LATITUDINAL VARIATION OF CHORUS FREQUENCY OBSERVED BY THE ISIS SATELLITES

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Abstract: Latitudinal variations of chorus band frequency have been investigated to examine a model of the magnetospheric chorus obtained from OGO-1 and OGO-3 VLF observation by using VLF electric field data (50 Hz−30 kHz) from ISIS-1 and ISIS-2 received at Syowa Station, Antarctica in 1977 and 1978.

The upper and lower limit frequencies of the dayside chorus decrease with L-value (or invariant latitude) and their latitudinal variations roughly agree with a latitudinal variation of one half of the equatorial gyrofrequency. This result supports the model of dayside magnetospheric chorus in which the chorus generated near the equatorial plane propagates along the field lines in the ducted mode or propagates inwards from the original field line in the nonducted mode.

Nightside choruses were observed in disturbed periods by ISIS satellites as well as the nightside magnetospheric chorus. The upper and lower limit frequencies of choruses observed in the early morning, late evening and nighttime do not show any significant variation with L-value (invariant latitude). This may be due to different generation mechanism of the nightside chorus from the dayside one.

Furthermore, we have found a new case that chorus band frequencies in latitudes beyond the plasmapause are higher than those in latitudes inside the plasmapause. Such a case has never been reported for observations of the magnetospheric chorus.

1. Introduction

Ground observations of the chorus show that the maximum occurrence region of chorus moves from the auroral zone in geomagnetically quiet periods to geomagnetic latitude around 58°N in disturbed periods (YOSHIDA and HATANAKA, 1961; HELLIWELL and CARPENTER, 1961). GURNETT and O'BRIEN (1964) reported from INJUN-3 observations that the chorus intensity became maximum for 10–11 hours in satellite local time around geocentric distance of 5 earth radii. In fact VLF and ELF discrete emissions such as chorus have been observed at ground latitudes corresponding to magnetospheric regions just beyond the plasmapause for more than a decade (CARPENTER, 1963).

Many researchers have postulated that chorus emissions are whistler-mode waves of finite duration triggered either by whistlers, by powerful VLF transmissions from the ground, or are spontaneously generated by some wave-particle interaction such as the electron gyroresonance. ONDOH (1965) has shown statistically a close association between the chorus intensity and the cosmic noise absorption below 2.0 dB or an f_{min} increase above 3 MHz in the dayside auroral zone. Enhanced fluxes of precipitated electrons above 40 keV during VLF chorus bursts were observed along a geomagnetic field line by the low-altitude satellite, INJUN-3 (OLIVEN and GURNETT, 1968). BURTON and HOLZER (1974) have presented clear evidence that chorus emissions are generated in the region between the plasmapause and the magnetopause principally on the dayside by electrons of 5–150 keV and near the geomagnetic equator.

BURTIS and HELLIWELL (1976) have shown from the OGO-3 VLF observations ($L \leqq 10$) that the center frequency of the chorus band varies as L^{-3} and that it is closely related to the electron gyrofrequency along the dipole field line through the satellite. They have interpreted the chorus in terms of a gyroresonant feedback interaction and the whistler mode propagation theory.

In this paper we will report on latitudinal variations of the chorus frequency observed by ISIS-1 and ISIS-2 in the topside ionosphere. Then we will compare this result with the magnetospheric chorus model proposed by BURTIS and HELLIWELL (1976).

2. Characteristics of Magnetospheric Chorus

BURTIS and HELLIWELL (1976) have plotted the occurrence rate of the magnetospheric chorus as a function of f/f_H in four 10° ranges of dipole latitude, where f denotes the chorus frequency and f_H the local electron gyrofrequency. The occurrence rate of the magnetospheric chorus becomes maximum around the normalized frequency of $f/f_H=0.5$ at dipole latitudes between 0° and 10°, and the occurrence rate maximum of chorus shifts to lower values of f/f_H at high dipole latitudes. BURTIS and HELLIWELL (1976) have interpreted this in terms of ducted propagation of the magnetospheric chorus away from a near equatorial generation region. But the distribution of normalized chorus frequency becomes broad at high dipole latitudes. This may be due to the nonducted propagation of magnetospheric chorus at low altitudes because the OGO-3 orbit has a perigee of about 600 km, apogee of about 19 earth radii and inclination of 31°. In fact the latitudinal distribution of the chorus occurrence rate as a function of the ratio of the chorus frequency to the equatorial electron gyrofrequency, f_{H0}, on the field line through the satellite has the same trend, that is, the decrease in f/f_{H0} with latitude, as the above distribution for the normalized chorus frequency to the local electron gyrofrequency. If the magnetospheric chorus propagates in the ducted mode along geomagnetic field lines from the equatorial plane, we may expect no change in f/f_{H0} with latitude, but this is not the case. An inward deviation of the chorus ray paths to lower L-values (higher f_{H0}) results in lower f/f_{H0} and an outward deviation to higher L-values (lower f_{H0}) results in higher f/f_{H0}. Thus the decrease in f/f_{H0} with latitude is equivalent to an inward deviation of rays starting at the equator. A detailed ray-tracing of nonducted VLF waves shows that VLF waves with initial wave normal angles of zero to the field line starting from the geomagnetic equatorial plane are refracted inward from the original field line outside the plasmapause as they propagate earthwards (AIKYO and ONDOH, 1971).

