Interrelations of Upper Atmosphere Disturbance Phenomena in the Auroral Zone

T. OGUTI

Geophysics Research Laboratory,
University of Tokyo, Tokyo, Japan

Abstract: Interrelations of the phenomena of upper atmosphere disturbances in high latitudes, such as magnetic disturbance, auroral displays, anomalous ionization in the ionosphere, X-ray and radio wave emissions, are discussed with special reference 1) to the numerical relations of quantities of the disturbances and 2) to the spatial distribution of disturbance area.

As to the numerical relations, the effects of primary electron beams, for example, ionization, excitation and emission of X-ray and radio waves, were shown to be consistent with the observational results, though a considerable scattering of numerical values occurs owing to the fluctuation of energy spectrum of primary electrons.

The examination of spatial distribution of disturbance area has led to a conclusion that 1) the electron precipitation responsible for various disturbance phenomana can be divided into three groups, *i. e.* flash precipitation group, quasi-steady precipitation group and noon precipitation group, and 2) these groups would correspond respectively to the electron precipitation from the open-close boundary of magnetic lines of force in geomagnetic cavity, to the electron precipitation from the trapping region, and to that from neutral regions of cavity surface in the day side.

1. Introduction

Existence of a close relation between auroral appearance and geomagnetic disturbances in the auroral zone has long been known since as early as 1889. Commencement of continuous recording of geomagnetic variations, in place of visual observation, made it possible to examine a much more precise relation on the simultaneous increase in activities of the two phenomena. The close relation has led many research workers to conclude that the two phenomena have a common origin, and that the geomagnetic disturbance during auroral displays would be due to an electric current in or near auroral forms.

It was not until the discovery of the ionosphere that a physical meaning of the supposed electric current has been clarified. The ionosonde technique has become one of the most powerful means to study the mechanism of auroral displays and associated geomagnetic disturbances, since it has clearly shown that the electron density in the ionospheric level increases corresponding to simultaneous auroral displays and geomagnetic disturbances (*e. g.* MEEK, 1952).

Though a vertical ionosonde reveals itself as a very useful technique to observe the variation in electron densities in the ionospheric level, it has a serious limitation of observation during heavily disturbed periods. Because, no reflected echo can be obtained during severe disturbances due to a strong attenuation of radio waves in the lower ionosphere. An effort to avoid the limitation, and to pick up some information of ionization during ionospheric blackout, had led to development of two other techniques. One is an auroral radar and the other is a riometer. It is quite reasonable to test a possibility of application of the radar technique in measuring the irregularities of electron densities since considerable electronic irregularities may be expected to exist in and near aurora. After a number of tests, the reliability of the auroral radar technique was established using radio waves with frequency of about 100 Mc/s (*e. g.* CURRIE, FORSYTH and VAWTER, 1953). On the other hand, the passive riometer technique made it possible to measure ionospheric absorption of radio waves coming from an extraterrestrial source (LITTLE and LEINBACH, 1959). This technique, as well as the auroral radar, has proved very useful for measuring the grade of ionization in the lower ionosphere even when the ordinary ionosonde gives no information due to blackout.

Quite a different kind of observation of auroral displays has been begun by WINKLER and PETERSON (1957), using X-ray counter and balloon. A number of reports have shown that the auroral displays are frequently associated with X-ray emission. X-ray emission has an important significance as a tracer of precipitating electrons, since it would be due to bremsstrahlung emission from these electrons in the upper atmosphere.

Auroral radio emissions, such as, plasma waves with heavily dense electronic cloud which may exist in the auroral forms, synchrotron emission and VLF emission from precipitating electrons, are also very useful tracers of physical states of ionosphere and dumping electrons.

These ground observations are, of course, of great importance for the study of the mechanism of upper atmosphere disturbance phenomena. They can be operated continuously and simultaneously at many fixed stations on the earth. However, ground observation is more or less an indirect observation of upper atmosphere phenomena, that is to say, the quantities observed on the ground might not always give an original information, owing mostly to some filtrations and attenuations. They might be sometimes a secondary effect. Therefore, it has a great meaning to study the phenomena themselves, without secondary effect, at the localities they occur, using rocket-borne or satellite-borne instruments. Thus, rocket observation (McILWAIN, 1960) has shown that in the auroral forms fairly large amounts of electrons are precipitated with energy ranging from a few keV to a few hundred keV.

Direct observation of the source of electrons, which has been found at the rocket altitude, is a part of artificial satellite. The study of the energy spectrum and the flux intensity of electrons in the geomagnetic cavity and in the geomagnetic tail has been started and many characteristics features have become known.

The purpose of this paper is, in the first place, to bring together as many as possible the phenomenological and numerical relations of the results of ground observation mentioned above, and secondly to give some theoretical consideration with special reference to electron precipitation, and finally to examine the correlation of these phenomena with the magnetospheric plasma and energetic particles.

2. Numerical Relations of Upper Atmosphere Disturbance Phenomena

a) *Relation between auroral luminosity and ionospheric electron density*

The first experiment on the numerical relation between auroral luminosity and ionospheric electron density was carried out by OMHOLT (1955). Using the data obtained at Tromso, he showed that the auroral luminosity of negative group of N_2^+ is roughly proportional to the square of maximum electron density in the E region for the same period (Fig. 1(a)). His experiment led to the following empirical relation between these two quantities:

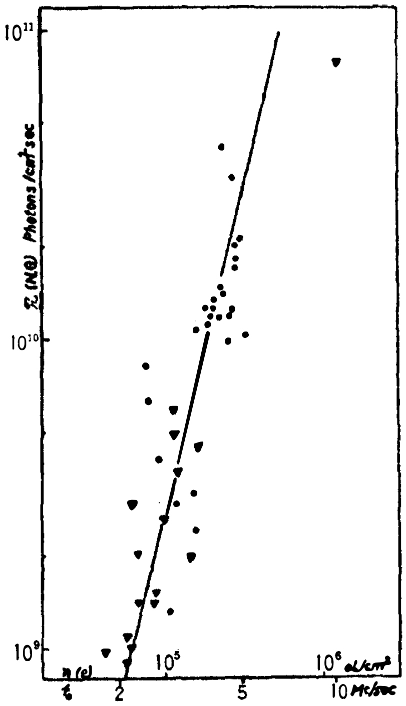

Fig. 1(a). The critical frequency of the E_a-layer against the photon emission π (N.G.) of the negative nitrogen bands from the aurora in zenith (After OMHOLT).

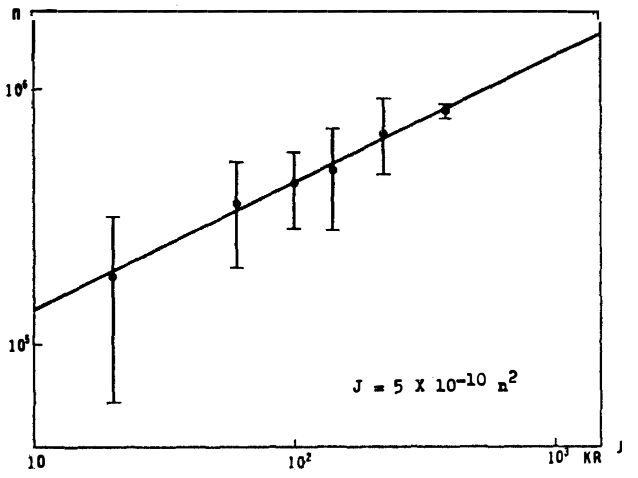

Fig. 1(b). The top frequency of f-E_s layer against the luminosity of auroral green line from aurora in zenith observed at Syowa Station.

$$J_{NG}=2.5\times 10^{-10}\ n_{\max}^2 \quad \cdots\cdots(1)$$

where J and $n_{\max}$ represent respectively the auroral luminosity in unit of KR and the maximum electron number density. The same kind of examination was carried out on the correlation between the auroral green line (λ 5577) and the top frequency of the E_s-region during sharp negative bay disturbances around midnight at Syowa Station in the southern auroral zone (Fig. 1(b), OGUTI and NAGATA, 1962). The relation is given by

$$J_{5577}=5\times 10^{-10}\ n_{\max}^2 \quad \cdots\cdots(2)$$

Comparing this equation with the first, it is found that the numerical relations are consistent with each other, with a discrepancy of factor 2 or 3 since the statistical ratio of auroral luminosity of negative group to that of green line is about 1–1.9. The discrepancy of the factor would have probably no meaning. Anyhow, it can be concluded that a clear numerical relation exists between the anomalous ionization in the ionospheric E level and the simultaneous auroral luminosity.

