URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

The Angular Distribution of Chorus Waves and the Importance of Plumes in the Chorus-to-Hiss Mechanism

David P. Hartley* (1), Lunjin Chen (2), Craig A. Kletzing(1), Richard B. Horne(3), and Ondrej Santolík(4, 5)
(1) University of Iowa, Iowa City, IA, USA.
(2) University of Texas at Dallas, Richardson, TX, USA.
(3) British Antarctic Survey, Cambridge, UK.
(4) Institute of Atmospheric Physics, Prague, Czech Republic.
(5) Charles University, Prague, Czech Republic.

Abstract

Van Allen Probes EMFISIS observations in both survey and burst mode are coupled with ray tracing simulations to determine the percentage of chorus wave power that exists with the conditions required to access the plasmasphere and evolve into plasmaspheric hiss. For most chorus source locations, we find only an extremely small fraction of power with the required wave vector orientation. The exception to this is when the chorus source is located on the edge of a plasmaspheric plume. In these cases, strong azimuthal density gradients modify the wave propagation so that large fractions, up to 96%, of chorus wave power can gain access to the plasmasphere. We conclude that this region of the magnetosphere, close to plasmaspheric plume structures, provides an important access region for chorus waves to enter the plasmasphere. However, given that chorus wave power is typically weaker in the region where plumes are frequently observed, this result suggests that it is unlikely that chorus significantly contributes to plasmaspheric hiss. Finally, having identified this crucial region, we propose to directly study the wave properties and propagation characteristics of chorus that occurs in close proximity to plasmaspheric plumes.

1 Introduction

Whistler-mode waves are known to play a crucial role in driving both acceleration and loss of particles in the inner magnetosphere, and in the Van Allen radition belts in particular (e.g. [1, 2, 3]). Here, we focus on two types of whistler-mode waves, chorus and plasmaspheric hiss. Chorus waves occur at frequencies between about 0.05 and 0.90 of the equatorial electron cyclotron frequency (f_{ce}) with a characteristic minimum in wave power usually centered around 0.5 f_{ce}. Chorus typically consists of coherent burst emissions that may exhibit rising or falling tone structures [4, 5]. Occurring in the relatively low-density region outside of the plasmasphere, chorus is believed to be highly efficient for the acceleration of electrons up to relativistic energies in the heart of the Van Allen radiation belt. By comparison, plasmaspheric hiss waves are more broadband in nature, occurring between around 30 Hz up to several kHz and typically confined to the high-density region of the plasmasphere, or inside of plasmaspheric plumes [6, 7]. Plasmasphseric hiss is reported as being the primary driver of losses in the slot region between the inner and outer radiation belts [8].

Using data from numerous spacecraft missions, direct observations of strong correlation of between chorus waves plasmaspheric hiss have been reported [9, 10, 11, 12]. A causal link between the two wave modes has been proposed, with chorus waves propagating up to high latitudes, across the plasmapause boundary, entering the plasmasphere, and subsequently evolving into plasmaspheric hiss. The plausibility of this process has been confirmed using extensive ray tracing simulations where the typical features of plasmaspheric hiss (e.g. amplitude, frequency range, and spatial structure) have been well reproduced, albeit using an angular distribution of chorus wave power that had not been observationally verified [13, 14, 15]. These modeling efforts established that chorus waves occurring with a specific set of initial conditions were key to this process. The key parameters for chorus waves to enter the plasmasphere were identified as; source locations within ~3 R_E of the plasmapause, wave vectors oriented both oblique with respect to the background magnetic field and azimuthally towards the Earth, and wave frequencies less than 0.30 f_{ce} [16].

Here, we use a dual approach of ray racing simulations, coupled with both survey and burst mode observations from the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) Waves instrument onboard the Van Allen Probes spacecraft, to quantify the amount of chorus wave power that exists with the conditions required to enter the plasmasphere and be a source of plasmaspheric hiss [17].

The ray tracing simulations demonstrate that, generally speaking, only a very small range of initial chorus wave orientations result in a wave propagating into the plasmasphere. However, if the chorus source is located close to a plasmaspheric plume, azimuthal density gradients modify the wave propagation to permit a large range of initial chorus wave vector orientations to propagate into the plasmasphere. The results of these ray tracing simulations are subsequently compared to observations of chorus wave power as a function of wave vector orientation. Both survey and burst mode observations demonstrate that without a plume present, only a small fraction (< 2%) of chorus wave power exists with the required wave vector orientation to propagate into the plasmasphere. In the presence of a plume, up to 96% of chorus wave power is shown to be able to access the plasmasphere. We therefore identify plasmaspheric plumes as an important access region if a significant fraction of chorus wave power is to enter the plasmasphere and be a source of plasmaspheric hiss. As such, particular attention is devoted to this region.

