MAGNETOSPHERIC CHORUS EMISSIONS: A REVIEW

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Abstract—A review of chorus emissions observed on ground-based stations and in the Earth’s magnetosphere is presented. Different approaches to modelling these emissions are discussed. It is pointed out that the most likely energy source of chorus emissions lies in the anisotropic hot electrons in the equatorial magnetosphere. The energy of these electrons is transferred to waves via the electron cyclotron instability. Then the non-linear deformation of the hot electron distribution function under the influence of these waves produces almost monochromatic wavelets which, in their turn, generate a chorus element in a manner similar to the generation of artificially stimulated emissions by ground-based transmitters.

1. INTRODUCTION

Chorus is distinguished from other types of low frequency whistler-mode emissions by the form of its frequency–time spectrum which presents a close superposition or intersection of quasi-monochromatic (with a bandwidth sometimes as small as 100 Hz) signals in the frequency range from hundreds of hertz to 5 kHz. Its frequency, in most cases, increases with time (risers), although sometimes it can decrease (falling tones); it can decrease, then increase (hooks), or increase followed by a decrease (inverted hooks) or show some more complicated combinations. Isolated quasi-monochromatic signals with similar forms of spectrograms, observed mostly on the Earth’s surface, are known as discrete emissions (Helliwell, 1965, 1969). However, it is often difficult to determine the degree of isolation of these signals in a quantitative manner and from this point of view it seems justified to consider chorus as an assembly of quasi-monochromatic signals, without determining the degree of their isolation. Essentially the same definition of chorus was used earlier when analysing the results of its observation onboard the satellites (Burtis, 1974; Burtis and Helliwell, 1969, 1975, 1976) and it is used in this paper. Note that emissions similar to the Earth’s magnetospheric chorus were also observed in the magnetospheres of other planets, e.g. Jupiter (Inan et al., 1983; Inan, 1986). Chorus is aurally perceived as a “birds’ dawn chorus”, as was first suggested by K. W. Tremellen in England (Isted and Millington, 1957). This term could also be justified by the observation of the most intense chorus events at approximately 06:00 L.T. (Storey, 1953; Maeda, 1962). However, a more detailed consideration of the phenomenon revealed that this local time maximum was typical for chorus observed at mid-latitude stations ($\phi \approx 55^\circ$) and that for chorus observed at high-latitude stations ($\phi \approx 75^\circ$) it shifted to 12:00 L.T. (Allcock, 1957; Pope, 1957, 1960). Moreover, it was noticed that high-latitude chorus was observed at lower frequencies than mid-latitude chorus (Ungstrup, 1959). Hence it seemed to be justified to consider these types of chorus as morphologically different phenomena and call them polar and mid-latitude chorus, respectively (Ungstrup and Jackerott, 1963). Hayashi and Kokubun (1971) later considered a principally new type of chorus—auroral chorus, which was typical for post-midnight hours of the auroral zone (Syowa station $\phi = -69.6^\circ$). Finally, Francis et al. (1983) described chorus events in the auroral zone (Halley, Antarctica, $L = 4.3$) in the frequency range 6–9 kHz, which could not be attributed to any of the above-mentioned types of chorus. This type of chorus will be called (6–9) kHz chorus. These types of chorus events are considered in Section 2 based on the results of their observation at the ground-based stations. The results of satellite observations of chorus emissions are summarized in Section 3. In Section 4, we discuss
different approaches to the modelling of chorus phenomena.

This review is mainly intended for those who are already familiar with chorus phenomena and just need to update or to amend their information. For this reason we avoided any illustrative material (e.g. dynamic spectra of different events), but tried to present the reference list as completely as possible.

2. GROUND-BASED OBSERVATION

2.1. Mid-latitude chorus

As already mentioned, mid-latitude chorus emissions are typical for dawn local times of the subauroral zone although they were often observed up to the auroral zone stations (Lovozero, L = 4.9: Sazhin and Titova, 1977). They were mainly observed at frequencies 2–4 kHz, though sometimes this frequency range could extend up to 1.5–5 kHz (Kokubun et al., 1981). Those frequencies tended to decrease from dawn to noon and further increase from noon to dusk; they appeared to be minimal during summer time and maximal during equinoxes (Pope, 1963).

Magnetic impulses (impulsive magnetic variations) with a duration ~ 2 s coincided with the occurrence of groups of VLF risers with a similar duration in the local morning-to-noon sector, according to Park Side station (L = 4.4) data. These impulses were interpreted as a result of ionospheric conductivity enhancement due to the electron precipitation induced by whistler-mode waves (Kokubun et al., 1981).

More convincing results concerning the relationship between chorus and electron precipitation events came from the study of the correlation between chorus risers and X-ray bursts (caused by 30 keV electrons) recorded on the balloons (Rosenberg et al., 1971, 1981, 1990; Foster and Rosenberg, 1976). In particular, using Siple station (L = 4.1) data, it was pointed out that each strong X-ray burst was related to the corresponding riser and vice versa. Correlated pairs of X-ray bursts and risers appeared quasi-periodically with the dominant period of about 6 s. The waves led the X-ray bursts by 0.3–0.4 s which was interpreted as showing that the waves generated in the equatorial magnetosphere due to whistler cyclotron instability propagated to the observer's hemisphere along the magnetic field lines, while the resonant electrons travelled first to the opposite hemisphere and then were reflected back to precipitate into the ionosphere of the observer's hemisphere (Rosenberg et al., 1971). Further study of correlated electron microbursts (50 < \(W_e\) < 200 keV) and chorus in the frequency range 2 kHz < \(f\) < 4 kHz when using the data of conjugate stations of Roberval and Siple (L = 4.1), revealed that the electron microbursts in one hemisphere (Roberval) were observed to lag behind the associated risers in the opposite hemisphere by 0.07–0.08 s. This result was interpreted as the possibility of generation of microbursts away from the geomagnetic equator for large L-values (Rosenberg et al., 1981). Detailed one-to-one correspondence between microbursts and chorus elements was not a consistent feature of the data from Super Arcas sounding rocket and ground-based observations in Siple. Significant correlation was found between Siple X-ray precipitation and the Roberval VLF waves with an arrival time delay of about 0.1 s (Roeder et al., 1985).

