ELECTRODYNAMICS OF THE IONOSPHERE

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Abstract. We review various important studies in the field of electrodynamics of the ionosphere. Four topics are presented; (1) conductivity, (2) wind and the dynamo theory, (3) drift and its effect on the ionosphere formation and (4) interaction between wind and electromagnetic field.

We point out some important future problems. They are: (1) We need to consider in the dynamo theory of the geomagnetic daily variation the connection of the ionosphere of both hemispheres by lines of force of the geomagnetic field. (2) Non-periodic wind may be important for producing electric field. (3) Drift to cause interchange of ionization contained in tubes of the geomagnetic field lines, and diffusion of ionization in these tubes control dynamic behaviours of the F2 region. (4) Interaction between wind and electric current presents a new problem. (5) The ionosphere and the magnetosphere react to each other.

1. Introduction

1.1 History

Schuster analysed the geomagnetic daily variation in the light of Gauss's potential theory and proved that this variation originates from an external source. He developed Stewart's suggestion that this source is in a region in the upper atmosphere where electric current flows and produces this variation. The discovery of the ionosphere almost confirmed the existence of such conductive region, and Chapman and others further developed this idea and established the dynamo theory of the solar quiet and lunar daily variations (S_q and L respectively). This dynamo theory (e.g. CHAPMAN and BARTELS, 1940) propounds that the wind of the region traverses the geomagnetic field and induces an electromotive force, thereby causing electric current responsible for the geomagnetic S_q or L variation. This is the same principle as that of a dynamo and hence bears its name. The development of this theory required, beside measurements of the region now identified with the ionosphere, theoretical study on the electric state of ionized gas.

Such requirement has also occurred in a more practical way, as the study on radio wave transmission through the ionosphere. We have thus met with the establishment of the magneto-ionic theory of Appleton-Hartree's (e.g. RATCLIFFE, 1959) which has elucidated the motion of charged particles, especially of electrons in ionized gases under the influence of electromagnetic fields of radio waves and the geomagnetic field. In the magneto-ionic theory, by diminishing wave frequencies, we arrive at a quasi-stationary state which is met in the S_q or L variation.

However, only difference exists between situations in the magneto-ionic theory and those in the dynamo theory. This is the motion of ions which acquire a negligibly small velocity from radio wave field, but play important parts in the frequency range less than the gyrofrequency of ions.

Recent progress of hydromagnetics has shed light on such intermediate regions (between magneto-ionic theory and dynamo theory) and we now can solve various problems on a wider scale of time and space in electrodynamics of the ionosphere. It seems timely therefore that we review the past achievements in this field and know our present situation. We may find that some problems classically solved revive in the new world or need more precise treatment.

1.2 Basic concepts

The dynamo theory above mentioned teaches that the air moves with the velocity **V**, inducing the dynamo field $(\mathbf{V} \times \mathbf{B}_0)$ ($\mathbf{B}_0$ = geomagnetic flux density). Strictly, **V** is the mass velocity of the medium, but in the lower ionosphere **V** is approximately equal to the neutral particle velocity because of predominantly numerous neutral particles over charged ones. This induction field $(\mathbf{V} \times \mathbf{B}_0)$ drives electric current **J** which will satisfy the relation

$$\operatorname{div} \mathbf{J} = 0 . \tag{1}$$

Equation (1) is approximately valid to such an extent that the displacement current can be neglected. Note that we cannot put div $\mathbf{E}=0$ (**E** = electric field), though the electrical neutrality is a highly correct approximation in other relations; a surprisingly small deviation from this neutrality produces a strong electric field (e.g. Alfvèn, 1950). The electric current **J** is related to $(\mathbf{V} \times \mathbf{B}_0)$ as

$$\mathbf{J} = [\sigma] \, (\mathbf{E} + \mathbf{V} \times \mathbf{B}_0) , \tag{2}$$

where $[\sigma]$ is the conductivity tensor.

We may interpret (2) thus that $(\mathbf{V} \times \mathbf{B}_0)$ sets up a static field **E** to satisfy (1) ($\mathbf{E}'$ is usually called the total field), or (2) is the relation between electric current and the electric field transformed (Lorentz transformation) to a system moving with **V** i.e. $\mathbf{E}' = \mathbf{E} + \mathbf{V} \times \mathbf{B}_0$. Equation (2) is valid as far as $[\sigma]$ can be defined i.e. as far as the total number of collisions of all charged particles in a volume small compared with the total volume of the gas is statistically large (Piddington, 1955); even in a very rarefied gas as met with in space physics, this is accepted on many occasions.

We find that two quantities $[\sigma]$ and **V** govern the phenomenon and constitute the main subjects of our concern, appearing in Sections 2 and 3 respectively.

Charged particles move not only along **J** but in the direction perpendicular to it i.e. along $(\mathbf{J} \times \mathbf{B}_0)$. Velocity component along $(\mathbf{J} \times \mathbf{B}_0)$ should be equal for both electrons and ions, because otherwise **J** will exist along it. This velocity component is named neutral ionization drift (Martyn, 1953). Physical implication of this drift motion was discussed firstly by MARTYN (1953), who showed that the Ampère force $(\mathbf{J} \times \mathbf{B}_0)$ balances with the frictional force upon collisions of charged particles with quasi-stationary neutral particles. It has been revealed that this motion tremendously affects the ionosphere, and is explained in Section 4.

The balance between $(\mathbf{J} \times \mathbf{B}_0)$ and the frictional force is lost increasingly rapidly with height because neutral particles decrease in density with height and are easily affected by the motion of charged particles. In other words that the Ampère force

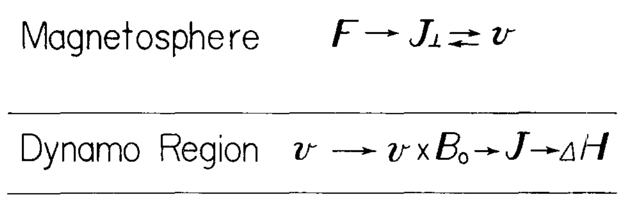


Fig. 1. Electrodynamic state of the ionosphere. **F** denotes a mechanical force, Δ**H** the geomagnetic variation and $\mathbf{J}_\perp$ the current perpendicular to $\mathbf{B}_0$.

causes a motion of neutral particles, that is, the reaction of charged particles on neutral ones, which is not considered in the dynamo theory. This force is decisive above the F region where, not the electric field, but the mechanical force against $(\mathbf{J} \times \mathbf{B}_0)$ decides **J**. Figure 1 illustrates these situations. Even in the E region we have such situation over a fairly long time scale. The dynamo theory is an approximation to regard this time to be infinitely long in comparison with that characteristic to the S_q and L variations. This new problem will be explained in Section 5.

2. Conductivities

CHAPMAN and COWLING (1939) discussed the conductivity of an ionized gas pervaded by magnetic field. They started with the Boltzman equation. However, we have not yet known the exact solution because of complication of the collision integral. Collisional cross sections are not well known either theoretically or experimentally.

