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Observational Evidence for Three Time-Scale Modulations in the Pulsating Aurora

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Key Points:

- We report a conjugate event in which the pulsating aurora (PsA) has a one-to-one correspondence with chorus bursts
- The frequency spectra of auroral intensities obtained by wavelet analysis and fast Fourier transform (FFT) show the coexistence of ~0.3 Hz, 4 Hz, and >10 Hz modulations
- Spatial distributions show that the internal and fast modulations are well-structured within aurora patches

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Abstract We report an Arase-all sky imager (ASI) conjugate event in which the pulsating aurora (PsA) has a one-to-one correspondence with chorus bursts. Wavelet analysis displayed three peaks at ~0.3 Hz, 4 Hz, and >10 Hz, corresponding to the main pulsation, internal modulation, and fast modulation, respectively. These correspond to the old terms of ~5–15 s pulsations, chorus risers/elements and subelements/subpackets, respectively. Electron "microbursts" correspond to the 4-Hz peak. The internal and fast modulations are further verified by the analysis based on fast Fourier transform analyses. Moreover, the spatial distributions of the Fourier spectral amplitude show that the internal and fast modulations are well-structured within auroral patches. The above results indicate a paradigm shift away from quasilinear theory which implicitly assumes diffuse wave generation. The three time-scale modulations are consistent with coherent chorus which has been theoretically argued to lead to pitch angle transport three orders of magnitude faster.

Plain Language Summary Pulsating aurora exhibit irregular patches of brightness with quasiperiodic on-off transitions (~2–20 s). More rapid modulations, such as internal modulation (~3–4 Hz) or fast modulation (>10 Hz), have been detected within the pulsation "on" time. However, due to the measurement limitations, the simultaneous observation of three time-scale modulations has never been reported. In this study, we analyze the conjugate observations of the pulsating aurora (PsA) and chorus recorded by the ground-based Arase-all sky imager and the Arase satellite, which demonstrates the coexistence of three time-scale modulations in the PsA. The spatial distributions of Fourier spectral amplitude show that the internal and fast modulations are well-structured within the aurora patches. The three time scales of chorus modulation have been previously called chorus 5–15 s pulsations, risers/elements and subelements/subpackets corresponding to the three aurora peaks. This study verifies the existence of internal and fast modulations in PsA, implying an extremely rapid electron loss mechanism. Quasilinear theory cannot explain any of the three time-scale modulations. The discovery that chorus is coherent and will lead to pitch angle transport 1,000 times faster than diffuse waves is consistent with the fast modulations shown in this paper. A new theory of chorus generation is needed to update that of quasilinear theory.

1. Introduction

Pulsating auroras are characterized by quasiperiodic 2–20 s on-off transitions in either the optical brightness of irregular patches or X-ray bremsstrahlung (balloon) observations (Anderson & Milton, 1964; Barcus et al., 1971; Brekke & Pettersen, 1971; Brown et al., 1965; Nishimura et al., 2020; Nishiyama et al., 2014; Royrvik & Davis, 1977; Tsurutani et al., 2013; Yamamoto, 1988). The energetic electrons which cause the pulsations deposit their energy at an altitude of approximately one hundred kilometers. The on-off transition, called the pulsation, is in the range of 2–20 s or longer (Anderson & Milton, 1964; Barcus et al., 1971; Nishimura et al., 2020; Yamamoto, 1988). Theoretical calculations and observations have indicated that electron pitch angle scattering (a few keV to 10 s keV) caused by chorus waves in the near-equator region of the magnetosphere is a primary process in the formation of pulsating aurora (PsA) (S. Kasahara et al., 2018; Li et al., 2012; Miyoshi et al., 2010, 2020; Miyoshi, Oyama, et al., 2015; Miyoshi, Saito, et al., 2015; Nishimura et al., 2010; Tsurutani & Smith, 1974). Nishimura et al. (2010) presented that the ground-based optical observations of PsA are highly correlated with quasiperiodic chorus waves (∼10 s, called chorus bursts/pulsations). S. Kasahara et al. (2018) provided direct evidence that energetic electrons are scattered by chorus bursts, which was measured by the Arase satellite, and then the resultant quasiperiodic precipitating electrons further lead to the formation of PsA, which was simultaneously observed by ground-based Arase-all sky imager (ASI) (S. Kasahara et al., 2018). Particle pitch angle scattering due to cyclotron resonance with electromagnetic chorus waves is considered to be the dominant driver for diffuse/PsA (Thorne et al., 2010), which is further verified by Gao et al. (2023).

