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Key Points:
- Significant flux enhancements of electrons with energies up to 7.7 MeV are reported during a small to moderate storm
- The phase space density evolution of ultrarelativistic electrons during this storm is analyzed and simulated using a radial diffusion model
- The results suggest that the physical mechanism causing ultrarelativistic electron flux enhancements during this storm is energy-dependent

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The Acceleration of Ultrarelativistic Electrons During a Small to Moderate Storm of 21 April 2017

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Abstract The ultrarelativistic electrons ($E >$ ~3 MeV) in the outer radiation belt received limited attention in the past due to sparse measurements. Nowadays, the Van Allen Probes measurements of ultrarelativistic electrons with high energy resolution provide an unprecedented opportunity to study the dynamics of this population. In this study, using data from the Van Allen Probes, we report significant flux enhancements of ultrarelativistic electrons with energies up to 7.7 MeV during a small to moderate geomagnetic storm. The underlying physical mechanisms are investigated by analyzing and simulating the evolution of electron phase space density. The results suggest that during this storm, the acceleration mechanism for ultrarelativistic electrons in the outer belt is energy-dependent: local acceleration plays the most important role in the flux enhancements of ~3–5 MeV electrons, while inward radial diffusion is the main acceleration mechanism for ~7 MeV electrons at the center of the outer radiation belt.

Plain Language Summary The Earth's radiation belt electrons exhibit frequent flux variations under the effect of various physical mechanisms. The inward radial diffusion and local acceleration by whistler mode waves are recognized to be the most important acceleration mechanisms for outer belt electrons, while their effectiveness and relative importance are still under considerable debate. In the past decades, intensive studies have been performed on the acceleration of energetic and relativistic electrons (hundreds of keV to ~2 MeV). However, ultrarelativistic electrons ($>$ ~3 MeV) received limited attention due to sparse measurements. The Van Allen Probes provide high-resolution measurements of ultrarelativistic electrons and thus an unprecedented opportunity to study the dynamics of this population. In this study, using data from Van Allen Probes, we report significant flux enhancements of ultrarelativistic electrons with energies up to 7.7 MeV during a small to moderate storm. The analysis and simulation of electron phase space density evolution indicate that the acceleration mechanism for ultrarelativistic electrons during this storm is energy-dependent: local acceleration plays the most important role for ~3–5 MeV electron acceleration, while the inward radial diffusion is the most important mechanism causing ~7 MeV electron acceleration at the center of outer belt.

1. Introduction

The radiation belts, consisting of outer radiation belt and inner radiation belt, are the regions filled with geomagnetically trapped energetic particles azimuthally drifting around the Earth (e.g., Roederer, 1970). The outer radiation belt is occupied with relativistic electrons of energies from hundreds of keV to $>$10 MeV. It is highly dynamic and the relativistic electrons in the outer belt often exhibit significant and prompt variations (e.g., Baker et al., 1986; Li et al., 2011). The acceleration, transport, and loss of outer belt electrons and corresponding physical mechanisms have been extensively and intensively studied, though the effectiveness and relative importance of physical mechanisms on the electron dynamics are still under considerable debate (e.g., Liu et al., 2018; Ma et al., 2016; Reeves et al., 2013; Thorne et al., 2013). Specifically, the study on the ultrarelativistic electrons ($E >$ ~3 MeV) in the outer belt attracted limited attention in the past due to sparse measurements prior to the Van Allen Probes era. The Relativistic Electron Proton Telescope (REPT) instruments on the Van Allen Probes provide unprecedented measurements of ultrarelativistic electrons with high energy resolution and wide energy coverage up to ~20 MeV (Baker et al., 2012), which gives us a great opportunity to study the dynamics of this population.

Statistical analysis has been conducted to investigate the relation between ultrarelativistic electrons and solar wind conditions/geomagnetic activities. Zhao et al. (2017), using data from the Van Allen Probes for over three years, showed that good correlations exist between ultrarelativistic electron enhancements and solar wind speed as well as the AL index. Moya et al. (2017) performed a statistical study to examine the effect of geomagnetic storms on the ultrarelativistic electron flux variations. Using observations during 78 storms, they showed that the probability of enhancement and loss of ultrarelativistic electrons during geomagnetic storms strongly depend on the electron energy and L shell, and fewer enhancement events were observed for higher-energy electrons at any given L.

