FIVE YEARS OF INVESTIGATION OF WHISTLER-MODE CHORUS USING THE MEASUREMENTS OF THE CLUSTER SPACEFLEET

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ABSTRACT

We summarize results obtained during investigation of whistler-mode chorus emissions by the four Cluster spacecraft during their first five years of operation. The results can be divided into several broader categories. (i) Substructure of chorus wave packets have been observed at time scales of 1–40 ms, with decreasing occurrence rate for longer durations. Their growth rate is between 30 and 400 s^{-1}, and amplitudes reach up to 30 mV/m or 300 nT in the disturbed times. Maximum amplitudes are inside the larger chorus wave packets which occur at time scales above 100 ms. (ii) Frequency differences have been observed for chorus wave packets which were simultaneously detected by different spacecraft. These differences have been interpreted as differential Doppler shift from rapidly moving elementary chorus sources at speeds comparable to the parallel velocity of counter-streaming resonant electrons. (iii) At the altitude of the perigee of Cluster satellites (≈4 Earth's radii), multipoint measurement of the Poynting flux show that the central position of the chorus source region is located close to the geomagnetic equatorial plane, fluctuating with amplitude of ≈3000 km and at speeds of the order of 100 km/s. Size of the source region along the field line, as obtained from multipoint measurement of electromagnetic planarity, is 3000-5000 km. Multipoint correlation analysis of chorus wave packets has resulted in the size of the source region of 100 km if measured perpendicular to the field line. (iv) Studies of propagation of chorus from its source region show that chorus can magnetospherically reflect and return back to the equatorial plane at a lower altitude and with a lower frequency than locally generated chorus. (v) Comparison with nonlinear theory shows that many observed parameters of chorus emissions can be understood on the basis of the backward wave oscillator model.

Key words: waves in plasmas; whistler mode; chorus.

1. INTRODUCTION

Chorus is an electromagnetic wave emission in the frequency range from a few hundreds of hertz to several kHz, often containing many distinct short-duration wave packets. It was first observed on the ground [*Storey*, 1953]. The wave packets change their frequency at time scales of a fraction of a second, [see reviews *Sazhin and Hayakawa*, 1992, *Omura et al.*, 1991]. The generation mechanism of chorus is not yet well understood. It is most often accepted that chorus is generated by a nonlinear process [*Nunn et al.*, 1997, *Trakhtengerts*, 1999] which involves the electron cyclotron resonance of whistler-mode waves with energetic electrons in the Earth magnetosphere [*Kennel and Petschek*, 1966].

Spacecraft measurements confirmed its predominant occurrence during the local morning and day time [e.g., *Burtis and Helliwell*, 1976, *Koons and Roeder*, 1990]. This has been explained by the source population of electrons, drifting in the Earth's magnetic field from the magnetospheric tail earthward and toward the local morning. Measurements have also shown that the generation of chorus takes place close to the geomagnetic equatorial plane [*Helliwell*, 1967, *Burton and Holzer*, 1974, *LeDocq et al.*, 1998, *Lauben et al.*, 2002, *Santolík et al.*, 2003, *Parrot et al.*, 2003, *Santolík et al.*, 2004b, 2005a].

In its source region, chorus has been observed in two frequency bands [*Burtis and Helliwell*, 1976], below and above one half of the local electron cyclotron frequency. These bands are separated by a narrow frequency interval of decreased intensity whose origin has not yet been explained.

Importance of whistler-mode chorus can be demonstrated by an increased attention that these emissions recently received in connection with the acceleration of energetic electrons. Whistler-mode chorus is being considered as a possible source of highly accelerated electrons in the outer Van Allen radiation belt [*Meredith et al.*,

