

Distribution characteristics of trapped Terrestrial Myriametric Radiation in the magnetosphere

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Key Points:

- The trapped Terrestrial Myriametric Radiation (TMR) occurs more frequently on the nightside than on the dayside.
- The occurrence rate of trapped TMR increases with the increasing magnetic latitude.
- Fast (slow) Z-mode of trapped TMR is predominantly observed at high (low) L -shell in the magnetosphere.

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Abstract: The trapped Terrestrial Myriametric Radiation (TMR) is a widely observed emission in the magnetosphere with wavelengths of myriameters (frequencies ≤ 30 kHz), and consists of the fast and slow Z-modes. Based on measurements from the Arase satellite during the period of 23 March 2017 to 31 October 2022, we investigate the distribution characteristics of trapped TMR in the magnetosphere. We analyze trapped TMR events with the electric field power spectral density $\geq 10^{-8} \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1}$ and in the frequency range of 7–30 kHz. Statistical results show that the trapped TMR occurs more frequently on the nightside, and the corresponding occurrence rate increases with the increasing magnetic latitude in the region of 0° – 45° . The occurrence rate of fast (slow) Z-mode increases (decreases) as the L -shell increases. In addition, the fast (slow) Z-mode occurs more frequently in the southern (northern) hemisphere. This study enriches our understanding of various electromagnetic waves in the magnetosphere.

Keywords: Terrestrial Myriametric Radiation; spatial distribution; Z-mode

1. Introduction

Terrestrial myriametric radiation (TMR) is a type of nonthermal continuum radiation with wavelengths of myriameters (Gurnett and Shaw, 1973; Gurnett, 1975; Hashimoto et al., 1994; Jones, 1980). TMR originates mainly from the equatorial plasmopause and the magnetopause (Gurnett, 1975; Jones, 1981). A variety of generation mechanisms have been proposed to account for TMR, and these can be broadly categorized as linear or nonlinear (Jones, 1980). The most prominent among these is linear mode conversion window theory proposed by Jones (1980), which suggests that electrostatic waves convert into electromagnetic radiation as they propagate through a radio window (Deng ZK et al., 2025). Subsequent observations have identified several distinct components of TMR, including continuum enhancement (Gough, 1982; Filbert and Kellogg, 1989; Kasaba et al., 1998), auroral myriametric radiation (Hashimoto et al., 1994), and terrestrial myriametric radio burst (Fung SF et al., 2013). Radiations similar to TMR have also been detected on other planets in the solar system

(Jones, 1987; Wu SY et al., 2022).

The frequency range of TMR typically extends from a few kHz to 100 kHz, with a low-frequency cutoff can be as low as 500 Hz in the low-density regions of the distant magnetotail (Gurnett and Shaw, 1973; Gurnett, 1975). For frequencies below a critical threshold of ~ 30 kHz, TMR is confined within the Earth's magnetosphere and called the trapped TMR (Gurnett, 1975). At frequencies above this threshold, TMR can propagate freely to regions outside the Earth's magnetosphere (the escaping component) (Jones, 1980; Nagano et al., 2003) and overlap in frequency with auroral kilometric radiation (Xiao FL et al., 2006; Zhang S et al., 2020, 2021). Therefore, the dominant TMR component observed by the satellites in the magnetosphere is the trapped part. This critical frequency (30 kHz) is related to the solar wind plasma frequency or magnetosheath plasma frequency, which is controlled by the electron density (Hashimoto et al., 1999; Horne, 1989; Zhou et al., 2022; Jones, 1981, 1982).

Based on the dispersion relation of plasma waves, the trapped TMR includes the fast Z-mode and the slow Z-mode. The fast Z-mode is the lower-frequency branch (below the local plasma frequency f_{pe}) of superluminous waves, and the slow Z-mode is the higher-frequency branch (above f_{pe}) of the subluminal waves (Benson et al., 2006; Menietti et al., 2023). The fast Z-mode,

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also referred to as the left-extraordinary mode of superluminous waves, has been detected by the Arase satellite (Zhang S et al., 2024; He YH et al., 2026). Wave–particle interaction is a fundamental process in the magnetosphere (Xiao FL et al., 2010, 2012; Li T et al., 2023). Previous studies have shown that the slow Z-mode can efficiently accelerate or pitch angle scatter energetic electrons under suitable conditions (Xiao FL et al., 2012; Gu XD et al., 2013; Woodfield et al., 2018). These energized or scattered electrons can cause ozone destruction or severe damage to spacecrafts (Baker, 2002; Callis et al., 1998; Thorne et al., 2005). Z-mode waves have been observed at Saturn’s magnetosphere (Ye SY et al., 2010; Menietti et al., 2016). However, due to limited observational data, our understanding of the differences between fast and slow Z-modes remains incomplete. In particular, the spatial and temporal distributions of plasma waves are crucial for magnetosphere–ionosphere–atmosphere coupling (Xiao FL et al., 2022; Li P et al., 2024; Tang JY et al., 2025; Zhang S et al., 2026). Here, using the observations from the Arase satellite during the period of 23 March 2017 to 31 October 2022, we analyze the spatial distribution characteristics of trapped TMR in the region of $L = 1–11$ and $|\text{Mlat}| \leq 45^\circ$.

