AFRL-AFOSR-VA-TR-2019-0338

Quantifying the physical processes affecting highly relativistic electron dynamics in the Earths radiation belts and their relation to solar wind conditions

Jacob Bortnik
UNIVERSITY OF CALIFORNIA LOS ANGELES

10/29/2019
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
12-11-2019

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
15 Aug 2015 to 14 Aug 2019

4. TITLE AND SUBTITLE
Quantifying the physical processes affecting highly relativistic electron dynamics in the Earths radiation belts and their relation to solar wind conditions

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-15-1-0158

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Jacob Bortnik

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF CALIFORNIA LOS ANGELES
11000 KINROSS AVE STE 102
LOS ANGELES, CA 90095-0001 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2019-0338

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Over the course of this project (08/15/201508/14/2019) we have published 42 papers in major scientific journals relevant to this funding to UCLA and Boston University. The most significant accomplishments since last report (August 2018) are summarized below.
1. We also published four review papers on 'Understanding Radiation Belt Electron Dynamics Due to Wave-Particle Interactions', which includes an overview of the various physical processes driving radiation belt electron dynamics. One of the papers is an invited review paper as one of them JGR Centennial papers (10.1029/2018JA025940).
2. We analyzed energetic electron precipitation driven by three types of whistler mode waves: plume whistler mode waves, plasmaspheric hiss, and exohiss observed outside the plasmapause. By quantitatively analyzing three conjunction events between Van Allen Probes and POES/MetOp satellites, together with quasi-linear calculation, we found that plume whistler mode waves are most effective in pitch angle scattering loss, particularly for the electrons from 10s to 100s keV. Our new finding provides the first direct evidence of effective pitch angle scattering driven by plume whistler mode waves and is critical for understanding energetic electron loss process in the inner magnetosphere. This result has been published in GRL in 2019 (10.1029/2019GL082095).

15. SUBJECT TERMS
Radiation Belts, Relativistic Electrons, Space Environment

16. SECURITY CLASSIFICATION OF:

17. LIMITATION OF ABSTRACT

18. NUMBER OF

a. REPORT	b. ABSTRACT	c. THIS PAGE		PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU		MOSES, JULIE
					19b. TELEPHONE NUMBER *(Include area code)*
					703-696-9586

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

FINAL REPORT ON AFOSR FA9550-15-1-0158

Title: Quantifying the Physical Processes Affecting Highly-Relativistic Electron Dynamics in The Earth's Radiation Belts and Their Relation to Solar Wind Conditions

Principle Investigator: Jacob Bortnik (UCLA)

Original Principle Investigator: Wen Li (Boston University)

Project Period: 08/15/2015–08/14/2019

Over the course of this project (08/15/2015–08/14/2019) we have published 42 papers in major scientific journals relevant to this funding to UCLA and Boston University. The most significant accomplishments are summarized below.

1. Using a superposed epoch analysis based on Van Allen Probes electron observations from 2012 to 2015, we have determined critical solar wind conditions leading to efficient radiation belt electron acceleration; these are prolonged southward Bz, high solar wind speed, and low dynamic pressure. We have also evaluated chorus wave evolution using the superposed epoch analysis for the identified efficient and inefficient acceleration events and found that chorus wave intensity is much stronger and lasts longer during efficient electron acceleration events, supporting the scenario that chorus waves play a key role in MeV electron acceleration. The result is published in doi:10.1002/2015GL065342.
2. We quantitatively evaluated the relative roles of various physical processes during the largest storm over the past decade (17 March 2015) using a 3-D diffusion simulation. By quantitatively comparing the observed and simulated electron evolution, we provided convincing evidence that chorus plays a critical role in accelerating electrons up to several MeV near the developing peak location and produces characteristic flat-top pitch angle distributions. By only including radial diffusion, the simulation result underestimates the observed electron acceleration. Moreover, plasmaspheric hiss is found to provide efficient pitch angle scattering losses for hundreds of keV electrons, while its scattering effect on > 1 MeV electrons is relatively slow. The result is published in doi:10.1002/2016JA022400.
3. We have evaluated chorus wave properties using Van Allen Probes wave data, and identified two distinct modes of lower band chorus: a quasi-parallel mode and a quasi-electrostatic mode. Our statistical results indicate that the quasi-electrostatic (quasi-parallel) mode preferentially occurs during relatively quiet (disturbed) geomagnetic activity at lower (higher) L-shells. Our new findings suggest that chorus-driven energetic electron dynamics needs a careful examination by considering the properties of these two distinct modes. The result is publisehd in doi:10.1002/2016GL068780.
4. We have also evaluated the importance of electron scattering by magnetosonic waves in the Earth's inner magnetosphere and found that intense magnetosonic waves potentially cause the butterfly distribution of radiation belt electrons, but electron acceleration due to magnetosonic waves is generally not as effective as chorus wave acceleration. An interesting case study has

