Typical properties of rising and falling tone chorus waves

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[1] Chorus waves, which have received intense attention recently due to their significant role in radiation belt electron dynamics, frequently exhibit rising and falling tones. Lower-band chorus waves, observed using THEMIS wave burst data, are analyzed to obtain the typical properties of either class of chorus emissions. Our results show that rising tones are more likely to be quasi field-aligned, whereas falling tones are typically very oblique, close to the resonance cone. Furthermore, rising tones occur significantly more often than falling tones, and magnetic amplitudes of rising tones are generally much larger than those of falling tones. We also show the preferential regions of rising and falling tones dependent on MLT and magnetic latitude. Our new findings suggest that two separate mechanisms may be responsible for the generation and nonlinear evolution of rising and falling tone chorus. **Citation:** Li, W., R. M. Thorne, J. Bortnik, Y. Y. Shprits, Y. Nishimura, V. Angelopoulos, C. Chaston, O. Le Contel, and J. W. Bonnell (2011), Typical properties of rising and falling tone chorus waves, *Geophys. Res. Lett.*, *38*, L14103, doi:10.1029/2011GL047925.

1. Introduction

[2] Chorus emissions are among one of the most intense electromagnetic waves, that are generated naturally in the magnetosphere [e.g., *Burtis and Helliwell*, 1969; *Tsurutani and Smith*, 1977; *Hayakawa et al.*, 1990]. Chorus is typically observed over the frequency range 0.1–0.8 f_{ce}, where f_{ce} is the equatorial electron cyclotron frequency, and often exhibits two distinct frequency bands (lower-band and upper-band) with a minimum wave power near 0.5 f_{ce} [e.g., *Tsurutani and Smith*, 1974; *Koons and Roeder*, 1990]. Chorus usually consists of discrete elements with rising or falling tones, and sometimes short impulsive bursts [e.g., *Burtis and Helliwell*, 1969; *Burton and Holzer*, 1974; *Hayakawa et al.*, 1984; *Santolik et al.*, 2003a]. *Burtis and Helliwell* [1976] showed that rising tones were observed most commonly (77% of the samples), followed by falling tones (16%), constant frequency tones (12%) and hooks (6%). Summarizing previous studies of rising and falling tones, *Hayakawa et al.* [1990] concluded that on the nightside, different chorus structure types are observed, including falling tones, constant frequency tones and normal rising tones, whereas on the dayside, normal rising tones and impulsive (or burstlike) emissions are mainly observed. *Burtis and Helliwell* [1976], however, found that in the noon quadrant although rising tones showed above average occurrence (85%), other structure types, such as falling and constant tones, were also observed. The wave normal angles of typical rising tones have been shown to be less than 20° by *Burton and Holzer* [1974] and quoted as 5°–20° by *Hayakawa et al.* [1984]. *Cornilleau-Wehrlin et al.* [1976] studied one chorus event using OGO 5 search coil magnetometer data in the equatorial region near midnight and their preliminary results indicated that falling tones seem to have higher values of wave normal angle than rising tones and falling tones are weaker than rising tones. However, using near-midnight passes of OGO 5 data within 5° of the magnetic equator, *Goldstein and Tsurutani* [1984] showed that the majority of chorus waves including rising and falling tones propagate within 20° of the magnetic field. More recently, using wave observation from the Cluster spacecraft, *Santolik et al.* [2009] showed one case study of oblique falling tone chorus, close to the resonance cone.

[3] Despite these previous studies, no general agreement has been reached on the global MLT and L-shell distribution of rising and falling tones, or the wave normal distribution of each class of chorus. A systematic investigation of the characteristics of rising and falling tones is essential to further understand the generation mechanism and nonlinear evolution of rising and falling tones. Consequently, the objective of this study is to investigate the polarization properties and the preferential region of excitation for rising and falling tone lower-band chorus, using extensive waveform data from the THEMIS spacecraft.

