Text corrected.

113-115 I think that a wide number of small sentences can break the fluency of the discussion. So, in this case, I would suggest to remove the last one and write: "[...] the decimal logarithms of the fluxes J, in unit of (cm²s ster MeV/n)⁻¹, are shown near each iso-lines" AC: I agree. Text corrected.

116 "[...] but also very convenient [...]" AC: I agree. Text corrected.

118-119 I think that both sentences inside the parenthesis () could be removed here. AC: I agree. Text corrected.

120-143 This whole paragraph is crucial for the reader to better understand the meaning of Figures 1-6 and how they were built. So, the concept should be expressed in a more concise and linear way; therefore, I strongly suggest to review this paragraph. Meanwhile, I suggest a possible rewording: "The points in Figs. 1-6 have been ob-

C7

tained from the values of the single ion fluxes J(L) as a function of energy (the average energy for each channel of the instrument) and with an equatorial pitch angle close to 90°. Unlike electron fluxes or ion fluxes measured during geo-active conditions, the ion fluxes considered here (i.e. during quiet periods), usually have only one maximum. As a result, for each experiment, 1 or 2 points were obtained (both shown on the outer/inner edges of the E vs L profiles). Sometimes, especially for low fluxes, only one point was obtained: in these cases, the radial profile of the ion fluxes was cutoff at small values of L due to a significant background of contaminating particles and no interpolation/extrapolation has been performed whatsoever. Each iso-line, shown in these figures, has been evaluated separately from the corresponding set of experimental points (icons); thus, in more abundantly populated sectors of the plots (i.e. for protons with E > 1 MeV at L > 2) such iso-lines are mixing in Figs. 1-2. In case of a large distance between neighboring points, the corresponding segments of the iso-lines are shown as dashed arcs. The radial profiles of the differential fluxes J(L) of particles with different energy tend to intersect with each other in those regions where the energy spectra present some local maxima or minima. On the contrary, the iso-lines cannot intersect with each other: because this would mean that, at the same point in the {E, L} space, proton fluxes differ very significantly (by an order of magnitude). Such uncertainty does not have a physical sense and a special analysis is needed to identify other possible sources of error." I agree. Text corrected. 159-161 "[...] There is a large number of experimental data concerning ERB protons; the most important of them are presented in Figs. 1 and 2. These figures serve as a comparison with similar distributions of Z₂ ions (Figs. 3– 6)." AC: I agree. Text corrected.

162 "[...] Figure 1 represents results from the satellites [...]" AC: I agree. Text corrected.

164 "[...] have been collected during minimum periods of various solar cycles, i. e. between [...]" AC: I agree. Text corrected.

173-174 "[...] These results were obtained during maximum periods of solar cycles:

C8

20th (1968-1971), 22nd (1990-1991), 20rd (2000), and 24th (2012- 2017) [...] " AC: I agree. Text corrected.

175-178 "The data [...] are given in both Fig 1 and 2 because solar-cyclic variations of the ERB proton fluxes are negligible [...]" AC: I agree. Text corrected.

181-184 "[...] the proton fluxes during solar minima (Fig. 1) are higher than during maxima (Fig. 2). In addition, in the former the inner edge of the proton belt is less steep and it can reach smaller L shells [...]" AC: I agree. Text corrected.

191 "[...] The red line corresponds to the [...]" AC: I agree. Text corrected.

192-194 "[...] can be connected to a discrepancy between the real configuration of the magnetic field lines of the magnetic field and the dipolar configuration (used here for L shell calculation) [...]" AC: I agree. Text corrected.

197-198 "[...] correspond to certain values [...]" AC: I agree. Text corrected.

199 "[...] changes of fluxes with changing L [...]" AC: I agree. Text corrected.

200 "[...] transformations in a magnetic field [...]" AC: I agree. Text corrected.

201 "[...] It results from these [...]" AC: I agree. Text corrected.

202 "distances [...] increase [...]" AC: I agree. Text corrected.

206 "In this work, a wider range of L and E is considered [...]" AC: I agree. Text corrected.

208-210 "[...] This is due to the fact that the energy range is significantly extended toward higher values (up to 200 MeV), but here the ionization losses for protons rapidly decrease [...]" AC: I agree. Text corrected.

214 I would put "are presented " at the end of this sentence AC: I agree. Text corrected.

215 "Figure 3 represents [...]" AC: I agree. Text corrected.

C9

220 "Figure 4 represents [...]" AC: I agree. Text corrected.

215-224 For these sentences, I would suggest following the comments on lines 162-174 AC: I agree. Text corrected.

229 I suggest removing "are observed " I agree. Text corrected.

229-230 "[...AC:] but the distribution of helium ions is slightly shifted towards higher values of L shell [...]" AC: I agree. Text corrected.

