

Statistical study on the correlation between chorus waves and pitch angle distributions of outer radiation belt relativistic electrons

Hui Zhao^{1,2}, Chang Yang^{1,2*}, FuLiang Xiao^{1,2*}, Si Liu^{1,2}, QingHua Zhou^{1,2}, Sai Zhang^{1,2}, ZhongLei Gao^{1,2}, YuYue Jin^{1,2}, and Yihua He^{1,2}

¹School of Physics and Electronic Sciences, Changsha University of Science and Technology, Changsha 410114, China;

²Hunan Province Higher Education Key Laboratory of Modeling and Monitoring on the Near-Earth Electromagnetic Environments, Changsha University of Science and Technology, Changsha 410114, China

Key Points:

- Six years of statistical data on chorus waves amplitude and relativistic electron pitch angle distributions in the outer radiation belt are presented.
- When chorus waves intensify, outer belt relativistic electrons tend to exhibit pancake pitch angle distributions.
- Enhanced solar wind dynamic pressure or geomagnetic substorm activity favors pancake pitch angle distributions of relativistic electrons.

Citation: Zhao, H., Yang, C., Xiao, F. L., Liu, S., Zhou, Q. H., Zhang, S., Gao, Z. L., Jin, Y. Y., and He, Y. H. (2026). Statistical study on the correlation between chorus waves and pitch angle distributions of outer radiation belt relativistic electrons. *Earth Planet. Phys.*, 10(4), 659–667. <http://doi.org/10.26464/epp2026053>

Abstract: The Earth's outer radiation belt contains a large number of relativistic (> 500 keV) electrons, which can exhibit different pitch angle distributions (PADs). Whistler-mode chorus waves are considered an important factor governing the evolution of electron PADs, but their long-term and global effects remain insufficiently studied. This paper presents a statistical analysis using observations from the Van Allen Probes during 2013–2018. A pitch angle anisotropy index A is employed to characterize electron PADs, and its correlation with chorus waves is investigated. Statistical results show that when chorus waves intensify, the index A increases, implying that electrons tend to exhibit pancake PADs. In addition, the index A is found to be positively correlated with enhanced solar wind dynamic pressure or substorm activity. Our results demonstrate that chorus waves play an important role in accelerating relativistic electrons and reshaping their PADs, which contributes to a deeper insight into the physical mechanisms underlying the dynamic evolution of the outer radiation belt.

Keywords: outer radiation belt; relativistic electrons; pitch angle distribution; whistler-mode chorus; wave–particle Interaction

1. Introduction

The Earth's electron radiation belts generally consist of an inner belt and an outer belt, with the outer radiation belt containing a large number of relativistic (> 500 keV) electrons (Baker et al., 1986; Reeves et al., 2003; Zhou QH et al., 2022). These electrons can exhibit different pitch angle distributions (PADs), typically categorized as pancake, flat-top, and butterfly types (West et al., 1973; Su ZP et al., 2009b; Thorne et al., 2010; Zhao H et al., 2014; Ni BB et al., 2015). The pancake PAD is characterized by a peak in electron differential flux around pitch angle 90° , smoothly decreasing toward both sides (0° and 180°). The formation of pancake PADs can be attributed to wave-driven acceleration (Yang C et al., 2016), pitch angle diffusion and the subsequent precipitation loss, or

inward radial diffusion (Schulz and Lanzerotti, 1974). The butterfly PAD features a flux minimum around 90° , with maxima at relatively low pitch angles (typically 30° – 60° or 120° – 150° for outer belt electrons). Previous studies suggested that butterfly PADs of outer belt electrons can result from drift-shell splitting and the associated magnetopause shadowing effect (Sibeck et al., 1987), strong negative radial flux gradients (Selesnick and Blake, 2002), or wave–particle interactions (Horne et al., 2005; Xiao FL et al., 2015; Yang C et al., 2017; Li LY et al., 2022). The flat-top PAD shows nearly uniform flux over a wide range of pitch angles around 90° , which may arise from intense wave–particle interactions or represent a transitional state between pancake and butterfly distributions (Horne et al., 2003).

Whistler-mode chorus waves are right-handed circularly polarized low-frequency electromagnetic waves that often occur in low-density regions of the Earth's magnetosphere (Burtis and Helliwell, 1969; Santolík et al., 2003; Liu NG et al., 2019; Ren AJ et al., 2025). As an important factor affecting the evolution of the radiation belts, chorus waves can cause electron precipitation loss

First author: H. Zhao, zhaoh3920@gmail.com

Correspondence to: C. Yang, yangchang@163.com

F. L. Xiao, flxiao@126.com

Received 11 APR 2026; Accepted 29 MAY 2026.

First Published online 10 JUN 2026.

©2026 by Earth and Planetary Physics.

through pitch angle scattering (Xiao FL et al., 2009; Hikishima et al., 2010; Ni BB et al., 2018; Yu XD et al., 2023; Li T et al., 2023; He JB et al., 2025), or accelerate electrons via energy diffusion (Fu HS et al., 2011; Thorne et al., 2013; Xiao FL et al., 2014; Li W et al., 2014; Li LY et al., 2017; Guo DY et al., 2023). The influence of chorus-driven acceleration on electron PADs is complex. Chorus waves can transform PADs from butterfly or flat-top shapes into pancake shapes by efficiently accelerating electrons at large pitch angles (Yang C et al., 2016), or drive them toward butterfly shapes by preferentially accelerating electrons at medium pitch angles (Jin YY et al., 2018). These differences occur because wave–particle interactions produce different effects under different parameters, such as wave frequency, propagation angle, background plasma density, and initial electron distributions (Su ZP et al., 2009a; Xiao FL et al., 2009; Yang C et al., 2018).

Despite numerous observational case studies and numerical simulations on chorus–electron interactions conducted in previous works, the long-term and global effects of chorus waves on the evolution of outer belt electron PADs remain incompletely understood. This paper presents a statistical study using 6 years of observations from the Van Allen Probes. We adopt a pitch angle anisotropy index to characterize relativistic electron PADs and investigate its correlation with chorus waves.

2. Data and Methods

The data used in this study primarily originate from the Van Allen Probes spanning January 1, 2013, to December 31, 2018, and we obtained a total of 30, 140, 407 samples. Plasma wave measurements were obtained from the Wave Form Receiver (WFR) instruments of the Electromagnetic Field Instrument Suite and Integrated Science (EMFISIS) suite (Kletzing et al., 2013) onboard both satellites. Electron differential flux data were derived from the Magnetic Electron Ion Spectrometer (MagEIS) and Relativistic Electron Proton Telescope (REPT) instruments, both of which are part of the Energy Particle, Composition, and Thermal Ionosphere (ECT) suite (Spence et al., 2013) onboard the satellites. Background plasma density was inferred from the upper hybrid frequency observed by the satellites.

There are various types of plasma waves in Earth's magnetosphere. To identify chorus waves from satellite data, this study adopts the following criteria: (1) the background plasma density is less than 30 cm^{-3} to exclude plasmaspheric or plume hiss; (2) the magnetic field power spectral density is greater than $5 \times 10^{-9} \text{ nT}^2/\text{Hz}$ to suppress background noise; (3) the wave frequency range is set to $0.1\text{--}0.8f_{ce}$, where f_{ce} denotes the electron cyclotron frequency; (4) the wave planarity is greater than 0.4; (5) the wave ellipticity is greater than 0.7. Only waves satisfying all the above criteria are identified as chorus waves.