2 Ray Tracing Simulations

Ray tracing simulations are used to determine the initial chorus wave vector orientations that allow waves to propagate into the plasmasphere. For the ray tracing medium, we implement a plasma density model that is driven by the Rice Convection Model (RCM) electric field for the main phase of the 21 April 2001 geomagnetic storm [18, 19]. This density model is shown in greyscale in Figure 1, with the plasmapause boundary of 50 cm^{-3} indicated by the dashed pink line. A plasmaspheric plume density structure is evident on the duskside. Chorus (0.20 f_{ce}) is injected from different source locations in MLT and L, indicated by the blue (MLT = 14, L = 5), pink (MLT = 16, L = 6), and yellow (MLT = 12, L = 5) circles. The full range of wave normal angles is traced in order to determine which initial polar angles, theta (radial direction with 0° in plot center, 90° for outermost circle), and azimuthal angles, phi (tangential direction), result in a chorus wave being able to propagate into the plasmasphere from each source location. The region in theta-phi space is shown in green if a wave can enter the plasmasphere, and red if it cannot enter the plasmasphere.

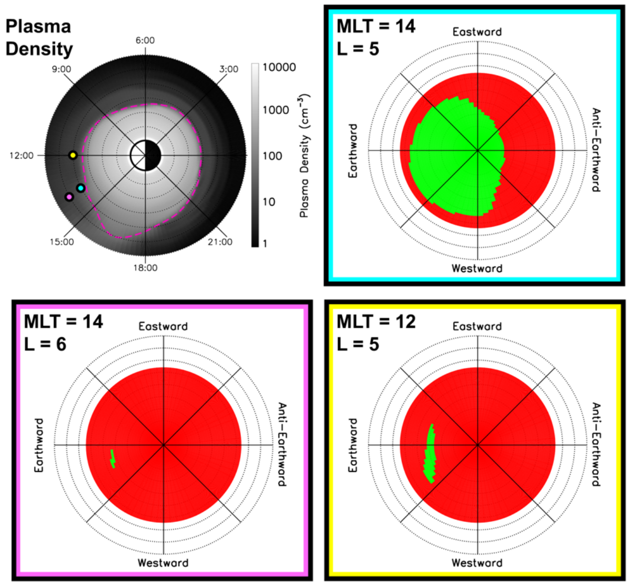

Figure 1. The plasma density model implemented in ray tracing simulations and the range of wave normal angles that can propagate into the plasmasphere (green region) for different source locations in MLT and L.

It is evident from Figure 1 that for the injection site located right on the edge of the plasmaspheric plume structure at MLT = 14 and L = 5 (blue), a broad range of initial wave normal angles can propagate into the plasmasphere, including field-aligned waves that are propagating parallel or anti-parallel with respect to the background magnetic field (center of plot). However, if the chorus source is moved radially outwards away from the plume structure, MLT = 14 and L = 6 (pink), the range of wave vector orientations that can propagate into the plasmasphere becomes extremely limited, restricted to only a very small range of obliquely propagating waves that are oriented azimuthally Earthwards. The same is true when the chorus source is moved azimuthally away from the plume structure to MLT = 12 and L = 5 (yellow). The range of wave normal angles that can access the plasmasphere substantially shrinks and is again limited to wave vectors that are both oblique and oriented Earthwards. This analysis has also been performed for 0.10 f_{ce}, and 0.15 f_{ce} chorus waves, with similar results obtained for all frequencies.

3 Angular Distributions of Chorus Waves

We present angular distributions detailing chorus wave power as a function of wave vector orientation using both survey and burst mode observations from the Van Allen Probes EMFISIS Waves instrument. Survey mode spectra are computed onboard the spacecraft based on 0.5s waveform captures every 6s. However, it has been reported that the wave vector angle can exhibit large variations over shorter timescales, within a single chorus subpacket [20]. These small-timescale variations cannot be resolved when analyzing data captured in survey mode and, as such, we also implement high-resolution burst mode measurements in this analysis. Using high-resolution burst mode data allows us to resolve individual chorus element structures and to take strides towards accounting for short-timescale variations in the wave vector angle.

Figure 2 contains angular distributions of wave power for 0.10 f_{ce} chorus observed in survey mode (left) and burst mode (right) for a range of different locations in MLT and L, from MLT = 14 and L = 5 (top), MLT = 14 and L = 6 (middle), and MLT = 12 and L = 5 (bottom). Each distribution is normalized such that the sum over the entire distribution is equal to unity, and as such, we consider these as probability distribution functions (PDFs) of wave power. In general, survey and burst mode observations are in agreement, with the majority of wave power occurring for waves oriented azimuthally anti-Earthwards and with a polar angle of less than ~30 degrees. This angular structure is a consequence of wave propagation, where a field-aligned wave vector in the equatorial source region becomes increasingly inclined in the anti-Earthward during as the wave propagates to higher latitudes. Some discrepancies between survey and burst mode are apparent, particularly for MLT = 12 and L = 5. This likely originates due to the very low quantities of wave power observed at this location. It should also be noted that burst mode observations are actively biased towards more geomagnetically active periods where wave amplitudes are typically elevated. Finally, we note that there actually only appears to be small variations in these angular distributions of wave power as a function of MLT and L.