been shown to provide clear evidence that magnetosonic waves play a key role in forming butterfly distribution for ultrarelativistic electrons through Landau resonance. These results are published in doi:10.1002/2015JA021992 and doi:10.1002/2016JA022370.

5. A quantitative diffusion-based simulation has also been performed to explain energy-dependent electron diffusion processes in the Earth's outer radiation belt, and our simulation results indicate that the radial extents of the energetic electrons during the storm recovery phase are determined by the coupled radial diffusion and the pitch angle scattering by electromagnetic ion cyclotron (EMIC) waves and plasmaspheric hiss. The result is published in doi:10.1002/2016JA022507.
6. We have also quantitatively evaluated the effect of EMIC waves on pitch angle scattering of ultrarelativistic electrons during the main phase of a storm, and provided direct evidence of EMIC wave-driven relativistic electron losses in the Earth's outer radiation belt. The result is published in doi:10.1002/2016JA022521.
7. We examined the excitation mechanisms of highly oblique, quasi-electrostatic lower band chorus waves using wave and electron data from Van Allen Probes, and identified two distinct excitation mechanisms for the first time. The first mechanism relies on cyclotron resonance with electrons possessing both a realistic temperature anisotropy at keV energies and a plateau at 100–500 eV in the parallel velocity distribution; the second mechanism corresponds to Landau resonance with a 100–500 eV beam. In both cases, a small low-energy beam-like component is necessary for suppressing an otherwise dominating Landau damping. This result has been published in Li et al., GRL, doi:10.1002/2016GL070386.
8. We investigated the characteristic energy range of electron flux decay due to the interaction with plasmaspheric hiss in the Earth's inner magnetosphere, and found that hiss causes a significant decay of 100 keV−1 MeV electrons with the strongest decay rate at ~ 340 keV. This result has been published in Ma et al., JGR, doi:10.1002/2016JA023311.
9. We constructed a statistical distribution of EMIC wave frequency spectra and their intensities based on Van Allen Probes measurements. Our statistical results clearly show that as the ratio of plasma frequency over electron gyrofrequency increases, EMIC wave power becomes progressively dominated by the helium band. Incorporating these realistic EMIC wave frequency spectra into radiation belt models will significantly improve the quantification of EMIC wave scattering effects in ultrarelativistic electron dynamics. This paper has been published in Zhang et al., JGR, doi:10.1002/2016GL071158.
10. We investigated how whole populations of 2-6 MeV electrons can be quickly lost from the Earth's outer radiation belt over L = 3-6 through precipitation into the atmosphere due to quasilinear pitch angle scattering by combined EMIC and whistler mode waves. Our analysis reveals that the fastest MeV electron dropouts occur roughly at the same rate over some high energy range and almost independently of EMIC wave amplitudes above a certain threshold. This paper has been published in Mourenas et al., GRL, doi:10.1002/2016JA023311.
11. Combining previously developed analytical expressions of electron lifetimes with recent statistical models of plasma density, ULF, whistler-mode, and EMIC waves, we demonstrate that geomagnetic activity and plasma density govern the inner structure of the radiation belts through several simple analytical scaling laws. This analytical model represents a very simple and powerful tool for exploring and better understanding the complex variations of the inner structure of the radiation belts with geomagnetic activity during relatively quiet times. This paper has been published in Mourenas et al., GRL, doi:10.1002/2016GL068921.
12. We simulate the radiation belt electron flux enhancements during selected Geospace