Moreover, a faster modulation of ∼4 Hz, called internal modulation, has been frequently detected in the "on" time pulsation (Hosokawa et al., 2020; Miyoshi, Saito, et al., 2015; Ozaki et al., 2018, 2019). Miyoshi, Saito, et al. (2015) reported a conjugate event between the PsA and precipitating electrons, and internal modulation (∼4 Hz) was identified in the precipitating electrons/microbursts. They have proposed a model in which a train of rising tone elements (the period is ∼0.1–1 s) in chorus bursts (Tsurutani & Smith, 1974) can drive the internal modulation, which has been reproduced by computer simulations (Miyoshi, Saito, et al., 2015). Observations and simulations indicate that the repetitive nature of chorus rising tone elements is related to the drift velocity of energetic electrons (referring to Gao et al., 2022; Lu et al., 2021). Recently, based on the conjugate observation of the ground-based ASI and the Arase satellite, the one-to-one correspondence between the internal modulation and the discrete rising-tone elements has been presented (Hosokawa et al., 2020; Ozaki et al., 2018, 2019). It should be noted that incoherent chorus waves as assumed in the Kennel and Petschek (1966) quasilinear theory cannot scatter the energetic electrons rapidly enough to create these internal modulation/microbursts. Only coherent chorus waves are able to cause this phenomenon (Tsurutani et al., 2009).

As a result, the main pulsation and internal modulation of PsA are related to chorus burst groupings and their rising-tone elements, respectively (Hosokawa et al., 2020; Miyoshi, Saito, et al., 2015, 2020). In addition to the main pulsation and internal modulation, a more rapid modulation (>10 Hz, called fast modulation) has been reported (Kataoka et al., 2012; Samara & Michell, 2010). Kataoka et al. (2012) showed a periodic 54-Hz modulation within the PsA observed at the Poker Flat Research Range of the University of Alaska Fairbanks, but they only found one interval with a fine measurement. The 54-Hz fast modulation is comparable to the temporal scale of chorus subpacket/subelement structures (H. Chen et al., 2023; Kataoka et al., 2012; R. Chen et al., 2022; Santolík et al., 2003, 2004, 2014; Tsurutani et al., 2009, 2020). Ozaki et al. (2018) compared the auroral intensity variations with chorus subpackets/subelements in a microscopic view and suggested that the fast modulation is possibly related to the chorus subpackets/subelements (with periods of several tens of milliseconds). Due to the limitation of the temporal resolution of ASIs and the rarity of conjugate observation, the simultaneous observation of three time-scale modulations has never been reported in the PsA. This even higher modulation rate can only be accomplished by coherent chorus waves.

In this study, we report a conjugate event of the PsA and chorus waves observed by the ground-based ASI and the Arase satellite. The property of temporal modulation of PsA has been analyzed. Modulations on three-time scales, including the main pulsation, internal modulation, and fast modulation, have been detected in PsA. Moreover, the spatial distribution of Fourier spectral amplitude at specific modulation frequencies (internal and fast modulation ranges) shows well-structured shapes within the aurora patches. As a result, our study provides sufficient evidence to demonstrate the coexistence of three different time-scale modulations in PsA, and the existence of internal modulation and fast modulation implies an extremely rapid electron loss mechanism.

2. Data Sources

The Exploration of energization and Radiation in Geospace (ERG) project (Miyoshi, Shinohara, et al., 2018), including both satellite (Arase) and ground-based observations, is designed to study the electron dynamics in the radiation belts and the dynamics of geospace substorms and storms. The Arase satellite operates entirely within the Earth's radiation belts and carries scientific instruments to measure plasma and field data (Miyoshi, Shinohara, et al., 2018). Ground-based instruments include magnetometers, all-sky imagers, VLF/ELF Network, etc (Hosokawa et al., 2023; Shiokawa et al., 2017). In this study, the Level-2 electric field waveform and spectrum data measured by the Waveform Capture (WFC) in the Plasma Wave Experiment (PWE) are used to investigate the properties of chorus waves (Y. Kasahara et al., 2018; Matsuda et al., 2018). The local magnetic field B_{loc} measured by the Magnetic Field Experiment (MGF, Matsuoka, Teramoto, Nomura, et al., 2018) is used to