231 I think that could be useful to better define "white spots". Do you mean that there are few experiments on ERB helium studies? AC: I agree. Text corrected.

232 "AC: corresponds to the lower [...]" AC: I agree. Text corrected. 234 "[...] If one takes into account [...]" AC: I agree. Text corrected.

238 "[...] , which pass above the red line at $L > 2.5$, correspond to an average value of [...]" AC: I agree. Text corrected.

239-240 I would summarize a bit this sentence, writing only "[...] For helium ions spectra, as for protons ones, the values of the parameters of the power-law tail are in good agreement with what has been found in [...]" AC: I agree. Text corrected.

243 It is not clear to me what you intend here... I guess "[...] deviate from the slope of the red line [...]" -is that correct? AC: Text corrected.

244-245 "[...] increase with decreasing L slower than expected from adiabatic transformation. " AC: I agree. Text corrected.

245-247 "This means that the ionization losses of the ERB helium ions significantly exceed these losses for protons, in agreement to well-known calculations [...]" AC: I agree. Text corrected.

249-256 See comments on lines 162-174, 215 and 220 AC: Text corrected.

257 \tilde{E}_Y [...] of the ion fluxes of the CNO group [...]" AC: Text corrected.

C10

258 See my comments on line 230 AC: I agree. Text corrected.

262 "[...] but the fluxes of the CNO group increase by one order of magnitude or more [...]" AC: I agree. Text corrected.

263-264 "[...] it is seen also that the fluxes of the CNO group change several times more than the fluxes of helium ions do [...]" AC: I agree. Text corrected.

265 "[...] This means that [...]" AC: I agree. Text corrected.

269-270 "[...] to adiabatic laws that are not reported here, but this line let us estimate such deviations [...]" AC: Text corrected.

281 "[...] If one takes into account [...]" AC: I agree. Text corrected. 287 "[...] following the results [...]" AC: I agree. Text corrected.

289 "[...] of the ERB have been studied in many works [...]" AC: I agree. Text corrected.

291-292 "[...] These variations reach one order [...]" AC: I agree. Text corrected.

300 "[...] This density depends on [...]" AC: I agree. Text corrected.

303 "decrease " AC: I agree. Text corrected.

306 "[...] the stationary proton fluxes will increase with the decreasing solar activity [...]" AC: I agree. Text corrected.

307-308 "[...] and this leads to a decrease in the amplitude of the solar-cyclic variations of proton fluxes [...]" AC: I agree. Text corrected.

308 "[...] depends on its energy [...]" AC: I agree. Text corrected.

313 "[...] These variations can be explained by the same mechanism that has been suggested for protons at $L < 2.5$ [...]" IAC: agree. Text corrected.

315-316 "[...] For ions with $Z \geq 2$ in the ERB, ionization losses are more significant than for protons and this can be connected to the absence of ion [...]" AC: I agree. Text

C11

corrected.

317-318 "[...] Such short lifetimes are manifested also [...]" AC: I agree. Text corrected.

320 "[...] $Z \geq 2$, the regions in which variations can manifest, should be [...]" AC: I agree. Text corrected.

322 "[...] in the energy ranges considered here [...]" AC: I agree. Text corrected.

324 "[...] of the same energy of the other ions under study [...]" AC: I agree. Text corrected.

326 "[...] These are very rough estimations, but they are in agreement with the results presented in [...]" AC: I agree. Text corrected.

329-330 "[...] for protons with $E > 10-20$ MeV at $L < 2.2$; in fact, protons form mainly under the action of the CRAND mechanism [...]" AC: I agree. Text corrected.

331 "form mainly [...]" AC: I agree. Text corrected.

333-335 "[...] the solar-cyclic variations of $Z \geq 2$ ion fluxes can be motivated only under the assumption that the effect related with an increase in the ionization losses of such ions significantly exceeds the effect connected with the possible enhance of radial diffusion of ions on the rising phase of solar activity [...]" AC: I agree. Text corrected.

339 "in logarithmic scale " AC: I agree. Text corrected.

340-341 "[...] the range of L , in which these dependencies for two energy channels are parallel to each other is connected to the power-law tail of the spectra [...]" AC: I agree. Text corrected.

341-343 "[...] Instead, on smaller values of L , these fluxes begin to converge and the radial dependencies of these fluxes intersect with each other, which is related to the maximum in the spectra. [...]" AC: I agree. Text corrected.

343-345 I suggest to remove this sentence here, or at least merge it with the following

C12

one on line 345: "Concerning the physical mechanisms leading to the formation of power-law distributions of ions, the main source of ions in the outer [...]" AC: I agree. Text corrected.

