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# Quasi-Periodic Emissions in Saturn's Magnetosphere and Their Effects on Electrons

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**Key Points:**

- Quasi-periodic (QP) whistler mode emissions were observed in Saturn's magnetosphere
- Each periodic modulation of QP emissions lasts for several minutes
- QP emissions can efficiently cause loss of electrons with energy from 10 to 60 keV

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## Abstract

Investigations into quasiperiodic (QP) whistler mode emissions within Saturn's magnetosphere have uncovered distinctive characteristics of these emissions, which display a nearly periodic rising tone structure in the wave spectrogram, characterized by modulation periods of several minutes. These QP emissions are predominantly observed at low L-shells around 5 and near the magnetic equator. Utilizing a quasi-linear analysis framework, we evaluate the effects of these waves on the dynamics of energetic electrons. Our analysis suggests that these QP emissions can efficiently cause the loss of electrons within the energy range from 10 to 60 keV over a timescale of tens of minutes. By incorporating these findings into Fokker-Planck simulations, we find minimal acceleration effects. This study is the first to examine QP emissions and their implications for energetic electron dynamics in Saturn's magnetosphere, highlighting their potentially significant contribution to the magnetospheric processes and dynamics.

## Plain Language Summary

This study investigates unique plasma wave patterns, called quasiperiodic (QP) whistler mode emissions, observed in Saturn's magnetospheric environment. These emissions display an interesting pattern of rising tone that occurs periodically, with each lasting several minutes. They are mainly observed in certain areas around Saturn, close to the magnetic equator. To understand how these emissions affect the behavior of energetic electrons in Saturn's magnetosphere, the study adopted the approach called quasi-linear analysis and performed the computer simulation. It is found that these QP emissions can efficiently cause the loss of electrons with energies between 10 and 60 keV within tens of minutes. However, these emissions did not significantly accelerate these particles. This study suggests that these emissions may play an important role in the overall processes and behavior of Saturn's magnetospheric environment.

## 1. Introduction

Quasi-periodic (QP) whistler mode waves, known as QP emissions, are electromagnetic emissions within the frequency range of 500 Hz to 10 kHz. Reports of QP emissions in the Earth's magnetosphere date back to Carson et al. (1965) and continue through recent studies like Hayosh et al. (2014) and Němec et al. (2013). These waves are characterized by a periodic modulation in wave intensity, typically ranging from tens of seconds to minutes. They may also exhibit a rising-tone structure in the frequency-time spectrogram. QP emissions are detected across a wide spatial range in the L-shell, from 1.1 to 7, predominantly on the dayside of the Earth's magnetosphere (Hayosh et al., 2014), with some occurrences on the nightside (Němec et al., 2018). Besides the intriguing characteristics, QP emissions also play an important role in transporting energy. Via wave-particle interaction, QP emissions could resonate with electrons and cause them to precipitate into the atmosphere. Some observations provide evidence to show the relationship between enhanced energetic electron precipitation and conjugate QP emissions (Hayosh et al., 2013; J. Li et al., 2021; Zhang et al., 2023). Theoretical investigations, as demonstrated by Demekhov and Trakhtengerts (1994), suggested that QP emissions can contribute to the formation of pulsating aurora.

The terrestrial magnetosphere is not the only domain for QP emissions, as they have also been detected in the outer planetary systems. Notably, when the Juno spacecraft traversed field lines connected to the outer boundary

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of Io within Jupiter's magnetosphere, its radio instrument identified QP emissions (Hospodarsky et al., 2020). Similar quasiperiodic phenomena, such as QP60 (quasiperiodic 60m) energetic ion conics, field-aligned energetic electron beams, auroral hiss, pulsating aurora, and magnetic field fluctuations, are widespread at Saturn (Carbary et al., 2016; Farrell et al., 2017; Mitchell et al., 2009, 2016; Palmaerts et al., 2016; Roussos et al., 2016; Teng et al., 2021). Two conference abstracts (Farrell et al., 2017; Leisner et al., 2010) have reported the presence of QP emissions in the magnetosphere of Saturn using data from the CASSINI spacecraft. However, to date, no comprehensive scientific paper has been published on this subject. This study represents the first detailed investigation into these QP emissions. Moreover, we quantify their impact on energetic electrons by calculating diffusion coefficients and perform Fokker-Planck simulations. Our findings indicate that these QP waves significantly contribute to energetic electron losses in Saturn's magnetosphere, while playing a negligible role in electron acceleration. Understanding the characteristics and effects of QP emissions on energetic electrons at Saturn could provide a clue to investigate the dynamical conditions within Saturn's magnetosphere. Furthermore, comparing the nature of QP emissions across different planetary space environments will enhance our comprehension of the wave generation mechanisms and the unique conditions in the extraterrestrial environments.

