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Multi-band Whistler-mode Chorus Emissions Observed by the Cluster Spacecraft

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Abstract. Whistler-mode chorus emissions are one of the most significant mechanisms causing the acceleration of electrons in the outer Van Allen radiation belt to relativistic energies. They consist of individual wave packets divided into two frequency bands separated close to the source region by a gap at 1/2 of the electron cyclotron frequency (f_{ce}). This configuration is called banded chorus and it is correlated with magnetic activity. Landau damping is one of the possible explanations describing the existence of the gap. On the other hand, the role of ducts in its formation was also discussed. We present several events of chorus combined with noisy or shapeless chorus-like emissions that are arranged in three or more frequency bands with two or more gaps and are observed mostly in a magnetic latitude range from 3 to 10 degrees on the both sides of the equator. We investigate possible influences of the magnetic local time (MLT), the Kp index, the McIlwain parameter and the plasma density on the formation of these multi-band emissions.

Introduction

Whistler-mode chorus waves are with the highest probability generated in the low-density region outside the plasmapause by Doppler-shifted cyclotron interactions between anisotropic distributions of energetic electrons (> few tens of keV) and ambient background VLF noise [*Thorne et al.*, 1977]. These unstable type of distributions can be the result from the substorm injection, which agrees with that chorus is most often seen in the morning and noon MLT sectors corresponding to eastward drifting electrons. Source region is found close to the geomagnetic equator from the Poyntig flux measurements at L-shells of 4–6 [*Santolík et al.*, 2003; *Parrot et al.*, 2003]. *Li et al.* [2010] observed chorus emissions using THEMIS measurements at larger L-shells. Chorus emissions are primarily observed within 5–10° on the nightside, but on the dayside they are observed over a much wider range of magnetic latitudes (up to 25 °) [*Burton and Helzer*, 1974; *Li et al.*, 2009].

Chorus waves can occur in the ELF range approximately from 100 Hz to several kilohertz and their discrete structures can take different forms, including individual wave packets rising or falling in the frequency, broadband vertical lines or hooks. These individual spectral shapes are often observed in combination with a formless hiss, or they are frequently changing into shapeless hiss, and oppositely, how they are propagating from the source region. Described types of spectral structures that are occurring in more than three frequency bands and have similar characteristics (value of the elipticity, planarity, Poynting flux) as chorus are called multi-banded chorus-like emissions in this study.

Simulations based on the backward wave oscillator regime [*Demekhov et al.*, 2008] and numerical Vlasov hybrid simulations provided by *Nunn et al.* [2009] were able to successfully reproduce chorus wave packets similar to those observed by the Cluster spacecraft and shown a frequency sweep rate as a function of the plasma density, which agrees with the statistical study based on Cluster measurements [*Macúšová et al.*, 2010]. *Omura et al.* [2008] pointed out that frequency sweep rates of chorus elements are growing with the increasing wave amplitudes [*Trakhtengerts et al.*, 2004]. The validity of this relation has been demonstrated in a full particle electromagnetic simulations [*Hikishima et al.*, 2009] as well as in the electron hybrid simulations [*Katoh and Omura*, 2011].

In situ measurements of chorus have shown that banded chorus [*Burtis and Helliwell*, 1976] consisting of two frequency bands separated by a gap at $1/2f_{ce}$ is most common in the midnight-noon MLT sector [*Tsurutani and Smith*, 1974].

Omura et al. [2009] explain the existence of the gap by the nonlinear damping. It is different from Landau damping which depends on the gradient of the velocity distribution function. Landau damping was first time mentioned in the gap origination by *Tsurutani and Smith* [1974]. *Bell et al.* [2009] discuss the role of ducts in the formation of the gap.

From two frequency bands of banded chorus, only the lower band (frequency range is from 0.1 to 0.5 f_{ce} [*Meredith et al.*, 2002]) could reach the ground, because the upper band is probably reflected at high altitudes due to its highly oblique wave normal angle [*Hayakawa et al.*, 1984; *Haque et al.*, 2010].