Following the previous work (Yu J et al., 2017), the amplitude of chorus waves is calculated using the formula below:

$$B_t^2 = \int_{f_{\min}}^{f_{\max}} B_{\text{PSD}}(f) df, \quad (1)$$

where B_t represents the amplitude, B_{PSD} is the magnetic field power spectral density, f is the wave frequency, and $f_{\max}$ and $f_{\min}$

are the maximum and minimum frequencies of the detected chorus waves, respectively.

To characterize electron PADs, we fit the electron differential flux using Legendre polynomials (Chen Y et al., 2014), with the formulas given as follows:

$$P_n(x) = \sum_{m=0}^M (-1)^m \frac{(2n-2m)!}{2^n m! (n-m)! (n-2m)!} x^{n-2m}, \quad (2)$$

$$\log_{10}[j(E_k, a)] = \sum_{n=0}^{\infty} C_n P_n[\cos(a)] = |C_0| \sum_{n=0}^{\infty} c_n P_n[\cos(a)], \quad (3)$$

$$c_n = \frac{C_n}{|C_0|} = \frac{(2n+1) \int_0^\pi \log_{10}[j(E_k, a)] \times P_n[\cos(a)] \times \sin(a) da}{\left| \int_0^\pi \log_{10}[j(E_k, a)] \times \sin(a) da \right|}. \quad (4)$$

Here, E_k is the electron kinetic energy, a is the electron pitch angle, j is the electron differential flux, and n is a non-negative integer (0, 1, 2, ...) that represents the order of the Legendre polynomial. M is equal to $n/2$ or $(n-1)/2$. The C_n represents the fitting coefficient, while c_n denotes the normalized fitting coefficient. Since the electron PADs are generally symmetric about 90° , the odd-order terms ($c_1, c_3, c_5, \dots$) are neglected in this study. Empirical evidence shows that the even-order Legendre polynomials up to the c_6 term are sufficient to fully reconstruct the observed PADs; thus, only the c_2, c_4 , and c_6 terms are used to fit the electron differential flux in this work (Chen Y et al., 2014).

Based on the electron differential flux fitted using the above method, we calculate the particle anisotropy index A as defined by Chen MW et al. (1999), which is used to effectively characterize the typical electron PADs: pancake, flat-top, and butterfly distributions. Given that the characteristic differences among these three distribution types are mainly manifested in the pitch angle range of 30° to 150° , we adopt the method proposed by Yu J et al. (2016) to calculate the electron anisotropy index. The formula is given as follows:

$$A = \frac{\int_0^{\pi/2} F\left(E_k, \frac{\pi + 4a_0}{6}\right) \sin^3 a_0 da_0}{2 \int_0^{\pi/2} F\left(E_k, \frac{\pi + 4a_0}{6}\right) \cos^2 a_0 \sin a_0 da_0} - 1. \quad (5)$$

Here, a_0 denotes the equatorial pitch angle, $F = j/p^2$ is the electron phase space density, where p is the electron momentum, and A is the anisotropy index. According to the study by Yu J et al. (2016), electron PAD types can be classified by the following criteria: pancake distribution for $A > 0.1$, flat-top distribution for $0 \leq A \leq 0.1$, and butterfly distribution for $A < 0$.

It should be noted that electrons with an equatorial pitch angle close to 90° (the so-called near-equator trapped electrons) have mirror points at low magnetic latitudes. To ensure the integrity of the electron PAD information, we select satellite data within a magnetic latitude range of $\pm 10^\circ$ for analysis.

3. Results

Figure 1 shows an observation case from 17:30 to 19:00 UT on December 23, 2016. The orange line in Figure 1a represents the

SYM- H index, which shows a small geomagnetic storm with a minimum value of -40 nT around 18:00 UT. The blue line in Figure 1a shows the background plasma density measured by the Van Allen Probe-B, which is about 2 cm^{-3} during this period. Figure 1b presents the magnetic field wave spectra from the same spacecraft. Figure 1c shows the time-frequency distribution of whistler-mode chorus waves, and Figure 1d shows the corresponding wave amplitude. Figure 1e presents the 1.8 MeV electron differential flux observed by the Probe-B and Figure 1f shows the calculated anisotropy index A . During this event, the satellite was located in the outer radiation belt ($L = 5.8\text{--}5.6$) near the magnetic equator (Mlat from -0.2 to -1.5) on the nightside (MLT = $21.8\text{--}22.7$). During 17:30–18:10 UT, the 1.8 MeV electron differential flux exhibited a distinct butterfly PAD, with peaks around 45° and 135°

(Figure 1e). The anisotropy index A was approximately from -0.2 to -0.5 during this interval (Figure 1f). After $\sim 18:12$ UT, the electron flux gradually transformed into a flat-top distribution (Figure 1e), with the anisotropy index A rising to around 0 (Figure 1f). This event demonstrates a clear correlation between chorus waves and the anisotropy index A of outer belt relativistic electrons.

To comprehensively investigate the correlation between outer belt relativistic electron PADs and chorus waves, we employ the previously described processing method to statistically analyze the global distribution of the anisotropy index A of relativistic electrons in the outer radiation belt across different chorus wave amplitudes, as shown in Figure 2. Each row in Figure 2 represents electrons with kinetic energy 579 keV, 909 keV, 1.8 MeV and 2.6 MeV, respectively, from top to bottom. Each column corre-

