Kato, Y.: Usually in lower or middle latitude the *pc* pulsations last several hours in the most active stage, but I think it needs not so strict definition as lasting for several hours. Actually I defined the activity of the pulsation as follows.

Activity=(the period of duration)×(the maximum range of the oscillations) and the period of duration is divided into four ranks, that is

if it lasts	10—15 minutes	. . . . . . put it rank	1
〃	15—30 〃	. . . . . 〃	2
〃	30—45 〃	. . . . . 〃	3
〃	45—60 〃	. . . . . 〃	4

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II-1B-6. Hydromagnetic Waves in the Earth's Exosphere and Geomagnetic Pulsations

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In the first place the qualitative discussion on the physical characters in the exosphere are given. Using the propagation equation of hydromagnetic waves (HM-waves) in the particular coordinates and assuming Johnson's model of the exosphere, refractive indices for downward propagation of external HM-waves with specified period and wave length in the lower latitudes are obtained as a function of altitudes. It is shown that HM-waves propagating to the perpendicular direction to lines of force will be reflected at the particular level corresponding to their period, and a part of their energy will be transported into the lower region (higher latitudes) by means of transverse waves propagating parallel to the line of force through this level. It is suggested that primary sources of daytime continuous pulsations are attributed to large amplitude HM-disturbances in the outermost exosphere as found by Sonett *et al.* Since these disturbances may have considerable wide band width of spectrum, $T \simeq 1$ sec$\sim 3\times10^2$ sec, observed characteristics of daytime pulsations at the surface will be explained in terms of the filtering effect of the dispersive inner exosphere. It is also suggested that damped type pulsation, *pt*'s, may be caused by the hydromagnetic compression of the local hot gas in the outer exosphere near the equatorial plane in the dark hemisphere, and this compression will occur as a result of the precipitation of trapped energetic electrons from this local region to the auroral zone.

§ 1. Physical State in the Exosphere

After Sonett *et al.*[1)-3)], we may have the following configuration of the magnetic field in the space surrounding the earth during the relatively undisturbed period, remembering that geocentric distances between the respective subregion will vary with rise and fall of the solar stream.

(I) $r/r_0 \leqq 5$; the magnetic cavity with the dipole field.

(II) $5 \leqq r/r_0 \leqq 7$; the gross deviation of the field from the dipolar form, solar energetic particle trapped, and there is the diamagnetic ring current.

(III) $7 \leqq r/r_0 \leqq 10$; the weak disturbed region, the ordered field exists.

(IV) $10 \leqq r/r_0 \leqq 14$; the intense disturbed region (the outermost exosphere), there are short period fluctuations of the field with the maximum cut off frequency of 1 c/s and their magnitude of intensity is about $1\sim1.5$ times the stationary field.

(V) $r/r_0 \geqq 14$; the steady interplanetary space with the field of about 2.5γ.

Observed short period fluctuation in the outermost exosphere should be interpreted as HM-disturbances caused by the interaction between the solar stream and the geomagnetic field[4]. The physical process involved is essentially of non-linear character (say hydromagnetic turbulence) and their detailed investigation is impossible at present. Considering the diffusive penetration of solar protons into this disturbed region, the minimum scale of field inhomogeneity is of the order $a \simeq 10^7$ cm[5]. With the observed maximum cut off frequency of $f_c \simeq 1$ c/s, the effective velocity of disturbances is $V_g \simeq a f_c^{-1} \simeq 10^7$ cm/sec. Then, the minimum and the maximum time scale of HM-disturbances in the outermost exosphere are approximately $T_{min} \simeq f_c^{-1} \simeq 1$ sec and $T_{max} \simeq L V_g^{-1} \simeq 3 \times 10^2$ sec, respectively, where L is the dimension of the outermost exosphere.

§ 2. Propagation of Hydromagnetic Waves in the Exosphere and Daytime Continuous Pulsations.