In contrast to Rosenberg et al. (1981), Imhof et al. (1989) could not identify any correlation between individual ground-based chorus elements and the bursts of electrons at energies above 6 keV recorded at a low altitude (~200 km) S8-1 satellite. The lack of such a correlation was tentatively related to the limited spatial extent of flux tubes excited by individual chorus elements. Durations in time of the VLF amplitude enhancements were comparable with those of the electron bursts.

Park et al. (1981) considered simultaneous observations of VLF chorus at Siple and electrons with energies below 50 keV at the ATS satellite (L = 6.6) on 10–21 August 1974. They distinguished two types of chorus events: one which was closely related to electron fluxes at energies above 5 keV, and another which was not related to electron fluxes and was believed to be triggered by whistlers or power line harmonic radiation (PLHR). The first was believed to be generated outside the plasmasphere, the second inside it; they will be further designated as extra-plasmaspheric and plasmaspheric chorus. Extraplasmaspheric chorus in most cases revealed a regular increase of its upper frequency with time (Carpenter et al., 1975). The latter phenomenon was also observed for mid-latitude hiss-type emissions (Hayakawa et al., 1986, 1988; Hayakawa, 1989).

Another manifestation of the relation between chorus and energetic electron events comes from the observed correlation between chorus emissions and pulsating aurora which was first observed in the late 1960s (Vigneron et al., 1969). Helliwell and Mende (1980) reported one-to-one correlation between \(\lambda = 4278\) \(\AA\) optical emissions and chorus events observed at Siple (L = 4.1), when the plasmapause was equatorward from the station. Photometer peaks lagged the wave peaks by 1–2 s. When interpreting this time difference, it was assumed that the waves propagating away from the equator after reflection in the ionosphere in the observer's hemisphere, trigger emissions and the emissions scatter the electrons.
which are precipitating into the ionosphere above the observer. A similar electron precipitation has been further discussed by Doolittle and Carpenter (1983). Tsuruda et al. (1981) claimed that chorus activity at Park Site ($L = 4.4$) was very low during the time when pulsating aurora was active over the station, which was interpreted as a result of strong chorus absorption in the $D$-region of the ionosphere. Six out of seven chorus events which were detected showed one-to-one correlation with the brightening of a pulsating patch. The brightening of the patch led chorus events by $0.1-0.2$ s, which was interpreted similarly to Rosenberg et al. (1971) (see above). As detected by a low-light-level TV camera, this patch had an oval shape $75$ km in the North–South direction and $150$ km in the East–West direction at the ionospheric altitudes, which was consistent with the size of precipitating region determined from magnetic field observations (Kokubun et al., 1981).

One important characteristic of chorus elements is the degree of their inclination $f'$ ($= df/dt$). Alcock and Mountjay (1970) were the first to point out an increase of $f'$ when $\Sigma K_p$ increased (where $\Sigma K_p$ is a daily sum of the $K_p$ index) when using Lauder station ($\phi = -52^\circ$ data). Smirnova et al. (1976) reported a gradual decrease of $f'$ for the lower latitude stations [Lovozero ($L = 4.9$), Sogra ($L = 3.7$), Borok ($L = 2.8$)]. Sazhin and Titova (1977) studied this problem further when using the Lovozero station data from November 1973 to January 1974, and paying attention on the local time dependence of the phenomenon. As follows from the results of their analysis, the values of $f'$ are larger for larger $\Sigma K_p$, being in agreement with the results of Alcock and Mountjay (1970), and decrease with local time when $\Sigma K_p > 8$ (this result was based on the results of mathematical statistics: see Taubenheim, 1969). The values of $f'$ for $\Sigma K_p \leqslant 8$ practically do not depend on local time. From the analysis of plasmapause location when using Binsack's (1967) formula, derived from direct observations of the plasmapause in the equatorial plane [a similar formula derived from whistler data has been obtained by Rycroft and Thomas (1970); see also Rycroft (1975)], it follows that chorus observation when $\Sigma K_p > 8$ ($\Sigma K_p \leqslant 8$) took place when Lovozero was outside (inside) the plasmasphere. Hence we can presumably identify the considered types of chorus with extra-plasmaspheric and plasmaspheric chorus which were determined based on the results of Park et al. (1981). The chorus elements observed by Sazhin and Titova (1977) in most cases had $f' < 2$ kHz s$^{-1}$, which agrees with the results obtained earlier by Alcock and Martin (1956) and Pope (1963). Most of the extra-plasmaspheric chorus was observed in the morning, while plasmaspheric chorus was recorded during the post-midday to dusk hours. This agrees with the results of Crouchley and Brice (1960) and Yoshida and Hatanaka (1962) who noticed a decrease of the latitude where chorus occurrence is maximal when $K_p$ increased.

Mid-latitude chorus was typical for disturbed periods with $K_p \geqslant 2$ (Dowden, 1971a), although it could be observed at $K_p < 1.5$ (Helliwell and Morgan, 1960; Alcock and Mountjay, 1970). At the Magadan ($\phi = 53^\circ$) station maximal chorus emission energy was observed when $\Sigma K_p \approx 30$ (Gorshkov, 1980).

Mid-latitude chorus was in most cases accompanied by hiss-type emissions and hence often called chorus and associated hiss (Helliwell, 1969) which is physically identical with the noise storms described by Fedyakina and Vershinin (1976), Fedyakina (1978) and Fedyakina and Khorosheva (1989). However, Dowden (1971a) reported slightly different regions of generation of chorus and the corresponding hiss.

The chorus emissions under consideration were observed mainly during equinox and winter time (Pope, 1963; Kimura, 1967) and recovery phase of the substorm (Tokuda, 1962; Vigneron et al., 1969); their power flux usually exceeded $10^{-15}$ W m$^{-2}$ Hz$^{-1}$ (Kleimenova et al., 1970).

2.2. Polar chorus

As in the case of the mid-latitude chorus, the polar chorus is closely connected with hiss-type emissions and often appears as an upper boundary of their spectra. Unlike mid-latitude chorus, polar chorus appears at lower frequencies (400–1500 Hz) with a bandwidth up to 500 Hz. A frequency at which polar chorus power flux is maximal ($> 10^{-14}$ W m$^{-2}$ Hz$^{-1}$), $f_{\text{max}}$, corresponds on average to 700 Hz (Egeland et al., 1965) increasing from 400 Hz at noon hours to 800 Hz at evening and morning hours; this frequency increases when $K_p$ increases (Kokubun et al., 1969).