## 2. Wave Observations

We utilize data acquired from the Radio and Plasma Wave Science (RPWS) instrument (Gurnett et al., 2004, 2005) onboard the Cassini (Matson et al., 2002) to investigate plasma waves within Saturn's magnetosphere. The RPWS instrument provides an excellent advantage for the analysis of plasma waves. Specifically, we focus on data obtained via the Wideband Receiver (WBR), which measures a single electric field component utilizing the $E_x$ antenna. The WBR data were processed through two distinct filter bandwidths (10 and 80 kHz). In the 10 kHz mode, the WBR operates with a high sampling rate of 27,777 samples per second, facilitating the time resolution down to approximately tens of microseconds. This high-resolution capability allows for detailed examination of the fine structures within plasma waves.

We identify a typical quasi-periodic whistler wave event occurring from 07:10 UT to 11:40 UT, with a total duration of 4.5 hr. To conduct a detailed analysis, we concentrate on a specific segment of this event. Figure 1a presents the zoom-in view of quasi-periodic wave structure between 07:15:05 UT and 07:55:00 UT, illustrating the electric field power spectral density in a color-coded format. During this interval, the maximum wave spectral density of the QP emissions reaches to about $10^{-5}$ (mV/m)$^2$/Hz. The wave spectrogram displayed characteristics of quasi-periodicity, with intensity modulation at a period of around 5 min. The QP emissions also featured individual rising tone structures, each persisting for approximately 10 min. These structures were marked by a frequency chirping rate of around 1 Hz/s. The frequency range spans from 800 to 1,500 Hz, which, when normalized to the electron gyrofrequency, corresponds to a frequency ratio of 0.07 $f_{ce}$ to 0.16 $f_{ce}$. To analyze the spatial and temporal evolution of these waves, we considered their occurrence at distances ranging from 4.5 to 3.6 $R_s$ from Saturn, where $R_s$ denotes the radius of Saturn. The Magnetic Local Time (MLT) values for these occurrences were confined between 15.6 and 19.7 hr. The latitude of the event spanned from $-7.6°$ to $14.8°$, and the electron density varied between 10 and 100 cm$^{-3}$. To select specific moments for detailed analysis, we focused on times when the wave activity was most intense, as indicated by the peak spectral density and the clarity of the rising tone structures.

The WBR data from Cassini spacecraft does not provide concurrent magnetic field measurements. Due to the absence of all three components of the electric field data, polarization analysis for determining wave propagation parameters is not feasible. In this study, we adopt the assumption that QP whistler waves propagate parallel to the background magnetic field and apply the dispersion relation to infer magnetic field information from the available electric field data. To apply quasi-linear approach, we conducted an averaging process over the time interval shown in Figure 1a for each frequency bin. The resultant wave magnetic field power spectrum as a function of wave frequency is presented in Figure 1b, with the blue dots indicating the average measured values and the red line representing the fitting result. For the fitting process, we employed a Gaussian function with the base form $B_w^2(\omega) = A\exp\left(-\frac{(\omega-\omega_m)^2}{\delta\omega^2}\right)$, where $A$ is the normalization constant, and $B_w^2$ denotes the wave intensity. The fitting results provide wave parameters, including the wave frequency, bandwidth and the intensity, obtained from the Gaussian fitting of the QP magnetic field. Specifically, $\omega_m = 0.1419$, $\delta\omega = 0.0062$, $B_0 = 6.2$ pT. Consequently, the dominant wave power is concentrated around 0.14 $f_{ce}$.

