The dynamics of Van Allen belts revisited

Mann et al. reply — We are pleased to address the comment on our paper1 from Shprits et al.2 since we believe it supports our conclusion that magnetopause shadowing and ultralow-frequency (ULF) wave outward transport can drive fast losses into the heart of the ultra-relativistic electron radiation belt and produce a remnant belt. As reported by Baker et al.3 , the September 2012 geomagnetic storm produced this phenomena, and we showed1 how such losses could explain it. However, Shprits et al. claim that for this single specific storm that electromagnetic ion cyclotron (EMIC) wave losses are essential for explaining the observed third belt. We dispute this interpretation. Contrary to the claims of Shprits et al., outward ULF wave radial diffusion can act on sufficiently short timescales4 to generate the observed remnant belt. For example, Supplementary Fig. 1 displays additional magnetopause shadowing simulation runs using the same approach described in ref. 1 showing an erosion of the outer belt and the generation of both monotonic and non-monotonic PSD profiles without invoking EMIC wave effects. Our ULF wave-driven radiation belt simulations not only reproduce the third belt morphology but also produce a narrower remnant belt at higher energies just as observed (Supplementary Fig. 2). The principal argument for the action of EMIC wave loss in the Shprits et al. Correspondence is based on analysis of electron phase space density (PSD) profiles. However, we disagree with their analysis and the derived PSD profiles since they do not appear to take into account uncertainties in measurements at the lowest REPT instrument energy channels, and effects from off-equatorial orbits (discussed in more detail in Supplementary Information). Figure 1 shows outbound Van Allen probe PSD profiles as a function of L* at fixed first adiabatic invariant μ = 3,500 MeV G–1, and at two fixed second invariant K = 0.05 RE G0.5 and 0.1 RE G0.5. This indicates a different sequence of events to those advanced by Shprits et al. Instead, it shows the development of PSD profiles that decrease with L* consistent with loss from magnetopause shadowing and ULF wave enhanced outward radial diffusion, a ~2.5 orders of magnitude decrease in PSD seen at L* ~ 5 from the initial conditions to the time of outbound orbit 4 at both K. See also Supplementary Figs 3 and 4, and 5 and 6, which show further data in support of this conclusion from both inbound and outbound orbits at 3,500 MeV G–1 and 2,500 MeV G–1, respectively. A smaller local dip in PSD is seen later in the evolution, and as discussed in the Supplementary Information might be related to EMIC wave losses, but this weaker loss is not responsible for creating the third belt morphology. Observations from multiple additional spacecraft such as the Los Alamos geosynchronous spacecraft (reaching L* as low as ~4.5; Supplementary Fig. 7 and the constellation of GPS satellites (Supplementary Figs 8 and 9) are also consistent with losses from enhanced outward ULF transport and magnetopause shadowing. Overall, our analysis indicates that our original conclusion in ref. 1 remains valid — the remnant belt and third belt morphology can be created by fast outward ULF wave transport and magnetopause shadowing, without resorting to a requirement for EMIC wave losses.

References 1. Mann, I. R. et al. Nat. Phys. 12, 978–983 (2016). 2. Shprits, Y. Y., Horne, R. B., Kellerman, A. C. & Drozdov, A. Y. Nat. Phys. 14, XXX–XXX (2017). 3. Baker, D. N. et al. Science 340, 186–190 (2013). 4. Mann, I. R. & Ozeke, L. G. J. Geophys. Res. Space Phys. 121, 5553–5558 (2016)