Environment Modeling (GEM) challenge events to quantitatively compare the major processes involved in relativistic electron acceleration under different conditions. By comparing the individual roles of local electron heating and radial transport, our simulation indicates that resonant interaction with chorus waves is the dominant process that accounts for the electron flux enhancement during the storm time event particularly near the flux peak locations, while radial diffusion by ultra-low frequency waves plays a dominant role in the enhancement during the non-storm time event. This paper has been published in Ma et al., JGR, doi: 10.1002/2017JA025114.

13. We investigate the gradual diffusion of energetic electrons from the inner edge of the outer radiation belt into the slot region. We simulated the radial intrusion and decay of electrons using a 3-dimentional diffusion code, which reproduced the energy-dependent transport of electrons from ~100 keV to 1 MeV in the slot region. At energies of 100-200 keV, the electrons experience fast transport across the slot region due to the dominance of radial diffusion; at energies of 200-600 keV, the electrons gradually diffuse and decay in the slot region due to the comparable rate of radial diffusion and pitch angle scattering by plasmaspheric hiss; at energies of $E > 700$ keV, the electrons stopped diffusing near the inner edge of outer radiation belt due to the dominant pitch angle scattering loss. In addition to plasmaspheric hiss, magnetosonic waves and VLF transmitters can cause the loss of high pitch angle electrons, relaxing the sharp 'top-hat' shaped pitch angle distributions created by plasmaspheric hiss. Our simulation indicates the importance of balance between radial diffusion and loss through pitch angle scattering in forming the diffusive intrusion of energetic electrons across the slot region. This paper has been published in Ma et al., JGR, doi: 10.1002/2017JA024452.
14. We present a neural-network based technique that allows for the reconstruction of the global, time-varying distribution of some physical quantity Q, that has been sparsely sampled at various locations within the magnetosphere, and at different times. We also show more advanced uses of the technique, including three-dimensional reconstruction of the plasma density, specification of chorus and hiss waves, and energetic particle fluxes. Furthermore, we discuss how machine learning techniques might be used to advance the state-of-the-art in space weather prediction, and insight discovery. This paper has been published in Bortnik et al., https://doi.org/10.1016/B978-0-12-811788-0.00011-1.
15. We quantitatively analyzed a conjunction event when RBSP-A was located approximately along the same magnetic field line as MetOp-01, which detected simultaneous precipitation of >30 keV protons and energetic electrons over an unexpectedly broad energy range (>~30 keV). Multi-point observations together with quasi-linear theory provide direct evidence that the observed electron precipitation at higher energy (>~700 keV) is primarily driven by EMIC waves. However, the newly observed feature of the simultaneous electron precipitation extending down to ~30 keV is not supported by existing theories and raises an interesting question on whether EMIC waves can scatter such low-energy electrons. This result has been published in Capannolo et al., GRL, 10.1029/2018GL078604.
16. We also published four review papers on "Understanding Radiation Belt Electron Dynamics Due to Wave-Particle Interactions", which includes an overview of the various physical processes driving radiation belt electron dynamics. One of the papers is an invited review paper as one of them JGR Centennial papers (10.1029/2018JA025940).
17. We analyzed energetic electron precipitation driven by three types of whistler mode waves: plume whistler mode waves, plasmaspheric hiss, and exohiss observed outside the plasmapause. By quantitatively analyzing three conjunction events between Van Allen

Probes and POES/MetOp satellites, together with quasi-linear calculation, we found that plume whistler mode waves are most effective in pitch angle scattering loss, particularly for the electrons from 10s to 100s keV. Our new finding provides the first direct evidence of effective pitch angle scattering driven by plume whistler mode waves and is critical for understanding energetic electron loss process in the inner magnetosphere. This result has been published in GRL in 2019 (10.1029/2019GL082095).

