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Editorial: Radiation belt dynamics: theory, observation and modeling

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Editorial on the Research Topic
Radiation belt dynamics: theory, observation and modeling

The relativistic electron fluxes in Earth's radiation belts are highly dynamic due to various source and loss processes (Reeves et al., 2003; Thorne, 2010; Turner et al., 2014). Satellite observations revealed that the outer radiation belt fluxes are strongly affected by solar wind and geomagnetic activities (e.g., Baker et al., 2019). The most important drivers of the radiation belt variability are radial diffusion due to ultra-low frequency waves (e.g., Mann et al., 2016) and local wave–particle interactions due to whistler-mode waves (e.g., Horne and Thorne, 1998), electron cyclotron harmonic waves (e.g., Zhang et al., 2015), and electromagnetic ion cyclotron (EMIC) waves (e.g., Summers and Thorne, 2003). Quasilinear and nonlinear theories were developed to demonstrate and quantify the importance of each process in the radiation belts (e.g., Albert, 1999; Omura et al., 2008). Numerical simulations generally reproduce the overall source and loss of radiation belt particles (e.g., Ma et al., 2016), but detailed quantification of the observed features is challenging. The machine learning technique has proven to be a useful tool in reproducing and forecasting the particle fluxes in radiation belts (e.g., Bortnik et al., 2018). Although the Van Allen Probes provided a great opportunity to improve the understanding of Earth's radiation belt dynamics, many science questions regarding the wave and particle properties, distributions, variability, and evolution remained unexplored after the end of the spacecraft mission (Li and Hudson, 2019).

This Research Topic, "*Radiation Belt Dynamics: Theory, Observation and Modeling*," aims in advancing the understanding of radiation belt dynamics and improving the capability to model and forecast the energetic particles and plasma waves in the magnetosphere. This Research Topic collected 11 research articles and 1 mini review article. The published papers address a wide range of topics in the theory, observation, and modeling of radiation belt dynamics.

Most of the radiation belt models are drift-averaged and consider the radial transport as a one-dimensional radial diffusion process. Lejosne and Albert developed a theoretical framework to retain drift phase information and resolve the effects of the bulk motion and diffusion of trapped particles. The authors derived formulas to evaluate the drift phase resolved diffusion coefficients and impacts of particle drift, as well as radial diffusion.

Following their theoretical work, Lejosne et al. applied their theory to model the trapped particle transport under the influence of random electric potential fluctuations. Numerical experiments were performed to track the radial diffusion and drift of trapped particles. Modeling resolves how the particle distribution function changes from being determined by drift motion to being well-described by diffusion. By considering the localized transport processes, the developed drift-diffusion equation provides a better spatiotemporal resolution than the standard radial diffusion model.

Chan et al. developed a radiation belt simulation model (K2) by combining global MHD simulations with guiding-center test-particle methods. The model resolves important global scale processes of particle motion in self-consistent MHD fields, as well as local wave–particle interactions. The authors used the K2 model to simulate the electron phase space density evolution during a strong geomagnetic storm event. The simulation indicates the importance of combined influences of local energization by chorus waves and radial transport in the electron flux enhancement during disturbed times.

Drozdov et al. combined the data assimilation method with the machine learning technique to reconstruct radiation belt electron fluxes. They used the multivariate linear regression and neural network methods to map Polar Orbiting Environmental Satellite (POES) measurements to the equator. The electron fluxes were then used in data assimilation with the Versatile Electron Radiation Belt model. Improved accuracy of radiation belt electron modeling was demonstrated using the above method after comparison with satellite observations.

Huang et al. used a neural network to model the total electron density and hiss wave variations in the radiation belts during a geomagnetic storm event. The simulation revealed detailed features of plasmasphere, plume, and hiss waves on a global scale. The authors modeled energetic electron evolution to explain the observed electron flux decay. The simulation quantified the relative roles of plasmaspheric hiss and plume hiss. The dynamic evolution of hiss waves was suggested to be important to study the radiation belt electron evolution.

Hua et al. analyzed the geomagnetic conditions favorable for radiation belt electron acceleration. Their study suggested that intense substorms contribute to the elevated source and seed electron fluxes. These electron populations are critical for the multi-MeV electron flux enhancements due to chorus waves. The correlation analysis suggests that the accumulative substorm impact is directly related to the high electron fluxes in the outer radiation belt.

Liu and Su reviewed the impacts of solar wind dynamic pressure pulses on the whistler-mode waves in the magnetosphere. The spatiotemporal variability of whistler-mode waves is ultimately driven by solar wind conditions. The authors reviewed several studies highlighting the enhancement and disappearance of chorus and hiss wave powers, following large variations in solar wind dynamic pressures. Liu and Su summarized the underlying mechanisms and raised outstanding questions.

Ma et al. evaluated the empirical model performances for the total electron density and whistler-mode wave amplitudes using Van Allen Probes measurements. The modeled electron densities align with satellite observations; the chorus and hiss wave models generally agree with satellite observations when the modeled plasmapause agrees with the observation or when the wave amplitudes are moderate. Significant discrepancies between the model and observation are found near the plasmapause boundary or in the plumes.

Qin et al. investigated the magnetospheric oscillations, the simultaneous whistler-mode chorus wave modulation, and the energetic electron precipitation, as evidenced by BARREL X-ray observations. The authors performed quasi-linear analysis to evaluate electron precipitation. The electron precipitation variations are directly driven by chorus wave amplitude modulation, aided by the modulation of background plasma conditions. The spatial scale of the magnetospheric oscillations is large, suggesting their significant role in global electron precipitation.

Hanzelka et al. performed test-particle simulations to analyze electron scattering and precipitation due to EMIC waves in Earth's radiation belts. By considering oblique wave normal angles, the authors confirmed the importance of multiple harmonic resonances in the electron scattering loss. The nonlinear force bunching causing positive advection at low pitch angles is balanced by the transport of electrons into the loss cone. The authors also revealed the contribution of fractional resonances to electron precipitation at energies below the minimum resonance energy.

Hanzelka et al. performed full-wave modeling of EMIC wave propagation in Earth's outer radiation belt using finite-difference time-domain simulations. The simulations suggest cold plasma density gradients could guide the quasiparallel EMIC waves and influence the wave mode conversion and wave reflection. For unducted waves, the wave normal angles increase rapidly with latitude and the waves are reflected when the wave frequency becomes the local ion hybrid frequency. The modeled wave fields are useful to study particle precipitation by EMIC waves in the future.

Shao et al. performed one-dimensional particle-in-cell simulations to study the magnetosonic wave propagation when the waves encounter density structures in Earth's magnetosphere. The simulations indicate the roles of wave energy absorption and wave reflection, both of which strongly depend on the height and width of local density structures. Magnetosonic wave power absorption was suggested to be important to understand the wave distribution in Earth's magnetosphere.

Author contributions

QM: conceptualization, investigation, writing–original draft, and writing–review and editing. XG: investigation and writing–review and editing. DW: writing–review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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