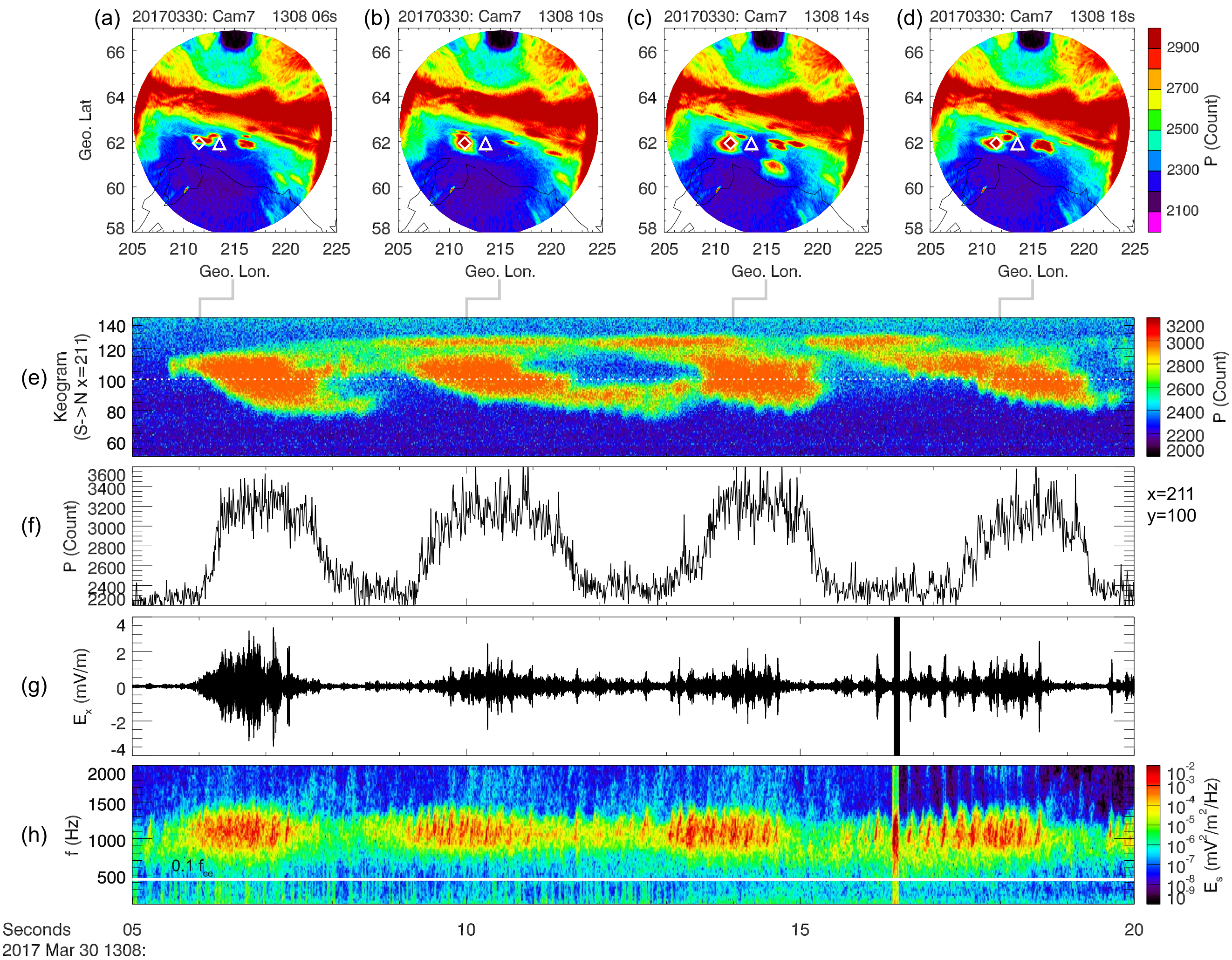

Figure 1. Event overview (a–d) Aurora images collected by Arase-all sky imager at Gakona station, (e) auroral keogram along the latitude direction from south to north at $x = 211$, (f) the time profile of aurora intensity at $x = 211$ and $y = 100$, (g) waveform of E_x component, and (h) spectrum of wave electric field component E_x. In panels (a–d), the triangle indicates the footprint of Arase satellite by field-line tracing based on the TS05 magnetic field model, and the diamond indicates the point where the highest correlation coefficient between chorus intensity and auroral intensity is obtained. In panel (h), the white line represents 0.1 f_{ce}. In panels (e–f), "x" and "y" indicate the pixel number along the longitude direction (from west to east) and latitude direction (from south to north).