Event studies have also been carried out to investigate the underlying physical mechanisms causing the ultrarelativistic electron acceleration. Li et al. (2009), using data measured by Polar High Energy Space Telescope, studied the flux enhancements of 4.5 MeV electrons down to L ~ 2.5 during the very intense "Halloween" storm in 2003 using a radial diffusion model. Their results suggest the fast inward radial transport to be the main cause of the observed 4.5 MeV electron flux enhancements. Reeves et al. (2013), using the Van Allen Probes data, showed significant flux enhancements of outer belt electrons during an intense geomagnetic storm of October 2012. The evolution of the phase space density (PSD) radial profile of electrons with μ = 3,433 MeV/G and K = 0.11 $G^{1/2}R_E$ during this storm shows a growing local PSD peak, which strongly suggests the local acceleration to be the physical mechanism responsible for the ultrarelativistic electron flux enhancements during this storm. Thorne et al. (2013), using a two-dimensional diffusion model, showed that the observed flux enhancements of 2–7 MeV electrons can be well explained by the whistler model chorus wave heating during the October 2012 storm. Similarly, Li et al. (2014) simulated the dynamics of ~500 keV to 5.6 MeV electrons during the intense storm on 17 March 2013 using a 2-D diffusion model. Their results suggest that the local acceleration by chorus waves play a critical role in accelerating electrons to ultrarelativistic energies. Li et al. (2016) studied the intense storm on 17 March 2015 using a 3-D diffusion model. They showed that the combined effect of chorus wave heating and radial diffusion reproduced flux variations of ultrarelativistic electrons with energies up to ~7 MeV during this storm well. Ma et al. (2016) also showed that for 3.4 MeV electrons, the local acceleration caused by the chorus waves is the most important mechanism causing significant flux enhancements during the geomagnetic storm on 1 March 2013. Baker et al. (2016), using data from REPT on the Van Allen Probes, reported complex and remarkable flux enhancements of ultrarelativistic electrons with energies up to ~10 MeV in the outer radiation belt during the two of the most intense storms in the past decade.

However, the majority of previous studies of ultrarelativistic electron dynamics has focused on that during intense geomagnetic storms with minimum Dst < -100 nT. This is possibly due to the common belief that significant flux enhancements of ultrarelativistic electrons usually occur during intense geomagnetic activities. In this study, using observations from REPT instruments on the Van Allen Probes, we report significant flux enhancements of ultrarelativistic electrons with energies up to 7.7 MeV in the outer radiation belt during a small to moderate storms with a minimum Dst of -50 nT. The evolution of PSD is investigated during this storm for electrons with different μ, and a radial diffusion model is conducted to examine the underlying physical mechanism causing the ultrarelativistic electron flux enhancements. The results suggest that the ultrarelativistic electron flux enhancements do occur during moderate solar wind conditions and geomagnetic activities, and the physical mechanism causing the ultrarelativistic electron acceleration in the outer belt is -energy-dependent.

2. Observations

A small to moderate geomagnetic storm with a minimum Dst index of -50 nT and a maximum AE index of ~1,000 nT occurred on 21 April 2017. During this storm, as Figure 1 shows, the solar wind speed was relatively fast (~500–700 km/s), and the z component of interplanetary magnetic field in geocentric solar magnetospheric coordinates was oscillating but the magnitude was not very large (minimum interplanetary magnetic field $B_z \sim -13$ nT). The relativistic electrons with energies of ~MeV all the way up to 7.7 MeV exhibited significant flux enhancements in the outer belt during this storm. Fluxes of electrons with relatively lower energies enhanced first and those of higher-energy electrons increased gradually. Specifically, for 7.7 MeV electrons, fluxes enhanced more than 1 order of magnitude at L ~ 4–5.5 during the recovery phase of this storm. These results suggest that the ultrarelativistic electron fluxes can enhance significantly even under moderate solar wind and geomagnetic activities. Note that the flux enhancements of 7.7 MeV electrons in the outer radiation belt also occurred during other moderate storms according to Van Allen Probes measurements, while this April 2017 storm is so far, the smallest geomagnetic storm (in terms of the Dst index) that triggered 7.7 MeV electron flux enhancements.

