Cluster observations of whistler mode ducts and banded chorus

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[1] Bell et al. (2009) proposed that the source region for banded chorus consists of whistler mode ducts of depleted electron density (N_e) for upper band (UB) chorus for all wave normal angles (θ) and ducts of either enhanced or depleted N_e for lower band (LB) chorus for small θ and θ near or greater than the Gendrin angle, respectively. This paper provides support for this model using new high resolution (17 km) N_e observations from the Cluster WHISPER and EFW instruments. Data is examined from January 20, 2004, when strong banded chorus was observed over 3000 km of the Cluster 2 orbit, ending at the magnetic equator. Previous analysis of LB chorus on this day indicated the wave normal angles were larger than the Gendrin angle. Using the N_e data, we show that the LB chorus is generated within depletion ducts in the source region and that the half-width of these ducts (~70 km) is comparable to the transverse scale (~100 km) of the chorus source region. Making use of the fact that the group velocity of the LB chorus waves has a significant cross-L component, we show that the source region extends over 500 km near the magnetic equator.
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1. Introduction

[2] Whistler mode chorus waves, intense naturally occurring plasma waves, are observed outside the plasmapause and propagate away from the magnetic equator where they are believed to be generated [*Santolík and Gurnett*, 2003; *Sazhin and Hayakawa*, 1992, and references therein]. These discrete emissions, containing rising and falling tones, range in frequency from hundreds of Hz to several kHz. Chorus is often observed in a banded configuration, with an upper band, UB, above the emission gap at $f_{ce}/2$ and a lower band, LB, below, where f_{ce} denotes equatorial electron gyrofrequency [*Sazhin and Hayakawa*, 1992; *Lauben et al.*, 2002].

[3] Banded chorus is seen during all local times for $L = 4$–9, but mostly occurs during the midnight-noon local time sector [*Sazhin and Hayakawa*, 1992]. *Bell et al.* [2009] suggested the source region of banded chorus consists of whistler mode ducts of either enhanced or depleted cold plasma density, N_e, which guide the waves during the generation process. The ducting depends on the polar wave normal angle, θ, between the wave vector and the ambient magnetic field, $\mathbf{B_o}$. UB chorus can be guided in depletion ducts for all θ. LB chorus can be guided in enhancement ducts for $\theta \sim 0°$ and in depletion ducts for θ near or greater than the Gendrin angle, θ_G, the nonzero angle at which the wave group velocity is parallel to $\mathbf{B_o}$ [*Gendrin*, 1960].

[4] Previous studies of interhemispheric plasmaspheric ducts show the half-width, the width of the duct at which the density enhancement is half its maximum value, ranges from 68 km to hundreds of km [*Scarf and Chappell*, 1973; *Koons*, 1989]. Beyond the plasmasphere, *Santolík and Gurnett* [2003] showed the source region of chorus has a scale of ~100 km transverse to $\mathbf{B_o}$, which may be the characteristic duct scale. If the irregularity is the size of the wavelength of the wave or less, there is considerable leakage of the wave and it is unable to be efficiently guided [*Strangeways*, 1986; *Streltsov et al.*, 2006]. However, if the irregularity is very large compared to a wavelength, the perpendicular gradient of N_e is small and the guidance properties of the duct are reduced. As a compromise, it is assumed that a reasonable half-width for efficient guidance is ~5 wavelengths. This half-width is determined from the electron density profile as a function of L-shell, after the density was projected onto the magnetic equator.

[5] To test the *Bell et al.* [2009] model, N_e must be characterized with high accuracy and with a spatial resolution of ~25 km or less to identify ducts. Such measurements have previously been unavailable. *Koons* [1989] derived densities using the SFR aboard the AMPTE IRM spacecraft, while *Moullard et al.* [2002] supplemented passive, without active, measurements from WHISPER [*Décréau et al.*, 2001] with data from EFW [*Gustafsson et al.*, 1997], both instruments on Cluster. Both investigations showed whistler mode waves are correlated with ducts located at $L = 4$–6.

[6] Figure 1a is a cartoon based on WHISPER N_e measurements from Cluster 1, showing the nature of the ducts for a particular orbit. The ducts shown have large enhancement or depletion factors for conceptual clarity, though usually these factors are much smaller. One possible arrangement of these ducts in the magnetic equatorial plane for L-shell versus East-West distance is seen in Figure 1b. As it is presently unknown how far the ducts extend along the field lines, they may or may not be closely field-aligned.

