VLF Emissions and Geomagnetic Disturbances at the Auroral Zone

Part II Chorus Increases and Geomagnetic Pulsations at the Auroral Zone

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Abstract

A close relation has been found between increases of chorus indices continuing for a few hours and geomagnetic pulsations at the auroral zone, using the chorus indices and rapid-run magnetograms at College, Alaska, during July, 1959 to December, 1960.

During this period 79 increases of chorus indices occurred in relatively quiet geomagnetic conditions after geomagnetic bay-like disturbances. Of 79 chorus increases, 52 were associated with geomagnetic pulsations with periods between 1 and 6 minutes and 11 were associated with pulsations having periods of about 30 seconds.

The chorus increases may be generated by penetration of high speed charged particles into the exosphere, which may also be related to the geomagnetic pulsations.

A possible mechanism of the generation of geomagnetic pulsation has been discussed.

1. Introduction

Aarons, Gustafsson, and Egeland (1960) firstly detected VLF emissions associated with the geomagnetic pulsations of which periods were of the order of 0.5–5 minutes at Kiruna (geomag. lat. 65.3°N ; geomag. long. 115.5°E), Sweden. Ellis (1960) also found at Camden, (geomag. lat. 42.0°S) Australia that bursts of VLF noises coincided with the geomagnetic pulsations having periods less than 1 minute on 6 occasions and about 1 minute period on 4 occasions, and that the quasi-sinusoidal oscillations of the geomagnetic field with periods between 10 and 60 minutes occurred either before or during noise bursts on 14 occasions.

Crouchley and Brice (1960), and Yoshida (1960) have found that the average strength or occurrence probability of chorus at the auroral zone reaches a maximum at moderate value of K-index and decreases with increasing K-index above this value.

Tokuda (1962) has shown that the chorus increases always occur about 9 hours on the average after geomagnetic bay-like disturbances at College, Alaska.

In this paper we show that the chorus increases are often accompanied by weak

geomagnetic disturbances such as geomagnetic pulsations with periods of 1–6 minutes at College, Alaska.

Ondoh (1962) has recently found a close correlation between the time variation of chorus indices and auroral absorption of cosmic radio noise of 27.6 Mc/s, using the data at College, Alaska. This result suggests a possibility of generation of VLF emissions by charged particles invading along geomagnetic lines of force.

Dokuchaev (1961) has indicated that if a velocity of an ionized stream along magnetic lines of force exceeds the velocity of Alfvén waves in the stream-plus-stationary-plasma system, hydromagnetic waves may appear in the system and they build up in time.

Referring to these results, we discuss a possible explanation of the chorus increases associated with the geomagnetic pulsations at the auroral zone.

2. Geomagnetic Conditions during Increases of Chorus Indices

In this section we statistically study relations of geomagnetic pulsations and auroral activities to chorus increases at the auroral zone, using normal-run magnetograms, rapid-run magnetograms, chorus activity indices, and auroral radar activity indices at College (geomag. lat. 64.7°N ; geomag. long. 256.5°), Alaska during July, 1959 to December, 1960.

The chorus data are sampled on an hourly basis for a duration of two minutes past each hour. The auroral radar activity indices are hourly values at each hour. Therefore we should compare the chorus data with other data considering a time lag of 35 minutes. But we have actually treated the chorus indices as hourly values without any consideration of the time lag.

The chorus activity index of 0 to 5 is assigned for each hour depending on an aurally subjective determination of the strength of the phenomenon, although the auroral activity index represents the duration of echoes of the 41 Mc/s auroral radar.

In spite of the subjective determination, the increases of chorus index from 1 or

Fig. 1 (a) The chorus increase, auroral radar echoes, and a copy of the normal-run magnetogram at College, Alaska on April 15, 1960 where the black and open circles represent the chorus and auroral indices respectively.

Fig. 1 (b) A copy of the H-trace of rapid-run magnetogram at College, Alaska on April 15, 1960.

Fig. 1 (c) A copy of the D-trace of rapid-run magnetogram at College,

Fig. 1 (d) A copy of the Z-trace of rapid-run magnetogram at College, Alaska on April 15, 1960.

2 to 4 or 5 may be clearly regarded as true increases of chorus intensity.

Next we show some examples of the chorus increases continuing several hours accompanied by geomagnetic pulsations.

Fig. 1 (a) shows an event on April 15, 1960 at College Alaska. In the figure black and open circles represent chorus indices and auroral indices respectively and an upper trace is a horizontal component of normal-run magnetogram.

