GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L11101, doi:10.1029/2009GL037629, 2009

Source regions of banded chorus

T. F. Bell,[1] U. S. Inan,[1] N. Haque,[1] and J. S. Pickett[2]

Received 12 February 2009; revised 19 April 2009; accepted 29 April 2009; published 5 June 2009.

[1] ELF/VLF chorus emissions are very intense electromagnetic plasma waves that are naturally and spontaneously excited near the magnetic equatorial plane outside the plasmasphere during periods of magnetic disturbance. These emissions are believed to play an important role in the acceleration of 10 to 100 keV radiation belt electrons to MeV energies during the disturbed time periods. Spacecraft observations near the magnetic equatorial plane in the regions where chorus emissions are generated show that the chorus often appears in two distinct frequency bands, one band below $f_{ce}/2$ and one band above $f_{ce}/2$, where f_{ce} is the local electron gyrofrequency. This configuration is known as banded chorus. In the present paper we show that this type of configuration can be readily explained if it is assumed that the chorus is excited in ducts of either enhanced or depleted cold plasma density. **Citation:** Bell, T. F., U. S. Inan, N. Haque, and J. S. Pickett (2009), Source regions of banded chorus, *Geophys. Res. Lett.*, *36*, L11101, doi:10.1029/2009GL037629.

1. Introduction

[2] ELF/VLF chorus emissions are very intense electromagnetic plasma waves that are naturally and spontaneously excited near the magnetic equatorial plane outside the plasmasphere during periods of magnetic disturbance [*Burtis and Helliwell*, 1969; *Burton and Holzer*, 1974; *Tsurutani and Smith*, 1974; *Santolík et al.*, 2003]. These emissions are believed to play an important role in the acceleration of 10 to 100 keV radiation belt electrons to MeV energies during the disturbed time periods [*Meredith et al.*, 2003]. Spacecraft observations near the magnetic equatorial plane in the regions where chorus emissions are generated show that the chorus often appears in two distinct frequency bands, one band below $f_{ce}/2$ and one band above $f_{ce}/2$, where f_{ce} is the local electron gyrofrequency [e.g., *Santolík et al.*, 2004]. This configuration is known as banded chorus.

[3] An example of banded chorus as observed on the CLUSTER 1 spacecraft by the Wide Band (WBD) instrument is shown in Figure 1, which consists of 5 seconds of plasma wave data displayed as a frequency-time spectrogram over the 1 to 5 kHz frequency range. This data was acquired when the spacecraft was located at a magnetic latitude of $\simeq 3°$, and the average value of f_{ce} was 6.8 kHz as measured by the onboard flux gate magnetometer (FGM) instrument. The lower-band chorus extends from approximately 1 to 3 kHz, while the upper-band chorus extends from $\simeq$3.3 to 4.5 kHz. In the 300 Hz gap between the two chorus bands, the plasma wave intensity is approximately 40 dB below that of the chorus. In general, the lower-cut-off frequency of the upper-band chorus lies slightly above the frequency $f \simeq f_{ce}/2$.

[4] During periods of magnetic disturbance, banded chorus has been observed on spacecraft at all local times in the region $4 \leq L \leq 9$, although it is most common in the midnight-noon LT sector [*Burtis and Helliwell*, 1969, 1976; *Tsurutani and Smith*, 1974; *Koons and Roeder*, 1990]. In general banded chorus follows the same spatial distribution as all chorus, but with a reduced frequency of occurrence. The width of the gap δf between the upper band and the lower band is variable and generally lies in the range: $0 \leq \delta f \leq f_{ce}/5$ [*Koons and Roeder*, 1990]. At the present time there is no commonly accepted explanation for the frequency gap which exists between the lower-band and upper-band chorus or why the frequency $f = f_{ce}/2$ commonly falls within this gap. Early workers suggested that the gap might be due either to propagation effects [*Tsurutani and Smith*, 1974; *Burtis and Helliwell*, 1969, 1976] or emission effects [*Maeda*, 1976; *Curtis*, 1978]. However these suggestions were not subsequently developed in detail. Recently *Bortnik et al.* [2006] found that Landau damping effects could produce a frequency gap near $f_{ce}/2$, but generally only after the chorus had propagated a significant distance away from the magnetic equator. As we discuss below, the two separate bands and the gap between them are characteristics that appear to arise from the properties of the chorus source regions.