estimate the magnetic field B_{eq} at the magnetic equator ($B_{eq} = B_{loc} \cdot B_{eq}^{Ts05} / B_{loc}^{Ts05}$, where B_{eq}^{Ts05} and B_{loc}^{Ts05} are equatorial and local magnetic fields from the TS05 model; Zhou et al., 2023). The auroral results presented here were collected by high-speed ASI (100 Hz) at Gakona station (Hosokawa et al., 2023). The ASI is composed of a fish-eye lens, an interference optical filter, and an electron multiplying charge-coupled device (EMCCD) detector, which collects 100 aurora images with a spatial resolution of 256 × 256 pixels at each second. The ASI is equipped with an RG665 interference optical filter (before September 2017), covering prompt emissions of nitrogen molecules extending from ~600 to >1,000 nm (N_2 first positive band). This filter can remove the contribution of slower aurora emissions (such as the emission at 557.7 and 630.0 nm). The filtered data are then used to investigate the rapid modulation of PsA (Hosokawa et al., 2023).

3. Observation Results

A conjugate event between the Arase satellite and the ground-based ASI at ~13:08 UT on 30 March 2017 was investigated. During the time interval, the Arase satellite was at $L = {\sim}4.6$, MLT = ~2.2 hr, and MLAT = −18.8° (L was derived from the IGRF model and MLT and MLAT were obtained from the SM coordinates). Figure 1 shows the event overview of PsA and chorus waves. Figure 1a–1d present the auroral images recorded by ASI at the Gakona station in Alaska. The PsA, appearing as a group of patches, is observed on the southern side of the intense discrete aurora. The footprint of Arase, estimated based on the TS05 magnetic field model (Tsyganenko & Sitnov, 2005), is marked by a triangle in Figures 1a–1d. Considering the difference between the instantaneous magnetic field and the magnetic field model, there may be several hundreds of kilometers between the actual footprint and the estimated value (Hosokawa et al., 2020). Therefore, we calculate the correlation coefficient between the chorus wave intensity and the PsA intensity within a 4-min time window (13:07–13:11 UT, including the time interval presented in Figure 1) without time delay to determine the actual footprint. The maximum correlation coefficient (the value is 0.63) marked by the diamond can be regarded as the actual footprint (Lat = 61.9°, Lon = 211.5°, corresponding to $x = 211$, $y = 100$ in the 256 × 256 spatial map), which is about tens of kilometers from the estimated value based on the TS05 model (triangle) in Figures 1a–1d.

The auroral keogram from south to north at $x = 211$ is presented in Figure 1e, which clearly illustrates an on-off pulsation (called the main pulsation, with a period of about 3–4 s) in temporal variations. Within the "on" time interval, especially in the fourth interval (13:08:16–13:08:19 UT), there are periodic jagged structures at the edge of the aurora patch, which indicates that a faster modulation (called internal modulation) is embedded. In addition, Figure 1f shows time variations of the auroral intensity at the actual footprint ($x = 211$ and $y = 100$, marked by the dashed horizontal line in Figure 1e). The auroral intensity is about 3,400 counts in the "on" time interval and about 2,300 counts in the "off" time interval. Figures 1g and 1h show the wave electric field component E_x and its power spectrum, simultaneously observed by the Arase satellite. Wave signals above 0.1 f_{ce} are electromagnetic chorus waves, and they are presented as discrete rising-tone elements that are clustered within a modulation of 3–4 s (called chorus bursts). Within the chorus bursts (13:08:17–13:08:19 UT), the repetitive period of chorus rising tones is approximately 0.2–0.3 s, which is in the range of recent statistics (Gao et al., 2022). Comparing Figure 1e with Figure 1h, there is a one-to-one correspondence between the main pulsation and chorus bursts, which is consistent with previous studies (S. Kasahara et al., 2018; Hosokawa et al., 2020), and the internal modulation should be related to repetitive rising tones/elements (Hosokawa et al., 2020; Miyoshi, Saito, et al., 2015; Ozaki et al., 2018).

