

Geophysical Research Letters[®]



RESEARCH LETTER

10.1029/2026GL125879

Key Points:

- Earth's inner radiation belt, regarded as an impenetrable barrier to ultra-relativistic electrons, can be broken
- Arase observations show that chorus waves locally accelerated electrons to multi-MeV energies deep inside this barrier in May 2024
- This acceleration was enabled by a low-density region created by severe plasmasphere erosion during a negative ionospheric storm

Correspondence to:

Y. Miyoshi,
miyoshi@isee.nagoya-u.ac.jp

Citation:

Miyoshi, Y., Kurita, S., Shinbori, A., Yamamoto, K., Jun, C.-W., Matsuda, S., et al. (2026). Local acceleration of multi-MeV electrons inside Earth's impenetrable barrier during the May 2024 superstorm. *Geophysical Research Letters*, 53, e2026GL125879. <https://doi.org/10.1029/2026GL125879>

Received 29 JUL 2026

Accepted 18 SEP 2026

Author Contributions:

Conceptualization: Y. Miyoshi

Data curation: Y. Miyoshi, S. Kurita, A. Shinbori, K. Yamamoto, C.-W. Jun, S. Matsuda, I. Shinohara, T. Takashima, T. Mitani, N. Higashio, A. Matsuoka, Y. Kasahara, F. Tsuchiya, A. Kumamoto, T. Hori, N. Kitamura, M. Teramoto

Formal analysis: Y. Miyoshi, S. Kurita, A. Shinbori

Funding acquisition: Y. Miyoshi, D. Wang, I. Shinohara

Investigation: Y. Miyoshi, S. Kurita, I. Shinohara, T. Takashima, T. Mitani, N. Higashio, A. Matsuoka

Methodology: Y. Miyoshi, S. Kurita

Project administration: Y. Miyoshi, I. Shinohara

Resources: S. Matsuda, I. Shinohara, T. Takashima, T. Mitani, N. Higashio,

Local Acceleration of Multi-MeV Electrons Inside Earth's Impenetrable Barrier During the May 2024 Superstorm

Y. Miyoshi^{1,2} , S. Kurita³ , A. Shinbori¹ , K. Yamamoto¹ , C.-W. Jun¹ , S. Matsuda⁴ , S. Saito⁵ , R. Kataoka⁶ , D. Wang⁷ , I. Shinohara⁸ , T. Takashima⁸ , T. Mitani⁸ , N. Higashio⁸ , A. Matsuoka³ , Y. Kasahara⁴ , F. Tsuchiya⁹ , A. Kumamoto⁹ , T. Hori¹ , N. Kitamura¹ , and M. Teramoto¹⁰ 

¹Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan, ²Kyung Hee University, Swon, Korea, ³Kyoto University, Kyoto, Japan, ⁴Kanazawa University, Kanazawa, Japan, ⁵National Institute of Information and Communications Technology, Tokyo, Japan, ⁶Okinawa Institute of Science and Technology, Okinawa, Japan, ⁷GFZ Helmholtz Centre for Geosciences, Potsdam, Germany, ⁸Japan Aerospace Exploration Agency, Sagami, Japan, ⁹Tohoku University, Sendai, Japan, ¹⁰Kyushu Institute for Technology, Kita-Kyushu, Japan

Abstract The inner radiation belt ($L^* < 3$) has long been considered an impenetrable barrier to ultra-relativistic electrons. Here we show that this barrier can be breached under extreme space weather conditions. Using continuous near-equatorial observations from the Arase satellite, we show that the May 2024 superstorm rapidly generated multi-MeV electrons deep inside the inner magnetosphere. Phase space density profiles reveal the development of a local maximum at $L^* \sim 3$, providing evidence that local in situ acceleration established multi-MeV electron source before supplying inward and outward radial diffusion. Simultaneous observations of intense chorus waves under a strongly depleted plasma region, maintained by enhanced convection and a negative ionospheric storm, are consistent with chorus-driven local acceleration. These findings demonstrate that local acceleration can establish a multi-MeV electron source inside the impenetrable barrier under extreme space weather conditions.

Plain Language Summary Earth's radiation belts contain high-energy electrons that can damage satellites. For more than a decade, satellite observations have shown that ultra-relativistic electrons cannot penetrate inside a natural boundary known as the “impenetrable barrier.” During the exceptional geomagnetic storm of May 2024, however, the Arase satellite observed a rapid increase of multi-MeV electrons well inside this region. Our observations show that these electrons were not simply transported inward from higher altitudes. Instead, they were accelerated locally near Earth's magnetic equator, forming a new source of multi-MeV electrons inside the barrier. This conclusion is supported by the appearance of a distinct peak in the electron phase space density. The storm strongly compressed the plasmasphere, and its recovery was delayed by an ionospheric negative storm, allowing a low-density plasma environment to persist. These conditions favored intense chorus waves, which are consistent with efficient acceleration of electrons to multi-MeV energies. Under extreme space weather conditions, ultra-relativistic electrons can be generated locally inside the barrier, providing new insight into radiation belt dynamics and improving our understanding of hazardous space weather.

1. Introduction

Earth's radiation belts consist of an inner belt, an outer belt, and occasionally a transient third belt, each exhibiting distinct responses to geomagnetic disturbances, with outer-belt electrons typically disappearing during the main phase and enhanced during recovery (Y. Miyoshi and Kataoka, 2005; Reeves et al., 2003). The importance of local acceleration in the outer belt is now firmly established (Y. Miyoshi et al., 2021; Reeves et al., 2013; Thorne et al., 2013), and discoveries such as the third belt (Baker et al., 2013) have significantly advanced our understanding of radiation belt dynamics.