2. Commonalities of Three Emission Types

[5] It is commonly believed that chorus emissions are generated spontaneously through a gyroresonance interaction in which a triggering plasma wave from the noise background is amplified by energetic radiation belt electrons with an anisotropic velocity distribution [*Burtis and Helliwell*, 1969; *Tsurutani and Smith*, 1974; *Meredith et al.*, 2003]. The condition for this interaction is given by the relation:

$$v_z \simeq (\omega_{ce}/\gamma - \omega)/k_z \qquad (1)$$

where v_z is the velocity of the energetic electrons along the direction of the Earth's magnetic field, $\mathbf{B_o}$, ω_{ce} is the electron gyrofrequency, $\gamma = 1/\sqrt{1 - v^2/c^2}$, ω is the wave frequency, and k_z is the component of the wave vector $\mathbf{k}$ along $\mathbf{B_o}$.

[6] The resonance condition given by equation (1) is common to two other processes in the magnetosphere by which emissions are also excited by triggering waves: (1) the triggering of ELF/VLF emissions in the plasmasphere by signals from ground based transmitters [*Helliwell and*

[1]STAR Laboratory, Stanford University, Stanford, California, USA.
[2]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA.

0094-8276/09/2009GL037629$05.00

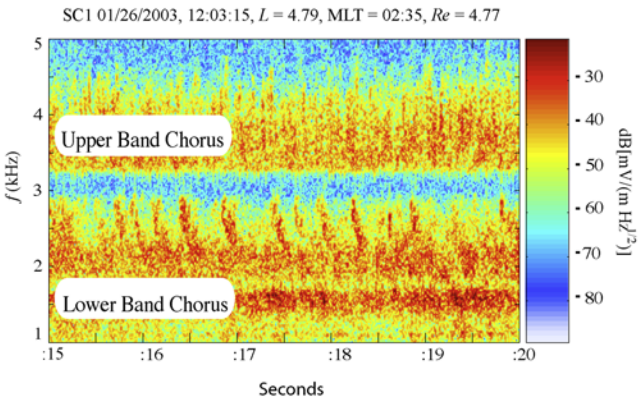

Figure 1. Frequency-time spectrogram showing an example of banded-chorus as observed on the CLUSTER 1 spacecraft on 01/26/2003.

Katsufrakis, 1974]; and (2) the triggering of Auroral Kilometric Radiation (AKR) in the polar regions by background plasma waves [*Gurnett*, 1974].

[7] Figure 2 shows an example of VLF emissions triggered in the plasmasphere by fixed frequency signals from the Siple Station ELF/VLF transmitter [*Helliwell and Katsufrakis*, 1974]. The instability of the plasma which gives rise to the emissions is known as the "coherent wave instability" (CWI) because the emissions are triggered only when a coherent ELF/VLF input wave is present as the triggering signal [*Mielke and Helliwell*, 1992]. In general triggered emissions such as these within the plasmasphere closely resemble many chorus emissions triggered outside the plasmasphere [e.g., *Pickett et al.*, 2004].

[8] Two decades of experiments at Siple Station, Antarctica, have demonstrated that the CWI takes place within whistler mode ducts, which are thought to be magnetic-field-aligned columns of enhanced cold plasma density extending between conjugate hemispheres [*Helliwell and Katsufrakis*, 1974]. In addition, ISEE-1 spacecraft observations showed that very few ELF/VLF emissions triggered by ground-based VLF transmitter signals were triggered outside whistler mode ducts [*Bell et al.*, 1981]. This leads to the conclusion that the CWI takes place predominantly within whistler mode ducts.