Figure 2a shows time variations in auroral intensity at the actual footprint ($x = 211$ and $y = 100$), which is the same as Figure 1f. The four "on" time intervals are labeled "On-01" through "On-04". Figure 2b presents the frequency spectrum of auroral intensity derived from the wavelet transform analysis. The frequency spectrum confirms the main pulsation of PsA, showing intense power at around 0.3 Hz. In the range of ∼3–10 Hz, there are clear power enhancements in the "on" time compared with that in the "off" time, except for "On-01", which indicates that there are internal modulations in the "On-02", "On-03", and "On-04" intervals but no (or weak) internal modulation in the "On-01" interval. Moreover, in the range of ∼10–50 Hz, the spectrum power shows slight enhancements for all four "on" time intervals, which suggests that there are more rapid modulations (called fast modulation) than internal modulation. To reduce the contamination caused by the on-off pulsation, the time derivative signals in Figure 2c based on the original signals are also used for the spectrum analysis (Figure 2d). Although the analysis based on the time derivative signals may enlarge the noise (Figure 2d), it can provide consistent result with those in Figure 2b. Moreover, fast Fourier transform (FFT) based on 1 s data with no overlapping window is applied for this time interval, and the result also shows clear enhancements for all four "on" time intervals. Therefore, three time-scale modulations, including the main pulsation (∼0.3 Hz), internal modulation (∼4 Hz), and fast modulation (>10 Hz) can be detected in this event.

To confirm the internal modulation and fast modulation presented in Figure 2, FFT is also applied in the analysis, and the analysis results are shown in Figure 3. Figures 3a–3d show the analysis results for four "on" time intervals at the actual footprint, and the superposition results are presented in Figures 3e and 3f. In the frequency range $f < 10$ Hz, except for the "On-01" interval, the other three intervals have strong amplitude enhancements at ∼4 Hz (Figures 3e and 3f), which further confirms the internal modulation. Moreover, in the frequency range $f > 10$ Hz, we can find different modulations in each on-time interval, such as ∼20-Hz modulation in "On-01", ∼14-Hz modulation in "On-02", ∼18-Hz modulation in "On-03", etc.

Based on the FFT analysis, we present the spatial distribution of auroral modulation at specific frequencies during "On-03" and "On-04" intervals (the 3-s intervals from 13:08:12 UT and 13:08:16.5 UT, respectively). Figure 4 presents the auroral patches and their distribution maps of Fourier spectral amplitude from 4 to 22 Hz. The two grayscale images show the auroral patches at 13:08:14.6 and 13:08:18.0 UT, respectively. The auroral patches are quite different from each other: the patch of "On-03" presents two separate shapes, while the patch of "On-04"