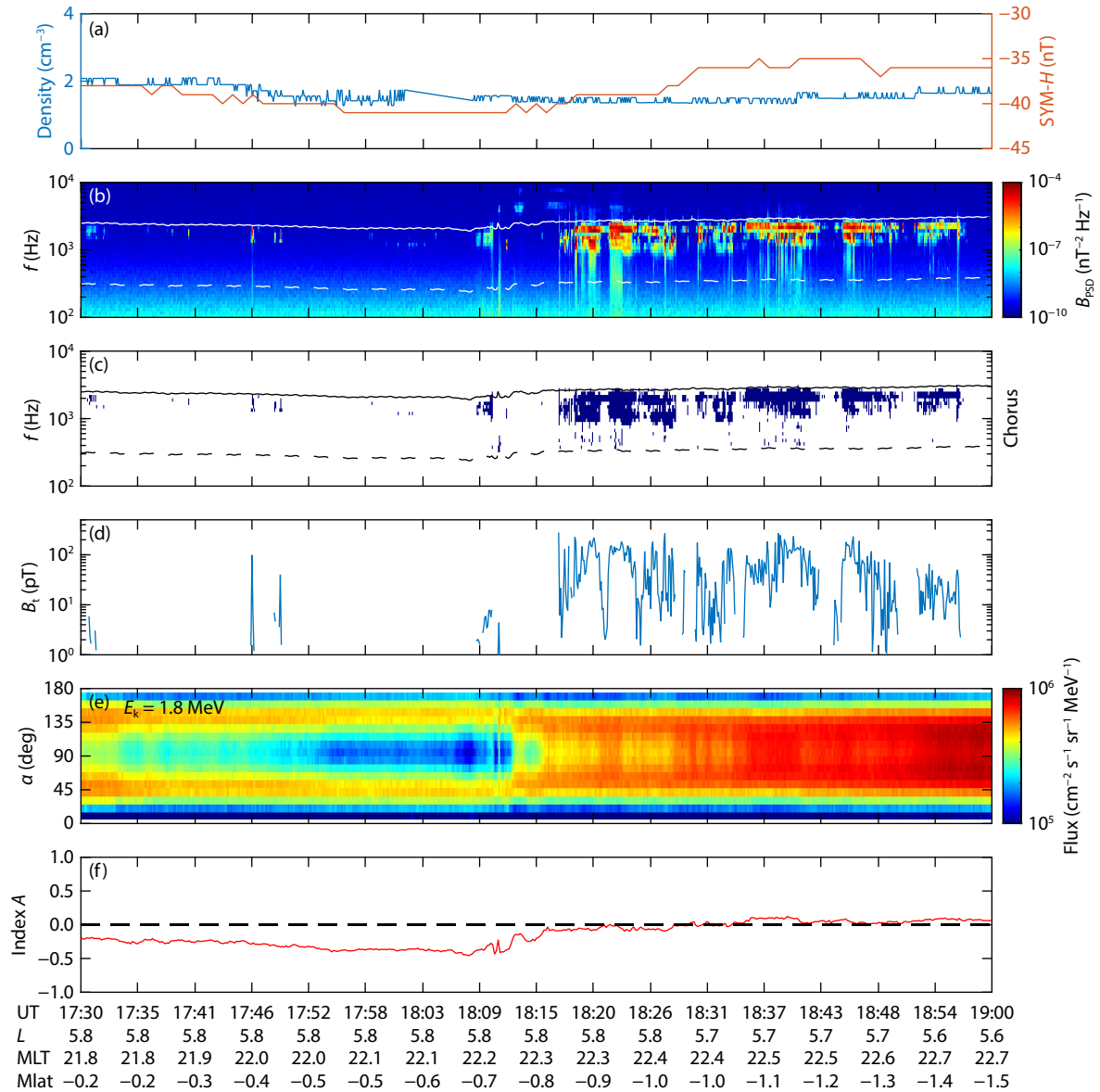


Figure 1. Chorus waves and electron differential flux observed by the Van Allen Probe-B during 17:30–19:00 UT on December 23, 2016. (a) SYM- H index (red line) and plasma density (blue line). (b) Magnetic field wave power spectral intensity. The solid and dashed lines represent $0.8f_{ce}$ and $0.1f_{ce}$, respectively. (c) Time–frequency distribution of chorus waves. (d) Chorus wave amplitude. (e) 1.8 MeV electron differential flux as a function of time and pitch angle α . (f) Anisotropy index A of 1.8 MeV electrons.

sponds to the chorus wave amplitudes, $B_t \leq 3$ pT, $3 < B_t \leq 30$ pT, and $B_t > 30$ pT, respectively, from left to right. The grid size of each pie chart in Figure 2 is $0.2L \times 1$ MLT. The values displayed in each grid are the median values of the anisotropy indices for all samples within that grid. In the following Figures 3 and 4, we also adopted the same grid processing method.

The leftmost column of Figure 2 shows the statistical results under the condition that chorus waves are very weak or absent. For electrons at 579 keV (Figure 2a) and 909 keV (Figure 2d), the anisotropy index A mainly ranges from 0 to 0.1 and shows negligible differences across different L -shells and MLTs. This indicates that these electrons tend to exhibit flat-top PADs. For electrons at

1.8 MeV (Figure 2g) and 2.6 MeV (Figure 2j), at relatively high L -shells on the dayside (MLT ≈ 12), the index $A \approx 0.2$ –0.4, indicating that pancake PADs often occur. In other regions, the index A is generally close to 0, indicating a dominance of flat-top PADs.

The results in Figure 2 also reveal a correlation between electron PADs and chorus waves in the outer radiation belt. As the wave amplitude increases (second and third columns of Figure 2), the anisotropy index A for all energies increases significantly. Taking the position $L = 4.5$ as an example, the index A increases by approximately 0.25–0.4 around MLT = 12, and by about 0.1–0.25 in other MLT regions. This indicates that the electron differential fluxes become more peaked near 90° pitch angle, or in other

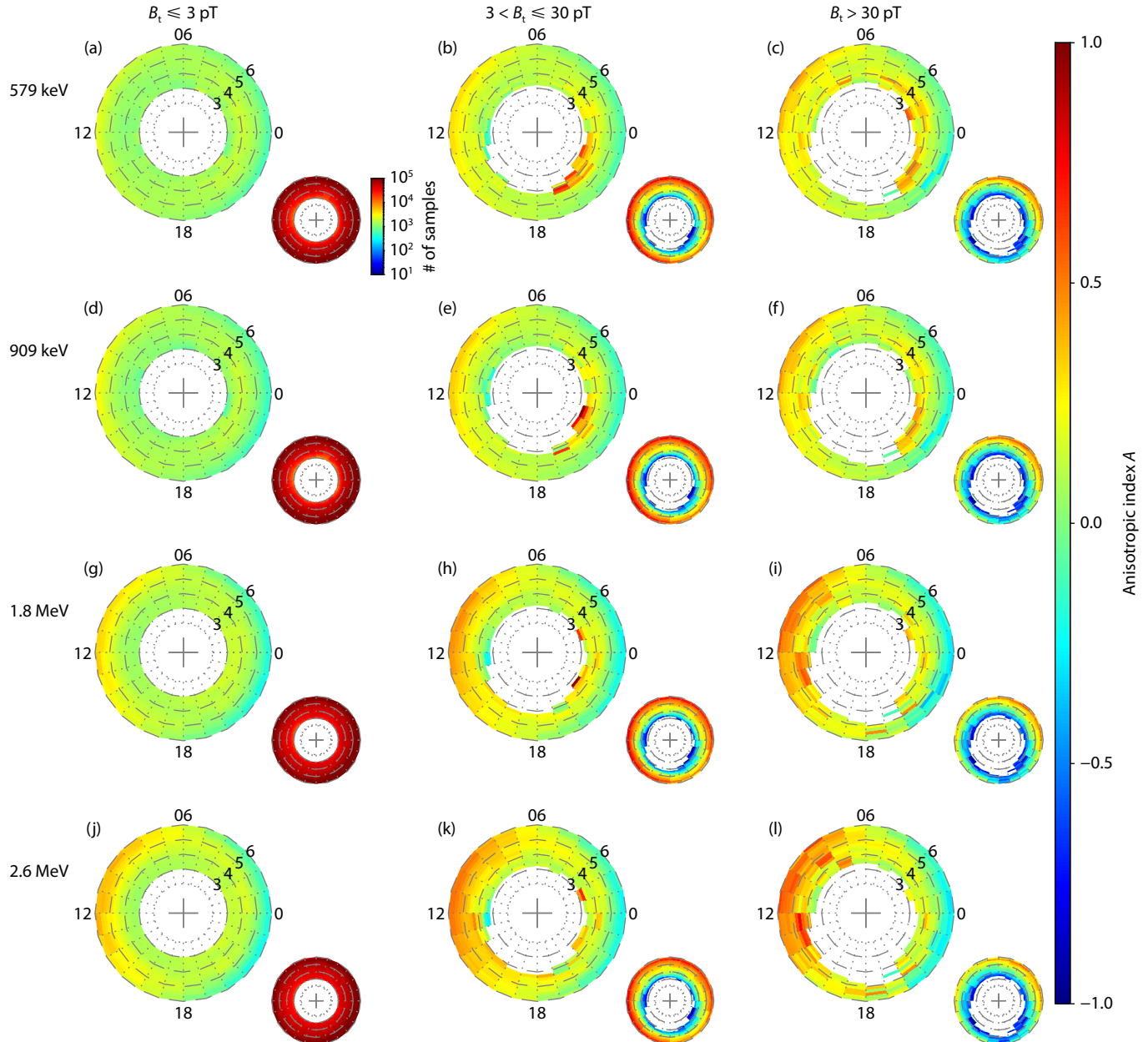


Figure 2. (L , MLT) maps of the anisotropy index A for the four indicated electron kinetic energies (from top to bottom: 579 keV, 909 keV, 1.8 MeV, and 2.6 MeV) under the three chorus wave conditions (from left to right: wave amplitude $B_t \leq 3$ pT, $3 < B_t \leq 30$ pT, and $B_t > 30$ pT) for the period from Jan 1, 2013 to Dec 31, 2018. The small maps at the bottom right of each subplot represent the number of statistical samples.