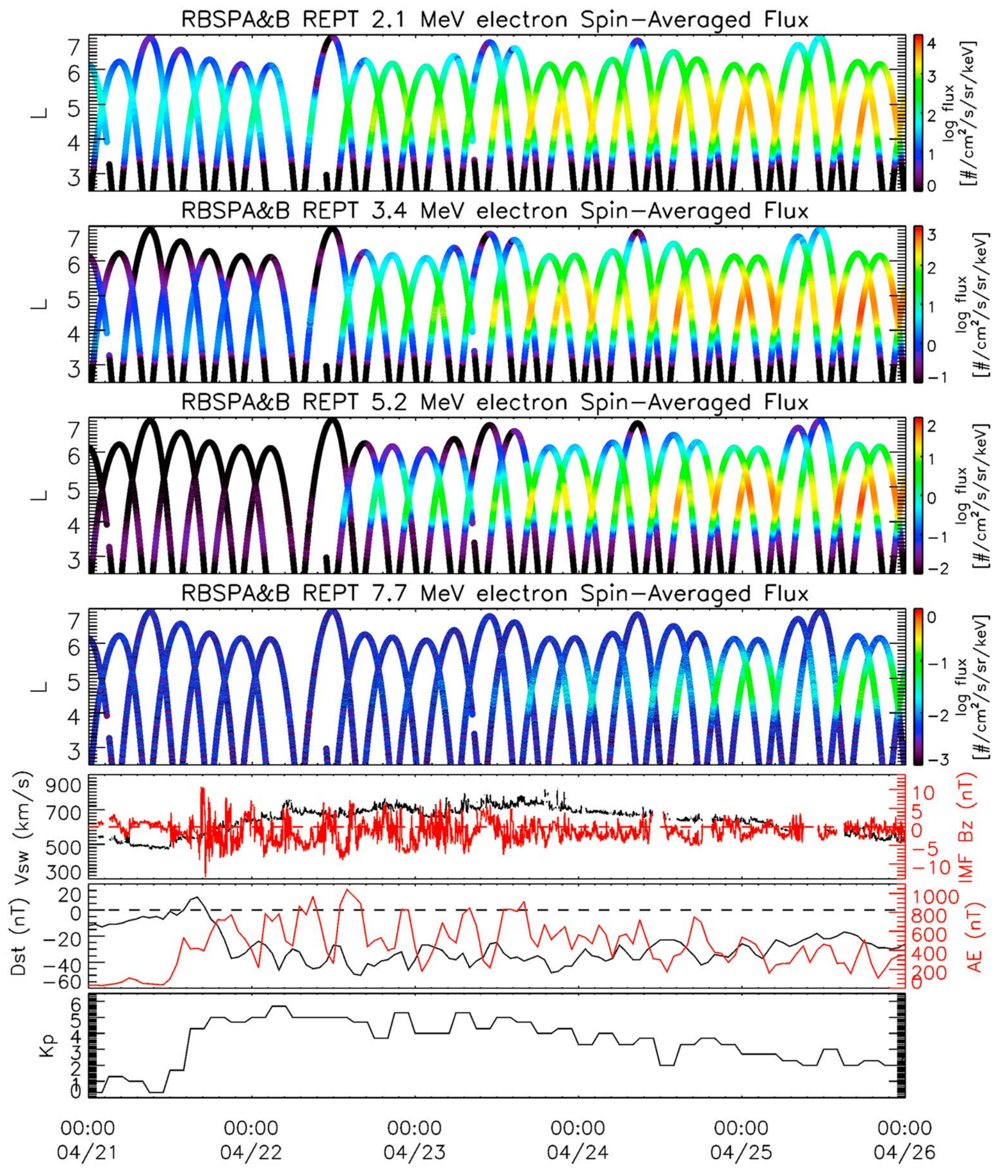

Figure 1. Spin-averaged fluxes of 2.1, 3.4, 5.2, and 7.7 MeV electrons measured by REPT instruments on the Van Allen Probes during 21–25 April 2017, along with the 1-min solar wind speed, interplanetary magnetic field (IMF) B_z, 1-hr Dst and AE indices, and 3-hr Kp index.

To investigate the physical mechanism responsible for the flux enhancements of ultrarelativistic electrons, the PSD evolution of ultrarelativistic electrons in the outer radiation belt is examined in details during the April 2017 storm. Pitch-angle-resolved level 3 data from REPT are used to calculate electron PSD under T89D geomagnetic field model (Tsyganenko, 1989), and the calculated PSDs are then interpolated onto tabulated μ and K grids. Figure 2 shows the energy (averaged across all magnetic local times) corresponding to electrons with $K = 0.1\ G^{1/2}R_E$ and different μ values as a function of L^* under different geomagnetic activities in T89D model. As shown in Figure 2, under relatively quiet geomagnetic activities (Kp = 2), the energy corresponding to μ = 4,000/10,000/16,000 MeV/G, $K = 0.1\ G^{1/2}R_E$ electrons is ~3.6/6.0/7.7 MeV at $L^* = 4.5$; during moderately disturbed times (Kp = 5), the energy of μ = 4,000/10,000/16,000 MeV/G, $K = 0.1\ G^{1/2}R_E$ electrons corresponds to ~3.1/5.2/6.6 MeV at $L^* = 4.5$.

