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COMMENTARY

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Radial Transport Versus Local Acceleration: The Long-Standing Debate

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Key Points:

- The summary of a joint panel discussion of the Geospace Environment Modeling 2021 Virtual Summer Workshop is presented
- Both radial diffusion and local acceleration are important mechanisms of observed electron flux enhancements and must be considered
- Advancements can be reached with multi-point measurements, analysis of phase space density, and new methods to assess diffusion coefficients

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Abstract On 28 July 2021, within the Geospace Environment Modeling Virtual Summer Workshop, a joint panel discussion organized by the "System Understanding of Radiation Belt Particle Dynamics through Multi-spacecraft and Ground-based Observations and Modeling" and "ULF wave Modeling, Effects, and Applications" focus groups was held. The panelists, organizers, and the audience discussed the nature and unresolved questions of radiation belt electron flux enhancements. In this commentary we provide the outcomes of this discussion.

1. Introduction

Understanding the mechanisms that drive the dynamics of the radiation belts is one of the main tasks of modern research. Significant progress in this area has been achieved thanks to NASA's Van Allen Probes mission; however, accurate modeling of the acceleration of radiation belt electrons remains a challenge. The observed enhancement of the radiation belt electron flux and phase space density can be a result of inward radial diffusion and transport, local acceleration due to wave-particle interaction, or the two mechanisms combined. The challenges that the scientific community faces can be summarized in the following questions:

Q1. Under what conditions are contributions from radial diffusion unable to explain observed radiation belt variations?
Q2. Why does diffusion work as well as it does (in simulations)?
Q3. What methods do we have to study the relative contributions of radial diffusion, transport, and local acceleration?
Q4. What advances are needed to improve the radiation belt models and/or resolve this debate?

These questions were discussed during the Geospace Environment Modeling (GEM) Virtual Summer Workshop, held on July 25–30, 2021. In this commentary, we present the results of the joint panel discussion organized by the "System Understanding of Radiation Belt Particle Dynamics through Multi-spacecraft and Ground-based Observations and Modeling" and "ULF wave Modeling, Effects, and Applications" focus groups.

2. General Overview of the Problem

Prior to the discussion of the above questions, the panelists presented a brief overview of the problem, which is summarized in this chapter.

Dr. Solène Lejosne provided an overview of existing radial diffusion models and common methods of radial diffusion derivation (Lejosne, 2019). The detailed review of radiation belt radial diffusion can be found in the recent paper by (Lejosne & Kollmann, 2020). Emphasis was made on terminology that must be used very carefully while discussing acceleration, as it can be adiabatic and nonadiabatic. It must be recognized that the dynamics of the radiation belts can be properly addressed only considering phase space density (e.g., Roederer & Lejosne, 2018). However, parameterizing PSD in adiabatic invariant space requires an accurate electromagnetic field model. For example, computation of L* requires determination of the drift shell that can be distorted by a large-scale electric field (e.g., Lejosne et al., 2021; Selesnick et al., 2016).

Prof. Mary Hudson also emphasized the importance of the phase space density analysis. The mapping of the observed flux to phase space density provides a dramatically different picture when compared to presentation of fluxes versus radial distance (or L-shell). During the Van Allen Probes era, both local acceleration and radial transport were observed during strong geomagnetic storms. In particular, during the 17 March 2013 and 17 March 2015 storms, local heating occurred, followed by inward radial convective and diffusive transport (Li et al., 2017). In addition, the Van Allen Probes observations during the period of the solar minimum (February 2018 - October 2019) raise the question of the relative contribution of the radial transport and local heating in the observed electron acceleration. However, it remains clear that both processes are important while occurring during different parts of the storms and/or under different types of driving conditions.

Dr. Hayley Allison showed that when accounting for both radial diffusion and local acceleration, simulations reproduce well the enhancement of the radiation belts across different energies (e.g., Wang & Shprits, 2019). However, changes in the plasma environment, such as electron plasma density and ion composition, may play a key role and influence the relative contributions of local and radial diffusion (Allison et al., 2021). Additionally, local loss, local acceleration, and radial diffusion can influence each other. Local acceleration can change phase space density profiles (creating a peak changing the phase space density gradients), hence affecting radial transport, and vice versa. The proper analysis of such phenomena can be achieved with multi-point satellite observations.