18. We quantitatively analyzed three cases of EMIC-driven precipitation, which occurred near the dusk sector observed by multiple Low-Earth-Orbiting (LEO) POES/MetOp satellites. During EMIC wave activity, the proton precipitation occurred from few 10s keV up to 100s keV, while the electron precipitation was mainly at relativistic energies. We compare observations of electron precipitation with calculations using quasi-linear theory. For all cases, we consider the effects of other magnetospheric waves observed simultaneously with EMIC waves, namely plasmaspheric hiss and magnetosonic waves, and find that the electron precipitation at MeV energies was predominantly caused by EMIC-driven pitch angle scattering. Interestingly, each precipitation event observed by a LEO satellite extended over a limited L-shell region ($\Delta L \sim 0.3$ on average), suggesting that the pitch angle scattering caused by EMIC waves occurs only when favorable conditions are met, likely in a localized region. This paper has been published in JGR in 2019 (10.1029/2018JA026291).

Publications Relevant to the Award

1) Li, W., R. M. Thorne, J. Bortnik, D. N. Baker, G. D. Reeves, S. G. Kanekal, H. E. Spence, and J. C. Green (2015), Solar wind conditions leading to efficient radiation belt electron acceleration: A superposed epoch analysis, Geophys. Res. Lett., 42, 6906-6915, doi:10.1002/2015GL065342.
2) Katsavrias, C., Daglis, I. A., Li, W., Dimitrakoudis, S., Georgiou, M., Turner, D. L., and Papadimitriou (2015), C.: Combined effects of concurrent Pc5 and chorus waves on relativistic electron dynamics, Ann. Geophys., 33, 1173-1181, doi:10.5194/angeo-33-1173-2015.
3) Li, W., et al. (2016a), Radiation belt electron acceleration during the 17 March 2015 geomagnetic storm: Observations and simulations, J. Geophys. Res. Space Physics, 121, 5520–5536, doi:10.1002/2016JA022400.
4) Li, W., O. Santolik, J. Bortnik, R. M. Thorne, C. A. Kletzing, W. S. Kurth, and G. B. Hospodarsky (2016b), New chorus wave properties near the equator from Van Allen Probes wave observations, Geophys. Res. Lett., 43, 4725–4735, doi:10.1002/2016GL068780.
5) Ma, Q., W. Li, R. M. Thorne, J. Bortnik, C. A. Kletzing, W. S. Kurth, and G. B. Hospodarsky (2016a), Electron scattering by magnetosonic waves in the inner magnetosphere, J. Geophys. Res. Space Physics, 121, 274-285, doi:10.1002/2015JA021992.
6) Ma, Q., W. Li, R. M. Thorne, Y. Nishimura, X.-J. Zhang, G. D. Reeves, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, M. G. Henderson, et al. (2016b), Simulation of energy-dependent electron diffusion processes in the Earth's outer radiation belt, J. Geophys. Res. Space Physics, 121, 4217–4231, doi:10.1002/2016JA022507.
7) Ma, Q., D. Mourenas, A. Artemyev, W. Li, R. M. Thorne, and J. Bortnik (2016c), Strong enhancement of 10–100 keV electron fluxes by combined effects of chorus waves and time domain structures, Geophys. Res. Lett., 43, 4683–4690, doi:10.1002/2016GL069125.