As for the ducted propagation of chorus, VLF waves may exit the duct at angles up to their final internal reflection angle, producing effectively an endfire waveguide antenna irradiating the region below the duct exit (FREDRICKS, 1975). Since, in mid-latitudes, the altitude of the $L=4$ field line is much lower than that of the $L=7$ (about 68° in invariant latitude) field line, the duct escape of chorus waves may be more common at lower L-values, but chorus waves may be largely ducted for higher L-values over mid-latitudes. This may be related to the more pronounced decrease of f/f_{H0} with latitude at lower L-values than at higher L-values. Therefore the decrease of the normalized chorus frequency, f/f_{H0}, with latitude is interpreted in terms of both the ducted and nonducted propagations of chorus away from a near equatorial generation region (BURTIS and HELLIWELL, 1976). Thus, the analyzed results of magnetospheric chorus indicate that the chorus band frequency observed in the topside ionosphere should decrease with increasing latitude regardless of the propagation mode.

3. Latitudinal Variations of Chorus Band Frequency Observed in the Topside Ionosphere

In this section, we will investigate latitudinal variations of chorus band frequency observed in the topside ionosphere using VLF electric field data (50 Hz—30 kHz) from ISIS-1 and ISIS-2 received at Syowa Station (geomagnetic latitude 69.7°S, longitude 77.7°E), Antarctica in 1977 and 1978.

Figures 1a to 1c are frequency-time spectra of a typical dayside chorus on the north-bound pass of ISIS-2 observed from 0917:20 UT to 0919:30 UT on November 22, 1978 at $Kp=4-$. The f-t spectra in Figs. 1a to 1c are similar to the dayside magnetospheric chorus of multiple rising tones (BURTON and HOLZER, 1974). The full scale of the ordinate axis in Figs. 1a to 1c is 10 kHz and linear in frequency, and the interval between bottom dots is one second in time. All f-t spectra used in this paper have the same frequency and time scale as Figs. 1a to 1c. A chorus band is seen from 3.3 kHz to 7.2 kHz at invariant latitude 59.3° ($L=3.83$) in Fig. 1a, from 4.5 kHz to 8.7 kHz at 58.1° ($L=3.58$) in Fig. 1b, and from 6.3 kHz to 9.6 kHz at 56.3° ($L=3.25$) in Fig. 1c respectively.

Fig. 1a.

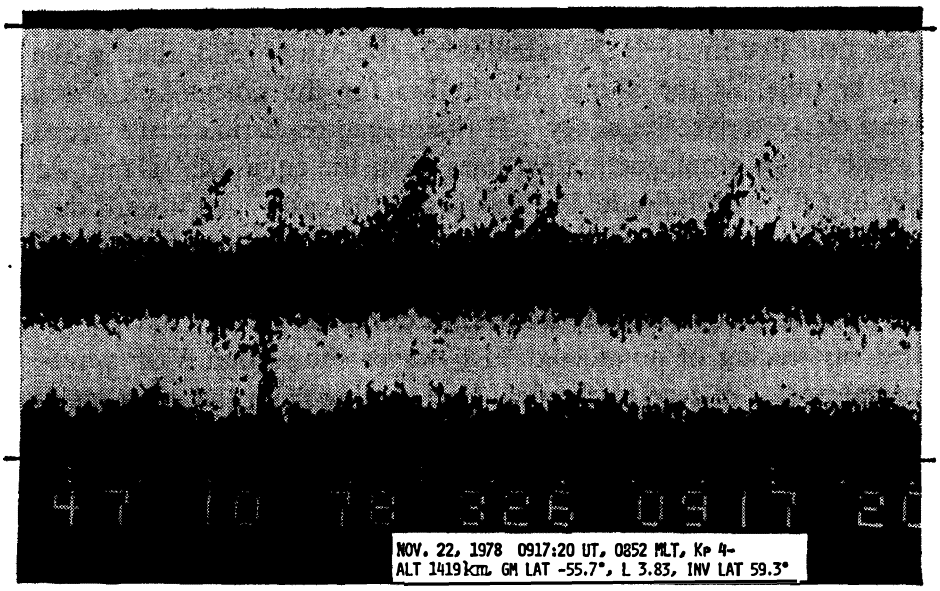


Fig. 1b.