Contraction of the magnetosphere related to sudden commencement (SC) triggers chorus or increases its intensity, while decrease in magnetic induction at the equatorial stations ($B_{eq}$) connected with magnetospheric expansion is accompanied by decrease of polar chorus activity or its complete fading out. An increase in $B_{eq}$ causes an increase in $f_{\text{max}}$; enhancement of the emissions was recorded about 30 s prior to the commencement of magnetic field variation; the latter time difference can obviously be interpreted in terms of the differences in transit times of hydromagnetic and whistler waves from the equatorial plane to the ionosphere (Hayashi et al., 1968; Sato, 1980). These results seem to agree with the more general connection between SC and VLF emissions reported by Yach-
menev et al. (1989) and Mullayarov and Yachmenev (1990). The polar chorus was usually observed simultaneously at conjugate stations, while the details of its conjugate properties appeared to be unclear (Sato et al., 1983; Suzuki and Sato, 1987). These emissions were most often observed at stations corresponding to the polar cusp projection: Godhavn (\(\phi = 77^\circ\)) (Kleimenova et al., 1983). Northward from the cusp projection polar chorus intensity decreased dramatically (Kleimenova and Kozyreva, 1991). Another maximum of polar chorus activity corresponded to \(L = 4.5\) on the basis of the results of these emission observations on the chain of Canadian stations from \(L = 4.15\) up to \(L = 5.1\) (Tsursud et al., 1982). An increase in chorus frequency with increasing local time was observed. Chorus events with starting frequencies close to 1 and 1.5 kHz were separated by a frequency gap (Tsursud et al., 1982).

From the study of arrival direction of polar chorus at Syowa station (\(\phi = -69^\circ\)) it followed that, in the morning sector, emissions came from both the East and West with nearly the same probability, while in the afternoon sector the tendency changed drastically such that emissions were dominantly coming from the West. In the early morning (04:00–07:00 M.L.T.), emissions came mostly from the North, the arrival direction shifting gradually from the North to the South toward noon. Then it gradually backed up from the South to the North during the afternoon (13:00–20:00 M.L.T.) (Sato, 1980).

An increase in polar chorus intensity was accompanied by an increase in ionospheric absorption (Morozumi, 1967), although the inverse was not obligatory (Kokubun et al., 1969). A difference between local time characteristics of ionospheric absorption and chorus activity was reported (Ondoh, 1963a,b). The polar chorus was more often observed in summer than in winter (Hayashi et al., 1968; Suzuki and Sato, 1987; Sato et al., 1990, 1991).

The occurrence of polar chorus emissions was maximum during the prenoon hours at \(Kp \sim 2–3\) and increased with the velocity and dynamic pressure of the solar wind (Kleimenova et al., 1983). ELF emissions at the dayside auroral oval described by Holtet et al. (1985) can also be referred to as polar chorus.

### 2.3. Auroral chorus

As already mentioned, the auroral chorus was considered as a separate type of chorus events according to Syowa station data (Hayashi and Kokubun, 1971) although an investigation of this phenomenon began much earlier (Morozumi, 1965; Ungstrup, 1966; Jørgensen, 1971). This type of chorus is typical for post-midnight hours, being a rather rare phenomenon when compared with other types of emissions recorded at Syowa. This can be attributed to its small power flux (<10^{-15} W m^{-2} H^{-1}) (Hayashi and Kokubun, 1971). The auroral chorus power flux observed at Husafell station, which was conjugate to Syowa, was much stronger (Sato et al., 1983).

The auroral chorus spectrum consists of quasi-monochromatic signals which are not accompanied by hiss emissions and whose frequency increases in time, being observed in the range 0.5–2 kHz. Separate auroral chorus risers appear intermittently in groups with a few seconds duration which follow periodically with an irregular period of about 10 s. Separate riser duration is about 0.1–0.3 s (Hayashi and Kokubun, 1971).

### 2.4. (6–9) kHz chorus

Rising-frequency (6–9) kHz chorus emissions considered when using Halley station (\(\phi = -77.5^\circ\); \(L = 4.3\)) data (Francis et al., 1983) can probably be identified as discrete emissions formally considered by Helliwell (1965). The risers constituting these emissions were split into two frequency groups, one with frequency in the range 6.0–7.7 kHz and the other with frequencies between 7.8 and 9.4 kHz, the former being more numerous. A clear gap (\(~500\) Hz) was seen between lower frequency risers in the range 6.0–7.7 kHz, and risers at higher frequencies in the range 7.8–9.4 kHz. Emissions in both frequency ranges exhibited many similar characteristics in their temporal variations in rate of occurrence, often simultaneous observation of the emissions in each group, and others. A noticeable feature is the occurrence of the emissions in both frequency ranges in bursts with a periodicity of about 4 min. These experimental results are consistent with the assumption that the emissions in each frequency range are generated in the same duct (enhanced field-aligned electron density). These emissions occurred during the recovery period following a minor geomagnetic storm. They can be presumably related to the plasmaspheric chorus considered by Park et al. (1981) and whistler-triggered VLF noise bursts studied by Smith et al. (1985).

### 3. Satellite Observations

Chorus emissions observation onboard the satellites and rockets made it possible not only to complement substantially the information obtained from ground-based observations but also to yield essentially new information. We can expect that ground observations are most closely connected with the satellite and rocket observations in the topside ionosphere which are considered in the next section.
3.1. Observations in the topside ionosphere

Chorus observations in the topside ionosphere at heights not exceeding 0.5 $R_E$ ($R_E$, Earth's radius) were made onboard many satellites, including: Injun-3, -5: OGO-6; OVI-17; Ariel-3, -4; Isis-1, -2; Aureol-3; Intercosmos-14 (Taylor and Gurnett, 1968; Oliver and Gurnett, 1968; Mosier and Gurnett, 1969; Bullough et al., 1969, 1975; Barrington et al., 1971; Holzer et al., 1974; Kelley et al., 1975; Kaiser and Bullough, 1975; Hayakawa et al., 1977; Ondoh et al., 1982a,b; Berthelier et al., 1982; Izrhichek et al., 1986). The Injun-3 satellite recorded chorus emissions approximately at those latitudes and local times where mid-latitude and polar chorus emissions were recorded on the ground (Gurnett and O'Brien, 1964); a good correlation was observed between chorus emissions and the electron fluxes at energies greater than 40 keV, which agrees with the already reported correlation between chorus emissions and X-ray bursts (Oliver and Gurnett, 1968). When using OGO-6 data, it has been pointed out that chorus peaks often do not coincide with electron precipitation peaks which can be interpreted by the difference in wave and electron trajectories in the magnetosphere: the latter are more close to the magnetospheric magnetic field lines (Holzer et al., 1974).

