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Radial Diffusion During Geomagnetic Storms

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Key Findings

- Radial diffusion is significantly enhanced during storms
- Enhancements are due to external solar wind driving as well as internal sources of wave power
- Ozeke et al. [2014][1] significantly underestimates storm time magnetic field diffusion coefficients.

The Radiation Belts at Earth

The radiation belts are highly energetic particles trapped by our global geomagnetic field. During geomagnetic storms, the radiation belts experience dramatic structural changes and intense energisation that is extremely hazardous to local spacecraft.

Understanding how & why the radiation belts change is a key goal of the Space Weather community.

What is Radial Diffusion?

Random electromagnetic fluctuations (~1–20 mHz frequencies) radially scatter radiation belt electrons. **Radial diffusion describes the average rate that the population is radially scattered**.

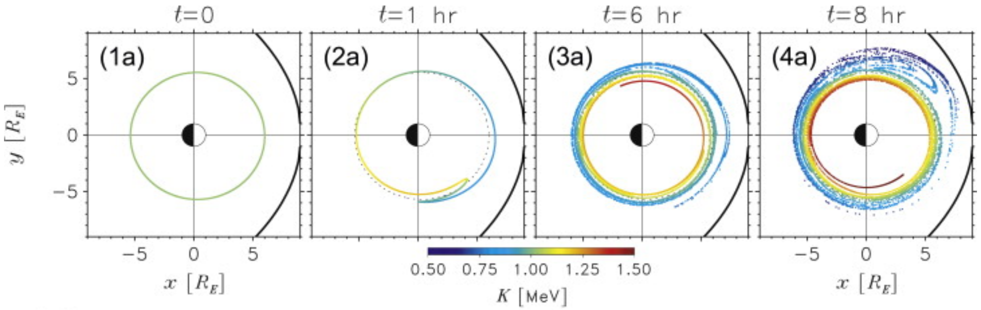

Figure 1. Test-particle simulation of electrons experiencing radial diffusion. Panels show different time steps in the simulation. Electron energy is indicated by colour. Figure adapted from Ukhorskiy & Sitnov, [2008][2].

Figure 1 illustrates radial diffusion and the imparted changes in electron energy (due to conservation laws). Radial diffusion has been attributed to playing an important and sometimes **key role in radiation belt energisation, rapid electron flux losses, and large-scale redistribution.**

In this study we quantify storm time radial diffusion and compare estimates to existing empirical models.

How is Radial Diffusion Measured?

1. Find the storms

An algorithm[3] identifies storms from characteristic signatures in ground magnetometer data.

2. Measure wave power

Magnetic and electric field data from the Van Allen Probes were taken from 2012 – 2019. Power spectral densities, P^B and P^E, were calculated for a frequency band of 1 – 15 mHz. Average wave power as a function of local time and radial distance indicates key sources of wave power (Figure 2).

3. Calculate radial diffusion coefficients

Radial diffusion coefficients describe the magnitude of radial diffusion and are directly estimated from the observed power spectral density using

$$D_{LL}^B = \frac{L^8 4\pi^2}{9\times 8B_E^2}\langle P^B f^2\rangle$$

$$D_{LL}^E = \frac{L^6}{8B_E^2 R_E^2}\langle P^E\rangle$$

where L is radial distance in the equatorial plane, f is wave frequency, and B_E is equatorial magnetic field strength[1].

Sources of Wave Power

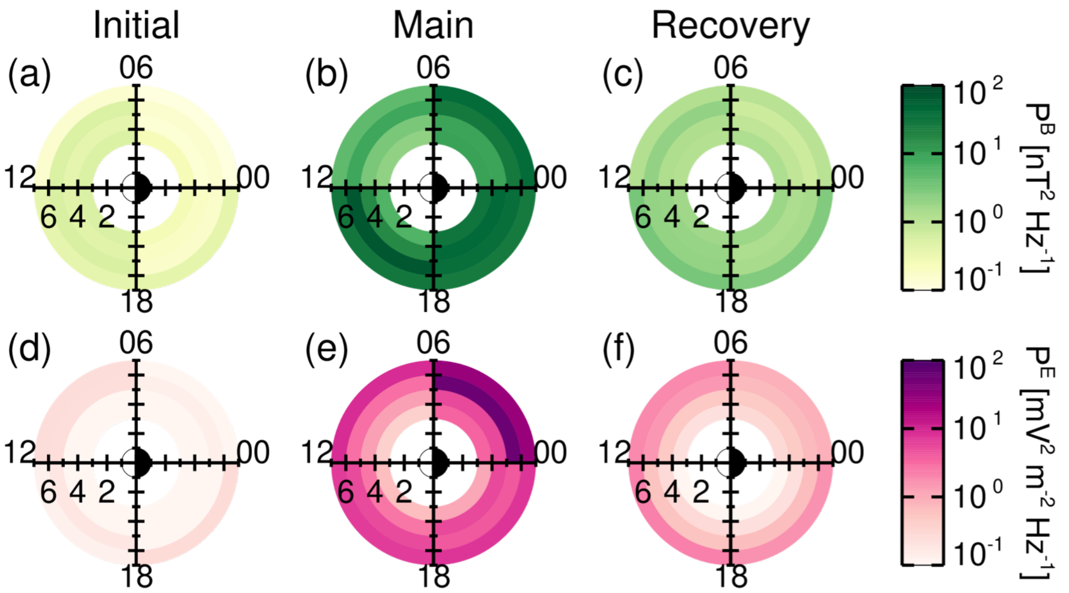

Figure 2. Spatial maps in the Earth's equatorial plane where bin colour indices median values of power spectral density for the (a-c) magnetic field and (d-f) electric field. Data is binned for storm phase, as labelled. Power is summed over 1 – 15 mHz. Radial distances are in Earth radii.

