Non-stormtime injection of energetic particles into the slot-region between Earth's inner and outer electron radiation belts as observed by STSAT-1 and NOAA-POES

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[1] The slot-region between Earth's inner and outer electron radiation belts was observed on 24 February 2004 by the satellite STSAT-1 to be populated by quasi-trapped electrons of energy 100-400 keV. This injection lasted for several hours and took place during a non-stormtime substorm. This appears to be the first observation of a slot-region electron injection that did not occur during a geomagnetic storm. We also report multi-instrument observations of this event from NOAA-POES and CPMN magnetic observatories, and we consider physical mechanisms that may account for the phenomenon. **Citation:** Park, J., et al. (2010), Non-stormtime injection of energetic particles into the slot-region between Earth's inner and outer electron radiation belts as observed by STSAT-1 and NOAA-POES, *Geophys. Res. Lett.*, *37*, L16102, doi:10.1029/2010GL043989.

1. Introduction

[2] The formation of the quiet-time slot region between the Earth's inner ($\sim 1.3 < L <\sim 2.5$) and outer ($\sim 3 < L <\sim 7$) electron radiation belts can be accounted for by a balance between Earthward radial transport and pitch-angle scattering loss of energetic electrons to the atmosphere caused by plasmaspheric whistler-mode hiss [*Lyons and Thorne*, 1973]. In the vicinity of the slot region and radiation belts, electrons are in the energy range 0.01–10 MeV [*Boscher and Bourdarie*, 2001]. Protons of energy tens to hundreds of keV are distributed more or less continuously from the inner to outer belts and contribute to the ring current formation.

[3] During the main and early recovery phases of a magnetic storm the slot region can be filled with energetic electrons [*Thorne et al.*, 2007]. *Loto'aniu et al.* [2006] demonstrated filling of the slot region by drift resonance between ultra low-frequency (ULF) waves and electrons, while *Shprits et al.* [2006] showed that local acceleration by very low-frequency (VLF) waves can also contribute to slot-region filling.

[4] Whistler-mode chorus waves can accelerate electrons locally outside the plasmapause [*Summers et al.*, 1998; *Horne et al.*, 2003], which can be eroded during a storm down to the nominal slot region ($L \sim 2$) [*Shprits et al.*, 2006]. Fluctuating substorm-associated convection E-fields are expected to transport ~100 keV electrons into the slot region [*Liu et al.*, 2003]. Almost all previous studies have dealt only with the filling of the slot-region during geomagnetic storms.

[5] In this study we report for the first time the injection of quasi-trapped electrons (100~400 keV) into the slot region during a non-stormtime substorm, which occurred well after the recovery phase of a medium-size ($Dst \sim -100$ nT) storm. The results are discussed in detail in Section 3, and summarized in Section 4.

2. Observations

[6] STSAT-1 is a Korean satellite on a sun-synchronous (1040–2240 LT) circular (altitude~680 km) orbit [*Lee et al.*, 2005]. It has two Solid-State Telescopes (SST) directed parallel and perpendicular to the local geomagnetic field, with an acceptance angle of 34°. SST employs silicon detectors (300 μ thick) to measure local electron fluxes in the energy range between 100 and 400 keV. Aluminum-coated LEXAN foils (0.15 μ thick) are placed at the apertures to stop protons, but a certain degree of proton contamination is still expected as SST adopts a similar structure to that of Medium Energy Proton and Electron Detector (MEPED) on board the NOAA-POES satellites. Nevertheless, we expect a substantial contribution to measured fluxes comes from the electrons (see discussions below) while the amount of proton contamination cannot be estimated in-situ due to the lack of an independent proton telescope on STSAT-1.

[7] Figure 1a shows observations of STSAT-1 on 24 February 2004. The day was in a nonstorm period with a minimum D_{st} (maximum K_p) value of −28 nT (3.3), and temporally well-separated from the main phase of the previous storm on 11 February. In Figure 1 the abscissa is the universal time. Figures 1 (top) and 1 (bottom) are spectrograms of quasitrapped (pitch angle ~ 90°) and precipitating (pitch angle ~ 0°) radiation-belt electrons (100~400 keV), respectively.