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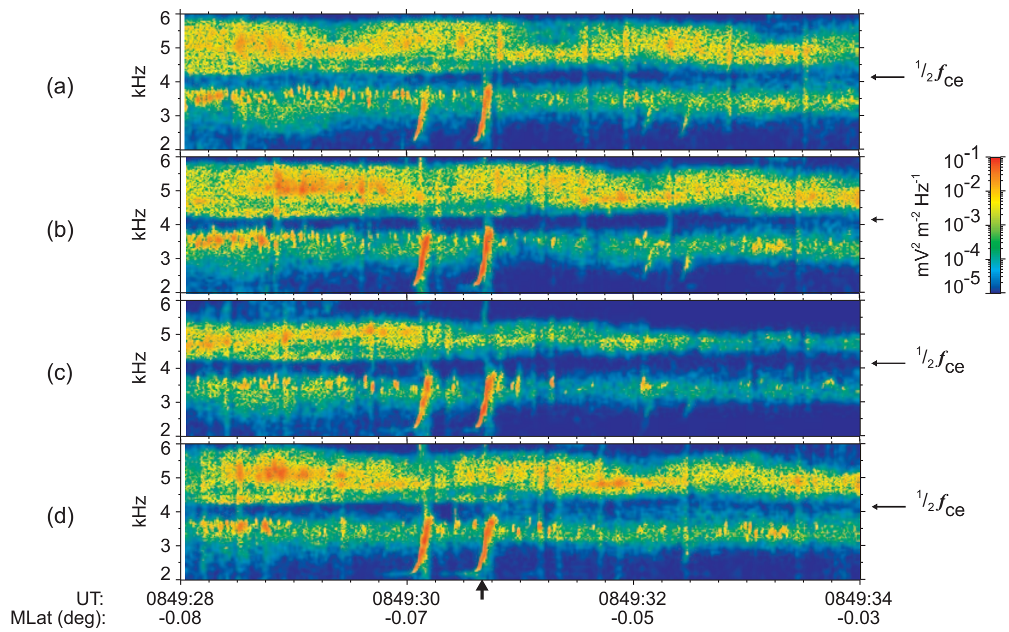

Figure 1. Detailed time-frequency power spectrograms of electric field fluctuations in the source region recorded by the WBD instruments on board all the four Cluster spacecraft on April 18, 2002 after 0849:28 UT. Panels (a-d) show data from Cluster 1-4, respectively. Horizontal arrows on the right indicate local $\frac{1}{2}f_{ce}$ for each spacecraft. Magnetic latitude (MLat) is given on the bottom for Cluster 1. Cluster 2-4 are shifted by $-0.39°$, $-0.53°$, $-0.25°$, respectively. A bold vertical arrow on the bottom points to the chorus element which is chosen for further analysis. From [Santolík et al., 2003].

2001, 2003, *Horne et al.*, 2003]. During magnetospherically disturbed times, these electrons can cause damages of spacecraft systems, and increase radiation risks of manned flights. Investigation of whistler-mode chorus might thus have, besides contribution to basic knowledge of our space environment, also some practical consequences.

In this paper we summarize results obtained during investigation of whistler-mode chorus emissions by the four Cluster spacecraft during their first five years of operation.

2. OVERVIEW OF RESULTS

The four Cluster spacecraft [*Escoubet et al.*, 1997] have been launched in 2000 on nearly identical elliptical orbits with an apogee radial distance of ≈20 R_E and a perigee radial distance of ≈4 R_E. Near their perigee region, the four spacecraft can measure emissions of whistler-mode chorus by sets of identical wave instruments. These instruments coordinate the measurements in the frame of the Cluster wave experiment consortium (WEC) which, on each spacecraft, consists of 5 devices: Digital Wave Processor (DWP), Electric Fields and Waves (EFW), Spatio-Temporal Analysis of Field Fluctuations (STAFF) [*Cornilleau-Wehrlin et al.*, 2003], Wide-Band Data (WBD) [*Gurnett et al.*, 2001], and High Frequency and Sounder for Probing of Electron Density by Relaxation (WHISPER) [*Décréau et al.*, 2001]. The results of these investigations can be divided into several broader categories.

2.1. Substructure of chorus wave packets

The chorus wave packets have been investigated using high resolution measurements of the WBD instrument during geomagnetic storms [*Santolík et al.*, 2003, 2004b]. The analysis concerned wave packets which, on power spectrograms, appeared as rising discrete elements of lower-band chorus with the frequency drift of 10–20 kHz/s. The waveforms of the electric field of the chorus wave packets has shown an internal fine structure consisting of separate subpackets.