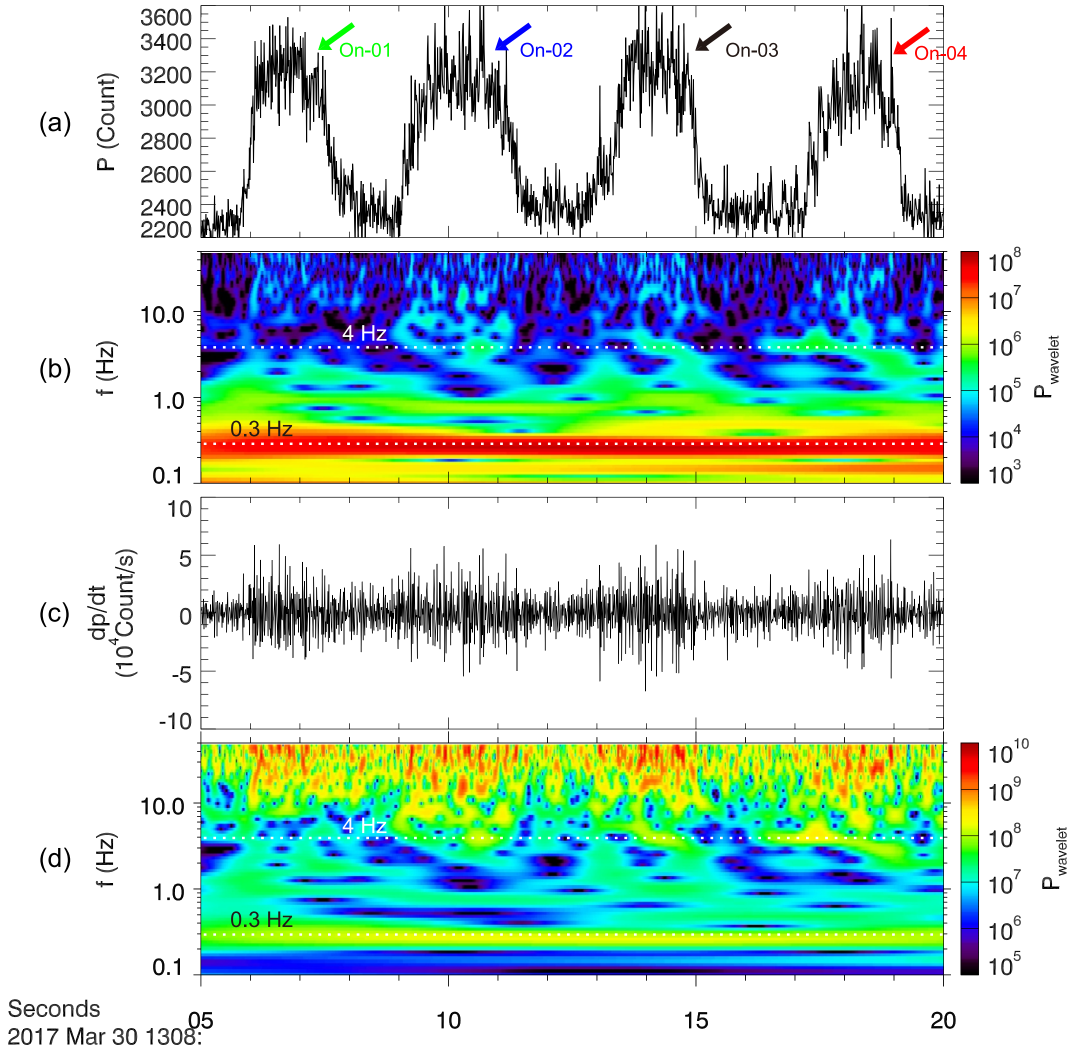

Figure 2. (a) The time profile of aurora intensity at $x = 211$ and $y = 100$, (b) frequency spectrum of aurora intensity derived from wavelet transform analysis, (c) the time derivative signals of aurora intensity, and (d) frequency spectrum of time derivative signals derived from wavelet transform analysis. Here, the wavelet spectra are within the confidence interval.

presents three separate shapes, and their spatial coverages are also different. At $f = 4$ Hz, corresponding to the internal modulation, the spatial maps show intense and well-structured shapes within the auroral patches. The intense amplitude of modulations is located at $x = \sim 200$ and $y = \sim 80$ for the "On-03" interval, and at $x = \sim 210$ and $y = \sim 110$ for the "On-04" interval. At $f = 6$ Hz, the amplitude is quite weak for "On-03", and the intense amplitude is located at $x = \sim 210$ and $y = \sim 105$ for the "On-04" interval. For $f = 10$, 14, 18 Hz, etc., the modulation signals can be detected within the auroral patches. Although the spatial distributions of the modulations are different between different auroral patches, these spatial distributions can provide sufficient evidence to demonstrate the existence of internal modulation and fast modulation in this event.

4. Summary and Discussion

In this study, we present conjugate observations of PsA and chorus waves based on the observation data from the ground-based ASI and the Arase satellite. The one-to-one correspondence between the PsA and chorus bursts is consistent with previous studies (S. Kasahara et al., 2018; Hosokawa et al., 2020), verifying the relation between PsA and chorus waves (Miyoshi, Saito, et al., 2015, 2020). The time profile of aurora intensity and its derivative signals show that more rapid modulations are embedded in the "on" time interval. Based on the wavelet analysis, the frequency spectrum of auroral intensity shows the main pulsation (~0.3 Hz), internal modulation (~4 Hz), and

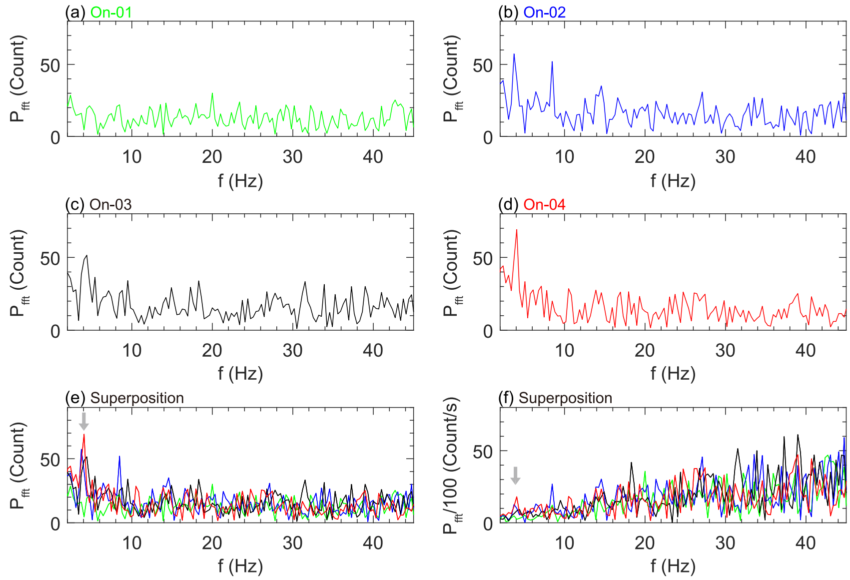

Figure 3. (a–d) Fourier spectral amplitude as a function of frequency for four "on" time intervals of 3 s from 13:08:05, 13:08:08.5, 13:08:12, and 13:08:16.5 UT on 30 March 2017, (e) the superposition result of panels (a–d), and (f) the superposition of the results based on the time derivative signals. The color indicates the number of the "on" time interval.