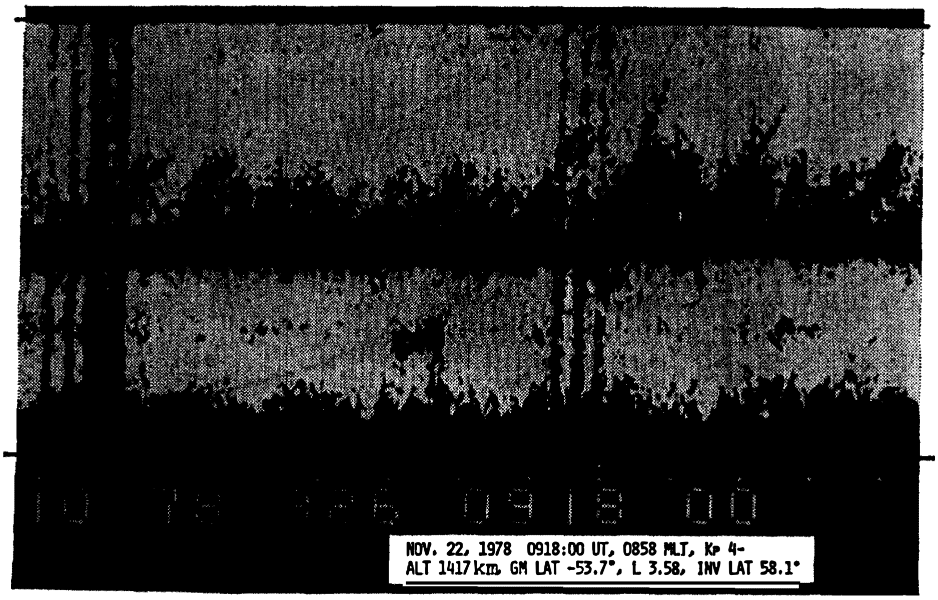
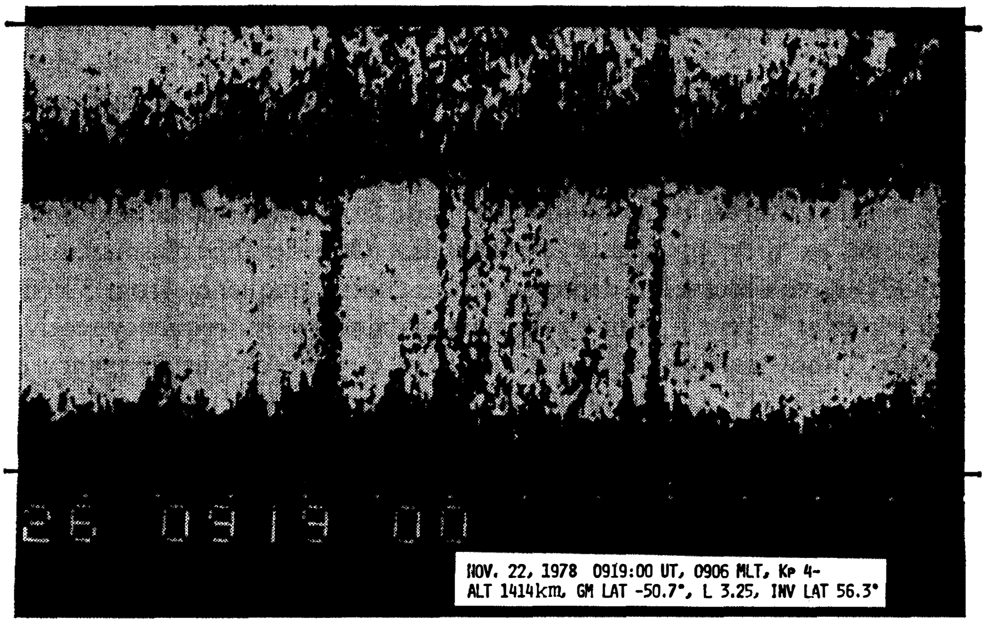


Fig. 1c.



Figs. 1a–c. Frequency-time spectrograms of dayside chorus observed at geomagnetic latitude of 55.7°S (1a), 53.7°S (1b), and 50.7°S (1c) on November 22, 1978 by ISIS-2. It is seen that chorus band frequency increases with decreasing latitude. The full scale of the frequency range is 10 kHz, and an interval between bottom dots is one second in time.

It is clearly seen that the chorus band frequency increases with decreasing invariant latitude. Figure 2 illustrates latitudinal variations of the upper and lower limit frequencies of chorus band observed for 0812–0909 magnetic local time (MLT) on November 22, 1978 by ISIS-2 and a curve showing the L-variation of one half the equatorial electron gyrofrequency which is supposed to approximate to the generation frequency of the chorus, where f_U denotes the upper limit frequency of chorus band and f_L the lower limit frequency. The chorus band frequencies, f_U and f_L decrease with L value

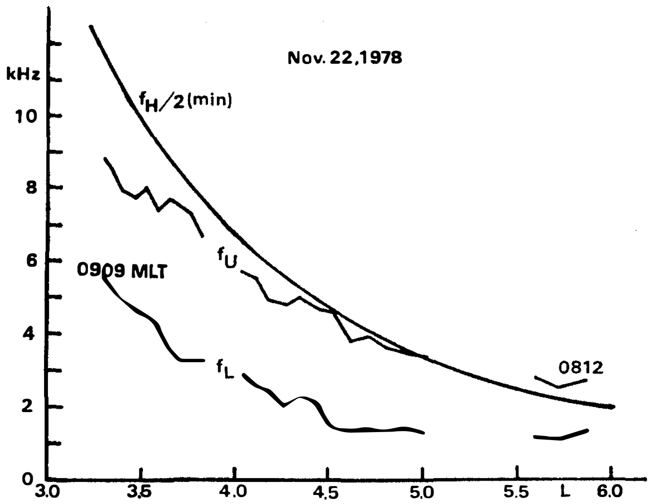


Fig. 2. Latitudinal (or L) variation of the dayside chorus band frequency observed in the local evening on November 22, 1978 by ISIS-2 and latitudinal (or L) variation of one half the equatorial electron gyrofrequency.

roughly parallel to the L-variation of $f_H/2$(minimum). The L-variation of chorus frequency observed approaches rather to that of $f_H/2$(minimum) at higher L-values above $L=5.0$. So, this case may support the magnetospheric chorus model (BURTIS and HELLIWELL, 1976), that is, chorus emissions are generated at a frequency around $f_H/2$ near the equatorial plane and they propagate in the ducted mode along field lines or they refract inwards in the nonducted mode from the original field line outside the plasmapause as they propagate earthwards. Outside the plasmapause, GURNETT *et al.* (1979) have observed a decrease of the chorus frequency from 5 kHz at 5 earth radii to 1 kHz at 7.2 earth radii by the narrow-band sweep frequency receiver of ISEE-1. Figure 3 shows also an L-variation of the dayside chorus frequency observed in the local evening (1715–1800 MLT) by ISIS-1 on July 11, 1977. The chorus band frequencies, f_U and f_L, decrease gradually with L but the trend of frequency decrease with L is not so clear as with the previous case of November 22, 1978. Chorus emissions rising from 2.1 kHz to 3.9 kHz in Fig. 4a were observed at an invariant latitude