Figure 2 shows spatial variations in wave power, separating storm phases. Enhancements occur during the main phase of the storm across all radial distances.

Both external and internal sources of wave power are important during storms.

- Dayside enhancements indicate an **external source of wave power from elevated solar wind conditions**[4,5,6].
- Nightside and duskside enhancements indicate **strong internal sources** of wave power (**drift-bounce resonance** with ring current ions[7,8] and **substorm driven wave activity**[9]). These internal sources are often neglected by previous studies & models.

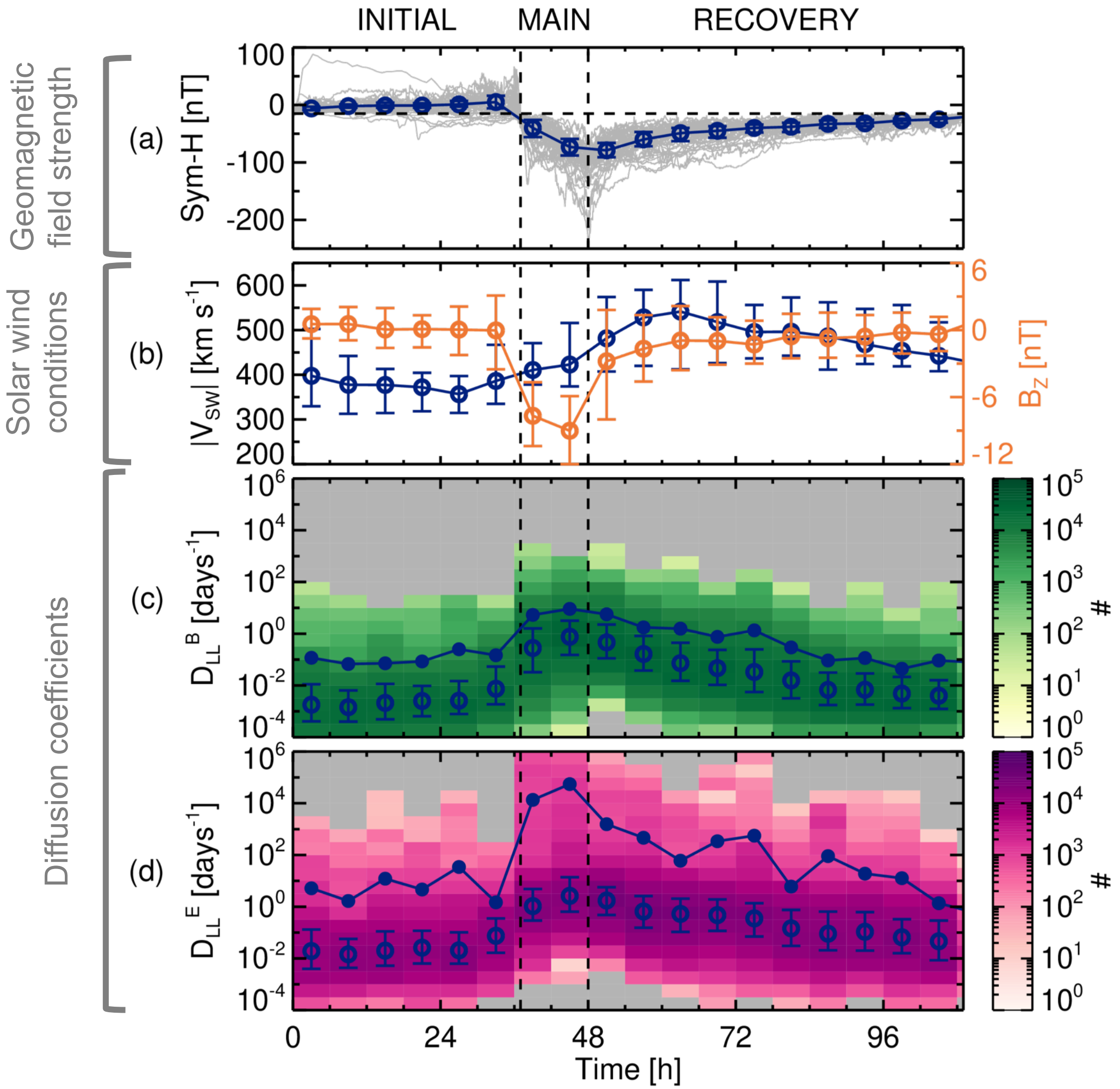

Figure 3. Normalized superposed multi-epoch analysis where dashed vertical lines show epoch times. Samples within $4 \leq L^* < 5$ are shown. Blue open circles show median values and bars show interquartile ranges. (a) Sym-H index, (b) solar wind speed and IMF Bz, (c) magnetic field diffusion coefficient, and (d) electric field diffusion coefficient. In panels (c,d) the colour of the bin indicates the number of samples in parameter space.