An initial study of this fine structure has been done using a sine-wave parametric model with a variable amplitude [*Santolík et al.*, 2003]. The subpackets often start with an exponential growth phase, and after reaching the saturation amplitude they can also show an exponential decay phase. The duration of subpackets is variable from a few milliseconds to a few tens of milliseconds, and they appear in the waveform randomly, with no clear periodicity. The growth rate of the initial linear phase (imaginary part of the wave frequency) is highly variable from case to case. Typical values vary between a few tens and a few hundreds of s^{-1} (see Figs. 1 and 2).

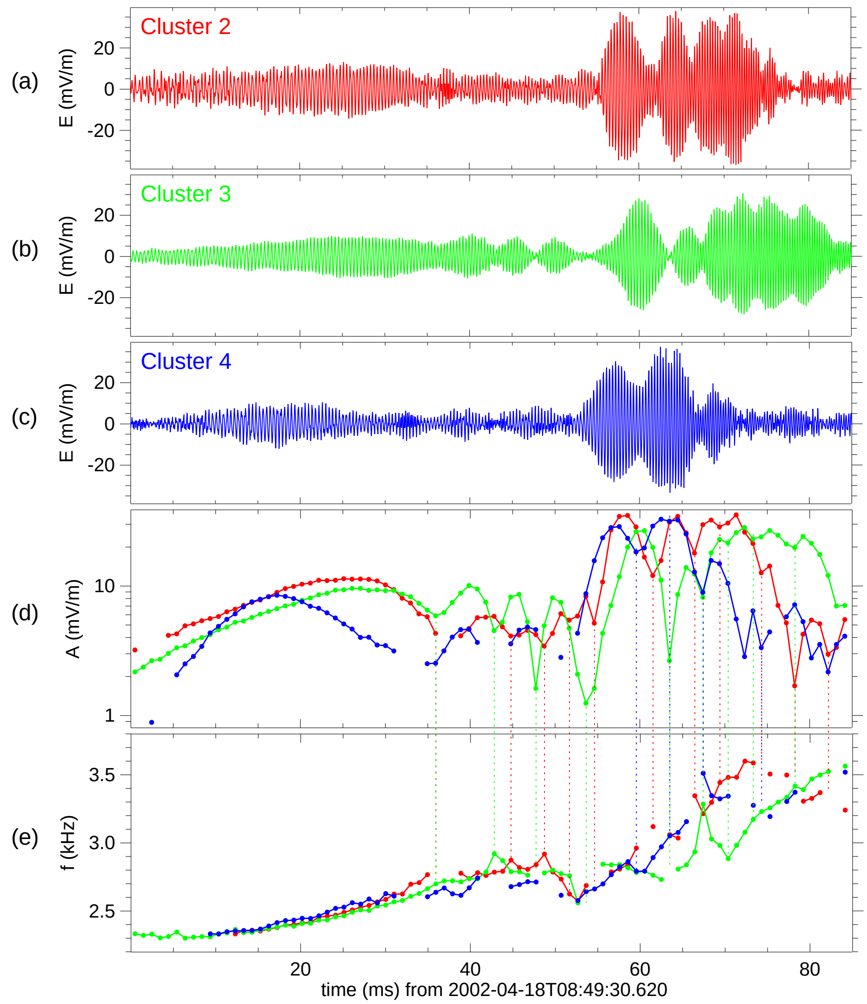

Figure 2. Waveforms and model parameters in an extended 85-ms time interval covering the second chorus element in Figure 1. (a-c) Broadband electric field waveform for Cluster 2-4, respectively; (d) Amplitude, (e) frequency. The results from the three spacecraft are color-coded. In order to demonstrate the fine structure, minima of amplitude are connected with the corresponding frequency estimates by vertical dotted lines. From [Santolík et al., 2003].

The maximum detected amplitudes of the subpackets is approximately 30 mV/m which, under the observed plasma conditions, approximately corresponds to 300 nT for the magnetic component of chorus. The same chorus wave packets simultaneously observed on the different closely separated spacecraft appear to have a different internal subpacket structure. The characteristic scales of the fine structure thus appear to be much lower than those of the chorus wave packet in which it is embedded (Fig. 3).