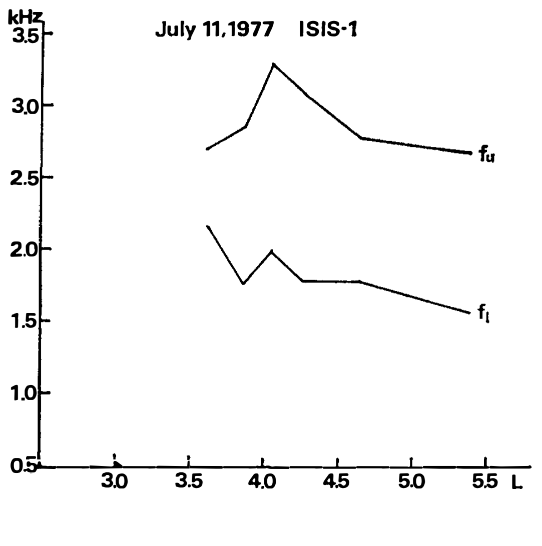


Fig. 3. Slow decrease of the chorus band frequency with L-value observed in the local early evening on July 11, 1977 by ISIS-1.

of 62.2° (L=4.51) by ISIS-1 at 1440: 40 UT on May 3, 1977 in a magnetic quiet period (Kp=1+). Solid lines of Fig. 5 do not show any significant variation of the chorus frequency with L-value in the evening hours between 1708 and 1740 MLT on May 3, 1977. This is very different from the decrease of the dayside chorus frequency with L-value as shown in Figs. 2 and 3, though riser structures of chorus emissions in Fig. 4a are similar to those in Figs. 1a to 1c.

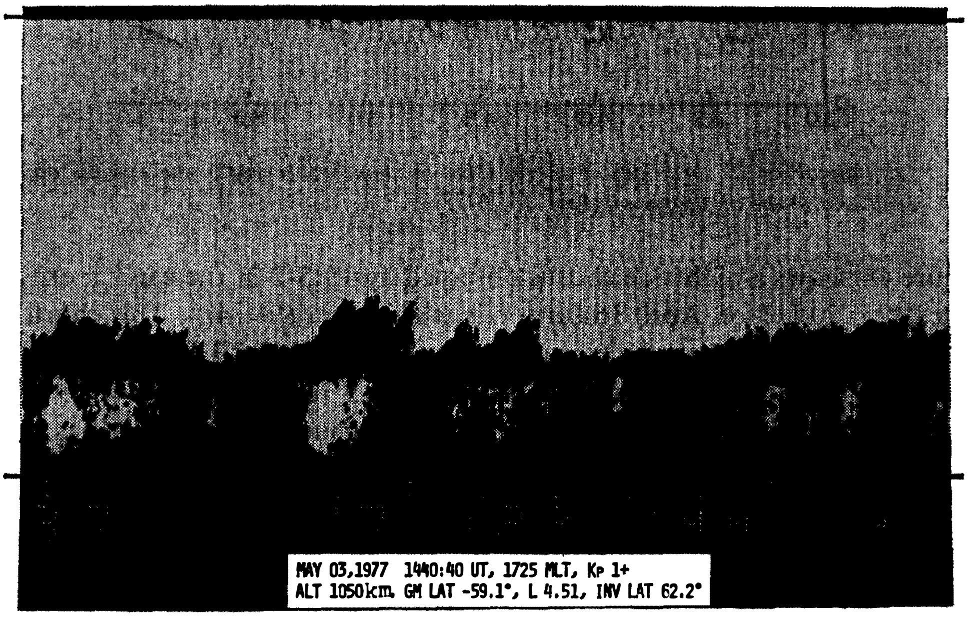


Fig. 4a. Chorus spectrogram observed at 1725 MLT (magnetic local time) on May 3, 1977 at geomagnetic latitude of 59.1°S by ISIS-1 (Kp=1+).