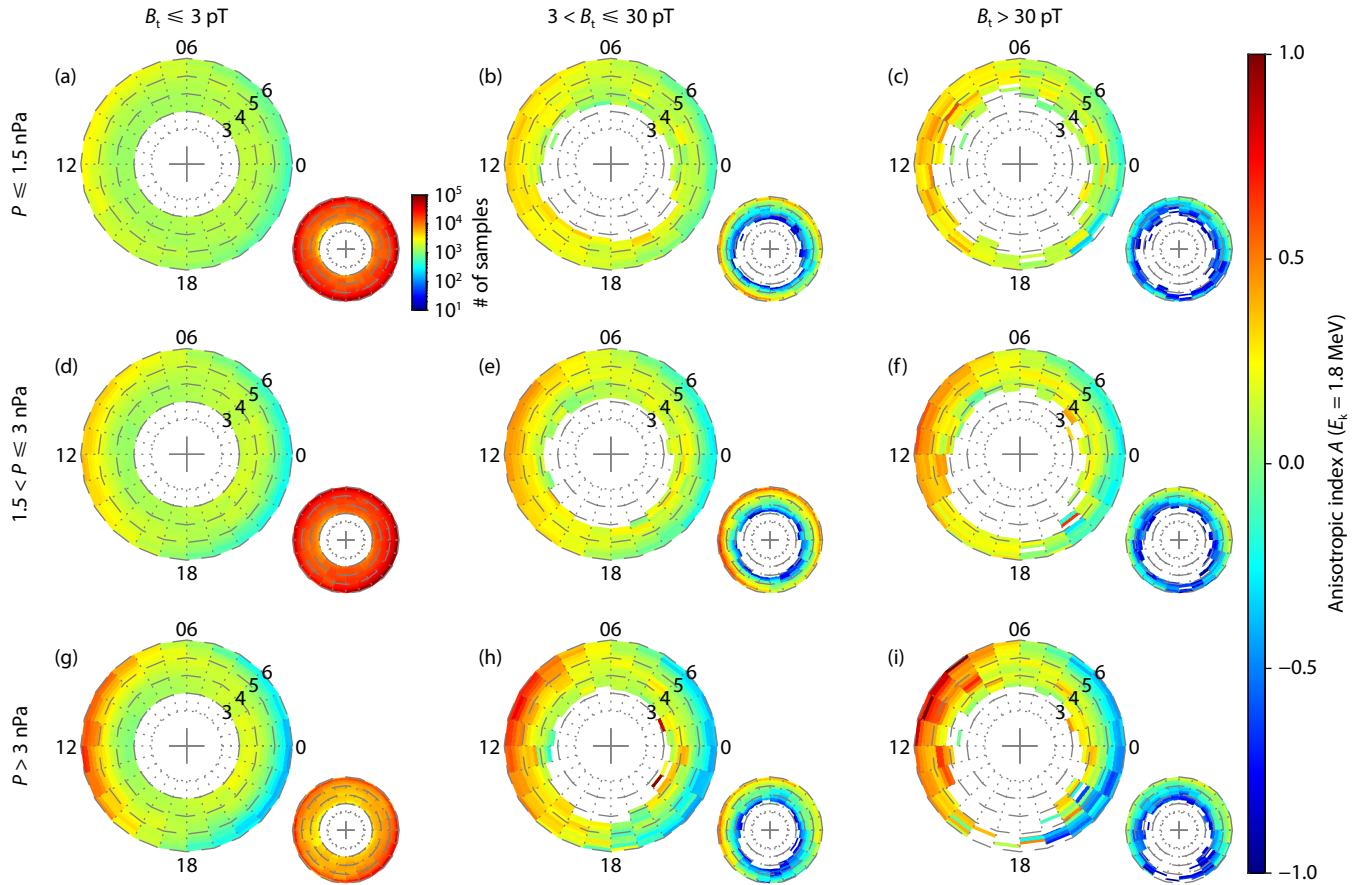


Figure 3. (L , MLT) maps of the anisotropy index A for 1.8 MeV electrons under the three indicated solar wind dynamic pressure (P) conditions (from top to bottom: $P \leq 1.5$ nPa, $1.5 < P \leq 3$ nPa, and $P > 3$ nPa) and the three chorus wave conditions (from left to right: wave amplitude $B_t \leq 3$ pT, $3 < B_t \leq 30$ pT, and $B_t > 30$ pT) for the period from Jan 1, 2013 to Dec 31, 2018.

words, the electron PADs tend to exhibit pancake shapes. At other L -shells, the index A generally increases with enhanced chorus waves, except at relatively high L -shells on the nightside (MLT ≈ 0), where the index A shows little variation with chorus wave amplitude.

The above statistical results indicate that the electron anisotropy index is positively correlated with chorus wave amplitude in most regions of the Earth's outer radiation belt. This phenomenon may arise from the efficient chorus-driven acceleration of electrons at large pitch angles. In contrast, at high L -shells on the nightside, no obvious correlation is observed between the anisotropy index A and chorus wave amplitude, which may be related to the electron drift-shell splitting and the magnetopause shadowing effect. Strong chorus waves typically occur during periods of intense geomagnetic activity, accompanied by enhanced solar wind dynamic pressure and inward compression of the dayside magnetopause. Under these conditions, large pitch angle electrons at high L -shells on the nightside can drift to the magnetopause and be lost, resulting in a decrease in the electron differential flux around 90° . Therefore, in this region, intensification of chorus waves does not necessarily lead to an increase in the anisotropy index A .

The evolution of electron PADs in the outer radiation belt is a complex issue that may be influenced by various factors. There-

fore, we also investigated the impact of different solar wind dynamic pressure conditions and substorm activity intensities on the electron anisotropy index A , as shown in Figures 3 and 4. In these two figures, we present the results for 1.8 MeV electrons, and the behavior of relativistic electrons at other energies is similar.

Each row in Figure 3 corresponds to solar wind dynamic pressure conditions of $P \leq 1.5$ nPa, $1.5 < P \leq 3$ nPa and $P > 3$ nPa, from top to bottom, respectively. The results show that as solar wind dynamic pressure increases, the electron anisotropy index A rises in most regions, most notably on the dayside at relatively high L -shells. The columns in Figure 3 represent conditions of chorus wave amplitude $B_t \leq 3$ pT, $3 < B_t \leq 30$ pT, and $B_t > 30$ pT, from left to right, respectively. The data indicate that when chorus waves are enhanced, the electron anisotropy index A increases significantly under all solar wind dynamic pressure conditions.