2. Observations

This study uses measurements from the High Frequency Analyzer (HFA) of the Plasma Wave Experiment (PWE) onboard the Arase satellite. HFA measures the electric field components of plasma waves from several kHz to 10 MHz and derives the power spectrum density (PSD) of electric field as well as the left-hand (E_L) and right-hand (E_R) electric fields using standard processing methods (Kasaba et al., 2017; Kumamoto et al., 2018). The axial *Ratio* of the wave is calculated as:

$$\text{Ratio} = \frac{E_R^2 - E_L^2}{E_R^2 + E_L^2}. \quad (1)$$

The polarization relative to the satellite’s spin axis (anti-sunward direction) is directly determined by the sign of the *Ratio*. A positive (negative) *Ratio* indicates right-hand (left-hand) polarization relative to the spin axis (Kumamoto et al., 2018). Wave polarization is defined relative to the magnetic field direction, and the magnetic fields in most magnetospheric regions is roughly parallel or antiparallel to the Sun–Earth line. Thus, we can determine the true wave polarization using the *Ratio* sign and the Arase position (He YH et al., 2026). According to the dispersion relation, the fast (slow) Z-mode correspond to the left-hand (right-hand) polarization (Benson et al., 2006; Nishimura et al., 2006; Menietti et al., 2023). We identify the fast and slow Z-modes based on the polarization and the wave frequency.

Figure 1 shows two trapped TMR events observed by Arase: Event I (17:07–18:30 UT on 20 January 2018) and Event II (23:00–23:45 UT on 5 October 2019). Figures 1a and 1b show observation of Event I in the region of $L \sim 6.3$, magnetic local time (MLT) ~ 11.4 , and magnetic latitude (Mlat) $\sim 20.0^\circ$. Strong TMR with PSD up to $\sim 10^{-5} \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1}$ was detected in the frequency range of 15–30 kHz. The black solid line represents the plasma frequency (f_{pe}). Polarization data show persistent left-hand polarization (L-H and R-H indicate the left-hand and right-hand polarization, respectively)

where wave power is significant ($\text{PSD} \geq 10^{-8} \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1}$) below f_{pe} . Figures 1c and 1d show observation for Event II in the region of $L \sim 6.0$, MLT ~ 3.9 , and Mlat $\sim -7.0^\circ$. Intense radiation ($\text{PSD} \sim 10^{-6} \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1}$) appears above f_{pe} , with right-hand polarization. Combined with the wave frequency and polarization, Event I (II) is identified as the fast (slow) Z-mode of trapped TMR.

In this study, we analyze trapped TMR in the frequency range of 7–30 kHz and with $\text{PSD} \geq 10^{-8} \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1}$. Whistler-mode waves have generally appeared in the frequency range below the electron cyclotron frequency (Min K, 2025). Therefore, there exist extremely fewer whistler-mode waves within our statistical frequency range. For these fewer cases, we have adopted a manual inspection approach to remove whistler-mode events. To ensure reliable polarization, we have evaluated a series of $|\text{Ratio}|$ thresholds from 0.1 to 0.9 and determined that a value of 0.3 optimally suppressed background noise while retaining the polarization characteristics. In addition, He YH et al. (2026) have also adopted the same threshold in their study, which has further corroborated the rationality of our choice. In total, 2507 (3108) trapped TMR events are identified as fast (slow) Z-modes during the period. For the spatial analysis, We have tested various binning schemes, an overly detailed binning scheme amplifies the Arase satellite’s sampling bias, while an overly coarse binning scheme smears local features and obscures key spatial variations. After multiple comparative testing, we have adopted the most appropriate binning scheme ($L = 0.1$, MLT = 1 h, and Mlat = 5°) for our analysis. It should be noted that while different binning schemes may yield varying sample count, the overall statistical results remain unchanged in this study. We count 20,411 (45,624) samples for the fast (slow) Z-mode and record satellite passings in each bin. The occurrence rate is defined as the ratio of total samples to satellite passings in a given region. The number of slow Z-mode samples is approximately twice that of fast Z-mode samples, and the average occurrence rate of the slow Z-mode is about twice that of the fast Z-mode. This might be due to the fact that the growth rates and propagation mechanisms of the fast Z-mode and the slow Z-mode are different.

3. Results

We plot the distribution of fast Z-mode and slow Z-mode in different coordinate systems. Figure 2 presents the sample number and occurrence rate for both modes as a function of MLT– L , together with the number of satellite passing. The region is gridded into bins with intervals of $L = 1$ and MLT = 1. Figure 2a (2b) is the number of the fast (slow) Z-mode samples as a function of MLT– L . As shown in Figure 2a, more fast Z-mode samples (82%) stay on the nightside. The most fast Z-mode samples (602) is observed in the region of MLT = 23–24 and $L = 5–6$. As shown in Figure 2b, more slow Z-mode samples (76%) stay on the nightside. The most slow Z-mode samples (1297) is observed in the region of MLT = 01–02 and $L = 2–3$. There are some slow Z-mode samples on the afternoon sector (MLT = 12–18). Two regions with few slow Z-mode samples appear at the dawn and dusk. These suggest that the trapped TMR (both modes) occurs more frequently on the nightside. Figure 2e plots the number of satellite passings during the period. The corresponding occurrence rate of fast (slow) Z-