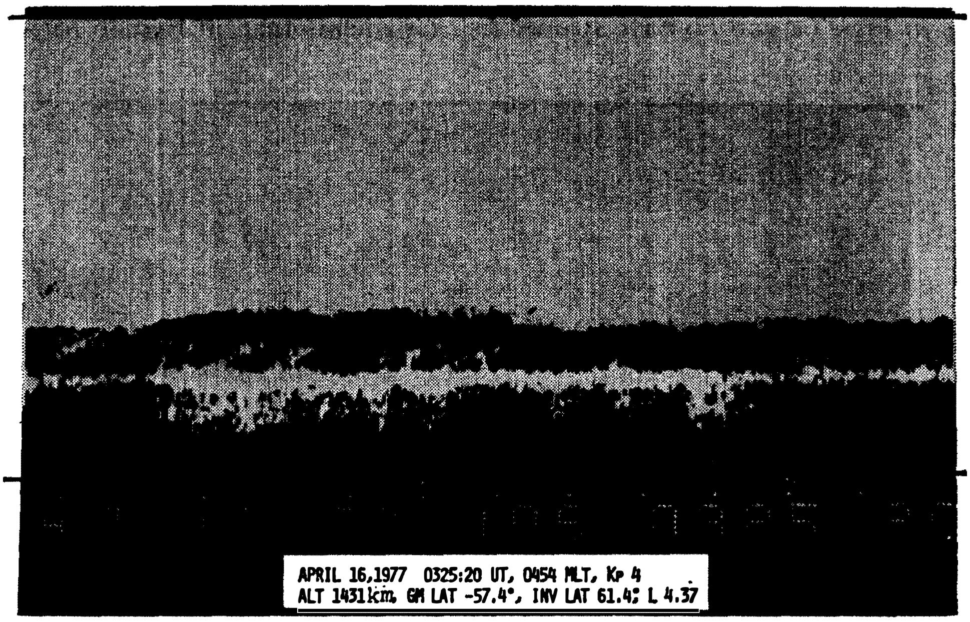


Fig. 4b. Spectrogram of chorus with slow rising structures observed in a disturbed nighttime (Kp=4) on April 16, 1977 at geomagnetic latitude of 57.4°S by ISIS-2.

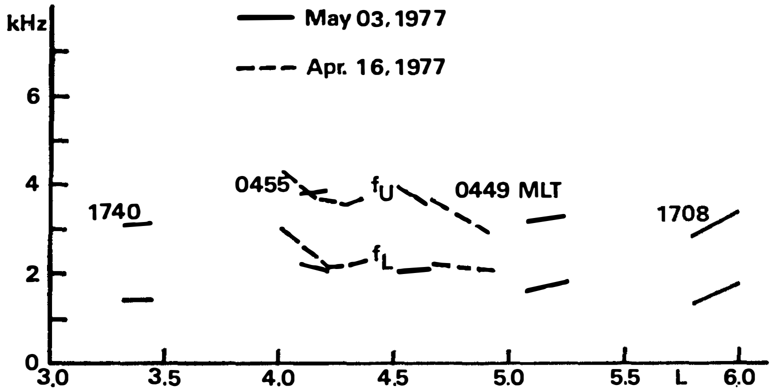
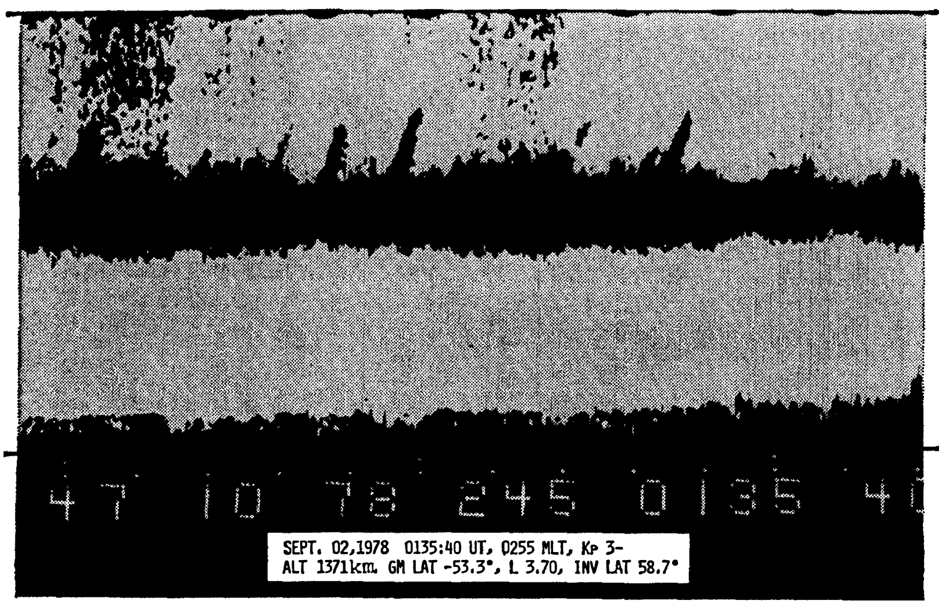


Fig. 5. Latitudinal (or L) variations of chorus band frequency observed in the evening on May 3, 1977 and in the nighttime on April 16, 1977.

Figure 4b shows a nightside chorus observed by ISIS-2 in the early morning (0454 MLT) at 0325: 20 UT on April 16 for a disturbed time ($Kp=4$). This chorus is composed of multiple slow risers which occur between 2.2 kHz and 3.6 kHz and at invariant latitude of 61.4° ($L=4.37$). Dashed lines in Fig. 5 represent an L-variation of the above chorus frequency which shows no significant change with L-value as is the case of May 3, 1977. The nightside magnetospheric chorus could be either rising or falling tones (never mixed) and was only observed under magnetically active conditions. So the nightside chorus is most probably associated with substorm activity (BURTON and HOLZER, 1974). Figures 6a and 6b are other examples of nightside magnetospheric chorus observed by ISIS-2 at invariant latitudes of 58.7° ($L=3.70$) and at 62.7° ($L=4.74$) respectively, after local midnight (0255 and 0240 MLT) on September 2, 1978. The chorus in Fig. 6a appears at frequencies between 4.6 kHz and 7.8 kHz and that in Fig. 6b at frequencies between 4.7 kHz and 7.1 kHz. The nightside choruses in Figs. 6a and 6b have steeper rising elements than in Fig. 4b for the early

Fig. 6a.



