Shprits, Y., Horne, R. B., Kellerman, A. C., Drozdov, A. Y. (2018): The dynamics of Van Allen belts revisited. - *Nature Physics*, *14*, pp. 102—103.

DOI: http://doi.org/10.1038/nphys4350

The dynamics of the radiation belts revisited

Yuri Y. Shprits[1,2,3,] Richard B. Horne[4], Adam C. Kellerman[2], and Alexander Y. Drozdov[2]

1. Helmholtz Centre Potsdam, GFZ, German Research Centre for Geosciences, Potsdam, Germany and University of Potsdam, Potsdam, Germany
2. Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA
3. Department of Earth Planetary and Space Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts
4. British Antarctic Survey, Cambridge, UK

In an effort to explain the formation of a narrow third radiation belt at ultra-relativistic energies detected during a solar storm in September 2012, Mann et al.[2] present simulations from which they conclude it can be explained by an outward radial diffusion alone and additional loss processes by higher frequency waves are not needed in this case. The comparison of observations with the model in Figures 2 and 3 of their Article clearly shows that even with strong radial diffusion rates, the model predicts a third belt near L^*=3 that is twice as wide as observed and approximately an order of magnitude more intense. We therefore disagree with their interpretation that "*The agreement between the absolute fluxes from the model and those observed by REPT shown on Figs 2 and 3 is excellent*". At multi-MeV energies, observations show an extremely narrow remnant belt. Radial diffusion tends to smooth the gradients in phase space density (PSD) and cannot produce narrow structures and sharp gradients.

Previous studies[3] have shown that outward radial diffusion plays a very important role in the dynamics of the outer belt and is capable of explaining rapid reductions in the electron flux. It has been also shown that it can produce remnant belts (Figure 2 of this long-term simulation study[4]). However, radial diffusion alone cannot explain the formation of the narrow third belt at multi-MeV during September 2012. An additional loss mechanism is required.

Higher radial diffusion rates cannot improve the comparison of the Ref 2 model with observations. A further increase in the radial diffusion rates (reported in Figure 4 of the Supplementary Information of Ref. 2) results in the overestimation of the outer belt fluxes by up to 3 orders of magnitude at energy of 3.4 MeV.

Observations at 2 MeV where belts show only a 2-zone structure, were not presented in the Reference 2. Simulations of electrons with energies below 2 MeV with the diffusion rates and boundary conditions used by Mann *et al*. would likely produce very strong depletions down to L=3-3.5, where L is radial distance from the center of the earth to the given field line in the equatorial plane. Observations do not show a non-adiabatic loss below L~4.5 for 2 MeV. Such different dynamics between 2 MeV and above 4 MeV at around L=3.5 are another indication that particles are scattered by electromagnetic ion cyclotron (EMIC) waves that affect only energies above a certain threshold.

Observations of the Phase Space Density (PSD) provide additional evidence for the local loss of electrons. Around L^*=3.5-4 PSD shows significant decrease by an order of magnitude starting in the afternoon of September 3 (Figures 1a), while PSD above L^*=4 is increasing. The minimum in PSD between L^*=3.5-4 continues to decrease until September 4. This evolution demonstrates that the loss is not produced by outward diffusion. Radial diffusion cannot produce deepening minimums, as it works to smooth gradients. Just as growing peaks in PSD show the presence of localized acceleration[5], deepening minimums show the presence of localized loss.

The minimum in the outer boundary is reached on the evening of September 2. After that, the outer boundary moves up, while the minimum decreases by approximately an order of magnitude, clearly showing that this main decrease cannot be explained by outward diffusion, and requires additional loss processes. The analysis of profiles of PSD is a standard tool used, for example, in the study about electron acceleration[5] and routinely used by the entire Van Allen Probes team. In the Supplementary Information, we show that this analysis is validated by using different magnetic field models.

Deepening minimums at multi-MeV during the times when the boundary flux increases are clearly seen in Figure 1a. They show that there must be localized loss, as radial diffusion cannot produce a minimum that becomes lower with time. At lower energies of 1-2 MeV, which corresponds to lower values of the first adiabatic invariant μ (Figure 1b), the profiles are monotonic between L^*=3–3.5, consistent with the absence of scattering by EMIC waves that affect only electrons above a certain energy threshold[6,7,8,9].

In summary, the results of the modeling and observations presented by Mann *et al*. do not lend support to the claim of explaining the dynamics of the ultra-relativistic third Van Allen radiation belt in terms of an outward radial diffusion process alone. While the outward radial diffusion driven by the loss to the magnetopause[2] is certainly operating during this storm, there is a compelling observational and modeling[6,2] evidence which shows that very efficient localized electron loss operates during this storm at multi-MeV energies, consistent with localized loss produced by EMIC waves.

