Correspondence Between Whistler Mode Ducts and Chorus Emissions Observed on the Cluster Spacecraft

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Chorus emissions are intense naturally occurring plasma waves generated outside the plasmapause near the magnetic equatorial plane. Chorus often appears in two frequency bands, with an upper band above f_{ce}/2 and a lower band below f_{ce}/2, where f_{ce} denotes equatorial gyrofrequency. *Bell et al.* [2009] proposed that the source region for this configuration, known as banded chorus, consists of whistler mode ducts of depleted electron density for upper band chorus and ducts of either enhanced or depleted density for lower band chorus. This paper provides support for this model by showing that the requisite ducts generally exist near the magnetic equatorial plane. We also present two examples of banded chorus and discuss how these cases may be related to the duct structure.

1. Introduction

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 [*LeDocq et al.*, 1998; *Santolík et al.*, 2003]. These discrete emissions, often containing rising and falling tones, range in frequency from hundreds of Hz up to several kHz [*Sazhin and Hayakawa*, 1992; *Lauben et al.*, 2002]. Chorus is often observed in a banded configuration, with an upper band above the emission gap at f_{ce}/2 and a lower band below, where f_{ce} denotes the equatorial gyrofrequency [*Tsurutani and Smith*, 1974; *Santolík et al.*, 2004].

Though banded chorus occurs less frequently than all chorus, it generally follows the same distribution. Banded chorus occurs commonly during the midnight-noon local time sector between *L*-shells 4-9 [*Tsurutani and Smith*, 1974; *Koons and Roeder*, 1990]. It was suggested by *Bell et al.* [2009] that the source regions of banded chorus can be ascribed to whistler mode ducts of either enhanced or depleted cold plasma density which guide the waves during the generation process. Banded chorus is characterized by the polar wave normal angle, θ, between the wave vector, *k*, and the ambient magnetic field, B_o. Upper band chorus can be guided in depletion ducts for all θ. Lower band chorus can be guided in enhancement ducts for $\theta \simeq 0^\circ$ and in depletion ducts for θ near the Gendrin angle, the minimum nonzero angle with group velocity parallel to B_o [*Gendrin*, 1960].

In order to test the *Bell et al.* [2009] model, the plasma density must be characterized with a spatial resolution of approximately 25 km or less in order to identify ducts of either enhanced or depleted density. However, plasma density data with this high resolution has not previously been available. In this study, we report new cases of plasma densities, which are derived not only from the passive measurements from WHISPER [*Décréau et al.*, 2001], which are then interpolated with EFW data [*Gustafsson et al.*, 1997], but also from the active measurements, which were manually determined and used for recalibration, giving electron density data with high spatial resolution on the order of 17 km. A previous study by *Pickett et al.* [2004] looked at the relationship between electron densities with respect to time and triggered emissions, not including chorus, at and near the plasmapause. This current study is unique in that it looks at electron densities in the equatorial plane with respect to L-shell, and further looks at the correspondence between these densities and banded chorus emissions, which take place well outside the plasmapause.

Figure 1a is a cartoon based on plasma density data from the Cluster 1 spacecraft, showing the nature of the ducts. This cartoon shows ducts with large enhancement or depletion factors for conceptual clarity, though in most cases, these factors are much smaller. One possible arrangement of these ducts is shown in the magnetic equatorial plane for *L*-shell versus East-West distance 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. This study will show the possible correspondence between ducts and chorus using observations from Cluster 1.

2. Qualitative Analysis

The correspondence between ducts and banded chorus can be shown qualitatively. The electron density profile in Figure 2a is derived from WHISPER data [*Décréau et al.*, 2001]. Though the original derived density is a function of magnetic latitude, that in Figure 2a is a smoothed projection onto the magnetic equator across magnetic meridians. This projection assumes the density varies as R^{-4}, where *R* denotes the radial distance from Earth [*Persoon et al.*, 1983]. The density, n_e, is determined from active and natural spectra provided by WHISPER, and is further interpolated with densities determined from spacecraft potential measurements taken from the EFW instrument [*Gustafsson et al.*, 1997]. This leads to electron densities with a time resolution of approximately 2.2 seconds and an accuracy within 1% [*Canu et al.*, 2001; *Trotignon et al.*, 2003].