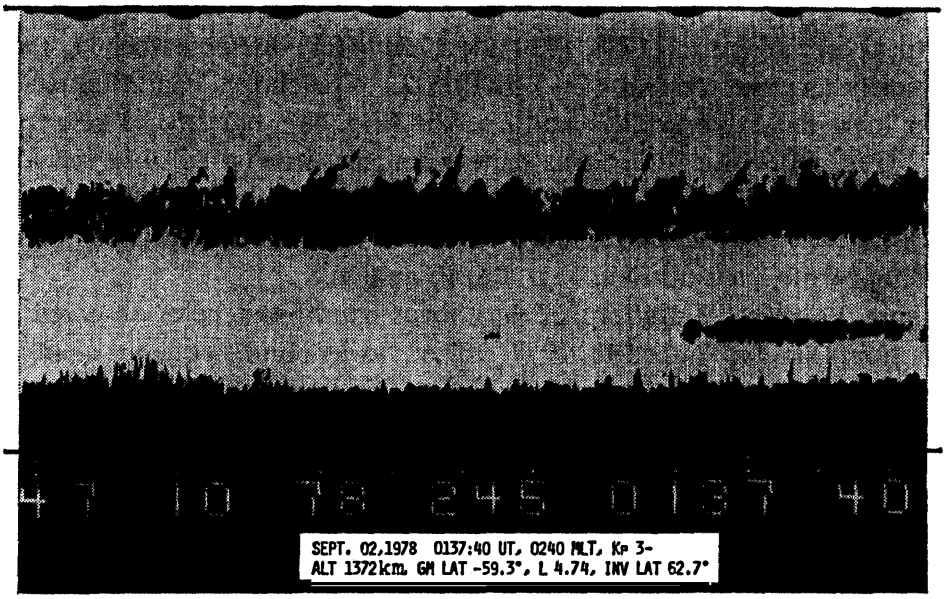


Fig. 6b.

Figs. 6a, b. Spectrograms of choruses observed by ISIS-2 at geomagnetic latitudes 53.3°S and 59.3°S on September 2, 1978. The chorus band frequency seems to be constant with latitude.

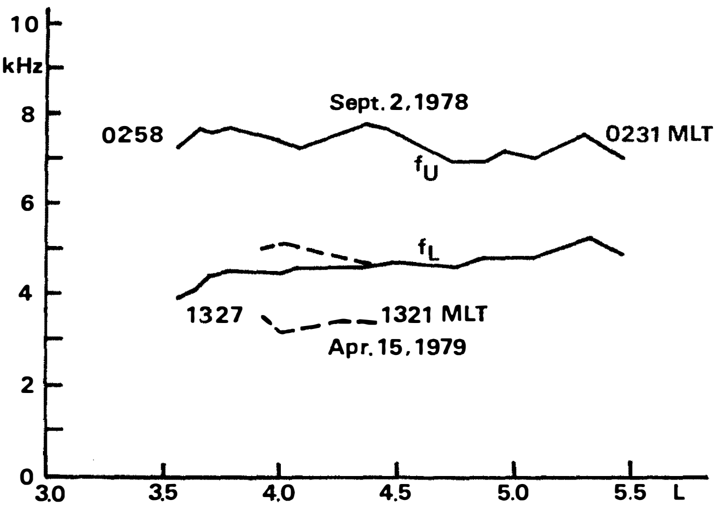


Fig. 7. Latitudinal (or L) variations of chorus band frequencies observed in the nighttime on September 2, 1978 and in the daytime on April 15, 1979.

morning (0454 MLT), although both choruses occurred in moderately disturbed periods, that is, at $Kp=4$ (Fig. 4b) and $Kp=3-$ (Figs. 6a and 6b) as discussed on the nightside magnetospheric chorus by BURTON and HOLZER (1974). Figure 7 shows L-variation of the nightside chorus band frequencies of Figs. 6a and 6b observed on September 2, 1978. The frequency band of the nightside chorus in Fig. 7 hardly changes with L-value between $L=3.6$ and 5.4, as in Fig. 5, while the frequency band of the dayside chorus in Fig. 2 clearly decreases with L-value. The L-variation trend of the dayside chorus frequency observed on April 15, 1979 (Fig. 7) is not clear because of shortness of the chorus data period. Figures 8a, 8b and 8c are *f-t* spectrograms of choruses observed in the local evening hours (1728, 1739 and 1750 MLT) on September 11, 1977 in a geomagnetically quiet period ($Kp=2-$) by ISIS-2. The chorus band frequency is 2.2–3.3 kHz for invariant latitude 62.0° and $L=4.54$ (Fig. 8a), and 2.5–3.3 kHz for 60.1° and $L=4.03$ (Fig. 8b). But the chorus band frequency in Fig. 8c observed at 57.2° and $L=3.49$ suddenly drops down to a band of 0.9–2.2 kHz from 2–3 kHz at latitudes above 60° ($L\geqq 4.0$). Rising structures of choruses and time intervals between rising elements are different from each other in Figs. 8a, 8b and 8c.

