Comparison between theory and observation of the frequency sweep rates of equatorial rising tone chorus

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[1] Theoretical predictions for chorus frequency sweep rates by Helliwell and Trakhtengerts are compared with observations from the THEMIS satellites and a previously published dataset from the Cluster satellites. We first extend the theories to use a general magnetic field model to include the effects of magnetic local time and geomagnetic activity, and then show that both theories give the same dependence of the frequency sweep rate on background plasma parameters. The theoretical scaling of frequency sweep rates are shown to agree very well with observations. We demonstrate that for a given equatorial magnetic field strength, nightside and dawnside chorus waves have higher frequency sweep rates because of the stretching of the magnetic field, while dayside chorus waves have lower frequency sweep rates because of the compression of the field. Increasing geomagnetic activity will enhance the asymmetry by increasing the day-night asymmetry of the background field. The results are important for understanding the generation mechanism of chorus waves. **Citation:** Tao, X., W. Li, J. Bortnik, R. M. Thorne, and V. Angelopoulos (2012), Comparison between theory and observation of the frequency sweep rates of equatorial rising tone chorus, *Geophys. Res. Lett.*, *39*, L08106, doi:10.1029/2012GL051413.

1. Introduction

[2] Chorus waves are important electromagnetic emissions in the inner magnetosphere of Earth, due to their controlling effects on the radiation belts, and generation of the diffuse aurora, the pulsating aurora, and plasmaspheric hiss [*Horne et al.*, 2005; *Bortnik et al.*, 2008, 2009; *Nishimura et al.*, 2010; *Thorne et al.*, 2010]. Chorus generally consists of discrete rising tones or falling tones, which frequently exhibit a power minimum around half the equatorial electron gyrofrequency dividing the chorus waves into a lower band and an upper band [*Tsurutani and Smith*, 1974; *Burtis and Helliwell*, 1976].

[3] As an important part of understanding its generation mechanism, various theories have been suggested to explain the frequency variation of chorus. *Helliwell* [1967] discussed a phenomenological theory for discrete Very Low Frequency emissions where the change of wave frequency f is caused by the inhomogeneity of the background field. *Trakhtengerts* [1995] and *Trakhtengerts et al.* [2004] considered the magnetosphere as a cyclotron maser (MCM) and proposed that chorus waves are generated in the backward wave oscillator (BWO) regime of the MCM. Both *Helliwell* [1967] and *Trakhtengerts* [1995] qualitatively estimated the frequency sweep rate $\Gamma \equiv \partial f/\partial t$ as a function of background plasma parameters such as the electron density and the dipole magnetic field. On the other hand, a recent numerical simulation and theory by *Omura et al.* [2008] suggested that the generation of chorus is caused by the resonant current formed by the electromagnetic phase space hole and the frequency sweep rate of chorus is directly related to the wave amplitude.

[4] Recently, these theoretical frequency sweep rates have begun to be tested using satellite observations. For example, *Macúsová et al.* [2010] used observations from the Cluster satellites and demonstrated the dependence of Γ on electron density n_e as $\Gamma \propto n_e^b$ with $b = -0.44 \pm 0.18$ or -0.46 ± 0.17, where Γ is in kHz/s and n_e is in cm^{-3}, depending on the slightly different input parameters used. They concluded that the scaling index b is close to the theoretical value of $-2/3$ from the BWO model by *Trakhtengerts* [1995] within the estimated experimental error. Another verification of the BWO model has been done by *Titova et al.* [2003] using MAGION 5 satellite data. *Cully et al.* [2011], on the other hand, used observations by THEMIS and demonstrated the relationship between Γ and wave amplitude predicted by *Omura et al.* [2008].

[5] Here we investigate the qualitative dependence of Γ only on various background plasma parameters including n_e, the equatorial radial distance, magnetic local time (MLT), and geomagnetic activity. Hence we will only compare theories of *Helliwell* [1967] and *Trakhtengerts* [1995] with observations, and we attempt no affirmation or repudiation of the theory of *Omura et al.* [2008]. To include the effects of MLT and geomagnetic activity, we first extend the theories of *Helliwell* [1967] and *Trakhtengerts* [1995] to use the T89 magnetic field model [*Tsyganenko*, 1989]. Subsequently we directly compare theoretical frequency sweep rates with observations from THEMIS [*Angelopoulos*, 2008] and the results of *Macúsová et al.* [2010].