Figure 3 shows the evolution of PSD radial profiles of electrons with different μ and K during 21–25 April 2017, using REPT data on the Van Allen Probes – B. Colors indicate the time of measurements during this storm. For electrons with μ = 4,000 MeV/G and $K = 0.1\ G^{1/2}R_E$ (~3 MeV at $L^* = 4.5$), a growing peak in PSD radial profile at

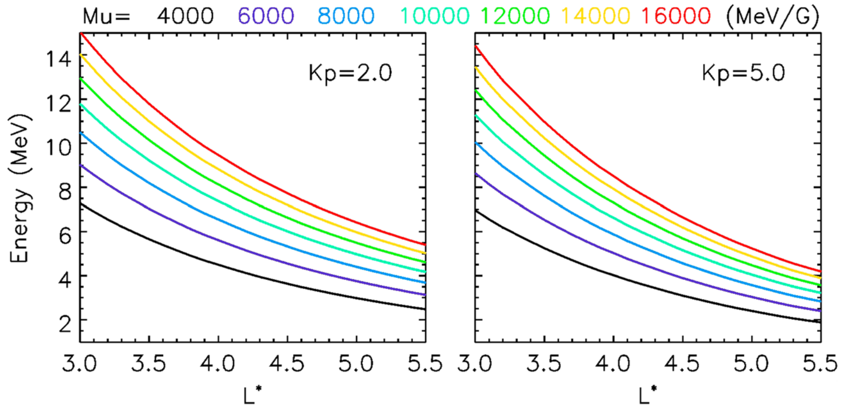

Figure 2. The energy (averaged across all MLTs) corresponding to μ = 4,000–16,000 MeV/G, *K* = 0.1 $G^{1/2}R_E$ electrons as a function of L^* under T89D geomagnetic field model with (left) Kp = 2 and (right) Kp = 5.

L^* ~ 4–4.5 can be clearly seen during this storm, indicating the local acceleration to be an important source process for this population. For μ = 8,000 MeV/G and *K* = 0.1 $G^{1/2}R_E$ electrons (~4.5 MeV at L^* = 4.5), the growing peak at L^* ~ 4.5 is even more significant. This is consistent with previous studies on the important role of chorus wave heating on several MeV electron flux enhancements in the outer belt (e.g., Ma et al., 2016; Thorne et al., 2013). Note that during this small to moderate storm, AE index reached ~1,000 nT, likely suggesting the electron injections into the inner magnetosphere, which could potentially excite chorus waves that are responsible for the local acceleration. However, as μ gets even higher, the local peak in PSD radial profiles started to diminish. For electrons with μ = 16,000 MeV/G and *K* = 0.1 $G^{1/2}R_E$ (~7 MeV at L^* = 4.5), no clear local PSD peak was observed at L^* = ~3–5.5, and the PSD radial gradient was mostly positive at this L^* range during this storm, which suggests the inward radial diffusion to be the most important source process for the energization of this population in the outer belt. These results

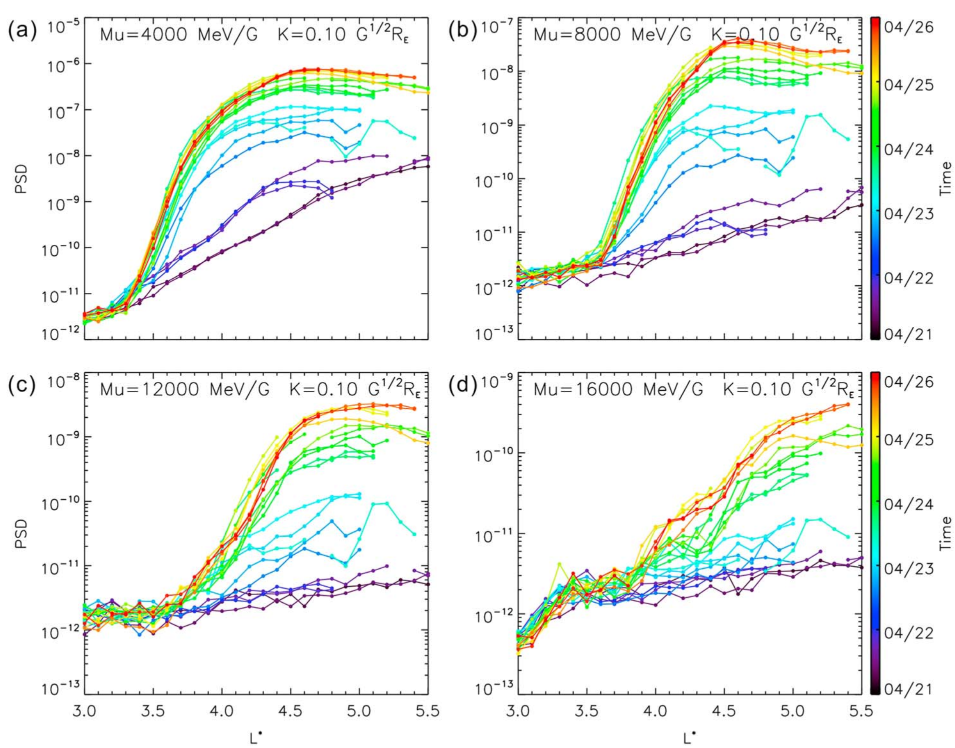

Figure 3. The evolution of PSD radial profiles of ultrarelativistic electrons with μ = (a) 4,000, (b) 8,000, (c) 12,000, and (d) 16,000 MeV/G and *K* = 0.1 $G^{1/2}R_E$ during 21–25 April 2017 using data from REPT on the Van Allen Probes – B.