Poynting flux measurements onboard Injun-5 have revealed that it is directed earthward up to the apogee of Injun-5 (2500 km) (Mosier and Gurnett, 1969). This makes unlikely early mechanisms of chorus generation in the topside ionosphere (see for example, MacArthur, 1959; Aarons et al., 1960; Chamberlain, 1961; Ondoh, 1961; Maeda and Kimura, 1962; Swift, 1968), although they seem to be confirmed by the observed relationship between chorus frequency and the proton gyrofrequency onboard Intercosmos-14 (Mikhailova et al., 1983; Bud'ko, 1984). The determination of chorus wave normal angle from the analysis of its polarization has shown that it is directed downward in the region away from the plasmapause; near the plasmapause it was inclined poleward, which was interpreted as a result of wave reflection from the plasmapause (Holzer et al., 1974).

A detailed analysis of latitudinal variation of chorus frequency observed in the topside ionosphere onboard Isis-1, -2, has revealed that the upper and lower limit frequencies of the dayside chorus decreased with L-value being almost always below one half of the equatorial gyrofrequency. The upper and lower frequencies of chorus observed in the early morning, late evening and night-time, did not show any significant variation with L-value (hence a localized source of these types of chorus emissions is to be expected). Night-time emissions were observed in disturbed periods. Furthermore, it was found that chorus frequency bands at latitudes beyond the plasmapause were higher than those at latitudes inside the plasmapause so that a gap between these bands was observed (Ondoh et al., 1982a,b). It seems that this gap has a similar nature to the corresponding gap which has been reported by Francis et al. (1983) (see Section 2.4). Observation on low-latitude polar orbiting satellites P78-1 and S81-1 revealed that chorus emissions were mainly responsible for electron precipitation from the day-side magnetosphere (Imhof et al., 1986), in agreement with the earlier results obtained by Oliver and Gurnett (1968) and ground-based observations (see Section 2.1).

Observations of daytime ELF emissions onboard the rocket at the height interval 180–200 km reported by Cartwright (1964) can also be referred to as polar chorus. Intensity of these emissions was about 8000–10,000 larger than that on the ground.

As follows from our analysis, most of the experimental data and, in particular, the earthward direction of the Poynting vector of chorus emissions at the ionospheric level, make it possible to assume that chorus emissions are generated not in the topside ionosphere, but in the equatorial magnetosphere. The results of in situ chorus observations in the latter region are considered in the next section.

3.2. Observations in the equatorial magnetosphere

The results of the first equatorial observations of chorus emissions onboard OGO satellites have been reported since the late 1960s (Dunckel and Helliwell, 1969; Burtis and Helliwell, 1969; Russell et al., 1969). The earlier results were reviewed by Russell et al. (1972). When considering the probability of chorus observation in the equatorial magnetosphere based on OGO-3 data, it was pointed out that the L-value of chorus usually increased when local time increased (Burtis, 1974; Burtis and Helliwell, 1976), which is consistent with ground-based observations (see Section 2.1). Most chorus events in the equatorial magnetosphere were observed outside the plasmasphere (Russell et al., 1972). When considering latitude dependence along the magnetospheric magnetic field line of chorus occurrence, based on OGO-5 data, a well-defined minimum at the latitude $\phi = 15^\circ$ was observed; at 00:00 < L.T. < 09:00 equatorial chorus emissions were the dominant, while high-latitude chorus emissions were essentially a daytime phenomenon with the maximal occurrence at 12:00. The latter emissions had a tendency to be recorded at larger L-values when compared with equatorial chorus (this result is consistent with ground-based observations of polar
chorus arrival direction; see Section 2.1), being often recorded in the region close (within 1–2 R_E) to the magnetopause. These properties of high-latitude chorus can be understood if we take into account the characteristic deformation of the dayside magnetosphere which results in the formation of the minimum B_0 regions away from the geomagnetic equator (Tsurutani and Smith, 1977). The observed localization of equatorial and high-latitude chorus is consistent with the earlier result of Burton and Holzer (1974). When analysing the distribution of chorus wave normals recorded onboard the same OGO-5 satellite they pointed out that post-midnight chorus was generated within 2° near the magnetospheric equator; for the dayside chorus this region extended up to 25°. Lefeuvre et al. (1981) and Buchalet and Lefeuvre (1981) have presented case events that the angular distribution of chorus energy has two maxima in the off-meridian plane similar to plasmaspheric hiss energy distribution.

The measurements of wave normal directions of chorus emissions were performed by Goldstein and Tsurutani (1984) and Hayakawa et al. (1984) in the equatorial plane and also by Hayakawa et al. (1990) in the off-equatorial region. Goldstein and Tsurutani (1984) and Hayakawa et al. (1984) have indicated that only a single plane wave is present in most cases of chorus events and the wave normal at lower frequencies (frequency ω smaller than 0.3 electron gyro-frequency, Ω) is close to the Earth’s magnetic field at the equator, in favour of the electron cyclotron instability. Furthermore, Goldstein and Tsurutani (1984) found a small concentration of wave energy at relatively large angles at around θ_p ≈ arcsin (2ω/Ω) (Gendrin angle: see Gendrin, 1960) in the frequency range, ω = 0.3–0.45 Ω, but Hayakawa et al. (1984) did not find this tendency. Also Hayakawa et al. (1984, 1990) have found that the value of the wave normal angle of chorus elements seems to increase with the increase of f' = df/dt. The off-equatorial direction finding based on GEOS-1 data by Hayakawa et al. (1990) have been used to suggest that the behaviour of wave normal directions of rising-tone chorus at the off-equatorial region can be explained in terms of the non-ducted propagation from the equatorial region, where the waves are generated at wave normal angles close to zero (see Hattori et al., 1990).