2. Theory

[6] *Helliwell* [1967] and *Trakhtengerts* [1995] estimated the frequency sweep rate in a dipole magnetic field, but it is straightforward to extend their results to a more general field where the magnetic field near the equatorial plane can be represented as $B(s) = B_0(1 + \beta s^2)$, where $B(s)$ is the magnetic field at a distance s along the field line from the equatorial plane. For a dipole field, the inhomogeneity parameter $\beta = 4.5/r_0^2$, where r_0 is the equatorial radial distance of the field line. To incorporate the effects of MLT and

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geomagnetic activity characterized by the Kp index, we use the T89 magnetic field model in this paper and obtain β by fitting $B(s)$ near the equatorial plane as a function of s^2 for a given MLT and Kp.

[7] In the work by *Helliwell* [1967], the change of frequency is mainly caused by the inhomogeneity of the background field. For the general parabolic field, it is easier to use equation (14) of *Helliwell* [1967] to calculate the theoretical frequency sweep rate $\Gamma_{\rm H}$ for a parallel propagating wave as

$$\Gamma_{\rm H} = \frac{{\rm d}f_{ce}}{{\rm d}s}\frac{v_g}{1+v_g/v_\parallel}\frac{3f/f_{ce}}{1+2f/f_{ce}}\left[1+\frac{1-f/f_{ce}}{3}\tan^2\alpha\right], \quad (1)$$

where f_{ce} is the local electron gyrofrequency at s, v_g is the wave group velocity, $v_\parallel$ is the corresponding parallel resonant velocity, and α is the pitch angle. Here and below the refractive index is assumed to be larger than one. We use $\alpha = 30°$, the working value derived by *Helliwell* [1967] to maximize the transverse current assuming an isotropic distribution and that all resonant electrons are phase-bunched. The ${\rm d}f_{ce}/{\rm d}s$ in equation (1) is evaluated at a characteristic location $l_{\rm H}$ where the relative phase between the unperturbed electron velocity and the magnetic field of the wave has changed by π. For the general parabolic field given above $l_{\rm H} = (v_\parallel/\beta f_{ce0})^{1/3}$ following *Helliwell* [1967] with f_{ce0} the equatorial electron cyclotron frequency. In our evaluation of $\Gamma_{\rm H}$ below, we will simply use a representative frequency $f = 0.3\ f_{ce0}$ for lower-band risers which generally extends from $0.25\ f_{ce0}$ to $0.4\ f_{ce0}$ [*Burtis and Helliwell*, 1976]. Correspondingly, we approximate $v_g/(1 + v_g/v_\parallel)$ by $0.4v_\parallel$, since $v_g/v_\parallel = 2f/f_{ce}$ for a parallel propagating wave. Note that with a generalized parabolic field with inhomogeneity parameter β, $\Gamma_{\rm H}$ is now dependent on MLT and Kp through β.

[8] The BWO model by *Trakhtengerts* [1995] and *Trakhtengerts et al.* [2004] assumes a discontinuity in the electron distribution function and gives the frequency sweep rate $\Gamma_{\rm BWO} \approx 0.5\gamma_{\rm BWO}^2$, with the growth rate of the absolute BWO instability $\gamma_{\rm BWO} = (\pi/2T_0)(Q - Q^{-2/3})$ [*Macúsová et al.*, 2010]. Here Q is a dimensionless parameter related to discontinuity size and cannot be determined from observation. We will simply use $Q \approx 2$ estimated by *Trakhtengerts et al.* [2004] in this work. The characteristic modulation period of the BWO model $T_0 = l_{\rm BWO}(1/v_\parallel + 1/v_g)$, and the characteristic length $l_{\rm BWO} = 1.76(3\pi/2k\beta)^{1/3}$ with k the wave number, following *Trakhtengerts* [1995] and *Trakhtengerts et al.* [2004].