By contrast, the inner region, particularly at $L^* < 3$, is generally regarded as stable and containing few ultra-relativistic electrons, even under disturbed conditions. This region, often referred to as the impenetrable barrier, has rarely shown variability in MeV electron populations (Baker et al., 2014; Ozeke et al., 2018), with long-term inner-belt variations instead attributed to cosmic ray albedo neutron decay modulated by the solar cycle (X. Li et al., 2017). During the “Halloween storms” of October–November 2003, unexpected increases in

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A. Matsuoka, Y. Kasahara, F. Tsuchiya,
A. Kumamoto, M. Teramoto
Software: Y. Miyoshi, S. Kurita,
A. Shinbori, C.-W. Jun
Validation: Y. Miyoshi, S. Kurita,
A. Shinbori
Visualization: Y. Miyoshi, S. Kurita
Writing – original draft: Y. Miyoshi
Writing – review & editing: Y. Miyoshi,
S. Kurita, A. Shinbori, K. Yamamoto, C.-
W. Jun, S. Matsuda, S. Saito, R. Kataoka,
D. Wang, I. Shinohara, T. Takashima,
T. Mitani, N. Higashio, A. Matsuoka,
Y. Kasahara, F. Tsuchiya, A. Kumamoto,
T. Hori, N. Kitamura, M. Teramoto

energetic electron fluxes were observed at low L-shells (Baker et al., 2004; Horne et al., 2005). Combined SAMPEX energetic electron and IMAGE EUV imaging observations of plasmasphere showed a close relationship between extreme plasmaspheric erosion and the reformation of the outer radiation belt (Baker et al., 2004), which numerical simulations attributed to local whistler-mode chorus acceleration in the low-density conditions (Y. Y. Shprits et al., 2006). However, because SAMPEX observed only at low altitude and the available Cluster chorus-wave observations were spatially limited to $L > 4$ (Horne et al., 2005), simultaneous near-equatorial observations of the phase space density (PSD), cold plasma density, and chorus waves were not available to directly resolve the formation and evolution of relativistic electrons.

In May 2024, a super geomagnetic storm occurred, ranking among the most intense events since 2003 (Hayakawa et al., 2025). Several studies reported substantial changes in the inner magnetosphere during this event by the Arase satellite (e.g., Jun et al., 2025, 2026; Kitamura et al., 2026; Kurihara et al., 2026; Lyu et al., 2026; Obana et al., 2026; Olifer et al., 2026; Shinbori et al., 2025). Low-Earth-orbiting satellites also reported MeV electron enhancements extending down to $L^* < 2$ (X. Li et al., 2025), where L^* is the Roeder L-shell. Sun et al. (2025), using MSS-1 and Arase observations, reported the rapid appearance of ~ 1 -MeV electrons followed by their gradual inward extension to $L_m \sim 1.5$, where L_m is the McIlwain L -value; the observed energy spectra, zebra-stripe structures, and pitch-angle distributions suggested that radial transport, radial diffusion, local acceleration, and pitch-angle scattering may all have contributed at different stages. However, these low-altitude observations cannot resolve the temporal evolution of the near-equatorial PSD required to identify where the MeV electron source population was initially produced.

In this letter, we identify the formation and growth of a pronounced local PSD maximum near $L^* \sim 3$ during the early recovery phase of the May 2024 superstorm. The development of this peak at fixed first and second adiabatic invariants provides strong observational evidence that local in situ acceleration established the near-equatorial MeV electron source population. The subsequent evolution of the PSD gradients indicates that this locally accelerated population was later redistributed both inward and outward. Coincident observations of intense dawnside chorus waves under strongly depleted plasma density conditions further support chorus driven wave–particle interactions as the acceleration mechanism.

2. Observations

Observations were conducted using the Arase (ERG) satellite (Y. Miyoshi et al., 2022; Y. Miyoshi, Shinohara, et al., 2018), which operated continuously throughout the May 2024 super geomagnetic storm. To investigate relativistic electron dynamics, we used data from the Extreme High-Energy Electron Experiment (XEP), which measured the electron fluxes in the 0.5–4-MeV energy range (Higashio et al., 2018a). Magnetic field data were obtained from Magnetic Field Experiment (MGF) (Matsuoka, Teramoto, Nomura, et al., 2018), whereas plasma-wave observations were provided by the Plasma Wave Experiment (PWE) (Kasahara, Kasaba, et al., 2018). During this time interval, Arase's apogee was on the noon side, and the satellite observed the inner magnetosphere mainly on the dawn and dusk sides. Electron densities were derived from the upper hybrid resonance (UHR) frequencies detected by the PWE High-Frequency Analyzer (HFA) (Kumamoto et al., 2018), and whistler-mode chorus-wave activity was analyzed using PWE spectral data in the 30 Hz–10 MHz range from the PWE Onboard Frequency Analyzer (OFA) (Matsuda et al., 2018) and HFA.

The PSD was computed from the XEP flux data by converting them into adiabatic invariant coordinates (Y. Miyoshi et al., 2021). Fixed values were used for the first and second adiabatic invariants: $M = 887.8$ MeV/G and $K = 0.14$ G^{1/2}·R_E, respectively. The pitch angles at the satellite location were determined using magnetic field data from Arase/MGF and then mapped to the magnetic equator based on a geomagnetic field model. The L^* values were obtained from Arase orbit Level-3 data using the Tsyganenko and Sitnov (2005) storm-time magnetic field model (TS05) (Y. Miyoshi, Shinohara, & Jun, 2018) to ensure accurate drift-shell mapping under storm-time conditions. Inbound (dusk-side) passes had systematically lower magnetic latitude ($|MLAT| \sim 18^\circ$) than outbound (dawn-side) passes ($|MLAT| \sim 27^\circ$), so that the $K = 0.14$ G^{1/2}·R_E mirror-point condition was satisfied more often and over longer continuous intervals on inbound passes; the radial PSD profiles (Figure 3) are therefore derived predominantly from inbound passes.