Burton and Holzer (1974) and Burton (1976) have pointed out that chorus emissions are observed only when the anisotropy (A_e = T_L/T_R) of energetic electrons was above unity, which is consistent with the hypothesis that these emissions are excited due to the whistler cyclotron instability. Correlation between chorus and energetic (1–10 keV) electron enhancements has been also observed by S3A (Explorer 45) (Maeda et al., 1976a,b; Anderson and Maeda, 1977) and JIKIKEN (Exos B) (Matsumoto et al., 1981a,b) satellites. Isenberg et al. (1982) reported simultaneous observations of the electrons in the range 10–100 keV, and chorus activity in the dawnside sector based on SCATHA (P78-2) satellite data. The discrepancy between this result and that which was obtained onboard S3A and JIKIKEN arises from the fact that the S3A orbit was inside the drift trajectories of electrons with energies greater than 10 keV and JIKIKEN simply did not record these electrons. Hence we can expect that chorus activity is primarily accompanied by the enhancement of electrons at energies greater than 10 keV, although their enhancement at lower energies was also observed. Tsurutani et al. (1979) pointed out that the correlation between chorus activity and energetic (> 55 keV) electrons appeared to be more typical for the equatorial chorus; for dayside high latitude chorus no such correlation was observed.

Cornilleau-Wehrlin et al. (1978) were the first to report the simultaneous observation of chorus and hiss emissions in the same frequency range onboard GEOS-1, although the intensity of the latter could be much lower. Essentially the same phenomenon was reported by Jones et al. (1983a,b) who applied cross-spectral phase analysis of VLF signals to the data of the same satellite. When using SCATHA satellite data Koons (1981) has shown that hiss emissions do not have a smooth spectrum; they can rather be considered as a superposition of numerous monochromatic waves which considerably change their amplitudes within less than a second. When this spectrum is integrated within a few seconds, it turns into a well-known smooth hiss spectrum. The structure of the hiss emissions was later extensively studied by Tsuji et al. (1989) and Hattori et al. (1991a,b). The latter authors have found, based on the fine resolution spectral analyses, that some parts of the hiss are very turbulent and incoherent, but other parts indicate the presence of wavelets or monochromatic wave components with considerable duration near the upper edge of the hiss band. Furthermore Hattori et al. (1991b) have pointed out that if the product of the intensity and duration of such wavelets is sufficiently large, then they generate a coherent chorus-type noise. These results seem to be important for modelling chorus events.

According to OGO-3 data, chorus average frequency was approximately proportional to L−3, while relative bandwidth was independent of L, increasing with increasing latitude along the magnetic field line. The latter can be explained by the convergence of the magnetic field lines: emissions recorded at high
latitudes come from the extended region of the equatorial magnetosphere. Chorus emissions were often (in 20% of cases), observed in two frequency bands with a well-defined gap in the vicinity of $\Omega_{ce}/2$, where $\Omega_{ce}$ was the electron gyrofrequency at the magnetospheric equator (Tsurutani and Smith, 1974; Burris and Helliwell, 1976). The same gap was also observed onboard other satellites, in particular $S^3A$ (Maeda et al., 1976a,b; Anderson and Maeda, 1977), JIKKEN (Matsumoto et al., 1981a,b) and GEOS-1 (Hayakawa et al., 1984; Muto et al., 1987). Emissions at frequencies above $\Omega_{ce}/2$ were more typical for the vicinity of the magnetospheric equator than for the region away from it (Burris, 1974; Maeda and Smith, 1981). These emissions can only be conventionally referred to chorus type because their spectrum can sometimes be of hiss type. The typical bandwidth of these emissions both in the equatorial and off-equatorial planes is 300–500 Hz (Hayakawa et al., 1984; Muto et al., 1987). The direction finding measurement by Hayakawa et al. (1984) has indicated that the upper band emissions at $\omega > \Omega_{ce}/2$ are quasi-electrostatic whistler-mode waves generated at the equator with wave normal close to the oblique resonance angle $\theta_{res}$. Further, the frequency gap between the two bands in the off-equatorial region was found to be always much smaller than the local $\Omega_{ce}/2$ which is indicative of the source being located at a position with smaller geomagnetic field. The analysis of wave normal angles of these waves at $\omega > \Omega_{ce}/2$, together with the inverse 3-D ray-tracing, indicates that they are most probably excited in the equatorial region of the magnetosphere with wave normal angles close to the resonance cone angle in a cold plasma $\theta_{res}$ (Muto and Hayakawa, 1987; Muto et al., 1987; Hayakawa, 1988) which is consistent with the results obtained in the equatorial plane. A broadening of the emission band below $\Omega_{ce}/2$ on the lower frequency side, observed onboard the $S^3A$ satellite, was reported by Maeda and Lin (1981) and Maeda and Anderson (1982). In the first case, this broadening was of a gradual type and was associated with the simultaneously observed spreading of the anisotropy of the ring current electrons to higher and wider energy ranges. In the second case, this broadening was of a burst type; it lasted less than 10 min and was accompanied by sudden enhancement of ring current electrons at energies below 10 keV.

Chorus emissions recorded onboard ISEE-1 and -2 were often accompanied by bursts of electrostatic waves at frequencies slightly below the electron plasma frequency (3–10 kHz). In some cases the electrostatic waves were modulated at the chorus frequency (0.1–0.8 kHz). Electrostatic bursts sometimes lasted longer than chorus bursts with their wave vector being directed along $B_0$. This phenomenon was interpreted in terms of electrostatic two-stream instability caused by electrons energized by chorus waves (Reinleitner et al., 1982, 1983; Gurnett and Reinleitner, 1983). Numerical analysis by Nunn (1991) has also confirmed that the non-linear wave–particle interaction in VLF signals can drive the plasma into electrostatic instability. Similar chorus related electrostatic bursts were observed in the magnetosphere of Jupiter (see Saikia et al., 1990). The onset of chorus emissions was reported to be preceded by the activity of electrostatic emissions at $3/2 \Omega$ during substorm development (Scarf et al., 1973).

The spectral characteristics of chorus emissions observed onboard OGO-3 appeared to be essentially the same as those observed on the ground or in the topside ionosphere (Burris, 1974; Burris and Helliwell, 1976). Risers were the most frequent elements (77%) followed by falling tones (16%) which were mostly observed in the vicinity of the magnetospheric equator. The average value of $f^*$ for the risers was 0.77 kHz s$^{-1}$; it decreased with increasing $L$ and local time and decreasing $K_p$, where $K_p$ was the maximal value of $K_p$ during the previous 24 h (these results are consistent with ground-based observations of $f^*$). An observed increase of $f^*$ with increasing latitude along the magnetospheric magnetic field line can presumably be explained by the dispersion of whistlers propagating from the vicinity of the magnetospheric equator.