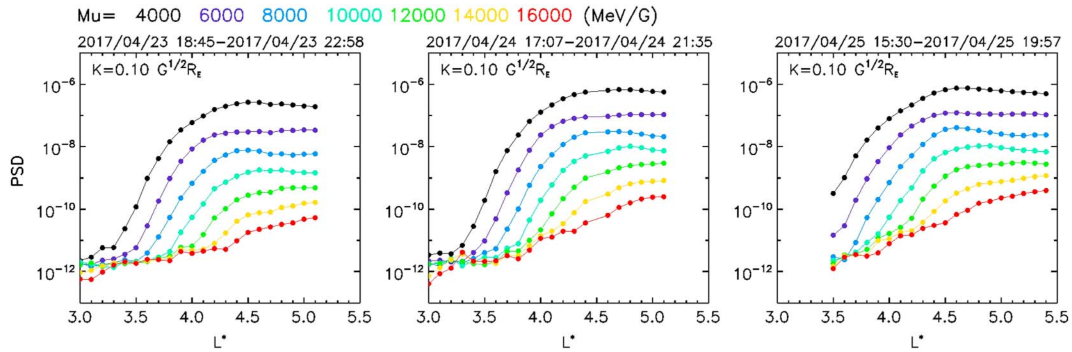

Figure 4. The PSD radial profiles for electrons with μ = 4,000–16,000 MeV/G and K = 0.1 $G^{1/2}R_E$ during three time intervals of the April 2017 storm using data from REPT on the Van Allen Probes – B. Different colors indicate PSD of electrons with different μ values.

indicate that the acceleration mechanism for ultrarelativistic electrons in the outer belt during this storm depends on μ value and thus the electron energy.

To further show the dependence of the PSD radial profile on the electron energy, Figure 4 compares the PSD radial profiles of electrons with μ = 4,000–16,000 MeV/G and K = 0.1 $G^{1/2}R_E$ during three time intervals of the April 2017 storm using data from REPT on the Van Allen Probes – B. Comparing PSD radial profiles of electrons with different μ during all three time intervals, the local peaks in PSD radial profiles were clear for μ = ~4,000–~10,000 MeV/G electrons (~3–5 MeV at L^* = 4.5), and the PSD peaks tended to move to higher L^* as μ increases. As μ gets even higher, the local PSD peak diminished at L^* = 3–5.5, and the PSD radial gradient was almost always positive at L^* = 3–5.5 during the entire course of the storm. This also suggests that during this storm, the physical mechanism causing the flux enhancements of ultrarelativistic electrons in the outer radiation belt is energy-dependent: for ultrarelativistic electrons with relatively lower μ, the local acceleration is found to be an important source process, while for those electrons with relatively higher μ, the inward radial diffusion is the main mechanism causing the outer belt flux enhancements. It is worth noting that the flux enhancements of ultrarelativistic electrons in the outer radiation belt require the local acceleration process by the wave-particle interaction, as the pure radial diffusion is not sufficient to accelerate plasmasheet electrons to such high energies. However, the results shown here suggest that for high μ electrons, during this small to moderate storm, the local acceleration process may have taken effect at even higher L-shells (beyond the apogee of Van Allen Probes) and the inward radial diffusion further transported and accelerated those electrons inward to the outer radiation belt and accounted for the observed flux enhancements of ultrarelativistic electrons. This is also supported by a recent study by Liu et al. (2018), which showed that during a moderate geomagnetic storm, chorus waves were observed at L-shells beyond the apogee of Van Allen Probes by Time History of Events and Macroscale Interactions during Substorms (THEMIS) and the numerical calculation suggested that the chorus wave heating at high L-shells and subsequent inward radial diffusion can explain the observed electron flux enhancements in the center of the outer belt.

