Interactive comment on "A statistical study of spatial distribution and source region size of chorus waves using Van Allen Probes data" by Shangchun Teng et al.

Anonymous Referee #1

We would like to thank the reviewer for helpful suggestions.

A statistical study of spatial distribution and source region size of chorus waves using Van Allen Probes data by Shangchun Teng et al. examines the spatial distribution of rising and falling tone chorus, plus the chorus source region size using the Van Allen Probe EMFISIS burst data. The paper presents new and interesting results and it should be published after the authors take into consideration the following comments/suggestions.

Page 3, first paragraph, you might want to include/discuss Taubenschuss et al., 2015 results in your intro since they also looked at rising and falling tones in the THEMIS data
Taubenschuss, U., Y. V. Khotyaintsev, O. Santolík, A. Vaivads, C. M. Cully, O. Le Contel, and V. Angelopoulos (2015), Wave normal angles of whistler mode chorus rising and falling tones, J. Geophys. Res. Space Physics, 119, 9567–9578, doi:10.1002/2014JA020575.

Thanks for pointing out this work. We have discussed this paper in Page 2 Lines 23-26.

Page 3, Line 29: What were the parameters of your fft? How many samples? Any overlap? I think it would be good to state/discuss what you did since it can make a big difference on the resolution and the types of structure you will see in the spectra.

The FFT parameters are as follows: FFT samples are 1024 point with an overlapping 512 points (50%). And we have added this information in the revised version (P3L30). The resulting spectrogram is shown in Figure 1, which shows that the parameters are good enough for our purpose.

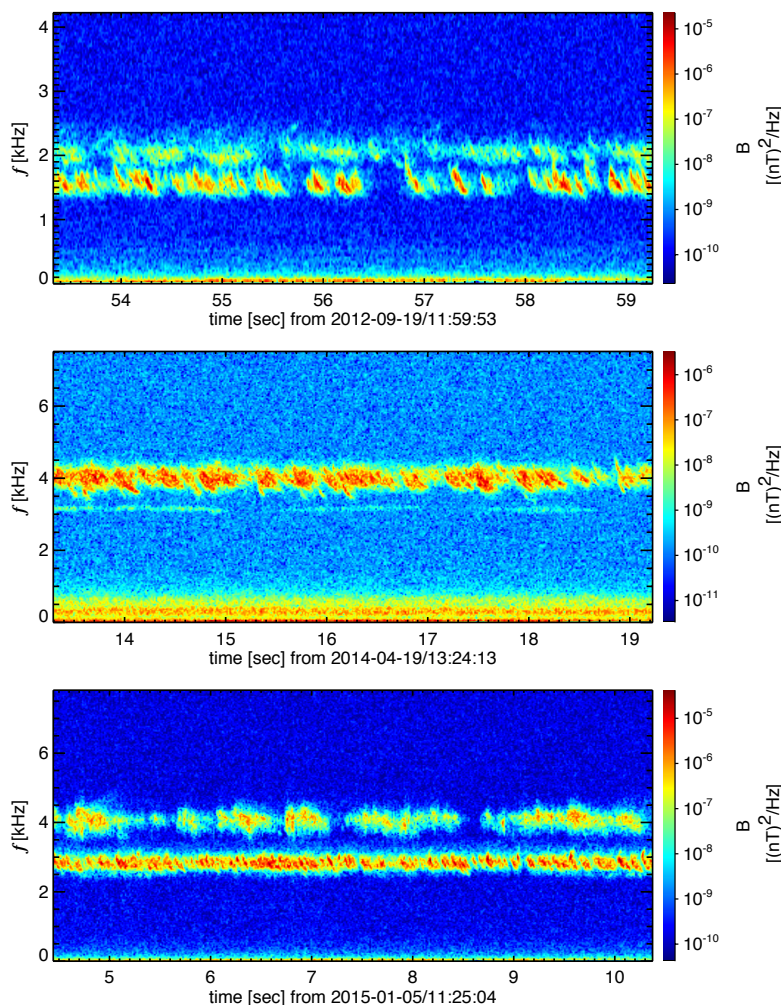
Page 4, Line 6: How is a chorus event (rising or falling) exactly defined? Is only a single element needed in a snapshot to be an event, or a number of elements? How "clear" does the element need to be to be defined as a riser or a faller? For example, in your Figure 1a, I think I can see rising elements buried in the broad band more hiss like structure, but from your test I believe this type of event was excluded from your chorus list. Can a 6 second snapshot period have both rising and falling tones? Please describe your methodology in more detail so we can better understand your process on determining a riser and/or faller event. Also, from my experience with the EMFISIS burst data, I am a little surprised there were that many falling tone events, so I want to be sure I understand how they were defined.

Thanks for pointing this out.

First, the events (rising and falling) collected in this study is mainly based on visual inspection. This inevitably introduces some subjectivity as pointed out by the reviewer using Fig 1a as an example. As far as we were aware of at the time we prepared the database for this study, the only published method that could automatically determine "chorus" events and "hiss" events was by Li et al.

Li, W., R. M. Thorne, J. Bortnik, X. Tao, and V. Angelopoulos (2012), Characteristics of hiss-like and discrete whistler-mode emissions, Geophys. Res. Lett., 39, L18106, doi: 10.1029/2012GL053206.

The Li-method was based on the variation of the peak PSD with time. We have also tried this method to automatically determine the events type, but we found that it could fail easily on some chorus events because of the overlapping of elements and the fluctuated frequency range used to determine the peak PSD. Note that Li et al also confirmed their automatically obtained results by visual inspection. We have also tried using techniques from imaging processing to develop an automatic method to identify chorus elements, but failed to find a method that gives high enough positive identification rate.

Therefore, we agree with the reviewer and we fully understand that the method based on visual inspection could miss some "chorus" events, but this is the best we could do. On the other hand, there is some ambiguity on labeling a given spectrogram such the spectrogram in Fig 1a as pointed out by the reviewer. For this study, we chose a more conservative approach when visually identifying chorus elements: we require that discrete elements should be clearly identifiable such as those in Fig 1b and 1c. Unfortunately, it is hard to give a quantitative criterion for visual identification. So we list here some representative spectrograms of falling tones.

Finally, by using a large amount of data, this approach should not affect our statistical results in a significant way, which is the lowest order estimate of the source region size.

It is possible to have both rising tone and falling tone elements in a 6-second burst. We have found a small number of events of this type, but they were not included in our database, because it is not clear which category (rising or falling) we should put them.

The number of falling tone events is large here, probably because we surveyed a large amount of wave bursts (1237851). The total number of falling tone events we found was 10477 out of 1237851 bursts, which gives a probability of roughly 1%. Among chorus events we selected, most of them are rising tone chorus (66739 out of 77216 events).

In short summary, it is not easy to automatically pick out "chorus events". We mainly used visual inspection and did the best we could. There is some subjectivity introduced by this process, but with large amount of data, we think this kind of subjectivity should not change our conclusion significantly.

Page 5, Line 24: I think you need to describe how you determine the electron density. Are you using the UHR band (Kurth et al., 2015), the EFW proxy density, or some other method? The Kurth reference is below in case that is what you are using. Kurth, W. S., De Pascuale, S., Faden, J. B., Kletzing, C. A., Hospodarsky, G. B., Thaller, S. and Wygant, J. R. (2015), Electron densities inferred from plasma wave spectra obtained by the Waves instrument on Van Allen Probes. J. Geophys. Res. Space Physics, 120: 904–914. doi: 10.1002/2014JA020857.

The electron density we use is from the EFW proxy density. The time resolution of EFW proxy density data is about 10s, which can meet our requirement. On the other hand, EMFISIS L4 data, based on Kurth method, also provides density information. But its time coverage is limited, so we choose the EFW proxy density. We have added clarification about this in Page 7 Lines 22-23.

Minor suggestions
Page 3, Line 28: I believe the sampling rate for the EMFISIS burst is set at 35 kHz and cannot be modified, so I would replace "up to" with "of"

Thanks. We have changed "up to" to "of".

Figure 1 and 4: I would put the time and date of these data so the reader could plot the original data if they wanted to do their own analysis to compare to your plots.

We have changed the labels in figures 1 and 4 as suggested.

We thank the reviewer again for these helpful comments.

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Anonymous Referee #2

This paper performs a statistical study of the spatial distribution and source region size of both rising tone and falling tone chorus waves based upon a Van Allen Probes data survey. They find that rising tone chorus waves have a higher occurrence rate near the geomagnetic equator, while the falling tone chorus waves have a higher possibility to be observed at lower L-shells and higher magnetic latitudes. They also conclude that both rising tone and falling tone chorus waves are generated near the equatorial plane, roughly consistent with previous theoretical estimates.
This study brings statistically new information about naturally discrete chorus emissions,

in terms of exploration of the unprecedented Van Allen Probes data sets. Since whistler mode chorus is a key contributor to the acceleration and loss of magnetospheric electrons and its generation mechanism remains not fully understood, the presented results act as a valuable and timely addition to the current knowledge about magnetospheric chorus and arouse further efforts to look into its drivers and associated quasi-linear / nonlinear wave-particle interactions as well.

We thank the reviewer for these comments.

Below are some specific comments for the authors to consider and address:
Specific:

1. A number of studies have adopted AE* (the maximum or average value of AE in previous hour) to investigate the geomagnetic activity dependence. Please justify or discuss the adoption of AE for such an analysis.

We re-analyzed our data using AE* and it does not make a significant difference. We understand that some studies used AE* and some used AE. We mainly followed the Meredith-2003 method.

Meredith N, Horne R, Thorne R, Anderson R (2003) Favored regions for chorus-driven electron acceleration to relativistic energies in the Earth's outer radiation belt. Geophys Res Lett 30:1871. https://doi. org/10.1029/2003GL017698

We have added a reference to this paper in Page 5 Line 20.

2. Figure 5 shows very interesting results of the chorus wave source region size and the good agreement between observations and theories. What is the error bar associated with the average observational results? Please clarify. By the way, for L = 4.5 on the bottom panel, is one blue line on the right missing (or overlapping)?

This is indeed a very good suggestion. But unfortunately we cannot put a good estimate of the error bar here, since errors of some factors cannot be estimated; e.g.,the error from the background magnetic field model used in this work to determine the geomagnetic equator and MLAT. The bottom line here is this study uses a large amount of data mainly to provide a lowest order estimate of the source region size. There are lots of factors we do not consider in this work; e.g., the move of the source region along a field line, which is only possible to identify using simultaneous observations from multiple closely spaced spacecraft.

For L = 4.5 on the bottom panel, the blue line on the right is overlapping with the red line. We have added a sentence in the caption to clarify this.

3. Also about the source region sizes of rising tone and falling tone chorus. The presented results show a clear dependence on the chorus spectral shape. Say, at L = 4.5 and 5, the former is statistically larger than the latter; and vice versa at L = 5.5 and 6. Is there any explanation for this feature? Please give some discussions.

We do not think the small difference (about 300-400 km) between the source region size of rising and falling tones is large enough to be considered important. As we stated in our manuscript, this is mainly to provide a statistical analysis of the rough source region size. Falling tone chorus is so poorly understood from the theoretical point of view that we really cannot provide an explanation for the difference about the source region size of rising tone and falling tone chorus. We will continue investigating the generation of falling tone chorus.