The good correlation is understandable, because the precipitating electrons have certain ionization cross sections and also effective cross sections for the excitation responsible for certain emissions. However, the total production rate of secondary electrons and that of excited molecules and atoms are the functions of altitudes. The dependence on altitude would vary with the abundance of atoms and molecules concerned, and with the electron decay constant and the

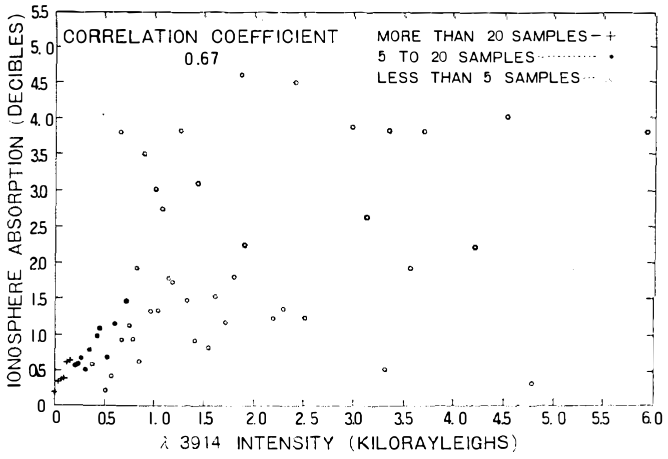

Fig. 2(a). Distribution of correlated amplitudes of ionospheric absorption and intensity of λ 3914 auroral coruscations for March 7 through April 8, 1960. Average values of absorption in corresponding coruscation intervals of 36 rayleighs are shown (After CAMPBELL).

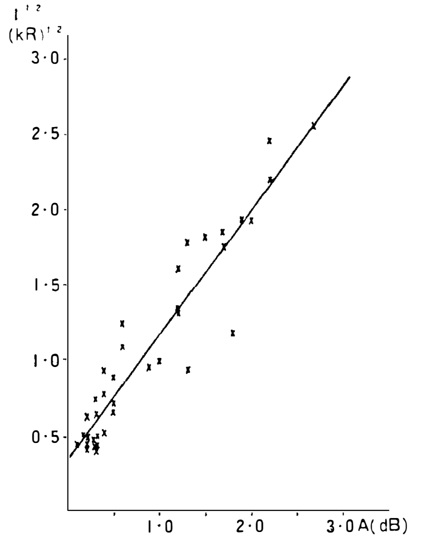

Fig. 2(b). Plot from the night 12–13th October 1963. Points represent readings made with 5 min intervals (After JOHANSEN).

energy spectrum of primary electrons.

The difference in the altitude-dependence of these factors would probably produce a scattering of the relation. The good correlation in this case, therefore, would show that the energy deposit from primary electrons in the form of excitation and in the form of ionization would take place around the same altitude, so that the rate of energy partition would remain rather constant in this relation. A more quantitative discussion will be given later.

b) *Auroral emission and radio wave absorption*

Auroral emission has a correlation also with radio wave absorption. This relation would be readily expected from the fact that the electron density increases in the ionospheric *E* region during auroral displays. Figure 2 (a) is a diagram of relation between the auroral intensity variation and the radio wave absorption obtained by Campbell (1961), and (b) shows the similar relation, not fluctuations but the average value in five minutes interval obtained by Johansen (1964, 1965). The numerical relations by Campbell and Johansen would be given as

$$Abs_{\text{in } db} = 1\sim 2 \cdot J_{3914} \qquad \text{Campbell} \cdots\cdots\cdots\cdots (3)$$

$$Abs_{\text{in } db} \simeq 1 \cdot J_{5577}^{\frac{1}{2}} \qquad \text{Johansen} \cdots\cdots\cdots\cdots (4)$$

Contrary to the first relation between the auroral luminosity and the electron density in the *E* region, a considerable scattering of the plotted points exist in this relation. It means that the energy deposit in the ionization in the lower *E* and *D* regions would not be correlated very well with the energy deposit in the excitation in the auroral forms.

If the fact that the electron production in the lower ionosphere, *i. e. D* region, is most effective to cause a radio wave absorption, and that the aurora is brightest around the *E* level in many cases, is taken into account, the correlation, in this case, poorer than the first pairs, would be understood, as it is probably due to a change in energy spectrum of primary electrons.

c) *Auroral luminosity, radio wave absorption and X-rays*

On the relations between X-rays and auroral luminosity, and between radio wave absorption and X-rays, many examples of good correlation have been obtained. For example, Figures 3 (a) and (b) show a comparison of auroral luminosity with X-ray obtained by Anderson and Dewitt (1963), and a comparison of luminosity, X-ray and absorption during an auroral event by Rosenberg (1965). The tests of a statistical correlation of these quantities seem to be still deficient for inducing reliable numerical relations. However, it is an observed fact that a quite good correlation exists between these quantities.

The relation between X-ray intensity and radio wave absorption would probably be better than that between X-ray intensity and auroral luminosity, because the energetic component is responsible for both bresstrahlung hard-X-ray detectable at the balloon altitude and radio wave absorption due to *D* ionization, while the low energy component will be responsible for auroral excitation.

It would be worthwhile to note another fact that an excellent conjugacy is found (BROWN *et al.*, 1965), between Kotzebue riometer data and Macquarie balloon X-ray data.

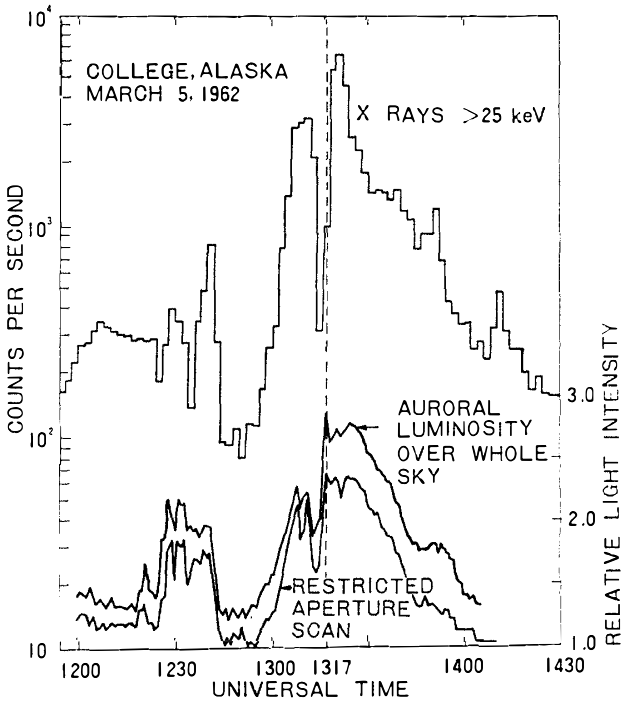

Fig. 3(a). Comparison of auroral luminosity obtained from all-sky camera picture with X-ray flux at balloon altitude (After ANDERSON *and* DEWITT*).*

d) *Auroral luminosity, radio wave absorption and X-ray emission related with geomagnetic disturbances*

Although the close relation between auroral displays and geomagnetic disturbances has long been known, their numerical relations have remained ambiguous. The most important reason for this would be a large scattering in the correlation between the auroral luminosity and the magnitude of geomagnetic variation. The large scattering is probably due, in the first place, to the change in energy spectrum of primary beams, and secondly to the change in electric field in the dynamo-region, no matter whether it is due to ionospheric wind or it comes from magnetospheric circulations (AXFORD and HINES, 1961). In this case, therefore, the two factors causing the largely scattering correlation are expected.