Figure 9 shows L-variations of the chorus band frequencies observed in the local evening hours on September 11, 1977. The chorus band frequency changes suddenly around $L=3.8$ (invariant latitude 59°), and the chorus band frequencies on higher latitude side of $L=3.8$ are higher than those on the lower latitude side. RYCROFT and

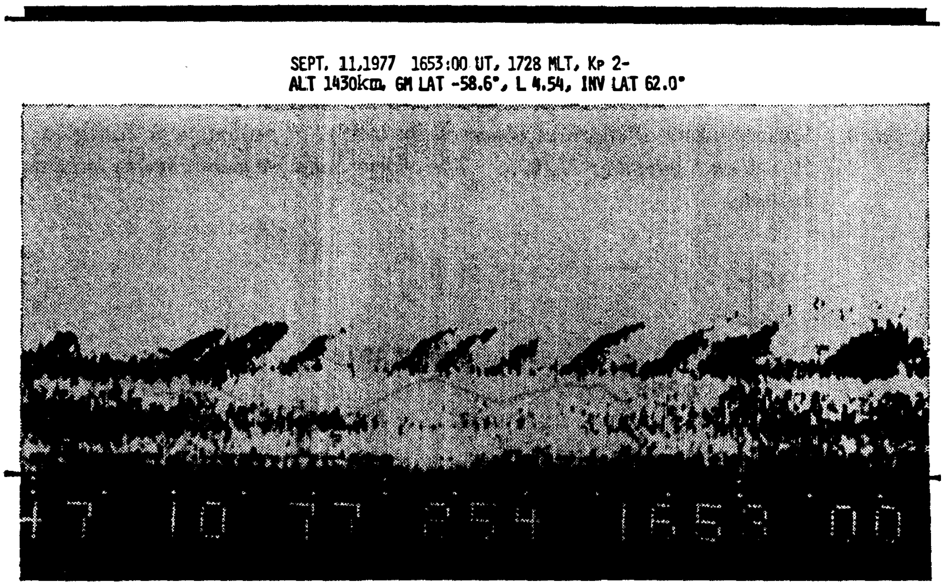


Fig. 8a.

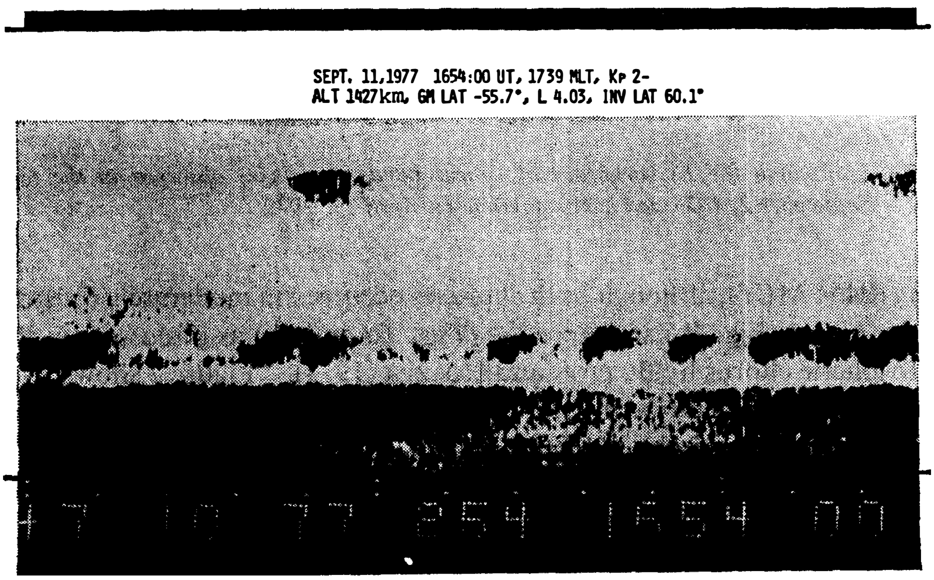
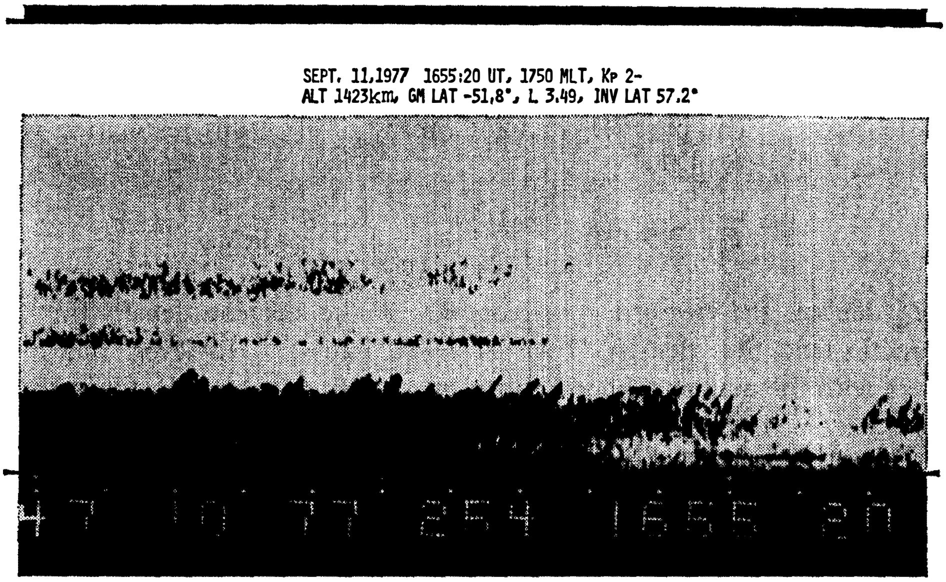


Fig. 8b.

Fig. 8c.