[7] The present paper examines the relationship between banded chorus and whistler mode ducts on January 20, 2004, as discussed in Sections 3 and 4. We make use of previously unavailable N_e data with high spatial resolution of ~17 km, which have been derived from both passive

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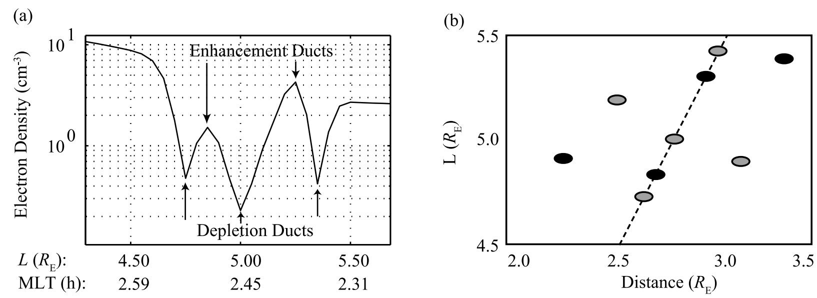

Figure 1. (a) Electron density versus dipole L-shell in Earth radii, R_E, in the equatorial plane with whistler mode enhancement and depletion ducts. Magnetic local time (MLT) in hours is given on the bottom. (b) Possible arrangement of enhancement (black) and depletion (gray) ducts consistent with Figure 1a. Duct distribution is shown in the magnetic equatorial plane for L-shell versus East-West distance. Dashed line indicates equatorial projection of Cluster 1 orbit.

and active measurements from WHISPER, as well as from EFW, as discussed in Section 2.

2. Derivation of Electron Density

[8] The electron density for Cluster 2 on January 20, 2004 is shown in Figure 2b and was derived from WHISPER, which can determine the local plasma frequency over the range of 2–80 kHz and operates in two different modes. In the passive mode, the transmitter is turned off and only natural waves are monitored. In the active mode, WHISPER acts like a topside sounder, triggering resonances at characteristic frequencies, including the plasma frequency, upper hybrid resonance frequency, and the Bernstein modes. Two active spectra, separated by 1.12 seconds, are available every 52 seconds [*Décréau et al.*, 2001]. For each of these spectra, the different resonances were manually identified and the plasma frequency was determined. Given a Cluster orbital velocity of ~5 km/s, WHISPER provides N_e with spatial resolution of ~250 km.

[9] Data from EFW is used to increase the resolution of N_e. The observed plasma frequency from the natural spectra, with time resolution of 1.7 seconds, is used to calibrate N_e derived from the spacecraft potential from EFW. The calibrated N_e is then interpolated between the density points manually determined by the active spectra to obtain the highest resolution and most accurate electron density. Using this method, N_e has a spatial resolution of ~17 km and a time resolution of ~2.2 seconds and is accurate to within 1% [*Canu et al.*, 2001; *Trotignon et al.*, 2003].

3. Relationship Between Chorus and N_e

[10] Figure 2a shows an E field frequency-time spectrogram of WBD [*Gurnett et al.*, 2001] data from Cluster 2 on January 20, 2004, 19:27–19:36 UT, with ephemeris at the bottom. Of primary interest are two sets of banded chorus: Set 1 occurring during 19:27:15–19:30:30 UT and Set 2 occurring during 19:31:15–19:34:30 UT. Set 2 is observed close to the magnetic equator and displays the classic form of banded chorus in the source region, with UB chorus located above $f_{ce}/2$, indicated by the white line, and LB chorus located below. It can be seen that the chorus intensity is much weaker near 19:31 UT and 19:34 UT. A discussion of this effect is given by *Santolík et al.* [2009].

[11] Set 1, located farther from the magnetic equator, has somewhat different characteristics, with the center of the gap between the chorus bands located well below $f_{ce}/2$ and the center frequencies of UB and LB chorus decreasing as $|\lambda|$ increases. These characteristics suggest that the chorus elements in Set 1 were generated near the magnetic equator at higher L shells and subsequently propagated down to Cluster 2. Thus Set 1 is not related to Set 2, but demonstrates that numerous sources of banded chorus were present near the magnetic equatorial plane during this time, a common circumstance when banded chorus is observed.

[12] *Chum et al.* [2009] and *Santolík et al.* [2009] calculated the wave normal distribution for the LB chorus elements shown in Figure 2a using the SVD method [*Santolík et al.*, 2003] on measurements from the STAFF instrument, which has a frequency range up to 4 kHz [*Cornilleau-Wehrlin et al.*, 2003]. For the LB chorus, they found $\theta \sim 70°–80°$ for Set 1 and $\theta \sim 55°–60°$ for Set 2. Since both these angular ranges are greater than θ_G, the LB chorus waves can be guided only in depletion ducts [*Bell et al.*, 2009].

[13] N_e is shown in Figure 2b for the same time interval as Figure 2a. During this interval, Cluster 2 moves ~3000 km parallel to, and ~400 km perpendicular to, the L = 4.3 magnetic field line. Though the L range is not large, N_e still has a number of interesting features.