However, if certain characteristic magnetic disturbances were specified, the numerical relation between the auroral luminosity and the corresponding variation in geomagnetic field would be much more revised. For example, if sharp negative bays around midnight were selected, the numerical relation with auroral luminosity would be given by

$$J_{5577}=3\times 10^{-3}|\Delta H|^{2} \cdots\cdots\cdots\cdots (5)$$

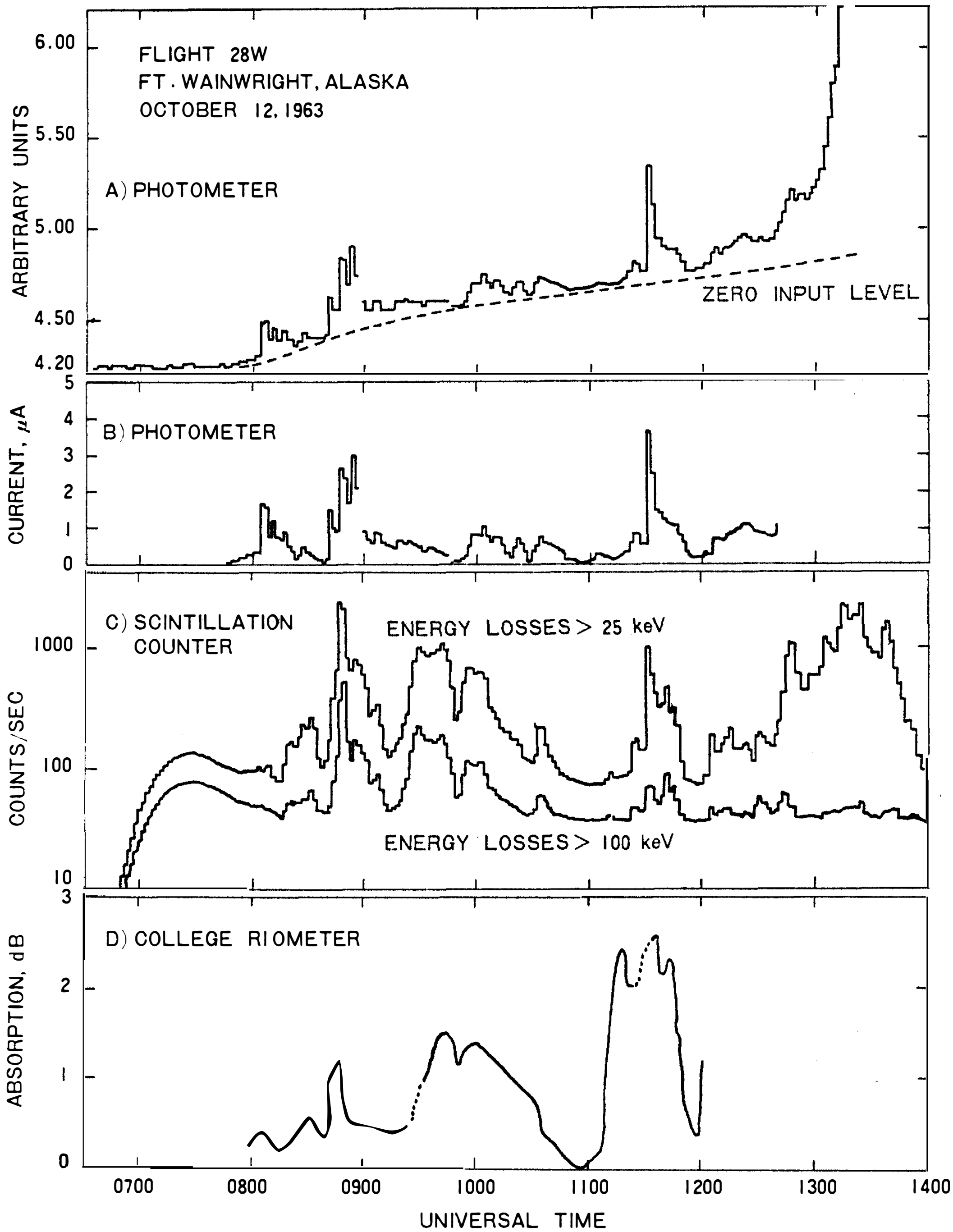

Fig. 3(b). Luminosity, X-ray and ionospheric absorption measurements for the auroral events during Flight 28W on October 12, 1963 (After R*OSENBERG).*

where J and $\boldsymbol{H}$ represent respectively the auroral luminosity of green line in unit of KR and the magnitude of horizontal geomagnetic disturbance vector, in unit of γ, based on the data obtained at Syowa Station in the southern auroral zone (Oguti and Nagata, 1962; Oguti, 1963).

Table 1. Change in the ratio $J(5577)/|\Delta \boldsymbol{H}|^2$ at various geomagnetic latitudes.

Station	Geomagnetic latitude	$J(5577)/\|\Delta \boldsymbol{H}\|^2$
Point Barrow	68°.5	3.2×10^{-3} kR/γ^2
College	64°.7	5.6×10^{-3} kR/γ^2
Syowa Station	−69°.4	3×10^{-3} kR/γ^2
Little America	−73°.1	4.0×10^{-3} kR/γ^2

The relation of the same kind has been shown to hold between the white auroral luminosity and the magnitude of disturbance vector in the northern auroral zone, by Kaneda and Nagata (1965). Kaneda and Nagata also pointed out that there is a general tendency of the proportional constant to increase with increasing distance from auroral zone, as shown in Table 1. On the other hand, the relation is shown to become much poorer than that in the case of sharp negative bays, though the ratio $J/|\Delta \boldsymbol{H}|^2$ generally tends to decrease, during broad bay disturbances, positive bay disturbances and severe magnetic storms (Oguti, 1963).

e) *Local time dependence of numerical relations*

Two figures showing the local time dependence of the numerical relations

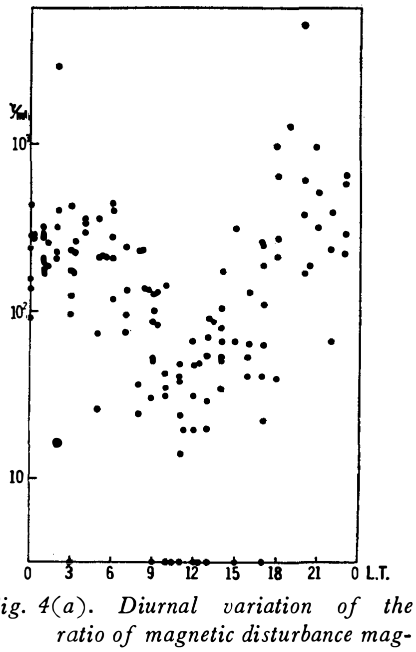

Fig. 4(a). Diurnal variation of the ratio of magnetic disturbance magnitude with associated ionospheric absorption, at College.

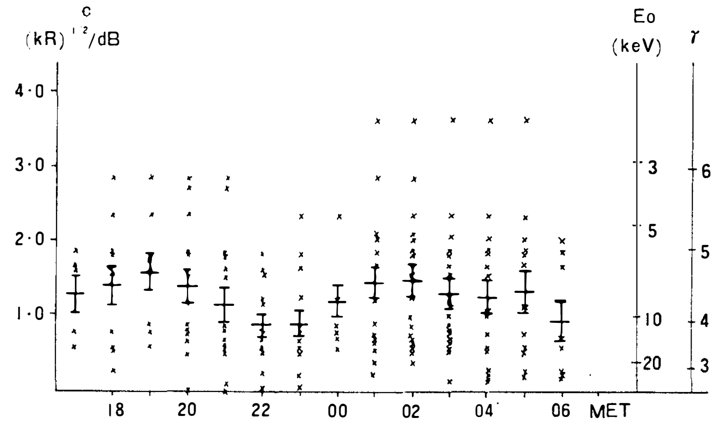

Fig. 4(b). Observed slope of regression line plotted versus local time. Arithmetic mean and standard deviation are indicated. At right corresponding values of the e-folding energy E_0 and the exponent γ in exponential law and power law electron energy spectra respectively are given (After Johansen).

are reproduced here. Figure 4 (a) shows the local time dependence of the ratio of the magnitude of geomagnetic disturbances and the corresponding radio wave absorption obtained at College, Alaska (OGUTI, 1963), and Figure 4(b) represents the local time dependence of the ratio of auroral luminosity to corresponding radio wave absorption (JOHANSEN, 1965). The average relations are given by

$$A_{\text{in } db} \simeq 280\,|\Delta \boldsymbol{H}|_{\text{in } \gamma} \cdots\cdots\cdots \text{OGUTI} \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

$$A_{\text{in } db} \simeq J_{5577}{}^{\frac{1}{2}} \text{ in } KR \cdots\cdots\cdots \text{JOHANSEN} \cdots\cdots\cdots\cdots\cdots (7)$$

It is clear in these two figures that the ratio H/A or J/A is smaller in daytime than at night, and the scattering in daytime is much larger than at night. The average ratio in daytime, which amounts up to about 1/10 times that at night, would be mostly due to the hard energy spectrum of primary electron in daytime around the auroral zone, though it may partly due to the effect of negative ions. The large scattering of the ratio in daytime, consequently, would be understood as a result of the fluctuation of energy spectrum of primary electron beams.

f) *Rapid variation*

As to the short-term variations, some interesting results have been obtained. A characteristic long-period pulsation in high latitude, Pc-5, is sometimes as-