2. THEMIS Waveform Data Analysis

[4] The THEMIS spacecraft, comprising of 5 probes in near-equatorial orbits with apogees above 10 R_E and perigees below 2 R_E [*Angelopoulos*, 2008], are well situated to measure chorus emissions in the near-equatorial magnetosphere. The Search-Coil Magnetometer (SCM) [*Le Contel et al.*, 2008; *Roux et al.*, 2008] measures low-frequency magnetic field fluctuations and waves in three orthogonal directions over a frequency range from 0.1 Hz to 4 kHz. The Electric Field Instrument (EFI) provides waveforms in three orthogonal directions from DC up to ~16 kHz [*Bonnell et al.*, 2008]. Over a 24-hour orbit, wave burst data are available simultaneously for both electric and magnetic fields for ~43 sec with a sampling frequency up to ~16 kHz. Several waveform data set are collected per day with one set lasting ~8 sec. The

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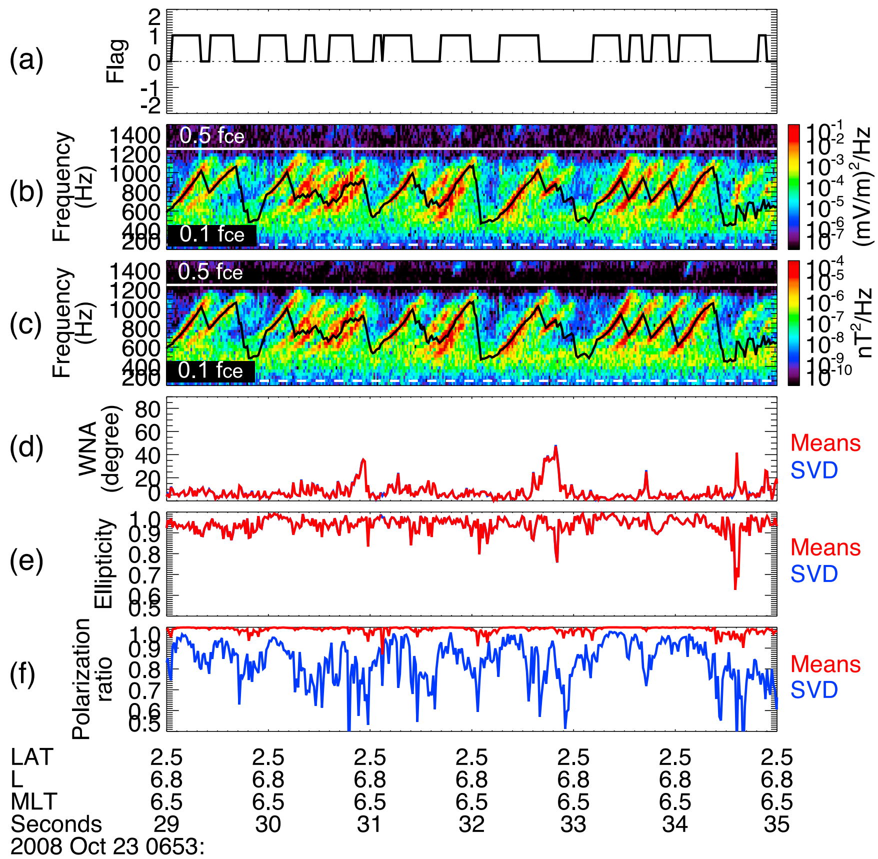

Figure 1. A rising tone event observed from 06:53:29 to 06:53:35 UT on 23 October 2008 by THEMIS D. (a) Flag indicating rising (+1) or falling tones (−1). (b and c) Wave spectral density in electric and magnetic fields respectively. (d–f) Wave normal angle, ellipticity, and polarization ratio of waves obtained using the method following *Bortnik et al.* [2007] (red) and *Santolík et al.* [2003b] (blue). The white solid line in Figures 1b and 1c indicates 0.5 f_{ce}, and the black solid line in Figure 1c represents the frequency at which wave magnetic field spectral density maximized over the frequency of 0.1–0.5 f_{ce}.