While there are many plasma enhancements and depletions seen in the density profile, not all of these irregularities may be capable of efficiently guiding chorus waves. For example, both *Strangeways* [1986] and *Streltsov et al.* [2006] conclude that considerable leakage from ducts occurs for widths around the size of the wavelength of the wave. In the present work, it is assumed that the minimum duct width for wave guidance is approximately four wavelengths. This width is measured at half maximum. The necessary duct width varies with frequency and thus the two chorus bands require different duct widths.

The red asterisks on the density profile, plotted with respect to *L*-shell, in Figure 2a, denote the irregularities that qualify as ducts based on the full width at half maximum requirement. The letters, (a), (b), and (c), correspond to the locations, mapped to the equatorial plane, of the spacecraft at which the data shown in Figures 2b, 2c, and 2d were obtained. An observation of banded chorus on 12/21/2006 by the WBD instrument on Cluster 1 is shown in the frequency-time spectrogram in Figure 2b. The spectrogram displays 10 seconds of plasma wave data, with two distinct chorus bands. The white line indicates f_{ce}/2, with a value 7.71 kHz, determined from the magnetic field measurement by the Cluster FGM instrument. The *L*-shell was calculated assuming a dipole model.

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The lower band of chorus seen in Figure 2b may have been generated in one or more of the enhancement and depletion ducts seen in Figure 2a which lie between the spacecraft and the magnetic equator. The upper band of chorus may have been generated in one or more of the depletion ducts seen in Figure 2a which lie between the spacecraft and the magnetic equator. The two bands of chorus are observed continuously until the spacecraft moves near the magnetic equator, where neither upper band nor lower band chorus is observed. The absence of the chorus indicates that the spacecraft is not in a chorus generation region as it nears the magnetic equator and suggests that the generation regions are finite in size and number.

Figure 2d shows the banded chorus activity after the spacecraft has passed the magnetic equator and moved into the conjugate hemisphere. The chorus observed here may have been generated in one or more of the enhancement or depletion ducts seen in Figure 2a which lie between the spacecraft and the magnetic equator.

Another case illustrating this correspondence is shown in Figure 3. Figure 3b shows banded chorus observed a few degrees to the south of the magnetic equator, which may have been generated in one or more of the enhancement or depletion ducts seen in Figure 3a which lie between the spacecraft and the magnetic equator. The two chorus bands are observed continuously until the spacecraft nears the magnetic equator, where the lower band chorus is almost completely absent, as shown in Figure 3c. At this time the spacecraft is located within a depletion duct which may have provided the guiding structure for the observed upper band chorus. Observations in the conjugate hemisphere, shown in Figure 3d, indicate that only upper band chorus is present, and that its frequency range and element characteristics differ significantly from those of the upper chorus band shown in Figure 3b. The chorus of Figure 3d may have been generated in one, or both, of the depletion ducts which lie between the spacecraft position and the magnetic equator.

3. Discussion and Conclusion

Using new high resolution plasma density observations, we have identified enhancement and depletion ducts which have the necessary structure to guide chorus waves during the generation process. Our two previous examples of chorus show it's possible banded chorus is excited in ducts. The length of such ducts has been estimated to lie in the range 2000-10000 km [*Bell et al.*, 2009]. A simple cartoon model seen in Figure 4a shows one duct of length 2000 km at L=3.66 and another at L=3.73 with the red asterisks and letters denoting the locations of the three different spectrograms of Figure 2. The upper duct is modeled as a field-aligned duct, while the lower duct is not. At position (b) at L=3.73, the spacecraft may observe chorus elements from both ducts. As the spacecraft moves to lower L-shells, it may only observe chorus from one duct. Near the equator, (c) in Figure 4a, the spacecraft doesn't observe chorus from either duct, corresponding to the lack of emissions seen in Figure 2c. As the spacecraft approaches position (d) at L=3.66, it is located approximately 575 km to the east of position (b), where presumably it is illuminated by the chorus from another set of ducts, which is not shown.

Assuming the repetition rate of the upper band chorus of Figure 3 is related to duct length [*Bell et al.*, 2009], the lengths for the ducts range from 2344 to 4688 km. The model in Figure 4b shows part of a $\simeq$3500 km long duct, which guides the waves for Figure 3c. The density irregularities are not shown for Figures 3b or 3d.