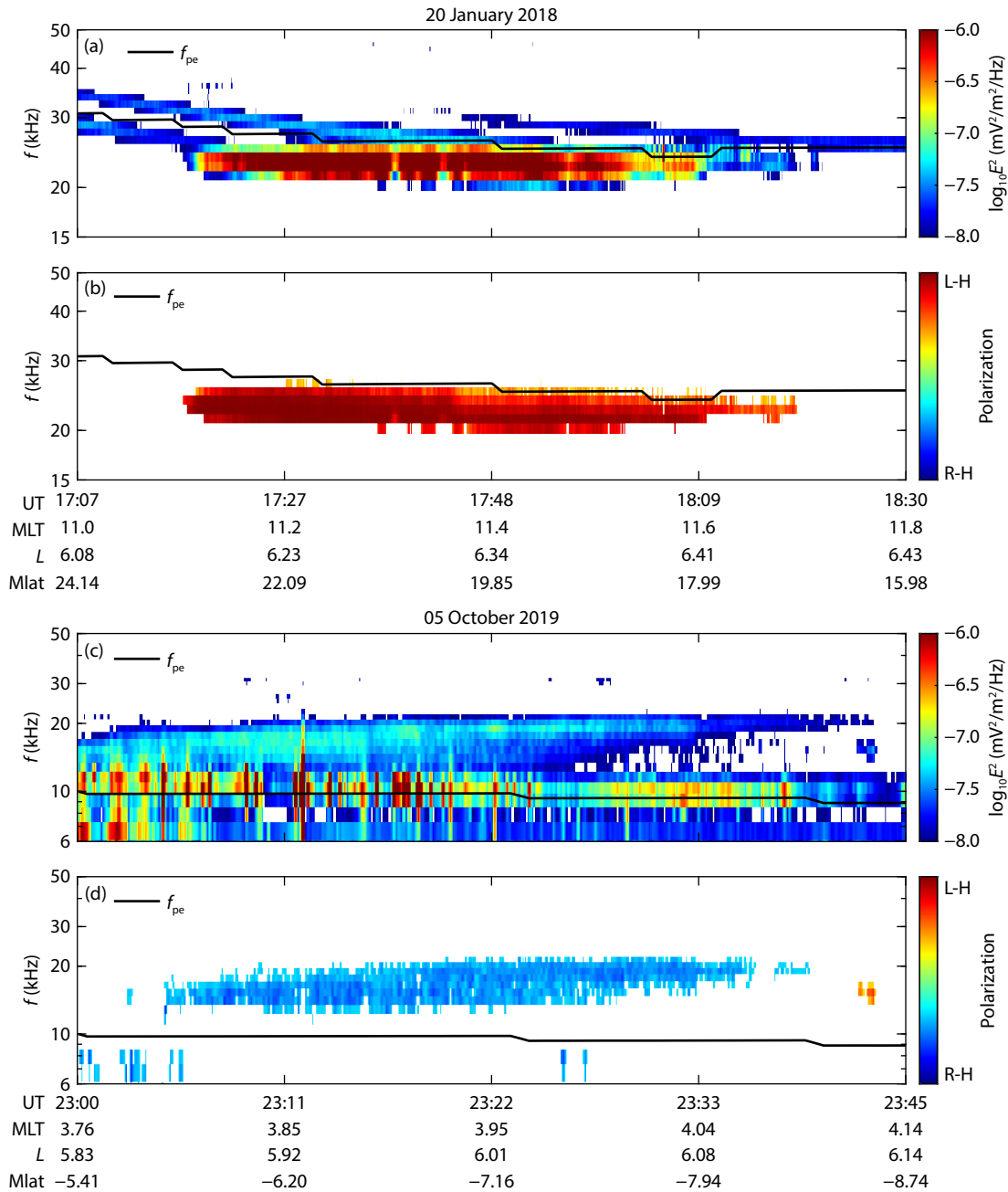


Figure 1. TMR events observed by the Arase satellite. (a, b) The fast Z-mode observed on 20 January 2018. (c, d) The slow Z-mode observed on 5 October 2019. (a, c) The PSD of electric field (E^2) measured by the HFA (the black solid line denotes the local plasma frequency f_{pe}). (b, d) The polarization of emissions with $\text{PSD} \geq 10^{-8} \text{ mV}^2 \text{ m}^{-2} \text{ Hz}^{-1}$ (the black solid line is f_{pe}).

mode is shown in Figure 2c (2d). The higher occurrence rate (>10%) of fast Z-mode is concentrated in the region of MLT = 20–03 and $L = 7–11$. The higher occurrence rate (>10%) of slow Z-mode is concentrated in the region of MLT = 22–03 and $L = 1–5$. The maximum occurrence rate (~30%) of fast Z-mode occurs in the region of MLT = 21–22 and $L = 10–11$. The maximum occurrence rate (~20%) of slow Z-mode occurs in the region of MLT = 01–02 and $L = 2–4$. Two distinct gaps also emerge in the occurrence rate of slow Z-mode at the dawn and dusk. These results indicate that the fast Z-mode exhibits stronger concentration than the slow Z-mode, and the occurrence rate of fast (slow) Z-

mode increases (decreases) as the L increases.