Figure 4 is similar to Figure 3, but each row represents different conditions of AE^* index ($AE^* \leq 100$ nT, $100 < AE^* \leq 300$ nT and $AE^* > 300$ nT, from top to bottom, respectively). The definition of AE^* here is the average value of the AE index within one hour before the sampling time, which reflects the average intensity of magnetospheric substorm activities. The results in Figure 4 show that as AE^* increases, the electron anisotropy index A generally rises, most notably on the dayside at relatively high L -shells. The

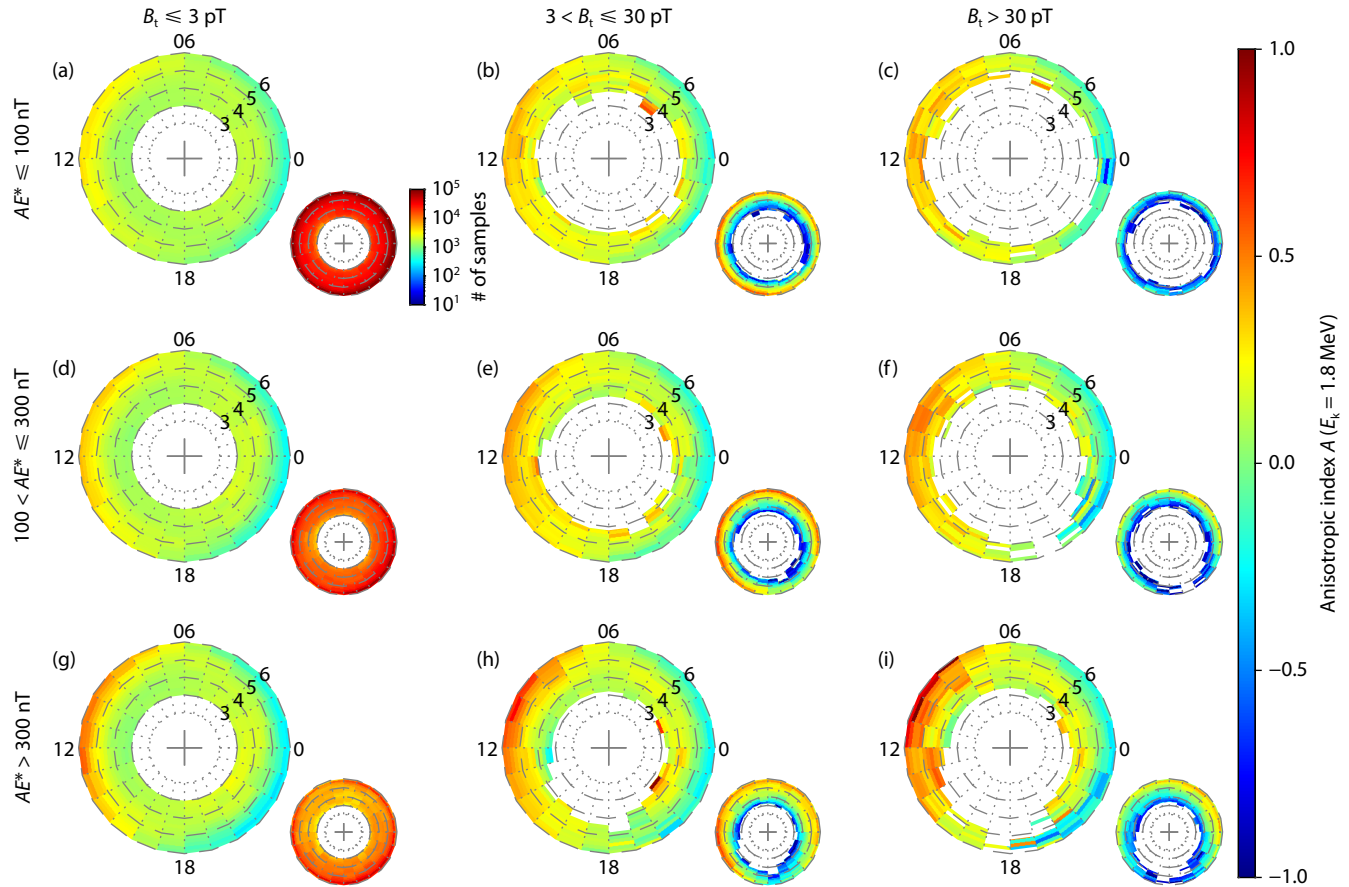


Figure 4. (L , MLT) maps of the anisotropy index A for 1.8 MeV electrons under the three indicated AE^* (averaged AE index in the previous 1 h) conditions (from top to bottom: $AE^* \leq 100$ nT, $100 < AE^* \leq 300$ nT, and $AE^* > 300$ nT) and the three chorus wave conditions (from left to right: wave amplitude $B_t \leq 3$ pT, $3 < B_t \leq 30$ pT, and $B_t > 30$ pT) for the period from Jan 1, 2013 to Dec 31, 2018.

columns in Figure 4 represent the chorus wave amplitude conditions $B_t \leq 3$ pT, $3 < B_t \leq 30$ pT, and $B_t > 30$ pT from left to right, which is consistent with Figure 3. The results are also similar to those in Figure 3: under all levels of AE^* , the index A exhibits a positive correlation with chorus wave amplitude.

The results shown in Figures 3 and 4 indicate that the relativistic electron PADs in the outer radiation belt undergo complex evolution, modulated by multiple factors such as interplanetary conditions and geomagnetic activity. Meanwhile, these data also demonstrate that the electron anisotropy index A is positively correlated with chorus wave amplitude in most regions of the outer radiation belt under different space weather conditions. This positive correlation may arise from the stochastic acceleration of electrons by chorus waves. The effect of chorus-driven acceleration varies under different parametric conditions: these waves may preferentially accelerate electrons at large pitch angles in some cases, while acting preferentially on those at medium pitch angles in others. Overall, the above statistical results indicate that chorus waves tend to enhance relativistic electron differential fluxes more effectively at large pitch angles than at medium pitch angles.

4. Discussion

Due to the azimuthal drift motion around the Earth, electron

properties are jointly determined by multiple physical processes including acceleration, loss and transport along the full drift trajectory. A single satellite can only perform observations at a single local location at a specific time, and this limitation undoubtedly imposes a constraint on our research. Nevertheless, the typical spatial coverage of chorus waves can exceed 50% of an electron drift trajectory in the outer belt (Summers et al., 2007; Li W et al., 2009), with durations ranging from several hours to several days, longer than the orbital period of the Van Allen Probes (~ 8 hours). Hence, chorus wave events in the outer radiation belt have a high probability of being detected by the Van Allen Probes. It is believed that long-term satellite data can effectively eliminate deviations caused by local observations.

It should be noted that although this study focuses on chorus-electron interactions, we do not rule out the contributions of other physical mechanisms. For instance, Yu J et al. (2016) demonstrated that enhanced solar wind dynamic pressure strengthens the dayside magnetic field and weakens the nightside magnetic field, while strong southward interplanetary magnetic field also reduces the nightside magnetic field at high L -shells. In the outer radiation belt with prominent azimuthal geomagnetic asymmetry at high L -shells, the drift-shell splitting effect—a phenomenon in which the drift shells separate radially for charged particles with common guiding centers but with different pitch angles—can

induce obvious day-night asymmetry in electron PADs. When intense solar wind activity causes significant inward compression of the magnetopause, the magnetopause shadowing effect and the associated outward radial diffusion can facilitate the formation of butterfly PADs at high L -shells in the nightside (Turner et al., 2012; Ni BB et al., 2013). As shown in Figure 3, under identical chorus wave amplitude conditions, the electron anisotropy index A decreases at high L -shells on the nightside as the solar wind dynamic pressure increases. This phenomenon may be mainly caused by the drift-shell splitting and magnetopause shadowing effect. Furthermore, with the enhancement of geomagnetic substorm activity, energetic particles injected from the magnetotail can excite various very-low-frequency plasma waves in the inner magnetosphere. Apart from chorus waves, these waves also include whistler-mode hiss, electromagnetic ion cyclotron (EMIC) and magnetosonic (MS) waves, all of which can exert a significant influence on radiation belt electron PADs. For instance, hiss or EMIC waves can lead to precipitation loss of electrons at small pitch angles (Ni BB et al., 2015a; Cao X et al., 2017), which facilitates the formation of pancake distributions; MS waves are capable of accelerating electrons at moderate pitch angles and consequently generating butterfly distributions (Xiao FL et al., 2015; Li JX et al., 2016). In addition, solar wind dynamic pressure disturbances and substorm activities can both amplify ultra-low-frequency (ULF) waves. ULF waves can interact with relativistic electrons via drift resonance, induce radial diffusion and modify their distributions (Su ZP et al., 2015; Sarris et al., 2024). As shown in Figures 3 and 4, at high L -shells on the dayside and under identical chorus wave amplitudes, the electron anisotropy index A rises distinctly with the enhancement of solar wind dynamic pressure or substorm intensity, which may result from the combined effects of the aforementioned multiple physical mechanisms.