How Does Radial Diffusion Vary During Storms?

Figure 3 shows temporal variations in radial diffusion coefficients during geomagnetic storms. All events are averaged together and ordered by the timings of storm phases (dashed lines). We identify several key features of the diffusion coefficients (D_{LL}^{B}, D_{LL}^{E}):

- **Huge variability** throughout storms, with values spanning ~ 6 orders of magnitude.
- Positively skewed distributions are observed throughout storms.
- **Values peak in the main phase, coincident with enhanced solar wind conditions** (speed and field magnitude), and remain elevated during the early recovery phase.

New & Improved Storm Time Diffusion Coefficients!

Figure 4 shows estimated radial diffusion coefficients as a function of the electrons' radial location, L^*, and storm phase. Main phase enhancements in D_{LL}^B and D_{LL}^E are present across all L^* values. Figure 4c shows the total diffusion coefficient $(D_{LL}^B + D_{LL}^B)$.

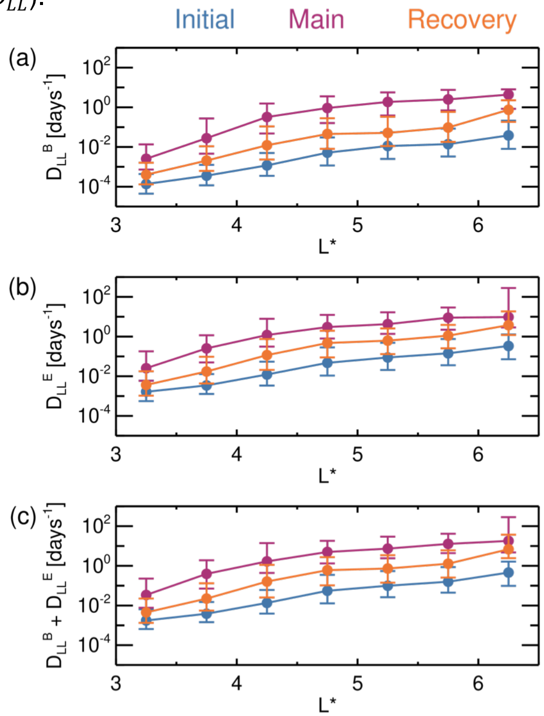

Figure 4. (a) Magnetic field diffusion coefficient, (b) electric field diffusion coefficient, and (c) the sum of the magnetic and electric field diffusion coefficients as a function of L*. The profiles show the median values and the bars show the interquartile ranges. Samples are binned for storm phase, as indicated by colour.

A Comparison to Ozeke et al. [2014]

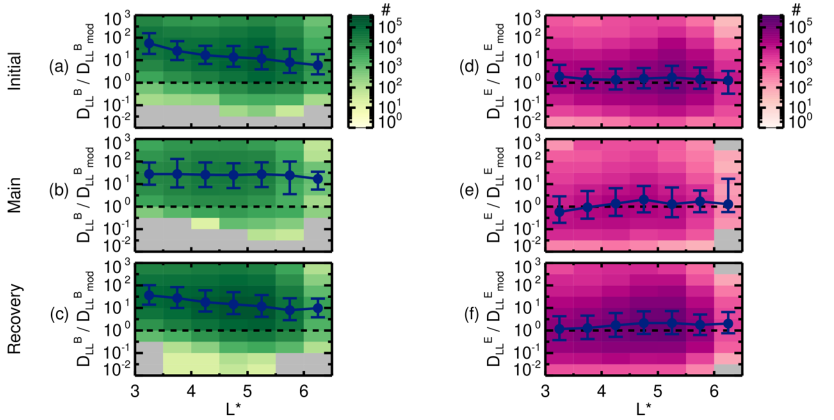

Figure 5. (a-c) Samples binned for the ratio of the observed to modelled magnetic field diffusion coefficients and L*. (d-f). Electric field diffusion coefficients in the same format as (a-c). Colour indicates the number of samples in a bin, blue profiles show the median values as a function of L*, and blue bars show the interquartile ranges. Data is binned for storm phase.

Existing empirical models of radial diffusion are simply parameterised by an activity index.

Are current models realistic during storms?

Figure 5 shows a comparison of the in situ radial diffusion coefficients to the Ozeke et al. [2014][1] empirical model. Whilst the electric field component is well described, the **magnetic field component is significantly larger than modelled values** during all storm phases.

We provide the community with **new storm time diffusion coefficients** that can be directly inputted into existing radiation belt models and enable **more accurate radiation belt forecasting capabilities**.