4. Lines 19 – 20: Please add the following references about chorus-driven diffuse auroral precipitation Ni, B., R. M. Thorne, Y. Y. Shprits, and J. Bortnik (2008), Resonant

scattering of plasma sheet electrons by whistler-mode chorus: Contribution to diffuse auroral precipitation, Geophys. Res. Lett., 35, L11106, doi:10.1029/2008GL034032.
Ni, B., R. M. Thorne, X. Zhang, J. Bortnik, Z. Pu, L. Xie, Z.-J. Hu, D. Han, R. Shi, C. Zhou, and X. Gu (2016), Origins of the Earth's diffuse auroral precipitation, Space Sci. Rev., 200(1), 205-259, doi:10.1007/s11214-016-0234-7.

Thanks for pointing these references out. They have been added in the revised manuscript.

Minor: Page 1: Lines 6-7: better read as "at lower L-shells and higher magnetic latitudes"
Line 10: the observations
Page 3: Line 12: better remove "conditions"
Page 4: Line 4: using the quasilinear theory
Page 9: Line 23: better read "during periods of different geomagnetic activities" and "at the dayside sector"
Line 27: at higher geomagnetic latitudes
Line 28: between the equator and higher latitudes (< 10ˆo)

These corrections have been made. Thanks.

We thank the reviewer again for these helpful comments.

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The manuscript "A statistical study of spatial distribution and source region size of chorus waves using Van Allen Probes data" by Shangchun Teng, Xin Tao, Wen Li, Yi Qi, Xinliang Gao, Lei Dai, Quanming Lu, and Shui Wang is dedicated to the study of the chorus source size along the magnetic field. The study is based on unprecedented big VLF waveform database from the 3 years Van Allen Probes measurements. The separated processing of rising and falling tones provides an interesting information about chorus properties in the outer radiation belt. I think a couple of points in the manuscript might be presented with more details that improves the material presented.

The local minimum of the background magnetic field can be displaced from the geomagnetic equator up to 2-3 degrees at L=4-6. Also, the local minimum can be shifted by large amplitude magnetic field perturbations. This correspondingly shifts the generation region location (see Santolik et al., PSS2004; Kozelov et al., JGR2008; Vaivads et al., GRL2010), which actually looks as a step-like change of the Pointing flux direction in the continuous record (Santolik et al., PSS2004; Agapitov et al., JGR2011). Statistically, this shift is seen as spreading of the Poynting flux predominant direction and intermediate value of <S>, which is discussed in the manuscript as the "source size". Thus, the presented results more likely could provide the distribution of the local magnetic field minimum than the chorus source size estimation. I would suggest to discuss this in the text and to provide the physics-based definition for the "source region".

Dear Dr. Agapitov,

Thanks for pointing this out.

First, we agree with you that the displacement of the local minimum B position could affect the location of the generation region location. Their effect should be similar to the moving of the source

region along a field line as discussed in the manuscript. These two effects should be best investigated using simultaneous observations from multiple spacecraft as discussed in the comment. Since the current study is superposing a large number of single point measurements, the size of the source region defined here cannot eliminate the effects of a moving source or the displacement of minimum B. This is certainly a limitation of this work, whose aim is to provide the lowest order estimate of the source region size.

Second, it is difficult for us to understand physically why the generation region of chorus should correspond to a step like change in the Poynting flux direction. This kind of behavior of Poynting flux direction change should indicate a very sharp boundary of the generation region. Could this be caused by the observation itself? We think more investigation is needed to understand this point in your comment.

But in any case, we agree that the moving of the source region or the displacement of B could cause a spreading of intermediate value of <S>, making the boundary of <S> less sharp than it should be.

The physics related to the definition of <S> is based on that, in the generation region of chorus, background noise from which whistler waves are amplified from should have equal probability to propagate in both directions, because most chorus is driven unstable by a distribution with temperature anisotropy instead of a uni-directional electron beam. Therefore, the Poynting flux direction should have equal probability in both directions in the center of the generation region. This is what our definition of <S> is based on and why we define the source region based on <S> and its probability interpretation in Equation (3).

We have added a paragraph discussing the above points related to the limitation of the statistical approach raised by the comment. Thanks for pointing out these studies.

Minor Comments:
P3L5: "The characteristic spatial correlation scale size transverse to the local magnetic field is estimated to be in the 28003000 km range (Agapitov et al., 2010), and for lower-band chorus it is about 100 km (Santolík and Gurnett, 2003)." - The source scale in (Agapitov et al., 2010) is determined from THEMIS measurements at L11, so, is not relevant here. I suggest citing (Agapitov et al., JGR2011) and (Agapitov et al., GRL2017) instead, where the transverse correlation scale was found to be 600-800 km in the outer radiation belt.

Thanks. We have changed the referred paper as suggested.

The similar statistical value as <S> in Eq.(3) based on the Poynting flux direction was processed in (Agapitov et al., GRL2011,2012).

We apologize for missing the mentioned papers, which use a variable similar to <S>. Note that our <S> is obtained from three values (+1,-1, and 0), while the mentioned papers effectively used two (+1 and -1). The use of the three values allow us to give <S> an interpretation about the probability of S at a given location, which is the basis for our definition of the boundary of the generation region. We have added these references .

Agapitov, O., Krasnoselskikh, V., Dudok de Wit, T., Khotyaintsev, Y., Pickett, J. S., Santolík, O., & Rolland, G. (2011). Multispacecraft observations of chorus emissions as a tool for the plasma density fluctuations' remote sensing. Journal of Geophysical Research: Space Physics (1978–2012), 116(A9).

Agapitov, O., Krasnoselskikh, V., Khotyaintsev, Y. V., & Rolland, G. (2011). A statistical study of the propagation characteristics of whistler waves observed by Cluster.

Geophysical Research Letters, 38, L20103. https://doi.org/10.1029/2011GL049597

Agapitov, O., Krasnoselskikh, V., Khotyaintsev, Y. V., & Rolland, G. (2012). Correction to "A statistical study of the propagation characteristics of whistler waves observed by Cluster." Geophysical Research Letters, 39, L24102. https://doi.org/10.1029/2012GL054320

Agapitov, O., Blum, L. W., Mozer, F. S., Bonnell, J. W., & Wygant, J. (2017). Chorus whistler wave source scales as determined from multipoint Van Allen Probe measurements. Geophysical Research Letters, 44(6), 2017GL072701. https://doi.org/10.1002/2017GL072701

Kozelov, B. V., Demekhov, A. G., Titova, E. E., Trakhtengerts, V. Y., Santolik, O., Macusova, E., : : : Pickett, J. S. (2008). Variations in the chorus source location deduced from fluctuations of the ambient magnetic field: Comparison of Cluster data and the backward wave oscillator model. Journal of Geophysical Research: Space Physics, 113(A6), A06216. https://doi.org/10.1029/2007JA012886

Santolik, O., Gurnett, D. A., & Pickett, J. S. (2004). Multipoint investigation of the source region of storm-time chorus. In Annales Geophysicae (Vol. 22, pp. 2555–2563). Retrieved from https://hal-insu.archives-ouvertes.fr/docs/00/31/75/19/PDF/angeo-22-2555-2004.pdf

Vaivads, A., Santolík, O., Stenberg, G., André, M., Owen, C. J., Canu, P., & Dunlop, M. (2007). Source of whistler emissions at the dayside magnetopause. Geophysical Research Letters, 34(9), L09106. https://doi.org/10.1029/2006GL029195

We thank you again for these helpful comments.

A statistical study of spatial distribution and source region size of chorus waves using Van Allen Probes data

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Abstract. Spatial distribution and source region size of chorus waves are important parameters in understanding their generation. In this work, we analyze over 3 years of continuous wave burst mode data from Van Allen Probes and build a data set of rising and falling tone chorus. For the L shell range covered by Van Allen Probes data ($3.5 \leq L \leq 7$), statistical results demonstrate that the sector where rising tones are most likely to be observed is the dayside during geomagnetically quiet and moderate times and the dawnside during active times. Moreover, rising tone chorus waves have a higher occurrence rate near the equatorial plane, while the falling tone chorus waves have a higher possibility to be observed at lower L-shell and higher magnetic ~~latitude~~latitudes. By analyzing the direction of Poynting wave vector, we statistically investigate the chorus source region size along a field line, and compare the results with previous theoretical estimates. Our analysis confirms previous conclusions that both rising tone and falling tone chorus waves are generated near the equatorial plane, and shows that previous theoretical estimates roughly agree with the observation within a factor of two. Our results provide important insights into further understanding of chorus generation.

1 Introduction

Chorus waves are whistler mode waves consisting of discrete coherent elements with frequency chirping. These waves play important roles in energetic electron dynamics in the inner magnetosphere (Thorne et al., 2010). Through resonant wave-particle interactions, chorus waves can accelerate a few $100\,\mathrm{keV}$ electrons to MeV energy range during disturbed times, contributing to the enhancement of relativistic electron flux in the outer radiation belt (Horne and Thorne, 1998; Summers et al., 1998; Albert and Young, 2005; Horne et al., 2005a, b; Li et al., 2007; Tao et al., 2008; Thorne et al., 2013). These waves can also lead to losses of MeV electrons, forming MeV electron microburst (Lorentzen et al., 2001; Kersten et al., 2011; Saito et al., 2012; Tsurutani et al., 2013), and of keV electrons, forming diffuse aurora and electron pancake distributions ~~(Nishimura et al., 2010; Thorne et al., 2010; Ni et al., 2011; Tao et al., 2011; Nishimura et al., 2013)~~(Ni et al., 2008, 2011, 2016; Nishimu

The detailed wave-particle interaction process, being diffusive or nonlinear, is also undergoing intense debate and research (Albert, 2002; Bortnik et al., 2008; Hikishima et al., 2010; Yoon, 2011; Tao et al., 2012, 2013, 2014a).

Chorus waves have two main spectral shapes, rising tone and falling tone chorus (Burtis and Helliwell, 1969), depending on the sign of the frequency sweep rate. Observations have shown that rising tone and falling tone chorus have quite different characteristics, suggesting that different physical processes might be involved in their generation (Li et al., 2011). Rising tone chorus waves are more likely to be quasi field-aligned and therefore have stronger magnetic field. In contrast, falling tone chorus waves typically have a wave normal angle close to the resonance cone angle and therefore are quasi-electrostatic (Burton and Holzer, 1974; Cornilleau-Wehrlin et al., 1976; Li et al., 2011). Theoretically, it is widely accepted that chorus waves are generated nonlinearly (Helliwell, 1967; Vomvoridis et al., 1982; Omura et al., 2008; Tao et al., 2017b, c), although the detailed physical process is still an ongoing research topic. Most existing theories and particle-in-cell type simulations are about rising tone chorus waves (Helliwell, 1965; Sudan and Ott, 1971; Nunn, 1974; Vomvoridis et al., 1982; Trakhtengerts, 1995; Omura et al., 2008; Tao, 2014); only a few theoretical models have been proposed for falling tone chorus (Nunn and Omura, 2012; Soto-Chavez et al., 2014; Mourenas et al., 2015). In this work, we consider rising tone and falling tone chorus waves separately.