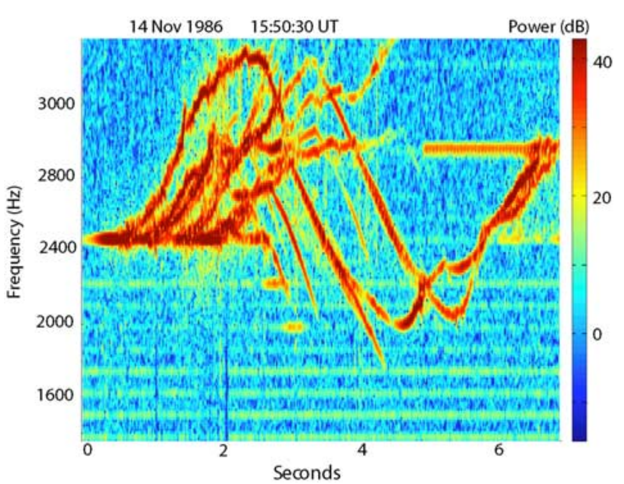

Figure 2. Frequency-time spectrogram showing a two second-duration, fixed frequency pulse at 2.46 kHz from the Siple Station transmitter as received in the northern hemisphere at Lake Mistissini. The Siple pulse triggers a series of emissions which closely resemble chorus emissions.

[9] AKR is believed to be excited at $f \simeq f_{ce}$ at relatively low altitudes, and thus is observed at much higher frequency than chorus. However it generally consists of many discrete narrow band emissions [*Gurnett and Anderson*, 1981] whose form resembles the form of many chorus emissions. AKR is believed to be generated within auroral depletion ducts (cavities) in which the cold plasma density is much less than the local ambient density average.

[10] Noting that the three types of emissions discussed above are generated through gyroresonance according to a common relationship expressed by equation (1), that many of the frequency-time characteristics of the emissions are similar, and that two of these classes of emissions are generated within either enhancement or depletion ducts, it appears reasonable to suggest that the third class of emissions, ELF/VLF banded-chorus, is also generated within either enhancement or depletion ducts. As discussed below, this assumption leads to a simple explanation of the banded structure of chorus.

3. Ducting of Whistler Mode Waves

[11] *Santolík et al.* [2003] have found that chorus waves propagate with their **k** vector at very small wave normal angles ψ with respect to $\mathbf{B_o}$. According to *Smith et al.* [1960], when $\psi \simeq 0$ whistler mode waves can be trapped within ducts of enhanced or depleted plasma density only under the following conditions:

[12] 1. For frequencies in the range $0 \leq f < f_{ce}/2$, whistler mode waves can be trapped only in ducts of enhanced cold plasma density.

[13] 2. For frequencies in the range $f_{ce}/2 \leq f \leq f_{ce}$, whistler mode waves can be trapped only in ducts of depleted cold plasma density.

[14] Considering the above, the structure of banded chorus can be explained if the lower-band chorus is generated within enhancement ducts while the upper-band chorus is generated within depletion ducts. Since the enhancement duct cannot guide whistler mode waves when $f = f_{ce}/2$, there will be a small gap between the upper and lower chorus bands.

[15] The ducting conditions given above assume that the ducts are isolated, that the cold plasma density N_o varies

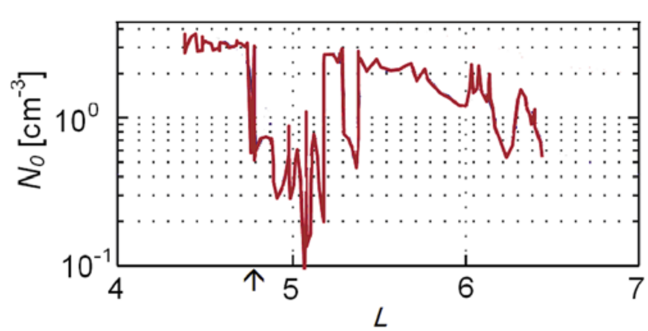

Figure 3. A plot of cold plasma density as a function of L shell in the magnetic equatorial plane.

smoothly in the plane perpendicular to $\mathbf{B_o}$ and that gradients in N_o and $\mathbf{B_o}$ along the direction of $\mathbf{B_o}$ are negligible. If one includes the curvature of $\mathbf{B_o}$ and the gradient of N_o along $\mathbf{B_o}$ in the ducting model, it is found that the upper cutoff frequency of the lower-band chorus is further reduced below $f_{ce}/2$, while the lower cutoff frequency of the upper-band chorus is relatively less affected.