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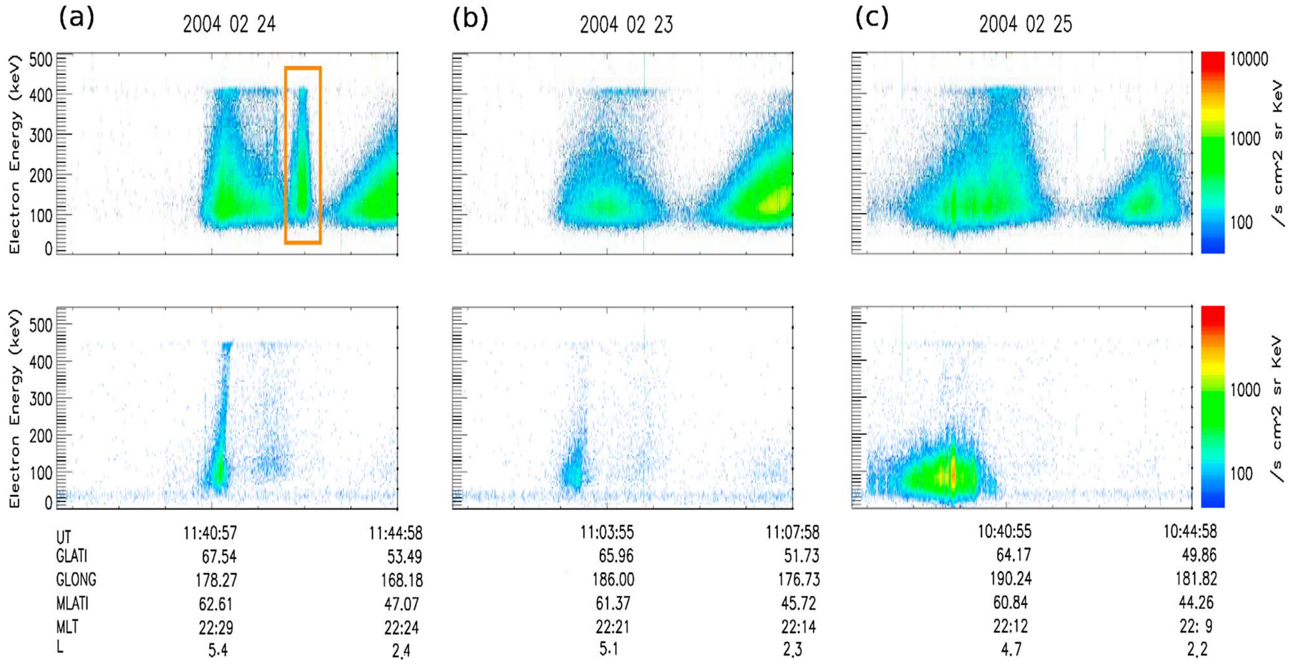

Figure 1. STSAT-1 observations on (a) 24, (b) 23, and (c) 25 February 2004: spectrograms of (top) quasi-trapped and (bottom) precipitating radiation-belt electrons as observed by SST.

[8] Figure 1 (top) shows quasi-trapped electrons form three distinct belts on the nightside. The flux peak of the equatorward belt seems to be located beyond the nightside observation limit of STSAT-1 (at 11:44:58 UT, L ~ 2.4), corresponding to the location of the inner radiation belt. The L-shell value calculated at the flux peak of the poleward belt (around 11:40:57 UT) is ~5.2, which is consistent with the known location of the outer radiation belt. Between the two belts, where a region devoid of energetic particles (the slot region) is expected, appears a population of electrons (at 11:42:57 UT, L ~ 3.4), which we refer to as the "injection".

[9] Figure 1 (bottom) shows the precipitating electron flux, whose structure is quite different from that of the quasi-trapped electrons. Noticeable precipitation exists only around 11:40:57 UT at the outer belt of quasi-trapped electrons. After 1 minute, a much weaker precipitation was observed between the outer belt and the injection.

[10] Figures 1b and 1c show similar plots on the previous and following days. The observed longitudes and magnetic local times (MLTs) are nearly the same as those of Figure 1a. No injection can be found in Figure 1a (top). STSAT-1 conducted polar observations only for 3 passes per day in February 2004. However, only the last pass on each day had good field-aligned attitude and full latitudinal coverage, and is shown in Figure 1.