In this study, we investigate the spatial distribution and the source region size along a magnetic field line for the two types of chorus waves. The spatial distribution of chorus can give clues about what parameters may affect the excitation of chorus, and has been studied extensively in previous work (e.g., Li et al., 2009; Meredith et al., 2014). Using THEMIS data, Li et al. (2009) found that chorus waves have a higher occurrence rate at dayside, although no difference between rising tone and falling tone chorus was made. The higher occurrence rate of chorus waves at dayside was suggested to be caused by the more homogeneous magnetic field, which lowers the threshold of the free energy drive to excite chorus (Spasojevic and Inan, 2010; Keika et al., 2012; Katoh and Omura, 2013; Tao et al., 2014b). Note that this threshold condition is different from that for broadband whistler mode waves (Gary, 1993; Gary and Wang, 1996; Viñas et al., 2015), since the generation of broadband whistler waves should be describable using quasilinear theory (Ossakow et al., 1972; Tao et al., 2017a). Recently, ~~using Van Allen Probes wave observations, Li et al. (2016) reported that chorus~~ Taubenschuss et al. (2014) compared the wave normal angle of rising and falling tone chorus waves using THEMIS data and found that rising tone chorus can be either quasi-parallel or very oblique with wave normal angle ~~exhibits a bi-modal distribution, with one peak near the quasi-parallel direction and the other peak near the~~ (WNA) close to the resonance cone angle, while chorus fallers typically have WNA close to the resonance cone. ~~They also~~ Using Van Allen Probes wave observations, Li et al. (2016) found that quasi-parallel chorus waves dominate over quasi-electrostatic ones during more disturbed geomagnetic periods and at higher L shells. However, they did not differentiate between rising or falling tones in the statistical results, since they used the survey mode wave data from the Van Allen Probes, which has low time resolution (1 sample / 6 seconds), while the frequency of discrete elements of chorus changes on the order of 1 kHz typically within less than a second. In this study, we use high resolution burst mode waveform data with a sampling rate ~~up to~~ of 35 kHz from Van Allen Probes to analyze the spatial distribution of the rising and falling tone chorus under different geomagnetic activity conditions.

The source region size characterizes the spatial scale of the nonlinear generation process, and can be used to constrain theoretical models (Helliwell, 1967; Trakhtengerts, 1995). The source region of chorus waves is believed to be located close to the geomagnetic equator, or more generally the minimum B-field region along a field line (Burtis and Helliwell, 1976; LeDocq et al., 1998; Kurita et al., 2012). This is related to the fact that the energetic electron flux is largest and the non-uniformity of the background magnetic field is smallest in the minimum-B region along a given field line. Kurita et al. (2012) shows that falling tone chorus propagates from the equator, in the same way as rising tone chorus. Other relevant work (Parrot et al., 2003; Breneman et al., 2009; Santolík et al., 2009) all give the same conclusion. Several previous studies have performed case analysis using multiple satellite observations simultaneously to identify the dimension of chorus source region ~~(Santolík and Gurnett, 2003; Agapitov et al., 2010)~~(Santolík and Gurnett, 2003). For example, Santolík et al. (2004) determined that the source region size was about $3000 - 5000$ km along the background magnetic field line at about 4 Earth radii with the Poynting flux measurements by the Cluster satellites. The characteristic spatial correlation scale size transverse to the local magnetic field is estimated to be in the ~~2800 − 3000 km range (Agapitov et al., 2010)~~600 − 800 km range (Agapitov et al., 2011a, 2017), and for lower-band chorus it is about 100 km (Santolík and Gurnett, 2003). One purpose of this study is to analyze statistically the source region of rising tone and falling tone chorus waves along the magnetic field line. We will also compare previous theoretical estimate of the source region size with the observational data.

The remainder of the paper is organized as follows. We briefly describe our data set in Section 2. A statistical analysis of the global distribution of rising tone and falling tone chorus for different levels of geomagnetic activity ~~conditions~~ using Van Allen Probes data is given in Section 3. We present studies about chorus source region size in Section 4, with the method of obtaining the source region size given in Section 4.1. The comparison between our observational results and previous theoretical models and the implication of our results to chorus waves at other planets are given in Section 4.2. Finally, we summarize our findings in Section 5.

2   Data base and event selection

The Van Allen Probes mission, consisting of two identical spacecraft (Probe A and B), operate in an elliptical orbit with an apogee of 5.8 R_{E}, perigee ~ 600 km, and an inclination of approximately $10°$. The orbital precession rate is about $200°$ per year, thus the Van Allen Probes can sweep all MLT and complete one full precession within about 22 months (Kessel et al., 2013; Mauk et al., 2013). Each Van Allen Probe includes an EMFISIS (Electric and Magnetic Field Instrument Suite and Integrated Science) instrument (Kletzing et al., 2013) that provides high time resolution measurements of electric and magnetic fields covering the frequency range from 10 Hz up to 400 kHz. The EMFISIS instrument suite measures the background magnetic field by a tri-axial fluxgate magnetometer (MAG) (Kletzing et al., 2013).

In the present statistical study, we use the 3D Electric and Magnetic field waveform data obtained in a continuous wave burst mode by EMFISIS from September 2012 to December 2015. Each waveform data lasts approximately 6 seconds with a sampling rate ~~up to~~ of 35kHz. Such high time-frequency resolution is sufficient to resolve individual chorus elements. In this work, each 6-second waveform data will be defined as an "event", and there are in total about 1237851 events. We then

perform the ~~fast Fourier transform~~short-time Fourier transform, with 1024 samples in each segment with 512 samples to overlap between segments, on waveforms to obtain the magnetic and electric power spectral density (PSD) of all events.
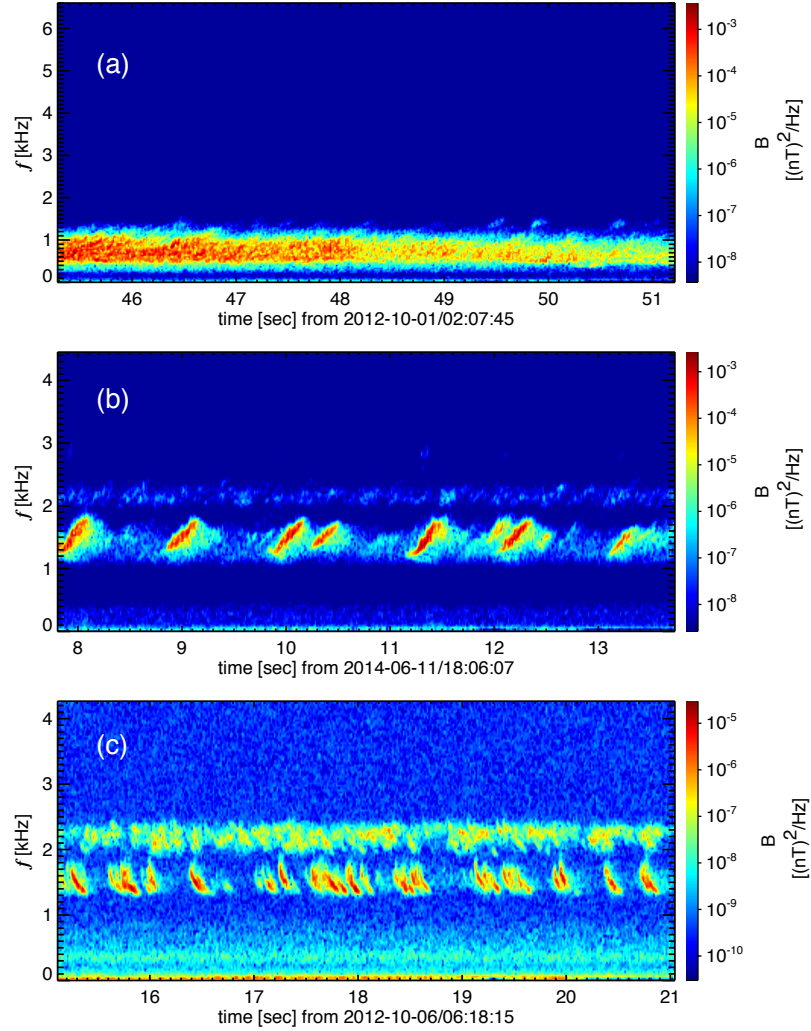
Figure 1. Three typical spectrograms of whistler mode electromagnetic emissions with frequency below the electron cyclotron frequency: (a) broadband whistler mode waves, (b) rising tone chorus, and (c) falling tone chorus.

Figure 1 shows three typical spectrograms of electromagnetic emissions with frequency $f < f_{ce}$, where f_{ce} is the electron cyclotron frequency. The upper limit of y axis in all spectrogram plots in this work is set to f_{ce}. These emissions are broadband whistler mode waves (Figure 1a), rising tone chorus (Figure 1b), and falling tone chorus (Figure 1c). The term "chorus" in this study specifically means the types of whistler mode emissions shown in Figure 1b or 1c; i.e., emissions consisting of discrete elements with frequency chirping. The generation process of frequency chirping chorus waves is believed to be nonlinear (Helliwell, 1967; Vomvoridis et al., 1982; Katoh and Omura, 2007; Omura et al., 2008; Tao, 2014; Tao et al., 2017b). On the contrary, the generation and saturation of broadband whistler mode waves, shown in Figure 1a, might be understandable using quasilinear theory (Kennel and Engelmann, 1966; Kennel and Petschek, 1966; Ossakow et al., 1972; Tao et al., 2017a; Kim et al., 2017). By visually inspecting the power spectrogram of each event, we have found 77216 chorus events in total, including 66739 rising tone chorus events and 10477 falling tone chorus events. Parameters such as MLT (magnetic local time), MLAT (magnetic latitude) and L shell are derived from TS04D magnetic field model (Tsyganenko and Sitnov, 2005). For 72 events that TS04D model data are not available, we use OP77Q (Olson and Pfitzer, 1982) external magnetic field model instead. Considering that most of the events we found are located in the inner magnetosphere with $3.5 \leq L \leq 7$, the mixed use of two magnetic field models does not make a big difference.

3 Spatial distribution of rising and falling tone chorus

The spatial distribution of chorus waves has been studied using data from previous satellite missions such as THEMIS (Li et al., 2009) and CLUSTER (Meredith et al., 2014). In this section, we present the spatial distribution analysis for rising tone and falling tone chorus waves separately using Van Allen Probes data.

Figure 2 presents the distribution of the occurrence rate of rising tone chorus and falling tone chorus, and the number of all events under different levels of geomagnetic activity conditions as a function of L and MLT. Both types of chorus waves and samples are sorted into three different levels according to the AE index (quiet: $AE < 100\,\text{nT}$, moderate:$100 \leq AE \leq 300\,\text{nT}$, strong: $AE > 300\,\text{nT}$), following Meredith et al. (2003). Each bin has a size of $0.5R_{\text{E}} \times 0.5\text{MLT}$. The occurrence rate of chorus is defined as the ratio of the number of chorus wave events to the total number of all events sampled in each bin. As can be seen from the bottom three panels of Figure 2, the most well sampled region is located from $L = 5.5$ to $L = 6$ and from 1400 MLT to 2000 MLT during geomagnetically quiet and moderate times, and 1100 MLT to 1800 MLT during geomagnetically active times. The fact that the most well sampled region is located at L shells between 5.5 and 6 is not only because of the orbit of the Van Allen Probes, but also the time periods when the continuous waveform data were collected.