fast modulation (>10 Hz). The internal modulation and fast modulation are further verified by the analysis results obtained by the FFT. Moreover, the spatial distributions show that the internal modulation (∼4 Hz) and fast modulation (>10 Hz) are well structured within the auroral patches. Our study provides strong evidence for the coexistence of different three time-scale modulations within PsA.

Both wavelet analysis and FFT analysis reveal that more rapid modulations, that is, internal modulation and fast modulation, than the on-off main pulsation, are embedded in the "on" time of PsA. The internal modulation is caused by discrete rising-tone elements, which is consistent with previous models and observations (Gao et al., 2022; Hosokawa et al., 2020; Lu et al., 2021; Miyoshi, Saito, et al., 2015; Ozaki et al., 2018). Recent studies have shown that rising-tone elements are composed of a series of coherent subpackets/subelements, and the duration of coherent subpackets is in the range of ∼10–100 s msec (Tsurutani et al., 2009, 2020; R. Chen et al., 2022; H. Chen et al., 2023). Tsurutani et al. (2009) demonstrated that chorus subelements/subpackets were coherent, and Lakhina et al. (2010) theoretically verified that wave-particle interactions involving coherent chorus subelements/subpackets can cause the pitch angle scattering of electrons at a rate approximately three orders of magnitude faster than that predicted by the incoherent waves assumed by Kennel and Petschek (1966). Wave-particle interactions between coherent subelements/subpackets (∼10 s msec) and energetic electrons can cause rapid pitch angle transport of electrons by ∼5° within ∼10 m s (Bellan, 2013; Lakhina et al., 2010; Tsurutani et al., 2009). Therefore, the rapid (millisecond level) wave-particle interaction can efficiently cause the electron precipitation to rapidly modulate the PsA. In this study, the fast modulation of PsA and chorus subpackets (tens of milliseconds, corresponding to the >10 Hz modulation, not shown) are simultaneously detected, which implies the relationship predicted by theory and explains the rapid electron loss mechanism first known as microbursts (Anderson & Milton, 1964). The zoom-in figures show the potential correspondence between chorus subelements/subpackets and the fast modulation of PsA, especially in the interval with long-duration or large-intensity subelements/subpackets.

In addition, the frequency spectra (Figures 2b and 2d) and the spatial distributions (Figure 4) present that rapid modulation signals from ∼10 to 50 Hz clearly display continuous signals within the auroral patches, which is different from the results (peaks at 54 Hz) in Kataoka et al. (2012). This phenomenon can be explained. Chorus subelements/subpackets have a wide duration range even within one rising-tone element (e.g., from a few milliseconds to several tens milliseconds; Santolík et al., 2003, 2004, 2014; Tsurutani et al., 2009, 2020; R. Chen et al., 2022), and these subelements/subpackets are under rapid evolution within a short-time scale (H. Chen et al., 2023). Therefore, the rapid modulation caused by these chorus subelements/subpackets is nonperiodic as