In summary, outer radiation belt electron PADs are related not only to locally observed chorus waves but also to various other physical processes, and electron drift motion should also be taken into account. This explains why the electron anisotropy index A increases more significantly on the dayside as chorus wave amplitude rises, despite the fact that in the dawn sector (MLT = 00–06) chorus waves have higher average intensity (Meredith et al., 2020).

5. Conclusions

To comprehensively investigate the effects of chorus waves on relativistic electron PADs in the Earth's outer radiation belt, we performed a statistical analysis using data from the Van Allen Probes spanning January 1, 2013, to December 31, 2018. A pitch angle anisotropy index is adopted to characterize relativistic electron PADs, and its correlation with chorus waves is investigated. The influences of solar wind dynamic pressure and substorm activity intensity are also examined. The main conclusions of this study are summarized as follows:

(1) When chorus waves are weak or absent, the anisotropy index A is generally close to 0, indicating that relativistic electrons predominantly exhibit flat-top PADs. When chorus waves intensify, the anisotropy index A increases significantly, implying that relativistic electrons are more likely to present pancake PADs.

(2) As solar wind dynamic pressure (or geomagnetic substorm activity intensity) increases, the electron anisotropy index A rises in most regions, most notably on the dayside around $L = 6$.

(3) Under all levels of solar wind dynamic pressure (or geomagnetic substorm activity intensity), the electron anisotropy index A shows a positive correlation with chorus wave amplitude.

Our statistical results demonstrate that chorus waves play a persistent and comprehensive role in shaping relativistic electron PADs. This work provides new insights into the physical mechanisms underlying the dynamic evolution of the Earth's outer radiation belt.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (grants 42230209, 42374215, 42374199, 42304183, 42274212, and 42441829), the Natural Science Foundation of Hunan Province Grant 2023JJ20038, and the Science and Technology Innovation Program of Hunan Province 2024RC3167. The authors thank the Van Allen Probe scientific instrument teams for making their data publicly available. The Van Allen Probe data are available at <https://spdf.gsfc.nasa.gov/pub/data/rbsp> for the EMFISIS and ECT. Solar wind parameters and geomagnetic indices are available at <https://spdf.gsfc.nasa.gov/pub/data/omni>.

References

- Baker, D. N., Blake, J. B., Klebesadel, R. W., and Higbie, P. R. (1986). Highly relativistic electrons in the Earth's outer magnetosphere: 1. Lifetimes and temporal history 1979–1984. *J. Geophys. Res.: Space Phys.*, 91(A4), 4265–4276. <https://doi.org/10.1029/JA091iA04p04265>
- Burtis, W. J., and Helliwell, R. A. (1969). Banded chorus—A new type of VLF radiation observed in the magnetosphere byOGO 1 andOGO 3. *J. Geophys. Res.: Space Phys.*, 74(11), 3002–3010. <https://doi.org/10.1029/JA074i011p03002>
- Cao, X., Ni, B. B., Summers, D., Bortnik, J., Tao, X., Shprits, Y. Y., Lou, Y. Q., Gu, X. D., Fu, S., ... Wang, Q. (2017). Bounce resonance scattering of radiation belt electrons by H⁺ band EMIC waves. *J. Geophys. Res.: Space Phys.*, 122(2), 1702–1713. <https://doi.org/10.1002/2016JA023607>
- Chen, M. W., Roeder, J. L., Fennell, J. F., Lyons, L. R., Lambour, R. L., and Schulz, M. (1999). Proton ring current pitch angle distributions: Comparison of simulations with CRRES observations. *J. Geophys. Res.: Space Phys.*, 104(A8), 17379–17389. <https://doi.org/10.1029/1999JA000142>
- Chen, Y., Friedel, R. H. W., Henderson, M. G., Claudepierre, S. G., Morley, S. K., and Spence, H. E. (2014). REPAD: An empirical model of pitch angle distributions for energetic electrons in the Earth's outer radiation belt. *J. Geophys. Res.: Space Phys.*, 119(3), 1693–1708. <https://doi.org/10.1002/2013JA019431>
- Fu, H. S., Cao, J. B., Yang, B., and Lu, H. Y. (2011). Electron loss and acceleration during storm time: The contribution of wave-particle interaction, radial diffusion, and transport processes. *J. Geophys. Res.: Space Phys.*, 116(A10), A10210. <https://doi.org/10.1029/2011JA016672>
- Guo, D. Y., Xiang, Z., Ni, B. B., Jin, T. F., Zhou, R. X., Yi, J., Liu, Y. X. Z., and Dong, J. H. (2023). Three-dimensional simulations of ultra-relativistic electron acceleration during the 21 April 2017 storm. *J. Geophys. Res.: Space Phys.*, 128(4), e2023JA031407. <https://doi.org/10.1029/2023JA031407>
- He, J. B., Chen, L. J., Xia, Z. Y., Shumko, M., and Blum, L. (2025). Association of relativistic electron microbursts duration with chorus wave properties. *Geophys. Res. Lett.*, 52(8), e2024GL113694. <https://doi.org/10.1029/2024GL113694>
- Hikishima, M., Omura, Y., and Summers, D. (2010). Microburst precipitation of energetic electrons associated with chorus wave generation. *Geophys. Res.*