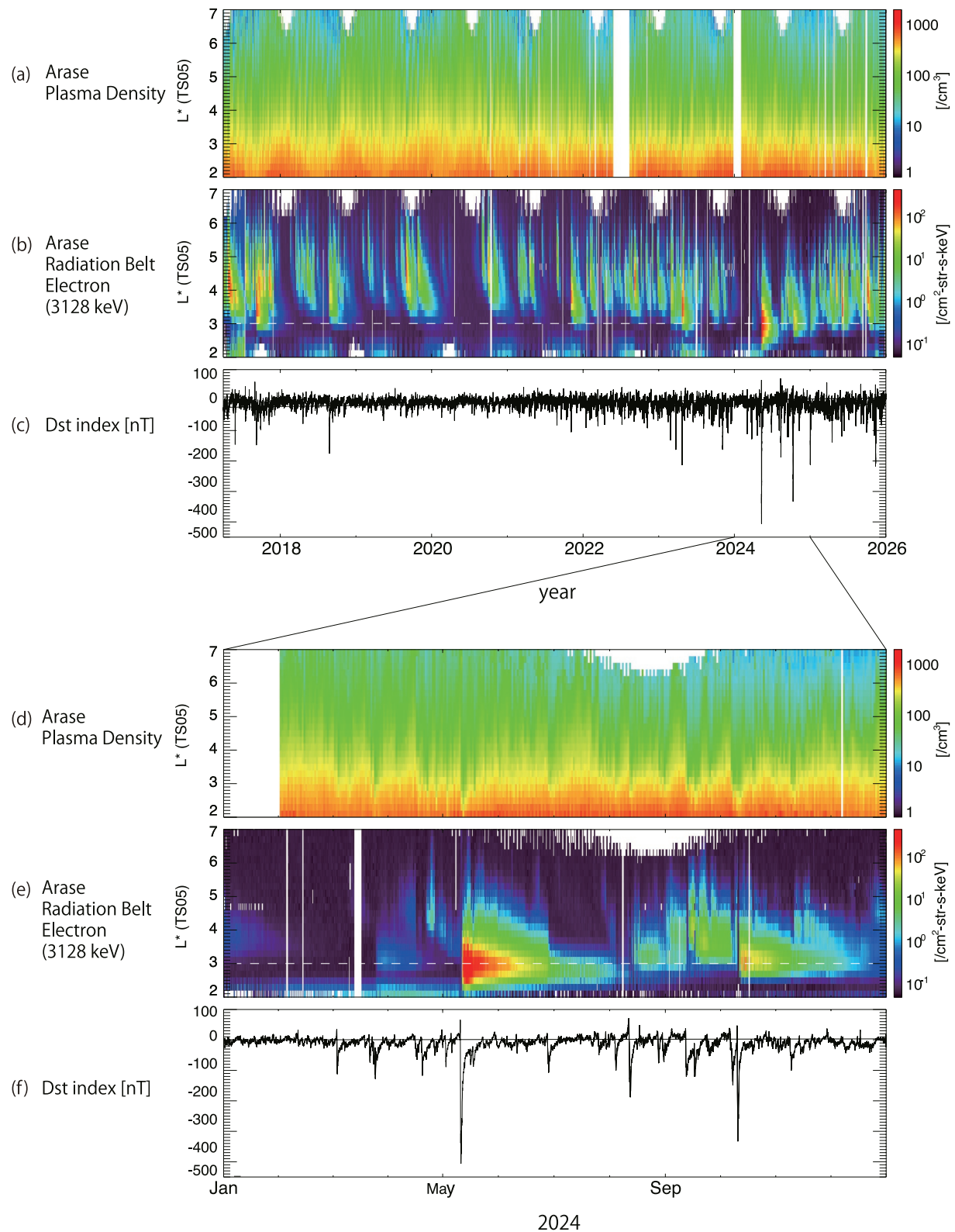


Figure 1. Long-term plasmasphere and radiation belt evolution observed by Arase, with zoomed-in views corresponding to the May 2024 event. (a–c) Long-term Arase observations for 2017–2026 showing the plasma density, ~ 3 MeV electron flux (3,128 keV) as a function of L^* (TS05), and Dst index, respectively. (d–f) Expanded views for 2024. White dashed lines in panels (b) and (e) correspond to $L^* = 3$, that is, the impenetrable barrier.

3. Results

3.1. Long-Term Plasmasphere and Radiation Belt Evolution

To provide long-term context for the May 2024 superstorm, we first examined the plasmasphere and radiation belt evolution using continuous observations obtained by Arase since regular operations began in 2017 (Figure 1). This data set provides the first continuous near-equatorial record, offering more than 8 years of information on plasma density and MeV electrons in the inner magnetosphere.

Throughout Arase's operation, MeV electrons were largely confined outside $L^* \sim 3$ (while lines in Figures 1b and 1e), consistent with the impenetrable barrier (Baker et al., 2014; Ozeke et al., 2018). Although multiple geomagnetic storms produced significant variability in the outer radiation belt and plasmasphere, no comparable MeV electron enhancement at $L^* < 3$ was observed. By contrast, the May 2024 event is unique in the Arase record; MeV electrons appeared and intensified deep inside the barrier, accompanied by a prolonged erosion of the plasmasphere. This combination of low- L electron enhancement and strong plasmasphere erosion was not observed in other storms during the Arase mission.