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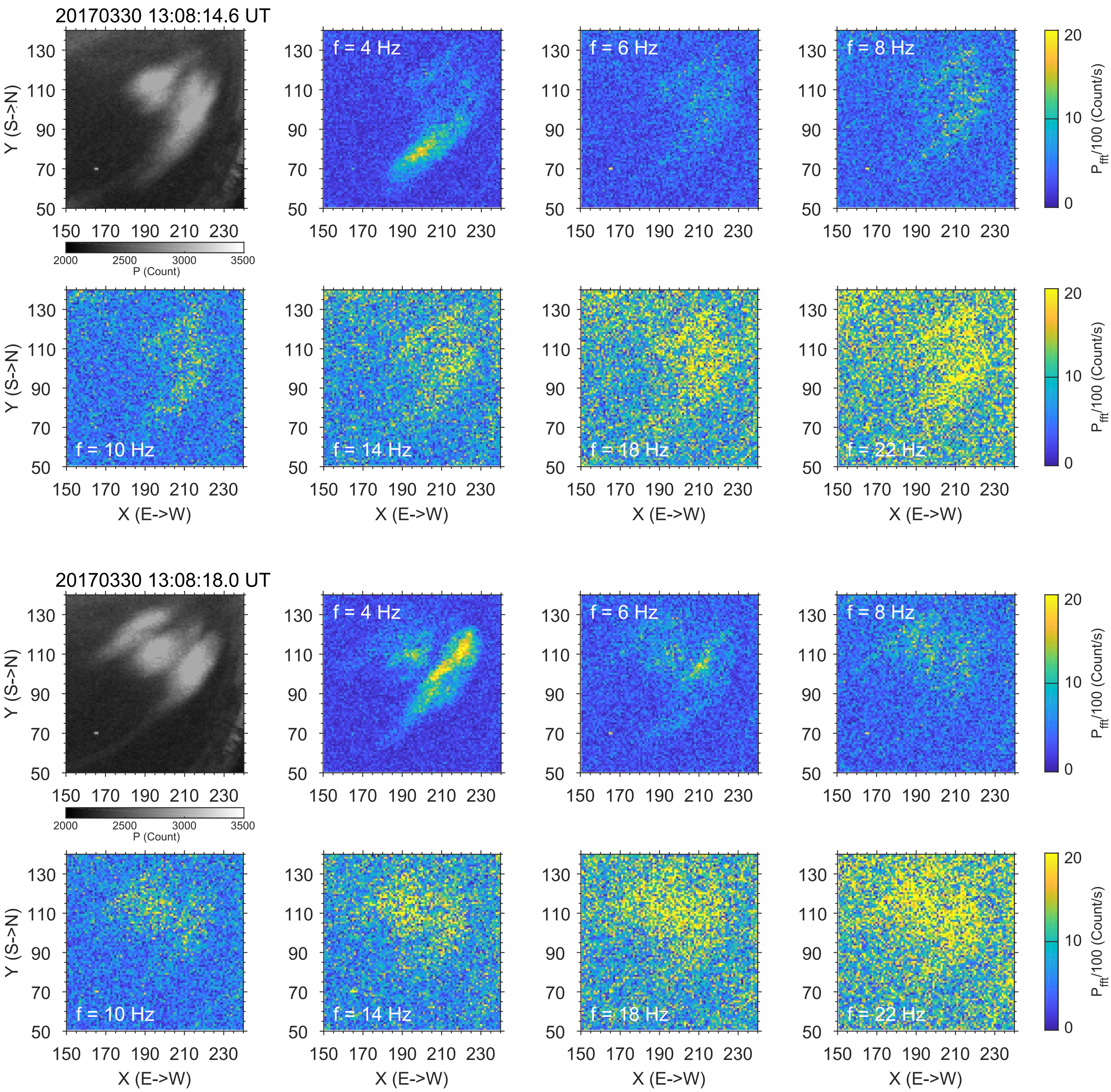

Figure 4. Spatial distribution of aurora patches and Fourier spectral amplitude at specific frequencies during the two "on" time intervals (the 3-s intervals from 13:08:12 UT and 13:08:16.5 UT, respectively).

suggested by Ozaki et al. (2018). Moreover, the precipitating electrons by wave-particle interaction are not mono-energetic (Miyoshi, Saito, et al., 2015, 2020; S. Kasahara et al., 2018) but have a wide-energy range, and therefore the broadband energy range of these electrons should lead to differences in their bounce periods, which can be considered as the origin of spatial non-uniformities of the rapid modulation.

Data Availability Statement

Science data of the ERG (Arase) satellite were obtained from the ERG Science Center operated by ISAS/JAXA and ISEE/Nagoya University (Miyoshi, Hori, et al., 2018). In this study, we used PWE/WFC-L2 electric field waveform data v01_01 (data is available at Y. Kasahara et al., 2020a) and electric field spectrum data v01_01 (data is available at Y. Kasahara et al., 2020b), MGF-L2 8 s spin-averaged data v03_04 (data is available at Matsuoka, Teramoto, Imajo, et al., 2018), (Matsuoka, Teramoto, Imajo, et al., 2018), and Orbit L2 v03 data (data is available at Miyoshi, Shinohara, & Jun, 2018). The data analysis is carried out using the Space Physics Environment Data Analysis System (SPEDAS; Angelopoulos et al., 2019) and "ERG-SC" plug-in tools. The detailed information about the TS05 magnetic field model is available at Tsyganenko and Sitnov (2005), and its input parameters can be obtained at Tsyganenko (2022).

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