A bay-like disturbance occurred at about 01 LT on April 15 and a chorus increase lasted from 05 LT to 14 LT, while auroral indices were zero. During the chorus increase the H-trace of normal-run magnetogram shows a series of oscillations of geomagnetic field except for large excursions about 09 30 LT. In order to examine fine structures of the oscillations we show the H,D, and Z traces of rapid-run magnetogram in Fig. 1 (b), 1(c), and 1(d).

A periodical variation appeared about 06 LT which approximately coincided with the commencement of chorus increase. Especially geomagnetic pulsations with period of about 5 minutes occurred after 07 45 LT. Since chorus indices began to decrease, geomagnetic pulsations with period of less than 1 minute had occurred after 13 00 LT.

A chorus increase on September 19, 1959 is shown in Fig. 2 (a). A negative bay-like disturbance occurred between 01 and 02 LT after appearances of auroral radar echoes.

We see in Fig. 2(a) that the chorus increase appeared during 10 to 14 LT while auroral indices were zero, and in Fig. 2 (b) that geomagnetic pulsations with periods between 3 and 6 minutes occurred before and during the same period.

Fig. 2 (a) The chorus increase, auroral radar echoes, and a copy of the normal-run magnetogram at College, Alaska on September 19, 1959 where the black and open circles represent the chorus and auroral indices respectively.

Fig. 2 (b) A copy of the H-trace of rapid-run magnetogram at College, Alaska on September 19, 1959.

Fig. 3 (a) The chorus increase, auroral radar echoes, and a copy of the normal-run magnetogram at College, Alaska on March 18, 1960 where the black and open circles represent the chorus and auroral indices respectively.

Fig. 3 (b) A copy of the H-trace of rapid-run magnetogram at College, Alaska on March 18, 1960.

In Fig. 3(a) and 3(b) we show a chorus increase accompanied by geomagnetic pulsations having periods of about 30 seconds on March 18, 1960. Geomagnetic bay-like disturbances which were preceded by long durations of the auroral radar echoes, lasted approximately from 23 LT on March 17 to 05 LT on March 18. A small chorus increase of an index 3 began around 05 LT as the bay-like disturbances recovered and then a large chorus increase occurred from 12 to 18 LT. It is shown in Fig. 3(b) that geomagnetic pulsations with periods of about 30 seconds continued during a period of 06 to 16 LT that coincided approximately with the duration of chorus increases.

As for this event, we see also in Fig. 3(a) that auroral indices were zero during the chorus increases. The above three events are examples on geomagnetic quiet days.

The common features of the events are as follows:

- 1) Geomagnetic pulsations last before and/or during the chorus increase.
- 2) During the chorus increase the auroral indices are zero.
- 3) The chorus increase occurs from 11 to 16 LT that hours may correspond well to the time of diurnal maximum of the chorus at the auroral zone found by Allcock (1957) and Pope (1957, 1959).
- 4) The chorus increase is preceded by geomagnetic bay-like disturbances which occur near the mid-night, and which are well known as the daily phenomenon at the auroral zone.

Next in Fig. 4(a) and 4(b), we show a chorus increase on March 16, 1960 as an example on geomagnetically disturbed day. Geomagnetic bay-like disturbances associated with appearances of auroral radar echoes occurred between 22 LT on March 15 and 07 LT on March 16.

A moderate chorus increase started about 03 LT at the late stage of the disturbances, when the auroral index was zero. A sudden disturbance such as a sc* occurred at approximately 07 45 LT and it was followed by a negative bay-like disturbance and

Fig. 4 (a) The chorus increases, auroral radar echoes, and a copy of the normal-run magnetogram at College, Alaska on March 16, 1960 where the black and open circles represent the chorus and auroral indices respectively.

auroral radio echoes.

Fig. 4(a) shows that the chorus index increased together with the auroral index at 09 LT.

But considering the time lag of 35 minutes of the chorus index we must admit the chorus index at 09 LT as that at 09 35 LT. Another chorus increase lasted between 09 and 16 LT,

Fig. 4 (b) A copy of the H-trace of rapid-run magnetogram at College, Alaska on March 16, 1960.

* It is seen in Fig. 4(b) that pulsation-like disturbances occurred from 09 30 LT to 16 LT, and that geomagnetic pulsations of periods between 3 and 5 minutes also occurred from 17 40 LT to 20 00 LT during which third small chorus increase lasted. During these chorus increases the auroral indices were small or zero.

Thus even on the geomagnetic disturbed day the chorus increase may be associated with geomagnetic pulsation-like disturbances.

Moreover we have statistically investigated the association of geomagnetic pulsations with the chorus increases above the index 4 lasting several hours, using the data

at College, Alaska from July, 1959 to December, 1960.