[11] In 2004 three NOAA-POES satellites observed the radiation belt at an altitude of ~800 km. A 90° telescope of MEPED detects quasi-trapped particles with an acceptance angle of 30° [*Rodger et al.*, 2010], similar to that of STSAT-1/SST. In the inner belt and the slot region (L < 4) such low-altitude instruments may encounter stably trapped particles just within a small longitude range around the South Atlantic Anomaly (SAA) (http://www.altfuels.org/sampex). In the other regions they only observe particles in the drift loss cone (DLC); quasi-trapped.

[12] In Figure 2 quasi-trapped electron (proton) flux in the energy range >100 keV (80–240 keV) is plotted in linear scale as solid (dashed) lines. Black (red) color corresponds to the northern (southern) hemisphere. To avoid proton contamination [*Rodger et al.*, 2010], proton flux between 240 and 6900 keV has been subtracted from the raw electron flux. Figures 2 (left) and 2 (right) relate to the midnight-dawn-noon and noon-dusk-midnight sectors, respectively. The slot region is located at $L \sim 3 - 4$. In the region POES 15, 16, and 17 observed injection at ~10:51 UT, ~11:01–14:23 UT, and ~10:47 UT, respectively. Each electron flux enhancement was accompanied with that of proton flux. STSAT-1 observed injection at ~11:43 UT. Therefore, the injection seems to have lasted at least from 10:50 UT (POES 17) to 14:23 UT (POES 16). However, it was observed only from the noon to midnight sector. Dramatically, POES 16 at ~11:30 UT (~14:00 LT) and STSAT-1 at ~11:43 UT (~22:30 LT) observed injection while POES 16 at ~11:51 UT (~03:00 LT) barely observed it. After 11:44 UT, faint electron injection is observed only around the SAA, where POES can observe electrons with larger equatorial pitch angle (more stably-trapped electrons).

3. Discussion

[13] Energetic (~100–300 keV) electrons/protons in DLC were observed in the low-altitude (680 ~ 800 km altitude) slot region for several hours. We are not sure that >300 keV electrons also existed in the slot region because corresponding MEPED data are contaminated by proton flux. One may suppose that the particles are a remnant of the slot-region filling by the storm on 11 February, which filled the slot region with energetic electrons as can be seen in the POES summary plots (http://poes.ngdc.noaa.gov). However, the slot region slowly reforms in the POES data when the region