346 "[...] usually spectra have an exponential shape [...]" AC: I agree. Text corrected.

352 "[...] The most likely region for this to happen is the plasma sheet [...]" AC: I agree. Text corrected.

354 "[...] the exponents of these spectra are close [...]" AC: I agree. Text corrected.

356 I think that the acronym for IMP-7 and 8 is well known to people reading this paper, I would leave only the reference to Sarris et al. AC: I agree. Text corrected.

357 "[...] the shape of the ion spectra of the PS usually do not change during [...]" AC: I agree. Text corrected.

359-360 "[...] in the PS exceed the times of substorms [...]" AC: I agree. Text corrected.

364 "[...] representations of the mechanisms [...]" ". I would also suggest removing "and character" AC: I agree. Text corrected.

365 "[...] this part of the ion energy spectra is formed in the PS by stochastic mechanisms of ion acceleration; this hypothesis is supported by many experimental results [...]" AC: I agree. Text corrected.

367-372 "[...] The statistical aspect of these mechanisms reveals itself, in particular, in the fact that the ratios of fluxes (and partial densities) of ions with different Z can differ, even greatly, at low and high energies. During their passage in the phase space, ions gradually lose information about their origin and, therefore, the high-energy tails of their spectra contain ambiguous information on the partial densities of different components of ions in the source [...]" AC: I agree. Text corrected.

373-378 The high-energy portion of the ion spectra of the PS can be generated by the mechanisms of acceleration of particles on magnetic irregularities moving with respect

C13

to each other (Fermi mechanism). The fractal structures of the PS are revealed on scales from ~ 0.4 to ~ 8 thousands kilometers, for example, in the data of the satellite Geotail [...]. If the mass of the ions are small compared to the mass of the magnetic irregularities in the PS, the average values of the index of the power-law tail should not depend on mass and charge of such nuclei " AC: I agree. Text corrected.

381 "it follows " AC: I agree. Text corrected.

382 "[...] <1, increases monotonically [...]" AC: I agree. Text corrected.

385-386 "[...] and their spectral density decreases rapidly with increasing [...]" AC: I agree. Text corrected.

388 "corresponds to the condition [...]" AC: I agree. Text corrected.

393 "[...] form analogous to that of ion spectra in the ERB [...]" AC: I agree. Text corrected.

398-399 "[...] In this work, the experimental results [...] plane, have been analyzed [...]" AC: I agree. Text corrected.

401-404 "[...] The degree of such similarity increases with [...] and it is linked to the nature of the main sources and on the universality [...]" AC: I agree. Text corrected.

405-407 "[...] Moreover, solar-cyclic (11-year) variations of the spatial-energy distributions of the ERB ion fluxes have been investigated, It has been noted that the ERB ion fluxes are weaker with increasing solar activity and this effect increases with increasing atomic number Z. " AC: I agree. Text corrected.

408 "[...] is typical, also, for faster [...]" AC: I agree. Text corrected. 409-410 "[...] as has been underlined in [...]" AC: I agree. Text corrected.

412 "[...] their radial diffusion can be neglected [...]" AC: I agree. Text corrected.

417-418 "[...] As Z and energy become larger and L becomes smaller, the uncertainties

C14

in the values of the ERB fluxes become larger [...] " AC: I agree. Text corrected.

418-421 "These gaps must be filled by the results of future experiments on satellites; for now, the extensive gaps in the experimental data for fluxes of ions with $Z \geq 2$ do not allow to create sufficiently complete and reliable empirical models of the ERB for these ions. " AC: I agree. Text corrected.

599-603 "The numbers on the curves refer to the values of the decimal logarithms of J where J [...] is the differential flux of protons with [...] . Data of satellites are associated [...] symbols. The red line corresponds to [...] , while green line corresponds to [...] " AC: I agree. Text corrected.

605-609 See comments for lines 599-603 AC: I agree. Text corrected.

611-615 See comments for lines 599-603 AC: I agree. Text corrected.

617-621 See comments for lines 599-603 AC: I agree. Text corrected.

623-627 See comments for lines 599-603 AC: I agree. Text corrected.

629-633 See comments for lines 599-603 AC: I agree. Text corrected.

I am very grateful to Referee #1 for such an exclusively generous and thorough review. All these comments are very helpful for me and it is taken into account in the manuscript.

With grand regard, Alexander S. Kovtyukh

Please also note the supplement to this comment:

<https://www.ann-geophys-discuss.net/angeo-2019-152/angeo-2019-152-AC1-supplement.pdf>

Interactive comment on Ann. Geophys. Discuss., <https://doi.org/10.5194/angeo-2019-152>, 2019.

C15

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Fig. 1.

C16