[9] It is interesting to compare the frequency sweep rates of *Helliwell* [1967] and *Trakhtengerts* [1995]. Using the property that the resonance wave number $k = 2\pi|f_{ce} - f|/v_\parallel$, we can show that $\Gamma_{\rm H} \approx 0.48 f_{ce0}^{\frac{2}{3}}\beta^{\frac{2}{3}}v_\parallel^{\frac{4}{3}}$ and $\Gamma_{\rm BWO} \approx 0.12 f_{ce0}^{\frac{2}{3}}\beta^{\frac{2}{3}}v_\parallel^{\frac{4}{3}}$ for $f = 0.3f_{ce0}$. Here f_{ce0} and β depend on r_0, MLT, and Kp. The resonant velocity $v_\parallel = c(f_{ce} - f)^{3/2}/f_{pe}f^{1/2}$ for a parallel propagating wave, where $f_{pe} \propto n_e^{1/2}$ is the plasma frequency. Thus both theories give the same dependence of Γ on the background plasma parameters, and $\Gamma_{\rm BWO}$ is smaller than $\Gamma_{\rm H}$ by roughly a factor of 4, given that we use $\alpha = 30°$ in $\Gamma_{\rm H}$ and $Q = 2$ in $\Gamma_{\rm BWO}$. Since we are mainly interested in the qualitative dependence of the frequency sweep rate on background plasma parameters, we will only show calculations using $\Gamma_{\rm H}$ below.

3. Comparison Between Theory and Observation

[10] We use magnetic field waveform data measured by the Search-Coil Magnetometer (SCM) [*Le Contel et al.*, 2008] from the three inner THEMIS satellites [*Angelopoulos*, 2008] during the period of 2008/06/01 to 2011/06/01. The Flux-Gate Magnetometer (FGM) [*Auster et al.*, 2008] measures the background magnetic field, which is utilized in this study to calculate local electron gyrofrequencies. The standard deviation of the background magnetic field measurement is insignificant ($\sim$0.1 nT). The total plasma density is inferred from the spacecraft potential and the electron thermal speed following the method of *Li et al.* [2010], which generally has an uncertainty within a factor of two [*Li et al.*, 2010]. We select time intervals where chorus packets and frequency sweep rates can be clearly identified visually. Each time interval lasts about 6 to 14 seconds, and only lower band risers are considered in this work. We also limit $|\lambda_M| \le 3°$, with λ_M the magnetic latitude, to minimize the effects of wave propagation on Γ. The wave spectrum of one selected time interval is shown in Figure 1 (bottom). In total, the database includes 149 different time intervals and 1106 chorus packets within them. Our selected chorus waves are mainly distributed on the dayside and dawnside, with r_0 between 5 and 9, as shown in Figure 1. Most events occur when the electron densities are less than 16 cm^{-3}, and those having very high n_e occur in plasmaspheric plumes. The maximum and the median Kp index for these time intervals are about 4 and 2 respectively, thus all selected events occur in a moderately disturbed period.

[11] To calculate the frequency sweep rate of observed chorus packets, we manually select a few points along each packet on the time-frequency spectrogram and perform a linear fitting of f to time t to obtain the slope $\Gamma_{\rm OB}$, as demonstrated by one packet in Figure 1 (bottom). The distribution of $\Gamma_{\rm OB}$ with respect to the equatorial radial distance r_0 is shown in Figure 2 by black dots. The theoretical frequency sweep rates $\Gamma_{\rm H}$ (light blue dots) in Figure 2 are calculated by equation (1) using the T89 magnetic field model and n_e, MLT, Kp index, and r_0 from observation. For a given value of α in equation (1), the main uncertainty of calculating $\Gamma_{\rm H}$ is from the use of T89 magnetic field model and the measurement error of the electron density. While we do not have an estimate of the uncertainty associated with T89 model, the uncertainty of $\Gamma_{\rm H}$ due to the error of n_e can be estimated as $\delta\Gamma_{\rm H}/\Gamma_{\rm H} = -(2/3)\delta n_e/n_e$. Because $\delta n_e/n_e$ has a value ranging from -0.5 to 1 [*Li et al.*, 2010], the value of $\delta\Gamma_{\rm H}/\Gamma_{\rm H}$ is estimated to be from -0.67 to 0.33. Using a better magnetic field model or multi-point measurement of the background magnetic field [e.g., *Kozelov et al.*, 2008] might further improve the accuracy of $\Gamma_{\rm H}$. The black line in Figure 2 given by $y = 17719\ r_0^{-5.08}$ is a power-law fitting to $\Gamma_{\rm OB}$ and the light blue line is $y = 8640\ r_0^{-5.13}$, the power-law fitting to $\Gamma_{\rm H}$. Dashed lines are the corresponding standard deviation of the results from the fitting function. It could be seen that in general $\Gamma_{\rm H}$ is smaller than $\Gamma_{\rm OB}$ by about a factor of two, while the theoretical scaling of the frequency sweep rate with respect to r_0 is in good agreement with observation. It should be noted, however, the value of