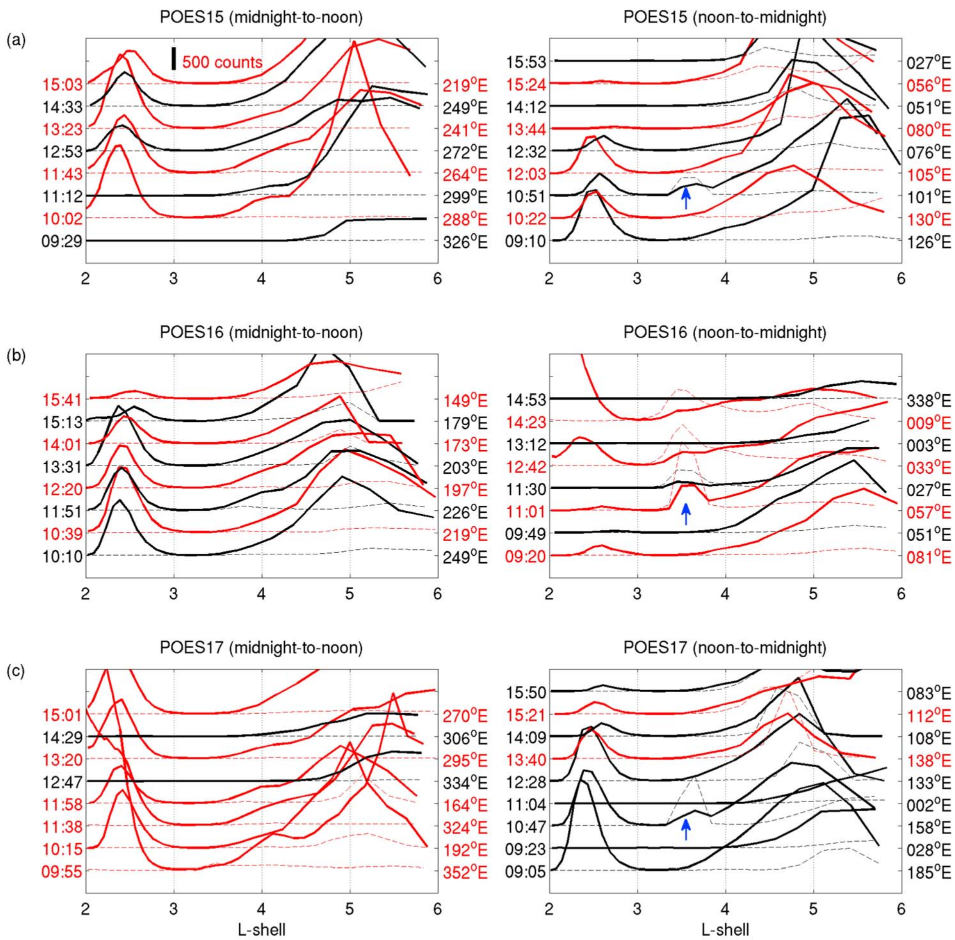

Figure 2. Flux of electrons (protons) in the energy range >100 keV (80–240 keV) observed by the "perpendicular" MEPED onboard POES (a) 15, (b) 16, and (c) 17 are shown as solid (dashed) lines. (left) The midnight-dawn-noon and (right) noon-dusk-midnight sectors. UT and geographic longitude at the center of each orbit are shown. The scale bar is given in Figure 2a (left).

is nearly devoid of energetic electrons around 24 February. The slot region observed by STSAT-1 on 23 February (Figure 1b) was also empty. Therefore, we deduce that the injection on 24 February cannot be a remnant of the previous storm. Though whistler-mode chorus waves can fill the slot region with energetic electrons [*Shprits et al.*, 2006], we should note that they can also induce scattering loss of <500 keV electrons [*Summers et al.*, 2002, 2007]; they cannot explain our observations.

[14] A relatively strong substorm occurred at 09:40 and 10:10 UT on 24 February (Figure 3a). Substorms are associated with large zonal electric fields transporting plasma toward the Earth [*Liu et al.*, 2003]. If this process conserves the first invariant, both electrons and protons transported from $L = 10$ to $L = 3$ can have substantial increase in energy. For a dipole field, energy increases in proportion to L^{-3} leading to an increase in energy by a factor of ~ 40. Modeling work by *Liu et al.* [2003] suggests that locally enhanced E-field (~ 2 mV/m) in the inner magnetosphere can fill the slot region with ~100 keV electrons.

[15] *Sergeev et al.* [1998] observed zonal E-field of 1.2 mV/m at $L \sim 5$ around a substorm onset. *Ganushkina et al.* [2000] observed fast inward ion injection (2 R_E during 1 hour) and attributed it to local inductive E-field exceeding 1 mV/m. Hence, substorm E-field as the origin of injection seems plausible. Unfortunately, we have no observational profile of substorm E-field during our event.

[16] *Liu et al.* [2003] also suggested that fluctuating E-field can result in higher slot-region electron flux than static E-field. *Loto'aniu et al.* [2006] reported ULF waves of ~200 nT p- p in the slot region during the 2003 Halloween storm. They estimated the radial diffusion time to be 12–24 hours at L ~3. We checked ULF activity observed by the Circum-pan Pacific Magnetometer Network (CPMN) observatories: Zyryanka (ZYK, L ~ 3.97) and Magadan (MGD, $L \sim 2.87$). Amplitude of ULF waves were of the order of 10 nT p-p (figure not shown). Though ULF waves on 24 February 2004 were much weaker than those of the Halloween 2003 storm, high-m (azimuthal wave number) ULF waves, which cannot be observed on the ground, may have contributed to electron acceleration. It is also possible that electron flux just below the SST energy range (~ 70 keV) had been high and that electrons were accelerated by the ULF wave enhancements. More observations are needed to clarify this point.