Below we shall give the expression of $[\sigma]$ based on a simple gas kinetic theory. This is only of the first order approximation, but has been proved to be very useful in many applications. If we take a Cartesian coordinate with its x-axis along $\mathbf{B}_0$,

$$[\sigma] = \begin{bmatrix} \sigma_0 & 0 & 0 \\ 0 & \sigma_1 & -\sigma_2 \\ 0 & \sigma_2 & \sigma_1 \end{bmatrix}. \tag{3}$$

In this expression $\sigma_{0,1,2}$ are named parallel, Pedersen and Hall conductivities and given as in emu

$$\left.\begin{aligned}\sigma_0 &= \frac{1}{B_0}\sum_i \left(\frac{n_i\omega_i}{\nu_i}\right) e_i\,,\\ \sigma_1 &= \frac{1}{B_0}\sum_i \left(\frac{n_i\nu_i\omega_i}{\nu_i^2+\omega_i^2}\right) e_i\,,\\ \sigma_2 &= -\frac{1}{B_0}\sum_i \left(\frac{n_i\omega_i^2}{\nu_i^2+\omega_i^2}\right) e_i\,,\end{aligned}\right\} \tag{4}$$

where subscript i denotes the i-th species of charged particles and the summation is carried over all the species of charged particles and e_i = charge ($e_i = -e$ for electrons), $\omega_i = (e_i B_0)/m_i$, ν_i=collision frequency with neutral particles, n_i=density of charged particles, m_i= mass of charged particles. Equation (4) does not consider collision between charged particles. In a lightly ionized gas such as the lower ionosphere, this is valid, but with increasing height this neglection becomes serious. We may improve the situation to some extent by involving this neglected effect in ν_i (MAEDA, H., 1953; MAEDA, K. and MATSUMOTO, 1962).

Equation (4) shows that $\sigma_{0,1,2}$ are dependent on n_i, m_i and ν_i which is a function of neutral particle density. These parameters vary with time and in space, horizontally and vertically; neutral particles change their composition and decrease their number density with height (Figure 2); charged particle consists of electrons and molecular and atomic ions as N_2^+, O_2^+, O^+, O_2^-, O^-, etc. in the E region and lower F region but mainly of electrons and H_e^+ at about 1000 km height and finally electrons and H^+.

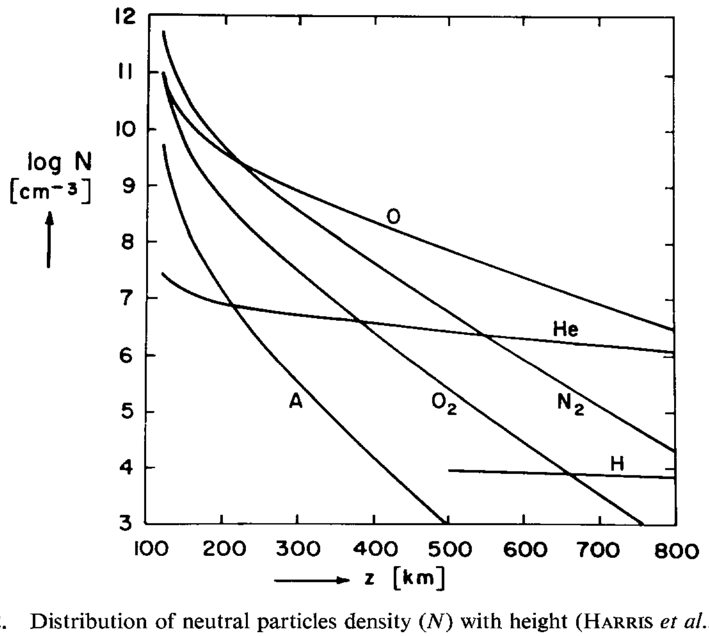


Fig. 2. Distribution of neutral particles density (N) with height (HARRIS *et al.*, 1964).

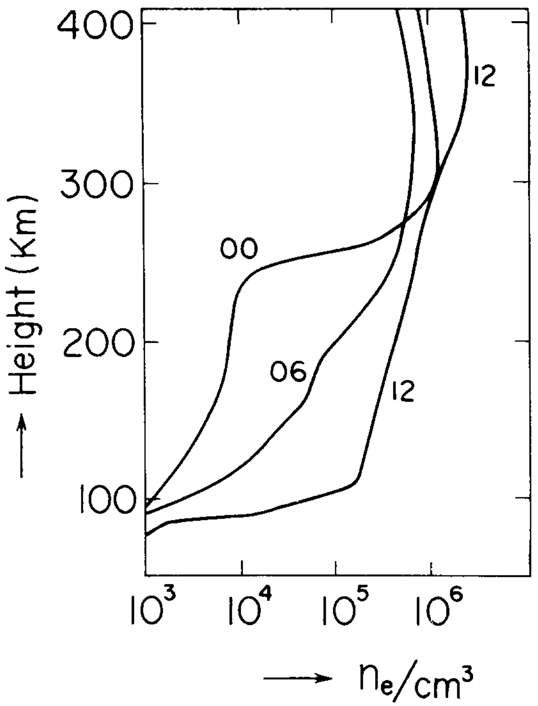


Fig. 3a. Electron density for local time 00 (midnight), 06 (morning), and 12 (noon) after MAEDA and MATSUMOTO (1962).

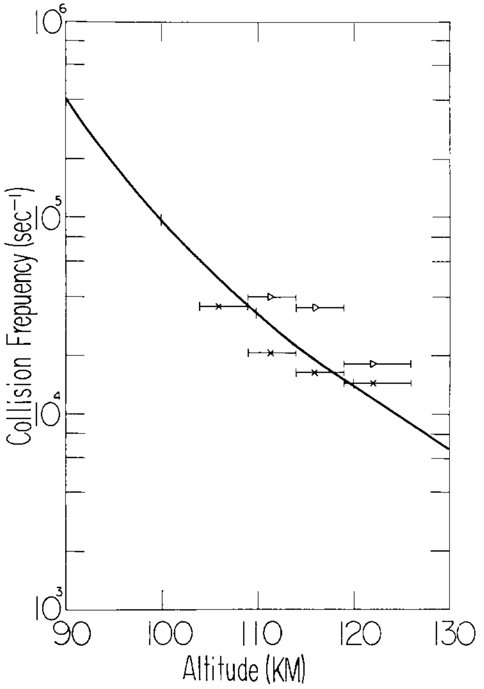


Fig. 3b. Distribution of electron collision frequency after DALGARNO (1961).

This affects m_i in Equation (4). n_i is lower at night than in daytime, save at high latitudes. Figure 3 shows a distribution of electron density (MAEDA, K. and MATSUMOTO, 1962) and their collision frequency (DALGARNO, 1961) representing the state at low and temperate latitudes. Detailed information of the atmospheric parameters is available elsewhere (e.g. HARRIS *et al.*, 1964). Distribution of $[\sigma]$ with height have been calculated with these parameters (MAEDA, K., 1952; FEJER, 1953; BAKER and MARTYN, 1953; MAEDA, H., 1953; CHAPMAN, 1956; MAEDA. K. and MATSUMOTO, 1962) and Figure 4 gives a result of these calculations (MAEDA, K. and MATSUMOTO, 1962).

The result depends on the model of the atmosphere, varying from one to another. But in general $\sigma_{1,2}$ reach the maximum around 140 km and 110 km respectively.

The ionospheric conductivity plays a vital part in the dynamo theory, and whether the conductivity is great enough to explain the geomagnetic S_q and L variations has been one of the controversial subjects throughout the development of the dynamo theory. It is not until recently that this problem has been solved by introducing σ_2 (MARTYN, 1948; HIRONO, 1950ab, 1952, 1953; MAEDA, K., 1952; FEJER, 1953).