While the above examples provide support for the correspondence between ducts and banded chorus, it is possible other explanations may exist. More examples from Cluster or other spacecraft must be studied to further test this theory. The conclusions from these studies should determine whether the source region of banded chorus is limited to duct-like structures in the magnetosphere. If so, the total number of electrons that can be accelerated by banded chorus may be limited.

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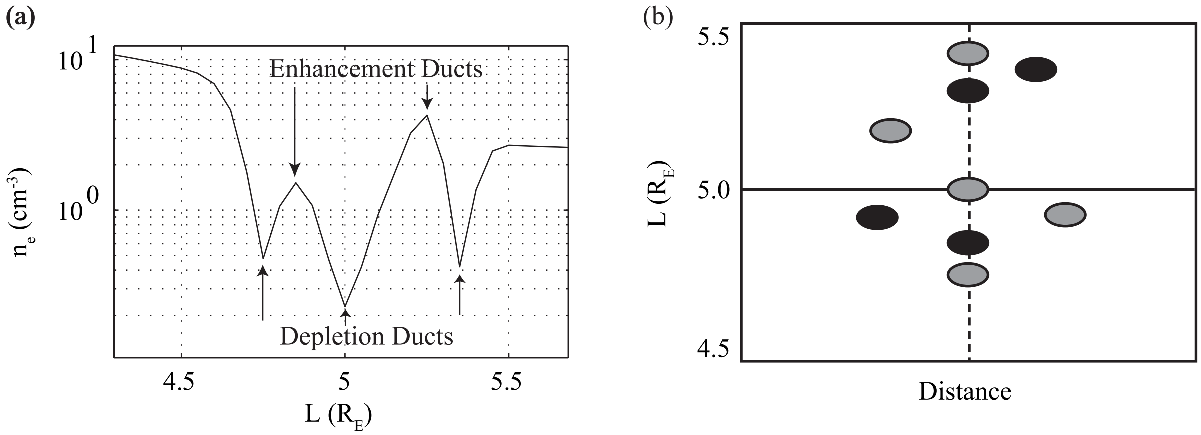

Figure 1. (a) Electron density versus *L*-shell in the equatorial plane with whistler mode enhancement and depletion ducts. (b) Possible arrangement of enhancement (black) and depletion (gray) ducts consistent with (a). Duct distribution is shown in the equatorial plane for *L*-shell versus East-West distance. Dashed line indicates equatorial projection of Cluster 1 orbit.

