Anonymous Referee #2 Received and published: 7 July 2019

General comment

The review written by the author and published last year in the journal Space Science Reviews (SSR) concluded that there is a need for the development of radiation belt heavy ion empirical models. The submitted paper gathers available heavy ion measurements obtained all over the space age and tries to pave the way for the development of such models. To do so, invariant parameters (that are constant over a given range of L) are detailed and available measurements are shown on Figures and discussed in detail. The solar cycle variation of heavy ion fluxes is for the first time explored in the submitted article. Finally, the presented measurement database is important to explore the physical mechanisms that govern the heavy ion radiation belts, what is done by the author in sections 3 and 4. Comparative lessons with what is known for the protons are drawn.

There is no doubt that the work presented here is important and may contribute to advances in our understanding and prediction of the heavy ion radiation belts. The submitted article may therefore, according to the reviewer, be ultimately published after several clarifications. The article needs to first be edited for English, in order to make it easily understandable so that it would have an impact on the work of others. There viewer is then wondering: what is new in this article, compared in particular with there view published in SSR last year (see specific comments)? I recommend the article to be revised and reviewed again to see if, after English proof and clarifications, the article would be suitable for publication in Annales Geophysicae.

> I am very grateful to the reviewer for very helpful comments on the manuscript.
>
> I will try to eliminate my errors in the English language.
>
> In this manuscript is a new presentation of experimental data, as well as a comparison of this presentation with the invariants of the spatial-energetic structure of the ERB ion fluxes, and the physical conclusions that follow from these presentations. The comparison and analysis of data on ions with $Z > 1$ obtained in years near the minimum and maximum of solar activity made for the first time. The methods proposed here that allows progress in the problem of constructing empirical models of heavy ions (data for which is clearly not enough) is also a new.

Specific comments

Section 2: would it be possible to clarify if the invariant parameter values given here come from previous publications or are the outputs of the new study? The values reported here are very important. If the values have now been recomputed or updated, would it be possible to have them highlighted in a table, for instance? A possible use from other researchers would be to compare them with what has been observed by now two orbiters around Jupiter, as these orbiters performed numerous observations of trapped heavy ions (helium, oxygen, sulfur).

Would it be possible to remind, with maybe one sentence, the criterion used to select quiet periods over which the measurements are averaged?

The measurements are averaged near solar cycle minimum and near solar cycle maximum. Are the measurements very dispersed around this average in each case or are the standard deviations small compared to the shown averages? A comment may be added in the main text about this.

The dataset of heavy ion measurements is limited, but is it large enough to conclude if there is any observable Magnetic Local Time asymmetry in the heavy ion radiation belts, in particular at the lowest considered kinetic energies?

Section 4: What are the new conclusions on the physics of the heavy ion radiation belts? If you confirm what has already been reported in previous publications, would it be possible to add a sentence to state it? Otherwise, new findings may be more highlighted in this section and in the conclusion.

Lines 453-454: "Here, the experimental database is significantly expanded, many modern measurements of the ion fluxes of the ERB have been added", what are the modern heavy ion measurements added since the article published by the author in 2001? For the protons, one can see the GEO-3 and Van Allen Probe observations, however there does not seem to be any "modern" measurement of heavier ions.

> Section 2. The invariants of the ERB structure were obtained in the works of the author 1984-2000 (see references in the manuscript). Of course, I compared the values of these invariants with the results of experiments that were published after 2000, but this had no effect on the average values of the invariants and their variance.
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> When I finished this cycle of works, I looked to the distributions of ions in the belts of other planets (Jupiter, Saturn) and made sure that these belts have such invariants also and their values correspond to the mechanisms discussed in section 4 (for the magnetic fields of these planets). I did not develop this subject, because I had many other interesting and immediate problems.
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> The absence of storms and substorms and Kp < 2-3 were chosen as the criterion for the quiet magnetosphere.
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> The values of scatter of the structure invariants connected mainly with instrumental errors and with the inevitable methodical errors of my analysis (see lines 135-139). For many experiments, the scatter of these values is much smaller, but by averaging the results, we obtain the ranges of values that are given in lines 122-125 and 128-131. For heavy ions, this scatter is much larger than for protons: there was less data and the instruments had less resolution for them. These invariants are observed in all satellite data in the near-equatorial ERB regions.
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> In my analysis 1984-2001 the solar-cyclic variations were considered in detail only for the last parameter (similarity of the spectra of the different ionic components), which varied greatly during the solar cycle. The invariants connected with the maximum of the spectra and with the intermediate exponential part of the spectra changed significantly less, and the invariants connected with the power-law tail of the spectra were almost independent of solar activity (see lines 140-143). These conclusions are confirmed by Figs. 1-6 and correspond to the mechanisms of formation of these invariants, discussed in Section 4.
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> The results given in section 2 were published only in Russian journals (in the review in SSR and in my articles in Annales Geophysicae they were only mentioned). These results most fully prove the fact of radial diffusion of ions with conservation their first adiabatic invariant in a wide ERB region.
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> Of course, even with a limited set of experimental data, we can conclude that at *L* > 5-6 even in quiet periods there is a dependency of ion fluxes on MLT. This applies not only to ions of very low energies (ring current) and to the ERB ions also. But

for quiet periods on the data of the geosynchronous satellite Gorizont and using averaged empirical model of the magnetic field at the GSO it was established that the dependence of structural invariants on MLT is not here.