- Let., 37(7), L07103. <https://doi.org/10.1029/2010GL042678>
- Horne, R. B., Meredith, N. P., Thorne, R. M., Heynderickx, D., Iles, R. H. A., and Anderson, R. R. (2003). Evolution of energetic electron pitch angle distributions during storm time electron acceleration to megaelectronvolt energies. *J. Geophys. Res.: Space Phys.*, 108(A1), 1016. <https://doi.org/10.1029/2001JA009165>
- Horne, R. B., Thorne, R. M., Glauert, S. A., Albert, J. M., Meredith, N. P., and Anderson, R. R. (2005). Timescale for radiation belt electron acceleration by whistler mode chorus waves. *J. Geophys. Res.: Space Phys.*, 110(A3), A03225. <https://doi.org/10.1029/2004JA010811>
- Jin, Y. Y., Yang, C., He, Y. H., Liu, S., Zhou, Q. H., and Xiao, F. L. (2018). Butterfly distribution of Earth's radiation belt relativistic electrons induced by dayside chorus. *Sci. China Technol. Sci.*, 61(2), 212–218. <https://doi.org/10.1007/s11431-017-9067-y>
- Kletzing, C. A., Kurth, W. S., Acuna, M., MacDowall, R. J., Torbert, R. B., Averkamp, T., Bodet, D., Bounds, S. R., Chutter, M., ... Tyler, J. (2013). The electric and magnetic field instrument suite and integrated science (EMFISIS) on RBSP. *Space Sci. Rev.*, 179(1–4), 127–181. <https://doi.org/10.1007/s11214-013-9993-6>
- Li, J. X., Ni, B. B., Ma, Q. L., Xie, L., Pu, Z. Y., Fu, S. Y., Thorne, R. M., Bortnik, J., Chen, L. J., ... Summers, D. (2016). Formation of energetic electron butterfly distributions by magnetosonic waves via Landau resonance. *Geophys. Res. Lett.*, 43(7), 3009–3016. <https://doi.org/10.1002/2016GL067853>
- Li, L. Y., Yu, J., Cao, J. B., Yang, J. Y., Li, X., Baker, D. N., Reeves, G. D., and Spence, H. (2017). Roles of whistler mode waves and magnetosonic waves in changing the outer radiation belt and the slot region. *J. Geophys. Res.: Space Phys.*, 122(5), 5431–5448. <https://doi.org/10.1002/2016JA023634>
- Li, L. Y., Yu, J., Cao, J. B., Chen, L. J., Reeves, G. D., and Blake, J. B. (2022). Competitive influences of different plasma waves on the pitch angle distribution of energetic electrons inside and outside plasmasphere. *Geophys. Res. Lett.*, 49(1), e2021GL096062. <https://doi.org/10.1029/2021GL096062>
- Li, T., Liu, S., Yang, C., Xiao, F. L., Yang, H. M., Zhang, S., Gao, Z. L., He, Q., Zhou, Q. H., ... He, Y. H. (2023). Direct evidence for efficient scattering of suprathermal electrons by whistler mode waves in the Martian magnetosphere. *Earth Planet. Phys.*, 7(6), 607–614. <https://doi.org/10.26464/epp2023086>
- Li, W., Thorne, R. M., Angelopoulos, V., Bortnik, J., Cully, C. M., Ni, B., LeContel, O., Roux, A., Auster, U., and Magnes, W. (2009). Global distribution of whistler-mode chorus waves observed on the Themis spacecraft. *Geophys. Res. Lett.*, 36(9), L09104. <https://doi.org/10.1029/2009GL037595>
- Li, W., Thorne, R. M., Ma, Q., Ni, B., Bortnik, J., Baker, D. N., Spence, H. E., Reeves, G. D., Kanekal, S. G., ... Claudepierre, S. G. (2014). Radiation belt electron acceleration by chorus waves during the 17 March 2013 storm. *J. Geophys. Res.: Space Phys.*, 119(6), 4681–4693. <https://doi.org/10.1002/2014JA019945>
- Liu, N. G., Su, Z. P., Gao, Z. L., Zheng, H. N., Wang, Y. M., and Wang, S. (2019). Magnetospheric chorus, exohiss, and magnetosonic emissions simultaneously modulated by fundamental toroidal standing Alfvén waves following solar wind dynamic pressure fluctuations. *Geophys. Res. Lett.*, 46(4), 1900–1910. <https://doi.org/10.1029/2018GL081500>
- Meredith, N. P., Horne, R. B., Shen, X. C., Li, W., and Bortnik, J. (2020). Global model of whistler mode chorus in the near-equatorial region ($|\lambda_m| < 18^\circ$). *Geophys. Res. Lett.*, 47(11), e2020GL087311. <https://doi.org/10.1029/2020GL087311>
- Ni, B. B., Shprits, Y. Y., Friedel, R. H. W., Thorne, R. M., Daae, M., and Chen, Y. (2013). Responses of Earth's radiation belts to solar wind dynamic pressure variations in 2002 analyzed using multisatellite data and Kalman filtering. *J. Geophys. Res.: Space Phys.*, 118(7), 4400–4414. <https://doi.org/10.1002/jgra.50437>
- Ni, B. B., Cao, X., Zou, Z. Y., Zhou, C., Gu, X. D., Bortnik, J., Zhang, J. C., Fu, S., Zhao, Z. Y., ... Xie, L. (2015a). Resonant scattering of outer zone relativistic electrons by multiband emic waves and resultant electron loss time scales. *J. Geophys. Res.: Space Phys.*, 120(9), 7357–7373. <https://doi.org/10.1002/2015JA021466>
- Ni, B. B., Zou, Z. Y., Gu, X. D., Zhou, C., Thorne, R. M., Bortnik, J., Shi, R., Zhao, Z. Y., Baker, D. N., ... Li, X. L. (2015b). Variability of the pitch angle distribution of radiation belt ultrarelativistic electrons during and following intense geomagnetic storms: Van Allen probes observations. *J. Geophys. Res.: Space Phys.*, 120(6), 4863–4876. <https://doi.org/10.1002/2015JA021065>
- Ni, B. B., Huang, J., Ge, Y. S., Cui, J., Wei, Y., Gu, X. D., Fu, S., Xiang, Z., and Zhao, Z. Y. (2018). Radiation belt electron scattering by whistler-mode chorus in the Jovian magnetosphere: Importance of ambient and wave parameters. *Earth Planet. Phys.*, 2(1), 1–14. <https://doi.org/10.26464/epp2018001>
- Reeves, G. D., McAdams, K. L., Friedel, R. H. W., and O'Brien, T. P. (2003). Acceleration and loss of relativistic electrons during geomagnetic storms. *Geophys. Res. Lett.*, 30(10), 1529. <https://doi.org/10.1029/2002GL016513>
- Ren, A. J., Yu, J., Wang, J., Chen, Z. Z., and Liu, X. M. (2025). Statistical analysis on the validity of the cold plasma approximation for chorus waves based on van Allen probe observations and their effects on radiation belt electrons. *Earth Planet. Phys.*, 9(1), 159–170. <https://doi.org/10.26464/epp2024057>
- Santolík, O., Gurnett, D. A., Pickett, J. S., Parrot, M., and Cornilleau-Wehrlin, N. (2003). Spatio-temporal structure of storm-time chorus. *J. Geophys. Res.: Space Phys.*, 108(A7), 1278. <https://doi.org/10.1029/2002JA009791>
- Sarris, T. E., Li, X. L., Zhao, H., Tu, W. C., Papadakis, K., Tourgaidis, S., Liu, W. L., Yan, L., Rankin, R., ... Pinaris, P. (2024). On the contribution of latitude-dependent ULF waves to the radial transport of off-equatorial relativistic electrons in the radiation belts. *J. Geophys. Res.: Space Phys.*, 129(11), e2024JA032905. <https://doi.org/10.1029/2024JA032905>
- Schulz, M., and Lanzerotti, L. J. (1974). *Particle Diffusion in the Radiation Belts*. Berlin: Springer. <https://doi.org/10.1007/978-3-642-65675-0>
- Selesnick, R. S., and Blake, J. B. (2002). Relativistic electron drift shell splitting. *J. Geophys. Res.: Space Phys.*, 107(A9), 1262. <https://doi.org/10.1029/2001JA009179>
- Sibeck, D. G., McEntire, R. W., Lui, A. T. Y., Lopez, R. E., and Krimigis, S. M. (1987). Magnetic field drift shell splitting: Cause of unusual dayside particle pitch angle distributions during storms and substorms. *J. Geophys. Res.: Space Phys.*, 92(A12), 13485–13497. <https://doi.org/10.1029/JA092iA12p13485>
- Spence, H. E., Reeves, G. D., Baker, D. N., Blake, J. B., Bolton, M., Bourdardie, S., Chan, A. A., Claudepierre, S. G., Clemmons, J. H., ... Thorne, R. M. (2013). Science goals and overview of the radiation belt storm probes (RBSP) energetic particle, composition, and thermal plasma (ECT) suite on NASA's van Allen probes mission. *Space Sci. Rev.*, 179(1–4), 311–336. <https://doi.org/10.1007/s11214-013-0007-5>
- Su, Z. P., Zheng, H. N., and Wang, S. (2009a). Dynamic evolution of energetic outer zone electrons due to whistler mode chorus based on a realistic density model. *J. Geophys. Res.: Space Phys.*, 114(A7), A07201. <https://doi.org/10.1029/2008JA014013>
- Su, Z. P., Zheng, H. N., and Wang, S. (2009b). Evolution of electron pitch angle distribution due to interactions with whistler mode chorus following substorm injections. *J. Geophys. Res.: Space Phys.*, 114(A8), A08202. <https://doi.org/10.1029/2009JA014269>
- Su, Z. P., Zhu, H., Xiao, F. L., Zong, Q. G., Zhou, X. Z., Zheng, H. N., Wang, Y. M., Wang, S., Hao, Y. X., ... Wygant, J. R. (2015). Ultra-low-frequency wave-driven diffusion of radiation belt relativistic electrons. *Nat. Commun.*, 6, 10096. <https://doi.org/10.1038/ncomms10096>
- Summers, D., Ni, B. B., and Meredith, N. P. (2007). Timescales for radiation belt electron acceleration and loss due to resonant wave-particle interactions: 2. Evaluation for VLF chorus, ELF hiss, and electromagnetic ion cyclotron waves. *J. Geophys. Res.: Space Phys.*, 112(A4), A04207. <https://doi.org/10.1029/2006JA011993>
- Thorne, R. M., Ni, B. B., Tao, X., Horne, R. B., and Meredith, N. P. (2010). Scattering by chorus waves as the dominant cause of diffuse auroral precipitation. *Nature*, 467(7318), 943–946. <https://doi.org/10.1038/nature09467>
- Thorne, R. M., Li, W., Ni, B., Ma, Q., Bortnik, J., Chen, L., Baker, D. N., Spence, H. E., Reeves, G. D., ... Kanekal, S. G. (2013). Rapid local acceleration of relativistic radiation-belt electrons by magnetospheric chorus. *Nature*, 504(7480), 411–414. <https://doi.org/10.1038/nature12889>
- Turner, D. L., Shprits, Y., Hartinger, M., and Angelopoulos, V. (2012). Explaining sudden losses of outer radiation belt electrons during geomagnetic storms. *Nat. Phys.*, 8(3), 208–212. <https://doi.org/10.1038/nphys2185>