Figure 3 shows the numbers and the corresponding occurrence rates of both modes in the function of Mlat– L . Here, the bins are set with intervals 5° in Mlat and 1 in L . As shown in Figure 3a, there are the most (751) fast Z-mode samples in the region of Mlat = -35° to -40° and $L = 8–9$. The number of fast Z-mode samples increases as the Mlat increases. It is worth noting that the region of Mlat = -5° to 10° and $L = 2–3$ is an exception. The most (1781) slow Z-mode samples occur in the region of Mlat = $20^\circ–25^\circ$ and $L = 1–2$ (Figure 3b). The number of slow Z-mode samples increases as the L decreases and Mlat increases. As shown in

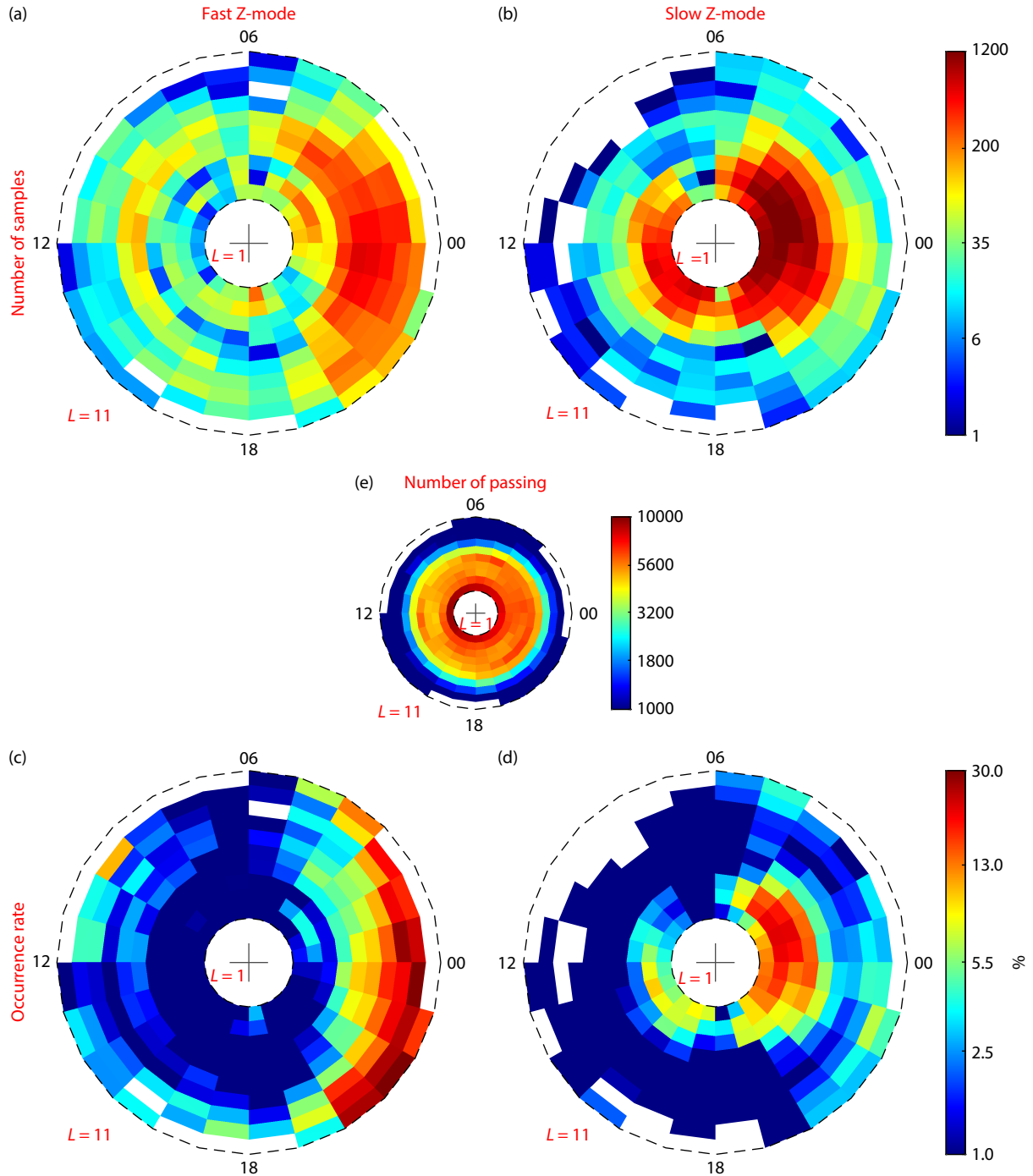


Figure 2. Distribution of TMR as a function of MLT– L . (a) The number of fast Z-mode samples. (b) The number of slow Z-mode samples. (c) The corresponding occurrence rate of fast Z-mode. (d) The corresponding occurrence rate of slow Z-mode. (e) The number of satellite passings.