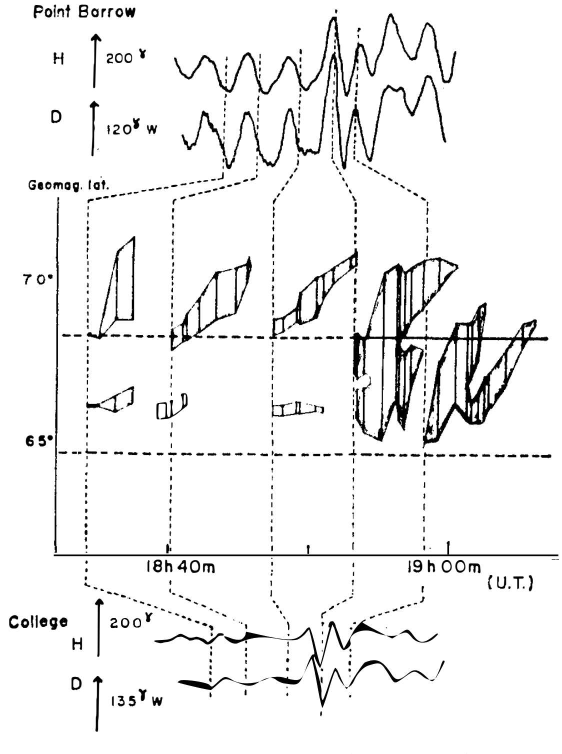

Fig. 5. An example of range variation in ARE and corresponding variation on magnetogram in the event of December 8, 1957.

sociated with the fluctuation of auroral luminosity of the same period. A statistical treatment of these magnetic and auroral pulsations observed at Syowa Station has revealed a characteristic relationship between these fluctuations. That is, the Pc-5 pulsation of pure sinusoidal form, which characteristically appears in daytime, has little or no correlation with variation of auroral luminosity, while the Pc-5 pulsation of a little irregular form is often associated with luminosity fluctuation of aurora (Oguti, 1963), and periodic appearance of auroral radar echoes (Kaneda, Kokubun, Oguti and Nagata, 1964). Auroral radar echo seems to occur around the area where the pulsation of geomagnetic north component shows a phase difference of about π, namely, around the area where horizontal geomagnetic disturbance vector shows a periodic divergence or convergence. The numerical relation between the amplitude of irregular Pc-5 and that of the associated auroral pulsation in luminosity is geven by

$$J_{5577}=1.4|\Delta H| \quad \cdots\cdots\cdots(8)$$

Pc-5 pulsations are sometimes associated also with the fluctuation of radio wave absorption of the same period (Sato, 1964).

Storm sudden commencements, as well as Pc-5 pulsations, are often associated with luminosity increase of aurora (Nagata and Oguti, 1961) and the increase of radio wave absorption (Orter *et al.*, 1962). The relationship with luminosity change and increase in absorption of *SSC* is closely similar to that of pc-5 pulsations of the second kind.

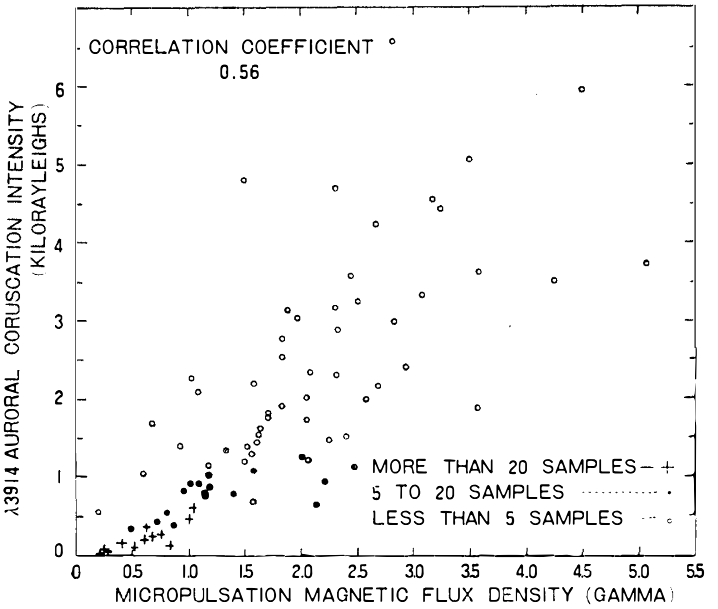

Fig. 6(a). Distribution of correlated amplitudes of λ 3914 coruscation intensity and magnetic field micropulsations for the period November 3 through April 8, 1960 (After Campbeil).

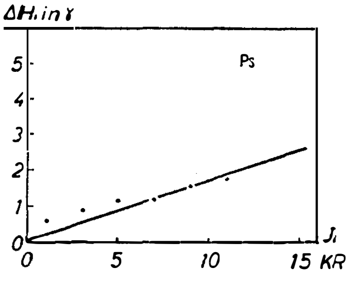

Fig. 6(b). Amplitude of geomagnetic short period pulsations versus auroral λ 5577 pulsations in zenith.

Campbell and Ress (1961) have shown that the fluctuation of auroral intensity is associated with magnetic pulsations of short period, which leads to a numerical relations as

$$J_{3914}=1\times|\Delta H| \quad\cdots\cdots(9)$$

using the data obtained at College, Alaska. In the southern auroral zone, the same kind of correlation was recognized at Syowa Station between the λ 5577 luminosity and the amplitude of geomagnetic pulsation with period of 9 sec (Oguti and Nagata, 1962), as given by

$$J_{5577}=6.6|\Delta H| \quad\cdots\cdots(10)$$

A characteristic feature of this relation is the proportionality of the luminosity change to the amplitude of geomagnetic disturbance field, which is characteristically different from the luminosity-amplitude relation in the case of bay disturbances where the luminosity seems to be proportional to the square of amplitude of magnetic variation.

Another characteristic feature of the relation is the high value of the $J/\Delta H$ ratio which amounts up to 6.6 KR/γ in the short-period variation.

Corresponding to the short-period pulsation of geomagnetic field, X-ray pulsation events have been found by Barcus *et al.* (1966). Their analysis of power spectrum of X-ray intensity variation indicated that there is a predominant peak around 8 seconds. This period would be a characteristic time constant of the fluctuation of primary electron beams. Concerning much more rapid variations, we have not yet sufficient data of auroral luminosity, magnetic fluctuations, and radio wave absorption. Probably, the fluctuation with period about 1 sec and 0.2 sec found in the spectrum of fluctuation in X-ray intensity (Winkler *et al.*, 1962; Anderson and Milton, 1964) would be found also in the fluctuations of auroral luminosity, magnetic variations and radio wave absorption, having characteristic numerial relations with each other.

Generally speaking, variations in respective quantities have respective time constants, so that the numerical ratio among these quantities would vary with the period concerned, namely, the relative magnitude of variation with a short-time constant would become large, and that with a long-time constant would tend to decrease, as the period decreases.

3. Theoretical Interpretation of the Numerical Relations

Theoretical study of the upper atmosphere disturbance phenomena, especially of the phenomena associated with electron precipitation, seems to have almost suceeded to interpret the relative occurrence of these phenomena, and furthermore the numerical relations between these disturbance quantities.

The outline of the study would be summarized as follows:

The excitation rate η of the respective atoms or molecules responsible for the respective emissions due to primary electron beams is given by

$$\eta=\int\varepsilon(E,\lambda)\, n_A(z) f_e(Ez)\, dE_0 \quad\cdots\cdots(11)$$

where $\varepsilon(E, \lambda)$, $n_A(z)$, and $f_e(E, z)$ represent the respective excitation cross section, the number density of respective atoms or molecules, and the differential energy spectrum of primary electron flux, respectively. The integration should be carried out between the two energy levels, corresponding to the high and low cutoff energy of primary electron flux.

The relation between the energy of primary electrons at the top of the atmosphere E and that at the concerning level E' is given by

$$E' = E - \int_0^{n(z)} L(E)\, dn \quad \cdots\cdots(12)$$

where $L(E)$ represents the effective energy loss rate in unit depth of the atmosphere, taking the pitch angle effect into consideration.

The auroral luminosity J, therefore, is given by

$$J_\lambda = \int_{z_0}^{\infty} \kappa_\lambda \, \eta_\lambda \, dz \quad \cdots\cdots(13)$$

where κ_λ means the effective emission rate of respective auroral emissions.

If the excitation energy level is low enough, the excitation due to secondary electrons must be taken into account.

The production rate of secondary electrons would be given by

$$q = \int Q(E)\, n_B(z) f_e(Ez)\, dE_0 \quad \cdots\cdots(14)$$

where $Q(E)$ represents the ionization cross section.

The energy spectrum of the secondary electrons would probably be in an exponential form $e^{-\frac{E}{E_0}}$. The loss mechamism of electrons will determine the energy spectrum of secondary electrons in the stationary state. Thus, postulating that the main electron removal is due to recombination, the electron density n in the stationary state will be obtained as

$$n = \sqrt{\frac{q}{\alpha_{\mathrm{eff}}}} \quad \cdots\cdots(15)$$

by neglecting of multiple interactions. The flux due to these secondary electrons must be added to the primary electron flux.