- West, H. I. Jr., Buck, R. M., and Walton, J. R. (1973). Electron pitch angle distributions throughout the magnetosphere as observed on Ogo 5. *J. Geophys. Res.: Space Phys.*, 78(7), 1064–1081. <https://doi.org/10.1029/JA078i007p01064>
- Xiao, F. L., Su, Z. P., Zheng, H. N., and Wang, S. (2009a). Modeling of outer radiation belt electrons by multidimensional diffusion process. *J. Geophys. Res.: Space Phys.*, 114(A3), A03201. <https://doi.org/10.1029/2008JA013580>
- Xiao, F. L., Zong, Q. G., and Chen, L. X. (2009b). Pitch-angle distribution evolution of energetic electrons in the inner radiation belt and slot region during the 2003 Halloween storm. *J. Geophys. Res.: Space Phys.*, 114(A1), A01215. <https://doi.org/10.1029/2008JA013068>
- Xiao, F. L., Yang, C., He, Z. G., Su, Z. P., Zhou, Q. H., He, Y. H., Kletzing, C. A., Kurth, W. S., Hospodarsky, G. B., ... Wygant, J. R. (2014). Chorus acceleration of radiation belt relativistic electrons during March 2013 geomagnetic storm. *J. Geophys. Res.: Space Phys.*, 119(5), 3325–3332. <https://doi.org/10.1002/2014JA019822>
- Xiao, F. L., Yang, C., Su, Z. P., Zhou, Q. H., He, Z. G., He, Y. H., Baker, D. N., Spence, H. E., Funsten, H. O., and Blake, J. B. (2015). Wave-driven butterfly distribution of Van Allen belt relativistic electrons. *Nat. Commun.*, 6, 8590. <https://doi.org/10.1038/ncomms9590>
- Yang, C., Su, Z. P., Xiao, F. L., Zheng, H. N., Wang, Y. N., Wang, S., Wang, S., Spence, H. E., Reeves, G. D., ... Funsten, H. O. (2016). Rapid flattening of butterfly pitch angle distributions of radiation belt electrons by whistler-mode chorus. *Geophys. Res. Lett.*, 43(16), 8339–8347. <https://doi.org/10.1002/2016GL070194>
- Yang, C., Su, Z. P., Xiao, F. L., Zheng, H. N., Wang, Y. M., Wang, S., Spence, H. E., Reeves, G. D., Baker, D. N., ... Funsten, H. O. (2017). A positive correlation between energetic electron butterfly distributions and magnetosonic waves in the radiation belt slot region. *Geophys. Res. Lett.*, 44(9), 3980–3990. <https://doi.org/10.1002/2017GL073116>
- Yang, C., Xiao, F. L., He, Y. H., Liu, S., Zhou, Q. H., Guo, M. Y., and Zhao, W. L. (2018). Storm time evolution of outer radiation belt relativistic electrons by a nearly continuous distribution of chorus. *Geophys. Res. Lett.*, 45(5), 2159–2167. <https://doi.org/10.1002/2017GL075894>
- Yu, J., Li, L., Cao, J. B., Reeves, G. D., Baker, D. N., and Spence, H. (2016). The influences of solar wind pressure and interplanetary magnetic field on global magnetic field and outer radiation belt electrons. *Geophys. Res. Lett.*, 43(14), 7319–7327. <https://doi.org/10.1002/2016GL069029>
- Yu, J., Li, L., Cao, J. B., Chen, L., Wang, J., and Yang, J. (2017). Propagation characteristics of plasmaspheric hiss: Van Allen probe observations and global empirical models. *J. Geophys. Res.: Space Phys.*, 122(4), 4156–4167. <https://doi.org/10.1002/2016JA023372>
- Yu, X. D., Yuan, Z. G., Yu, J., Wang, D. D., Deng, D., and Funsten, H. O. (2023). Diffuse auroral precipitation driven by lower-band chorus second harmonics. *Nat. Commun.*, 14(1), 438. <https://doi.org/10.1038/s41467-023-36095-x>
- Zhao, H., Li, X., Blake, J. B., Fennell, J. F., Claudepierre, S. G., Baker, D. N., Jaynes, A. N., Malaspina, D. M., and Kanekal, S. G. (2014). Peculiar pitch angle distribution of relativistic electrons in the inner radiation belt and slot region. *Geophys. Res. Lett.*, 41(7), 2250–2257. <https://doi.org/10.1002/2014GL059725>
- Zhou, Q. H., Chen, Y. X., Xiao, F. L., Zhang, S., Liu, S., Yang, C., He, Y. H., and Gao, Z. L. (2022). A machine-learning-based electron density (MLED) model in the inner magnetosphere. *Earth Planet. Phys.*, 6(4), 350–358. <https://doi.org/10.26464/epp2022036>