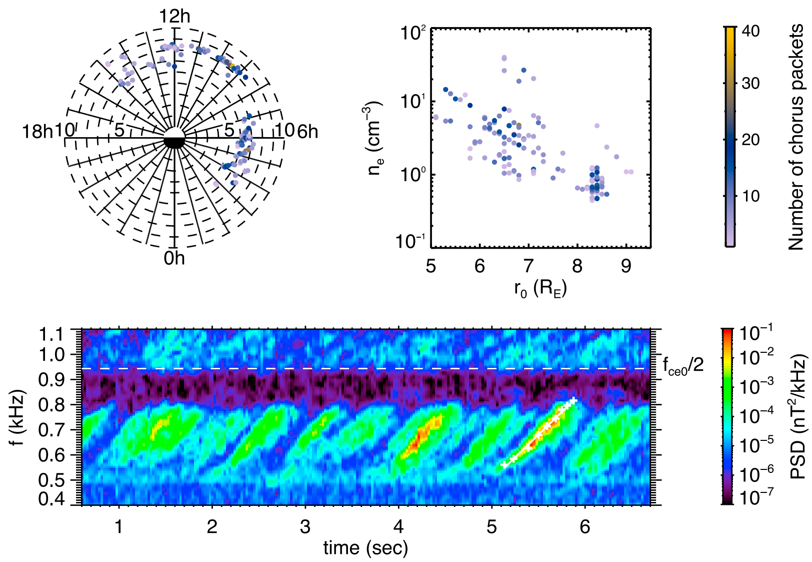

Figure 1. The distribution of THEMIS data (top left) as a function of MLT and the radial distance r_0 in units of Earth radius R_E, and (top right) as a function of electron density (n_e) and radial distance r_0. Color coded is the number of selected chorus packets within each time interval which lasts about 6 to 14 seconds. (bottom) One chosen time interval of chorus packets from THEMIS A on 2008/07/26 starting from 13:52:23.668 UT (r_0 = 8.0 R_E, MLT = 11.9 h, and λ_M = 2.7°), where the dashed line represents $f_{ce0}/2$. Crosses represent manually selected points within the packet between 5 s and 6 s, and the solid white line is the linear fitting whose slope gives the frequency sweep rate. Color coded is the magnetic field wave power spectral density.

α = 30° derived by *Helliwell* [1967] might be too small, because it is generally easier to phase bunch electrons with α between roughly 40° and 75° [*Inan et al.*, 1978]. Using a larger α in equation (1) can further improve the agreement between theory and data. For example, using α = 72° brings the average agreement between the fitted value of Γ_H and Γ_{OB} within ~3%. Similarly, the value of Q in the BWO model used above (Q = 2) might also be underestimated; e.g., *Titova et al.* [2011] suggested that, on average, $Q \approx 8$ for lower band chorus calculated using observational frequency sweep rates. However, the exact value of α or Q should be determined through more rigorous numerical simulations and observed distribution functions.