3. Modeling Results

To further investigate the acceleration mechanisms of ultrarelativistic electrons during the April 2017 storm, a radial diffusion model is utilized to simulate the acceleration of μ = 8,000 MeV/G and 16,000 MeV/G, K = 0.1 $G^{1/2}R_E$ electrons. The radial diffusion model uses the Fokker-Planck equation (Schulz & Lanzerotti, 1974):

$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\left(\frac{D_{LL}}{L^{*2}}\frac{\partial f}{\partial L^*}\right) - \frac{f}{\tau}$$

where f is the drift-averaged PSD, D_{LL} is the radial diffusion coefficient, and τ is the electron lifetime. In this study, the Kp-dependent radial diffusion coefficient $D_{LL} = 10^{0.506Kp - 9.325}L^{*10}$ given by Brautigam and Albert (2000) is used. Since the loss rates of ultrarelativistic electrons by plasmaspheric hiss waves inside

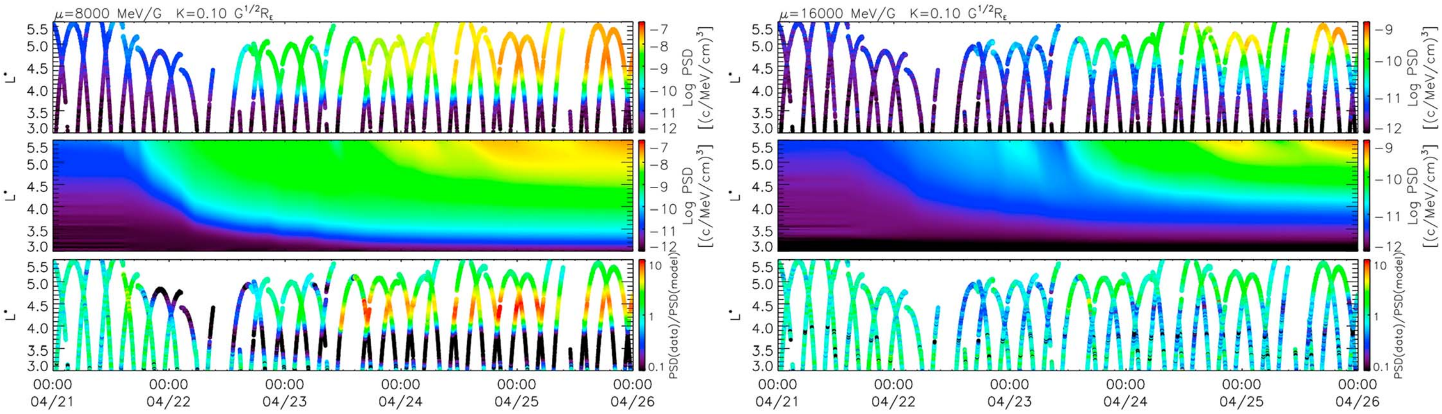

Figure 5. (top) The PSD calculated using data from REPT on the Van Allen Probes, (middle) simulated PSD by the radial diffusion model, and (bottom) differences between data and model results for μ = (left) 8,000 MeV/G and (right) 16,000 MeV/G, K = 0.1 $G^{1/2}R_E$ electrons during 21–25 April 2017.

the plasmasphere are very low (e.g., Ni et al., 2013) and we only perform simulation over several days, τ is set as infinity. The outer boundary of the radial diffusion model is set at L^* = 5.5 and the inner boundary is at L^* = 3. The PSDs at the beginning of the storm, outer boundary, and inner boundary were calculated using REPT data from two Van Allen Probes and interpolated across data gaps.

From top to bottom, Figure 5 shows the PSD data, simulated PSD derived from the radial diffusion model, and the differences between data and model results (PSD data/PSD model results) during 21–25 April 2017, for two different populations: μ = 8,000 MeV/G, K = 0.1 $G^{1/2}R_E$ electrons and μ = 16,000 MeV/G, K = 0.1 $G^{1/2}R_E$ electrons. It is clear that for μ = 8,000 MeV/G, K = 0.1 $G^{1/2}R_E$ electrons, the model results significantly underestimated the PSD at L^* ~ 4.5, which suggests that the inward radial diffusion alone cannot well explain the acceleration of these electrons in the center of outer belt and local heating mechanism is needed to fully explain the observed PSD enhancements. However, for μ = 16,000 MeV/G, K = 0.1 $G^{1/2}R_E$ electrons, as the right panels of Figure 5 show, using a pure radial diffusion model and an empirical Kp-dependent diffusion coefficient, the PSD enhancements of these electrons during the 21 April 2017 storm can be well explained and the differences between data and model results are mostly within a factor of ~3. Furthermore, some detailed features, like the flux decreases around 10:00 on 23 April and 08:00 on 25 April as well as the local PSD peak around 08:00 on 25 April, both potentially caused by the outward radial diffusion, agree well with the observations. These results, again, indicate that the acceleration mechanism for ultrarelativistic electrons in the outer radiation belt during this small to moderate storm is energy-dependent. For relatively lower μ electrons, the local acceleration in the outer belt is essential to explain the observed flux enhancements. For higher μ electrons, though wave heating mechanism beyond the apogee of Van Allen Probes is still required, at L^* ~ 3–5.5, the most important mechanism causing the observed flux enhancements was the inward radial diffusion, and the diffusion coefficient during this storm was similar to the empirical Kp-dependent diffusion coefficient from Brautigam and Albert (2000).