It has been shown by TOHMATSU and NAGATA (1962) that the effect of secondary electron might play a certain role in the emission of the auroral green line (5577 A) and the red line (6300 A, 6364 A). It must be noted that the height-change in effective emission rate κ also plays an important role in the emission of the auroral red line.

If the energy spectrum of primary electron beams is given, the auroral luminosity is proportional to the electron flux, primary plus secondary. The secondary flux would be proportional to the square root of primary flux at the recombination removal of electrons, while it would be proportional to primary flux in the attachment removal. Then, if the secondary flux plays an important role in emission, the auroral luminosity should be proportional to the secondary electron density in both cases. Only in the case where the electron removal is due to recombination and the auroral excitation is mainly due to primary electron beams, the relation $n^2 \propto J$ holds. Therefore, the observational facts that the numerical relation $n^2 \propto J$ approximately valid in the real auroral displays, both negative group and green line with electron density, and that the intensity correlation between negative group and green line is fairly good, seem to suggest that both emissions are mainly due to the primary electron flux, and that the electron removal in the auroral forms are mainly due to the recombination process.

In fact, in the case of auroral green line and maximum electron density, the theory would give an average constant of the proportionality $1 \sim 2 \times^{-10}$ $KR/$(electrons/cm^3)^2, though it depends on the energy spectrum of primary electron beams, being consistent substantially with the observational results.

The scattering in the $n^2 - J$ relation is due to change in energy spectrum of primary electrons. For exmple, as to the green line, the flatter the energy spectrum beyond a critical slope, the weaker the luminosity to be observed, since the abundance of atomic oxygen tends to sharply decrease below 100 km level. The ratio J/n^2 would decrease for soft component also, due to the fact that the attachment effect plays an important role in electron removal at high altitude. The effect of recombination coefficient α_{eff}, however, is to reduce n and to cause increase in J/n^2 corresponding to hard components.

As the ratio J/n^2 depends on energy spectrum in a complex way as mentioned above, it may not be suitable for estimation of energy spectrum from this relation. Another possibility for estimation, is to examine the radio wave absorption.

The radio wave absorption in the ionospheric level is given by

$$\Gamma = \int \frac{\nu}{2c\mu} \frac{ne^2}{m\mathcal{E}_0\{(\omega \pm \omega_H)^2 + \nu^2\}} dl \quad \cdots\cdots\cdots\cdots (16)$$

where ν, n, μ, ω and ω_{HL} represents the mean collisional frequency, the electron density, the refractive index, and the angular frequency of radio wave and longitudinal component of electron gyro-frequency, respectively.

ν is a function of sharp decrease with height. The absorption, therefore, is maximum in the lower D region for radio waves of ordinary frequency of riometers, say 27 Mc/s. In other words, the absorption is a weighted mean of electron densities, where the weight function is maximum around the D region.

The total absorption is proportional to the electron density under a given energy spectrum, and therefore, it is proportional again to the square root of primary electron flux, and to the square root of auroral luminosity.

The scatting in this relation is, as in the preceding examples, due to the change in energy spectrum of primary electron beams. For example, assuming the energy spectrum to be propotional to E^{-4} and E^{-5}, the ratio n_{max}/Abs is obtained as those in the following Table 2.

The same kind of relation holds between auroral luminosity and absorption. Thus, the systematic daily change in the ratio, *e. g.* n/A and J/A, is attributable to the change in energy spectrum of primary electrons. The energy spectrum

Table 2. *Ratio $N_{max}(E_s)$/Absorption in unit f electrons/cm³/db, calculated under the assumption that the energy spectrum of primary electron is given by $N(E)dE = KE^{-\gamma}\,dE$.*

K \ γ	Night	Daytime		
	10^{10}	10^{10}	10^{11}	10^{12}
4	5.2×10^5	3.1×10^5	3.2×10^5	3.2×10^5
5	9.4×10^5	1.2×10^6	1.1×10^6	8.9×10^5

of electron flux causing night auroral events is obtained as $E^{-4}-E^{-5}$ and that in daytime is obtained as $E^{-2}-E^{-4}$ with a large fluctuation of spectrum up to E^{-7} (OGUTI, 1963).

The radio wave absorption during auroral displays has been sometimes considered as having mainly resulted from the ionization in the lower D region due to bremsstrahlung X-ray emitted from the stopping primary electrons. However, a theoretical estimation readily points out that the effect of bremsstrahlung X-ray is much less than that of original electron beams, being generally less than 1 per cent of the total absorption.

X-ray is still a very important and useful tracer of primary electron beams, since the X-ray emission is one of the most direct effects of electron precipitation.

According to ANDERSON and ENEMARK (1960) the X-ray spectrum in the medium of radiation length l is given by

$$n_p = \frac{K}{2000l(\gamma-1)(\gamma-2)} E^{-\gamma+1} \cdots\cdots\cdots\cdots(17)$$

provided that the energy spectrum of electron precipitation is

$$n_e(E)\,dE = KE^{-\gamma}\,dE \cdots\cdots\cdots\cdots(18)$$

If the range-energy relation of electrons, which they used, is replaced by the following form, according to experimental results,

$$R = 10^{-6}\,E^2 \cdots\cdots\cdots\cdots(19)$$

where range R is in unit of cm and energy E is in unit of MeV, the X-ray spectrum would be modified as

$$n_p = \frac{2\times10^{-6}K}{l(\gamma-1)(\gamma-3)^2} E^{-\gamma+2} \cdots\cdots\cdots\cdots(20)$$

The statistical data are not sufficient yet to determine which is more likely to fit the observational results.

Numerical relation of magnetic disturbances to the other disturbance quantities, such as electron density and auroral luminosity, would be understood as follows:

The ionospheric electric current density is given by

$$\boldsymbol{j} = (\sigma)\boldsymbol{E} \cdots\cdots\cdots\cdots(21)$$

where (σ) represents the conductivity tensor.

In the auroral forms, generally limitted in latitudinal and vertical dimensions. (σ) is probably replaced by σ_3. Therefore, a rough estimation of electric current in an auroral form is made as

$$j_{\text{Total}}=\iint \sigma_3(n)\, \boldsymbol{E}\, dl\, dl' \quad \cdots\cdots\cdots\cdots\cdots\cdots(22)$$

Then, in the statistical meaning, j is proportional to the conductivity σ_3, accordingly to the electron density and consequently to the square of the primary flux, postulating that $\boldsymbol{E}$ is constant. Apparently, σ_3 is a function of altitude z, having a sharp maximum around a dynamo-region. The only effective contribution to the integral comes from values of z near the altitude of maximum σ_3.

Since the energy spectrum of the primary electrons is responsible for the secondary electron profile, we can understand the change in energy spectrum to be responsible for scattering of correlation diagrams between magnetic variation and the others.

Besides being affected by the change in energy spectrum, the correlation in this case would be reduced also by the change in electric field and the change in the shape and dimension of ionized region. The shape effect can be readily estimated taking an elliptic ionized area. Suppose an enhanced ionization of an elliptic area, with major axis a and minor axis b, the electron density becomes k times that outside. The additional current intensity along the long axis and that along the short axis of an ellipse is given by

$$\left.\begin{aligned} i_x&=\frac{\left(\frac{k}{\sqrt{1-e^2}}+1\right)\cos\theta-\beta(k-1)\sin\theta}{\alpha(k-1)^2+k\left(\frac{1}{\sqrt{1-e^2}}+1\right)^2}\cdot\frac{k-1}{\sqrt{1-e^2}}\sigma_3\, E_0 \\ i_y&=\frac{\beta\frac{k-1}{\sqrt{1-e^2}}\cos\theta+\left(k+\frac{1}{\sqrt{1-e^2}}\right)\sin\theta}{\alpha(k-1)^2+k\left(\frac{1}{\sqrt{1-e^2}}+1\right)^2}(k-1)\,\sigma_3\, E_0 \end{aligned}\right\}\cdots\cdots\cdots(23)$$

where $\alpha=\sigma_3/\sigma_1$, $\beta=\sigma_2/\sigma_1$, and θ represents the angle between the direction of the electric field and the major axis of the elliptic area, so that i_x, the currens along the major axis, varies from $\frac{\cos\theta-\beta\sin\theta}{\alpha}\sigma_3 E_0$ to $\cos\theta\, k\, \sigma_3 E_0$ as ellipticity changes from zero to unity provided that $k\gg 1$. From this formulation, the previous estimation of j is known to be the limitting case of a line current approximation. The large dispersion in the correlation diagram, including magnetic variation, is probably due to the summation of these three effects.