Coroniti et al. (1971), Stiles (1975) and Cornilleau-Wehrlin et al. (1976) gave detailed analyses of fine structure of chorus based on OGO-5 data. In particular, the latter authors paid attention to the fact that the value of $f^*$ was not conserved within individual chorus elements; at the end of the elements it became close to zero. The amplitude of chorus elements could change up to 12 dB within 20–40 ms. The value of wave normal angle $\theta$ could change up to the factor 2 within individual chorus elements. The values of $\theta$ for the falling tones were observed to be larger than for the risers.

$DE-1$ observations in the inner magnetosphere at $L < 3$ have led to the identification of a new type of discrete whistler-mode emission occurring at middle to low latitude (Poulsen and Inan, 1988; Gurnett and Inan, 1988). As the properties of these emissions are in many respects similar to chorus emissions, it seems reasonable to consider them as a subtype of the latter. In summary, the emission elements are confined to a bandwidth of 1–5 kHz, with the lower cutoff frequency of the band varying with $L$-shell, being equal to $\sim 0.2–0.5 \Omega_{ce}$. The discrete and burstlike nature of
the emissions was similar to that of chorus emissions typically observed at higher L; however, the dispersion of individual elements was often different from typical chorus, and the emissions were observed inside as well as outside the plasmasphere (cf. observations of mid-latitude chorus inside the plasmasphere). The phenomenon seemed to occur mainly in the early morning local time sector (04:00–08:00 M.L.T.), and was well correlated with geomagnetic activity, occurring mostly when daily sum of $K_p$ exceeded 30. The analysis of data from the low-altitude ISIS-2 and the high-altitude DE-1 satellites indicated that the emissions might be generated near the equatorial plane at frequencies of $\sim 0.2 \Omega_{eq}$ inside and $\sim 0.35 \Omega_{eq}$ outside the plasmasphere (Gurnett and Inan, 1988). The same kinds of chorus emission have been observed onboard Intercosmos satellites (Boškova et al., 1986), which have indicated that the frequency of their intensity maximum varies continuously with geomagnetic latitude and approximately parallels the value of a quarter of the equatorial gyrofrequency. Boškova et al. (1988, 1990) have shown that discrete plasmaspheric emissions can be quasi-electrostatic whistler waves generated in the near-equatorial region at the frequency above one half the gyrofrequency, such as observed by Tsurutani and Smith (1974), Hayakawa et al. (1984) and Muto and Hayakawa (1987), which then propagate in a nonducted way (quasi-resonance mode) to the point of observation.

4. GENERATION MECHANISMS

When considering chorus generation mechanisms one needs to explain: (a) the frequency band in which chorus is observed and its dynamics; (b) the origin of monochromatic elements that constitute the fine structure of chorus; and (c) the frequency–time behaviour of these elements. These problems are considered in Sections 4.1, 4.2 and 4.3, respectively. Other morphological properties of chorus emissions will be discussed in connection with the models under consideration.

4.1. Frequency band of the emissions

The observed correlation between chorus emissions and anisotropic fluxes of energetic ($>1$ keV) electrons makes it possible to assume that these electrons constitute an energy reservoir for the emissions and the energy transfers from electrons to waves due to whistler cyclotron instability (see e.g., Brice, 1964; Kennel and Petschek, 1966). The generation of lower frequency ($\omega < 0.3 \Omega$) chorus in terms of electron cyclotron instability with $\theta \approx 0^\circ$ is furthermore evidenced by the in situ wave normal direction finding (Goldstein and Turutani, 1984; Hayakawa et al., 1984, 1990), but this does not seem to be the case for chorus at $\omega = 0.3 \sim 0.45 \Omega$ (see Goldstein and Turutani, 1984). The generation mechanism of emissions above $\Omega/2$, as well as the origin of the gap between two frequency bands, remain obscure. Maeda et al. (1976b) attempted to explain the two-band structure of chorus emissions by assuming that these emissions were generated in different regions of the equatorial magnetosphere. When propagating away from the magnetospheric equator these waves are reflected at the lower hybrid frequency, become trapped in the magnetospheric duct, and further propagate up to another place of the equatorial plane which is closer to the Earth, where the locally excited and incoming waves are observed simultaneously. The efficiency of this process is strongly controlled by the efficiency of the reflection and trapping processes.

Burtis and Helliwell (1976) attempted to explain chorus upper frequency band by whistler-mode energy focusing along the magnetic field line at frequencies close to $\Omega/2$ based on a cold plasma model. This mechanism seems to be even more effective when plasma finite temperature and anisotropy are taken into account, which results in wave focusing at frequencies above $\Omega/2$ (see Sazhin, 1982). Nevertheless, this mechanism does not seem to be the dominant one, because the observed upper frequency band emissions are presented not as an enhanced continuation of the lower frequency emissions, but as the emissions having completely different frequency–time structure which were often not accompanied by lower frequency emissions (Maeda et al., 1976a, b). The latter fact also does not seem to be compatible with the mechanism suggested by Tsurutani and Smith (1974) according to which the gap between chorus emissions is due to Landau damping of the waves.

Curtis (1978) assumed that chorus emissions at frequencies above $\Omega/2$ propagated not in the whistler mode, but rather in the ordinary mode. Ordinary-mode waves were assumed to be generated at the same place in the magnetosphere as the whistler-mode waves which were responsible for the lower frequency emissions, but the ordinary-mode waves were excited by different electrons. This model seems to be compatible with the observations by Maeda and Smith (1981) which have shown that the emissions at frequencies above $\Omega/2$ are concentrated mostly in the near-equatorial region of the magnetosphere (ordinary mode propagates nearly perpendicular to the magnetic field). However, Curtis's (1978) model is valid only in a rarefied plasma when $\Pi$ (angular electron plasma
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frequency) is less than \( \Omega \) which seems to be the exception rather than the rule for the equatorial magnetosphere, even in the region outside the plasmasphere. Moreover, the theory of wave propagation and excitation in such a rarefied plasma should have been based on the weakly relativistic approximation (see e.g. Sazhin, 1987a), rather than on the non-relativistic approximation used by Curtis (1978).