Upper band chorus (frequency range is from 0.5 to 0.7 f_{ce}) is the controlling scattering process for electrons from 100 eV to 2 keV, and lower band chorus is most effective for precipitating the higher energy (>2 keV) plasma sheet electrons in the inner magnetosphere [*Ni et al.*, 2011]. Chorus scattering is therefore a major contributor to the origin of the diffuse aurora and should also control the MLT distribution of injected plasma sheet electrons [*Ni et al.*, 2008] and is dominantly responsible for diffuse auroral precipitation in the inner magnetosphere [*Ni et al.*, 2011].

In this study we focus on the chorus waves with three or more frequency bands and two or more gaps (we will call this type the multi-band chorus-like emission) observed simultaneously by the two wave instruments. We try to found parameters which may play role in the formation of the multi-band chorus-like structure.

Structure of chorus emissions

The data set used in this paper is based on Cluster wave instruments (STAFF-SA and WBD) measurements. The unique Cluster four spacecraft mission has operated from the end of the year 2000 and chorus emissions were observed in November 2000 [*Gurnett et al.*, 2001] for the first time. Information about the source region, propagation and polarization was obtained from the STAFF-SA instrument [*Cornilleau-Wehrlin*, 1997] and the detail time-frequency resolution and the information about the chorus spectral structure we got from the WBD instrument [*Gurnett et al.*, 1997].

The selection procedure of different type of whistler-mode chorus structures (risers, fallers, the multi-band chorus-like structures etc.) is described by *Macúšová and Santolík* [2010]. Our study uses extended data set from the mentioned paper and focuses on chorus emission with three or more frequency bands. From January 2001 to September 2010 we found 33 events of the multi-band chorus-like emissions outside the plasmapause which lasted at least 5 minutes and were detected in the region of magnetic latitudes (λ_m) within 30 degrees. It gives 263 time intervals and eight hours of data where the multi-band chorus-like structures were observed. Numbers of this type of chorus emissions are summarized in Table 1 year by year.

The spacecraft orbit was changed during Cluster operation period. Approximately until the end of year 2006 we observed chorus emissions at L-shells around 4–6 within the equatorial plane, but from the year 2007 we found chorus further from the Earth due to the orbit change.

Table 1. Processed years are arranged in the chronological order in the first row. In the second row are total numbers of chorus emissions observed in the given year and in the third row are numbers of chorus with the multi-band chorus-like structures.

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total nr. of chorus events	34	23	31	18	19	24	39	42	44	35
Nr. of the more banded ch.	6	3	9	3	1	4	2	0	3	2