[14] Three depletion ducts, with widths of 70 km or more, are denoted by labels Duct A, B, and C in Figure 2b. While all three ducts are capable of guiding LB chorus waves, Ducts B and C are of primary interest because they extend throughout the source region, $\lambda \simeq -2°$ up to the magnetic equator for this case. As seen in Figure 2, the banded chorus of Set 2 is generated within either Duct B or C.

[15] While there are many small plasma irregularities within Ducts B and C, most of these are too small to efficiently guide chorus as their half-widths are less than a wavelength. For example, a wave with $f \sim 3.6$ kHz has a wavelength calculated to be ~17 km for $\theta \simeq 0°$ or ~14 km for $\theta \simeq \theta_G$.

[16] Following a method similar to *Lauben et al.* [2002], backward ray tracing was performed on a falling LB chorus element at the beginning of Set 1 located at $L = 4.31$ and $\lambda = -4.60°$ with $\theta \sim 70°$, according to *Chum et al.* [2009] and *Santolík et al.* [2009]. The source location of the element was found to be $L = 4.51$ and $\lambda = -0.46°$, with $\theta = 56.2°$. Although Set 1 is observed simultaneously with Duct A, the chorus is not generated at the same L-shell as Duct A and cannot be guided by it. Since the electron density is unknown for the region near L = 4.51, no association between Set 1 and depletion ducts can be made.

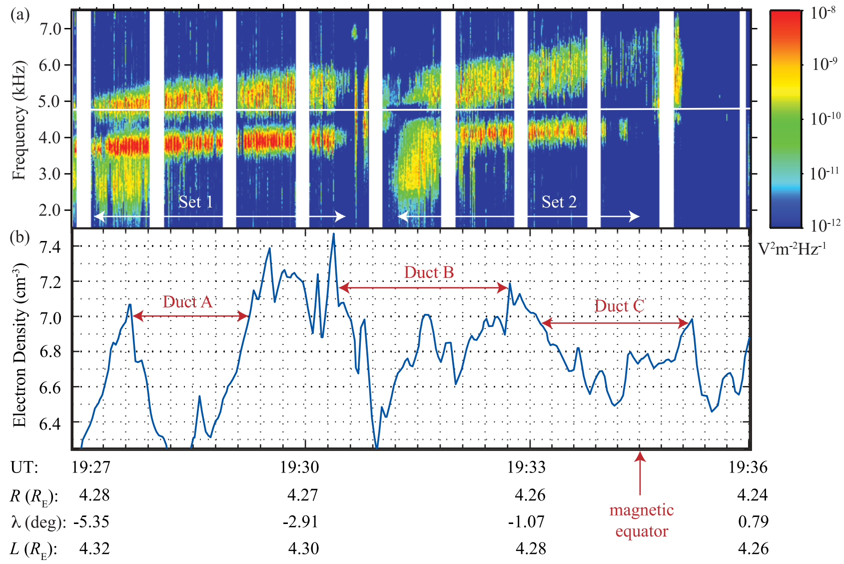

Figure 2. Measurements for Cluster 2 on January 20, 2004 from 19:27–19:36 UT. (a) E field frequency-time spectrogram from WBD measurements showing an event with banded chorus. The vertical white gaps represent times during which the magnetic antenna was sampled, while the horizontal white line represents $f_{ce}/2$. Two sets of banded chorus are denoted as Set 1, further from the magnetic equator, and Set 2, near the magnetic equator. (b) Electron density, with spatial resolution of 17 km, derived from passive and active measurements from WHISPER, along with measurements from EFW. Three depletion ducts, with widths of 70 km or more, are denoted by labels Duct A, B, and C. Ephemeris data for Cluster 2 is given on the bottom. R is radial distance in R_E, λ is magnetic dipole latitude in degrees, and L is dipole L-shell in R_E. The MLT, not shown, has a nearly constant value of 2.76 hours.

[17] A recent study of chorus by *Li et al.* [2011a, 2011b] using THEMIS data demonstrates that density depletions, similar to those shown in Figure 2b, are well correlated with increased chorus intensities. Given the THEMIS data was acquired at $L \sim 6$ and $L \sim 9$, it is not directly comparable to the data of Figure 2. However, it would seem to support the idea that chorus may be generated within whistler mode ducts.

4. Discussion and Conclusion

[18] Using new high resolution N_e observations, we have examined the banded chorus event from January 20, 2004 and found that the LB chorus is excited within whistler mode depletion ducts. Since the LB chorus waves have $\theta > \theta_G$, they can be guided only by depletion ducts. According to the suggestion of *Bell et al.* [2009], this guidance may be a necessary factor in the generation of banded chorus.