Figure 2 demonstrates that rising tone and falling tone chorus waves have different spatial distribution features. From the top three panels of Figure 2, the highest occurrence rate of rising tone chorus is located at dawnside and dayside between $L = 5.5$ and 6.5. During quiet and moderate conditions, rising tone chorus has the highest occurrence rate on the dayside and at $L \geq 5.5$. However, during strongly disturbed periods, the largest occurrence rates are seen at the dawnside between 0400 MLT and 0900 MLT at $5 \leq L \leq 6.5$. The L shell range covered by the Van Allen Probes data is from $3.5 \leq L \leq 7$; therefore, higher L shell regions at dayside are not sampled. Note that the waveform data from the EMFISIS instrument onboard Van
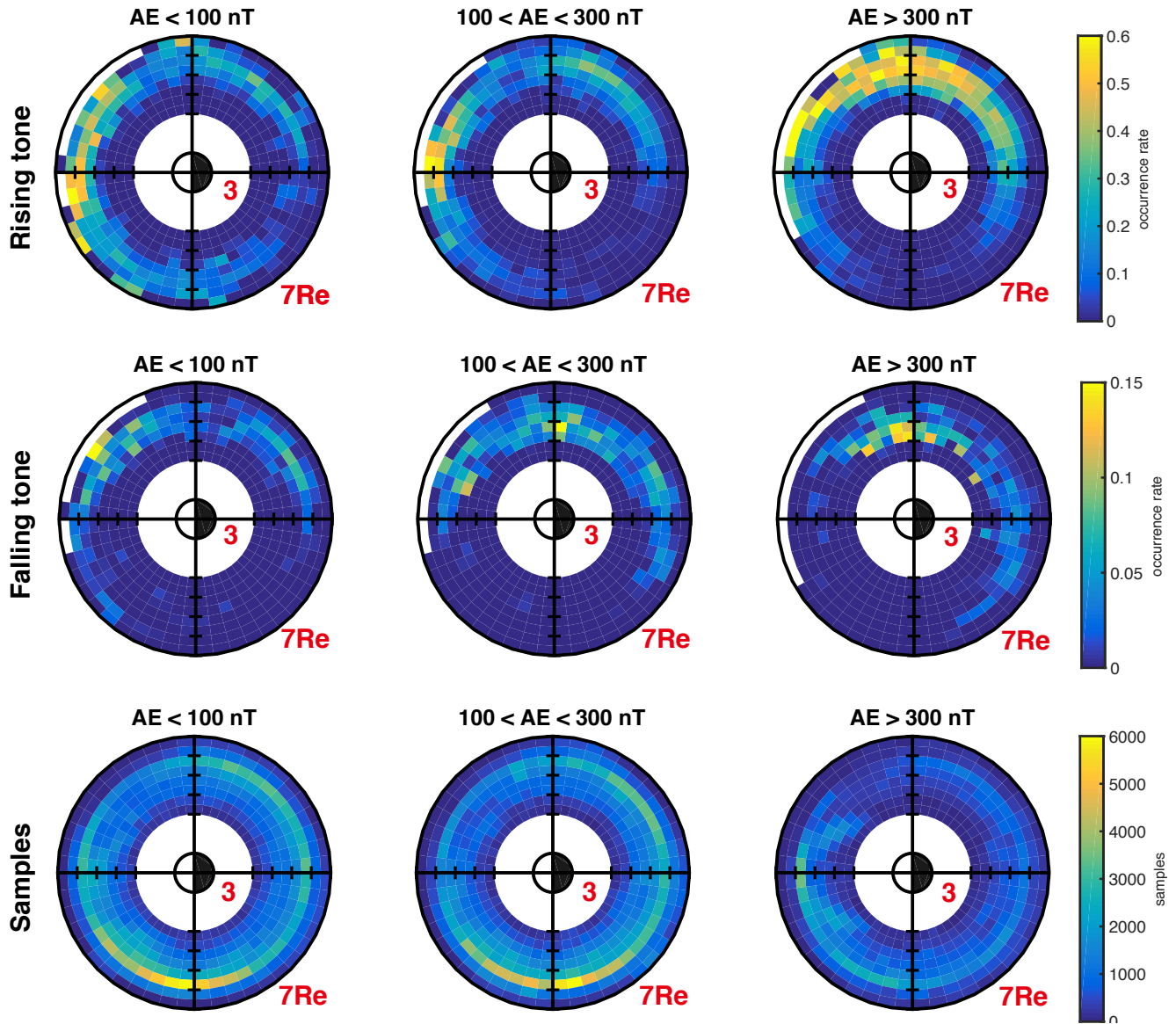
Figure 2. Spatial distribution of the occurrence rate of rising tone (top), falling tone (middle) chorus, and the number of samples (bottom) in MLT-L coordinates categorized by different AE index.

Allen Probes were not collected randomly, but mostly based on wave amplitudes. Therefore, the statistical results shown in Figure 2 may have a bias on the larger-amplitude chorus, which potentially reduces the occurrence rate of falling tones, whose amplitudes are typically lower than those of the rising tones (e.g., Li et al., 2011; Gao et al., 2014). Furthermore, the present statistical results are very complementary to the previous statistical results based on the THEMIS waveform data (Li et al.,

2011; Gao et al., 2014), since THEMIS provides good coverage of chorus wave measurements at L shells over 5-10, compared to the Van Allen Probes coverage over L shells of 3-7.

The distribution of falling tone chorus is shown in the middle three panels. During quiet time periods ($AE < 100\,\text{nT}$), falling tone chorus is distributed almost uniformly across dawnside between $4.5 \leq L \leq 6$, and peaks between 0900 MLT and 1000 MLT at $6 \leq L \leq 6.5$. Under moderately disturbed conditions ($100 < AE < 300\,\text{nT}$), falling tone chorus waves have a higher occurrence rate at dawnside in L shell between 4.5 and 5.5. During strongly disturbed periods, the highest occurrence rate of falling tone chorus occurs in a narrow MLT range between 0500 MLT and 0700 MLT and $4 \leq L \leq 5$. Compared with the most intense region for rising tone chorus ($5 \leq L \leq 6.5$), falling tone chorus tends to occur at lower L shells ($4 \leq L \leq 5$) and smaller MLT range for $AE > 300\,\text{nT}$. Because falling tone chorus waves tend to be quasi-electrostatic (Li et al., 2011), our result is consistent with that of Li et al. (2016), who found that quasi-electrostatic whistler mode waves preferentially occur at lower L-shell's compared to quasi-parallel ones. Note that Li et al. (2016) based their analysis on the propagation direction of whistler mode waves only. The physical reason for the preference of quasi-electrostatic whistler mode waves to occur at lower L shell is unknown at this time.

Figure 3 shows the distribution of two types of chorus and the total number of samples in MLAT-L coordinates. The bin size is $0.1 R_{\text{E}} \times 1°\text{MLAT}$. The majority of sampled data are located between 5.5 and $6\,R_{\text{E}}$ near the equator, typically less than MLAT$=10°$ for any geomagnetic conditions. Top panels show that rising tone chorus waves have a more uniformly distributed occurrence rate around $L = 5.5$ under all geomagnetic conditions, while falling tone chorus waves tend to have a higher occurrence rate at higher magnetic ~~latitude~~ latitudes than at the equatorial region at any L shell. This is also consistent with the THEMIS statistical results shown in Li et al. (2011). Further work is needed to understand the different distributions of rising tone and falling tone chorus waves.

4 The Source Region Size of Chorus

In this section, we statistically analyze properties of source region of rising tone and falling tone chorus. To reduce the effect of the electron number density on the theoretical estimate of the source region size (see Section 4.2), we exclude 1549 events whose electron number density is larger than $100\,\text{cm}^{-3}$. The electron density is obtained from the Electric Field and Waves density data (Wygant et al., 2013), which was estimated from the spacecraft potential, calibrated from the EMFISIS upper hybrid line. The automatic algorithm described below failed in about 18% of the events (see Section 4.1). In total, there are 54283 rising tone chorus events and 7901 falling tone chorus events used in the following analysis.

4.1 Observation

We statistically determine the source region of chorus using the direction of the Poynting vector with respect to the background magnetic field. The Poynting flux vector $\boldsymbol{P}$ is defined by

$$\boldsymbol{P} = \frac{1}{\mu_0} \delta \boldsymbol{E} \times \delta \boldsymbol{B}, \tag{1}$$
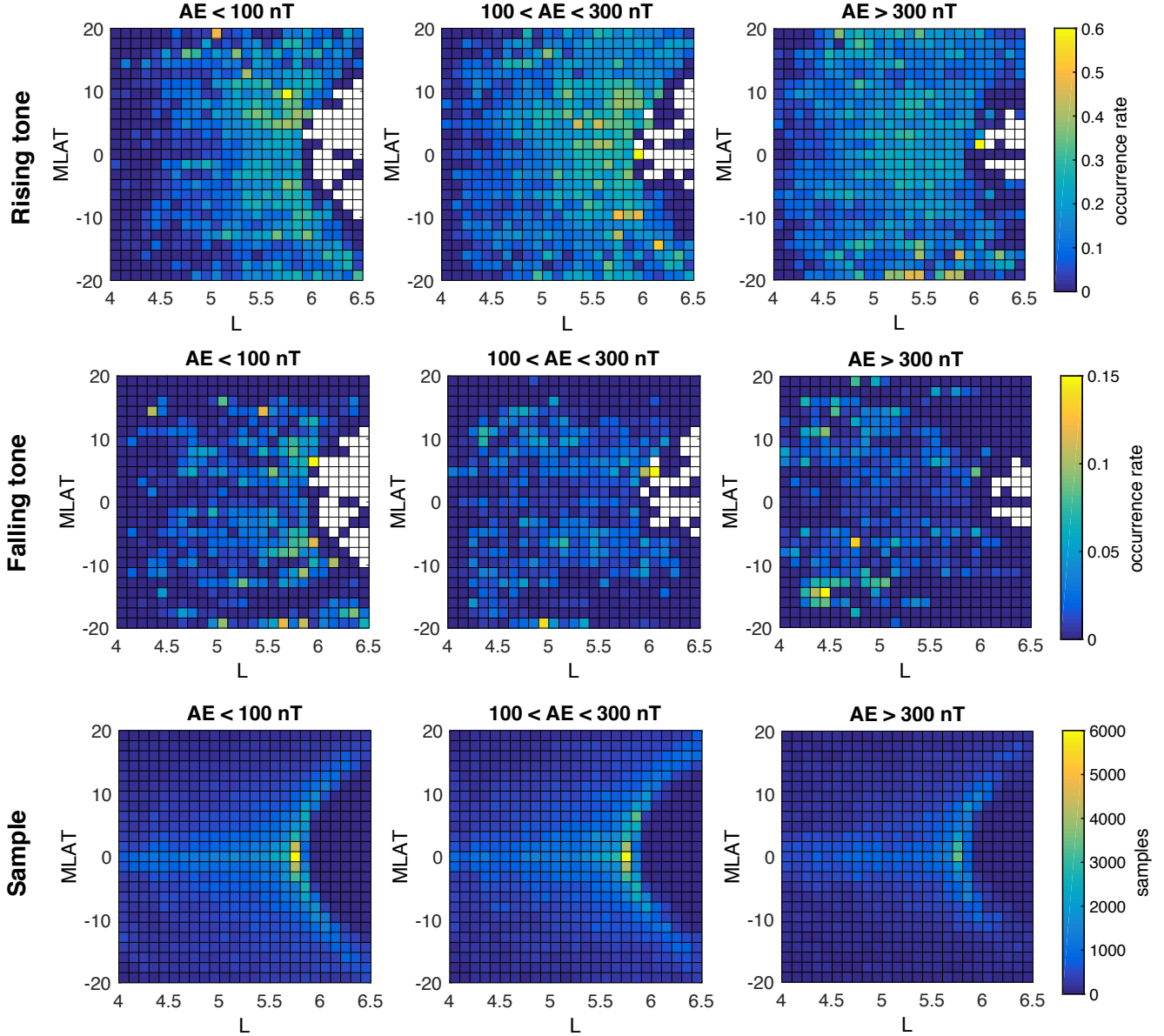
Figure 3. Similar to Figure 2 but in MLAT-L coordinates.