We change the coordinates as the x-axis horizontally southward and the z-axis vertically upward. Then from (3) follows the usual tensor transformation as

$$[\sigma] = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}. \tag{5}$$

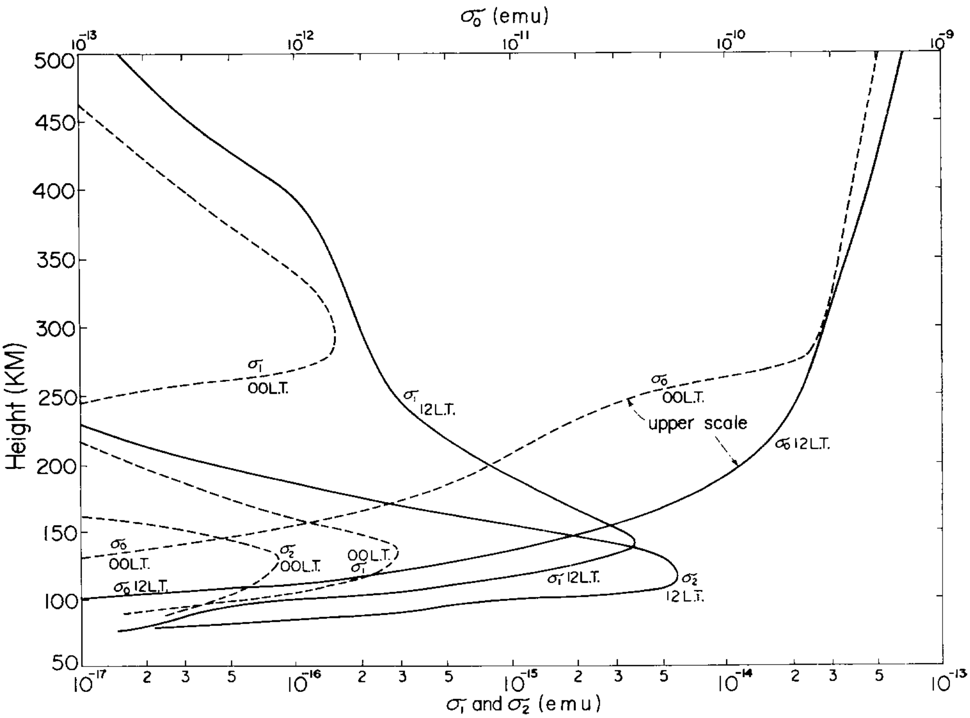


Fig. 4. Electric conductivity for various local time after MAEDA and MATSUMOTO (1962).

A general expression of the tensor elements is given elsewhere (MAEDA, K., 1952). If the geomagnetic coordinates are used i.e. the east-west component of $\mathbf{B}_0$ vanishes, we have

$$\left.\begin{aligned}
\sigma_{xx} &= \sigma_0 \cos^2\phi + \sigma_1 \sin^2\phi\,,\\
\sigma_{xy} &= -\,\sigma_{yx} = \sigma_2 \sin^2\phi\,,\\
\sigma_{xz} &= -\,\sigma_{zx} = (\sigma_0 - \sigma_1)\cos\phi\,\sin\phi\,,\\
\sigma_{yy} &= \sigma_1\,,\\
\sigma_{yz} &= -\,\sigma_{zy} = \sigma_2 \cos\phi\,,\\
\sigma_{zz} &= \sigma_0 \sin^2\phi + \sigma_1 \cos^2\phi\,,
\end{aligned}\right\} \tag{6}$$

where ϕ is the dip angle measured downwards from horizontal.

If the current $\mathbf{J}$ is vertically inhibited,

$$J_z = 0\,, \tag{7}$$

and then

$$\left.\begin{aligned}
J_x &= \overline{\sigma_{xx}} E'_x + \overline{\sigma_{xy}} E'_y\,,\\
J_y &= -\,\overline{\sigma_{xy}} E'_x + \overline{\sigma_{yy}} E'_y\,,
\end{aligned}\right\} \tag{8}$$

where

$$\left.\begin{aligned}
\overline{\sigma_{xx}} &= \frac{\sigma_0\sigma_1}{\sigma_0 \sin^2\phi + \sigma_1 \cos^2\phi}\,,\\
\overline{\sigma_{xy}} &= \frac{\sigma_0\sigma_2 \sin\phi}{\sigma_0 \sin^2\phi + \sigma_1 \cos^2\phi}\,,\\
\overline{\sigma_{yy}} &= \frac{\sigma_0\sigma_1 \sin^2\phi + (\sigma_1^2 + \sigma_2^2)\cos^2\phi}{\sigma_0 \sin^2\phi + \sigma_1 \cos^2\phi}\,.
\end{aligned}\right\} \tag{9}$$

At $\phi=0$ i.e. the magnetic equator, $\sigma_{xx}=\sigma_0$, $\sigma_{xy}=0$ and

$$\overline{\sigma_{yy}} = \sigma_1 + \frac{\sigma_2^2}{\sigma_1}\,, \tag{10}$$

which amounts to approximately 1×10^{-13} emu as the maximum at 110 km during daytime. This enhancement of $\overline{\sigma_{yy}}$ has successfully explained the equatorial electrojet (MARTYN, 1948; HIRONO, 1950 and MAEDA, K., 1952).

Assumption (7) was based, save at $\phi \approx 0$, on a vague inference that $[\sigma]$ is predominantly large only in the lower E region and any vertical current is inhibited by a polarization set-up. However, σ_0 is very large everywhere in an above the ionosphere and any slight field set up along $\mathbf{B}_0$ should dissipate very swiftly (along $\mathbf{B}_0$). This situation presents a new problem in the dynamo theory and little is known as yet (FARLEY, 1959, 1960; MATSUSHITA, 1960; WESCOTT *et al.*, 1963). A recent study has shown that $J_z=0$ is approximately valid, though the total vertical current flowing from one hemisphere to the other is appreciable (MAEDA, K. and MURATA, 1965).

We measure the geomagnetic variation which is due to the spacial integration of electric current by Biot-Savart's law. Until we know enough about the ionospheric wind varying with height, we can only adopt such an approximation that $\mathbf{E}'$ represents the mean total field (given by the theorem of mean value in differential calculus). The total conductivity tensor $[\Sigma]$ is defined by

$$\mathbf{I} = \int \mathbf{J}\, \mathrm{d}z \approx \int [\sigma]\, \mathrm{d}z\, \mathbf{E}'_{z=z_1} = [\Sigma]\mathbf{E}', \tag{11}$$

where $\mathbf{I}$ is the total current and z_1 is a height between the lower and upper limits of the integral. $[\Sigma]$ is given as follows.

$$\begin{aligned} \Sigma_{xx} &= \int \overline{\sigma_{xx}}\, \mathrm{d}z, \\ \Sigma_{xy} &= \int \overline{\sigma_{xy}}\, \mathrm{d}z, \\ \Sigma_{yy} &= \int \overline{\sigma_{yy}}\, \mathrm{d}z. \end{aligned} \tag{12}$$

The height range of the above integrals is practically from about 90 km to 130 km.

The ionosphere changes with time of day and so does its conductivity (Figure 4). We do not well know $[\sigma]$ at night especially in the E region where the dynamo current of the S_q and perhaps the L variations originates. However, the conductivity may decrease at night to $\frac{1}{10}$ of the daytime value or less.

We have seen a very different approach to estimate the ionospheric conductivity. NAGATA (1950) deduced the total conductivity from the geomagnetic variation during the solar flare activity. His estimate was 5×10^{-8} emu. HASEGAWA and MAEDA, H., (1951) and MAEDA, H. (1952, 1956) tried to determine the daily variation of the conductivity from the geomagnetic S_q variation, finding that the conductivity at night would be about $\frac{1}{10}$ of that in daytime. These interesting studies, however, were based on a primitive concept of the conductivity of ionized gas.