8) Zhang, X.-J., W. Li, Q. Ma, R. M. Thorne, V. Angelopoulos, J. Bortnik, L. Chen, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, et al. (2016a), Direct Evidence for EMIC Wave Scattering of Relativistic Electrons in Space, J. Geophys. Res. Space Physics, 121, 6620–6631, doi:10.1002/2016JA022521.
9) Zhang, X.-J., W. Li, R. M. Thorne, V. Angelopoulos, Q. Ma, J. Li, J. Bortnik, L. Chen, D. N. Baker, G. D. Reeves, H. E. Spence, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, J. B. Blake, and J. F. Fennell (2016b), Physical mechanism causing rapid changes in ultrarelativistic electron pitch angle distributions right after a shock arrival: Evaluation of an electron dropout event, J. Geophys. Res. Space Physics,121, doi:10.1002/2016JA022517.
10) Li, J., J. Bortnik, R. M. Thorne, W. Li, Q. Ma, D. N. Baker, G. D. Reeves, J. F. Fennell, H. E. Spence, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, V. Angelopoulos, and J. B. Blake (2016), Ultrarelativistic electron butterfly distributions created by parallel acceleration due to magnetosonic waves, J. Geophys. Res. Space Physics, 121, 3212–3222, doi:10.1002/2016JA022370.
11) Goldstein, J. D. N. Baker, J. B. Blake, S. De Pascuale, H. O. Funsten, A. Jaynes, J. Jahn, C. A. Kletzing, W. S. Kurth, W. Li, G. D. Reeves, H. Spence (2016), The relationship between the plasmapause and outer belt electrons, J. Geophys. Res. Space Physics, 121, doi:10.1002/2016JA023046.
12) Li, W., D. Mourenas, A. V. Artemyev, J. Bortnik, R. M. Thorne, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, G. D. Reeves, H. O. Funsten, and H. E. Spence (2016), Unraveling the generation mechanism of very oblique lower-band chorus waves, Geophys. Res. Lett., 43, 8867–8875, doi:10.1002/2016GL070386.
13) Ma, Q., W. Li, R. M. Thorne, J. Bortnik, G. D. Reeves, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, H. E. Spence, D. N. Baker, J. B. Blake, J. F. Fennell, S. G. Claudepierre, and V. Angelopoulos (2016), Characteristic energy range of electron scattering due to plasmaspheric hiss, J. Geophys. Res. Space Physics, 121, 11,737–11,749, doi:10.1002/2016JA023311.
14) Zhang, X.-J., W. Li, R. M. Thorne, V. Angelopoulos, J. Bortnik, C. A. Kletzing, W. S. Kurth, and G. B. Hospodarsky (2016), Statistical distribution of EMIC wave spectra: Observations from Van Allen Probes, Geophys. Res. Lett., 43, 12,348–12,355, doi:10.1002/2016GL071158.
15) Mourenas, D., A. V. Artemyev, Q. Ma, O. V. Agapitov, and W. Li (2016), Fast dropouts of multi-MeV electrons due to combined effects of EMIC and whistler-mode waves, Geophys. Res. Lett., 43, 4155–4163, doi:10.1002/2016GL068921.
16) Mourenas, D., Q. Ma, A. V. Artemyev, and W. Li (2017), Scaling laws for the inner structure of the radiation belts, Geophys. Res. Lett., 44, 3009–3018, doi:10.1002/2017GL072987.
17) Ma, Q., Artemyev, A. V., Mourenas, D., Li, W., Thorne, R. M., Kletzing, C. A., …Wygant, J. (2017). Very oblique whistler mode propagation in the radiation belts: Effects of hot plasma and Landau damping. Geophysical Research Letters, 44, 12,057–12,066. https://doi.org/10.1002/2017GL075892.
18) Lei, M., Xie, L., Li, J., Pu, Z., Fu, S., Ni, B., Hua, M., Chen, L. & Li, W. (2017). The Radiation Belt Electron Scattering by Magnetosonic Wave: Dependence on Key Parameters. Journal of Geophysical Research: Space Physics, 122, 12,338–12,352. https://doi.org/10.1002/2016JA023801.
19) Ma, Q., Li, W., Thorne, R. M., Bortnik, J., Reeves, G. D., Spence, H. E., … Baker, D. N. (2017). Diffusive transport of several hundred keV electrons in the Earth's slot

region. Journal of Geophysical Research: Space Physics, 122, 10,235–10,246. https://doi.org/10.1002/2017JA024452.