Figure 3c, the high occurrence rate ($>10\%$) of fast Z-mode is primarily centered in the region of $Mlat = -30^\circ$ to -45° and $L = 8-11$. The occurrence rates of fast Z-mode in the southern hemisphere are greater than those in the northern hemisphere. The higher occurrence rate ($>10\%$) of slow Z-mode waves is primarily located in the region of $Mlat = 20^\circ-45^\circ$ and $L = 2-5$ (Figure 3d). The occurrence rates of slow Z-mode in the northern hemisphere are greater than those in the southern hemisphere. These results suggest that fast Z-modes are more frequently observed at larger L -shells in the southern hemisphere, whereas slow Z-mode waves

are preferentially observed at smaller L -shells in the northern hemisphere.

In total, 9068 (11,343) samples for fast Z-mode and 17,171 (28,453) samples for slow Z-mode wave samples are identified in the southern (northern) hemisphere. Figures 4a, 4c, and 4e present the number of fast Z-mode samples, the number of satellites passing, and the corresponding occurrence rate in the northern hemisphere as the function of MLT and $Mlat$, respectively. The most samples (332) are detected in the region of $MLT = 23-24$ and

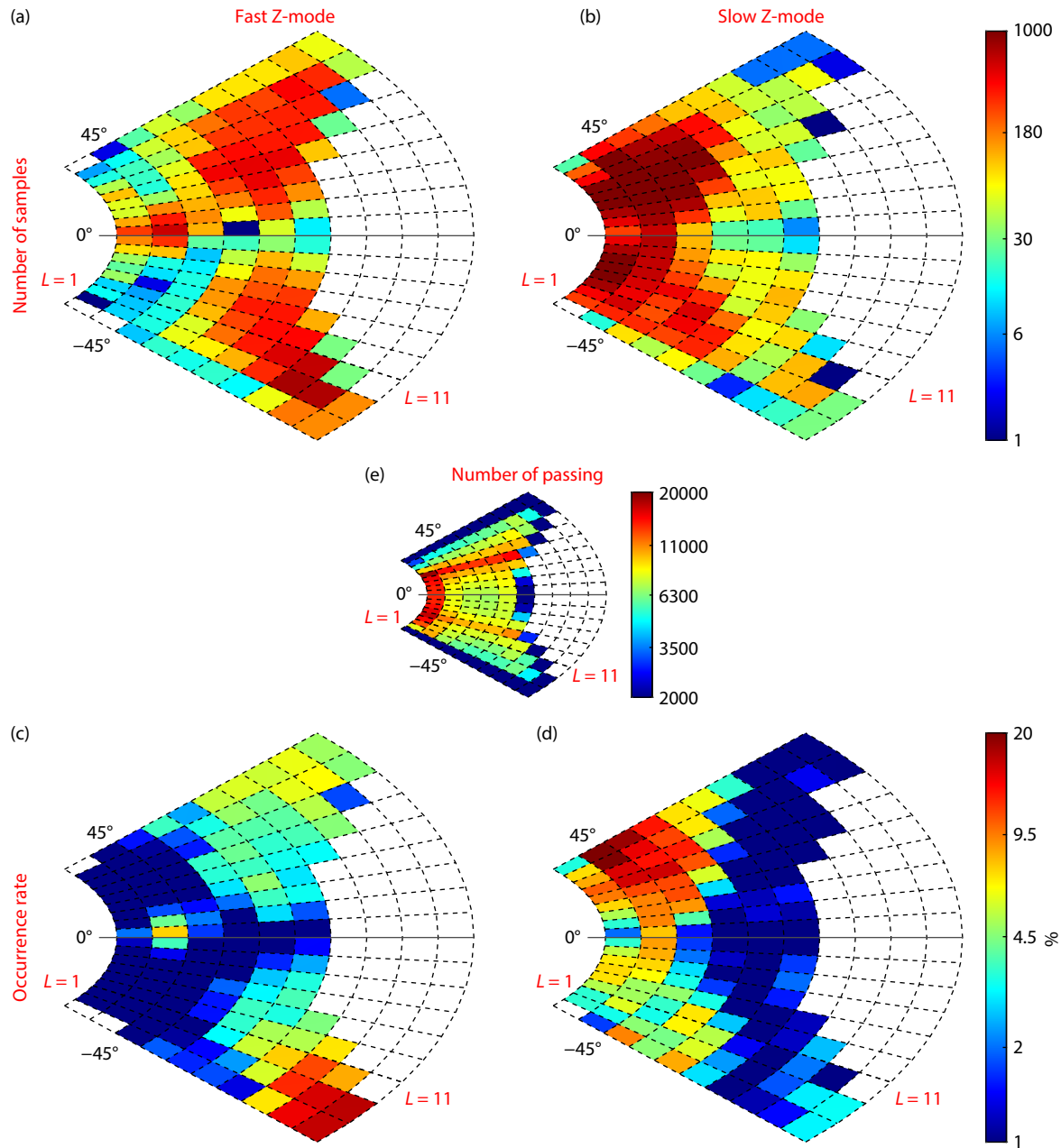


Figure 3. Distribution of TMR as a function of Mlat–L. (a) The number of fast Z-mode samples. (b) The number of slow Z-mode samples. (c) The corresponding occurrence rate of fast Z-mode. (d) The corresponding occurrence rate of slow Z-mode. (e) The number of satellite passings.