Flux-Gate Magnetometer (FGM) [*Auster et al.*, 2008] measures background magnetic fields and their low frequency fluctuations (up to 64 Hz). In this study, FGM data (“fgl”) are utilized to evaluate local electron cyclotron frequencies in order to scale the chorus frequencies.

[5] Detailed wave polarization properties of lower-band chorus waves were obtained by analyzing three components of the wave magnetic field (converted into the magnetic field-aligned coordinates after band-pass filtering over 0.1–0.5 f_{ce}) from the wave burst data using the method of *Bortnik et al.* [2007] (essentially an implementation of *Means* [1972]). Since we used only magnetic field components, there is a 180° ambiguity in the wave normal determination, and we converted all wave normal directions into values less than 90°. These obtained wave polarization properties have a resolution of ~0.016 sec in time. The polarization ratio (R_p) indicates the ratio of polarized power to total power [*Bortnik et al.*, 2007]. Ellipticity is defined as the ratio of the minor axis to the major axis in the plane perpendicular to the wave vector with positive (negative) value corresponding to right-hand (left-hand) rotation about the wave vector. For waves with sufficiently large values of the polarization ratio ($R_p > 0.9$), the wave polarization method of *Bortnik et al.* [2007] provides reliable polarization parameters. Since chorus waves are normally highly polarized, in our analysis we only recorded wave polarization parameters for waves with $R_p > 0.9$ over the corresponding lower-band chorus wave frequency (0.1–0.5 f_{ce}).

3. Observational Results

[6] Figure 1 shows a typical rising tone event observed by THEMIS D on 23 October 2008. Figures 1b–1f show wave characteristics including the wave spectral density in the electric and magnetic fields, wave normal angle, ellipticity, and polarization ratio. We also compared the wave polarization properties obtained by the method of *Bortnik et al.* [2007] to those by the singular value decomposition (SVD) method [*Santolík et al.*, 2003b]. The comparison result shows almost identical values for wave normal angle (Figure 1d) and ellipticity (Figure 1e). The difference in polarization ratio (Figure 1f) is caused by its different definition, and the two values nevertheless show a similar trend. A flag is used to identify whether the chorus emissions are rising or falling tones (Figure 1a). The flag is equal to 1 for rising tone chorus, and −1 for falling tone chorus, and 0 for emissions that are ambiguous. At each recording time, the frequency at which the magnetic field spectral density maximized (over the lower-band chorus frequency range of 0.1–0.5 f_{ce}) was recorded after smoothing over the adjacent three points and is shown with the black solid line in Figure 1c. Subsequently, the sweep rate at each point was