3. Ionospheric Wind and the Dynamo Theory

The basic idea of the dynamo theory of the geomagnetic daily variations (e.g. CHAPMAN and BARTELS, 1940) is that $\mathbf{V}$, the wind velocity, causes an electric current responsible for the variations. The cause and the effect are connected simply by $\mathbf{J} = [\sigma]\,(\mathbf{E} + \mathbf{V} \times \mathbf{B}_0)$. $\mathbf{J}$ and $\mathbf{E}$ are required to satisfy the following relations,

$$\begin{aligned} &\mathrm{div}\, \mathbf{J} = 0, \quad \text{(see (1))} \\ &\mathrm{curl}\, \mathbf{E} = 0, \end{aligned} \tag{13}$$

which enable us to know the relation between $\mathbf{V}$ and $\mathbf{E}$, or $\mathbf{V}$ and $\mathbf{J}$:

$$\mathrm{div}\, \{[\sigma]\,(\mathbf{E} + \mathbf{V} \times \mathbf{B}_0)\} = 0, \tag{14}$$

$$\mathrm{curl}\, \{[\sigma]^{-1}\mathbf{J}\} = \mathrm{curl}\, \mathbf{E}' = \mathrm{curl}\, (\mathbf{V} \times \mathbf{B}_0). \tag{15}$$

If either (14) or (15) is solved, the rest is readily obtained from $\mathbf{J} = [\sigma]\,(\mathbf{E} + \mathbf{V} \times \mathbf{B}_0)$.

Measurement of the geomagnetic S_q variations on the ground gives the equivalent overhead current flowing horizontally at a certain height. This sheet current $\mathbf{I} = (I_x, I_y)$

and the geomagnetic variation $\Delta\mathbf{H} = (\Delta H_x, \Delta H_y)$ are approximately related as (e.g. CHAPMAN and BARTELS, 1940)

$$\left.\begin{aligned} I_x &= f\Delta H_y/2\pi ,\\ I_y &= -\, f\Delta H_x/2\pi , \end{aligned}\right\} \tag{16}$$

where f is a fraction of the variation due to external current i.e. in the ionosphere; the rest is due to internal current i.e. inside the earth; $f \approx 0.6$. From the observed geomagnetic variations we can determine the global distribution of $\mathbf{I}$ which is the total current, i.e. the integration of J along height ((11)). Following a strict method of the potential theory, using tesseral harmonics, we can obtain the exact relation between I and ΔH, and hence the exact current system (Figure 5). Equation (11) gives

$$\begin{bmatrix} E'_x \\ E'_y \end{bmatrix} = -\frac{1}{\Sigma_{xx}\Sigma_{xy} + \Sigma_{xy}^2} \begin{bmatrix} \Sigma_{yy} I_x - \Sigma_{xy} I_y \\ \Sigma_{xy} I_x + \Sigma_{xx} I_y \end{bmatrix}, \tag{17}$$

By (17) and (15) we can determine $\mathbf{V}$ (at $z = z_1$ as shown in (11) where z_1 is assumed

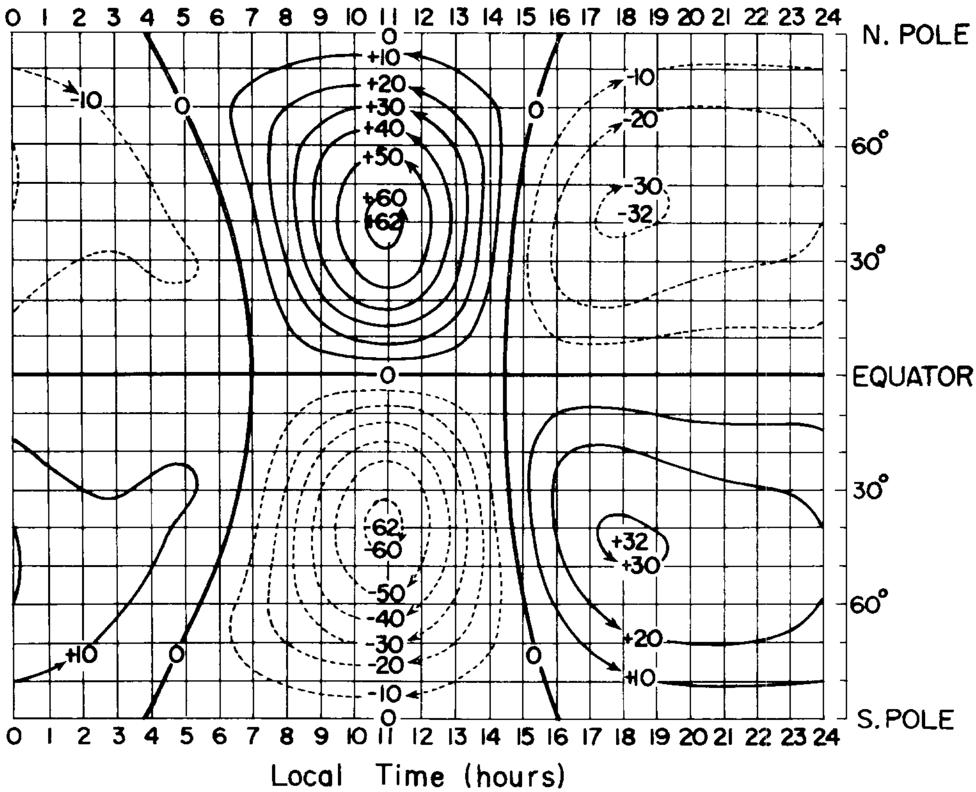


Fig. 5. Electric current systems for the solar daily magnetic variations (S_q) in equinox after CHAPMAN and BARTELS (1940). Between consecutive stream lines 10000 amperes flow in the direction of the arrows.

(a)