A study [*Santolík et al.*, 2004b] based on analysis of a large number of chorus wave packets showed that the subpackets with largest amplitudes are always embedded in the interior of the wave packets. The typical delay between the two neighboring maxima of the wave amplitude is a few milliseconds with a decreasing probability density toward longer delays.

2.2. Frequency differences of chorus wave packets observed by different spacecraft

Rather unexpected frequency differences of around 1 kHz between nearly identical discrete wave packets have been observed simultaneously by different spacecraft already in the initial period of the Cluster project [*Gurnett et al.*, 2001]. In [*Inan et al.*, 2004] these observations have been interpreted by differential Doppler shift from rapidly moving elementary sources at speeds comparable to the parallel velocity of counter-streaming resonant electrons. This interpretation is based on the dependence of the whistler-mode refractive index on the wave normal angle between the wave vector and the static magnetic field and the rapid motion of highly localized source regions of chorus moving at speeds of 20,000 km/s to 25,000 km/s. Waves from the localized sources propagate to two spacecraft at different wave normal angles, and are observed at different frequencies due to the differential Doppler shift between the two spacecraft. This results in differences in frequency, as well as the different times of arrival of the similar emissions at the different spacecraft.

2.3. Position and size of the chorus source region

When the separation of the Cluster spacecraft was very close (of the order of hundreds of km), very similar chorus emissions were observed in their generation region close to the magnetic equatorial plane at a radial distance of 4.4 Earth's radii (Fig. 4). Both linear and rank correlation analysis have been used in [*Santolík and Gurnett*, 2003] and [*Santolík et al.*, 2004a] to define perpendicular dimensions of the sources of lower-band chorus elements below one half of the electron cyclotron frequency. Correlation was significant in the range of separation distances of up to 260 km parallel to the field line and up to 100 km in the perpendicular plane. At these scales, the correlation coefficient is independent for parallel separations, and decreased with perpendicular separation. This characteristic scale varied between 60 and 200 km for different data intervals inside the source region. This variation was consistent with a simultaneously acting effect of random positions of locations at which the individual chorus wave packets were generated. The statistical properties of the observations were consistent with a model of the source region assuming individual sources as gaussian peaks of power radiated from individual active areas with a common half-width of 35 km perpendicular to the magnetic field [*Santolík et al.*, 2004a]. This characteristic scale was comparable to the wavelength of observed whistler-mode waves.

Central position of the source region from multipoint measurement of the Poynting flux is located close to the geomagnetic equatorial plane [*Parrot et al.*, 2003, *Santolík et al.*, 2004b, 2005a]. Observed spatio-temporal variations of the direction of the Poynting flux consistently show that the central position of the chorus source fluctuates at time scales of minutes within 1000-2000 km of the geomagnetic equator (see Fig. 5). Estimates of the electromagnetic planarity can be used to characterize the extent of the source in the direction parallel to the field line, obtaining a range of 3000-5000 km [*Santolík et al.*, 2004b, 2005a]. The typical order of magnitude of the speed of this motion is 100 km/s. Note that this is a global speed of motion of the central position of the entire source region. It has been determined from the Poynting flux measurements where we always average propagation properties of several chorus wave packets. On the other hand, the much higher speeds mentioned in section 2.2 have been obtained assuming very compact small sources of the individual elements. The values of the two speeds thus are not easily comparable and they do not directly contradict.

2.4. Propagation of chorus from its source region

It has also been observed by the four Cluster spacecraft that intense chorus waves propagate away from the equator simultaneously with lower-intensity waves propagating toward the equator [*Parrot et al.*, 2004a,b]. Using the observed wave normal directions of these waves, a backward ray tracing study predicts that the lower-intensity waves undergo the Lower Hybrid Resonance (LHR) reflection at low altitudes [*Parrot et al.*, 2004a]. The rays of these waves then lead us back to their anticipated source region located close to the geomagnetic equator. This source region is, however, located at a different radial distance compared to the place of observation. The intensity ratio between magnetic component of the waves coming directly from the equator and waves returning to the equator has been observed between 0.005 and 0.01. The observations also show that waves returning to the equator after the magnetospherical reflection still have a high degree of polarization, even if they started to lose the coherent structure of the chorus elements [*Parrot et al.*, 2004b].