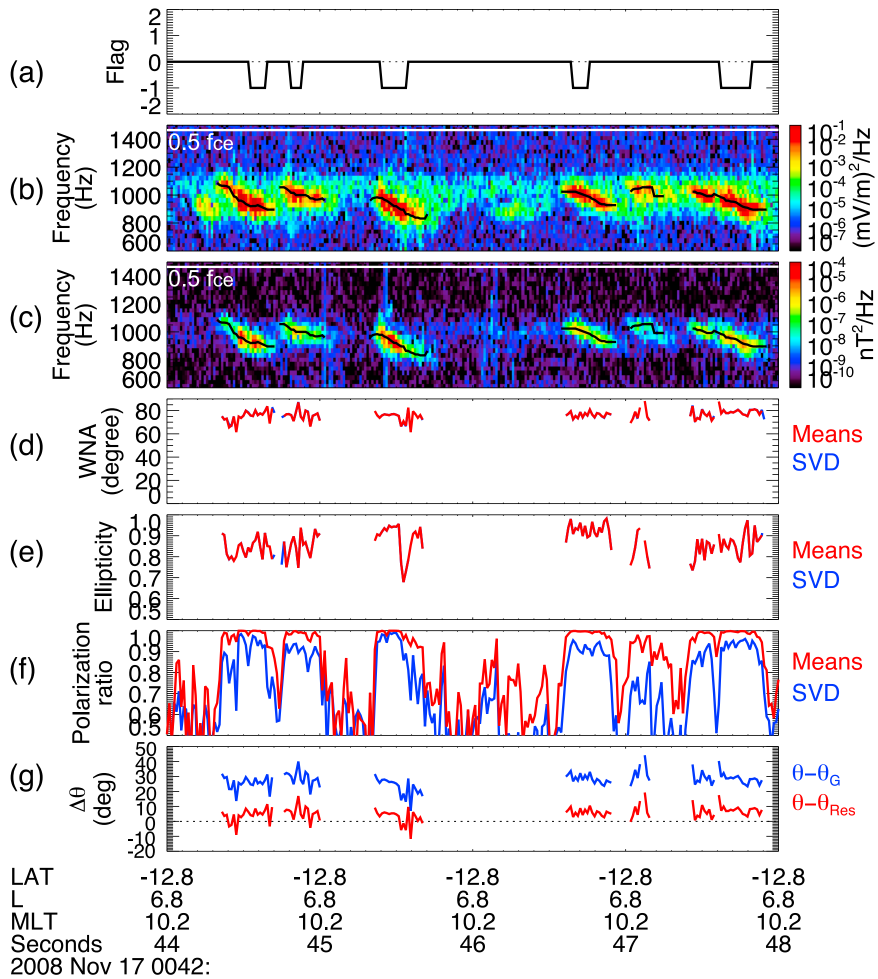

Figure 2. (a–f) Similar format to Figure 1 but for a falling tone event observed from 00:42:44 to 00:42:48 UT on 17 November 2008 by THEMIS E. (g) The difference between the wave normal angle and the Gendrin angle ($\theta-\theta_G$) (blue) and the difference between the wave normal angle and the resonance cone ($\theta-\theta_{Res}$) (red).

calculated using the adjacent 7 points. If a positive (negative) sweep rate is maintained for longer than ~0.1 sec, the flag is set to 1 (−1); otherwise it is equal to 0. The flag shown in Figure 1a identified the rising tone elements remarkably well. The exhibited rising tones are strong with wave magnetic field spectral density up to ~10^{-4} nT^2/Hz; the wave normal angle is mostly quasi field-aligned (<15°); and the ellipticity is close to 1.

[7] Figure 2 shows a typical falling tone event observed by THEMIS E on 17 November 2008, in a similar format to Figure 1. The hodograms of the wave magnetic components at ~00:42:44.5 UT are shown in Figure S1 in the auxiliary material.[1] Interestingly, the polarization properties of the falling tones are very different from those of the rising tones. These falling tones have larger wave normal angles (>~70°) and weaker wave magnetic field spectral density. The wave normal angles of falling tones tend to be larger than the Gendrin angle and are close to the resonance cone (Figure 2g) (please see the definition of the Gendrin angle and resonance cone by *Goldstein and Tsurutani* [1984]). Here the Gendrin angle and the resonance cone were calculated for the wave frequency where the wave magnetic spectral density peaked (black line in Figure 2c). These very oblique falling tones are also nearly circularly polarized with an ellipticity of ~0.9.