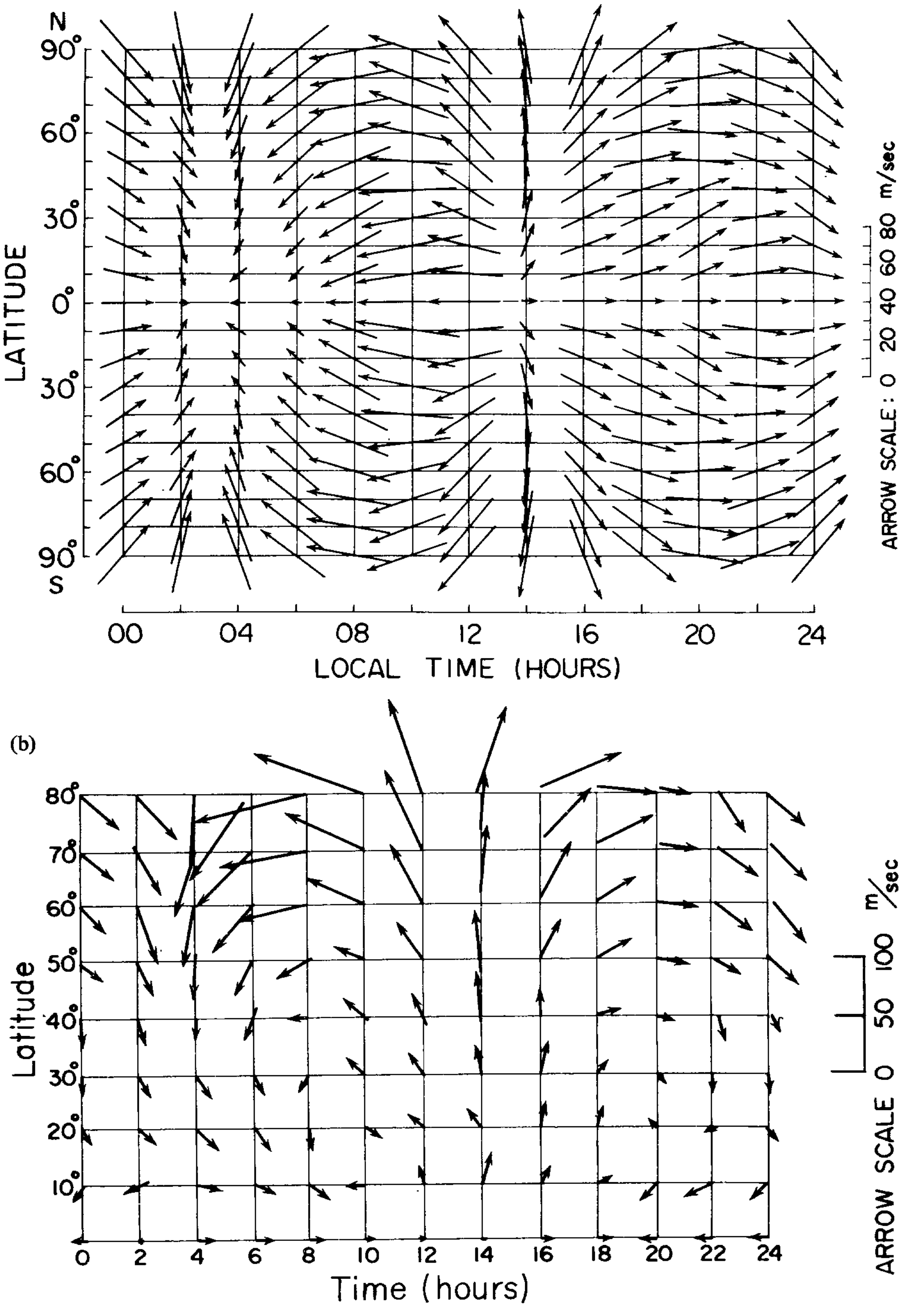


Fig. 6. Wind systems deduced from the geomagnetic S_q variations. (a) curl V = 0 after MAEDA, H. (1957). (b) Both rotational and irrotational motions are considered after KATO (1957).

to be not much different in horizontal direction), and **E** is obtained by subtracting $(\mathbf{V}\times\mathbf{B}_0)$ from **E**′.

If **V** is known from measurement, we can use either (14) or (15) to determine **E** and **J**. Many investigations have been made along this line (e.g. FUKUSHIMA, 1950; BAKER, 1953; FEJER, 1953; MATSUSHITA, 1953; MAEDA, K. and MATSUMOTO, 1962). These results show that a proper combination of the diurnal and semi-diurnal winds can explain observed geomagnetic variations. Measurement of **V** has recently been conducted at several places (GREENHOW *et al.*, 1956; ELFORD, 1959; ELFORD *et al.*, 1964; KANTOR *et al.*, 1964; SMITH *et al.*, 1964), but we are still far from establishing any systematic model of the global pattern of **V**. It is therefore a sounder approach to start, not from **V** as above, but from the geomagnetic daily variations which have been known for many years at many stations all over the world. Nevertheless, not until recently has such an approach been attempted.

In order to determine **V** from (15) we need an additional condition on **V**. Conventionally **V** is assumed to be irrotational i.e. $\mathbf{V}=-\operatorname{grad}\psi$ where ψ is a potential. Rigorously, however, we must use the equation of motion of the atmosphere. The diurnal or semi-diurnal wind contains an appreciable amount of rotational part caused by the Colioris force affecting strongly such wind motion. These complicated problems were treated by MAEDA, H. (1955, 1957), KATO (1956, 1957), HIRONO *et al.* (1956) and HIRONO, MAEDA, H. and KATO (1959). The results are given in Figures 6a and 6b. One of the results is that the diurnal wind motion predominates over the semi-diurnal one. This is an important result, because if the wind is of tidal origin, the semi-diurnal component was expected to be greater by considering its resonance amplification in the upper atmosphere (e.g. WILKES, 1949). However, the wind deduced from the S_q variation indicated the importance of the diurnal wind which is very probably excited thermally. This problem has recently been discussed in detail (MACDONALD, 1963; KATO. 1965b). We readily know that if energy enough to produce temperature variation of a few degrees K is available, **V** attains several tens of meters $\sec^{-1}$.

Measurement has detected, beside the periodic wind such as diurnal and semi-diurnal one, a prevailing wind blowing constantly in direction and magnitude over a fairly long period, though changing seasonally. This is mainly along the east-west direction (ELFORD *et al.*, 1959; KANTOR *et al.*, 1964). It is interesting to examine possible effects of this wind on the geomagnetic variations. If the rotation axis of the earth coincides with that of the geomagnetic dipole and **V** is constant with height, we readily expect that $\mathbf{E}+\mathbf{V}\times\mathbf{B}_0=0$ and hence $\mathbf{J}=0$ provided no vertical leakage of the current occurs (KATO, 1957b). But the variation of **V** with height results in inducing **J**, which amounts to a fairly large value in some cases (VAN SABBEN, 1962) as shown in Figure 7. A similar situation may occur if the discrepancy between the rotation axis and the magnetic dipole axis is considered. Even if $\mathbf{E}+\mathbf{V}\times\mathbf{B}_0=0$, we expect an interesting effect on the magnetosphere: **E** penetrates there along the geomagnetic field lines and causes motion which is a new problem to be pursued.

In measuring **V** in the ionosphere by some radio wave methods we trace the

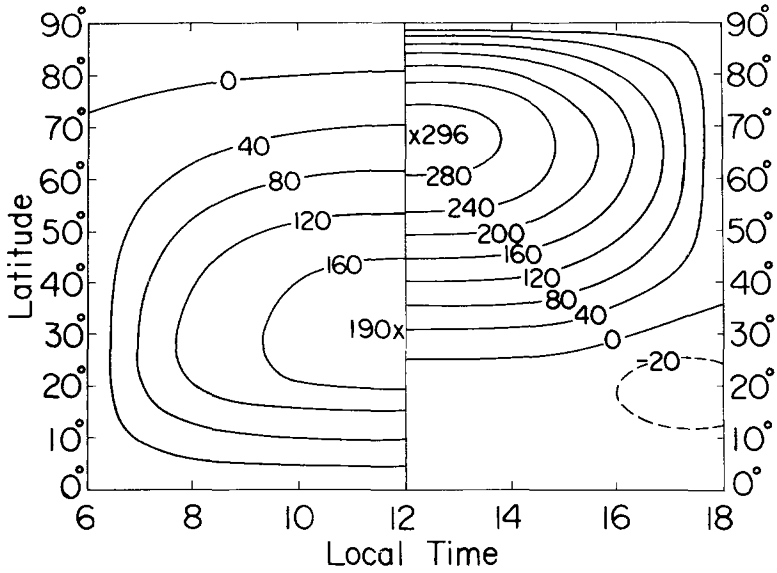


Fig. 7. Electric current due to non-periodic wind after VAN SABBEN (1962). The right half gives current systems caused by a meridional wind which is independent of longitude and height but dependent on latitude. The left half gives current systems caused by a zonal wind. For reasons of symmetry only the afternoon part (for the right half) or the forenoon part (for the left half) is shown. The number on each curve (stream line) is the relative value of current function. The current flowing along the region bounded by two curves is given by the difference of the two numbers corresponding to these two curves. The left half shows a considerable resemblance to the S_q variation (Fig. 5).

movement of ionization irregularity (e.g. SKINNER *et al.*, 1962; OSBORNE *et al.*, 1963), which is produced by meteors (e.g. ELFORD, 1959) or other particles bombarding the atmosphere, or sporadic **E** clouds (BOWLES *et al.*, 1962). Below 90 km the difference between **V** and the velocity of ionization irregularity is small, but becomes appreciable with increasing height (WEEKES, 1957). It is known (KATO, 1963, 1964 and 1965a) that (weak) irregularity moves relatively to neutral particles with the following velocity **C**.