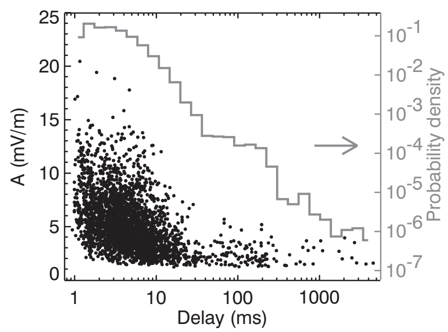

Figure 3. Scatter plot of local maxima of the amplitudes of the electric field fluctuations versus the time delays between them, as obtained from high-resolution measurements of chorus on 31 March 2001. Histogram of time delays between the local maxima is plotted by the grey line with the right-hand side vertical scale. From [Santolík et al., 2004b].

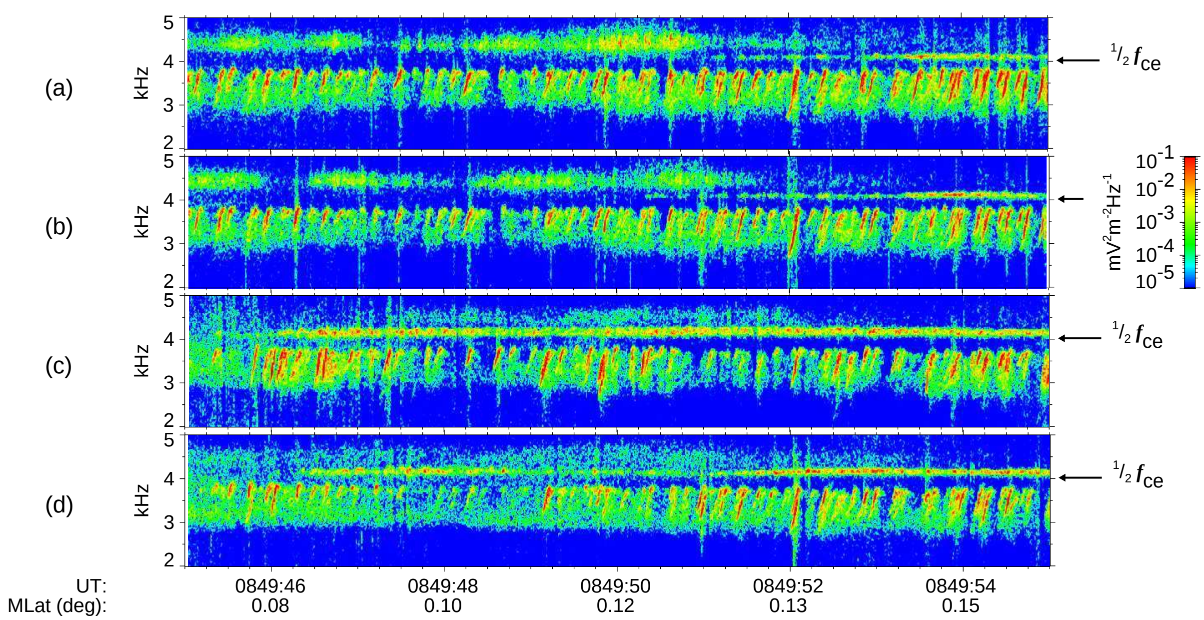

Figure 4. Detailed time-frequency power spectrograms of electric field fluctuations in the source region recorded by the WBD instruments on board the four Cluster spacecraft on April 18, 2002. Panels (a-d) show data from Cluster 1-4, respectively. Arrows indicate local $\frac{1}{2} f_{\rm ce}$ for each spacecraft. Magnetic dipole latitude is given on the bottom for Cluster 1. Radial distance is 4.37 $R_{\rm E}$, and magnetic local time is 21.01 h during this interval. From [Santolík and Gurnett, 2003].