[17] The MLT dependence seen in POES warrants further discussion. In Figures 3b and 3c filled (blank) circles relate to filled (empty) slot region, and black (red) color to northern

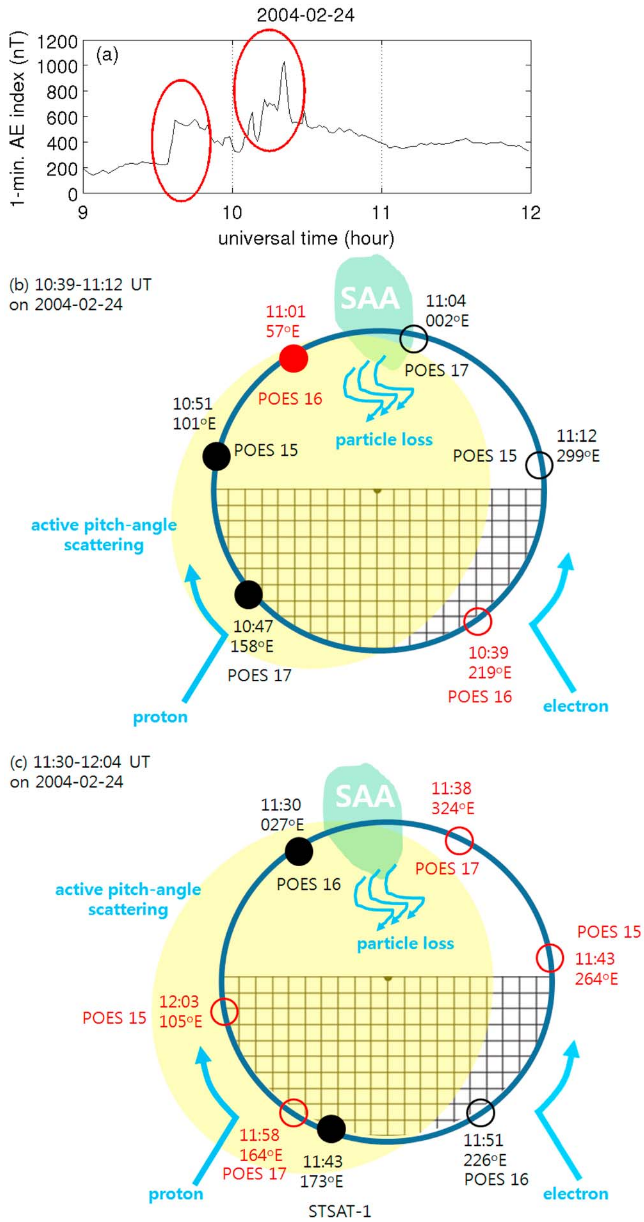

Figure 3. A summary plot of Figures 1 and 2: (a) *AE* index, (b) cartoon for 10:39–11:12 UT, and (c) cartoon for 11:30–12:04 UT. Filled (blank) circles relate to filled (empty) slot region, and black (red) color to northern (southern) hemisphere. Filling of the drift loss cone is assumed to be active in the yellow-shaded region. The green-shaded (hatched) region signifies the SAA (local nighttime).

(southern) hemisphere. Filling of DLC is assumed to be active in the yellow-shaded region, which signifies a region of enhanced hiss during active times [*Meredith et al.*, 2004]. The green-shaded (hatched) region signifies the SAA (local nighttime). Injection was observed by POES and STSAT-1 from noon to midnight, but not in the other sector. Outside the SAA, slot-region electrons observed by MEPED are in DLC; they are permanently lost in the SAA. In other words, wave-induced pitch-angle scattering should fill DLC continuously to make electrons reach the POES altitude. We assume the following scenario. Due to eastward (westward) drift during inward injection, stably trapped electrons (ions) enter the slot region mainly in the post- (pre-)midnight sector. Electrons keep drifting eastward and safely pass the SAA. Plasmaspheric hiss is generally active (inactive) on the day-to-evening (post-midnight) sector for disturbed (quiet) geomagnetic conditions [*Meredith et al.*, 2004]. The electrons are scattered into DLC by such waves and reach the altitudes of POES or STSAT-1. Electron pitch angles keep decreasing until local midnight so that the electrons are lost to the atmosphere.