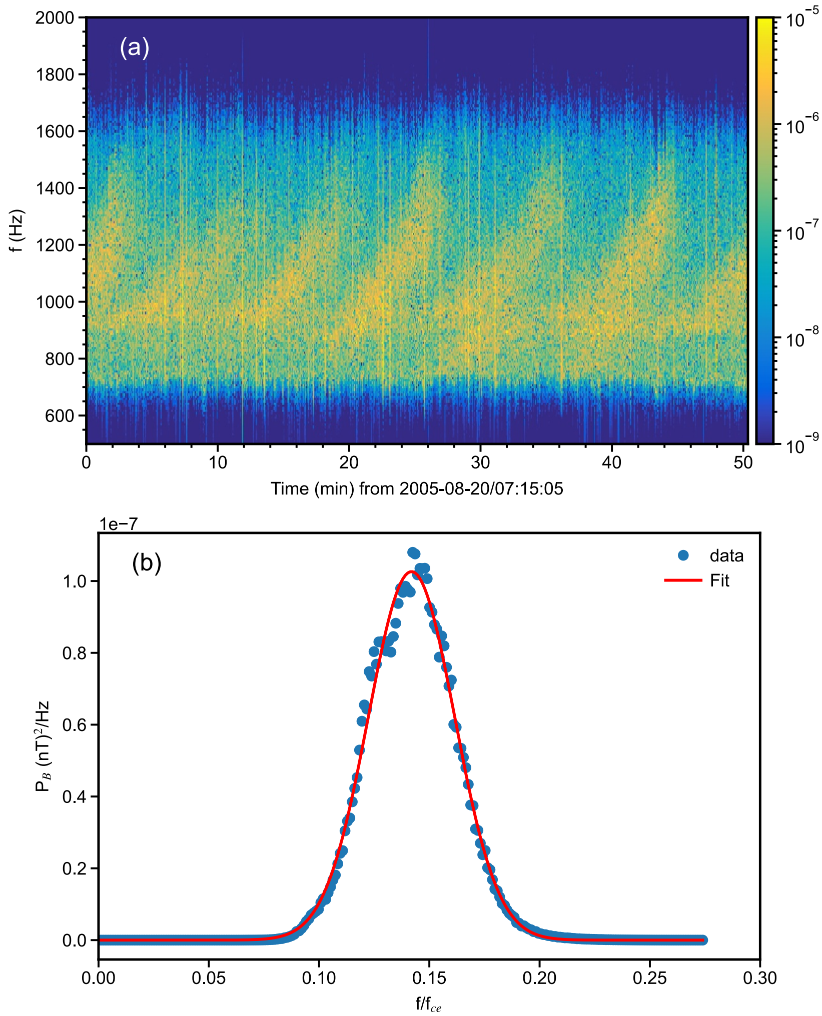


**Figure 1.** The typical quasi-periodic whistler mode waves observed by Cassini on DOY (Day of Year) 232, 2005. (a) The electric field dynamic power spectral density from RPWS data during the time interval between 07:15 UT and 07:55 UT. (b) The averaged wave power spectrogram in the time interval shown in panel (a), where blue dots represent averaged measurement values, and the red line represents the Gaussian fitted result.

## 3. Wave Effects

To evaluate the scattering effects of these QP emissions on energetic electrons, we utilize the Full Diffusion Code (FDC) (e.g., Ni et al., 2008; Orlova & Shprits, 2011; Shprits & Ni, 2009) to calculate the bounce-averaged diffusion coefficients using the wave information provided by Section 2. Then, we perform numerical simulation for the evolution process of electron phase space density using the Versatile Electron Radiation Belt (VERB) code (e.g., Shprits et al., 2008; Shprits et al., 2009). The FDC and VERB code were initially developed for the Earth's magnetosphere and later adapted to the planetary's magnetosphere (e.g., De Soria-Santacruz et al., 2017; Shprits et al., 2012). In this study, we use the VERB code adapted for Saturn's magnetosphere to solve the following 2D bounce-averaged Fokker-Planck equation at L shell equal to 4.2:

$$\frac{\partial f}{\partial t} = \frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\bigg|_p T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial f}{\partial \alpha_0}\bigg|_p + D_{p\alpha_0}\frac{\partial f}{\partial p}\bigg|_{\alpha_0}\right)$$
$$+\frac{1}{p^2}\frac{\partial}{\partial p^2}\bigg|_{\alpha_0} p^2\left(D_{pp}\frac{\partial f}{\partial p}\bigg|_{\alpha_0} + D_{p\alpha_0}\frac{\partial f}{\partial \alpha_0}\bigg|_p\right) - \frac{f}{\tau}, \tag{1}$$