Figs. 8a–c. *Chorus spectrograms observed by ISIS-2 at invariant latitude of 62.0°, 60.1 and 57.2°, respectively in the local evening hours on September 11, 1977 (Kp=2−). It is seen that the chorus band frequency suddenly drops down from above about 2 kHz (Figs. 8a and 8b) to below 2 kHz (Fig. 8c).*

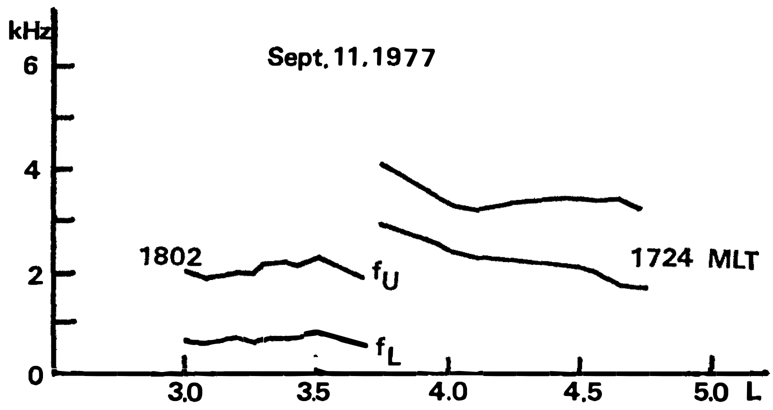


Fig. 9. *Latitudinal (or L) variations of chorus band frequency observed in the local evening on September 11, 1977. Sudden change of the chorus band frequency occurs at L=3.8 as deduced from the spectrum difference of the chorus riser structures between Figs. 8a, 8b, and 8c.*

Thomas (1970) have derived the plasmapause position in the nighttime as $Lp=5.64-(1.09\pm0.22)\sqrt{Kp}$ using the Alouette I electron density data. Substituting $Kp=2$ into the above expression, we have $Lp=4.1\pm0.3$ as an approximate location of the plasmapause. The lower limit of the above plasmapause location may explain the sudden change of the chorus band frequencies, f_U and f_L, at $L=3.8$. Thus it is inferred that there occurred two kinds of chorus, one on each side of the plasmapause.

The OGO results show equatorial electron (>36 keV) fluxes of 10^7–10^8 $cm^{-2}\cdot s^{-1}$ for $L=3.5$–4.5 (Vette, 1971). If cyclotron instabilities of 50 keV-electrons occur in an equatorial region between $L=3$ and $L=5$ on the both sides of the plasmapause, they may explain the mean chorus frequency of 1.5 kHz inside the plasmapause and the mean chorus frequency of 3.0 kHz beyond the plasmapause when the equatorial ambient plasma density is $N=10^3/\,m^3$ inside the plasmapause and is $N=10/cm^3$ beyond the plasmapause. The parallel resonant energy of electrons resonating with whistler mode waves (f) is given by

$$E_r=2.5\times 10^{21}\cdot\frac{f_H}{f}\left(1-\frac{f}{f_H}\right)^3\cdot\frac{B^2}{N}\ \mathrm{keV}\ ,$$

where f_H denotes the electron gyrofrequency, N the electron density (m^{-3}) and B the geomagnetic field flux density (1 $wb\cdot m^{-2}=10^4$ gauss). However, this model is not consistent with the magnetospheric chorus model (BURTIS and HELLIWELL, 1976) which roughly agrees with the latitudinal variation of daytime chorus observed in the topside ionosphere as discussed in Section 3. Thus, it is difficult to explain the different chorus frequencies observed on the both sides of the daytime plasmapause by the same generation mechanism as the magnetospheric chorus model in which the original chorus frequency is taken as one half of the equatorial electron gyrofrequency.

4. Conclusion

Latitudinal variations of chorus band frequency have been obtained from frequency-time VLF spectrograms of relatively long ISIS passes received at Syowa Station, Antarctica in 1977 and 1978. Selected chorus spectrograms on the relatively long ISIS passes were observed in the daytime, early morning, evening and nighttime in magnetic local time. The upper and lower limit frequencies of the dayside chorus observed for 08–09 magnetic local time by ISIS-2 decrease with L-value, and, in particularly they agree well with the curve of one half of the equatorial electron gyrofrequency vs. L-value for L-values higher than 5. This latitudinal decrease of the chorus band frequency is consistent with the dayside magnetospheric chorus model in which the chorus generated near the equatorial magnetosphere propagates earthward either along the field lines in the ducted mode or inwards from the original field line in the nonducted mode. While the chorus band frequency observed in the nighttime, evening and early morning does not show any significant variation with L-value. The nightside choruses were observed in geomagnetically disturbed periods as reported for the nightside magnetospheric chorus. Thus the generation mechanism of the nightside chorus seems to be different from that of the dayside chorus. However, more analysis of chorus data observed in the topside ionosphere will be necessary to demonstrate a difference between the dayside and nightside choruses although rather typical examples of the chorus have been studied in this paper.

As for the chorus observed in the local evening hours on September 11, 1977, the chorus band lies at frequencies between 2.0 and 4.0 kHz for L-values higher than the plasmapause ($L=3.8$) and at frequencies between 0.9 and 2.2 kHz for L-values lower than the plasmapause, however the usual chorus band frequency decreases gradually with L-value. This kind of chorus has never been reported in observations of magnetospheric chorus. In particular, it should be noted that the chorus band frequency at latitudes inside the plasmapause is lower than the lowest frequency of the chorus band observed at a latitude just beyond the plasmapause. Electron cyclotron instabilities caused by the same energy electrons on the both sides of the plasmapause are considered as a possible generation mechanism for the above case. However, it is difficult to explain this case consistently with the typical daytime chorus observed in the topside ionosphere.

Acknowledgments

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