[12] The chorus frequency sweep rate is also dependent on Kp and MLT as demonstrated previously by *Burtis and Helliwell* [1976]. We show the effects of MLT by comparing Γ_{OB} from dayside (MLT > 8 h) and dawnside (MLT < 8 h) in Figure 3 (left). To minimize the effects of n_e, we only select data with $n_e \leq 15$ cm^{-3}. It could be seen that in general dawnside chorus has a larger frequency sweep rate for a given f_{ce0}. According to theories of *Helliwell* [1967] and *Trakhtengerts* [1995], both MLT and the geomagnetic

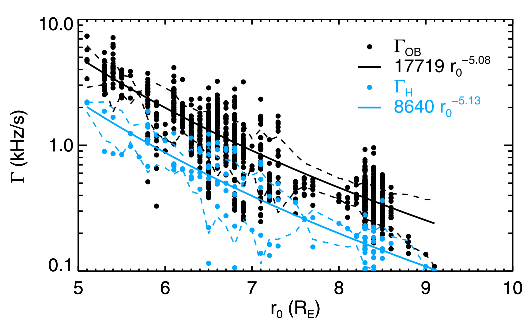

Figure 2. The comparison between the observed frequency sweep rate Γ_{OB} (black dots) and the theoretical frequency sweep rate Γ_H from *Helliwell* [1967] (light blue dots). The theoretical frequency sweep rate Γ_H is calculated using observed MLT, Kp, n_e, and r_0 with the T89 magnetic field model. The solid black line is a power-law fitting of Γ_{OB} as a function of r_0 while the solid light blue line is a power-law fitting of Γ_H as a function of r_0. The dash lines are the corresponding standard deviation of the results from the fitting functions.

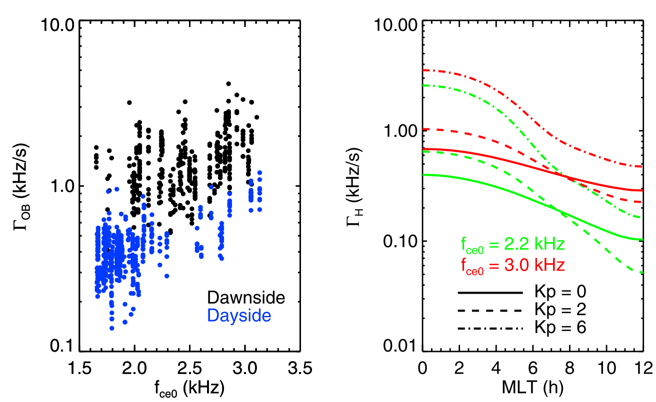

Figure 3. (left) The comparison between Γ_{OB} from dayside (MLT > 8 h, blue dots) and dawnside (MLT < 8 h, black dots). (right) The theoretical value of Γ_H for two f_{ce0}'s at three different Kp's as a function of MLT. Green lines are for f_{ce0} = 2.2 kHz and red lines f_{ce0} = 3.0 kHz. Solid lines represent Kp = 0, dashed lines Kp = 2, and dash dotted lines Kp = 6.

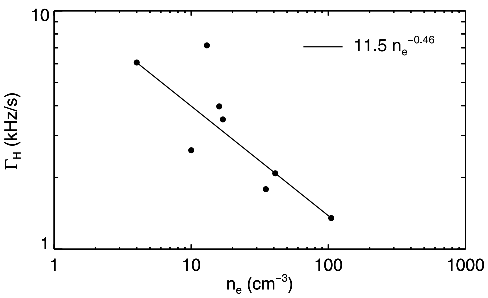

Figure 4. The theoretical frequency sweep rate Γ_H calculated using input parameters (MLT, Kp, r_0, and n_e) from Table 1 of *Macúsová et al.* [2010] (black dots) and the corresponding power-law fitting of Γ_H as a function of n_e (the black line).

activity affect the chorus frequency sweep rate by changing the magnetic field configuration and thus the inhomogeneity parameter β. To demonstrate the effects of MLT and Kp, we show Γ_H as a function of MLT for two constant equatorial cyclotron frequencies (f_{ce0} = 2.2 kHz and 3.0 kHz, and n_e = 5 cm^{-3}) at three different Kp's in Figure 3 (right). Generally, Γ_H is higher on the nightside and dawnside than on the dayside, consistent with observations, because of the compression of the background field on the dayside and the stretching of the field on the nightside. Increasing geomagnetic activity (larger Kp) will increase the asymmetry in Γ_H. Also the MLT and Kp effects are more important for larger r_0 (f_{ce0} = 2.2 kHz), because the magnetic field of the outer magnetosphere (larger r_0) is more strongly affected by geomagnetic activity.