The linear relation between magnetic fluctuation and fluctuation of auroral luminosity may be a differential form of the quasi-steady relation $J\propto|\Delta \boldsymbol{H}|^2$. The high value of $J/|\Delta \boldsymbol{H}|$ in short period oscillation is probably due to the impedance effect on electron removal, the time constant of which is relatively long compared with the characteristic time of the fluctuation itself (Oguti, 1963).

As to the synchrotron radiation, a comprehensive study by Twiss and Roberts (1958) has shown that an appreciable amount of higher harmonic waves of an ordinary mode, as well as of an extra-ordinary mode, can be emitted from gyrating electrons with energy approximately equal to that of auroral electrons, and that the waves can propagate.

According to their estimation, the total power emitted in a forward direction in the fundamental mode, the second harmonic and the third harmonic, are proportional to $\beta^2(1-\beta^2)H$, $\beta^4(1-\beta^2)H$ and $\beta^6(1-\beta^2)H$ respectively. The frequency of fundamental wave is given by $\omega_H\sqrt{1-\beta^2}$. Therefore, if we can estimate the emitted synchrotron radiation from aurora, after making an appropriate correction for absorption to the ground observation, it would be possible to bring out the energy spectrum of primary electrons on the energetic side as well as its flux, from the synchrotron radiation intensity as

$$P(\omega)=K\left\{A\left(1-\frac{\omega^2}{\omega_H{}^2}\right)^{-(\gamma-1)}\left(\frac{\omega}{\omega_H}\right)^{\gamma+2}+B\left(1-\frac{\omega}{4\omega_H{}^2}\right)^{-(\gamma-2)}\left(\frac{\omega}{2\omega_H}\right)^{\gamma+2}+\cdots\cdots\right\} \quad \cdots\cdots(24)$$

This method would probably be as useful for monitoring primary electron beams as the X-ray observation, though only a few observation results have been reported (*e. g.* by Parthasarathy and Berkey, 1964).

Many possibilities have been proposed to explain the VLF emissions associated with auroral displays. However, any exclusive theory of the VLF emmision does not seem to have been established. Suffice it to note here, then, that the existence of two kinds of VLF emissions associated with auroral displays, such as auroral hiss and auroral chorus, found by Morozumi (1965), would be a strong indication that there are at least two kinds of emission mechanisms, corresponding probably to the trapped radiation and the dumping radiation.

4. Spatial Distribution of Electron Precipitation

It has become plausible, in the preceding section, that the numerical relations between the polar aeronomical disturbances, for example, auroral luminosity, electron density, geomagnetic disturbances, X-ray and radio emissions, are understood as the direct consequence of primary electon precipitations. Among the confirmated interrelation theoreticaly expected, based on the observational facts, some of them are satisfactory while some others are not so complete yet. Though the proton precipitation is supposed to play a certain role in the auroral zone phenomena, the numerical relation between the luminosity of hydrogen emissions in the aurora and the other disturbance quantities has not been studied as widely as the electron precipitation.

Generally speaking, hydrogen emission shows little or no correlation with the other emissions in auroral light, while the correlation between the auroral emissions except hydrogen lines is fairly good. For example, Table 3 shows the

Table 3. Correlation coefficients between luminosities of various auroral emissions.

H - 3805	0. 18	4709 - 3805	0. 89
H - 4709	0. 27	3805 - 6624	0. 82
H - 6364	0. 27	4709 - 6624	0. 81
H - 6624	0. 13	4709 - 5577	0. 81
H - 5577	0. 25	3805 - 5577	0. 80
		5577 - 6624	0. 79
		6364 - 5577	0. 67

correlation coefficent between auroral emission lines, based on the data obtained at Alaska by ROMICK (1963). This fact strongly suggests that the hydrogen does not participate in the auroral excitation at least, as a regular member. Accordingly, the discussion in this section is mostly concerned with the electron precipitation.

The electron precipitation would be divided into three groups. One is, as it were, flash precipitation, the second is quasi-steady precipitation, and the third, which might be a part of the first group, is noon precipitation. Though an independence of the third group has not been confirmed yet, it will be discussed below as an independent group.

a) *Flash precipitation zone*

This kind of precipitation would cause discrete aurora, geomagnetic sharp negative bay, sporadic E ionization of f and a types, sudden increase in radio wave absorption and in X-rays.

Figure 7 shows that the patterns of occurrence of these phenomena are almost completely overlapping each other. The discreteness of auroral forms, small spatial dimension of magnetic disturbance, irregular characteristics of E_s region ionization, discrete auroral radar echo, and pulsation increase in radio wave absorption are all consistent with each other, and this nature readily suggests that the original electron precipitation is sharply time dependent and is of a small scale in linear dimensions. It must have a sharp boundary, and its occurrence must be intermittent. The most probable occurrence pattern of the flash precipitation lies almost along a circle of about 65°–70° in geomagnetic latitude around midnight, just overlapping the so-called auroral zone, and tends to shift polewards into both morning and evening sides. The highest latitude of the pattern, around noon, seems to be about 80° in geomagnetic latitude.

The activity along the pattern of flash precipitation shows a remarkable local geomagnetic-time dependence. The most active part is from 22^h to midnight in local geomagnetic hour. This can be seen especially in Fig. 7, in the result by SANDFORD (1964) on the average luminosity of auroral green line is reproduced. The locus of auroral maximum occurrence obtained by FELDSTEIN (1964) is just the same as SANDFORD's pattern. LASSEN's result (1963) on the distribution of auroral occurrence has shown also the similar distribution of flash precipitation, though, in his result, the maximum occurrence seems to take place from midnight

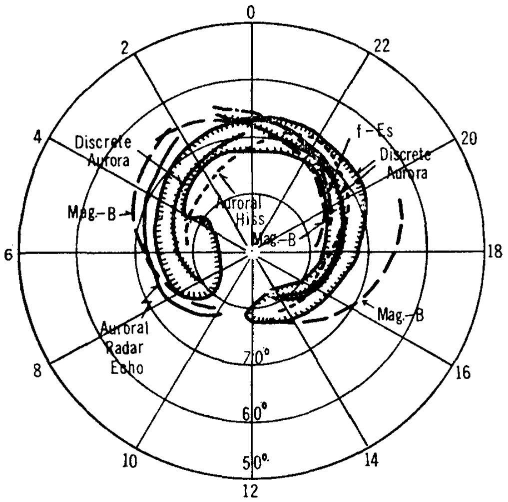

Fig. 7. Distribution of discrete aurora, abrupt magnetic variation, discrete auroral radar echo, f type E_s and auroral hiss in high latitudes.

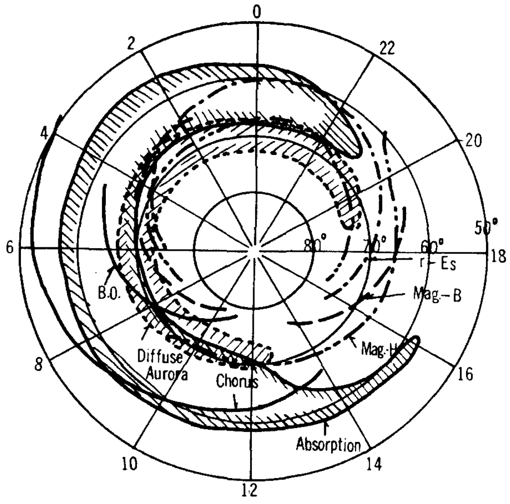

Fig. 8. Distribution of diffuse aurora, radio noise absorption, r type E_S, gradual magnetic variation, blackout and chorus emission around the auroral zone.

to early morning.

b) *Quasi-steady precipitation zone*

According to Sandford (1964), the diffuse aurora is distributed nearly along the so-called auroral zone. The occurrence pattern of *r*-type E_s, is quite similar (Montalbetti and McEwen, 1962). This group seems to include also broad negative bay and positive bay disturbances. Remarkable characteristics of this group are a quasi-steady nature of the variation, the diffuseness of the boundary and the relatively large scale of precipitation region.

The relatively slow variation of geomagnetic field, the stable and stratified nature of *r*-type E_s, and the diffuse radar echo all show that the original flux is a quasi-steady precipitation of electrons in a wide-spread zone.

Another characteristic of this group would be its association with radio noise absorption, as shown in Fig. 8, in which the average CNA data obtained at six stations in Alaska are used. It means that the precipitation responsible for this group of disturbances is statistically hard compared with that responsible for the first group. The large fluctuation of the ratio $J/(\Delta \boldsymbol{H})^2$, $J/|\Delta \boldsymbol{H}|$ or $A/|\Delta \boldsymbol{H}|$ also found in this group in daytime shows the energy spectrum widely ranging from E^{-2} to E^{-7}. This group is, contrary to the first, situated almost along the circle about 60°–65° in geomagnetic latitude, regardless of the local geomagnetic hours.