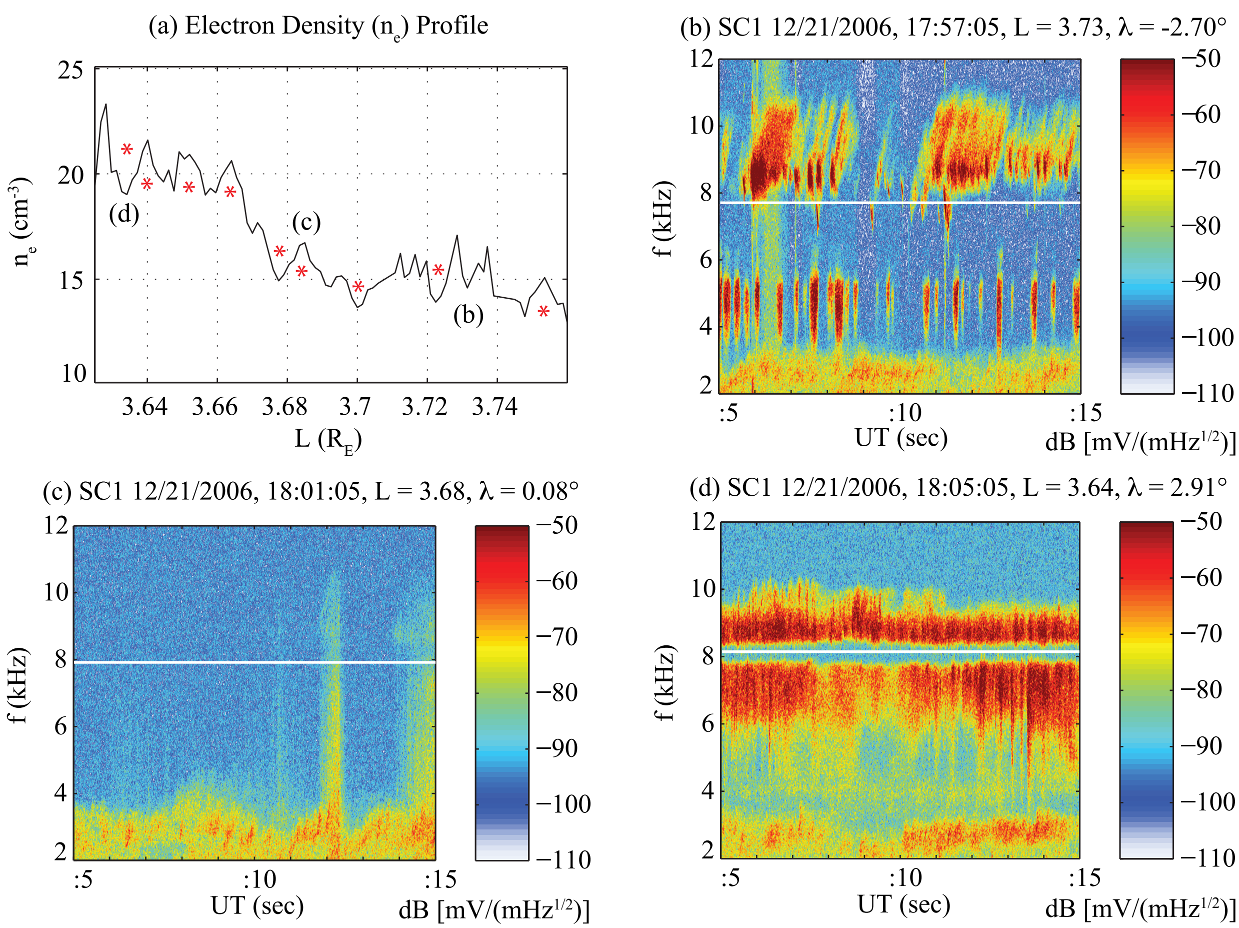

Figure 2. (a) Electron density versus *L*-shell in the equatorial plane for 12/21/2006 for 17:48:19-18:16:04 UT. The red asterisks denote ducts, while the letters shown in (a) correspond to the locations to which the spectrograms apply, each shown for a 10 second period, at (b) 17:57:05 UT, (c) 18:01:05 UT, and (d) 18:05:05 UT.