20) Ma, Q., D. Mourenas, W. Li, A. Artemyev, and R. M. Thorne (2017), VLF waves from ground-based transmitters observed by the Van Allen Probes: Statistical model and effects on plasmaspheric electrons, Geophys. Res. Lett., 44, 6483–6491, doi:10.1002/2017GL073885.
21) Chu, X. N., J. Bortnik, W. Li, Q. Ma, V. Angelopoulos, and R. M. Thorne (2017a), A neural network model of three-dimensional dynamic electron density in the inner magnetosphere, *J. Geophys. Res. Space Physics*, 122, 9183–9197, doi:10.1002/ 2017JA024464.
22) Chu, X. N., J. Bortnik, W. Li, Q. Ma, R. Denton, C. Yue, V. Angelopoulos, R. M. Thorne, F. Darrouzet, P. Ozhogin, C. A. Kletzing, Y. Wang, and J. Menietti (2017b), A neural network model of three-dimensional dynamic electron density in the inner magnetosphere, *J. Geophys. Res. Space Physics*, 122, 9183-9197, doi:10.1002/ 2017JA024464.
23) Horne, R. B., M. W. Phillips, S. A. Glauert, N.P. Meredith, A. Hands, K. Ryden, and **W. Li**. (2018), Realistic worst case for a severe space weather event driven by a fast solar wind stream, *Space Weather*, 16, 1202–1215. https://doi.org/10.1029/2018SW001948
24) Capannolo, L., Li, W., Ma, Q., Zhang, X.-J., Redmon, R. J., Rodriguez, J. V., et al (2018). Understanding the Driver of Energetic Electron Precipitation Using Coordinated Multi-Satellite Measurements. *Geophysical Research Letters*, 45. https://doi.org/10.1029/2018GL078604
25) Bortnik, J., X. Chu, Q. Ma, W. Li, X. Zhang, R. M. Thorne et al. (2018), Artificial neural networks for determining magnetospheric conditions, Machine Learning Techniques for Space Weather, pages 279–300, https://doi.org/10.1016/B978-0-12-811788-0.00011-1.
26) Ma, Q., Li, W., Bortnik, J., Thorne, R. M., Chu, X., Ozeke, L. G., et al. (2018). Quantitative evaluation of radial diffusion and local acceleration processes during GEM challenge events. *Journal of Geophysical Research: Space Physics*, 123, 1938–1952. https://doi.org/10.1002/2017JA025114.
27) Pinto, V. A., Bortnik, J., Moya, P. S., Lyons, L. R., Sibeck, D. G., Kanekal, S. G., et al. (2018). Characteristics, occurrence, and decay rates of remnant belts associated with three-belt events in the Earth's radiation belts. *Geophysical Research Letters*, 45, 12,099–12,107. https://doi.org/10.1029/2018GL080274
28) Kang, S.-B., Fok, M.-C., Komar, C., Glocer, A., Li, W., & Buzulukova, N. (2018). An energetic electron flux dropout due to magnetopause shadowing on 1 June 2013. *Journal of Geophysical Research: Space Physics*, 123, 1178–1190. https://doi.org/10.1002/2017JA024879.
29) Meredith N.P., R.B. Horne, T. Kersten, W. Li, J. Bortnik, A. Sicard-Piet, and K.H. Yearby. (2018), Global model of plasmaspheric hiss from multiple satellite observations, *J. Geophys. Res. Space Physics*, 123. https://doi.org/10.1029/2018JA025226.
30) Li, J., Bortnik, J., An, X., Li, W., Russell, C. T., Zhou, M., et al. (2018). Local excitation of whistler mode waves and associated Langmuir waves at dayside reconnection regions. *Geophysical Research Letters*, 45, 8793–8802. https://doi.org/10.1029/2018GL078287
31) Kim, H., Hwang, J., Park, J., Bortnik, J., & Lee, J. (2018). Global characteristics of electromagnetic ion cyclotron waves deduced from Swarm satellites. *Journal of Geophysical Research: Space Physics*, 123, 1325–1336. https://doi.org/ 10.1002/2017JA024888