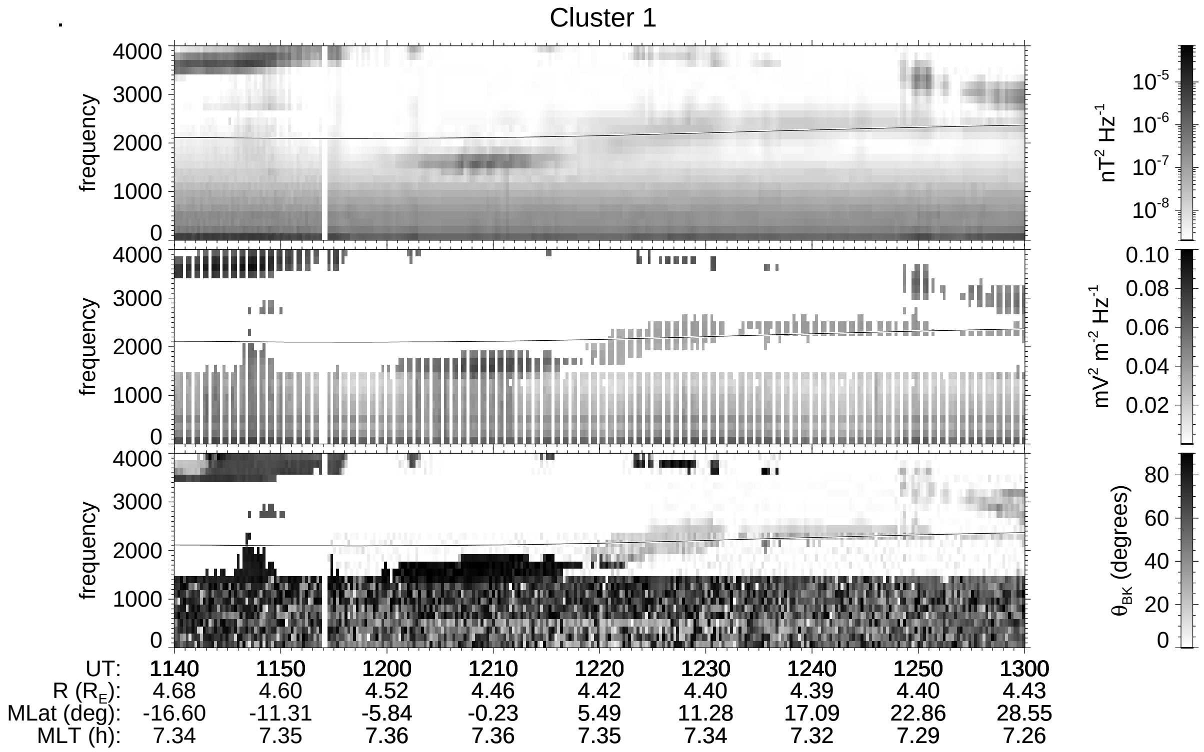


Figure 1. Chorus measured on November 19, 2001 by the STAFF-SA instrument. The first panel from the top represents frequency-time spectrogram of the power-spectral density of magnetic field fluctuations; the second panel is the power-spectral density of the electric field fluctuations; the third panel is the angle between the wave vector and the ambient magnetic field. The thin black line situated in the thicker white line is the lower hybrid frequency. The spacecraft position is shown on the bottom: UT (Universal time); R_E (the Earth radius); Mlat (magnetic dipole latitude) and MLT (magnetic local time).

This effect caused an extension of the L-shells interval, where chorus emissions were observed in their source region.

From Table 1 it looks like that the change of the Cluster orbit could has an influence on the occurrence rate of the multi-band chorus-like structures. The multi-band chorus-like emissions are observed at lower L-shells (up to 6) more often than at the larger L-shell values. This effect could be caused also be the decrease of the geomagnetic activity in the year 2007.

Figure 1 shows frequency-time spectrograms of the electric (first panel from the top) and the magnetic field fluctuations (second panel) measured by Cluster 1 on November 19, 2001. Chorus emission is the most intense part of these two spectrograms in the frequency range between 2.6 and 4 kHz (above the lower hybrid frequency represented by thin black line that is situated inside the thicker white line). Chorus is falling in the frequency during its propagation from the source region to larger magnetic latitudes. The large value of the angle between the wave vector and the ambient magnetic field in the third panel determines the highly oblique chorus waves propagation. Most of chorus studies observed parallel propagation, but recent studies also show some oblique propagation [*Santolík et al.*, 2009].

The detailed one minute time-frequency interval with the multi-band chorus-like emission measured by the WBD instrument on November 19, 2001 is given in Figure 2. Two lower frequency bands consist of shapeless hiss and individual wave packets are observable in the third upper band. The second gap is above the main gap that is usually localized at $1/2 f_{ce}$. In some other cases the second gap is below the main gap. We could not say if the third frequency band was caused by the local reflection, because the STAFF-SA data determining the direction of propagation are available only up to 4 kHz. The second gap can be caused by the local damping or by another mechanism.