During this period 79 chorus increases occurred and 78 % of these lasted above 4 hours.

Of the 79 chorus increases, 52 were associated with geomagnetic pulsations of 1-6 minutes period, which continued for approximately 20-30 minutes, 11 were accompanied by geomagnetic pulsations of about 30 seconds period, and 16 appeared for very quiet periods on the rapid-run magnetograms.

From the above result we can deduce that the chorus increases often occur together with the geomagnetic pulsations having periods between 1 and 6 minutes. This relation may coincide with the eleven events found by Aarons, Gustafsson, and Egeland (1960).

Ondoh, Kitamura, and Maeda (1960) found a negative correlation between the chorus activity and auroral radar activity, using the data at College, Alaska. Tokuda (1962) has also obtained a negative correlation between them during the chorus increases. These results may suggest that the auroral particles do not significantly contribute to the generation of chorus.

Ondoh (1962) has pointed out a close relation between the chorus increase and the auroral absorption of cosmic radio noise of 27.6 Mc/s for the diurnal variations of them on geomagnetic quiet day and disturbed day, and for the storm-time variation of them.

Therefore it seems likely that the chorus increases and geomagnetic pulsations may be generated by interactions of incoming charged particles producing the auroral absorption of cosmic radio noise with the exosphere.

3. A Possible Explanation of the Chorus Increases associated with the Geomagnetic Pulsations

Dokuchaev (1960) has studied the growth of hydromagnetic waves in a plasma stream moving along lines of force of a uniform external magnetic field through a stationary ionized gas.

Both plasmas are assumed to be fully ionized and quasi-neutral. Using generalized Ohm's law in the moving and stationary plasmas, hydrodynamic equations of the plasmas, and the Maxwell's equations Dokuchaev (1960) has derived the following dispersion equation for plane electromagnetic waves propagating along the line of the magnetic field H at very low frequencies ($\omega \ll \omega_H$, $\omega/k \ll c$) on the assumption that collisions of electrons with ions are negligible. When $kVo \ll \omega_H$, the dispersion equation is given by

$$k^2 = (\omega - kVo)^2 / Vas^2 + \omega^2 / Vap^2,$$

where Vo is the velocity of the stream, ω the wave frequency, k the wave number, ω_H the gyrofrequency of ion, $Vap^2 = H^2 / 4\pi\rho_p$, $Vas^2 = H^2 / 4\pi\rho_s$, $\rho_{s,p} = (m_e + m_i)Ns$, p the mass density, $m_{e,i}$ the electron or ion mass, Ns , p the number density of the stream or the stationary plasma, and c the velocity of light.

From this equation we have

$$\omega/k = \frac{V_0 \pm Va \sqrt{(Np/Ns)(1 - V_0^2/Va^2)}}{1 + Np/Ns} \dots\dots\dots (1),$$

where $Va^2 = Vas^2 + Vap^2$.

Thus if the velocity of the stream exceeds the Alfvén velocity ($V_0 > Va$), hydromagnetic waves appear in the stationary-plus-streaming plasma system. These waves build up in time. This result has also been indicated by Stepanov and Kitsenko (1961), and Kovner (1961). We apply the above result to the geomagnetic pulsation. The exosphere may be regarded as the stationary plasma during the periods of geomagnetic pulsations since the pulsations treated in section 2 occurred in geomagnetically quiet periods.

The number densities of the exosphere and the extra-terrestrial stream penetrating with a velocity of 10^8 cm/sec into the exosphere may be of the order of $Np = 10^2/\text{cm}^3$ and $Ns = 10/\text{cm}^3$ respectively, and both plasmas may consist mainly of protons ($m_i = 1.67 \times 10^{-24}$ gr) and electrons.

Adopting the geomagnetic field strength of 0.3 gauss on the earth's surface at the geomagnetic equator, we have $H = 1.1 \times 10^{-3}$ gauss, $H = 5.9 \times 10^{-4}$ gauss, and $H = 3.0 \times 10^{-4}$ gauss at 6.5 earth radii, 8 earth radii, and 10 earth radii in the geomagnetic equatorial plane respectively on the assumption of the centered dipole field. Using these values we obtain $Va = 9.7 \times 10^7$ cm/sec, $Va = 5.8 \times 10^7$ cm/sec, and $Va = 2.8 \times 10^7$ cm/sec at 6.5 earth radii, 8 earth radii, and 10 earth radii, respectively.