where δE and δB are the wave electric field and magnetic field, respectively. One reasonable assumption used in determining the source region of chorus waves or its size along a field line is that inside the source region, there is no preference for the direction of wave excitation with respect to the background magnetic field B. Therefore, waves propagating in both directions should be observed, and the Poynting vector in the source region should have mixed directions with respect to B. Outside the source region, waves propagate away from the generation region and would have a uniform direction of propagation. This

assumption has also been used by several previous studies to determine the source region or its size of chorus waves along a magnetic field line in case studies (e.g., Santolík et al., 2004; Hospodarsky et al., 2008). The direction of the background magnetic field is derived from the fluxgate magnetometer (MAG).

Figure 4 shows three events with different types of Poynting fluxes discussed above. The z component of the Poynting flux (hereafter denoted as P_z) of the three events is shown in the second row. The Poynting flux of all chorus elements of event (a) (the left column) is positive, and that of event (b) (the middle column) is negative. Event (c) (the right column) shows a case where chorus elements propagate in both directions, suggesting that this event is observed within its generation region. As demonstrated below, when using the Poynting flux to quantitatively estimate the source region size parallel to the magnetic field, we define a quantity which we call the sign of the event direction, denoted hereafter as S. This quantity takes the value of 1, -1 or 0. If S of an event is 1 (-1), it means that P_z of all chorus elements in the event is positive (negative). On the other hand, if $S = 0$, there are both northward and southward propagating chorus elements in the event.

The value of S for each event is determined automatically in three steps. First, using the spectrogram matrix of the wave magnetic field, we remove background noise and only keep strong wave signals. We define a reference value of the power spectral density (PSD) which is the mean value of the maximum five PSD's for waves between $0.1f_{ce}$ and $0.8f_{ce}$, which is the typical frequency range of chorus (Li et al., 2009). Any data points with power spectral density three orders of magnitude lower than the reference PSD will not be considered in the next two steps. Second, we calculate the Poynting flux using the wave magnetic and electric field, and separate the Poynting flux into P_{zN} ($P_z > 0$) and P_{zS} ($P_z < 0$). Here subscripts "N" and "S" refer to northward and southward propagating waves, respectively. The calculated Poynting flux matrix may contain isolated data points that do not belong to any chorus element, which typically consists of continuous data points in the PSD or P_z matrix. To remove these isolated data points, we define a bin to be 0.015 second. This is also the length of the window when performing the moving-window FFT to calculate the PSD spectrogram. Statistical study shows that chorus elements typically last about $0.1 - 0.8$ second (Teng et al., 2017); therefore, a chorus element typically covers a few tens of bins. To consider only data points of chorus elements, we only include bins with more than eight data points and data points that are distributed in three continuous bins. After the first two steps of pre-processing data, the resulting Poynting flux data points are verified to belong to actual chorus elements. These first two steps work correctly for about 82% of the events previously selected. The remaining 18% of the events cannot be handled automatically due to too much noise signals and are therefore excluded from the final data base.

The third and fourth rows of Figure 4 show the final Poynting flux matrices for all three events. To determine the value of S for a given event, we calculate the summation of P_z of all selected data points, $\sum P_z$. Note that $\int P_z \mathrm{d}f \mathrm{d}t / T \approx \sum P_z \Delta f \Delta t / T$, with $T = 6$ second, is the average Poynting flux of all waves. If $\sum P_{zS} = 0$ (or $\sum P_{zN} = 0$), then $S = 1$ (or -1). In case neither $\sum P_{zS}$ nor $\sum P_{zN}$ is 0, the value of S for a given event is determined by

$$
S = \begin{cases}
1, & \log_{10}(\sum P_{zN} / |\sum P_{zS}|) > 3; \\
-1, & \log_{10}(|\sum P_{zS}| / \sum P_{zN}) > 3; \\
0, & |\log_{10}(\sum P_{zN} / |\sum P_{zS}|)| < 3.
\end{cases}
\tag{2}
$$

This means that if $\sum P_{zN}$ ($|\sum P_{zS}|$) is larger than $|\sum P_{zS}|$ ($\sum P_{zN}$) by three orders of magnitude, then $S = 1$ (-1). On the other hand, if the difference between $\sum P_{zN}$ and $|\sum P_{zS}|$ is within three orders of magnitude, it means that waves propagate both northward and southward and therefore $S = 0$. We set the threshold value to be three orders of magnitude through experimenting on a subset of the whole database. This process of determining the value of S is illustrated in Figure 4 for these three types of events.

Figure 5 illustrates the method we use to statistically analyze the source region size of chorus waves at a given L shell bin with the event direction S defined above. For a bin whose center is at L, we select all events located between $L - \Delta L$ and $L + \Delta L$, where ΔL is the width of the bin. We choose $\Delta L = 0.5$ in all analyses in this study. Figure 5 displays different L shell's centering at $L = 4.5, 5, 5.5, 6$ for rising and falling tone chorus. We uniformly divide the MLAT into 40 bins from -20° to 20°, so each bin is 1° in MLAT. For all events in a given MLAT bin, we then calculate the average value of S, denoted by $\langle S \rangle$. A similar quantity has been used by Agapitov et al. (2011b, 2012) to analyze the propagation characteristics of whistler waves. Because of the definition of S, we ~~have~~ can re-interpret $\langle S \rangle$ as

$$\langle S \rangle = \frac{N(S=1) \times 1 + N(S=0) \times 0 + N(S=-1) \times (-1)}{N_t}$$

$$\approx \mathcal{P}(S=1) - \mathcal{P}(S=-1), \tag{3}$$

where $N(S=1)$ is the number of events with $S = 1$, N_t is the total number of events for a given bin, and $\mathcal{P}(S=1) \approx N(S=1)/N_t$ is the estimated probability of $S = 1$ for that bin. Other variables are defined similarly. Therefore, if $\langle S \rangle = 0$ for a bin, it means that the probabilities for chorus elements to propagate northward and southward are the same. If $\langle S \rangle = 0.9$, because $\mathcal{P} \geq 0$, this means that at least 90% of the events in the bin propagate north. Data are represented by gray circles in the selected MLAT bin in Figure 5. Clearly, for events located in the center of the source region, we expect $\langle S \rangle$ to be close to 0. As one moves away from the center of the source region, the absolute value of $\langle S \rangle$ increases and eventually becomes 1 as one is completely outside the source region. The top (bottom) four panels of Figure 5 is $\langle S \rangle$ as a function of MLAT for rising (falling) tone chorus. As can be easily seen, for both types of chorus waves, $\langle S \rangle$ is closer to 0 near the equator (MLAT $= 0$), and becomes larger and closer to 1 (-1) as MLAT increases (decreases). Moreover, the sign of S shows that waves propagate northward (southward) in the northern (southern) hemisphere. This confirms previous results of Kurita et al. (2012) that the both type of chorus waves are generated near the equator, despite their different characteristics.

Ideally, to obtain the source region size l, one would use $|\langle S \rangle| = 1$ to define the boundary of the source region and estimate l. However, as can be seen from Figure 5, $\partial |\langle S \rangle| / \partial \lambda \sim 0$ as $|\langle S \rangle| \sim 1$, where λ is MLAT. Correspondingly, a small change in $|\langle S \rangle|$ can lead to a very large variation in the source region size. Accordingly, the method we use here is to estimate three boundary sizes determined using $|\langle S \rangle| = 0.85$, $|\langle S \rangle| = 0.9$ and $|\langle S \rangle| = 0.95$, and use the average of three l's to represent the final boundary size. The average of three estimates of l is used to reduce the statistical variation. The source region sizes for the four L's are shown in Figure 5 and marked by blue dashed lines. The size of the source region is also expressed in kilometers, which is converted from MLAT assuming a dipole field. From these figures, we conclude that the source region of chorus is located within about $3°$ in MLAT for all four L's for both types of chorus waves. Note that the actual source region of chorus waves for a given event might be time dependent, and could move rapidly around the equator as suggested by

previous studies (Inan et al., 2004; Santolík et al., 2004; Santolík et al., 2005). The local minimum of the background magnetic field displacement could also affect the location of the generation region location (Santolik et al., 2004; Kozelov et al., 2008). These effects should be best investigated using simultaneous observations from multiple spacecraft. Since the current study is superposing a large number of single point measurements, the size of the source region defined here cannot eliminate the above two effects. Therefore, our way of statistically estimating the source region size should be interpreted to be the lowest order estimate, and the resulting l might be different from the actual source region size for a particular event.

4.2 Comparison between the theoretical source region size and observation

In this section, we compare the source region size from observation with previous theoretical estimates. Helliwell (1967) estimated that the length of the resonance region parallel to the magnetic field region is roughly

$$l_H = 2l_H^* = 2\left(\frac{2\pi v_{\parallel}}{\beta \Omega_0}\right)^{1/3}, \tag{4}$$

Here β is the inhomogeneity factor, resulting from approximating the magnetic field strength as a function of s using a parabolic function near the equator; i.e., $B \approx B_0(1 + \beta s^2)$ with B_0 the magnetic field strength at $s = 0$. For a dipole field, $\beta = 4.5/(LR_p)^2$, where R_p is planet radius. The cyclotron resonance frequency at equator $\Omega_0 = qB_0/mc$. The cyclotron resonant velocity at the equator is

$$v_{\parallel} = c\frac{(\Omega_0 - \omega)^{3/2}}{\omega_{pe}\omega^{1/2}}, \tag{5}$$

where ω_{pe} is the plasma frequency, and ω is wave frequency. The physical meaning of l_H^* is essentially the distance for the wave particle interaction phase angle to be changed by π from the equator. Based on the same principle, the source region size estimated by Trakhtengerts (1995) is

$$l_T = \left(\frac{3\pi}{2}\frac{v_{\parallel}}{\beta(\Omega_0 - \omega)}\right)^{1/3}. \tag{6}$$

Therefore l_T and l_H have the same dependence on the electron number density, L shell, and planet radius R_p. Choosing a characteristic frequency of chorus $\omega = 0.3\Omega_0$, $l_T/l_H^* \approx 1$. The estimates in Equations (4) and (6) should be considered as the lowest order approximation instead of a rigorous theoretical calculation (Helliwell, 1967; Trakhtengerts, 1995). In analysis below, we only use l_H as the theoretical estimate for simplicity.