Some previous studies (e.g., Thorne et al., 2013) showed that local acceleration by chorus waves can well explain the flux enhancements of ultrarelativistic electrons in the outer belt during intense geomagnetic storms. Local acceleration is required to explain the ultrarelativistic electron flux enhancements in the outer belt since the inward radial diffusion will not be sufficient to accelerate plasmasheet electrons to ultrarelativistic energies. However, in this small to moderate storm, we studied, for μ = 16,000 MeV/G, K = 0.1 $G^{1/2}R_E$ electrons (~7 MeV at L^* = 4.5), the local acceleration process likely occurred at higher L-shells beyond the apogee of the Van Allen Probes and the inward radial diffusion was the main mechanism acting at $L^* < 5.5$, which further transported electrons inward and accelerated them to even higher energies. The different physical mechanisms suggested by those previous studies and this study could be due to differences in storm intensities or could simply be storm-dependent.

It is worth to note that in our radial diffusion model, we did not include potential losses caused by electromagnetic ion cyclotron (EMIC) wave scattering, which can be an efficient loss mechanism for ultrarelativistic electrons. If present, EMIC waves could cause losses of these ultrarelativistic electrons during this storm.

However, the occurrence rate of EMIC waves inside the geosynchronous orbit is shown to be quite low and EMIC waves are shown to be less efficient to scatter those near equatorially trapped electrons (e.g., Usanova et al., 2012, 2014), thus are not very likely to significantly influence our simulation results. Nevertheless, future work on acceleration of ultrarelativistic electrons using diffusion models including energy diffusion and pitch angle diffusion will be able to provide more sophisticated results and further improve our understanding of the ultrarelativistic electron dynamics.

4. Conclusion

In this study, using REPT measurements on the Van Allen Probes, significant flux enhancements of ultrarelativistic electrons during a small to moderate geomagnetic storm are reported and the underlying physical mechanism are investigated. The results indicate that ultrarelativistic electrons in the outer radiation belt can exhibit significant acceleration even during moderate solar wind and geomagnetic activities. During the studied storm, the growing PSD peak in the outer belt can be clearly observed for μ = ~4,000–10,000 MeV/G, $K = 0.1\ G^{1/2}R_E$ electrons (~3–5 MeV at $L^* = 4.5$), while the L^* of the PSD peak increases as μ increases. However, for μ = 16,000 MeV/G electrons (~7 MeV at $L^* = 4.5$), no PSD peak can be observed at L^* = 3–5.5, and PSD radial gradient was almost always positive in this L^* range during this storm. Using a radial diffusion model with an empirical Kp-dependent diffusion coefficient, the flux enhancements of electrons with μ = 16,000 MeV/G, $K = 0.1\ G^{1/2}R_E$ can be well reproduced, suggesting the inward radial diffusion to be the main acceleration mechanism for this population in the outer radiation belt, while for electrons with μ = 8,000 MeV/G, $K = 0.1\ G^{1/2}R_E$, the radial diffusion model significantly underestimated the flux enhancements in the center of outer belt, indicating the important role of local acceleration in the energization of this population in the outer belt. These results indicate that during this small to moderate storm, the acceleration mechanism for ultrarelativistic electrons is energy-dependent.

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References

Baker, D. N., Blake, J. B., Klebesadel, R. W., & Higbie, P. R. (1986). Highly relativistic electrons in the Earth's outer magnetosphere: 1. Lifetimes and temporal history 1979–1984. *Journal of Geophysical Research*, *91*(A4), 4265–4276. https://doi.org/10.1029/JA091iA04p04265

Baker, D. N., Jaynes, A. N., Kanekal, S. G., Foster, J. C., Erickson, P. J., Fennell, J. F., et al. (2016). Highly relativistic radiation belt electron acceleration, transport, and loss: Large solar storm events of March and June 2015. *Journal of Geophysical Research: Space Physics*, *121*, 6647–6660. https://doi.org/10.1002/2016JA022502

Baker, D. N., Kanekal, S. G., Hoxie, V. C., Batiste, S., Bolton, M., Li, X., et al. (2012). The Relativistic Electron-Proton Telescope (REPT) instrument on board the Radiation Belt Storm Probes (RBSP) spacecraft: Characterization of Earth's radiation belt high-energy particle populations. *Space Science Reviews*, *179*(1-4), 337–381. https://doi.org/10.1007/s11214-012-9950-9

Brautigam, D. H., & Albert, J. M. (2000). Radial diffusion analysis of outer radiation belt electrons during the October 9, 1990, magnetic storm. *Journal of Geophysical Research*, *105*(A1), 291–309. https://doi.org/10.1029/1999JA900344