In connection with these comments, I will revision the text in the Section 2 of the manuscript and try to clarify and expand it.

Section 4. Most of the conclusions of Section 4 were published in Russian journals (Kovtyukh, 1999b, 2001). But they are losting in the literature. In addition, these conclusions supplemented. For the first time, the role of fluctuations of the thickness of the plasma sheet of the magnetospheric tail in the formation of the power-law tail of the ion spectra of the ERB is highlighted. These findings will be highlighted in this section and in the Conclusions.

Lines 453-454. In my publications of 1984-2001 considered only the ERB region at $L > 3$. Here I considered a wider range of L (from 1.2 to 8) and E (up to 200 MeV), i.e. considered also the inner belt. In the general picture included not only the latest data, but also other data obtained at $L < 3$. Figures 1 and 2 includes data for protons at $L < 3$ from the satellites Relay-1, Azur, CRRES, Molniya-1, Explorer-45, ISEE-1, OHZORA, ETS-VI, Akebono, GEO-3 and Van Allen Probes. Due to this, we succeeded in tracing the invariants corresponding to the power-law tail of the proton spectra up to $L = 1.8$. Figures 3 and 4 includes data for helium ions at $L < 3$ from the satellites OV1-19, Explorer-45, Molniya-2, Prognoz-5, ISEE-1 and Akebono. Figures 5 and 6 includes data for ions of the CNO group at $L <3$ from the satellites Explorer 45 and ISEE-1.

Figures 8 and 9 present data of the satellite Polar for protons and helium ions, which I had not previously considered because of the significant deviation of this satellite's orbit from the equatorial plane. Most of these data refer to areas with $B/B0 >> 1$, where the ERB structure have not invariants. In addition, a main results of this satellite were published after 1999.

After the results of these satellites, for the ERB heavy ions with energies above hundreds of keV, unfortunately, nothing new appeared (although many very interesting results were obtained for the ion composition and dynamics of ion fluxes of lower energies, i.e. for the ring current).

These explanations will be added to Section 3.

Technical corrections

The article needs to be edited for English.

It would help the reading to explain in the figure captions what the colored lines refer to, even if it is explained in the main text. In the main text, would it be possible to clarify what the maximum deviations shown by the colored vertical segments are: are they based on energy spectra measured by all the satellites, or only a subset? Would it also be possible to clarify the meaning of the following statement “on a logarithmic energy scale, the magnitudes of these segments do not depend on L shell”? Does it mean that the size of the segments changes a little bit with L, but not enough to be clearly seen when plotted with a logarithmic scale?

Section 3: this section is quite long, would it be possible to add subsection titles to help the reader? You may have a subsection on the protons in the (E, L) space that would start after line 170, one on the helium ions in (E, L) space that would start after line 259, one on the CNO ions in (E, L) space starting after line 287, and finally one on the protons and helium ions in the (L, B/B0) space starting after line 319.

I will edit and correct the text of the manuscript according to English.

Additional explanations in the captions for figures will be added.

The maximum deviations of the colored lines correspond to the dispersions of the parameters given in Section 2. For many experiments, especially with heavy ions, the values of these invariants are determined much more accurately not by the spectra, but by the radial profiles of the ion fluxes for different pairs of energy channels. For example, the range L, in which these profiles are parallel to each other, corresponds to the power-law tail of the spectra. On smaller L these profiles begin to converge and intersect with each other; this region corresponds to the exponential part and to the maximum in the spectra.

I will clarify this point in the text.

All figures presented on a logarithmic scale. For particles moving in the equatorial plane, as in Fig. 1-6, the first adiabatic invariant is $E/B(L)$. The ratios of the upper and lower values for each invariant do not depend on L. Consequently, the difference of the logarithms of these values is also independent on L. Therefore, the vertical segments on the colored lines can be shifted along the corresponding lines without changing their sizes on the energy scale. In other words, "on a logarithmic energy scale the magnitudes of these segments do not depend on L shell". This is also true for magnetic traps of non-dipole type, i.e., in our case, for large L.

Invariants corresponding to index of the power-law tail and similarity of the distributions of various ionic components cannot be plotted in Fig. 1-6 by color lines: they do not depend on E and L. First from these invariants manifests itself in a parallel course of isolines on sufficiently large L and is calculated over the intervals between these isolines. Second from these invariants is manifested only if overlapped Figs. 1-3-5 and also Figs. 2-4-6 (in this case, it is necessary leave only the isolines and give them a different color or thickness). With such an overlay, one can see that on $L > 3.5$, the structure of isolines in even figures (minimum solar activity) is closer to each other than on odd figures (maximum solar activity). Since on the figures energy is presented in MeV/n, this means that at the minimum of solar activity the similarity parameter of these distributions is closer to M_i (as in the heliosphere), and at the maximum of solar activity this is closer to Q_i (as in the ring current). From the experimental spectra and the radial profiles of the fluxes ratios for different ion components this parameter calculated more precisely.

I will supplement these remarks in Section 3 of the manuscript.

I agree to break up Section 3 into subsections for different ionic components.