Before we compare l_H with l, we show the dependence of l_H on L shell and other parameters. Substituting $v_{\parallel}$ (Equation (5)) and β into Equation (4) results in

$$l_H = 2\left[c\frac{(1 - \omega/\Omega_0)^{3/2}}{\omega_{pe}(\omega/\Omega_0)^{1/2}}\frac{(LR_p)^2}{4.5}\right]^{1/3}. \tag{7}$$

For a given ω/Ω_0,

$$l_H \propto n_e^{-1/6}L^{2/3}R_p^{2/3}. \tag{8}$$

It is clear that l_H has a very weak dependence on n_e. The value of n_e for chorus wave events used in the source region analysis are all below $100\,\mathrm{cm}^{-3}$. In the following analysis, we use a typical electron number density outside the plasmapause $n_e = 10\,\mathrm{cm}^{-3}$. For a given planet such as Earth, Equation (8) suggests that the source region size increases with increasing L as $L^{2/3}$. Physically, this conclusion can also be understood using Equation (4). The inhomogeneity factor β decreases with increasing L as $\beta \propto L^{-2}$. The background magnetic field becomes more homogeneous as L increases, and correspondingly the source region size increases.

To estimate l_H, we use a representative frequency $\omega = 0.3\Omega_0$. The theoretical source region size is shown by red dashed lines in Figure 5. For simplicity, the boundary of theoretical source region size in MLAT is determined from l_H, assuming a dipole field and a north-south symmetric source region. For both rising tone and falling tone chorus at all four L shell's, l_H agrees with l within a factor of two. Given the crude simplification of the theory, and the statistical nature of our analysis, we conclude that the theoretical estimate roughly agrees with observation. Note here that we do not compare the observed source region size with that of Omura et al. (2009), because the source region size of Omura et al. (2009) depends on the wave amplitude δB, which can vary significantly during propagation.

Observations of chorus at other planets should be helpful to further test previous theoretical estimates of chorus source region size. For example, the radius of Saturn is roughly ten times larger than that of Earth. At a given L shell, the source region size of chorus at Saturn should be larger than that at Earth by roughly about a factor of $10^{2/3} \approx 5$, following Equation (8). Similar conclusions can be reached for Jupiter. However, these tests depend on the accumulation of enough observational data of chorus waves at these planets.

5 Summary

In this work, we statistically analyzed the distribution and the source region size parallel to the background magnetic field of rising tone and falling tone chorus waves using burst mode waveform data from Van Allen Probes. A total of 77216 rising and falling tone chorus events were identified visually. Our analysis shows that the spatial distribution of the occurrence rate of rising and falling tone chorus during ~~different magnetic~~ periods of different geomagnetic activities is different. Rising tone chorus mainly occurs at the dayside sector during quiet times and moves to dawnside during active conditions. Falling tone chorus is more likely to be observed at lower L shells, while rising tone chorus has a high occurrence rate at larger L shells. The feature is consistent with the recent finding that the quasi-electrostatic whistler mode waves preferentially occur at lower L shells compared to the quasi-parallel ones (Li et al., 2016). In addition, falling tone chorus tends to have a higher occurrence rate at higher magnetic ~~latitude~~ latitudes than at the equator, whereas rising tone chorus has a more uniform occurrence rate between the equator and ~~mid-latitude~~ higher latitudes ($10°$).

We then investigated the source region size parallel to the background magnetic field for both types of chorus waves using the direction of the Poynting flux vector. Our results suggest that both types of chorus waves are generated near the equator, despite their different characteristics. This conclusion confirms previous results by Kurita et al. (2012). We showed that statistically the source region of both types of chorus waves is within about $3°$ in MLAT. We also demonstrated that previous theoretical

estimates of the source region size by Helliwell (1967) and Trakhtengerts (1995) roughly agree with observation, and the difference is within about a factor of two. Our work should be helpful to further understand the generation mechanism of chorus.

Data availability. The EMFISIS data were obtained from the website (http://emfisis.physics.uiowa.edu/Flight/).

5   *Competing interests.* No competing interests are present.

Acknowledgements. This work was supported by NSFC grant 41631071, 41474142, and 41674174. We acknowledge the NASA Van Allen Probes mission and Dr. Craig Kletzing for the use of the data.

References

Agapitov, O., Krasnoselskikh, V., Zaliznyak, Y., Angelopoulos, V., Le Contel, O., and Rolland, G.: Chorus source region localization in the Earth's outer magnetosphere using THEMIS measurements, in: Annales Geophysicae, vol. 28, pp. 1377–1386, 2010.

Agapitov, O., Krasnoselskikh, V., Dudok de Wit, T., Khotyaintsev, Y., Pickett, J. S., Santolík, O., and Rolland, G.: Multispacecraft observations of chorus emissions as a tool for the plasma density fluctuations' remote sensing, Journal of Geophysical Research: Space Physics, 116, https://doi.org/10.1029/2011JA016540, 2011a.

Agapitov, O., Krasnoselskikh, V., Khotyaintsev, Y. V., and Rolland, G.: A statistical study of the propagation characteristics of whistler waves observed by Cluster, Geophysical Research Letters, 38, https://doi.org/10.1029/2011GL049597, 2011b.

Agapitov, O., Krasnoselskikh, V., Khotyaintsev, Y. V., and Rolland, G.: Correction to "A statistical study of the propagation characteristics of whistler waves observed by Cluster", Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL054320, 2012.

Agapitov, O., Blum, L., Mozer, F., Bonnell, J., and Wygant, J.: Chorus whistler wave source scales as determined from multipoint Van Allen Probe measurements, Geophysical Research Letters, 44, 2634–2642, https://doi.org/10.1002/2017GL072701, 2017.

Albert, J. M.: Nonlinear interaction of outer zone electrons with VLF waves, Geophys. Res. Lett., 29, 1275, https://doi.org/10.1029/2001GL013941, 2002.

Albert, J. M. and Young, S. L.: Multidimensional quasi-linear diffusion of radiation belt electrons, Geophys. Res. Lett., 32, L14110, https://doi.org/10.1029/2005GL023191, 2005.

Bortnik, J., Thorne, R. M., and Inan, U. S.: Nonlinear interaction of energetic electrons with large amplitude chorus, Geophys. Res. Lett., 35, L21102, https://doi.org/10.1029/2008GL035500, 2008.

Breneman, A. W., Kletzing, C. A., Pickett, J., Chum, J., and Santoík, O.: Statistics of multispacecraft observations of chorus dispersion and source location, J. Geophys. Res., 114, A06202, https://doi.org/10.1029/2008JA013549, 2009.

Burtis, W. and Helliwell, R.: Banded chorus-A new type of VLF radiation observed in the magnetosphere by OGO 1 and OGO 3, Journal of Geophysical Research, 74, 3002–3010, https://doi.org/10.1029/JA074i011p03002, 1969.

Burtis, W. J. and Helliwell, R. A.: Magnetospheric chorus: Occurrence patterns and normalized frequency, Planet. Space Sci., 24, 1007–1010, https://doi.org/10.1016/0032-0633(76)90119-7, 1976.

Burton, R. K. and Holzer, R. E.: The origin and propagation of chorus in the outer magnetosphere, Journal of Geophysical Research, 79, 1014–1023, https://doi.org/10.1029/JA079i007p01014, 1974.

Cornilleau-Wehrlin, N., Etcheto, J., and Burton, R.: Detailed analysis of magnetospheric ELF chorus: Preliminary results, Journal of Atmospheric and Terrestrial Physics, 38, 1201–1210, https://doi.org/10.1016/0021-9169(76)90052-0, 1976.

Gao, X., Li, W., Thorne, R. M., Bortnik, J., Angelopoulos, V., Lu, Q., Tao, X., and Wang, S.: Statistical results describing the bandwidth and coherence coefficient of whistler mode waves using THEMIS waveform data, J. Geophys. Res. Space Physics, 119, 8992–9003, https://doi.org/10.1002/2014JA020158, 2014.

Gary, S.: Theory of Space Plasma Microinstabilities, Cambridge Univ, Pres, New York, 1993.

Gary, S. P. and Wang, J.: Whistler instability: Electron anisotropy upper bound, J. Geophys. Res., 101, 10,749-10,754, https://doi.org/10.1029/96JA00323, 1996.

Helliwell, R. A.: Whistlers and Related Ionospheric Phenomena, Stanford University Press, Stanford, California, 1965.

Helliwell, R. A.: A theory of discrete VLF emissions from the magnetosphere, J. Geophys. Res., 72, 4773–4790, https://doi.org/10.1029/JZ072i019p04773, 1967.

Hikishima, M., Omura, Y., and Summers, D.: Microburst precipitation of energetic electrons associated with chorus wave generation, Geophys. Res. Lett., 37, L07103, https://doi.org/10.1029/2010GL042678, 2010.

Horne, R. B. and Thorne, R. M.: Potential waves for relativistic electron scattering and stochastic acceleration during magnetic storms, Geophys. Res. Lett., 25, 3011–3014, https://doi.org/10.1029/98GL01002, 1998.

5 Horne, R. B., Thorne, R. M., Glauert, S. A., Albert, J. M., Meredith, N. P., and Anderson, R. R.: Timescale for radiation belt electron acceleration by whistler mode chorus waves, J. Geophys. Res., 110, A03 225, https://doi.org/10.1029/2004JA010811, 2005a.

Horne, R. B., Thorne, R. M., Shprits, Y. Y., Meredith, N. P., Glauert, S. A., Smith, A. J., Kanekal, S. G., Baker, D. N., Engebretson, M. J., Posch, J. L., Spasojevic, M., Inan, U. S., Pickett, J. S., and Decreau, P. M. E.: Wave acceleration of electrons in the Van Allen radiation belts, Nature, 437, https://doi.org/10.1038/nature03939, 2005b.

10 Hospodarsky, G. B., Averkamp, T. F., Kurth, W. S., Gurnett, D. A., Menietti, J. D., Santoík, O., and Dougherty, M. K.: Observations of chorus at Saturn using the Cassini Radio and Plasma Wave Science instrument, J. Geophys. Res., 113, A12206, https://doi.org/10.1029/2008JA013237, 2008.

Inan, U. S., Platino, M., Bell, T. F., Gurnett, D. A., and Pickett, J. S.: Cluster measurements of rapidly moving sources of ELF/VLF chorus, J. Geophys. Res., 109, A05 214, https://doi.org/10.1029/2003JA010289, 2004.

15 Katoh, Y. and Omura, Y.: Computer simulation of chorus wave generation in the Earth's inner magnetosphere, Geophys. Res. Lett., 34, L03102, https://doi.org/10.1029/2006GL028594, 2007.

Katoh, Y. and Omura, Y.: Effect of the background magnetic field inhomogeneity on generation processes of whistler-mode chorus and broadband hiss-like emissions, J. Geophys. Res., 118, 4189–4198, https://doi.org/10.1002/jgra.50395, 2013.