Hashimoto and Kimura (1981), as well as Curtis (1978), assumed that chorus emissions at frequencies below and above \( \Omega/2 \) propagated in different wave modes. Propagation of the latter emissions was associated with quasi-electrostatic whistler mode which corresponded to whistler-mode propagation in a hot plasma with wave normal angle close to resonance angle \( \theta_{\text{res}} \). While Hashimoto and Kimura (1981) based their numerical analysis of these waves on electrostatic approximation, Ohmi and Hayakawa (1986a,b) analysed them based on the general electromagnetic equations, assuming that magnetospheric plasma consisted of cold and hot anisotropic electrons. They predicted the excitation of waves at frequencies above \( \Omega/2 \) when the anisotropy of hot electrons was very high \((A_e > 3)\), which seems to be unrealistic in the magnetospheric conditions. The propagation of quasi-electrostatic whistler-mode waves at \( \theta \approx \theta_{\text{res}} \) has been studied analytically (Sazhin, 1986, 1988, 1989a,b; Sazhin et al., 1990) and numerically (Ohmi and Hayakawa, 1986b; Sazhin and Walker, 1989; Horne and Sazhin, 1990; Sazhin et al., 1990). When making numerical computations both Hashimoto and Kimura (1981) and Ohmi and Hayakawa (1986a,b) considered a model in which \( \Pi > \Omega \). Hence their model and that of Curtis (1978) can be considered as complementary. Sazhin and Walker (1989) have shown that oblique quasi-electrostatic whistler mode waves are unstable predominantly at frequencies above \( \Omega/2 \) while the waves propagating parallel to the magnetic field are unstable predominantly at \( \omega < \Omega/2 \). This could predict another complementary explanation for a frequency gap between two bands of chorus emissions.

Two types of frequency band broadening of lower band chorus emissions, gradual and burst type, were associated with different physical mechanisms. The first was explained in terms of the corresponding changes of parallel whistler-mode instability connected with the spreading of the electron anisotropy to higher and wider energy ranges (Maeda and Lin, 1981). The second was explained in terms of oblique quasi-electrostatic whistler-mode instability of bi-Maxwellian electrons surging into the domain of relatively low density magnetized cold plasma in the region just outside of the night-time plasmasphere (Maeda and Anderson, 1982).

Some fine properties of chorus emissions in the off-equatorial regions of the magnetosphere could also be understood as a result of propagation effects (for details, see e.g. Cairo and Lefeuvre, 1986; Muto et al., 1987). Note that chorus emissions observed on the ground should either propagate in the magnetospheric ducts or in the vicinity of the plasmapause (Inan and Bell, 1977; Semenova and Trakhtengertz, 1980; Maltseva et al., 1985; Hattori et al., 1991a). The propagation of chorus through the ionosphere is accompanied by its damping (Helliwell, 1965; Hayakawa and Ohtsu, 1972), which can be considerably increased by low frequency \((f < 1 \text{ kHz})\) electrostatic turbulence in this area (Trakhtengertz and Titova, 1985).

4.2. The origin of monochromatic elements

Bespalov and Trakhtengertz (1974) noted that the drift velocity of the hot electrons, injected from a localized region in the night-time magnetosphere, around the Earth depended on their bounce period. This might lead to the formation of an electron distribution function, which is periodical with a period equal to the bounce period of the electrons \((T_B)\). If we assumed that chorus emissions were excited due to parallel whistler-mode instability in the equatorial region of the magnetosphere, the characteristic size of the cloud of electrons and the size of the region of possible development of the instability were small, then the electrons, when passing through the equatorial region of the magnetosphere, would stimulate the development of the instability in the wide frequency range, but during a very short period of time. The excited waves, propagating from the equatorial magnetosphere to the Earth's surface, would obtain the form of chorus rising tone element due to whistler frequency dispersion. Periodicity of the electron distribution function would lead to the corresponding periodicity of rising tones. Bespalov and Trakhtengertz (1975) considered essentially the same mechanism for the formation of chorus elements although they assumed \( \text{Cerenkov} \) rather than cyclotron excitation of the waves. Bespalov et al. (1977) claimed that the processes considered by Bespalov and Trakhtengertz (1974) could be intensified due to the development of low-frequency instability on the electron bounce resonance which would result in an additional modulation of electron density in the equatorial magnetosphere.

However, it is difficult to accept these models because: (1) they cannot explain the origin of chorus falling tone elements; (2) they cannot explain the origin of chorus rising tone elements, observed in the equatorial magnetosphere, which are essentially the
same as those of ground-based emissions; and (3) the assumption regarding the small region where instability develops in the equatorial plane seems to be too artificial: when it is relaxed the process gives rise to structureless noise bursts.

Bespalov and Trakhtengertz (1978) modified their original model in order that it might explain almost vertical chorus elements often observed on the ground. They claimed that the conditions for the development of cyclotron instability in the equatorial magnetosphere are strongly favoured if the time of whistler propagation between two hemispheres \( T_{\text{gr}} \) equals \( nT_{\text{th}} \), where \( n \) is an integer. For a given whistler ray path the latter equation determines preferentially several discrete frequencies which are excited. However in the actual magnetospheric conditions whistlers can simultaneously follow several ray paths corresponding to different \( L \). As a result one may observe whistler-mode waves in a wide frequency range as the signals propagating at different frequencies along different ray paths may have the same \( T_{\text{gr}} \). The bulk of these signals were identified with vertical chorus elements. As one can see, Bespalov and Trakhtengertz (1978) partly relaxed their original assumption regarding the small region of the instability development in the equatorial plane and assumed that the instability could develop at different \( L \)-shells simultaneously. However, they implicitly kept the assumption about meridional localization of this region which seems to be unjustified. We believe that the process under consideration is essentially responsible for the formation of chorus quasi-periodic structure with the period 2–3 s, which has been reported by Adjepong (1976), but not the fine structure of chorus elements.

Nunn (1974a, 1986) considered a completely different mechanism for the formation of the monochromatic elements, assuming that the latter originated from the pre-existing hiss-type emissions, which were approximated by the system of from 12 to 40 monochromatic waves with close frequencies. Mutual non-linear interaction between these waves and the resonant electrons, which was analysed by computer simulation methods, resulted in amplifying some waves and depressing others. Hence the whole system reduced to only a few monochromatic waves, which were identified which chorus elements. This approach seems to be supported by the experimental results reported by Koons (1981) and Hattori et al. (1991b,c), concerning the fine structure of hiss-type emissions and their association with chorus (see Section 3.2). and also by Kabanov (1990), who reported similarities in statistical structures in chorus and hiss emissions.