32) Tu, W., Li, W., Albert, J. M., & Morley, S. K. (2019). Quantitative assessment of radiation belt modeling. *Journal of Geophysical Research: Space Physics*, 124, 898– 904. https://doi.org/10.1029/2018JA026414
33) Capannolo, L., Li, W., Ma, Q., Shen, X.-C., Zhang, X.-J., Redmon, R. J., et al (2019). Energetic electron precipitation: multi-event analysis of its spatial extent during EMIC wave activity. *Journal of Geophysical Research: Space Physics*, 124, 2466–2483. https://doi.org/10.1029/2018JA026291
34) Li, W., Shen, X.-C., Ma, Q., Capannolo, L., Shi, R., Redmon, R. J., et al (2019). Quantification of Energetic Electron Precipitation Driven by Plume Whistler Mode Waves, Plasmaspheric Hiss, and Exohiss. *Geophysical Research Letters*, 46, 3615–3624. https://doi.org/10.1029/2019GL082095
35) Katsavrias, C., Daglis, I. A., and W. Li (2019), On the statistics of acceleration and loss of relativistic electrons in the outer radiation belt: a superposed epoch analysis, *J. Geophys. Res. Space Physics*, 124, 2755–2768 https://doi.org/10.1029/2019JA026569
36) Shen, X.-C.*, W. Li, Ma, Q., Agapitov, O., & Nishimura, Y. (2019). Statistical analysis of transverse size of lower band chorus waves using simultaneous multi-satellite observations. *Geophysical Research Letters*, 46, 5725–5734. https://doi.org/10.1029/2019GL083118
37) Katsavrias, C., Sandberg, I., Li, W., Podladchikova, O., Daglis, I. A., Papadimitriou, C., et al. (2019). Highly relativistic electron flux enhancement during the weak geomagnetic storm of April–May 2017. *Journal of Geophysical Research: Space Physics*, 124, 4402– 4413. https://doi.org/10.1029/2019JA026743
38) Ma, Q., Li, W., Yue, C., Thorne, R. M., Bortnik, J., Kletzing, C. A., et al. (2019). Ion heating by electromagnetic ion cyclotron waves and magnetosonic waves in the Earth's inner magnetosphere. *Geophysical Research Letters*, 46, 6258– 6267. https://doi.org/10.1029/2019GL083513
39) Li, J., J. Bortnik, X. An, W. Li, C. T. Russell, X.-C. Shen et al. (2019), Origin of two-band chorus in the Earth's radiation belt, *Nature Communication*, 10, 4672, 10.1038/s41467-019-12561-3.
40) Li, W., Q. Ma, J. Bortnik, and R. M. Thorne (2019), Recent Advances in Understanding Radiation Belt Electron Dynamics Due to Wave-Particle Interactions, AGU Monograph, In Press.
41) Li, W., and M. K. Hudson (2019), Earth's Van Allen Radiation Belts: From Discovery to the Van Allen Probes Era, *Journal of Geophysical Research: Space Physics* (Invited Centennial Paper), 124, doi: 10.1029/2018JA025940.
42) Thorne, R. M., J. Bortnik, W. Li, and Q. Ma (2019), "Wave-Particle Interactions in the Earth's Magnetosphere", AGU book, In Press.