[13] *Macúsová et al.* [2010] showed the dependence of Γ on electron density n_e using observations by the Cluster satellites. The dataset used by *Macúsová et al.* [2010] has McIlwain parameter L_M between 4 and 4.6 and the density n_e between 4 cm^{-3} and 105 cm^{-3}. Most of their data are obtained on the nightside or dawnside. They fit the observed frequency sweep rate Γ_M as a function of n_e by $\Gamma_M = a_M n_e^{b_M}$, with the mean value of a_M between 18.3 and 19.3 and b_M between −0.44 and −0.46, respectively. They compared b_M with −2/3 which is the theoretical scaling index if other parameters are kept constant. Here we assume that r_0 is roughly equal to L_M and use the published data (MLT, Kp, n_e, and r_0) of risers in Table 2 of *Macúsová et al.* [2010] to calculate theoretical frequency sweep rate Γ_H, shown in Figure 4. The calculated Γ_H's are then fitted by $\Gamma_H = a_H n_e^{b_H}$, and we have $a_H = 1.5$ and $b_H = -0.46$. Thus by including effects of MLT, Kp, and r_0 that were not considered by *Macúsová et al.* [2010], the agreement between the scaling indices of theoretical frequency sweep rates and of data is greatly improved. The value of a_H is again smaller than a_M by roughly a factor of two, consistent with the results obtained above using the THEMIS dataset.

4. Summary

[14] In this work, we showed the calculation of chorus frequency sweep rates using the theories of *Helliwell* [1967] and *Trakhtengerts* [1995] with the T89 magnetic field model to include the effects of MLT and geomagnetic activity. By assuming a previously used value for the undetermined parameter Q of *Trakhtengerts et al.* [2004] and α of *Helliwell* [1967], we showed that both theories give the same dependence of the frequency sweep rate on n_e, f_{ce0} and background magnetic field inhomogeneity parameter β. The estimated sweep rate Γ_{BWO} from *Trakhtengerts* [1995] is about four times smaller than Γ_H from *Helliwell* [1967], given the value of Q and α used. However, it should be noted that both theories of *Helliwell* [1967] and *Trakhtengerts* [1995] were developed to estimate frequency sweep rate only qualitatively. Thus we mainly focused on the qualitative dependence of the frequency sweep rate on background parameters in this work.

[15] The theoretical predictions were compared with observations from THEMIS and the published dataset of *Macúsová et al.* [2010]. We demonstrated the agreement between theories and observations in terms of the scaling of Γ as a function of r_0 and n_e by including the effects of MLT and geomagnetic activity that were not considered in previous work. We presented using observations from THEMIS that for a given f_{ce0}, the dawnside chorus has larger frequency sweep rates than the dayside chorus, consistent with previous results. We demonstrated that theoretically MLT and the geomagnetic activity affect the sweep rate by changing the background field configuration. For a given f_{ce0}, the dayside compression results in a smaller Γ, while the stretching of the background field on the nightside leads to a larger Γ, consistent with observations. This asymmetry in Γ will increase with increasing geomagnetic activity and radial distance, since the magnetic field configuration of the outer magnetosphere is more strongly affected by geomagnetic field activity.

[16] Various theories [*Trakhtengerts*, 1995; *Omura et al.*, 2008] have also predicted the relationship between the frequency sweep rate and the wave amplitude. *Cully et al.* [2011] have verified the relationship of *Omura et al.* [2008] using 21 chorus packets from a 12-minute time interval. While we focus on the dependence of Γ on background plasma parameters in this work, it is important to investigate whether the relationship between Γ and the wave amplitude holds for the larger dataset used in this work where all background parameters vary significantly. We leave this to future work.

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