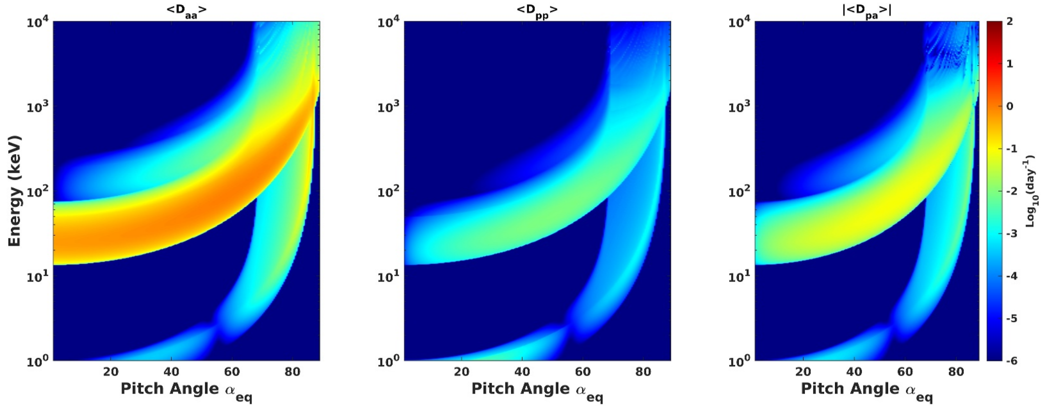


**Figure 2.** 2-D bounce-averaged diffusion coefficients in units of 1/day for interaction between QP wave and electrons at L of 4.2.

where $f$ is the electron phase space density, $\alpha_0$ is electron equatorial pitch-angle and $p$ is the relativistic momentum. $T(\alpha_0)$ is a function related to the particle's bounce time period. $\tau$ is the lifetime parameter accounting for losses of particles inside the loss cone due to collisions with atmospheric neutral atoms. $\tau$ is usually set as a quarter of a bounce period for electrons inside the loss cone and as infinity outside the loss-cone. $D_{\alpha_0\alpha_0}$ and $D_{pp}$ are the bounce-averaged pitch angle and momentum diffusion coefficients, respectively, and $D_{p\alpha_0}$ is the bounce-averaged mixed diffusion term calculated by FDC.

The diffusion coefficients are determined by the wave input provided by Section 2. The ambient magnetic field model used is a dipole field. The electron number density of 45 cm$^{-3}$ is used and the electron density does not change with latitude. The QP wave frequency spectrogram is adopted based on the fitting result of Figure 1b. The QP emissions are assumed to be field-aligned propagating and the wave normal angle ($\Psi$) distribution is a Gaussian distribution in $X = \tan\Psi$, with central wave normal $\Psi_m = 0^\circ$, wave normal width $\Psi_\omega = 1^\circ$, upper cutoff at $1^\circ$ and lower cutoff at $0^\circ$. Considering the waves are observed at near equatorial region, the wave latitudinal range is assumed to be from the magnetic equator to $10^\circ$ magnetic latitude.

Figure 2 shows the calculated bounce-averaged diffusion coefficients due to QP whistler waves at $L = 4.2$. The columns from the left to the right correspond to the bounce-averaged pitch angle, momentum, and mixed pitch angle-momentum diffusion coefficients ($<D_{\alpha\alpha}>$, $<D_{pp}>$ and $<D_{p\alpha}>$). Resonance numbers from $-1$ to 1 are calculated. Cyclotron resonance mainly influences electrons above 10 keV to 1 MeV. Landau resonance can influence electrons with lower energy at lower pitch angles, or higher energy at higher pitch angles.

To quantify the outcome of the competition between acceleration and loss, we perform 2D Fokker-Planck simulations using these diffusion coefficients. The Versatile Electron Radiation Belt (VERB) code was adapted to the Saturn's magnetosphere. The left panel in Figure 3 shows the initial condition as a function of energy and equatorial pitch-angle, which was interpolated from the average electron spectrograms measured by the Low Energy Magnetospheric Measurement System (LEMMS) onboard of Cassini with sin pitch-angle distribution (e.g., Hao et al., 2020). The color coded is the flux calculated from the initial phase space density (PSD). The middle panel in Figure 3 shows the simulation results after 10 days. To illustrate the dynamic change after 10 days, The right panel in Figure 3 shows the logarithmic difference between the simulation results and the initial condition. It can be seen that these QP emissions mainly cause loss of electrons with energy from 10 to 60 keV. The effect of acceleration is much slower than the effect of loss. Some minor acceleration happened for electrons with energy higher than 60 keV.