$$\mathbf{C} = \frac{\mathbf{J} \times \mathbf{B}_0 - \left(\frac{\sigma_2}{\sigma_1}\right) B_0 \mathbf{J}_\perp}{\sum_i n_i m_i \nu_i}, \tag{18}$$

where the term proportional to $(\mathbf{J} \times \mathbf{B}_0)$ is $\mathbf{V}_d$ (see (20)), and the other is a wave velocity. This wave velocity amounts to a few hundred meters sec^{-1} if

$$\frac{\sigma_2}{\sigma_1} \approx 10$$

(Figure 8), and around 100 km height approximately equals the component of the

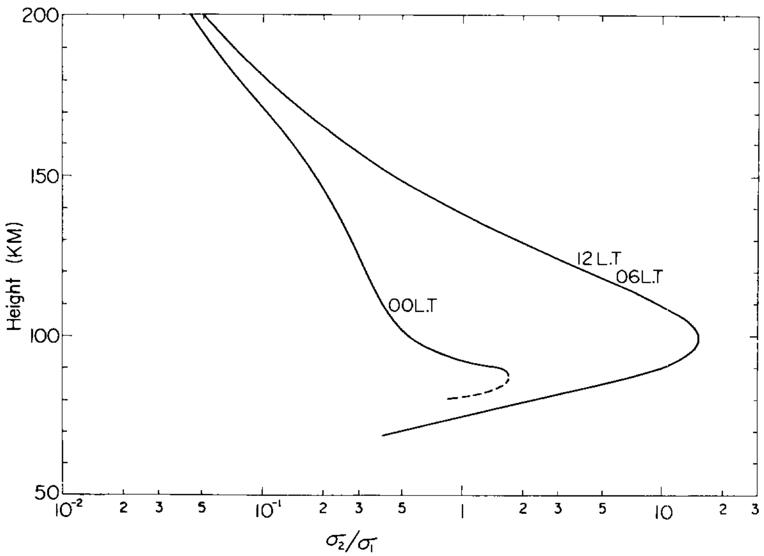


Fig. 8. σ_2/σ_1 for day- and night-time (after MAEDA and MATSUMOTO, 1962).

electron velocity along $\mathbf{J}_\perp$ which is

$$-\frac{\sum_i (\nu_i/\omega_i)\, B_0\, \mathbf{J}_\perp}{\sum n_i m_i \nu_i} \tag{19}$$

because

$$\sum_i \left(\frac{\nu_i}{\omega_i}\right) \approx \frac{\sigma_2}{\sigma_1}.$$

Therefore we may determine from $\mathbf{C}$ (irregularity movement in the dynamo layer) $\mathbf{E}'$ which is a fascinating possibility to be explored. With further increasing height, $\mathbf{C}$ tends to $\mathbf{V}_\mathrm{d}$ (see (20)).

4. Ionization Drift and Its Effects on the Ionosphere Formation

Charged particles move *relative to neutral particles* in the direction of $(\mathbf{J} \times \mathbf{B}_0)$ with the following velocity

$$\mathbf{V}_\mathrm{d} = \frac{\mathbf{J} \times \mathbf{B}_0}{\sum n_i m_i \nu_i}. \tag{20}$$

The velocity $\mathbf{V}_\mathrm{d}$ is common to all kinds of charged particles, arising under the balance between the Ampère force $(\mathbf{J} \times \mathbf{B}_0)$ and the collisional friction force $\sum n_i m_i \nu_i \mathbf{V}_i$ with neutral particles, which is taken to be at rest. We call this motion the (ionization) drift after MARTYN (1953) who discussed the importance of $\mathbf{V}_\mathrm{d}$ in the ionospheric motion. By Ohm's law (2) and conductivity relation (4), we express (20) in terms of $\mathbf{E}'$ and other parameters as n_i, v_i, $\omega_{e,i}$. In the F region we can adopt the following simple relation.

$$\mathbf{V}_d = \frac{\mathbf{E} \times \mathbf{B}_0}{B_0^2}, \tag{21}$$

or

$$\left.\begin{aligned} V_{dx} &= -\frac{E_y}{B_0} \sin\phi, \\ V_{dy} &= \frac{E_x}{B_0} \sin\phi, \\ V_{dz} &= \frac{E_y}{H} \cos\phi, \end{aligned}\right\} \tag{21'}$$

$\mathbf{V}_d'$ depends only on electrostatic field perpendicular to $\mathbf{B}_0$ which is almost constant along the geomagnetic field lines in the ionosphere; we can estimate $\mathbf{E}$ in the F region from that in the dynamo region; $\mathbf{E}$ in the dynamo region is known from the geomagnetic daily variation on the ground (see (16)), by solving the dynamo equation as explained in Section 3. As seen from (20) and (21) $\mathbf{V}_d$ is determined by geomagnetic field $\mathbf{B}_0$ at each point and, as the most important point, by $\mathbf{J}$ or electric field $\mathbf{E}$, thus relating the charged particle motion in the ionosphere closely to the geomagnetic variations. Figure 9 is the result of such calculation of $\mathbf{V}_d$ in the F region. As this is based on the Second Polar Year's data of the S_q variation, this $\mathbf{V}_d$ is for a quiet sun period.

This drift transports charged particles, affecting the distribution of the electron density of the ionosphere. MAEDA, K. (1953, 1954, 1955) discussed the F_2 region variation near the magnetic equator, finding that $\mathbf{V}_d$ during daytime causes the region to rise and its density to decrease. Later HIRONO and MAEDA, H. (1954) discussed the same problem, successfully explaining various characteristics of the region, even such detailed points as the two maxima of f_0F_2, one before and the other after noon, varying their relative magnitudes with the solar activity. This geomagnetic control of the F_2 region indicates the importance of electrodynamic effects on the ionosphere variation (Figure 10).

Another important work is the attempt to explain along similar but very simple lines the equatorial anomaly of the F_2 region by DUNCAN (1960) following MARTYN's suggestion (1955). Ionization produced in the F region near the magnetic equator is lifted perpendicularly to $\mathbf{B}_0$, but eventually falls down by the action of gravity along the geomagnetic field lines, thus piling up around point about 15 degrees in latitude away from the magnetic equator. This produces the well-known equatorial dip of the f_0F_2 (e.g. MITRA, 1952). BAXTER (1964) developed a similar theory and obtained the latitude distribution of the layer for various values of the drift. Recent result of the topside sounder satellite Alouette has shown that to the south and the north of the magnetic equator the electron density of the F_2 region at a given height attains the