Dr. Louis Ozeke discussed the challenges of the phase space density analysis. The rapid variation of the outer boundary in combination with the orbital characteristic of the satellite can lead to the observations of phantom peaks in the absence of chorus waves (Olifer et al., 2021; Selesnick & Blake, 2000). Hence, the presence of an isolated L* peak in phase space is not always an indication of the local acceleration. An example of how the peak in phase space density, observed by Reeves et al. (2013), can be produced in a purely radial diffusion model, was presented. In addition, insufficient accuracy of the magnetic field model, while calculating the phase space density profiles, may provide inconclusive results in identification of local acceleration (Loridan et al., 2019). A proposed solution of such a problem is the necessity of comparison of the modeled and observed in situ magnetic field prior to calculation of the phase space density profiles.

Prof. Allison Jaynes provided an overview of a two-step acceleration process that involves a combination of the two mechanisms (Jaynes et al., 2018; Katsavrias et al., 2019; Zhao et al., 2018). Local acceleration provides an initial accelerated electron population, which is then further accelerated by inward radial diffusion over a longer period of time in the recovery phase. The emphasis was made on the timescale of the models. For example, the long-term simulations (several months) may provide good results (Drozdov et al., 2020); however, accurately capturing the electron dynamics on an hourly time scale remains a challenge. The simulation can be improved using event-specific parameters (e.g., Tu et al., 2014; Tu et al., 2019); however, an overall understanding of the problem requires multi-point measurements covering a wide energy range. Future missions like REAL, CIRBE, AEPEX, and GTOSat provide a great opportunity for such measurements, especially in conjunction with balloon (e.g., BARREL (Blum et al., 2013; Breneman et al., 2015; Millan et al., 2013)) or sounding rocket (e.g., LAMP) observations. However, there is a gap in observations outside of geostationary orbit (e.g., between Van Allen Probes and MMS) which is crucial for resolving peaks in phase space density profiles identifying the region of seed electron acceleration, and quantifying the contribution of the two acceleration mechanisms. In addition, this region outside of GEO is crucial for understanding the role of plasma sheet convection and injections in the building up of the inner magnetosphere population.

3. Discussion of the Questions

After the overview, the discussion of the four main questions (see Introduction) took place. This chapter summarizes the results of the discussion.

Q1. Under what conditions are contributions from radial diffusion unable to explain observed radiation belt variations?

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This question was extended, and the participants of the session discussed when radial diffusion is sufficient or insufficient to explain the observed radiation belts dynamics. In addition, the panel conveners proposed an additional question: "Are there certain timescales or event types where radial diffusion provides a substantial contribution or the opposite?" R diffusion and the local acceleration are observed under different geomagnetic conditions. It remains unclear which processes play a dominant role and whether the balance between processes is different during CIR storms in comparison to CME storms, or perhaps dependent on the sub-structure of the solar wind transient (e.g., Kilpua et al., 2019). Local acceleration has been observed during the recovery phase of CME shock storms and the long CIR-driven events (e.g., Bingham et al., 2018). However, the effect of radial diffusion is often observed on a longer time scale following a storm event (Jaynes et al., 2018). Unfortunately, the current observational infrastructure does not always provide a clear picture of the electron dynamics at the boundary (at geostationary orbit). It remains challenging to predict the radiation belt dynamics due to the spatio-temporal uncertainty that can be defined by the variation of the boundaries. Nevertheless, the advancement in understanding of electron acceleration leads us to fewer assumptions; hence, our analysis has to be broadened across the system including the plasmasphere and ring current boundaries along with other related boundaries and phenomena. The existence of the electron source population and the wave-generation condition that can lead to local acceleration must be considered. The substantial contribution of radial diffusion or transport is undeniable, as the particles have to be moved inward from the potential source region (beyond GEO); however, whether the initial particles are accelerated by chorus waves or other processes must be a subject of future research.