## 4. Discussion

We examined WBR data from the Browse folder on the PDS website and identified four events with similar wave characteristics, each exhibiting a periodic rising structure over several minutes. The RPWS Waveform Receiver (WFR) data can provide full-time coverage, helping us to identify a more comprehensive data set of QP emissions for our future work. Figures 4a and 4b show the spatial distribution of these waves within $L < 6$ on the meridian

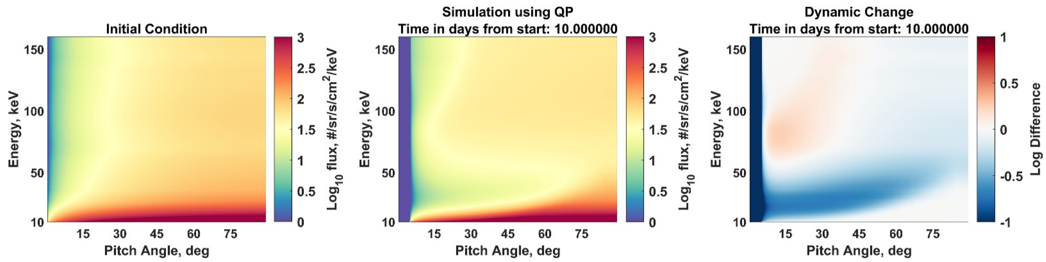


**Figure 3.** Evolution of phase space density as a function of pitch angle and energy. The color coded in the left and the middle panel is the flux calculated from the initial phase space density (PSD) and the simulation results. The left panel shows the initial condition. The panel in the middle shows the simulation results after 10 days. The panel on the right shows the logarithmic difference between the simulation results and the initial condition.

plane and equatorial plane. The trajectory of these events is indicated by the solid gray line, while the dashed lines represent the orbits of different moons of Saturn. These four wave events occur near Enceladus orbit in the L shell range between 3 and 5, and near the magnetic equatorial region. Particles ejected by Enceladus' geysers may become ionized, providing free energy for QP excitation. Previous conference reports also indicate QP wave events occur at higher L shell. A comprehensive analysis of the wave source region and their position relative to the Enceladus will be addressed in future studies.

The generation mechanism of QP emissions in the Earth's magnetosphere has been discussed extensively, but the source of the QP emissions remains debated. QP emissions exhibit distinct characteristics when compared to the typical whistler mode chorus waves, which are characterized by their discrete, repetitive, and rapid rising tone elements (W. Li et al., 2011; Santolík et al., 2004; Teng et al., 2019; Tsurutani & Smith, 1974). Based on the recently proposed "Trap-Release-Amplify" (TaRA) model (Tao et al., 2021; Teng et al., 2023; Wu et al., 2023), we analyzed the event and calculated the theoretical chirping rate with the following observed parameters: an electron density of 45 cm$^{-3}$, a magnetic field strength of 260 nT, and an L shell value of 4.2. Utilizing these parameters, we calculated the expected chirping rate for whistler mode chorus waves to be ~100 Hz/s, which is much greater than the observed chirping rate of around 1 Hz/s for the QP emissions under investigation. Therefore, the formation mechanism of the rising tone structure for QP emissions is different from the rising tone whistler mode chorus waves caused by nonlinear wave particle interactions.