When the velocity of the stream is of the order of 10^8 cm/sec, the inequality of $V_0 > Va$ is clearly satisfied in the outer exosphere. Thus hydromagnetic waves may appear in the exosphere-plus-stream system under the conditions mentioned above. These waves may be growing waves as suggested by Dokuchaev.

Putting $\omega_0 = \frac{kV_0}{1 + Np/Ns}$ and $\omega_0/k = V$, we have $V = \frac{V_0}{1 + Np/Ns}$ where ω_0 is the frequency of the hydromagnetic waves appeared and V is the phase velocity of the waves. When $Np = 10^2/\text{cm}^3$, $Ns = 10/\text{cm}^3$, and $V_0 = 10^8$ cm/sec, V may be of the order of Va in the outer exosphere. These hydromagnetic waves may propagate toward the earth in the plasma stream moving along the geomagnetic lines of force through the exosphere in a duct type mode. Ondoh (1962) has recently found a close correlation between the chorus intensity and the ionospheric absorption of cosmic radio noise at the auroral zone. From this we can expect that at the periods of the chorus increases associated with the pulsations another stream with the velocity of 10^9 cm/sec and the number density of $1/\text{cm}^3$ invades into the exosphere together with the stream with the velocity of 10^8 cm/sec and the number density of $10/\text{cm}^3$.

The high-velocity stream may cause VLF emissions in the mechanism similar to the operation of a traveling-wave tube (Gallet and Helliwell, 1959; Gallet, 1959; Bell and Helliwell, 1959) or in the amplification due to the interaction of radio wave with a cyclotron mode of a proton beam (Kimura, 1961; Maeda and Kimura, 1961) or in the Čerenkov radiation (Ellis, 1960; Ondoh, 1961; McInnes, 1961; Chamberlain, 1961; Gintsburg, 1961).

Combining the condition of generation of Čerenkov emission $V_1 \cos \theta = c/n$ and the refractive index of extraordinary radio wave $n = \left[1 + \frac{f_p^2}{f(f_H \cos \theta - f)} \right]^{\frac{1}{2}}$, we have the wave frequency as

$$f = 1/2 f_H \cos \theta \left[1 \pm \left\{ 1 - \left(2 \frac{f_p}{f_H} \cdot \frac{V_1}{c} \cdot \frac{1}{\sqrt{1 - \frac{V_1^2}{c^2} \cos^2 \theta}} \right)^2 \right\}^{\frac{1}{2}} \right]$$

(Ondoh, 1961), where V_1 is the velocity of charged particles, c the velocity of light, f_p the plasma frequency of electron, f the wave frequency, f_H the electron gyrofrequency and θ the angle between the wave normal direction and the geomagnetic line of force.

At distances greater than about 4 earth radii from the center of the earth $\left(2 \frac{f_p}{f_H} \cdot \frac{V_1}{c} \right)^2 > 1$ for $V_1 \approx 10^9$ cm/sec (Gallet, 1959). Thus the wave frequency becomes the complex frequency of $f = f_0 \pm i\gamma/2\pi$ in the outer exosphere, where $f_0 = 1/2 f_H \cos \theta$ and

$$\gamma = \pi f_H \cos \theta \left[\left(2 \frac{f_p}{f_H} \cdot \frac{V_1}{c} \cdot \frac{1}{\sqrt{1 - \frac{V_1^2}{c^2} \cos^2 \theta}} \right)^2 - 1 \right]^{\frac{1}{2}}.$$

In the outer exosphere $1/2 f_H \cos \theta$ may lie in the audio frequency range for small values of θ . Substituting the complex frequency into the plane wave solution, we have $E = E_0 \exp(\mp \gamma t) \exp\{i(2\pi f_0 t - kx)\}$ where the x -direction is taken along the geomagnetic line of force. Thus when $n(=k/k_0)$ is positive, the growing waves due to the Čerenkov instability may appear in the outer exosphere (Ondoh, 1962).

Hereafter we shall consider only the growing waves. The average number density of electrons or protons in the outer exosphere and that in the stream with the velocity of 10^9 cm/sec may be of the order of $10^2/\text{cm}^3$ and $1/\text{cm}^3$ respectively. At the top (about 6.5 earth radii) of the geomagnetic line of force connecting with the earth's surface at geomagnetic latitude of 67° , f_H may be 3.1 kc/s and so f_0 may be 1.6 kc/s.