Keika, K., Spasojevic, M., Li, W., Bortnik, J., Miyoshi, Y., and Angelopoulos, V.: PENGUIn/AGO and THEMIS conjugate observations of 20 whistler mode chorus waves in the dayside uniform zone under steady solar wind and quiet geomagnetic conditions, J. Geophys. Res., 117, A07212, https://doi.org/10.1029/2012JA017708, 2012.

Kennel, C. F. and Engelmann, F.: Velocity space diffusion from weak plasma turbulence in a magnetic field, Phys. Fluids, 9, https://doi.org/10.1063/1.1761629, 1966.

Kennel, C. F. and Petschek, H. E.: Limit on stably trapped particle fluxes, J. Geophys. Res., 71, 1–28, 25 https://doi.org/10.1029/JZ071i001p00001, 1966.

Kersten, K., Cattell, C. A., Breneman, A., Goetz, K., Kellogg, P. J., Wygant, J. R., Wilson III, L. B., Blake, J. B., Looper, M. D., and Roth, I.: Observation of relativistic electron microbursts in conjunction with intense radiation belt whistler-mode waves, Geophys. Res. Lett., 38, L08107, https://doi.org/10.1029/2011GL046810, 2011.

Kessel, R., Fox, N., and Weiss, M.: The radiation belt storm probes (RBSP) and space weather, Space Science Reviews, 179, 531–543, 30 https://doi.org/10.1007/s11214-012-9953-6, 2013.

Kim, H., Hwang, J., Seough, J., and Yoon, P.: Electron temperature anisotropy regulation by whistler instability, Journal of Geophysical Research: Space Physics, 122, 4410–4419, https://doi.org/10.1002/2016JA023558, 2017.

Kletzing, C., Kurth, W., Acuna, M., MacDowall, R., Torbert, R., Averkamp, T., Bodet, D., Bounds, S., Chutter, M., Connerney, J., et al.: The electric and magnetic field instrument suite and integrated science (EMFISIS) on RBSP, in: The Van Allen Probes Mission, pp. 127–181, 35 Springer, https://doi.org/10.1007/s11214-013-9993-6, 2013.

Kozelov, B. V., Demekhov, A. G., Titova, E. E., Trakhtengerts, V. Y., Santolik, O., Macusova, E., Gurnett, D. A., and Pickett, J. S.: Variations in the chorus source location deduced from fluctuations of the ambient magnetic field: Comparison of Cluster data and the backward wave oscillator model, J. Geophys. Res., 113, A06 216, https://doi.org/10.1029/2007JA012886, 2008.

Kurita, S., Misawa, H., Cully, C. M., Contel, O. L., and Angelopoulos, V.: Source location of falling tone chorus, Geophys. Res. Lett., 39, L22102, https://doi.org/10.1029/2012GL053929, 2012.

LeDocq, M. J., Gurnett, D. A., and Hospodarsky, G. B.: Chorus source locations from VLF Poynting flux measurements with the Polar spacecraft, Geophys. Res. Lett., 25, 4063–4066, https://doi.org/10.1029/1998GL900071, 1998.

5 Li, W., Shprits, Y. Y., and Thorne, R. M.: Dynamic evolution of energetic outer zone electrons due to wave-particle interactions during storms, J. Geophys. Res., 112, A10220, https://doi.org/10.1029/2007JA012368, 2007.

Li, W., Thorne, R. M., Angelopoulos, V., Bortnik, J., Cully, C. M., Ni, B., LeContel, O., Roux, A., Auster, U., and Magnes, W.: Global distribution of whistler-mode chorus waves observed on the THEMIS spacecraft, Geophys. Res. Lett., 36, L09 104, https://doi.org/10.1029/2009GL037595, 2009.

10 Li, W., Thorne, R. M., Bortnik, J., Shprits, Y. Y., Nishimura, Y., Angelopoulos, V., Chaston, C., Contel, O. L., and Bonnell, J. W.: Typical properties of rising and falling tone chorus waves, Geophys. Res. Lett., 38, L14 103, https://doi.org/10.1029/2011GL047925, 2011.

Li, W., Santolik, O., Bortnik, J., Thorne, R., Kletzing, C., Kurth, W., and Hospodarsky, G.: New chorus wave properties near the equator from Van Allen Probes wave observations, Geophysical Research Letters, 43, 4725–4735, https://doi.org/10.1002/2016GL068780., 2016.

Lorentzen, K. R., Blake, J. B., Inan, U. S., and Bortnik, J.: Observations of relativistic electron microbursts in association with VLF chorus,
15 J. Geophys. Res., 106, 6017–6027, https://doi.org/10.1029/2000JA003018, 2001.

Mauk, B., Fox, N. J., Kanekal, S., Kessel, R., Sibeck, D., and Ukhorskiy, A.: Science objectives and rationale for the radiation belt storm probes mission, Space Science Reviews, 179, 3–27, https://doi.org/10.1007/s11214-012-9908-y, 2013.

Meredith, N. P., Horne, R. B., Thorne, R. M., and Anderson, R. R.: Favored regions for chorus-driven electron acceleration to relativistic energies in the Earth's outer radiation belt, Geophys. Res. Lett., 30, https://doi.org/10.1029/2003GL017698, 2003.

20 Meredith, N. P., Horne, R. B., Li, W., Thorne, R. M., and Sicard-Piet, A.: Global model of low-frequency chorus ($f_{LHR} < f < 0.1 f_{ce}$) from multiple satellite observations, Geophys. Res. Lett., 41, 280–286, https://doi.org/10.1002/2013GL059050, 2014.

Mourenas, D., Artemyev, A. V., Agapitov, O. V., Krasnoselskikh, V., and Mozer, F. S.: Very oblique whistler generation by low-energy electron streams, J. Geophys. Res. Space Physics, 120, 3665–3683, https://doi.org/10.1002/2015JA021135, 2015.

Ni, B., Thorne, R. M., Shprits, Y. Y., and Bortnik, J.: Resonant scattering of plasma sheet electrons by whistler-mode chorus: Contribution
25 to diffuse auroral precipitation, Geophys. Res. Lett., 35, L11 106, https://doi.org/10.1029/2008GL034032, 2008.

Ni, B., Thorne, R. M., Meredith, N. P., Horne, R. B., and Shprits, Y. Y.: Resonant scattering of plasma sheet electrons leading to diffuse auroral precipitation: 2. Evaluation for whistler mode chorus waves, J. Geophys. Res., 116, A04 219, https://doi.org/10.1029/2010JA016233, 2011.

Ni, B., Thorne, R. M., Zhang, X., Bortnik, J., Pu, Z., Xie, L., Hu, Z.-j., Han, D., Shi, R., Zhou, C., et al.: Origins of the Earth's diffuse auroral precipitation, Space Science Reviews, 200, 205–259, https://doi.org/10.1007/s11214-016-0234-7, 2016.

30 Nishimura, Y., Bortnik, J., Li, W., Thorne, R. M., Lyons, L. R., Angelopoulos, V., Mende, S. B., Bonnell, J. W., Contel, O. L., Cully, C., Ergun, R., and Auster, U.: Identifying the driver of pulsating aurora, Science, 330, 81–84, https://doi.org/10.1126/science.1193186, 2010.

Nishimura, Y., Bortnik, J., Li, W., Thorne, R. M., Ni, B., Lyons, L. R., Angelopoulos, V., Ebihara, Y., Bonnell, J. W., Le Contel, O., and Auster, U.: Structures of dayside whistler-mode waves deduced from conjugate diffuse aurora, J. Geophys. Res., 118, 664–673, https://doi.org/10.1029/2012JA018242, 2013.

35 Nunn, D.: A self-consistent theory of triggered VLF emissions, Planet. Space Sci., 22, 349–378, https://doi.org/10.1016/0032-0633(74)90070-1, 1974.

Nunn, D. and Omura, Y.: A computational and theoretical analysis of falling frequency VLF emissions, J. Geophys. Res., 117, A08 228, https://doi.org/10.1029/2012JA017557, 2012.

Olson, W. and Pfitzer, K. A.: A dynamic model of the magnetospheric magnetic and electric fields for July 29, 1977, Journal of Geophysical Research: Space Physics, 87, 5943–5948, https://doi.org/10.1029/JA087iA08p05943, 1982.

Omura, Y., Katoh, Y., and Summers, D.: Theory and simulation of the generation of whistler-mode chorus, J. Geophys. Res., 113, A04 223, https://doi.org/10.1029/2007JA012622, 2008.

5   Omura, Y., Hikishima, M., Katoh, Y., Summers, D., and Yagitani, S.: Nonlinear mechanisms of lower-band and upper-band VLF chorus emissions in the magnetosphere, J. Geophys. Res., 114, A07 217, https://doi.org/10.1029/2009JA014206, 2009.

Ossakow, S. L., Ott, E., and Haber, I.: Nonlinear evolution of whistler instabilities, Phys. Fluids, 15, 2314–2326, https://doi.org/10.1063/1.1693875, 1972.

Parrot, M., Santolik, O., Cornilleau-Wehrlin, N., Maksimovic, M., and Harvey, C.: Source location of chorus emissions observed by Cluster,

10   in: Annales Geophysicae, vol. 21, pp. 473–480, 2003.

Saito, S., Miyoshi, Y., and Seki, K.: Relativistic electron microbursts associated with whistler chorus rising tone elements: GEMSIS-RBW simulations, J. Geophys. Res., 117, A10 206, https://doi.org/10.1029/2012JA018020, 2012.

Santolík, O. and Gurnett, D. A.: Transverse dimensions of chorus in the source region, Geophysical Research Letters, 30, https://doi.org/10.1029/2002GL016178, 2003.

15   Santolik, O., Gurnett, D., and Pickett, J.: Multipoint investigation of the source region of storm-time chorus, in: Annales Geophysicae, vol. 22, pp. 2555–2563, 2004.

Santolík, O., Gurnett, D. A., Pickett, J. S., Parrot, M., and Cornilleau-Wehrlin, N.: A microscopic and nanoscopic view of storm-time chorus on 31 March 2001, Geophys. Res. Lett., 31, L02 801, https://doi.org/10.1029/2003GL018757, 2004.

Santolík, O., Gurnett, D., Pickett, J., Parrot, M., and Cornilleau-Wehrlin, N.: Central position of the source region of storm-time chorus,

20   Planetary and Space Science, 53, 299–305, https://doi.org/doi:10.1016/j.pss.2004.09.056, 2005.

Santolík, O., Gurnett, D. A., Pickett, J. S., Chum, J., and Cornilleau-Wehrlin, N.: Oblique propagation of whistler mode waves in the chorus source region, J. Geophys. Res., 114, A00F03, https://doi.org/10.1029/2009JA014586, 2009.

Soto-Chavez, A. R., Wang, G., Bhattacharjee, A., Fu, G. Y., and Smith, H. M.: A model for falling-tone chorus, Geophys. Res. Lett., 41, 1838–1845, https://doi.org/10.1002/2014GL059320, 2014.

25   Spasojevic, M. and Inan, U. S.: Drivers of chorus in the outer dayside magnetosphere, J. Geophys. Res., 115, A00F09, https://doi.org/10.1029/2009JA014452, 2010.

Sudan, R. N. and Ott, E.: Theory of triggered VLF emissions, J. Geophys. Res., 76, 4463–4476, https://doi.org/10.1029/JA076i019p04463, 1971.