[8] To comprehensively investigate typical features of rising and falling tone chorus, we systematically surveyed all events observed on the three inner THEMIS spacecraft (A, D, and E), when wave burst data were available, between 1 June 2008 and 1 April 2011 (the event list of rising and falling tones is given in Tables S1 and S2 in the auxiliary material). Here we recorded the wave polarization parameters only when the flag was equal to either −1 or 1 and divided the data set into rising and falling tones separately. Finally, we filtered the events further by visual inspection to include only clear rising and falling tones. At each recording time, we also calculated magnetic wave amplitude for lower-band chorus by integrating the wave magnetic field spectral density over the frequency range of 0.1–0.5 f_{ce}. Figure 3 shows the occurrence rate of chorus magnetic wave amplitude and wave normal angle for rising (Figure 3, top) and falling tones (Figure 3, bottom), respectively. The depicted occurrence rate, the ratio of the number of samples in each specified wave characteristic to the total number of samples of rising (or falling) tones, is

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047925.

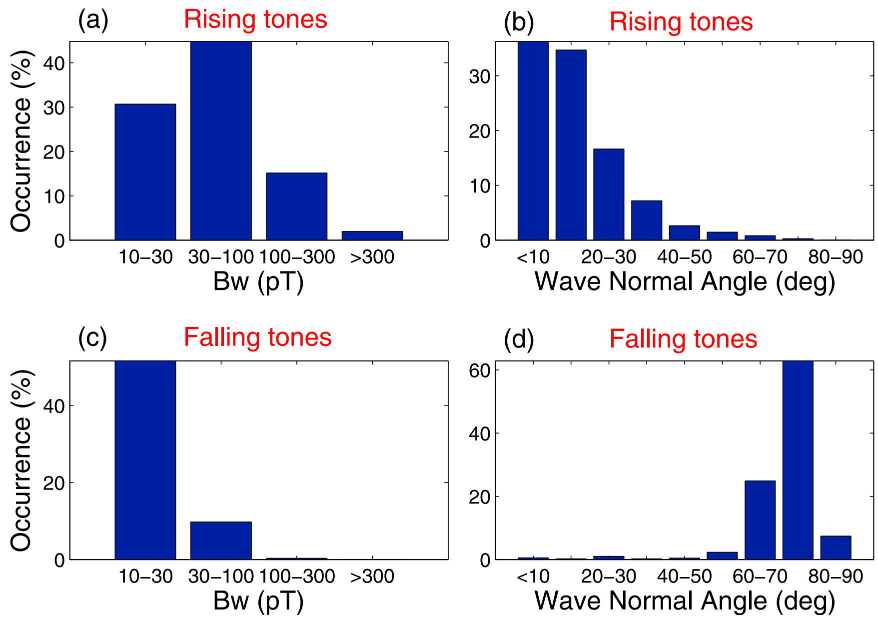

Figure 3. (a and b) The occurrence rate of chorus wave amplitude and wave normal angle for rising tones. (c and d) The same parameters for falling tones.

calculated for rising and falling tones separately. The occurrence of rising tone wave amplitude typically peaks for 30–100 pT (~45%) with ~2% occurrence for extremely large amplitude (>300 pT). However, magnetic wave amplitudes of falling tones are much weaker, typically less than 30 pT. Rising tones are typically quasi field-aligned, whereas falling tones are very oblique, with wave normal angles typically larger than 60°. In summary, a comparison of rising and falling tones clearly shows that the magnetic wave amplitude is stronger and the wave normal angle is smaller for rising tones than for falling tones.