If disturbances generated within the outermost exosphere penetrated into the weak disturbed region wherein the ordered field exists, transmitted energies will be transported to the lower region by means of HM-waves with periods of respective external disturbance. However there are some obstacles for the arrival of these disturbances to the earth's surface. Absorption of wave energy in the hydromagnetic range will be of two parts, the Joule dissipation and the phase mixing absorption process near the cyclotron frequency[6]. The former is negligible except in the ionospheric region for the periods considered. While the latter is important in the outer exosphere, particularly for higher frequencies. For example, the attenuation distance of the plane wave propagating normal to lines of force is about 2×10^8 cm at the frequency of 1 c/s, if we consider the following circumstance, the wave length in the direction of lines of force is 10^7 cm, the field strength of 10^{-4} gauss and the temperature and the concentration of the plasma are 10^4 °K and 10^2 particles/cm^3, respectively. Since this attenuation distance is much smaller than the dimension of the gross deviating region ($\simeq$ 2 earth radii), it is likely that the disturbance with the minimum scale cannot be penetrated into the inner exosphere.

In addition to two dissipating processes mentioned above, there is a dispersive, anisotropic character for the propagation of HM-waves with the wide band spectra in the non-uniform exosphere. If the frequency of disturbances is much smaller than the Larmor frequency of ions and the gas pressure of the medium is exceedingly small compared with the magnetic pressure as in the inner exosphere, there are two modes of HM-waves. Here we call them the transverse and the isotropic waves, respectively, according to Grad[7]. Energy flux of the former is only transported along the lines of force, while the latter propagates isotropically in all directions. These two modes are in general coupled each other except in the axisymmetric case.

Taking the dipolar coordinates system (ξ, η, φ), we can obtain the general propagation equations of HM-waves in the nonuniform exosphere under the dipole magnetic field. In axisymmetric case these equations become to two separate ones corresponding to the transverse and the isotropic waves, respectively, and it is easily shown that there is no reflection of transverse waves propagating parallel to lines of force. In the region near the geomagnetic equatorial plane, we can approximately reduce the general propagation equations into the more simple form and the expression of the square of the refractive index, μ, for the propagation in the perpendicular direction to lines of dipole field is obtained. If we assume the formal dependence on $e^{i(\omega t + m\varphi)}$ for the solution, μ is a function of ξ, ω, m and χ, where χ represents the dimension of waves in the direction of lines of force in the unit of earth's radius.

Assuming Johnson's theoretical model[8] for the distribution of ions in the exosphere above 600 km altitudes, the distribution of the velocity of HM-waves, V_A, is obtained and shown in Fig. 1. It seems that variation of V_A with altitudes is appreciable within the wavelength of waves with the period of several tens of seconds and application of the

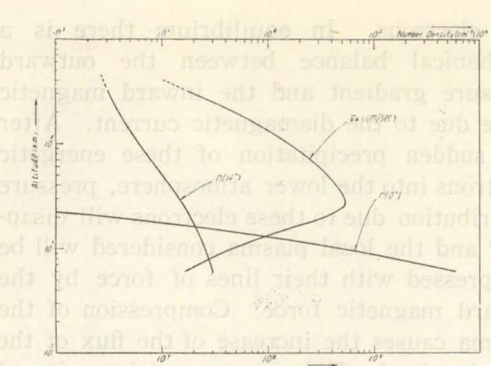

Fig. 1. Variations of Alfvén wave speed, V_A, of concentrations of O^+ and of H^+ with altitudes.

ray-path theory is impossible.

Using values of V_A thus obtained, we calculate numerically the distribution of μ with altitudes for several HM-waves with the specified period and χ. The results are shown in Figs. 2 and 3. For axisymmetric waves ($m=0$) the distribution of μ is relatively simple, while we have complicated oscillatory pattern in the non-axisymmetric ones ($m=1$). In the latter case which is the coupling mode between the transverse and the isotropic waves, there are singular levels of μ on which μ becomes infinity when the period exceeds the critical value. It is shown that these singularities disappear if we introduce effects of the compressibility and of the Hall current,

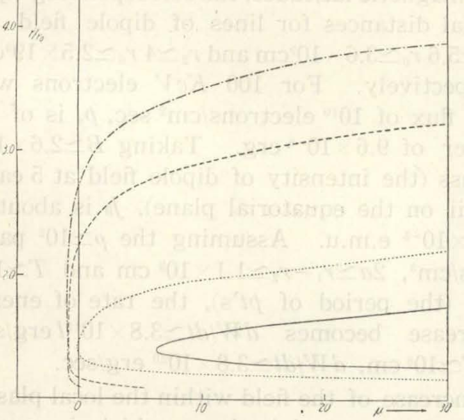

Fig. 2. Square of the refractive index *vs.* altitudes for axisymmetric waves with $m=0$ and $\chi=1.0$.