[19] According to *Chum et al.* [2009] and *Santolík et al.* [2009], the average wave normal angle for the LB chorus of Set 2 in the source region is $\theta_S \sim 60°$. Assuming $f \sim 3.6$ kHz and $f_{ce} \sim 9.6$ kHz, θ_S has a value between θ_G and θ_R, the resonance cone angle, which have values of 36° and 68°, respectively. These values can be seen on the refractive index surface in Figure 3, calculated for these parameters as well as for a plasma frequency, f_p, of 22 kHz.

[20] Using the values for f, f_{ce}, and f_p, the direction of the group velocity vector, $\mathbf{v_{GS}}$, of the chorus waves can be calculated. The angle between $\mathbf{B_o}$ and $\mathbf{v_{GS}}$ is ~20°, with $\mathbf{v_{GS}}$ pointing towards the Earth, shown in Figure 3.

[21] Since the tangent of 20° is ~1/3, for every 150 km the chorus waves propagate along $\mathbf{B_o}$, they will also propagate

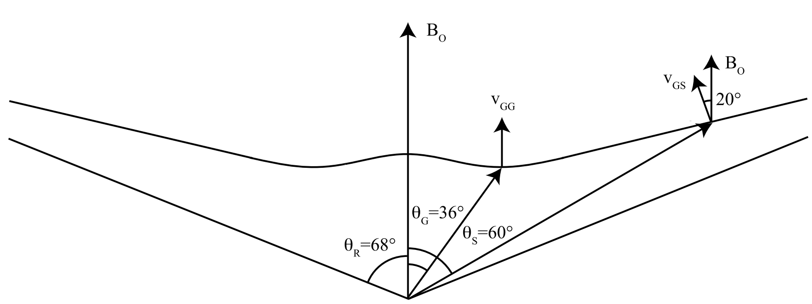

Figure 3. Refractive index surface for $f \sim 3.6$ kHz, $f_{ce} \sim 9.6$ kHz, and $f_p \sim 22$ kHz. The vertical axis shows the direction of $\mathbf{B_o}$. The Gendrin angle, its associated group velocity, and the resonance cone angle are shown as θ_G, $\mathbf{v_{GG}}$, θ_R, respectively. $\theta_S \sim 60°$ is the average wave normal angle of the lower band chorus of Set 2 in the source region. The angle between the associated group velocity, $\mathbf{v_{GS}}$, and $\mathbf{B_o}$ is ~20°.

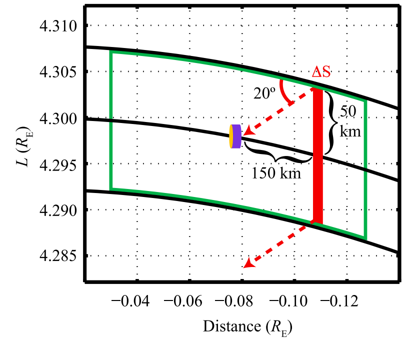

Figure 4. LB chorus propagation within magnetic meridian. Assume a LB chorus element is generated in a region with a scale of 100 km across $\mathbf{B_o}$ and extending a small distance ΔS along $\mathbf{B_o}$. Because the element's group velocity is directed 20° below the direction of $\mathbf{B_o}$, the element propagates toward smaller L values as shown by the dashed lines. After propagating 150 km parallel to $\mathbf{B_o}$, the element can no longer be observed on the magnetic field line which originally bisected the source region.

50 km across L towards the Earth. If the transverse scale of the source region for Set 2 is ~100 km, then Cluster 2 can only detect chorus waves generated within 150 km of the spacecraft position, shown in Figure 4.

[22] However, chorus was detected within the entire green outlined region, implying that chorus is generated everywhere along the L = 4.3 field line from $\lambda = -1.7°$ to $\lambda = -0.4°$, a distance of ~500 km. This result is important because LB chorus generally has small wave normal angles [*Santolík et al.*, 2009], making it difficult to determine if the chorus is generated within a small region near the magnetic equator and then propagates along $\mathbf{B_o}$ to the spacecraft, or if it is generated uniformly over an extended region. Our result suggests that uniform excitation of LB chorus over an extended region may be common.

[23] Since chorus wave normal information is only available for $f \leq 4$ kHz, the wave normal angles of the UB chorus in Figure 2 are not known. However, the UB chorus of Set 2 is clearly generated within the depletion ducts B and C shown in the source region of Figure 2, and can in principle be guided in these ducts. It is possible both UB and LB chorus may be guided in the same depletion duct.

[24] Though the above example provides support for the suggestion that banded chorus is generated in whistler mode ducts, more events from Cluster must be analyzed to further test this idea. The conclusions from these studies should determine whether the source region of banded chorus is limited to duct-like structures in the magnetosphere.

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