Q2. Why does diffusion work as well as it does (in simulations)?

In the context of the held discussion the question can be clarified as: "Why do radial diffusion models perform generally well in simulating the observed radiation belt dynamics?" As we know from observations, ULF waves are not always present and have irregular spatio-temporal dependency (see Engebretson et al., 2008; McPherron, 2005; Waters, 2000). Often, the ULF waves have a phase velocity against the electron drift velocity and, similar to chorus waves, can result in non-linear interaction (see Li et al., 2020). The successful diffusion simulations under conditions when quasi-linear and non-linear interations may take place can be explained by the combination of multiple effects that can balance each other. Besides Pc5 waves, the particles interact with local VLF waves (e.g., Li et al., 2014; Thorne et al., 2013) and other types of waves, such as EMIC (e.g., Albert, 2003), smoothing the contribution of each individual process. The simulations with existing radial diffusion models generally provide good results (e.g., Drozdov et al., 2021; Tu et al., 2013); hence, it is necessary to address the periods (e.g., short time scales of hours or days) or events when the existing approximation does not provide a good agreement. The radial diffusion coefficients are not always accurate and on an event-specific basis can be very variable (e.g., Lejosne, 2020; Murphy et al., 2016; Sandhu et al., 2021; Zhao & Li, 2013). The ULF wave power can be found to be different on the adjacent orbit under similar geomagnetic conditions. In addition, the ULF waves can be localized in MLT (e.g., Claudepierre et al., 2013), even though the drift trajectory-averaged ULF wave power is often much less sporadic than that seen at an individual location in space, or along a satellite trajectory. Hence, the variation of wave power can be less pronounced as the particles experience cumulative effect along the drift trajectory.

The advancement of radial diffusion models may be achieved by considering not only Kp, but other drivers as well (e.g., solar wind speed, IMF Bz, etc.). However, the advanced radial diffusion models may not be sufficient to distinguish its contribution from local acceleration. It requires systematic improvement of both radial diffusion and local acceleration models. The advancement also requires the search and analysis of isolated events that are driven solely by radial diffusion, although sudden electron enhancements or depletions across a wide range of L-shells during the short time interval (6–12 hr) may suggest non-diffusive transport. It is unclear under what timescales radial diffusion can describe the observed electrons dynamics. Such events require careful analysis, taking into account the nature of the variation at the boundaries, adiabatic and non-adiabatic effects, rapid magnetic field reconfiguration, and the measurements uncertainties due to the orbital characteristics. Finally, the data-driven boundary conditions and accounting for the last closed drift shell (Albert et al., 2018) can significantly improve the simulation results.

Q3. What methods do we have to study the relative contributions of radial diffusion, transport, and local acceleration?

Historically, the radial and local diffusion coefficients were derived from theoretical assumptions (e.g., Lyons et al., 1971; Schulz & Eviatar, 1969), and space- and ground-based measurements (e.g., Brautigam & Albert, 2000; Glauert & Horne, 2005). Future models should include in situ measurements; however, derivation of the radial diffusion coefficients from the satellite observations is based on many assumptions (see Ali et al., 2016; Drozdov et al., 2021; Lejosne & Kollmann, 2020). The data coverage can be increased by using data assimilation, and in situ electric/magnetic field measurements can be combined with ground-based maps. There are several techniques that can be considered for the validation of future models. Combining the model with artificial spacecraft trajectories can show if particle dynamics reveal a missing process in comparison to realistic measurements along the spacecraft orbit. The existing diffusion models, such as the VERB (Versatile Electron Radiation Belt code, Subbotin & Shprits, 2009; Shprits et al., 2015) code, can be used to study not just evolution of phase space density but its gradients as the manifestation of the diffusion process. The diffusion coefficients can be very large, but without a pronounced phase space density gradient, their contribution can be insignificant.