Mlat = 20°–25° (Figure 4a). The relatively high occurrence rate (>10%) is concentrated in the region of MLT = 22–02 and Mlat = 35°–45° (Figure 4e). The highest occurrence rate (~15.7%) of fast Z-mode in the northern hemisphere occurs in the region of MLT = 23–24 and Mlat = 40°–45°. Figures 4b, 4d, and 4f present the statistical results of the fast Z-mode in the southern hemisphere. There are the most samples (357) of fast Z-mode in the region of MLT = 00–01 and |Mlat| = 35°–40° (Figure 4b). The relatively high occurrence rate (>10%) is mainly concentrated in the region of MLT = 21–03 and |Mlat| = 35°–45° (Figure 4f). The highest occurrence rate (~19.6%) of fast Z-mode in the southern hemisphere occurs in the region of MLT = 00–01 and |Mlat| = 40°–45°. These figures indicate that the fast Z-mode can be more frequently

observed in the southern hemisphere. The statistical results of slow Z-mode in two hemispheres are presented in Figure 5. In the northern hemisphere, the most samples (555) occur in the region of MLT = 00–01 and Mlat = 20°–25° (Figure 5a). The relatively high occurrence rate (>10%) is mainly concentrated in the region of MLT = 21–03 and Mlat = 15°–45° (Figure 5e). The highest occurrence rate (~22.4%) of slow Z-mode in the northern hemisphere stays in the region of MLT = 23–24 and Mlat = 40°–45°. In the southern hemisphere, the most samples (406) occur in the region of MLT = 00–01 and |Mlat| = 20°–25° (Figure 5b). The relatively high occurrence rate (>10%) is mainly concentrated in the areas where MLT = 22–03 and |Mlat| = 10°–35° (Figure 5f). The highest occurrence rate (~14.3%) of slow Z-mode in the southern hemi-

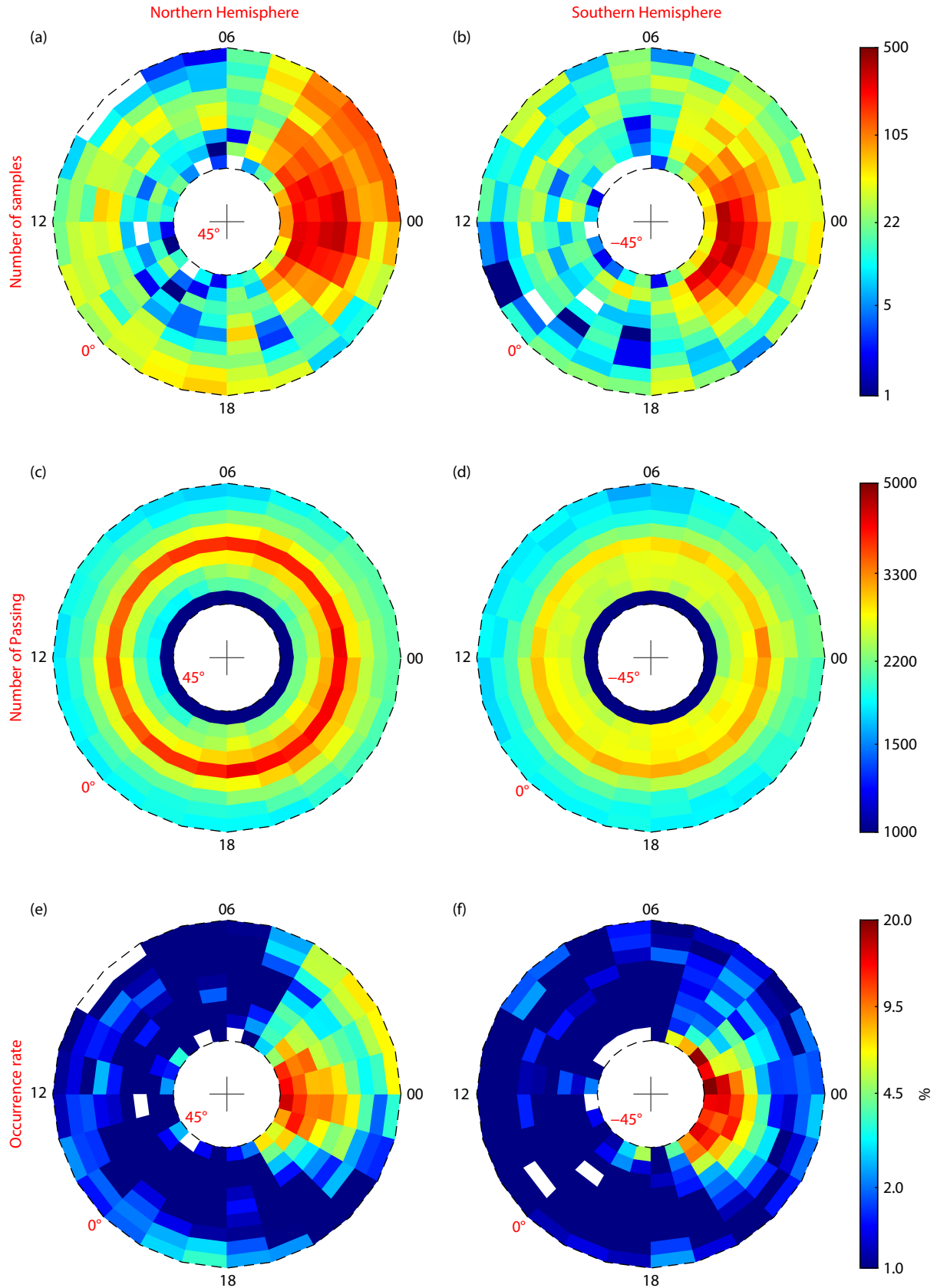


Figure 4. Distribution of fast Z-mode as a function of MLT–Mlat. (a–b) The number of fast Z-mode samples in the northern and southern hemisphere. (c–d) The number of satellite passings in the northern and southern hemisphere. (e–f) The corresponding occurrence rate of fast Z-mode in the northern and southern hemisphere.