[9] Figure 4 provides further information on the spatial distribution of rising and falling tones. Figures 4a and 4d show the total number of samples distributed in the L-MLT (0.5 L × 1 MLT) and L-MLAT (1 L × 5°) domains respectively, collected from all available wave burst data, regardless of the presence of chorus, between 1 June 2008 and 1 April 2011. Due to the near-equatorial orbits of the THEMIS spacecraft, the majority of the waveform data were collected from magnetic latitudes less than 20°. Figures 4b and 4c indicate that falling tones are confined between midnight and noon, whereas rising tones extend further into the afternoon sector. All of the rising and falling tone events were divided into nightside (18-06 MLT) and dayside (06-18 MLT) and are shown in Figures 4e and 4f. Both rising and falling tones are confined near the equator on the nightside (blue dots), but extend to the higher latitudes on the dayside (red dots). Figure 4g shows the total number of samples at various levels of magnetic latitude for the nightside and dayside. The corresponding occurrence rates at various magnetic latitudes for rising and falling tones are shown in Figures 4h and 4i, respectively. The occurrence rates are given as ratios between the number of samples of rising (or falling) tones and the total number of samples normalized at each magnetic latitude bin (calculated separately for the nightside and dayside). In general, the occurrence rate of rising tones is much higher than that of falling tones both on the dayside and nightside. For rising tones, the occurrence rate is higher at lower latitudes on the nightside, while little latitudinal dependence is found on the dayside. In contrast, falling tones have a small occurrence rate on the nightside, while on the dayside the largest occurrence rate is observed at higher latitudes (>10°). However, the small occurrence of falling tones on the nightside is inconsistent with the finding by *Tsurutani and Smith* [1974], who observed falling tones commonly occurring in the postmidnight sector. The occurrence of nightside chorus in the present study may be underestimated compared to the dayside chorus, since these occurrence rates were calculated by merging L-shells between 5 and 10 but nightside chorus is more confined to the lower *L*-shells (<8) [e.g., *Burtis and Helliwell*, 1976; *Tsurutani and Smith*, 1977; *Li et al.*, 2009]. Our observed latitudinal dependence of falling tones is consistent with *Burtis and Helliwell* [1976], who showed that very few chorus samples in the equatorial region included any falling tones, whereas just off the equator there was an increase in the occurrence of falling tones. Using the extensive THEMIS data set, our results clearly demonstrate a pronounced difference between rising and falling tones in the wave normal distribution, magnetic amplitudes, and the preferential locations.

4. Summary and Discussion

[10] Extensive waveform data for lower-band chorus from THEMIS have been utilized to investigate typical properties of rising and falling tones. The principal results of the present study can be summarized as follows:

[11] 1. Rising tones are typically quasi field-aligned and their magnetic wave amplitudes are generally large (30–100 pT). In sharp contrast, falling tones are typically very oblique, close to the resonance cone, and their magnetic wave amplitudes are generally much weaker (<30 pT).

[12] 2. The occurrence rate of rising tones is generally higher than that of falling tones both on the nightside and the dayside. Falling tones are observed from midnight to noon, and rising tones extend further into afternoon.