The ideas by Nunn (1974a, 1986) were further developed by Nunn and Sazhin (1991). They pointed out that band-limited VLF hiss emissions in the off-equatorial region of the magnetosphere can deform the electron distribution to give enhanced linear whistler instability near the upper cutoff frequency. Non-self-consistent computations of the non-linear resonant particle currents produced by a large amplitude hiss band confirmed a sharp peak in growth rate near the top of the band. At low amplitudes this peak appeared to be mainly due to the deformation of the phase-averaged distribution function by multipath interaction with the hiss band. At higher amplitudes of the order of 50 pT, non-linear wave–particle interaction effects seemed to predominate. It was believed that enhanced growth rates at the top of the band would produce coherent narrow band wavelets which could trigger chorus elements through non-linear wave–particle interaction effects (cf. Hattori et al., 1991b,c).

The latter problem is directly related to the problem of the origin of the so-called artificially stimulated emissions (see the recent review by Omura et al., 1991). Meanwhile we should note that the initial monochromatic waves may not only originate from the background hiss, but also be of artificial origin, being in particular associated with the PLHR (power line harmonic radiation) (Luette et al., 1977, 1979; Bullough, 1983; Bullough et al., 1985). Helliwell (1963) considered chorus elements to be triggered by some external signals. When echoing between opposite hemispheres these elements trigger other elements and hence the whole chorus phenomenon can be understood as a subtype of multiphase periodic emissions.

4.3. Frequency–time spectrum of the emissions

As has already been mentioned, when considering chorus morphology, the essential feature of these emissions is not only their monochromaticity at every moment of time, but also the rapid changes of frequency of the monochromatic elements (up to 10 kHz s\(^{-1}\)). The understanding of this phenomenon is considerably facilitated by its apparent relation to the corresponding frequency dynamics of the emissions, triggered by ground-based transmitters, that is, artificially stimulated emissions (ASE) (Helliwell, 1988). This makes it possible to assume that the monochromatic wave originating from hiss-type emissions or PLHR can be considered as a triggering signal for observed chorus elements.

The interaction of monochromatic waves with the resonant electrons can result in the deformation of the electron distribution function and in generation of two satellite waves at frequencies slightly different
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from the original wave. The first phenomenon can result in an electron precipitation (Karpman and Shklyar, 1977; Chang et al., 1983; Chang and Inan, 1983; Singh and Prasad, 1983; Torkar et al., 1987). The latter phenomenon was observed as a self-modulation of a transmitter signal observed in the conjugate point (Likhter et al., 1971; Bell and Helliwell, 1971). No regular frequency drift of the signal seems to appear as a result of this interaction.

The observed changes of the emission frequency were probably first explained by Dowden (1962), who assumed that electrons of a single energy and pitch angle were organized in phase by the Doppler-shifted cyclotron resonance with monochromatic waves. As the organized particles moved away from the equator, they were assumed to generate an emission at the frequencies at which they resonate with the waves as they move adiabatically along the geomagnetic field line. The early criticism of this original idea was presented by Brice (1962) who claimed that it was not compatible with the observation of hook-type emissions. This idea was further developed by Helliwell (1967) in his phenomenological model, as well as in numerous other papers (e.g. Sudan and Ott, 1971; Dysthe, 1971; Helliwell and Crystal, 1973; Nunn, 1974b; Istomin et al., 1976; Shapiro and Shevchenko, 1976; Roux and Pellat, 1978; Matsumoto, 1979; Molchanov, 1981; Molvig et al., 1988; Nunn, 1990, etc., as summarized in the review by Omura et al., 1991). Helliwell's (1967) model cannot, in any case, be considered as a rigorous one, yet it is most widely used when interpreting the observed phenomena. Its main merits are the simplicity of the mathematical analysis and the physical evidence of the processes under consideration.

In particular, Helliwell's (1967) model predicts that the value of \( f' = df/dt \) decreases when \( L \) increases and/or \( \Pi \) (angular electron plasma frequency) increases. Both of these predictions are compatible with the experimental results: the predicted \( L \) dependence of \( f' \) was observed when using ground-based as well as satellite data. In particular, the observed decrease of \( f' \) when local time increased for the extraplasmospheric chorus, which was mentioned in Section 2.1, is also compatible with this prediction, if we take into account that, under the influence of a large-scale electric field, the electrons drift towards larger \( L \)-shells when L.T. > 06:00. The observed dependence of \( f' \) vs L.T. was used by Pudovkin and Sazhin (1977) when estimating the value of the large-scale electric field (see also Sazhin, 1982).

After making some slight improvements of Helliwell's (1967) model Dowden (1971b) suggested a new tool for the diagnostics of electron energy spectrum from the analysis of the frequency–time behaviour of discrete emission elements. However, Brinca (1980) pointed out that Dowden's results would be significantly modified if the magnetospheric parallel electric field is taken into account: the latter would cause the increase of \( f' \) making preferable the observation of risers, which agrees with the experimental results. One of the main limitations of Brinca's model is that it was based on an oversimplified model of the parallel electric field: he considered it as either being constant or proportional to the distance from the equator. It seems relevant to consider the influence of a more realistic distribution of parallel electric field in the equatorial region of the magnetosphere (see for example Ponyavin et al., 1977; Whipple, 1977; Chiu and Schulz, 1978; Stern, 1981; Sazhin, 1987b) on the structure of chorus spectral elements.

The observed absence of conjugacy of chorus emissions has been interpreted in terms of an asymmetry of the reflection coefficients for the waves propagating towards the opposite hemispheres (Bespalov and Chukanov, 1980).

Quasi-periodic structure of chorus emissions and its theoretical interpretation were discussed by Sato (1980), Sato and Kokubun (1980), Sato and Fukunishi (1981), Sazhin (1987c), Bespalov and Kleimenova (1989) and others. Detailed discussion of this problem is beyond the scope of this review.

5. CONCLUSION

As has been shown in this review, a large amount of data referring to chorus emissions has been collected from ground-based, rocket and satellite observations. Although any further experimental studies of chorus emissions would definitely contribute to a more detailed understanding of this phenomenon, we believe that at this stage the highest priority should be given to the theoretical research. The latter could enable us to improve our understanding of the formation of chorus elements and their interaction with magnetospheric electrons, and thus could stimulate further experimental research. One way to construct a theoretical model lies in the numerical analysis of non-linear equations, another in the development of a simplified analytical model. We hope that an attempt to combine both approaches made by Nunn and Sazhin (1991) will eventually be developed into a self-consistent theory of chorus emissions.

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