3.2. Extreme Geomagnetic Storm and Its Initial Impact on the Radiation-Belt Structure

Next, we examined the solar wind and geomagnetic response during the May 2024 superstorm (Figure 2). The event was characterized by extreme solar wind parameters, with the density and speed exceeding 60 cm^{-3} and $1,200 \text{ km s}^{-1}$, respectively, and the interplanetary magnetic field B_z reaching below -44 nT (Figures 2a–2c), producing one of the most severe geomagnetic disturbances of the modern space-weather era. Severe substorms were continuously recorded, as shown by the AL index (Figure 2g), and the Dst index dropped below -406 nT (Figure 2h), marking the most intense storm since 2003. This extreme event compressed the magnetopause to $\sim 4.9 R_E$, likely leading to rapid loss of outer belt electrons through magnetopause shadowing (e.g., Lyu et al., 2026; Matsumura et al., 2011; Turner et al., 2012).

3.3. Relativistic Electron Enhancement Deep Inside the Impenetrable Barrier

During the recovery phase, Arase detected a remarkable enhancement in relativistic electron fluxes (692 keV, Figure 2e) and ultra-relativistic electrons (3,128 keV, Figure 2g) inside the stable inner magnetosphere. At $L^* < 3$, the ultra-relativistic electron flux increased by more than a factor of 5,000 relative to the pre-storm level. Specifically, the 3,128 keV flux increased from $\sim 10^0$ to $\sim 10^4 \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ keV}^{-1}$ at $L^* = 2.5$, and from $\sim 10^0$ to $\sim 5 \times 10^4 \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ keV}^{-1}$ at $L^* = 3.0$. Therefore, this event represents a rare occurrence of relativistic electron intensification at $L^* < 3$.

Notably, the fluxes of three energy channels shown in Figure 2 (692 keV, panel e; 1,093 keV, panel f; and 3,128 keV, panel g) do not increase simultaneously. The 692 keV electron flux first intensifies, the 1,093 keV electron flux follows roughly half a day later, and the 3,128 keV electron flux does not reach comparable flux levels until the early recovery phase, approximately one day after the 692 keV enhancement. This energy ordered, sequential onset is inconsistent with a single simultaneous transportation from outside the region and instead indicates gradual local energization from sub-MeV to multi-MeV energies over roughly one day, consistent with the local-acceleration picture. After the storm, the ultra-relativistic electron flux in these low- L -shell regions exhibited a gradual decay until October 2024, when another severe geomagnetic storm occurred, as shown in Figure 1e.

Simultaneous plasma density measurements derived from the UHR frequencies revealed that the plasmopause had contracted to below $L^* = 1.5$ (Figure 2d), and its refilling proceeded at an anomalously low rate due to the ionospheric negative storm (a storm-time decrease in ionospheric electron density; e.g., Kumar & Parkinson, 2017), lasting more than twice as long as in typical storms (Shinbori et al., 2025). The electron density at $L^* = 3.0$ decreased from several hundred cm^{-3} before the storm to below $\sim 200 \text{ cm}^{-3}$ afterward, maintaining extended regions with a low plasma frequency (fpe) to electron gyro frequency (fce) ratio, which is important for chorus-wave generation and efficient wave-particle interactions (e.g., Allison et al., 2021; Horne et al., 2003).