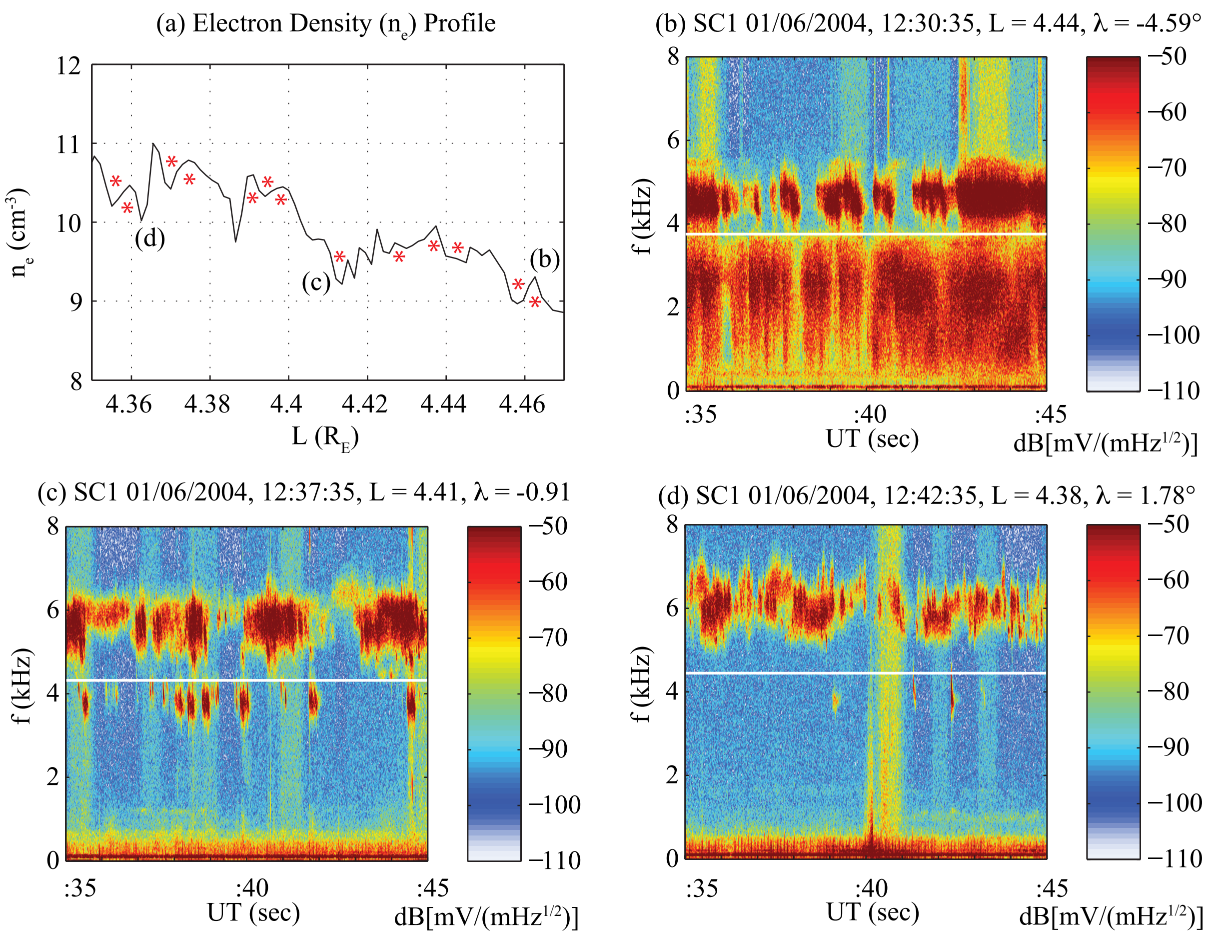

Figure 3. (a) Electron density versus *L*-shell in the equatorial plane for 01/06/2004 for 12:21:31-12:57:56 UT. The red asterisks denote ducts, while the letters shown in (a) correspond to the locations to which the spectrograms apply, each shown for a 10 second period, at (b) 12:35:35 UT, (c) 12:37:35 UT, and (d) 12:42:35 UT.

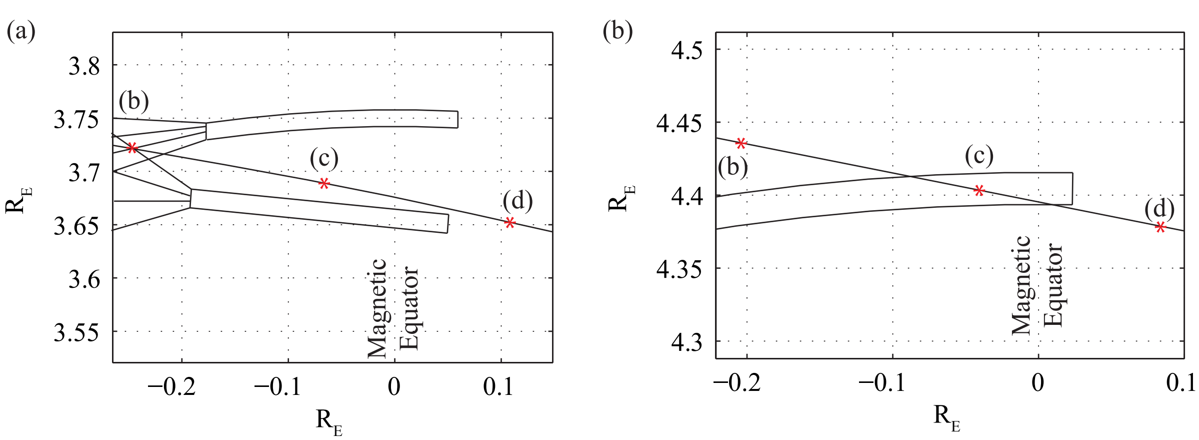

Figure 4. Simple model of whistler mode ducts for (a) 12/21/2006 and (b) 01/06/2004, with the red asterisks and letters denoting the locations of the three different spectrograms of Figures 2 and 3, respectively. The magnetic equator is parallel to the y-axis.