————————	period of 1 sec.
....	period of 20 sec.
— — — — — —	period of 120 scc.
—.—.—.—.—	period of 300 sec.

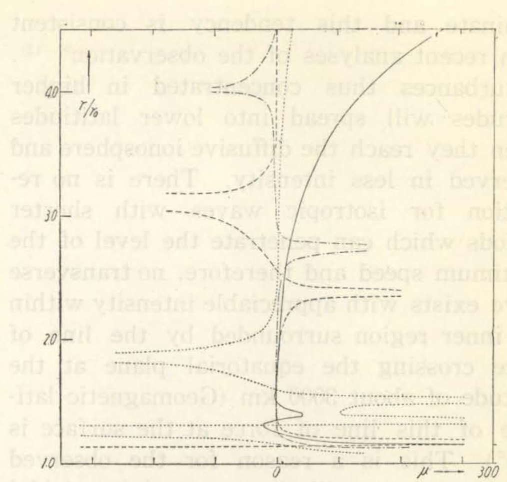

Fig. 3. Square of the refractive index *vs.* altitudes of non-axisymmetric waves. with $m=1$ and $\chi=1.0$.

————————	period of 1 sec.
....	period of 20 sec.
— — — — — —	period of 120 sec.
—.—.—.—.—	period of 300 sec.

and resulting values of μ at these levels become negative finite. External HM-waves propagating downwards with the period and the dimension, χ, being larger than corresponding values, cross the zero level of μ from the positive to the negative sides at first and reach the level of negative infinity. The region wherein μ becomes negative is the attenuation region and since no dissipative effect is introduced here, attenuation must be interpreted as a reflection of the incident wave at the critical level. Considering the transmission of waves in the the x-direction through the barrier of $\mu=a^2-(b/x)^2$, it is easily seen that waves are totally reflected at the level of $x=0$ ($\mu=-\infty$). Referring to this result, external non-axisymmetric waves will be totally reflected at the critical level corresponding to their period and dimension, and the part of their energy will be transported to lower region (higher latitudes) by means of waves propagating parallel to lines of force through this level. If χ is specified, the level of the reflection becomes higher with increase of period. From this behaviour of propagation of HM-waves in the exosphere we have the following expectation concerning the general character of pulsations at the surface that the latitude is higher, pulsations of longer period predominate and this tendency is consistent with recent analyses of the observation[9)-12)]. Disturbances thus concentrated in higher latitudes will spread into lower latitiudes when they reach the diffusive ionosphere and observed in less intensity. There is no reflection for isotropic waves with shorter periods which can penetrate the level of the maximum speed and therefore, no transverse wave exists with appreciable intensity within the inner region surrounded by the line of force crossing the equatorial plane at the altitude of about 3000 km (Geomagnetic latitude of this line of force at the surface is 34.5°). This is a reason for the observed character that oscillations are mainly poloidal in the middle and the the lower latitudes, while in higher latitudes torsional oscillations are included with the appreciable intensity. There is also a possibility that HM-waves with the special period will be strengthened by a kind of resonance effect in the lower exosphere as was suggested by Watanabe[13)].

§ 3. The Night Time Pulsations, *pt*.

Concentration of occurrence frequencies of damped type pulsations, *pt*'s, near the local midnight can not be understood in terms of HM-waves generated by the solar stream in the daylight side. *pt*'s are damped type oscillations with the duration of several minutes and often appear at the begining or in the developing stage of geomagnetic bay's. The latitudinal distribution of intensity of *pt*'s accompanied with the negative bay in the auroral zone has a strong maximum within the region with geomagnetic latitudes of 60°～65°[10)-12)]. Characteristics of *pt*'s mentioned above suggest to us that *pt*'s are phenomena associated with the precipitation of energetic particles to the night time auroral zone.