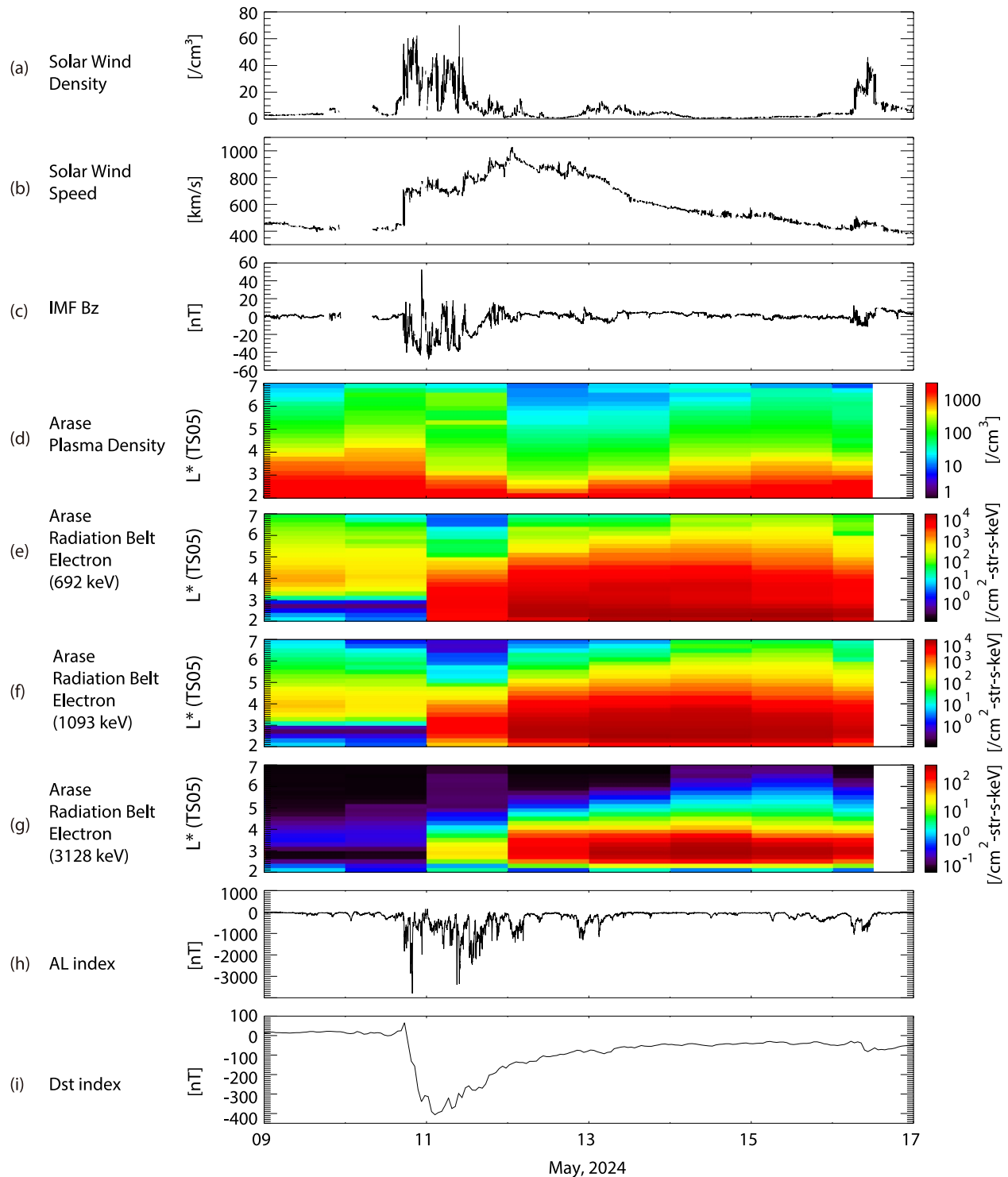


Figure 2. Solar wind forcing and inner-magnetospheric response during the May 2024 superstorm. Time series of solar wind, geomagnetic, and Arase observations for 9–17 May 2024. Panels show the (a) solar wind density, (b) solar wind speed, (c) interplanetary magnetic field (IMF) Bz, (d) Arase plasma density, (e) 692 keV, (f) 1,093 keV, and (g) 3,128 keV Arase electron fluxes, (h) AL index, and (i) Dst index. The superstorm was driven by extreme solar wind conditions, including high density and speed and a prolonged southward IMF. During this interval, the plasmapause contracted to below $L^* \sim 1.5$, while relativistic and ultra-relativistic electron fluxes showed a significant enhancement inside $L^* < 3$ (impenetrable barrier).

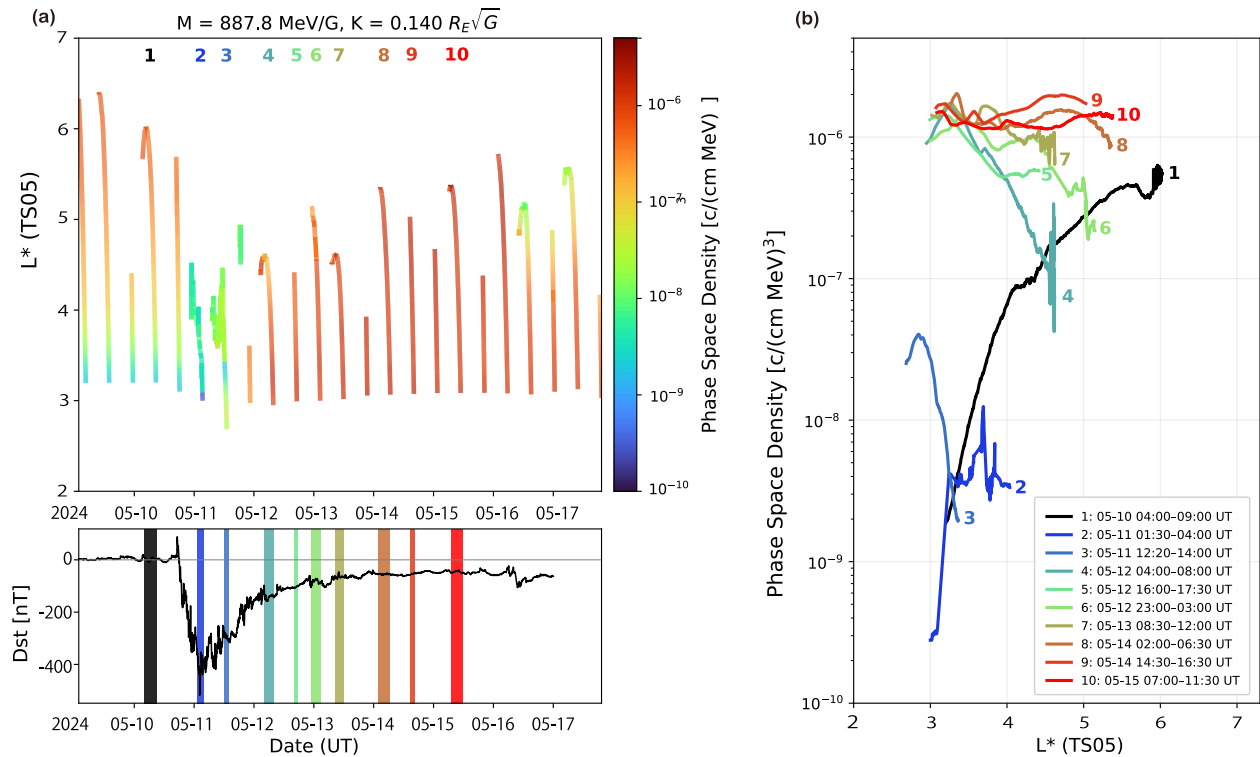


Figure 3. Phase space density (PSD) evolution revealing local acceleration and subsequent radial redistribution. (a) PSD of relativistic electrons ($M = 887.8$ MeV/G, $K = 0.14$ Re $G^{1/2}$) plotted along the actual Arase trajectory. The numbered intervals correspond to the radial PSD profiles shown in panel (b). (b) Radial PSD profiles for 10 selected orbital passes; the observation time window for each profile is listed in the panel.