[18] After 11:44 UT POES observed no injection outside the SAA; e.g., POES 15 (17) at 12:04 (11:58) UT. Only POES 16 near the SAA, where MEPED may reach stably trapped particles, observed faint signatures of injected electrons until 14:23 UT. Possibly, injected particle flux and pitch angle scattering became much weaker after 11:44 UT. Ions drift in the opposite direction to electrons. electromagnetic ion cyclotron (EMIC) waves, which also exhibit maximum activity from noon to midnight [*Meredith et al.*, 2003], can scatter ~100 keV protons [*Xiao et al.*, 2009] into DLC. Ions are finally lost around the SAA at noon. In all, the observed injection seems to be intermittent imprints of equatorially trapped particles onto DLC. However, it is not impossible that the slot region had no equatorially trapped electrons and that injection originates from the radial drift of inner-/outer-belt electrons already in DLC. Further observations of the high-/low-altitude slot region are needed to confirm our speculation.

[19] Visually inspecting the MEPED data in 2004 we found several other occasions when all the three POES satellites encountered injections during a non-stormtime period: 05 June, 27 June and 04 October. Though all the events occurred during/after substorms, high *AE* does not always guarantee injection. For example, on 05 June a substorm occurred preceding to injection; the maximum *AE* index was ~400 nT. On 04 June, though the maximum *AE* index exceeded 600 nT, no injection was encountered by POES. According to *Ganushkina et al.* [2000], even a moderate substorm ($AE \sim 150 - 200$ nT) can sometimes inject ions deep into the inner magnetosphere. As extensive observations of substorm E-field were unavailable for those occasions, the exact mechanism of particle injection cannot as yet be fully determined. In our next study, we will extend the data set and search for conjugate observations of POES with high-altitude satellite constellations such as THEMIS.

4. Summary and Conclusions

[20] From a coordinated, multi-instrument case study of Earth's radiation-belt slot region, we have found the following:

[21] 1. On 24 February 2004, STSAT-1 and POES observed a population of quasi-trapped protons and electrons (~100 keV) between the inner and outer radiation belts. Its lifetime was shorter than a day. This appears to be the first observation of an injection of ~100 keV electrons into the slot region during a non-stormtime substorm.

[22] 2. Localized enhancement of substorm E-field may explain the particle injection, but more in-situ observations are needed to verify it.

[23] 3. CPMN stations observed small enhancements of ULF waves, which seem insufficient to generate the particle injection. However, it is possible that higher azimuthal modes

that are not observed on the ground may have contributed to the injection.

[24] 4. The electron injection was observed by POES from noon to midnight MLT, while it was not observed in the post-midnight sector. Weaker plasmaspheric hiss after midnight may have prevented equatorially-trapped electrons from reaching POES, which generally observes the drift loss cone.

[25] Until now, slot-region filling has been investigated only for stormtime and MeV electrons. However, our observations show that the slot region is not a safe zone in non-storm periods, but several-hundred keV electrons can be injected into the slot region. An important ramification of non-stormtime electron injection into the slot region is that this reinforces the suggestion that substorm activity is more important than storm activity for inducing energetic electron events [e.g., *Hwang et al.*, 2004]. Further, the observation poses an important challenge for modeling substorm-associated electrodynamics in the inner magnetosphere.

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References

Boscher, D., and S. Bourdarie (2001), Modeling the radiation belts: What are the important physical processes to be taken into account in models?, *Adv. Space Res.*, *28*(12), 1739–1746.

Ganushkina, N. Y., et al. (2000), Entry of plasma sheet particles into the inner magnetosphere as observed by Polar/CAMMICE, *J. Geophys. Res.*, *105*(A11), 25,205–25,219.

Horne, R. B., S. A. Glauert, and R. M. Thorne (2003), Resonant diffusion of radiation belt electrons by whistler-mode chorus, *Geophys. Res. Lett.*, *30*(9), 1493, doi:10.1029/2003GL016963.

Hwang, J., K. W. Min, E. Lee, C. Lee, and D. Y. Lee (2004), A case study to determine the relationship of relativistic electron events to substorm injections and ULF power, *Geophys. Res. Lett.*, *31*, L23801, doi:10.1029/2004GL021544.