The intenesity of precipitation along this pattern, as readily seem in Fig. 8, is highest on the dawn side. The intensity on the dusk side is remarkably less than that in dawn, making a notable dawn-dusk asymmetry.

c) *Noon precipitation*

The third precipitation is characterized by an auroral red line (SANDFORD, 1964) and by an anomalous increase in f_0F_2 (OGUTI and MARUBASHI, 1965), occurring from forenoon through local geomagnetic noon, being situated at about 75° in geomagnetic latitude. This pattern is seen also in LASSEN's result on auroral occurrence just at the same position and at the same local time. A corresponding magnetic variation is a rather irregular fluctuation. The time variation of this precipitation seems to be as fairly large as that corresponding to the first group.

One of the most remarkable characteristics of this group is the high altitude of the variation region as expected from the red line and the change in f_0F_2, suggesting that the precipitation responsible is much softer than those in the first and the second groups.

Thus, the three groups are summarized in the following Table 4.

Table 4. A possible grouping of various aeronomical disturbance phenomena in high latitudes.

Group	Elements of which group consists	Time variation and the spatial dimension
Flash group	Discrete Aurora (Discrete radar echo) Magnetic sharp bay *a* and *f* type E_s Abrupt increase in absorption X-ray flash Auroral hiss	Rapid variation Discrete boundary Small dimension
Quasi-steady group	Diffuse aurora (Diffuse radar echo) Magnetic broad bay *r*-type E_s Steady increase in absorpion X-ray increase Auroral chorus	Relatively slow variation Diffuse boundary Large dimension
Noon group	Red aurora Increase in f_0F2	Rapid fluctuation Discrete boundary The linear dimension is not yet clear.

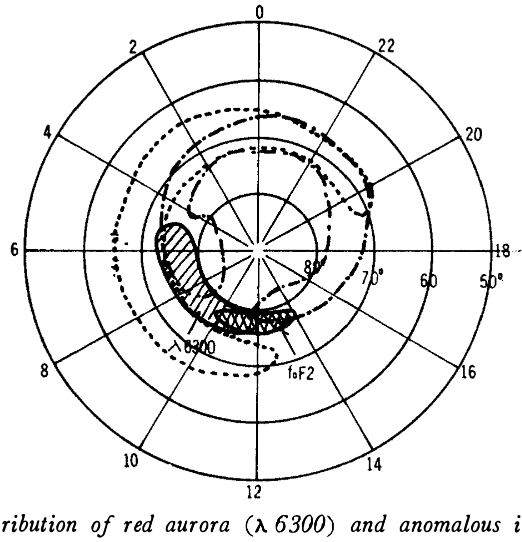

Fig. 9. Distribution of red aurora (λ 6300) and anomalous increase in f_0F2.

5. Comparison between the Precipitation Pattern and the Distribution of Magnetospheric Plasma

The characteristics of three groups of the precipitation mentioned in the preceding chapter, would be as follows:

The first group makes an oval pattern, passing through 65°–70° in geomagnetic latitude at night, and through about 80° in geomagnetic latitude at noon. The second group, slightly overlapping the first one at night, is situated roughly along the latitude circle of 60°–65° in geomagnetic latitude. The third pattern appears from forenoon through magnetic local noon around 75° in geomagnetic latitude. This pattern seems to cease abruptly towards dusk side, while on the dawn side it seems traceable to about 6^h, suggesting a possibility of its continuation with the first pattern. According to the projection from the polar pattern into the geomagnetic equatorial plane of the cavity along the magnetic lines of force, obtained by TAYLOR and HONES (1965), the three precipitation patterns may be transfered to the equatorial plane. The projected pattern is shown in Figs. 10(a), (b) and (c).

After comparing these patterns with the distribution of magnetic field and the plasma in the magnetic cavity (NESS, 1965), it would be concluded that, 1) the first group corresponds to the region of magnetic inflation or to the inner edge of neutral sheet, and accordingly to the plasma around cusp and skirt (ANDERSON, 1965), 2) the second group comes from the trapping region and 3) the third group would be a direct result of corpuscular invasion through the neutral region on the noon side of the geomagnetic cavity.

The rapid temporal variation of the first group would be understood as a result of the instability of the neutral sheet current at its inner edge, where the current pinch is apt to occur resulting in a magnetic field annihilation. The field annihilation would take place first around midnight, since both the magnetic intensity and the balancing current intensity are maximum on the inner edge of the current sheet around the midnight meridian. The field annihilation, causing acceleration of particles, and occurring around the inner edge of current sheet in midnight meridian, would propagate or would be blown away outward and also in E–W direction into the tail. The direct result of the expansion of annihilation region from midnight meridian would cause a rapid poleward shift of auroral bands associated also with downwards and duskward propagation of deformation of auroral band for the period of auroral breakup, as obtained by AKASOFU (1963).

The maximum intensity of the variation in the flash group around midnight is due to the maximum annihilation effect there, expectable from the maximum field intensity and the maximum sheet current intensity around the midnight meridian.

The second group comes mainly from the trapping region. The overlapping of the second group with the first around the midnight meridian suggests that the flux corresponding to the first group may be the source of the flux responsible

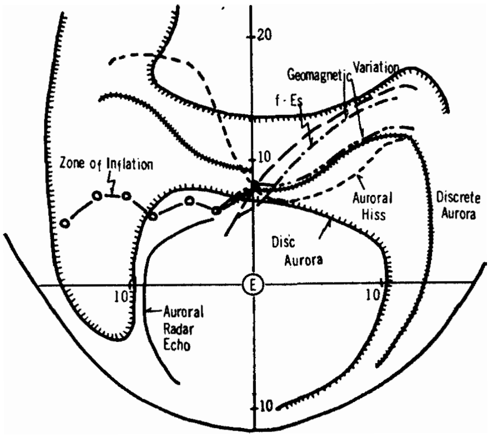

Fig. 10(a). The area around the magnetospheric equatorial plane where originates the electron precipitation of flash group.

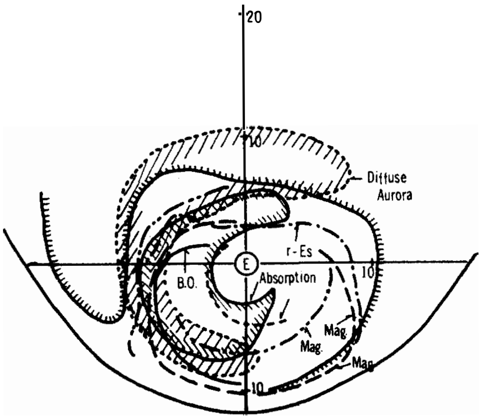

Fig. 10(b). The magnetosphere region corresponding to the precipitation of electron responsible for quasi-steady group.

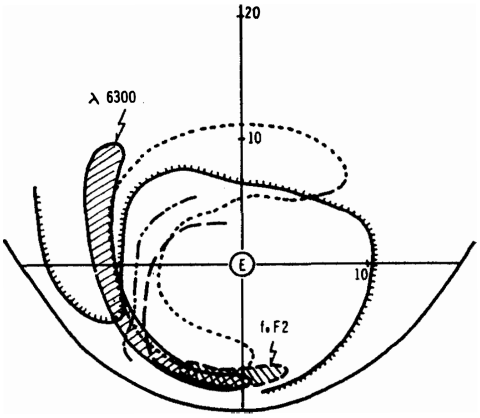

Fig. 10(c). The magnetosphere area corresponding to noon high latitude group.

for the second group. As a result of the field annihilation, some flux, may be brought into the trapping orbit, drifting eastward, and it may cause a maximum activity of the second group on the dawn side. The scantiness of the disturbances in dusk along the second pattern would be due to the scantiness of responsible particles and partially due to the inefficiency of the precipitation mechanism there.

The change in the kind of VLF emission at the auroral breakup, from auroral hiss before the breakup to the auroral chorus after the breakup (MOROZUMI, 1965) would be explained that the hiss corresponds to the plasma in the open field region, while the chorus corresponds to the plasma in the closed region (trapping region). After the breakup, as a result of the field annihilation and accordingly as a result of the decrease in the tail field, the open-close boundary (near inflated region) shifts outward. Therefore, the ground station at an appropriate latitude, situated in the open field region before breakup, abruptly brought forth to the closed field region after breakup, showing a rapid change of VLF emission from hiss to chorus.