3.4. Phase Space Density Signatures of Local Acceleration and Diffusion

The PSD of electrons with $M = 887.8$ MeV/G and $K = 0.14$ $G^{1/2} \cdot R_E$, corresponding to ~ 2 – 3 MeV at $L^* \sim 3$, exhibited a significant transformation during the storm (Figure 3a). Before the main phase, the PSD profiles exhibited outward gradients consistent with inward radial diffusion from an external source (Green & Kivelson, 2004; W. Li & Hudson, 2019). During the main phase, the PSD sharply decreased owing to strong losses, followed by a growing peak at $L^* \sim 3$ during the early recovery phase (Figure 3b), which is clear evidence of local in situ acceleration (Y. Miyoshi et al., 2021; Reeves et al., 2013). This is the first observation of such a process within the impenetrable barrier. Over subsequent days, the radial PSD gradients gradually flattened, indicating that the local maximum near $L^* \sim 3.0$ subsequently redistributed inward and outward, with possible additional contribution from inward diffusion of populations at higher L (Green & Kivelson, 2004; Reeves et al., 2013; Thorne et al., 2013).

3.5. Sustained Chorus-Driven Acceleration

Figure 4 presents wave spectrograms observed by Arase along the dawn-side trajectories for the pre-storm, main phase, and three recovery intervals. The plasmapause location, determined from the density-drop criterion of Carpenter and Anderson (1992) and cross-checked against plasmaspheric hiss and electrostatic cyclotron harmonic wave activity (Jun et al., 2026), is marked in each panel where it could be reliably identified ($L^* = 1.5$, 2.15, and 2.45 for panels b, d, and e, respectively; not determinable for panels a and c).

No chorus waves were observed before the storm, and the plasmasphere extended outward to $L^* \sim 5$ with plasmaspheric hiss. During the main phase, the plasmapause contracted unusually to $L^* \approx 1.5$, and strong lower-band chorus emissions appeared between $L^* = 1.5$ and 3.5. During the recovery phase, the plasmasphere gradually expanded, whereas intense chorus activity persisted for several days at $L^* \approx 3$, where a growing PSD peak was observed. Chorus waves were confined to the dawn sector, with no significant activity on the dusk side; this spatial and temporal correspondence with the PSD peak is consistent with chorus-driven local acceleration

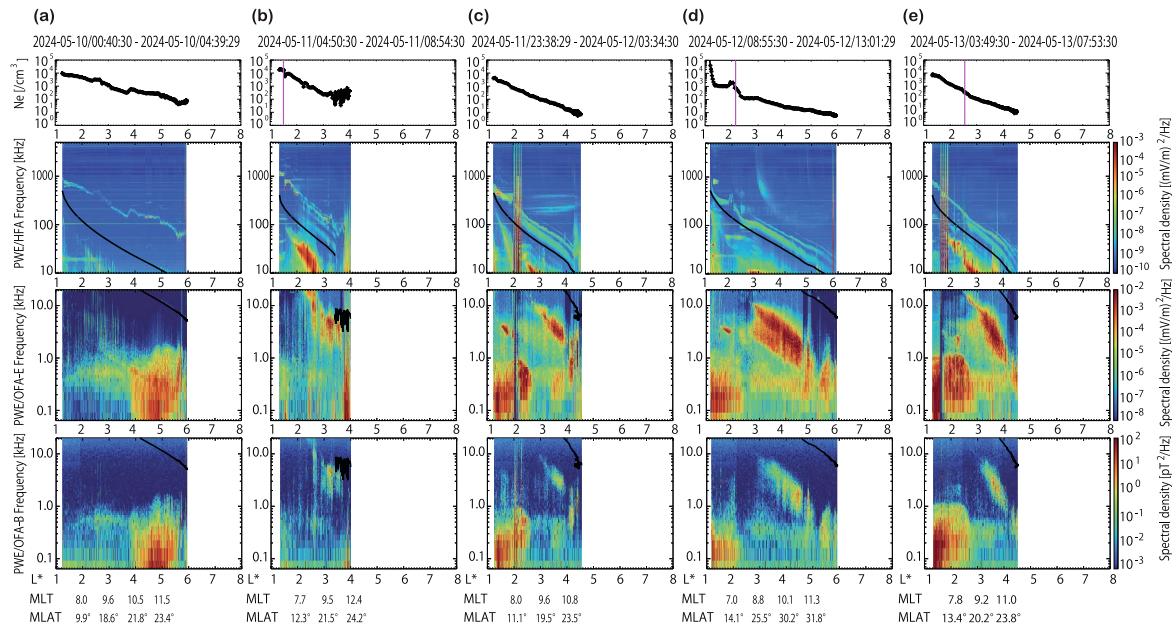


Figure 4. Spatiotemporal evolution of plasma-wave spectra along the dawn-side trajectories during the May 2024 superstorm. The five panels correspond to the pre-storm period, main phase, and three recovery intervals. From top to bottom: plasma density, high-frequency electric field spectra (20–1,000 kHz), and low-frequency electric and magnetic field spectra (50 Hz–20 kHz) as functions of $L^* = 1$ –8, with the corresponding MLT (magnetic local time) and MLAT (magnetic latitude) also indicated along the bottom axis of each panel. The solid black line denotes the fce at the magnetic equator calculated using the TS05 model; data are plotted only where L^* is defined. The vertical lines show the expected plasmopause. The plasmopause location was $L^* = 1.5$ (panel b), 2.15 (panel d) and 2.45 (panel e), while the location cannot be investigated at panels (a and c).

(e.g., Jaynes et al., 2015; Y. Miyoshi et al., 2013, 2016; Summers et al., 1998; Thorne et al., 2013). The chorus waves occurred in low-fpe/fce-ratio regions. Using the relativistic first-order cyclotron resonance condition with the cold-plasma whistler-mode dispersion relation (parallel propagation, chorus frequency $0.3 f_{ce_eq}$ (equatorial gyrofrequency)), the estimated resonant energies for equatorial pitch angles of 60° – 70° are ~ 1.5 – 2.5 MeV at $L^* = 3.2$ (126 cm^{-3}) and $L^* = 4.5$ (15 cm^{-3}), overlapping the multi-MeV energy range represented by the observed PSD maximum. The corresponding fpe/fce decreased from ~ 9 to 16 before the storm to ~ 2.7 – 3.4 during the recovery phase, favorable for chorus interactions with relativistic electrons.