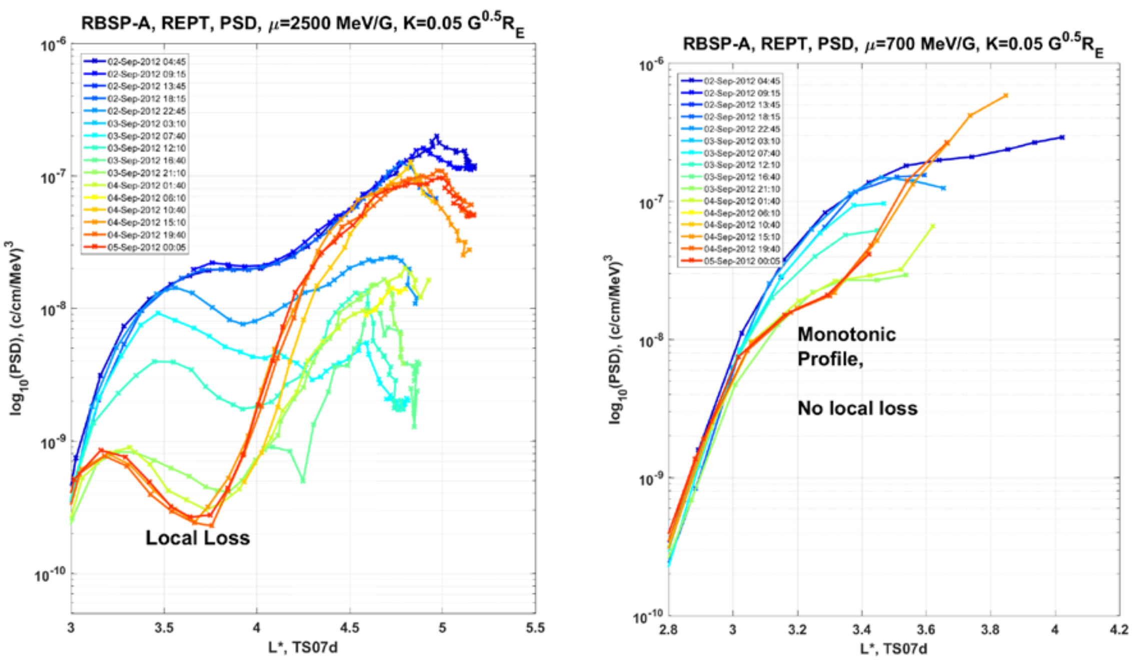

Figure 1 a) Similar to Supplementary Figure 3 of Ref. 2, but using TS07d[10] model and for μ=2500 MeV/G, K=0.05 $G^{0.5}R_E$. b) Similar to Supplementary Figure 3 of Ref. 2, but using TS07D model and for μ=700 MeV/G, corresponding to MeV energies in the heart of the belts.

References

1. D. N. Baker *et al*. A Long-Lived Relativistic Electron Storage Ring Embedded in Earth's Outer Van Allen Belt *Science* **40**, 186-190 (2013)
2. Mann, I. R. *et al*. Explaining the dynamics of the ultra-relativistic third Van Allen radiation belt. *Nat. Phys.* **12**, 978–983 (2016).
3. Shprits, Y. Y. *et al*. Outward radial diffusion driven by losses at magnetopause. *J. Geophys. Res. [Space Phys]* **111,** (2006).
4. Subbotin, D. A., Shprits, Y. Y. & Ni, B. Long-term radiation belt simulation with the VERB 3-D code: Comparison with CRRES observations. *J. Geophys. Res. [Space Phys]* **116,** A12210 (2011).
5. Reeves, G. D. *et al*. Electron acceleration in the heart of the Van Allen radiation belts. *Science* **341,** 991–994 (2013).
6. Shprits, Y. Y. *et al*. Unusual stable trapping of the ultrarelativistic electrons in the Van Allen radiation belts. *Nat. Phys.* **9,** 699–703 (2013).
7. Shprits, Y. Y. *et al*. Wave-induced loss of ultra-relativistic electrons in the Van Allen radiation belts. *Nat. Commun.* **7,** 12883 (2016).
8. Shprits, Y. Y., Kellerman, A., Aseev, N., Drozdov, A. Y. & Michaelis, I. Multi-MeV electron loss in the heart of the radiation belts. *Geophys. Res. Lett.* **44,** 2016GL072258 (2017).
9. Ma, Q. *et al*. Modeling inward diffusion and slow decay of energetic electrons in the Earth's outer radiation belt. *Geophys. Res. Lett.* **42,** 2014GL062977 (2015).
10. Tsyganenko, N. A. & Sitnov, M. I. Magnetospheric configurations from a high-resolution data-based magnetic field model. *J. Geophys. Res.* **112,** A06225 (2007).