[16] The actual ducting structures in the chorus generation region may not always conform to the assumption that the structures are isolated. For example in Figure 3 we show a plot of N_o versus L shell on 01/26/2003, the same orbit on which the wave data shown in Figure 1 was acquired. This plot was constructed from the data points given by *Platino et al.* [2004, Figure 4].

[17] Figure 3 shows that N_o is quite irregular and has a number of maxima and minima in the region $4.5 \leq L \leq 5.5$. Some, or all, of these maxima could possibly qualify as enhancement ducts. The minima between these maxima could also possibly qualify as depletion ducts. The arrow on the horizontal axis marks the position at which the data in Figure 1 was acquired. This point is at the edge of the first sharp decrease in N_o.

[18] Although in the case of the emissions excited through the CWI the enhancement ducts extend between conjugate hemispheres, this does not have to be true for the ducts in which banded-chorus is generated. For example, the dimensions of the region in which chorus is generated is thought to have a scale of $\simeq$100 km perpendicular to $\mathbf{B_o}$ and a scale of $\simeq$1000 km parallel to $\mathbf{B_o}$ [*Santolík and Gurnett*, 2003; *Santolík et al.*, 2004; *Trakhtengerts*, 1999; *Helliwell*, 1967]. Thus enhancement or depletion ducts connected with banded-chorus need only extend roughly 1000 km along $\mathbf{B_o}$.

[19] Chorus emissions are often seen to repeat in a periodic way. For example, Figure 4 shows CLUSTER observations of lower-band chorus consisting of similar multiple elements with linearly increasing frequency with a maximum repetition rate of $\simeq$4 to 10 per second. This behavior is consistent with chorus generation within whistler mode ducts. For example, as a chorus emission exits the duct, a small internally reflected component may propagate back to the other end of the duct where a second small internal reflection may take place. The twice reflected component may then act as a seed wave which triggers a second chorus emission. This process then repeats to produce periodic chorus elements. For a 1500 km long duct and a group velocity of $\simeq c/20$, the repetition rate of the emissions would be $\simeq$5 per second, which is consistent with the rates seen in Figure 4.

[20] It should be noted here that in principle lower-band chorus can also be trapped in depletion ducts if ψ is close to the Gendrin angle, ψ_g, which is the angle at which $k_z(\psi)$, has its least minimum [*Smith et al.*, 1960]. In a recent study of banded chorus observed on the POLAR spacecraft, *Lauben et al.* [2002] carried out a ray tracing simulation which suggested that many lower-band chorus elements appeared to be generated with $\psi \simeq \psi_g$. In addition, a later study by *Inan et al.* [2004] of banded chorus observed on CLUSTER suggested that lower-band chorus appeared to be generated with wave normal angles in the range: $0 \leq \psi \leq \psi_g$. The significance of these findings is difficult to assess because the ray tracing simulations in both studies were carried out under the assumption that all wave propagation took place

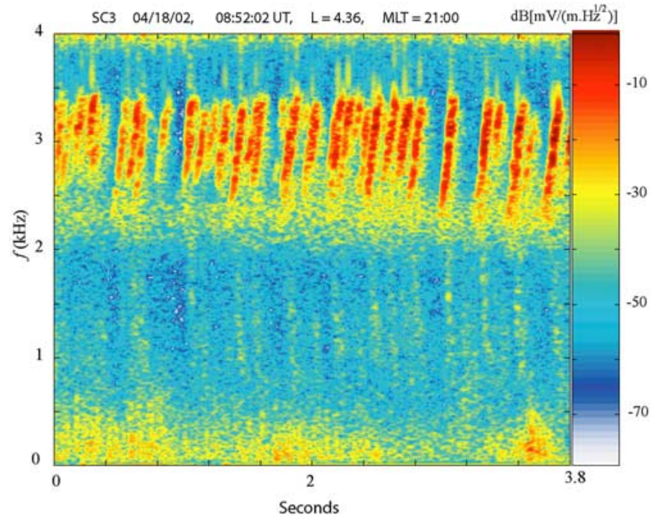

Figure 4. Lower-band chorus consisting of similar multiple elements with linearly increasing frequency. Maximum repetition rate is approximately 10 per second.

in a smoothly varying plasma that contained no ducts. However the consistency of the results suggests that some lower-band chorus may indeed be generated in depletion ducts. This possibility does not affect our model because the trapping of lower-band chorus in depletion ducts can only occur for $f < f_{ce}/2$.