4. Discussion and Summary

The principal advance of this study is the direct identification of a near-equatorial MeV electron source inside the impenetrable barrier. At fixed first and second adiabatic invariants, the PSD profiles evolved from a depleted profile during the main phase to a pronounced and growing local maximum near $L^* \sim 3$ during the early recovery phase. Inward radial transport from an external source can modify the PSD gradient, but it cannot by itself produce a growing local maximum (Green & Kivelson, 2004; Reeves et al., 2013). The observed PSD peak therefore provides observational evidence that local in situ acceleration established the multi-MeV electron source population near $L^* \sim 3$. The later development and flattening of the radial PSD gradients indicate that radial diffusion subsequently redistributed the locally accelerated electrons both inward and outward.

The May 2024 superstorm provided a natural laboratory for understanding the inner magnetosphere's response to extreme solar wind forcing. Figure 5 presents a schematic of the dynamic evolution of the plasmasphere, radiation belts, and chorus-wave activity. Before the storm, the plasmasphere extended outward to $L^* \sim 5$, with the outer belt bounded by the impenetrable barrier at $L^* = 3$. During the main phase, the magnetopause and plasmopause contracted drastically to $4.9 R_E$ and $L^* \sim 1.5$, respectively, allowing intense dawn-side chorus waves to develop outside the contracted plasmopause. As the recovery phase progressed, the plasmasphere and magnetopause expanded outward, whereas chorus waves persisted in the dawn sector. The radiation belt rebuilt itself inside the impenetrable barrier, peaking around $L^* \sim 3$, where the PSD showed a growing maximum. This schematic emphasizes that the local acceleration associated with chorus waves near $L^* \sim 3$ played a key role in regenerating

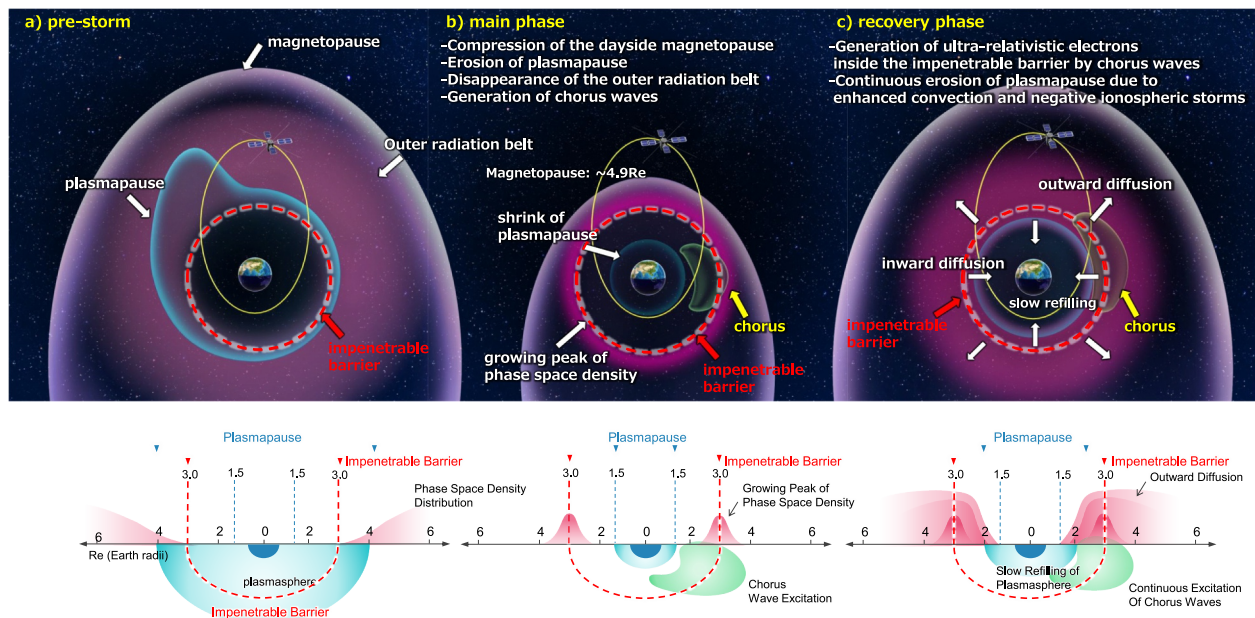


Figure 5. Schematic of the inner magnetosphere evolution during the May 2024 superstorm. (a) Pre-storm: The plasmasphere (blue) extends to $L^* \sim 6$, and the radiation belts (pink) are confined outside the impenetrable barrier (red dashed circle at $L^* \sim 3$). The magnetopause lies far from Earth, and no chorus waves are present. (b) Main phase: The plasmapause contracts to $L^* \sim 1.5$, and the magnetopause moves inward to $4.9 R_E$. The radiation belt reappears at $L^* = 2.3\text{--}3.2$, with the strongest enhancement near $L^* \approx 3$, just outside the plasmasphere. Intense dawn-side chorus waves (green) emerge just beyond the plasmapause. (c) Recovery phase: Both the plasmasphere and magnetopause expand outward, while chorus waves persist on the dawn side. The radiation belt intensifies and spreads radially from $L^* \sim 3$, where the growing peak of the phase space density is identified, leading to the re-formation of ultra-relativistic electrons inside the impenetrable barrier. The yellow ellipse in each panel represents the orbit of the Arase satellite during the storm.

the radiation belt deep inside the impenetrable barrier, a region conventionally regarded as stable against multi-MeV electron penetration.