The dawn-dusk asymmetry of corpuscular invasion into the geomagnetic cavity is seen also in plasma experiment of model magnetosphere (FUKUSHIMA and KAWASHIMA, 1965). Although, this experimental result is not likely to correspond to the dawn-dusk asymmetry in real geomagnetic cavity, since the similarity low is not valid at the points of mean collision distance and the gyration radius of particles, it still strongly suggests the possibility of asymmetrical invasion of changed particles into the real magnetosphere.

The third group, inferred from its position and the time of its occurrence, corresponds probably to the direct corpuscular invasion through the neutral regions. The soft spectrum of the energy resulting in the variation in the *F* region would be ascribed to the fact that the flux is not effectively accelerated, since it comes directly from the transient region of geomagnetic cavity, in contrast with the flux responsible for the first and the second groups which probably is subject to an appreciable amount of acceleration.

Acknowledgements

The author wishes to express his hearty thanks to Prof. T. NAGATA for his constant encouragement throughout this study. The author is also indebted to all of his colleagues for their valuable discussion and comments.

References

AKASOFU, S.I.: The dynamical morphology of the aurora polaris. J. Geophys. Res., **68**, 1667–1673, 1963.

ANDERSON, K. A.: Energetic electron fluxes in the tail of the geomagnetic field. J. Geophys. Res., **70**, 4741–4763, 1965.

ANDERSON, K.A. and R. DEWITT: Space-time association of auroral glow and X-rays at balloon altitude. J. Geophys. Res., **68**, 2669–2675, 1963.

ANDERSON, K. A. and D. C. ENEMARK: Balloon observation of X-rays in the auroral zone. J. Geophys. Res., **65**, 3521–3538, 1960.

ANDERSON, K. A. and D. W. MILTON: Balloon observations of X-rays in the auroral zone. 3. High time resolution studies. J. Geophys. Res., **69**, 4457–4479, 1964.

AXFORD, W. I. and C. D. HINES: A unifying theory of high latitude geophysical phenomena and geomagnetic storms. Canad. J. Phys., **39**, 1433–1463, 1961.

BARCUS, J. R., R. R. BROWN and T. J. ROSENBERG: The spatial and temporal character of fast variations in auroral zone X-rays. J. Geophys. Res., **71**, 125–141, 1966.

BROWN, R. R., J. R. BARCUS and N. R. PARSONS: Balloon observations of auroral zone X-rays in Conjugate regions. J. Geophys. Res., **70**, 2579–2612, 1965.

CAMPBELL, W. H. and H. LEINBACH: Ionospheric absorption at times of auroral and magnetic pulsations. J. Geophys. Res., **66**, 25–34, 1961.

CAMPBELL, W. H. and M. H. REES: A study of auroral coruscations. J. Geophys. Res., **66**, 41–55, 1961.

CURRIE, B. W., T. A. FORSYTH and F. E. VAWTER: Radio reflections from aurora. J. Geophys. Res., **58**, 179–200, 1953.

FELDSTEIN, Y. I. and E. K. SOLOMATINA: Geographycal distribution of aurora in the southern hemisphere. J. Phys. Soc. Japan, **17**, Suppl. A-1, 223–224, 1962.

FUKUSHIMA, N. and N. KAWASHIMA: Model experiment and natural phenomenon of interaction of solar plasma stream with geomagnetic field. Rep. Ionos. Space Res. Japan, **18**, 377–393, 1964,

HARANG, L.: The mean field of disturbance of polar geomagnetic storms. Terr. Mag., **51**, 353–380, 1946.

JOHANSEN, O. E.: Variations in energy spectrum of auroral electrons detected by simultaneous observation with photometer and riometer. Sci. Rep. Norwegian Def. Res. Board, 1964, and Planet. Space Sci., **13**, 225–235, 1965.

KANEDA, E., S. KOKUBUN, T. OGUTI and T. NAGATA: Auroral radar echoes associated with Pc-5 magnetic pulsation. Rep. Ionos. Space Res. Japan, **18**, 165–172, 1964.

KASUYA, I.: Statistical study on the ionosphere in the polar regions. Proc. WWSC Symp., Nice, Dec., 1961.

LASSEN, K.: Geographical distribution and temporal variations of polar aurora. Publ. Dct Damske Met. Inst., No. **16**, 1963.

LEONARD, S.: Distribution of radar auroras over Alaska. Univ. Alaska Sci. Rep., NSF Grant No. Y/22. 6/372, 1961.

McILWAIN, C. E.: Direct measurements of particles producing visible auroras. J. Geophys. Res., **65**, 2727–2747, 1960.

MEEK, J. H.: Correlation of magnetic, auroral and ionospheric variations at Saskatoon. J. Geophys. Res., **58**, 445–456, 1953.

MONTALBETTI, R. and D. J. McEWEN: Hydrogen emissions and sporadic *E* layer behaviour. J. Phys. Soc. Japan, **17** Suppl. A–I, 212–215, 1962.

MOROZUMI, H. M.: Diurnal variation of auroral zone geophysical disturbances. Rep. Ionos. Space Res. Japan, **19**, 286–298, 1965.

NAGATA, T. and E. KANEDA: An inter-relation between auroral luminosity and simultaneous geomagnetic disturbances. Rep. Ionos. Space Res. Japan, **16**, 410–414, 1962.

NAGATA, T. and T. OGUTI: Inter-relation between geomagnetic disturbances and aurorae during the July 1959 events at Syowa Station, Antarctica. Rep. I. U. G. G. Symposium, Helsinki, 1960.

NESS, N. F., C. S. SCEARCE, J. B. SEEK and J. M. WILCOX: A summary of results from the IMP-1 magnetic field experiment, X-612, 65–180, Goddard Space Flight Center, 1965.

Oguti, T. and T. Nagata: Interrelations among the upper atmosphere disturbance phenomena in the auroral zone. Rep. Ionos. Space Res. Japan, **15**, 31–50, 1961.

Oguti, T.: Geomagnetic bay disturbance and simultaneous increase in ionospheric absorption of cosmic radio noise in the auroral zone. Rep. Ionos. Space Res. Japan, **17**, 291–301, 1963.

Oguti, T.: Spriral pattern of the polar aeronomical disturbances. Rep. Ionos. Space Res. Japan, **16**, 363–386, 1962.

Oguti, T. and K. Marubashi: Enhances ionization in the ionospheric F2 region around geomagnetic noon in high latitudes. Rep. Ionos. Space Res. Japan, **20**, 96–100, 1966.

Omholt, A.: The auroral E-layer ionization and the auroral luminosity. J. Atmos. Terr. Phys., **7**, 73–79, 1955.

Ortner, J., B. Hultqvist, R. R. Brown, T. R. Hartz, O. Holt, B. Landmark. J. L. Hook and H. Leinbach: Cosmic noise absorption accompanying geomagnetic storm sudden commencements. J. Geophys. Res., **67**, 4169–4186, 1962.

Parthasarathy, R. and F. T. Berkey: Radio noise from the auroral electrons. J. Atmos. Terr. Phys., **26**, 199–203, 1964.

Romick, G. J.: Catalogue of HUET auroral spectra, Contract Nonr 1289(00). Univ. Alaska Sci. Rep., No. **2**, 1963.

Rosenbarg, T. J.: Observation on the association of auroral luminosity with auroral X-rays and cosmic noise absorption. J. Atmos. Terr. Phys., **27**, 751–759, 1965.

Sandford, B. P.: Aurora and airglow intensity variations with time and magnetic activity at southern high latitudes. J. Atmos. Terr. Phys., **26**, 749–769, 1964.

Sato, T.: Long period geomagnetic oscillations in southern high latitudes. Rep. Ionos. Space Res. Japan, **18**, 173–187, 1964.

Taylor, H. E. and E. W. Hones, Jr.: Adiabatic motion of auroral particles in a model of the electric and magnetic field surrounding the earth. J. Geophys. Res., **70**, 3605–3628, 1965.

Tohmatsu, T. and T. Nagata: Energy and flux of copuscluar streams impinging the earth's atmosphere. Rep. Ionos. Space Res. Japan, **14**, 301–319, 1960.

Twiss, R, Q. and J. A. Roberts: Electromagnetic radiaton from electrons rotation in an ionized medium under the action of a uniform magnetic field. Aust. J. Phys., **11**, 424–446, 1958.

Winkler, J. R. and L. Petersen: Large auroral effect on cosmic-ray detectors observed at 88/cm^2 at Minneapolis. Phys. Rev., **108**, 903–904, 1957.

Winkler, J. R., P. D. Bhavsar and K. A. Anderson: A study of the precipitation of energetic electrons from the geomagnetic field during magnetic storms. J. Geophys. Res., **67**, 3717–3736, 1962.