4. Summary and Discussion

[21] Noting the commonality of banded-chorus with two other types of triggered emissions which are known to be excited in either enhancement or depletion ducts, we suggest that banded-chorus is also excited within ducts. In particular we suggest that upper-band chorus is excited within whistler mode depletion ducts and that lower-band chorus is excited within enhancement ducts. Adoption of this suggestion leads to a straightforward explanation for the two bands, the gap between the two bands, and the fact that the frequency $f = f_{ce}/2$ lies within the gap.

[22] If our suggestions are correct, its consequences may have a far reaching effect upon our understanding of the conditions under which banded-chorus is excited and the locations where this excitation takes place. For example, in Figure 3 it can be seen that the maxima of N_o have values 2 to 4 times that of one of the adjacent mimima between the peaks. If these maxima and minima are typical of those in which banded-chorus is excited, then since N_o affects equation (1), this suggests that very different groups of energetic electrons may be involved in the excitation of the two chorus bands, even though the two bands are generally separated in frequency by less than 500 Hz.

[23] A second consequence would be the limitation of the banded-chorus sources to a finite number of locations within the magnetosphere, i.e., the maxima and minima of N_o as a function of L shell. Thus, banded-chorus would not be excited continuously near the magnetic equatorial plane over some large range of L outside the plasmapause. This limitation could affect the number of 10–100 keV electrons which can be accelerated to MeV energies by banded-chorus waves during a given time interval.

[24] One method of addressing the questions we have raised is to carry out a detailed study of the correlation between the WBD plasma wave data and the Whisper electric field data when one or more CLUSTER spacecraft are near, or within, the chorus generation region. The aim would be to determine the relationship between plasma density ducts of $\simeq$100 km scale transverse to $\mathbf{B_o}$ and the banded-chorus intensity and distribution. Wave normal measurements of the chorus with the CLUSTER STAFF-SA instrument would be important to determine if the chorus appears to propagate to the spacecraft from the ducts.

[25] Since banded-chorus is such a common form of chorus, if it is excited within whistler mode enhancement or depletion ducts as we suggest, then it is possible that most, or all, forms of chorus are excited within similar ducts. If this is the case, then we must learn much more about the properties of these ducts if we are to understand chorus.

[26] **Acknowledgments.** We are grateful to P. Decreau for providing the WHISPER data, and the FGM team for providing the magnetometer data though the ESA Cluster Active Archive. Stanford workers were supported in part by subcontract with the University of Iowa under NASA/GSFC grant NNX07AI24G, and in part by HAARP (High Frequency Active Auroral Research Program) under Department of Navy grant N00014-05-C-0525.

References

Bell, T. F., U. S. Inan, and R. A. Helliwell (1981), Nonducted coherent VLF waves and associated triggered emissions observed on the ISEE-1 satellite, *J. Geophys. Res.*, *86*, 4649.

Bortnik, J., U. S. Inan, and T. F. Bell (2006), Landau damping and resultant unidirectional propagation of chorus waves, *Geophys. Res. Lett.*, *33*, L03102, doi:10.1029/2005GL024553.

Burtis, W. J., and R. A. Helliwell (1969), Banded chorus—A new type of VLF radiation observed in the magnetosphere by OGO 1 and OGO 3, *J. Geophys. Res.*, *74*, 3002.

Burtis, W. J., and R. A. Helliwell (1976), Magnetospheric chorus: Occurrence patterns and normalized frequency, *Planet. Space Sci.*, *24*, 1007.

Burton, R. K., and R. E. Holzer (1974), The origin and propagation of chorus in the outer magnetosphere, *J. Geophys. Res.*, *79*, 1014.

Curtis, S. A. (1978), A theory for chorus generation by energetic electrons during substorms, *J. Geophys. Res.*, *83*, 3841.

Gurnett, D. A. (1974), The Earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res.*, *79*, 4227.