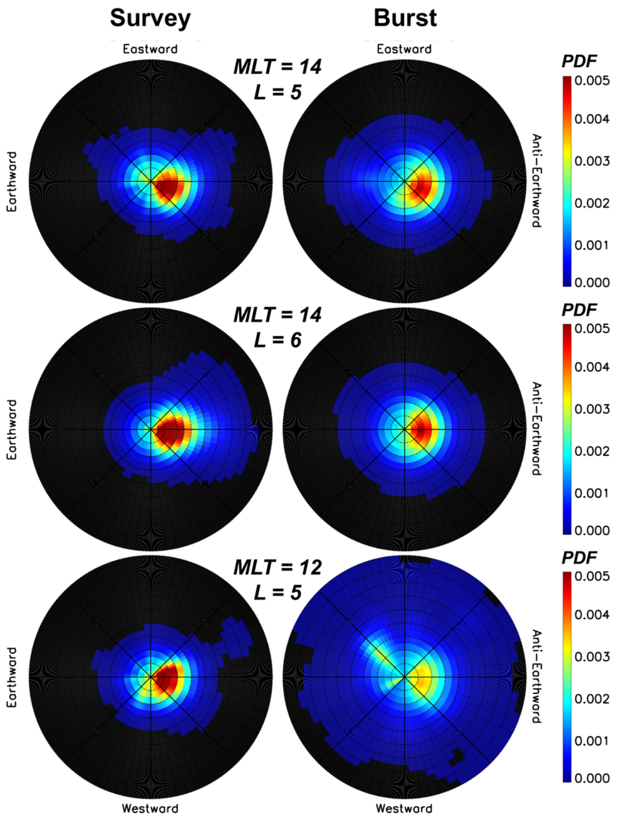

Figure 2. Probability distribution functions of chorus wave power based on survey (left) and burst (right) mode observations for different locations in MLT and L as listed.

Comparison between the angular distributions of chorus wave power and ray tracing simulations allows for an estimation of the fraction of chorus wave power that can propagate into the plasmasphere and potentially be a source of plasmaspheric hiss. That is, we essentially overlay the angular region that can access the plasmasphere, shown by the green region in Figure 1, on to the distributions of chorus wave power shown in Figure 2 and determine the percentage of wave power contained within the overlaid region. These percentages are computed for both survey and burst mode observations, for a range of different MLT and L values. These results are summarized in Table 1.

Whilst we do not show statistics for all MLT values in Table 1, we do note that on dawnside (where the peak in chorus wave power is typically observed) the azimuthal density gradients in the model become negligible, wave damping rates increase, and the percentages of chorus wave power that can access the plasmasphere are comparable to those obtained at MLT = 12, being ~1% or less. These results highlight that it is possible for a substantial fraction of chorus wave power to access the plasmasphere, but that this process seems to be localized to a small region in the vicinity of plasmaspheric plumes.

Table 1. Percentage of chorus wave power that can access plasmasphere for different source regions and frequencies for survey (top) and burst (bottom) mode observations.

L	**MLT**	**0.10 f_{ce}**	**0.15 f_{ce}**	**0.20 f_{ce}**
5	**12**	0.16% 2.0%	1.1% 2.9%	0.42% 1.1%
	14	94% 96%	86% 95%	82% 95%
6	**12**	0% 0%	0% 0%	0% 0%
	14	4.9% 6.9%	<0.01% 0.02%	<0.01% <0.01%

4 Conclusions

The angular distribution of chorus waves has been assessed and the fraction of power observed with the wave vector direction required to propagate into the plasmasphere and potentially evolve into plasmaspheric hiss has been computed. It was found that a significant fraction of chorus wave power can access the plasmasphere but only when the chorus source is located in close proximity to a plasmaspheric plume. For other source locations, only a very small fraction of chorus wave power can access the plasmasphere. This conclusion is reached regardless of whether EMFISIS survey or burst mode data is used. That is, considering the short-timescale variations in the wave vector angle does not significantly affect the percentage of chorus power that exists within the crucial range of wave vector orientations. To place these conclusions in context, we note that plumes are most commonly observed on the dusk side whereas chorus wave power typically peaks on the dawn side. The post-noon sector, where these two statistical distributions overlap, appears to be key for observing correlations between chorus and hiss. This result has been independently verified by statistics of correlations between chorus and hiss from THEMIS [12].