In order that the instability occurs under these conditions ($\gamma > 0$) V_1 must be larger than 5.23×10^8 cm/sec. When $V_1 = 10^9$ cm/sec we have $\gamma = 1.59 \times 10^4$. Thus at $t = 1.2 \times 10^{-3}$ seconds after the beginning of the instability the growth rate of initial waves will reach to $\exp(\gamma t) = e^{19} \approx 1.8 \times 10^8$. Considering the total Čerenkov emissions of a column of a column of length of 2×10^7 cm which consists of the charged particles with the velocity of 10^9 cm/sec along the geomagnetic line of force, we have $E_0 = 3.2 \times 10^{-22} W.m^{-2}.$ (c/s) $^{-1}$ at $f_0 = 1.6$ kc/s.

Therefore at $t = 1.2 \times 10^{-3}$ seconds after the onset of the instability an intensity flux at 1.6 kc/s may become $5.8 \times 10^{-14} W.m^{-2}.$ (c/s) $^{-1}$ which may be compared with the intensity flux on the ground. At geomagnetic latitude of 25° in the polar-coordinate originated at the center of earth on the same geomagnetic line of force, the instability can occur only when $V_1 > 10^9$ cm/s. At this point f_H and f_0 may be 6.0 kc/s and 3.0 kc/s for small values of θ respectively. Adopting $V_1 = 1.5 \times 10^9$ cm/s under the same densities as the previous case, we have $E_0 = 9.1 \times 10^{-22} W.m^{-2}.$ (c/s) $^{-1}$ at $f_0 = 3.0$ kc/s and $\gamma = 2.27 \times 10^4$.

At $t = 8.4 \times 10^{-4}$ seconds after the onset of instability an intensity flux at 3.0 kc/s may attain to $1.6 \times 10^{-13} W.m^{-2}.$ (c/s) $^{-1}$ which may also be compared with the intensity

flux on the ground. These waves may propagate toward the earth along the geomagnetic line of force in the whistler mode. From the above discussion we can infer that the chorus increases and the geomagnetic pulsations may be generated by the streams penetrating the exosphere along the geomagnetic line of force, and that the chorus increase may often be associated with the pulsation. In fact, Coleman, Sonett, Judge, and Smith (1960) found the existence of the sharp-crested hydromagnetic waves at 7–14 earth radii. Sonett, Sims and Abrams (1962) have also recently pointed out the presence of magnetoacoustic waves at geocentric distances of 3.7 to 7 earth radii from the data of Pioneer I.

Finally we examine limitations for the application of growing waves. If the velocity of the stream is small, the thermal motion of plasma protons may become significant since the damping of waves, such as the phase mixing of waves due to the thermal motion of plasma protons, becomes large. The geomagnetic pulsations treated in section 2 are associated with the chorus increases which may result from the interaction of high-speed charged particles with the exosphere.

A close correlation between the chorus increase and the cosmic noise absorption at the auroral zone (Ondoh, 1962) suggests invasions of electrons of energies up to a few hundred Kev or protons below one Mev during the chorus increases. Therefore we can expect the penetrations of streams with the velocity above 10^8 cm/sec during the chorus increase accompanied by the pulsations.

The thermal velocity of plasma protons may be of the order of 10^7 cm/sec– 10^6 cm/sec for the kinetic temperature of $T=10^6$ K– 10^4 K. Thus since for the model used the phase velocity of hydromagnetic waves appeared ($V=10^7$ cm/sec– 10^8 cm/sec) are greater than the thermal velocity of plasma protons and the densities of streams are not so low, we may neglect the effect of thermal motion of plasma protons.

4. Conclusion

We have found a close relation between the chorus increase and the geomagnetic pulsation with the period of 1–6 minutes at the auroral zone. The chorus increase may be generated by the Čerenkov instability resulting from the interaction of charged particles (10^9 cm/sec) with the exosphere. The power flux of the emission may become of the order of $10^{-14} W.m^{-2}.(c/s)^{-1}$ which may be compared with that on the ground, about one milli-second after the onset of instability. On the one hand, when the velocity of ionized stream exceeds the Alfvén wave velocity, the growing hydromagnetic waves may appear in the stationary-plus-streaming plasma system. The Alfvén velocity in the outer exosphere may be of the order of 10^7 cm/sec. Therefore when the ionized stream with velocity of 10^8 cm/sec and density of $10/cm^3$ invades into the exosphere along the geomagnetic line of force the growing hydromagnetic waves (10^7 cm/sec) may appear in the exosphere-plus-stream system. These hydromagnetic waves may propagate toward the earth in the stream moving along the geomagnetic line of force and may be observed as the geomagnetic pulsations.

Thus the interaction of charged particles or stream penetrating along the geo-

magnetic lines of force with the exosphere may explain the close relation between the chorus increase and geomagnetic pulsation at the auroral zone.

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