Lee, J.-J., et al. (2005), Energy spectra of ~170–360 keV electron microbursts measured by the Korean STSAT-1, *Geophys. Res. Lett.*, *32*, L13106, doi:10.1029/2005GL022996.

Liu, S., M. W. Chen, L. R. Lyons, H. Korth, J. M. Albert, J. L. Roeder, P. C. Anderson, and M. F. Thomsen (2003), Contribution of convective transport to stormtime ring current electron injection, *J. Geophys. Res.*, *108*(A10), 1372, doi:10.1029/2003JA010004.

Loto'aniu, T. M., I. R. Mann, L. G. Ozeke, A. A. Chan, Z. C. Dent, and D. K. Milling (2006), Radial diffusion of relativistic electrons into the radiation belt slot region during the 2003 Halloween geomagnetic storms, *J. Geophys. Res.*, *111*, A04218, doi:10.1029/2005JA011355.

Lyons, L., and R. Thorne (1973), Equilibrium structure of radiation belt electrons, *J. Geophys. Res.*, *78*(13), 2142–2149.

Meredith, N. P., R. M. Thorne, R. B. Horne, D. Summers, B. J. Fraser, and R. R. Anderson (2003), Statistical analysis of relativistic electron energies for cyclotron resonance with EMIC waves observed on CRRES, *J. Geophys. Res.*, *108*(A6), 1250, doi:10.1029/2002JA009700.

Meredith, N. P., R. B. Horne, R. M. Thorne, D. Summers, and R. R. Anderson (2004), Substorm dependence of plasmaspheric hiss, *J. Geophys. Res.*, *109*, A06209, doi:10.1029/2004JA010387.

Rodger, C. J., M. A. Clilverd, J. C. Green, and M. M. Lam (2010), Use of POES SEM-2 observations to examine radiation belt dynamics and energetic electron precipitation into the atmosphere, *J. Geophys. Res.*, *115*, A04202, doi:10.1029/2008JA014023.

Sergeev, V., M. Shukhtina, R. Rasinkangas, A. Korth, G. Reeves, H. Singer, M. Thomsen, and L. Vagina (1998), Event study of deep energetic particle injections during substorm, *J. Geophys. Res.*, *103*(A5), 9217–9234.

Shprits, Y. Y., R. M. Thorne, R. B. Horne, S. A. Glauert, M. Cartwright, C. T. Russell, D. N. Baker, and S. G. Kanekal (2006), Acceleration mechanism responsible for the formation of the new radiation belt during the 2003 Halloween solar storm, *Geophys. Res. Lett.*, *33*, L05104, doi:10.1029/2005GL024256.

Summers, D., R. Thorne, and F. Xiao (1998), Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the magnetosphere, *J. Geophys. Res.*, *103*(A9), 20,487–20,500.

Summers, D., C. Ma, N. P. Meredith, R. B. Horne, R. M. Thorne, D. Heynderickx, and R. R. Anderson (2002), Model of the energization of outer-zone electrons by whistler-mode chorus during the October 9, 1990 geomagnetic storm, *Geophys. Res. Lett.*, *29*(24), 2174, doi:10.1029/2002GL016039.

Summers, D., B. Ni, and N. P. Meredith (2007), Timescales for radiation belt electron acceleration and loss due to resonant wave-particle interactions: 2. Evaluation for VLF chorus, ELF hiss, and electromagnetic ion cyclotron waves, *J. Geophys. Res.*, *112*, A04207, doi:10.1029/2006JA011993.

Thorne, R. M., Y. Y. Shprits, N. P. Meredith, R. B. Horne, W. Li, and L. R. Lyons (2007), Refilling of the slot region between the inner and outer electron radiation belts during geomagnetic storms, *J. Geophys. Res.*, *112*, A06203, doi:10.1029/2006JA012176.

Xiao, F.-L., T. Tian, L.-X. Chen, Z.-P. Su, and H.-N. Zheng (2009), Evolution of ring current protons induced by electromagnetic ion cyclotron waves, *Chin. Phys. Lett.*, *26*(11), 119401, doi:10.1088/0256-307X/26/11/119401.

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