Gurnett, D. A., and R. R. Anderson (1981), The kilometric radio emission spectrum: Relation to auroral acceleration processes, in *Physics of Auroral Arc Formation*, *Geophys. Monogr. Ser.*, vol. 25, edited by S.-I. Akasofu and J. R. Kan, p. 341, AGU, Washington, D. C.

Helliwell, R. A. (1967), A theory of discrete VLF emissions from the magnetosphere, *J. Geophys. Res.*, *72*, 4773.

Helliwell, R. A., and J. P. Katsufrakis (1974), VLF wave injection into the magnetosphere from Siple Station, Antarctica, *J. Geophys. Res.*, *79*, 2511.

Inan, U. S., M. Platino, T. F. Bell, D. A. Gurnett, and J. S. Pickett (2004), Cluster measurements of rapidly moving sources of ELF/VLF chorus, *J. Geophys. Res.*, *109*, A05214, doi:10.1029/2003JA010289.

Koons, H. C., and J. L. Roeder (1990), A survey of equatorial magnetospheric wave activity between 5 and 8 R_E, *Planet. Space. Sci.*, *38*, 1335.

Lauben, D. S., U. S. Inan, T. F. Bell, and D. A. Gurnett (2002), Source characteristics of ELF/VLF chorus, *J. Geophys. Res.*, *107*(A12), 1429, doi:10.1029/2000JA003019.

Maeda, K. (1976), Cyclotron side-band emissions from ring current electrons, *Planet. Space Sci.*, *24*, 341.

Meredith, N. P., M. Cain, R. B. Horne, R. M. Thorne, D. Summers, and R. R. Anderson (2003), Evidence for chorus-driven electron acceleration to relativistic energies from a survey of geomagnetically disturbed periods, *J. Geophys. Res.*, *108*(A6), 1248, doi:10.1029/2002JA009764.

Mielke, T. A., and R. A. Helliwell (1992), An experiment on the threshold effect in the coherent wave instability, *Geophys. Res. Lett.*, *19*, 2075.

Pickett, J. S., et al. (2004), Multi-Point CLUSTER observations of VLF risers, fallers and hooks at and near the plasmapause, in *Multiscale Processes in the Earth's Magnetosphere: From Interball to Cluster*, *NATO Sci Ser., Ser. II*, p. 307, Kluwer Acad., Dordrecht, Netherlands.

Platino, M., U. S. Inan, T. F. Bell, J. S. Pickett, E. J. Kennedy, J. G. Trotignon, J. L. Rauch, and P. Canu (2004), Cluster observations of ELF/VLF signals generated by modulated heating of the lower ionosphere with the HAARP HF transmitter, *Ann. Geophys.*, *22*, 2643.

Santolík, O., and D. A. Gurnett (2003), Transverse dimensions of chorus in the source region, *Geophys. Res. Lett.*, *30*(2), 1031, doi:10.1029/2002GL016178.

Santolík, O., D. A. Gurnett, J. S. Pickett, M. Parrot, and N. Cornilleau-Wehrlin (2003), Spatio-temporal structure of storm-time chorus, *J. Geophys. Res.*, *108*(A7), 1278, doi:10.1029/2002JA009791.

Santolík, O., D. A. Gurnett, and J. S. Pickett (2004), Multipoint investigation of the source region of storm-time chorus, *Ann. Geophys.*, *22*, 2555.

Smith, R. L., R. A. Helliwell, and I. W. Yabroff (1960), A theory of trapping of whistlers in field-aligned columns of enhanced ionization, *J. Geophys. Res.*, *65*, 815.

Trakhtengerts, V. (1999), A generation mechanism for chorus emissions, *Ann. Geophys.*, *17*, 95.

Tsurutani, B. T., and E. J. Smith (1974), Postmidnight chorus: A substorm phenomenon, *J. Geophys. Res.*, *79*, 118.

T. F. Bell, N. Haque, and U. S. Inan, STAR Lab, Stanford University, 350 Serra Mall, Stanford, CA 94305-9515, USA. (bell@nova.stanford.edu)

J. S. Pickett, Department of Physics and Astronomy, University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242-1479, USA.