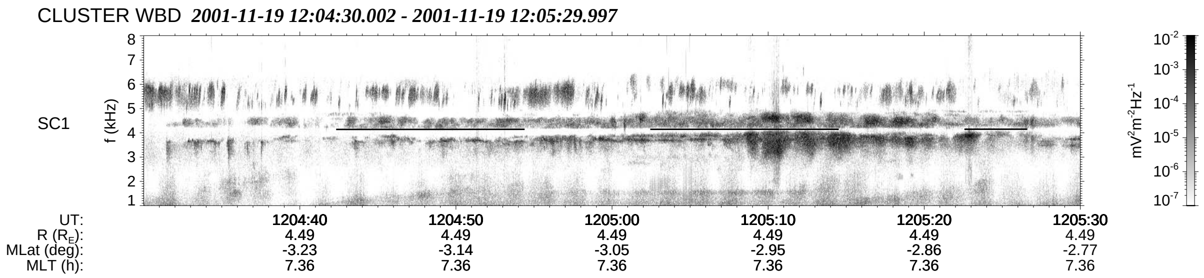
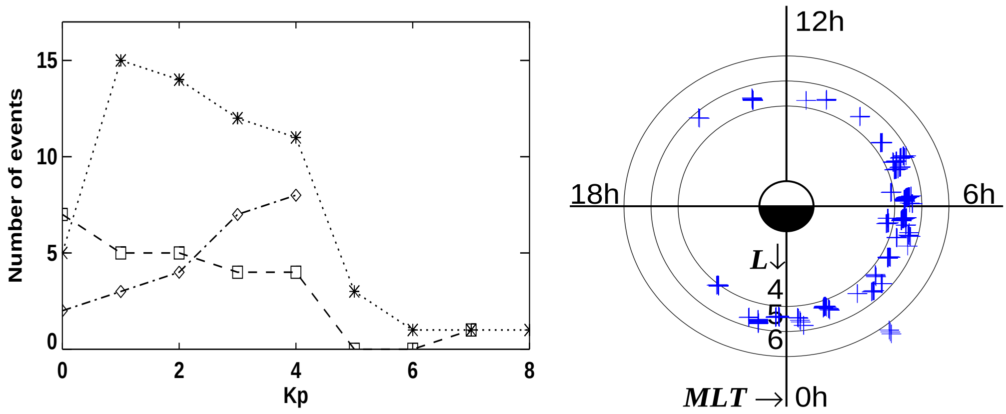


Figure 2. One minute example of chorus emissions with three frequency bands and two gaps measured by Cluster 1 on November 19, 2001. The gap localized at the $1/2 f_{ce}$ is marked with the black horizontal lines. Spacecraft position is the same as in Figure 1.



(a) (b)

Figure 3. **(a)** Histogram of the Kp index for different type of chorus emissions: Rising tones occurring in one or two frequency bands are represented by the dotted line, falling tones observed in one or two frequency bands are marked by the dashed line and the more chorus emissions are marked by the dot-dashed line. Numbers of chorus emissions for each value of the Kp index for all three mentioned types are shown by the different symbols (risers-asterisks, fallers-squares, the multi-band chorus-like emissions-diamonds). **(b)** The polar plot represents the Mcllwains L parameter and the magnetic local time. Each cros is one of the selected multi-band chorus-like emissions.

Conclusions and discussions

Our statistical study shows that the multi-band chorus-like structures occurred probably during more disturbed geomagnetic condition. It is not easy to distinguish if multi-banded chorus-like emissions almost disappeared as a result of the change of equatorial crossings to higher L-shells or as the effect of decreasing geomagnetic activity, because the geomagnetic activity has decreased in the same time as the Cluster orbit changed and crossed the equatorial plane at L-shells higher than 6.

The dot-dashed line in Figure 3a shows Kp index for all chorus emissions observed with more than two frequency bands. In this case the median value of the Kp index was three. The dotted line represents chorus emissions with one or two frequency bands composed of combination of rising tones and shapeless hiss and the dashed lines marks chorus structures with one or two frequency bands consisting of combination of falling tones and shapeless hiss. In these both cases were median values of the Kp index equal to two.

The distribution of the multi-band chorus-like emissions in the MLT sectors is almost the same as the distribution of all chorus emissions (see polar plot in Figure 3b), because most cases have been found in the dawn and the night MLT sector.

Multi-band chorus-like emissions were observed in 12 percent of all observed chorus structures and they were most of the time occurring at magnetic latitudes (–10°, 10°) and 87 % of them were found at L-shells smaller or equal than 6.

The second gap was found in more than 70 % above $1/2 f_{ce}$ near the source region, but at magnetic latitude larger than 10° the second gap was usually localized between 0.2–0.4 f_{ce}. Observed gaps are not multiples of any known frequency.

Our conclusions confirmed some previous results: most of the multi-band chorus-like events were observed in the dawn and night MLT sectors as well as chorus emissions with one or two frequency bands. Variability of plasma density was so high during processed cases that any influence on the formation of the more banded structure wasn't evident.

Our preliminary result need much more careful processing. We would like to find if the multi-band chorus-like structures are connected with wave-particle interactions, electrons accelerations to relativistic energies, or with the change of the chorus wave amplitude.

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