According to Akasofu and Chapman[14)], polar magnetic disturbances (geomagnetic bays in lower latitudes) are caused by the precipitation of trapped energetic electrons with the energy of 100 Kev and the flux of 10^{10} cm^{-2} sec^{-1} to the night time auroral zone. If these energetic electrons are trapped locally in the outer exosphere, the intensity of the magnetic field in this local region should be less than that for the surrounding region due to the diamagnetic effect of trapped electrons. In equilibrium there is a mechanical balance between the outward pressure gradient and the inward magnetic force due to the diamagnetic current. After the sudden precipitation of these energetic electrons into the lower atmosphere, pressure contribution due to these electrons will disappear and the local plasma considered will be compressed with their lines of force by the inward magnetic force. Compression of the plasma causes the increase of the flux of the field involved. This increase of intensity of the field is equivalent to the current which flows in the reverse direction to the original diamagnetic current and resulting magnetic force becomes outward. Thus, there is a possibility of the excitation of HM-waves associated with the disappearance of energetic electrons from the trapped region. If energetic electrons were trapped within the cylinder of the radius a and of the length $2l$ immersed in the uniform background plasma with the density of ρ under the axial field $\boldsymbol{B}$, the rate of energy increase associated with the compression of this cylinder is approximately $dW/dt \simeq 2\pi a l B^2 J_\theta^2 T\ (1-8\pi p_e B^{-2})/\rho r_e$, where T is the time scale for the compression, p_e and r_e are pressure and the Larmor radius of trapped energetic electrons, respectively, and $J_\theta \simeq (B/4\pi)\ [1-(1-8\pi p_e B^{-2})^{1/2}]$ is the intensity of the surface diamagnetic current. When the precipitation zone covers from 65° to 60° geomagnetic latitudes, the corresponding equatorial distances for lines of dipole field are $r_1 \simeq 5.6\ r_0 \simeq 3.6\times 10^9$cm and $r_2 \simeq 4\ r_0 \simeq 2.5\times 19^9$cm, respectively. For 100 KeV electrons with the flux of 10^{10} electrons/cm^2 sec, p_e is of the order of 9.6×10^{-8} erg. Taking $B\simeq 2.6\times 10^{-3}$ gauss (the intensity of dipole field at 5 earth radii on the equatorial plane), J_θ is about of 4.2×10^{-5} e.m.u. Assuming the $\rho \simeq 10^2$ particles/cm^3, $2a \simeq r_1 - r_2 \simeq 1.1\times 10^9$ cm and $T\simeq 10^{-2}$ sec (the period of *pt*'s), the rate of energy increase becomes $dW/dt \simeq 3.8\times 10^{12} l$ erg/sec. If $l \simeq 10^8$ cm, $dW/dt \simeq 3.8\times 10^{20}$ erg/sec.

Increase of the field within the local plasma near the equatorial plane, which is caused by the compression of this region associated with the disappearance of diamagnetic particles, will be transported into the lower region as HM-waves propagating parallel to lines of force through the compressed region. Current vortices will be generated within the lower ionosphere in the auroral zone in both hemispheres by the arrival of these waves. Leakage currents from the vortex will cause magnetic disturbances in the lower and the higher latitudes. Schematic representation for this circumstance is shown in Fig. 4. Disturbance vectors of the field in the region far distant from the vortex arrange as if they were converged to the vortex center in the northern hemisphere, on the other hand the situation becomes the reverse in the southern hemisphere. These behaviours are consistent with the observational result[15]. The rate of total dissipation of energy for *pt*, confined within the volume in the night time hemisphere between the surfaces of revolution of lines of force with latitudes of

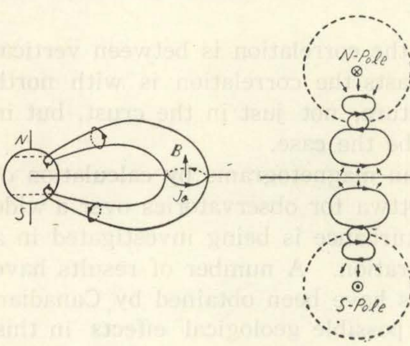

Fig. 4. Schematic representation of the vortex current system associated with the compression of the local hot gas in the outer exosphere. In the right figure, linear arrows stand for the disturbance horizontal vector of magnetic field at the earth's surface.

65° and 60°, is about 2.4×10^{19} erg/sec if the mean amplitude and damping time of *pt* are 100 γ and 300 sec, respectively. This is smaller than the rate of energy increase associated with the compression.

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