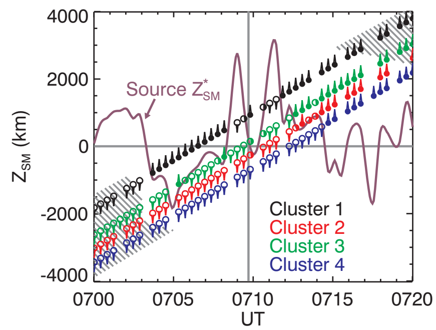

Figure 5. $Z_{\rm SM}$ coordinate of the four color-coded Cluster spacecraft during the geomagnetic storm on March 31, 2001, as a function of time. Sign of the parallel component of the Poynting flux is shown by downward arrows attached to the open symbols, and by upward arrows with the solid symbols, for southward and northward components, respectively. The half-filled symbols with no arrows indicate that the sign cannot be reliably determined. Horizontal grey line is at the magnetic equator, vertical grey line shows the time when center of mass of the four spacecraft crosses the equatorial plane. Shaded areas bound the regions of low values of the electromagnetic planarity. Purple line shows the calculated position where the Poynting flux changes its sign. From [Santolík et al., 2004b].

2.5. Comparison of observations with nonlinear theory

The above described results of the Cluster project provide an important feedback for non-linear theories concerning the chorus generation mechanism. These properties of the observed chorus emissions are compared in [*Trakhtengerts et al.*, 2004] with the theoretical properties of the backward wave oscillator mechanism. According to this theory, a succession of whistler wave packets is generated in a small near-equatorial region with temporal and spatial characteristics close to those observed by the four Cluster spacecraft. Amplitudes and frequency spectra, as well as dynamical features of the Poynting flux of chorus are estimated and compared with the Cluster measurements. A good agreement is found for the observed and predicted lengths of the generation region measured along the magnetic field lines, characteristic periods of succession and global time-frequency slopes of chorus wave packets, growth rates of the substructure, and for saturation wave amplitudes. According to the backward wave oscillator model, the nonlinear stage of chorus generation is determined by trapping of energetic particles at the step-like feature in their distribution function. This leads to wave sideband formation at a time scale, which is, for the observed plasma parameters between 6 and 60 ms. Therefore, a temporal modulation in wave amplitude can be expected, as confirmed by the results shown above.

3. CONCLUSIONS

Whistler-mode chorus emissions are receiving an increased attention in connection with the acceleration of energetic electrons in the radiation belts. The complementary set of wave instruments in the frame of the Cluster wave experiment consortium (WEC) provided a set of important results on chorus. New measurements planned in the perigee region of Cluster orbits of the the coming years can improve our knowledge on those intense waves. This research can provide us with tests of the existing theories of the chorus source mechanism and particle acceleration, and further motivate theoretical work. Studies will be done in collaboration with other wave and particle instruments on board Cluster. Multipoint studies are being planned with the Double Star spacecraft which routinely detects chorus emissions [*Santolík et al.*, 2005b], the low altitude DEMETER spacecraft, and with the ground-based measurements in the Antarctic and in Alaska. Simultaneous observations by multiple Cluster spacecraft will establish the global properties of chorus during magnetic storms, such as the onset time at each location and the overall spatial volume within which chorus is observed. This information is necessary in order to evaluate the effectiveness of chorus in accelerating electrons to MeV energies.

The measurements will allow us to

- characterize the chorus source regions (their size, relative fraction of compact sources, speed and direction of their motion, circumstances under which the motion occurs, configuration of the Earth's magnetic field lines, presence/absence of multiple minima in the magnetic field);
- investigate the spectral characteristics of waves in their source (chorus/hiss relations at large spatial and temporal scales, global time-frequency structure of wave packets at different positions and time, including lengths, amplitudes, and amplification/damping rates of their recently discovered inner subpackets);
- compare wave observations with measurements of the electron distribution function (anisotropies in pitch angle and flux levels necessary to produce chorus waves, signatures of accelerated electrons);

- investigate relationship between solar wind dynamic pressure and chorus intensity observed in space and on the ground (correlation between the observations of the Cluster and Double Star spacecraft at high altitudes, the DEMETER spacecraft at low altitudes and a chains of ground-based observatories in the Antarctic and Alaska, time of onset of chorus at these different locations during sudden increases in dynamic pressure, overall spatial volume within which chorus is observed during magnetic storms and distribution of wave intensities).

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