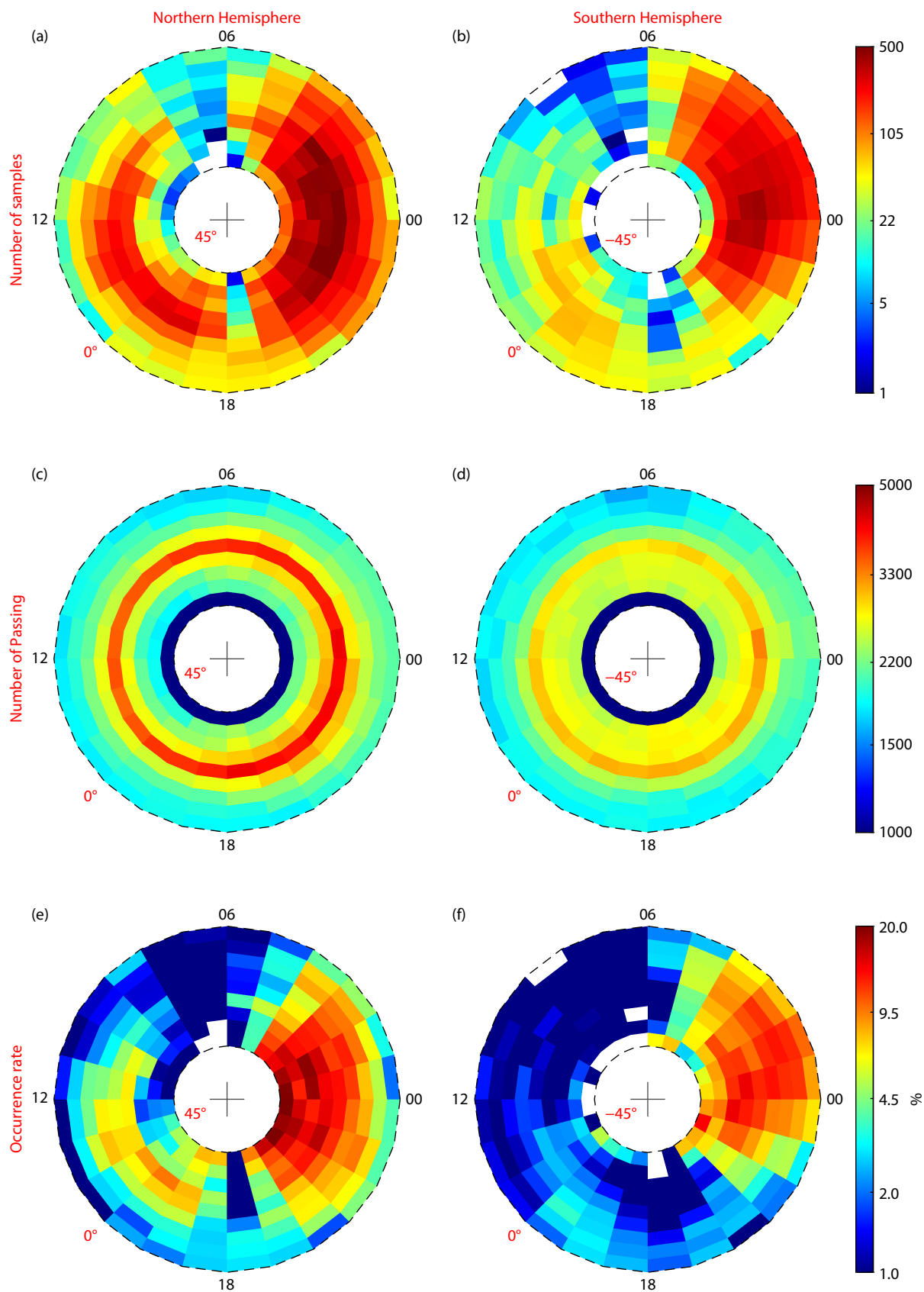


Figure 5. Distribution of slow Z-mode as a function of MLT–Mlat. (a–b) The number of slow Z-mode samples in the northern and southern hemisphere. (c–d) The number of satellite passings in the northern and southern hemisphere. (e–f) The corresponding occurrence rate of slow Z-mode in the northern and southern hemisphere.

sphere stays in the region of $MLT = 23\text{--}24$ and $|Mlat| = 30^\circ\text{--}35^\circ$. These results suggest that the slow Z-mode can be more frequently observed in the northern hemisphere.