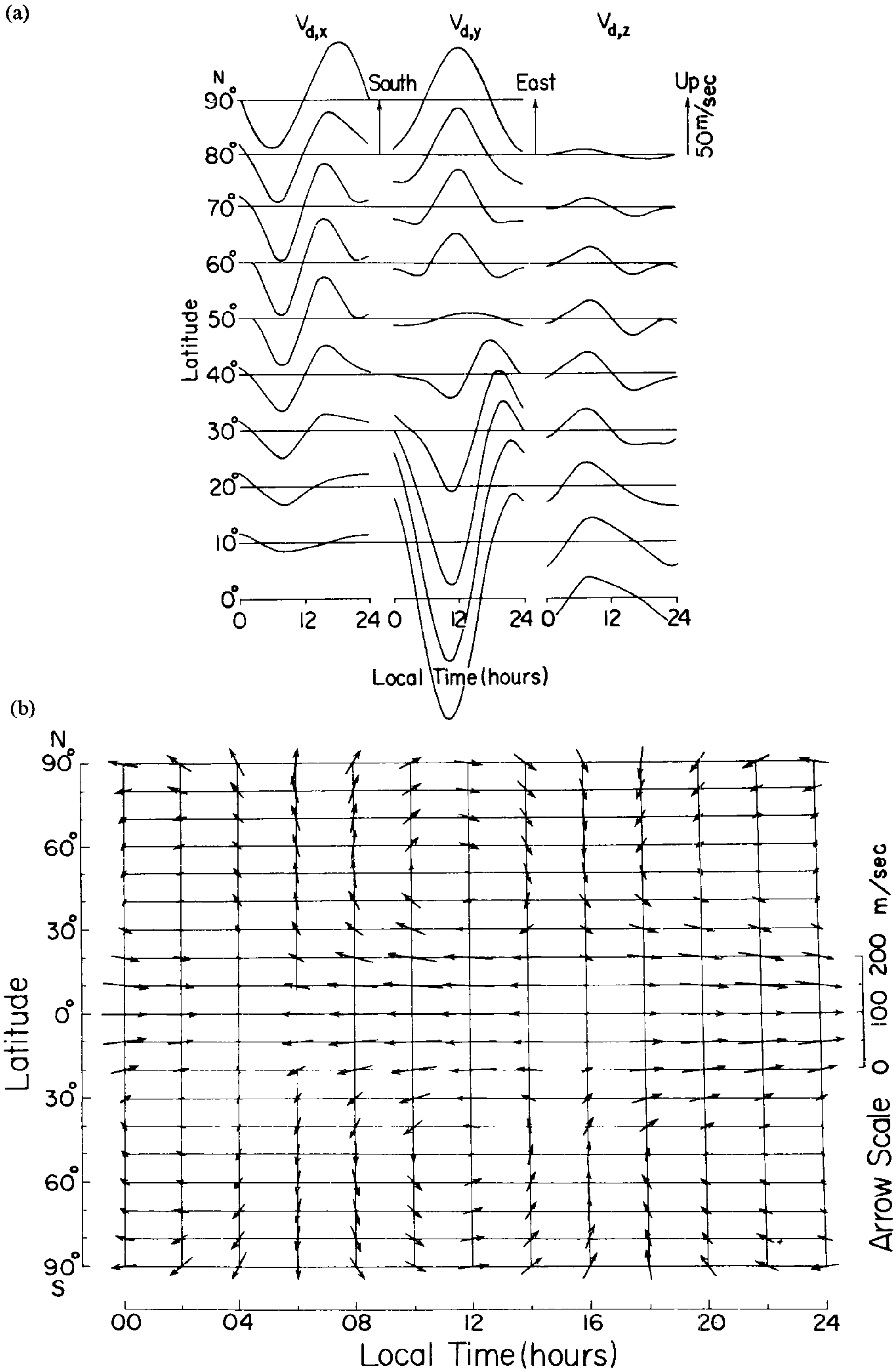
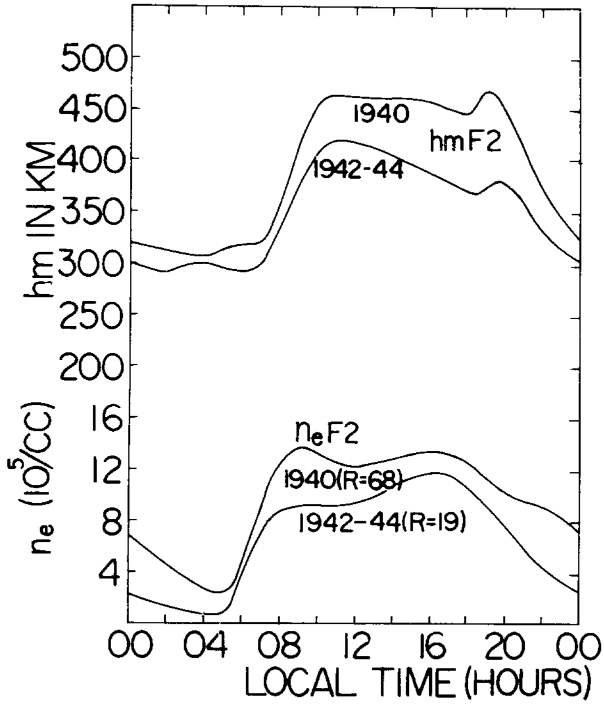
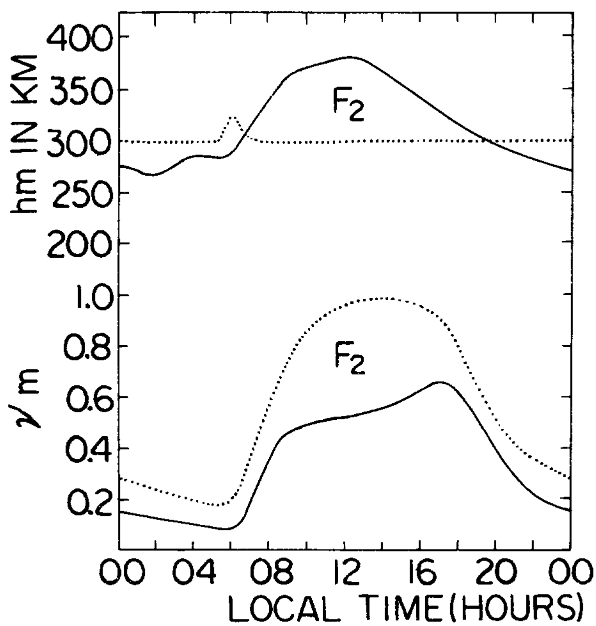


Fig. 9. Electrodynamic drift (V_d) in the F region after MAEDA, H. (1962). (a) Daily variation at various latitudes. (b) Global pattern of the horizontal component.

(a)


500
450
400
350
300
250
200
hm IN KM
1940
hmF2
1942-44
16
12
8
4
n_e (10^5/CC)
n_eF2
1940(R=68)
1942-44(R=19)
00 04 08 12 16 20 00
LOCAL TIME (HOURS)

(b)


400
350
300
250
200
hm IN KM
F_2
1.0
0.8
0.6
0.4
0.2
ν m
F_2
00 04 08 12 16 20 00
LOCAL TIME (HOURS)

(c)

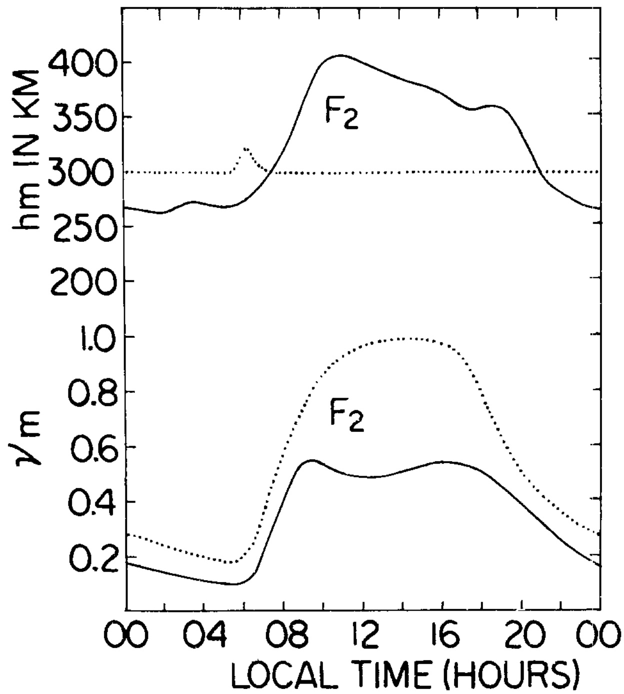


Fig. 10. Geomagnetic distortion of the F2 region on the magnetic equator after MAEDA, H. (1954). (a) Observed daily variations of the maximum n_e and h_m (the height of the maximum n_e) at Huancayo in years of different sunspot numbers; each curve carries the numbers showing its period and relative sunspot number (R) for that period.
(b) and (c) Calculated daily variations for smaller and larger sunspot numbers. n_e is measured relatively to the noon value of n_e for $V_d = 0$ and denoted by ν_m. The dotted curves are those for which $V_d = 0$ and only ion production and loss process (proportional to density) are considered. Each sold curve is the result for a given amplitude and phase of V_d. Comparison of the observed and calculated results shows that proper amplitude and phase of V_d can well explain the observed characteristic.

maximum along the field line which passes through height of about 600 km at the magnetic equator (Figure 11). This measurement can be favourably interpreted by the upward drift during daytime and also HIRONO'S estimate (1955) showing that above 600 km diffusion prevents ionization from being lifted by V_d. Beside these variations under quiet conditions, V_d has shown to explain to some extent the morphology of the F_2 region during disturbed time (MAEDA, K., 1953; SATO, 1956; MAEDA, K., and SATO, 1959).