In contrast to the October 2003 superstorms, where electron enhancements in the inner radiation belt were inferred only from low-altitude SAMPEX observations (Baker et al., 2004) and spatially limited high- L Cluster chorus-wave observations (Horne et al., 2005), Arase observations provide a comprehensive equatorial view of the PSD structure, cold plasma density, and wave activity across the inner magnetosphere. During the 2003 events, the absence of equatorial PSD and wave measurements made it impossible to determine whether the observed enhancements arose from external transportation, radial diffusion, or local processes. Arase has now enabled a comprehensive diagnosis of local acceleration conditions inside the impenetrable barrier. The formation and growth of the PSD maximum near $L^* \sim 3$, together with the coincident chorus activity, identify local acceleration as the process that formed the source population. The subsequent inward transport and pitch-angle redistribution reported by Sun et al. (2025) may therefore represent later stages in the evolution of electrons initially accelerated near $L^* \sim 3$.

The observed PSD peak and associated wave-particle interactions are consistent with previous theoretical and observational studies of chorus-driven local acceleration at higher L -shells (Allison & Shprits, 2020; Boyd et al., 2018; Y. Miyoshi et al., 2021; Reeves et al., 2013; Thorne et al., 2013). However, our findings reveal that this mechanism can also operate effectively inside the impenetrable barrier. The favorable conditions for sustained acceleration appear to have resulted from an intense and prolonged plasmasphere erosion caused by strong convection electric fields (Shinbori et al., 2025). This erosion allowed hot electrons to penetrate inward and excite low-frequency chorus waves (Jaynes et al., 2015; Y. Miyoshi et al., 2013). The subsequent plasmasphere refilling was unusually slow due to the negative ionospheric storms (Shinbori et al., 2025), maintaining an environment that was optimal for cyclotron resonance over an extended period (Allison et al., 2021; Horne et al., 2003; Y. A. Miyoshi et al., 2003; Y. Y. Shprits et al., 2026).

Kurihara et al. (2026) reported sub-MeV electron microbursts at $L_m \sim 2$ associated with enhanced chorus activity at $L_m \sim 2\text{--}4$ from Arase and International Space Station observations, indicating that chorus-driven pitch-angle

scattering also operated unusually deep in the inner magnetosphere. Together with the present PSD evidence, this suggests chorus waves contributed to both acceleration and precipitation loss of energetic electrons in the unusually low- L region during different storm phases.

These results are consistent with ideas developed following the 2003 Halloween storms, when combined SAMPEX and IMAGE observations first showed that severe plasmaspheric erosion could reform the outer radiation belt much closer to Earth (Baker et al., 2004), attributed to local chorus-driven acceleration (Y. Y. Shprits et al., 2006). Y. Shprits et al. (2011) further suggested that even stronger storms could erode the plasmasphere farther inward, potentially energizing electrons deep in the stable inner zone. The May 2024 event and the near-equatorial observations presented here provide direct observational evidence for this process.

These findings refine the interpretation of multi-MeV electron penetration into the inner radiation belt. Previous studies have shown that relativistic electrons can be transported into the inner zone during major geomagnetic storms (Claudepierre et al., 2019), and recent low-altitude observations established that MeV electrons reached $L < 2$ during the May 2024 event (X. Li et al., 2025; Sun et al., 2025). The impenetrable barrier was therefore not crossed solely through inward transport from the outer belt: under extreme conditions, chorus-driven local acceleration generated a new multi-MeV electron near $L^* \sim 3$, which supplied the source population for radial diffusion and may have contributed to the lower- L populations observed at low altitude. Deep plasmaspheric erosion from prolonged negative ionospheric storms and sustained chorus-wave activity appear to be key conditions enabling this acceleration, although further modeling is required to quantify the relative roles of radial transport, radial diffusion, local acceleration, and pitch-angle scattering.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The Arase satellite data used in this study are publicly available from the ERG Science Center operated by the Institute of Space and Astronautical Science (ISAS), JAXA, and the Institute for Space-Earth Environmental Research (<https://ergsc.isee.nagoya-u.ac.jp>, Y. Miyoshi, Hori et al., 2018). Solar wind and geomagnetic indices were obtained from NASA/GSFC's OMNIWeb service (<https://omniweb.gsfc.nasa.gov>). The AE and Dst indices were provided by the World Data Center for Geomagnetism, Kyoto (<http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html>). The present study analyzed XEP Level-2 2d flux data v01_00 (<https://doi.org/10.34515/DATA.ERG-00000>, Higashio et al., 2018b), XEP Level-2 Omniflux v01_00 (<https://doi.org/10.34515/DATA.ERG-00001>, Higashio et al., 2018c), MGF-L2 8 s spin-averaged data v04_06 (<https://doi.org/10.34515/DATA.ERG-06001>, Matsuoka, Teramoto, Imajo, et al., 2018), PWE/OFA Lv2. power spectrum data v02_05 (<https://doi.org/10.34515/DATA.ERG-08000>, Kasahara, Kojima et al., 2018), PWE/HFA Lv2. spectrum data v01_02 (<https://doi.org/10.34515/DATA.ERG-10000>, Kasahara, Kumamoto et al., 2018), PWE/HFA Lv3. electron density data v06_11 (<https://doi.org/10.34515/DATA.ERG-10001>, Kasahara et al., 2021) and Orbit L3 v02 data (<https://doi.org/10.34515/DATA.ERG-12001>, Y. Miyoshi, Shinohara and Jun, 2018).

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Acknowledgments

This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grants 22K21345, 23K25925, 24K07112, 26K00765, and 26H02088. D. W. acknowledges the support from the European Research Council (ERC) under the European Union's Horizon Europe research and innovative programme (Grant agreement number: 101124679-WIRE). We thank D. N. Baker and Y. Shprits for valuable discussions and suggestions.

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