5 Future Work

These results identified chorus sources located near plumes as a necessary criterion if chorus is to be a significant source of plasmaspheric hiss. It therefore follows that direct investigation of chorus waves near plumes is crucial to determining the coupling mechanism between chorus and hiss. To date, no such studies have taken place, and chorus wave properties and propagation characteristics in the vicinity of plumes has not been directly studied. This work is planned for a future study.

6 Acknowledgments

This work was performed under the support of JHU/APL contract 921647 under NASA Prime contract NAS5-01072. R. B. H. acknowledges the Natural Environment Research Council (NERC) Highlight Topic Grant NE/P01738X/1 (Rad-Sat). O. S. acknowledges support from grants LTAUSA17070 and from the Praemium

Academiae award. This paper summarizes, and extends, the results of previously published materials [17].

7 References

1. R. M. Thorne, "Radiation belt dynamics: The importance of wave-particle interactions", Geophys. Res. Lett., 37, L22107, 2010.

2. J. Bortnik and R. M. Thorne, "The dual role of ELF/VLF chorus waves in the acceleration and precipitation of radiation belt electrons", J. Atmos. Sol.-Terr. Phys, 69(3), 378-386, 2007.

3. D. Summers et al., "Timescales for radiation belt electron acceleration and loss due to resonant wave-particle interactions: 2. Evaluation for VLF chorus, ELF hiss, and electromagnetic ion cyclotron waves", J. Geophys. Res., 112, A04207, 2007.

4. D. A. Gurnett and B. J. O'Brien, "High latitude geophysical studies with satellite Injun 3: 5. Very low frequency electromagnetic radiation", J. Geophys. Res., 69(1), 65-89, 1964.

5. W. J. Burtis and R. A. Helliwell, "Banded chorus a new type of VLF radiation observed in the magnetosphere by OGO 1 and OGO 3", J. Geophys. Res., 74(11), 3002-3010, 1969.

6. R. M. Thorne et al., "Plasmaspheric hiss", J. Geophys. Res., 78(10), 1581-1596, 1973.

7. N. P. Meredith et al., "Substorm dependence of plasmaspheric hiss", J. Geophys. Res., 109, A06209, 2004.

8. L. Lyons et al., "Pitch-angle diffusion of radiation belt electrons within the plasmasphere", J. Geophys. Res., 77(19), 3455-3474, 1972.

9. J. Bortnik et al., "An observation linking the origin of plasmaspheric hiss to discrete chorus emissions", Science, 324(5928), 775-8, 2009.

10. C. Wang et al., "The relations between magnetospheric chorus and hiss inside and outside the plasmasphere boundary layer: Cluster observation", J. Geophys. Res., 116, A07221, 2011.

11. W. Li et al., "First evidence for chorus at a large geocentric distance as a source of plasmaspheric hiss: Coordinated THEMIS and Van Allen Probes observation", Geophys. Res. Lett., 42, 241-248, 2015.

12. O. Agapitov et al., "Spatial extent and temporal correlation of chorus and hiss: Statistical results from multipoint THEMIS observations", J. Geophys. Res., 123, 8317-8330, 2018.

13. L. Chen et al., "Modeling the properties of plasmaspheric hiss: 2. Dependence on the plasma density distribution", J. Geophys. Res.,117, A05202, 2012.

14. L. Chen et al., "Amplification of whistler-mode hiss inside the plasmasphere", Geophys. Res. Lett., 39, L08111, 2012.

15. N. P. Meredith et al., "Global statistical evidence for chorus as the embryonic source of plasmaspheric hiss", Geophys. Res. Lett., 40, 2891-2896, 2013.

16. L. Chen et al., "Modeling the properties of plasmaspheric hiss: 1. Dependence on chorus wave emission", J. Geophys. Res.,117, A05201, 2012.

17. D. P. Hartley et al., "Van Allen Probes observations of chorus wave vector orientations: Implications for the chorus-to-hiss mechanism", Geophys. Res. Lett., 46, 2337-2346, 2019.

18. L. Chen et al., "Three-dimensional ray tracing of VLF waves in a magnetospheric environment containing a plasmaspheric plume", Geophys. Res. Lett., 36, L22101, 2009.

19. J. Bortnik et al., "Modeling the propagation characteristics of chorus using CRRES suprathermal electron fluxes, J. Geophys. Res., 112, A08204, 2007.

20. O. Santolík et al., "Fine structure of large-amplitude chorus wave packets", Geophys. Res. Lett., 41, 293-299, doi:10.1002/2013GL058889, 2014.