Li, W., Ma, Q., Thorne, R. M., Bortnik, J., Zhang, X. J., Li, J., et al. (2016). Radiation belt electron acceleration during the 17 March 2015 geomagnetic storm: Observations and simulations. *Journal of Geophysical Research: Space Physics*, *121*, 5520–5536. https://doi.org/10.1002/2016JA022400

Li, W., Thorne, R. M., Ma, Q., Ni, B., Bortnik, J., Baker, D. N., et al. (2014). Radiation belt electron acceleration by chorus waves during the 17 March 2013 storm. *Journal of Geophysical Research: Space Physics*, *119*, 4681–4693. https://doi.org/10.1002/2014JA019945

Li, X., Barker, A. B., Baker, D. N., Tu, W. C., Sarris, T. E., Selesnick, R. S., et al. (2009). Modeling the deep penetration of outer belt electrons during the "Halloween" magnetic storm in 2003. *Space Weather*, *7*, S02004. https://doi.org/10.1029/2008SW000418

Li, X., Temerin, M., Baker, D. N., & Reeves, G. D. (2011). Behavior of MeV electrons at geosynchronous orbit during last two solar cycles. *Journal of Geophysical Research*, *116*, A11207. https://doi.org/10.1029/2011JA016934

Liu, S., Yan, Q., Yang, C., Zhou, Q., He, Z., He, Y., et al. (2018). Quantifying extremely rapid flux enhancements of radiation belt relativistic electrons associated with radial diffusion. *Geophysical Research Letters*, *45*, 1262–1270. https://doi.org/10.1002/2017GL076513

Ma, Q., Li, W., Thorne, R. M., Nishimura, Y., Zhang, X. J., Reeves, G. D., et al. (2016). Simulation of energy-dependent electron diffusion processes in the Earth's outer radiation belt. *Journal of Geophysical Research: Space Physics*, *121*, 4217–4231. https://doi.org/10.1002/2016JA022507

Moya, P. S., Pinto, V. A., Sibeck, D. G., Kanekal, S. G., & Baker, D. N. (2017). On the effect of geomagnetic storms on relativistic electrons in the outer radiation belt: Van Allen Probes observations. *Journal of Geophysical Research: Space Physics*, *122*. https://doi.org/10.1002/2017JA024735, 11,100–11,108.

Ni, B., Bortnik, J., Thorne, R. M., Ma, Q., & Chen, L. (2013). Resonant scattering and resultant pitch angle evolution of relativistic electrons by plasmaspheric hiss. *Journal of Geophysical Research: Space Physics*, *118*, 7740–7751. https://doi.org/10.1002/2013JA019260

Reeves, G. D., Spence, H. E., Henderson, M. G., Morley, S. K., Friedel, R. H. W., Funsten, H. O., et al. (2013). Electron acceleration in the heart of the Van Allen radiation belts. *Science*, *341*(6149), 991–994. https://doi.org/10.1126/science.1237743

Roederer, J. G. (1970). *Dynamics of geomagnetically trapped radiation*. New York: Springer.

Schulz, M., & Lanzerotti, L. (1974). *Particle diffusion in the radiation belts*. New York: Springer. https://doi.org/10.1007/978-3-642-65675-0

Thorne, R. M., Li, W., Ni, B., Ma, Q., Bortnik, J., Chen, L., et al. (2013). Rapid local acceleration of relativistic radiation belt electrons by magnetospheric chorus. *Nature*, *504*(7480), 411–414. https://doi.org/10.1038/nature12889

Tsyganenko, N. A. (1989). A magnetospheric magnetic field model with a warped tail current sheet. *Planetary and Space Science*, *37*(1), 5–20. https://doi.org/10.1016/0032-0633(89)90066-4

Usanova, M. E., Drozdov, A., Orlova, K., Mann, I. R., Shprits, Y., Robertson, M. T., et al. (2014). Effect of EMIC waves on relativistic and ultrarelativistic electron populations: Ground-based and Van Allen Probes observations. *Geophysical Research Letters*, *41*, 1375–1381. https://doi.org/10.1002/2013GL059024

Usanova, M. E., Mann, I. R., Bortnik, J., Shao, L., & Angelopoulos, V. (2012). THEMIS observations of electromagnetic ion cyclotron wave occurrence: Dependence on AE, SYMH, and solar wind dynamic pressure. *Journal of Geophysical Research*, *117*, A10218. https://doi.org/10.1029/2012JA018049

Zhao, H., Baker, D. N., Jaynes, A. N., Li, X., Elkington, S. R., Kanekal, S. G., et al. (2017). On the relation between radiation belt electrons and solar wind parameters/geomagnetic indices: Dependence on the first adiabatic invariant and L^*. *Journal of Geophysical Research: Space Physics*, *122*, 1624–1642. https://doi.org/10.1002/2016JA023658