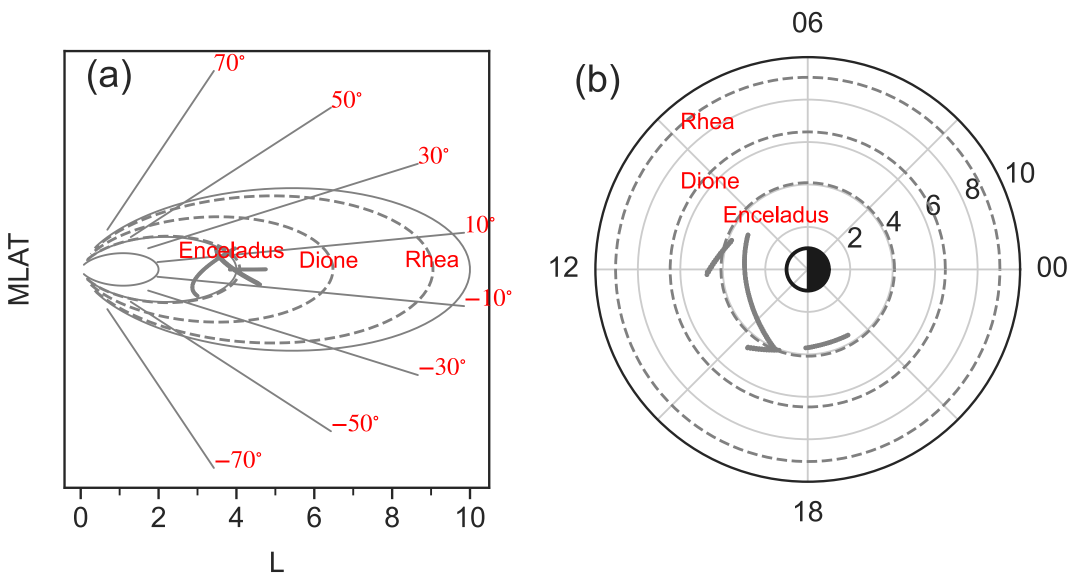


**Figure 4.** The spatial distribution of four QP whistler wave events in Mlat-L plane (a) and MLT-L plane (b). The dashed lines indicate different orbits of Saturn's satellites, from inside to outside, they are Enceladus, Dione, and Rhea.

As described by Němec et al. (2018) and references therein, there are two general hypotheses for the generation of the QP emissions. The first widely accepted theory is associated with the ULF modulation (Kimura, 1974; Tixier & Cornilleau-Wehrlin, 1986). ULF waves modulate the emission source region to control the whistler mode instability, thus to generate the periodic QP emission (Zhima et al., 2020). The generation of QP emissions correlates with periodic changes in energetic electron distribution functions (Titova et al., 2015), and periodic bursts of precipitating electrons (Hayosh et al., 2013; Němec et al., 2021). The second generation mechanism is related to flow cyclotron master. It assumes a wave bouncing along the magnetic field line, periodically passing through the source region, and the energetic electron distribution therein continuously replenished due to the azimuthal electron drift (Demekhov & Trakhtengerts, 1994). Throughout the entire duration of the QP wave activity, we observed no significant correlation between the ULF waves and the QP emissions. The azimuthally asymmetric and time-variable electrons might play a role in the wave generation. However, it is still uncertain whether this same mechanism accounts for the QP emissions observed both on Earth and Saturn.

## 5. Summary

In this study, we utilized measurements from the Cassini spacecraft to examine a characteristic rising-tone QP emission event that occurred in Saturn's magnetosphere on 20 August 2005. The emissions exhibited a series of rising structures over intervals ranging from 5 to 10 min with the electric field intensity peaking at approximately $10^{-5}$ $(\mathrm{mV/m})^2$/Hz. We calculate the quasi-linear bounce-averaged electron diffusion coefficients associated with the QP emissions and evaluate their effects on the precipitation of energetic electrons into Saturn's atmosphere. It is found that QP emissions are capable of efficiently facilitating the loss of electrons with energies ranging from 10 to 60 keV, within a timescale of tens of minutes. Although the electron pitch angle diffusion coefficients vary with the electron kinetic energy, pitch angle, and L-shell, our study highlights the importance of QP emissions in the loss of energetic electrons in Saturn's magnetosphere. In addition to the specific event analyzed, we identified another three QP emission events with rising tones. These events are found in the inner magnetosphere, around L $\approx$ 5, near the equatorial region, and persist for durations of approximately hours. The detection of QP emissions at Saturn suggests their presence in diverse plasma environments. Nevertheless, the exact generation mechanism of QP emissions remains to be investigated. Future research efforts should involve a statistical analysis of QP emissions using more comprehensive WFR survey data that covers all observational periods. The analysis should aim to characterize wave properties, investigate wave generation mechanisms, and compare the effects of these waves across different planetary environments.

## Data Availability Statement

The authors acknowledge the Cassini RPWS (https://pds-ppi.igpp.ucla.edu/data/CO-V_E_J_S_SS-RPWS-2-REFDR-WBRFULL-V1.0/) and MAG data (https://pds-ppi.igpp.ucla.edu/data/cassini-mag-cal/) from the Planetary Data System. The FDC and VERB code is available in this website: https://rbm.epss.ucla.edu/downloads/. The diffusion coefficient, simulation input and output are available at UCLA Dataverse (Drozdov, 2024).

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