To calculate the radial diffusion coefficients, the ensemble model approach can be applied to minimize the error in ULF and VLF wave power, which has a substantial statistical spread (e.g., Thompson et al., 2020). Although the diffusion is already averaged over random processes, the ensemble average can provide an improvement in comparison to the deterministic models. However, the improved diffusion models may not be sufficient, as they are limited by the simulation domains. It may be necessary to extend the domain, properly consider the environment such as background electric/magnetic fields, and determine drivers other than other Kp-index. Moreover, it is still an open question as to whether radial transport is actually diffusive, although the non-linear drift terms and other non-linear effects can be incorporated into the diffusion models. The diffusion models can also be used in combination with data assimilation and machine learning (taking into account the non-linear terms) to obtain the comprehensive picture of the radiation belt dynamics for further analysis. Another approach to this problem is using test-particle simulations under time-varying MHD-derived fields (e.g., Hudson et al., 2015; Sorathia et al., 2018). The results of such a simulation can be mapped to the satellite trajectory. However, there are many challenges that must be addressed to achieve precise modeling, among them an accurate accounting for ULF and VLF waves and determination of the event-specific boundary conditions. Also, consideration of the detailed evolution of the wave packet can violate the quasi-linear approximation, resulting in non-linear effects. As an intermediate step before comprehensive test-particle simulations, coupled with MHD modeling, the approach of using Green's functions can be applied for instance (e.g., Kubota & Omura, 2018; Zheng et al., 2019).

Q4. What advances are needed to improve the radiation belt models and/or resolve this debate?

The improvement of modern simulations became possible due to the increase in grid-scale and time resolution of the modeling, as well as increase in resolution of the observations. For example, the Van Allen Probes mission has provided an exceptional data set suitable for the analysis and understanding of the radiation belts. However, the modeling still performs under many assumptions of the simulation parameters and inputs (e.g., solar wind propagation, initial and boundary phase space density profiles, diffusion coefficients, etc). As mentioned above, the data-driven boundary conditions are a necessity for successful modeling. To distinguish between local acceleration and radial diffusion, a comprehensive multi-point overview of the particle distribution throughout the radiation belts, at geostationary orbit and beyond is required. It is critical to have measurements of the radiation belts boundaries over a short time scale (hours, or even minutes). The sampling time of the geo-transfer orbit (similar to the Van Allen Probes, approximately 9 hr) may be too limited to capture fast, localized processes. Distinguishing between averaged global/long time scale dynamics versus local/short time scale dynamics is a very difficult task; however, with larger constellations and partnerships with groups like StarLink, such tasks can be addressed. The GPS satellites (e.g., Morley et al., 2010) are good for capturing rapid overall changes of the upper region of radiation belts ($L > 4$); however, the existing satellite fleet is not always sufficient to sample the length scales of interest. In addition, the GPS data set has to be handled carefully due to its latitude distribution, energy resolution, and absence of the pitch-angle resolved observations. Summarizing the above, comprehensive multi-point measurements of the radiation belts, at their boundary and beyond on the time scale of an hour, are required to answer the raised questions.

4. Summary

Distinguishing between radial transport and local acceleration mechanisms in the Earth's radiation belts remains a challenging task. During the panel discussion, several keypoints were addressed that can help in advancement of this issue:

1. Both radial diffusion and local acceleration are important mechanisms of observed electron flux enhancements and must be considered.
2. The contribution of those processes can be studied on an event-specific basis (short time scale, isolated phenomena, events when either local acceleration or radial diffusion does not perform well in the modeling).
3. The analysis of phase space density profiles, their gradients, and the methods of their accurate calculation is required to distinguish between different processes.
4. The modeling requires the data-driven boundary condition with the defined variation on the time scale of an hour and corresponding in situ measurements for validation.
5. The diffusion coefficients can be improved and hence improve the modeling; however, the advancement of this issue may require a different approach, such as test-particle simulations coupled with MHD-derived fields.
6. Significant advancement can only be achieved with multi-point satellite measurements of the electrons and ions across populations of different energies, on the time scale of an hour or less inside the radiation belts, at the boundary, and beyond.

Data Availability Statement

No data has been used to write this commentary.

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