Summers, D., Thorne, R. M., and Xiao, F.: Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in

30   the magnetosphere, J. Geophys. Res., 103, 20 487–20 500, https://doi.org/10.1029/98JA01740, 1998.

Tao, X.: A numerical study of chorus generation and the related variation of wave intensity using the DAWN code, J. Geophys. Res. Space Physics, 119, 3362–3372, https://doi.org/10.1002/2014JA019820, 2014.

Tao, X., Chan, A. A., Albert, J. M., and Miller, J. A.: Stochastic modeling of multidimensional diffusion in the radiation belts, J. Geophys. Res., 113, A07 212, https://doi.org/10.1029/2007JA012985, 2008.

35   Tao, X., Thorne, R. M., Li, W., Ni, B., Meredith, N. P., and Horne, R. B.: Evolution of electron pitch-angle distributions following injection from the plasma sheet, J. Geophys. Res., 116, A04 229, https://doi.org/10.1029/2010JA016245, 2011.

Tao, X., Bortnik, J., Thorne, R. M., Albert, J., and Li, W.: Effects of amplitude modulation on nonlinear interactions between electrons and chorus waves, Geophys. Res. Lett., 39, L06 102, https://doi.org/10.1029/2012GL051202, 2012.

Tao, X., Bortnik, J., Albert, J. M., Thorne, R. M., and Li, W.: The importance of amplitude modulation in nonlinear interactions between electrons and large amplitude whistler waves, J. Atmos. Solar Terres. Phys., 99, 67–72, https://doi.org/10.1016/j.jastp.2012.05.012, 2013.

Tao, X., Bortnik, J., Albert, J. M., Thorne, R. M., and Li, W.: Effects of discreteness of chorus waves on quasilinear diffusion-based modeling of energetic electron dynamics, J. Geophys. Res. Space Physics, 119, 8848–8857, https://doi.org/10.1002/2014JA020022, 2014a.

5 Tao, X., Lu, Q., Wang, S., and Dai, L.: Effects of magnetic field configuration on the day-night asymmetry of chorus occurrence rate: A numerical study, Geophys. Res. Lett., 41, 6577–6582, https://doi.org/10.1002/2014GL061493, 2014b.

Tao, X., Chen, L., Liu, X., Lu, Q., and Wang, S.: Quasilinear analysis of saturation properties of broadband whistler mode waves, Geophysical Research Letters, 44, 8122–8129, https://doi.org/10.1002/2017GL074881, 2017a.

Tao, X., Zonca, F., and Chen, L.: Identify the nonlinear wave-particle interaction regime in rising tone chorus generation, Geophys. Res.
10 Lett., 44, 3441–3446, https://doi.org/10.1002/2017GL072624, 2017b.

Tao, X., Zonca, F., and Chen, L.: Investigations of the electron phase space dynamics in triggered whistler wave emissions using low noise δf method, ppcf, 59, 094 001, 2017c.

Taubenschuss, U., Khotyaintsev, Y. V., Santolík, O., Vaivads, A., Cully, C. M., Contel, O. L., and Angelopoulos, V.: Wave normal angles of whistler mode chorus rising and falling tones, J. Geophys. Res. Space Physics, 119, 9567–9578, https://doi.org/10.1002/2014JA020575,
15 2014.

Teng, S., Tao, X., Xie, Y., Zonca, F., Chen, L., Fang, W., and Wang, S.: Analysis of the Duration of Rising Tone Chorus Elements, Geophysical Research Letters, 44, 12,074–12,082, https://doi.org/10.1002/2017GL075824, 2017.

Thorne, R. M., Ni, B., Tao, X., Horne, R. B., and Meredith, N. P.: Scattering by chorus waves as the dominant cause of diffuse auroral precipitation, Nature, 467, 943–946, https://doi.org/10.1038/nature09467, 2010.

20 Thorne, R. M., Li, W., Ni, B., Ma, Q., Bortnik, J., Chen, L., Baker, D. N., Spence, H. E., Reeves, G. D., Henderson, M. G., Kletzing, C. A., Kurth, W. S., Hospodarsky, G. B., Blake, J. B., Fennell, J. F., Claudepierre, S. G., and Kanekal, S. G.: Rapid local acceleration of relativistic radiation-belt electrons by magnetospheric chorus, Nature, 504, 411–414, https://doi.org/10.1038/nature12889, 2013.

Trakhtengerts, V. Y.: Magnetosphere cyclotron maser: Backward wave oscillator generation regime, J. Geophys. Res., 100, 17 205–17 210, https://doi.org/10.1029/95JA00843, 1995.

25 Tsurutani, B. T., Lakhina, G. S., and Verkhoglyadova, O. P.: Energetic electron (> 10 keV) microburst precipitation,∼ 5–15 s X-ray pulsations, chorus, and wave-particle interactions: A review, Journal of Geophysical Research: Space Physics, 118, 2296–2312, https://doi.org/10.1002/jgra.50264, 2013.

Tsyganenko, N. and Sitnov, M.: Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms, J. Geophys. Res, 110, A03208, https://doi.org/10.1029/2004JA010798, 2005.

30 Viñas, A. F., Moya, P. S., Navarro, R. E., Valdivia, J. A., Araneda, J. A., and Muñoz, V.: Electromagnetic fluctuations of the whistler-cyclotron and firehose instabilities in a Maxwellian and Tsallis-kappa-like plasma, Journal of Geophysical Research: Space Physics, 120, 3307–3317, https://doi.org/10.1002/2014JA02055, 2015.

Vomvoridis, J. L., Crystal, T. L., and Denavit, J.: Theory and computer simulations of magnetospheric very low frequency emissions, J. Geophys. Res., 87, 1473–1489, https://doi.org/10.1029/JA087iA03p01473, 1982.

35 Wygant, J., Bonnell, J., Goetz, K., Ergun, R., Mozer, F., Bale, S., Ludlam, M., Turin, P., Harvey, P., Hochmann, R., et al.: The Electric Field and Waves Instruments on the Radiation Belt Storm Probes Mission, Space Science Reviews, 179, 183–220, https://doi.org/10.1007/s11214-013-0013-7, 2013.

Yoon, P. H.: Large-amplitude whistler waves and electron acceleration, Geophys. Res. Lett., 38, L12 105, https://doi.org/10.1029/2011GL047893, 2011.
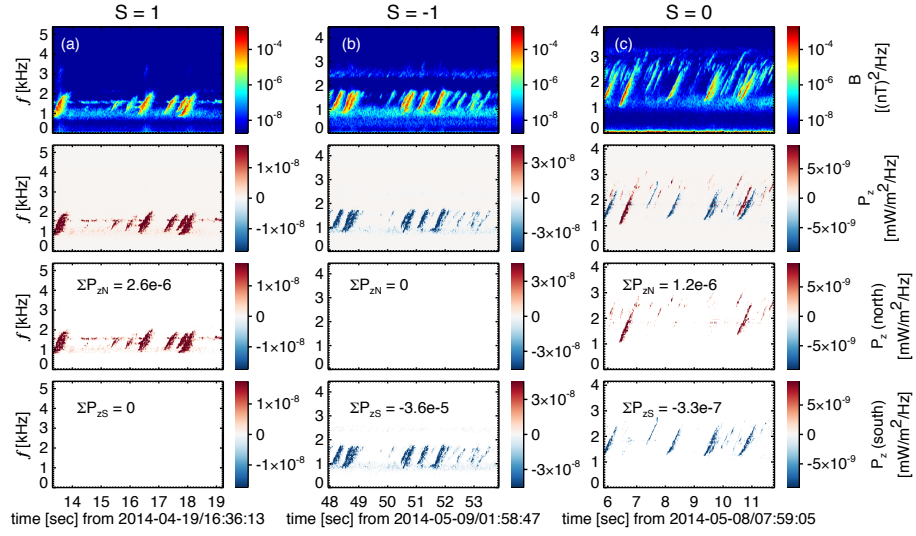
Figure 4. Illustration of three types of S: $S = 1$ (left), -1 (middle), and 0 (right). From top to bottom rows: the magnetic power spectra density, the z-component of the Poynting flux vector (P_z), and the northward and southward $\sum P_z$.
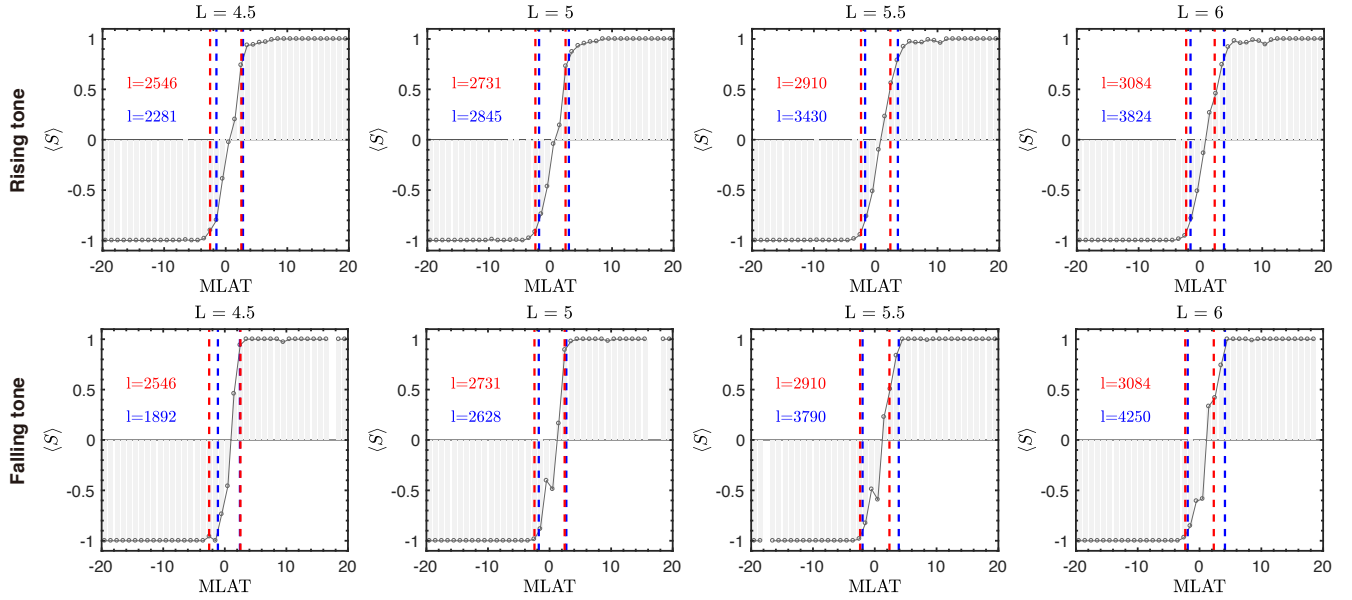
Figure 5. Comparison of the source region size between theoretical (red) and observational results (blue) at different L shell's. The top four panels are for rising tone chorus; the lower four, falling tone chorus (for L = 4.5 of falling tone, the blue line on the right is overlapping with the red line). Observational estimates of the source region size are marked by blue dashed lines; theoretical estimates, the red dashed lines. Source region sizes in km are shown in corresponding panels.