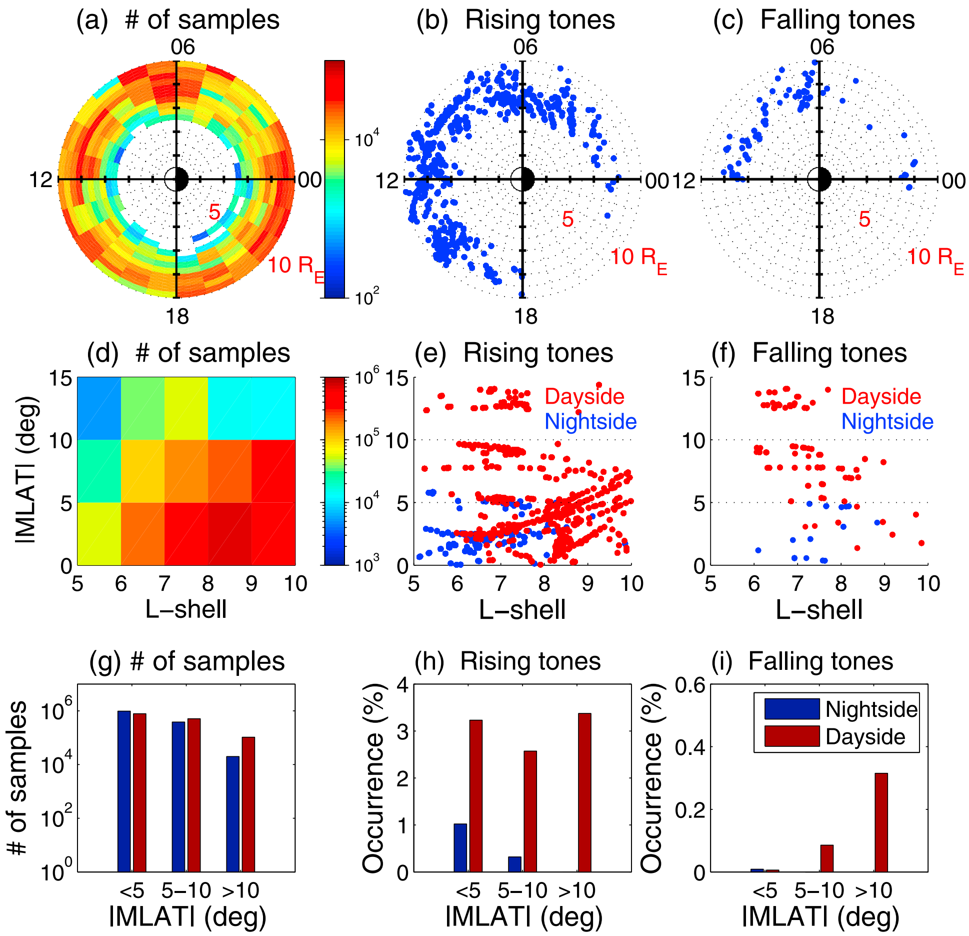

Figure 4. (a) Total number of samples, (b) distribution of rising tones, and (c) falling tones in the L-MLT domain between 5 and 10 R_E. (d) Total number of samples, (e) distribution of rising tones, and (f) falling tones in the L-MLAT domain on the nightside (blue) and dayside (red). (g) Total number of samples, (h) occurrence rate of rising tones, and (i) falling tones as a function of magnetic latitude (|MLAT|) on the nightside (blue) and dayside (red) respectively.

[13] 3. For rising tones, the occurrence rate is higher at lower latitude on the nightside, while little latitudinal dependence is shown on the dayside. For falling tones, a low occurrence rate is observed on the nightside, and the largest occurrence rate is observed on the dayside at higher latitude (>10°).

[14] Our finding of oblique falling tones is consistent with previous studies by *Cornilleau-Wehrlin et al.* [1976] and *Santolík et al.* [2009]. However, it is contrary to *Tsurutani and Smith* [1974] and *Goldstein and Tsurutani* [1984], who showed that both rising and falling tones are found to be quasi field-aligned near the equatorial midnight sector. This inconsistency may be caused by the limited statistics or the possibility that chorus properties are different in different periods or regions. Nevertheless, our findings on the typical properties of rising and falling tones show consistent features based on the waveform data from three THEMIS spacecraft over the past three years.

[15] The nonlinear generation mechanism of large amplitude discrete chorus emissions has received intense attention and is currently a subject of active research [e.g., *Nunn et al.*, 1997, 2009; *Katoh and Omura*, 2007; *Omura et al.*, 2008; *Macúšová et al.*, 2010; *Cully et al.*, 2011]. Previous theoretical models of chorus generation have typically assumed that the waves propagate parallel to the geomagnetic field, and have successfully reproduced rising tone elements [e.g., *Nunn et al.*, 1997, 2009; *Katoh and Omura*, 2007; *Omura et al.*, 2008]. Very few studies, however, are able to produce realistic falling tones [e.g., *Nunn et al.*, 2009; *Lampe et al.*, 2010]. Our results on the wave normal distribution of rising tones are roughly consistent with the assumption of field-aligned propagation in the nonlinear modeling of rising tones [*Omura et al.*, 2008], but clearly show that falling tones are very oblique. These new findings suggest that two separate excitation mechanisms may be responsible for the generation and nonlinear evolution of rising and falling tone chorus. After the generation of chorus waves, wave propagation effects may play a further role in the evolution of rising and falling tone chorus.

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