4. Conclusion

The trapped Terrestrial myriametric radiation (TMR) is a widely existing electromagnetic radiation in the magnetosphere with wavelengths of myriameters (frequencies ≤ 30 kHz). Using the observational data from Arase satellite during the period of 23 March 2017 to 31 October 2022, we analyze the distribution of trapped TMR in the region of $L = 1\text{--}11$, $MLT = 00\text{--}24$, and $|Mlat| = 0^\circ\text{--}45^\circ$. A total of 66,035 samples were observed during the period. To better reflect the spatial distribution characteristics, we calculate the occurrence rate as the ratio of the total number of samples to the number of satellite passing. The left-hand (right-hand) polarized trapped TMR is named as the fast (slow) Z-mode. We plot the statistical results in different coordinate systems to analyze the spatial distribution of two modes. The principal conclusions are as follows.

(1) The trapped TMR occurs more frequently on the nightside than that on the dayside. During the period, 51,544 (14,491) samples occur on the nightside (dayside). This may be attributed to stronger electron injection and lower plasma density on the nightside. Specifically, electron injection has been more intense on the nightside than on the dayside (Fu HS et al., 2010; Walsh et al., 2014). Enhanced electron injection has facilitated the amplification of electrostatic waves, thereby promoting the TMR generation (Gough, 1982; Zhang X and Angelopoulos, 2014). Meanwhile, the magnetosphere has been compressed by the solar wind on the dayside, resulting in a higher background plasma density than on the nightside, which has limited the propagation of TMR (Laakso et al., 2002; Jones, 1982). It should be noted that, due to the complexity of the generation and propagation of TMR, the quantitative relationship between its spatial distribution and the concurrent plasma/particle conditions is not yet fully clear. We plan to conduct a further study in the future research.

(2) The number of slow Z-mode (45,624 samples) is twice that of fast Z-mode (20,411 samples), and the averaged occurrence rate of slow Z-mode is twice that of fast Z-mode. This may be attributed to the different growth rates of the two modes, which have resulted in a higher generation efficiency of the fast Z-mode. Meanwhile, the difference in their cutoff frequencies has led to distinct propagation characteristics within the magnetosphere (Benson et al., 2006; Nishimura et al., 2006; Menietti et al., 2023). Consequently, the observed sample ratio between the slow Z-mode and fast Z-mode arises from the joint contribution of both generation efficiency and propagation characteristics.

(3) There are significant differences in fast and slow Z-mode distributions in the L direction. The fast Z-mode is more easily observable at larger L , whereas slow Z-mode waves are more easily observable at smaller L values. Relatively high occurrence rates of fast Z-mode ($>10\%$) are primarily observed in $L = 8\text{--}11$, whereas those of slow Z-mode occur primarily in $L = 2\text{--}5$. This might be due to the different frequency ranges of the two modes. The frequency ranges of different modes TMR are very sensitive to

plasma density, with the fast Z-mode falling below and the slow Z-mode above the f_{pe} . In the Earth's magnetosphere, the local plasma density increases with decreasing L -shell, and the f_{pe} increases with the density enhancement (Ripoll et al., 2024; Tu JN et al., 2006). This makes it more difficult for fast Z-mode, originating from the magnetopause, to propagate to low L -shells compared to slow Z-mode from the same source region. This leads to the difference in their L -shell dependence.

(4) Hemispheric asymmetry is present in the fast Z-mode and the slow Z-mode: the highest occurrence rate of fast (slow) Z-mode stays in the region of $Mlat \sim 40^\circ$ of the southern (northern) hemisphere. There are various possible causes for this asymmetric distribution characteristic. First, the frequency ranges of both the fast Z-mode and the slow Z-mode have been highly sensitive to the plasma density. Second, the difference of the magnetic pole offsets has given rise to asymmetric distributions of ionospheric conductivity and plasma density in the northern and southern hemispheres (Laundal et al., 2017). Additionally, the magnetic dipole tilt introduces a pronounced asymmetry in the field-aligned currents between the northern and southern hemispheres (Eggington et al., 2020). These factors may lead to differences in the source region locations and plasma environments between the northern and southern hemispheres, thereby resulting in distinct distribution characteristics of the two modes. However, a detailed investigation of these possibilities require ray-tracing simulations and magnetospheric plasma modeling, which we plan to pursue in subsequent studies.

(5) Anomalous regions are present in the spatial distribution of the fast Z-mode. The occurrence rate of the fast Z-mode is significantly higher than the surrounding regions at $Mlat = -5^\circ$ to 10° and $L = 2\text{--}3$. This anomalous distribution may be related to the influence of local plasma density irregularities at low L -shells. Liu X et al. (2021) have shown that density irregularities can regulate the propagation paths of whistler-mode waves and thus confine the wave position inside density crest/trough regions. At $L = 2\text{--}3$, plasma density irregularities modify the local plasma frequency, which changes the cutoff frequency of fast Z-mode and causes fast Z-mode to deviate from the normal distribution trend.

Open Research Section

Science data of the ERG (Arase) satellite was obtained from the ERG Science Center operated by ISAS/JAXA and ISEE/Nagoya University (<https://ergsc.isee.nagoya-u.ac.jp/data/ergsc/satellite/erg/>, Miyoshi, Hori et al., 2018). The present study analyzed PWE-HFA-L2 data (doi:10.34515/DATA.ERG-10000) and Orbit-L2 v02 data (10.34515/DATA.ERG-1 2000).

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