The geomagnetic control of the distribution of ionization arises also from the ambipolar diffusion of ionization only along the field lines. This effect is appreciable, as discussed by many workers, e.g. MARTYN (1956), DUNCAN (1956), YONEZAWA (1955, 1959) and RISHBETH *et al.* (1963). The diffusion and V_d should be altogether taken into account in determining the ionization distribution of the F_2 region, which requires complicated numerical integration of the equation of continuity. A stationary state due to these two combined effects was discussed, as mentioned above, by BAXTER (1964). SHIMAZAKI (1964) discussed the combined effects of diffusion and vertical drift on the night time variations of the F_2 region. A physical picture of the process is

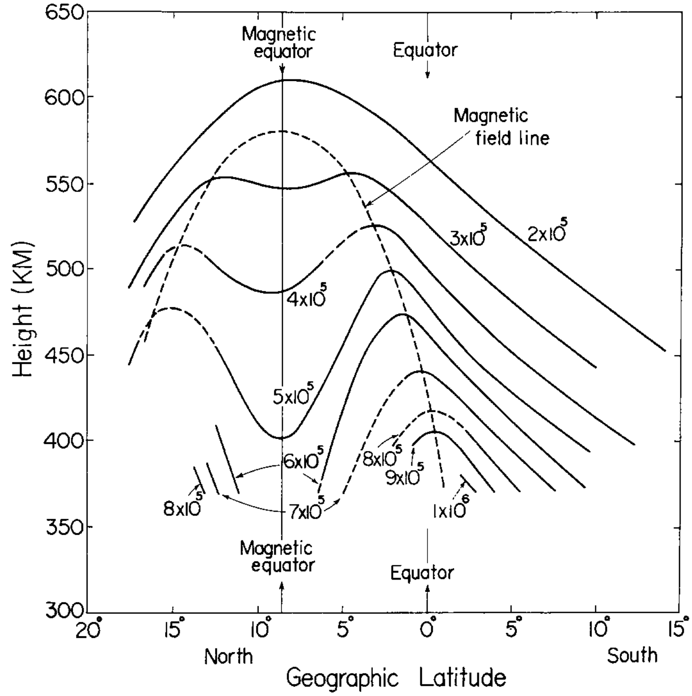


Fig. 11. Distribution of n_e measured by Alouette's topside sounder. The F2 dip disappears above 600 km. Each curve is an equidensity line with n_e (cm^{-3}) given by the number.

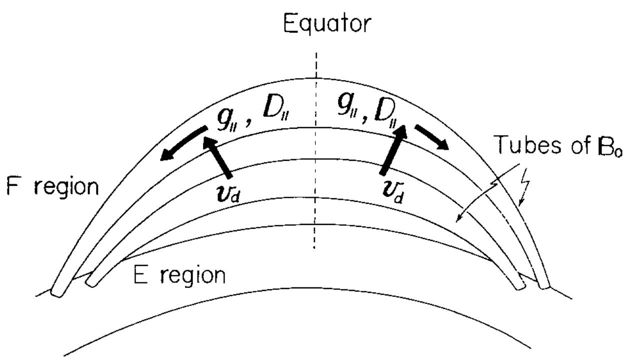


Fig. 12. Schematic concept of drift $\mathbf{V}_d$ and diffusion along $\mathbf{B}_0$. $\mathbf{D}_{\parallel}$ shows force produced by the pressure gradient along $\mathbf{B}_0$ and $\mathbf{g}_{\parallel}$ the gravity along $\mathbf{B}_0$.

fairly simple and clear: $\mathbf{V}_d$ ((20)) interchanges with time the ionization in a given tube of the field lines with that in another tube; in these tubes diffusion tends to establish (hydrostatic) equilibrium of ionization (Figure 12).

In the E region $\mathbf{V}_d$ can only slightly affect the density distribution, because of quick recombination of charged particles. SHIMAZAKI (1959) tried to deduce from measured density those variations which are produced by movement including the above drift. He found that these variations are not very small.

5. Interaction Between Wind and Electromagnetic Field

This topic contains many unsettled problems and we cannot discuss them in detail in this review paper. They belong to the future.

As was explained briefly in Section 1.2, in the lower region the motion of neutral particles is not influenced by that of charged particles which is less than 10^{-5} times of neutral particles in number. This situation, however, changes with increasing height. We now start with the following equation.

$$\rho \frac{d\mathbf{V}}{dt} = \mathbf{J} \times \mathbf{B}_0 + \rho \mathbf{F}, \tag{22}$$

where ρ = density of the plasma and $\mathbf{F}$ = non-electromagnetic force per unit mass.

$\mathbf{V}$ in (22) is the velocity representing plasma motion. In stationary state, (22) gives

$$\mathbf{J}_\perp = \frac{\rho(\mathbf{F} \times \mathbf{B}_0)}{B_0^2}, \tag{23}$$

where subscript $_\perp$ shows components perpendicular to $\mathbf{B}_0$. Equation (23) shows that electric current perpendicular to $\mathbf{B}_0$ is determined by non-electromagnetic force. This is very different from the dynamo theory of S_q. If $\mathbf{F}_\perp = 0$, then $\mathbf{J}_\perp = 0$. Then, by Ohm's law (2), $(\mathbf{E}_\perp + \mathbf{V} \times \mathbf{B}_0) = 0$. The microscopic picture for this situation is that all particles move the same way, except thermal random motion. We see that no matter how large, $[\sigma]$ may be, $\mathbf{J}_\perp$ vanishes. This point must be taken into consideration, when we discuss such a question as where electric current flows in the ionosphere.

However, such a completely stationary state is a limiting case and the time constant to approach this limit, t_0 is (BAKER and MARTYN, 1953; PIDDINGTON, 1955)

$$t_0 = \frac{\rho}{\sigma_1 B_0^2}. \tag{24}$$

Figure 13 illustrates t_0 with height.

In the S_q variation we concern such a long period as diurnal or semi-diurnal. We realize from Figure 13 that above 140 km as far as $\mathbf{F}_\perp = 0$, $\mathbf{E}_\perp + \mathbf{V} \times \mathbf{B}_0 = 0$ and hence $\mathbf{J}_\perp = 0$. If $\mathbf{F}_\perp \neq 0$, the current of (23) may flow. Such $\mathbf{F}_\perp$ may be the gravity or pressure variations produced by thermal expansion due to ultraviolet absorption or joule heating. Such forces deform the magnetic field lines and produce current by curl $\mathbf{B} = 4\pi J$ ($\mathbf{B}$ = magnetic flux density).

In faster variations we expect that current may flow in higher regions as known from Figure 13.

If $\mathbf{E}_\perp$ is applied from outside the ionosphere, what may happen? This is an important question in considering the interaction between the ionosphere and magneto-

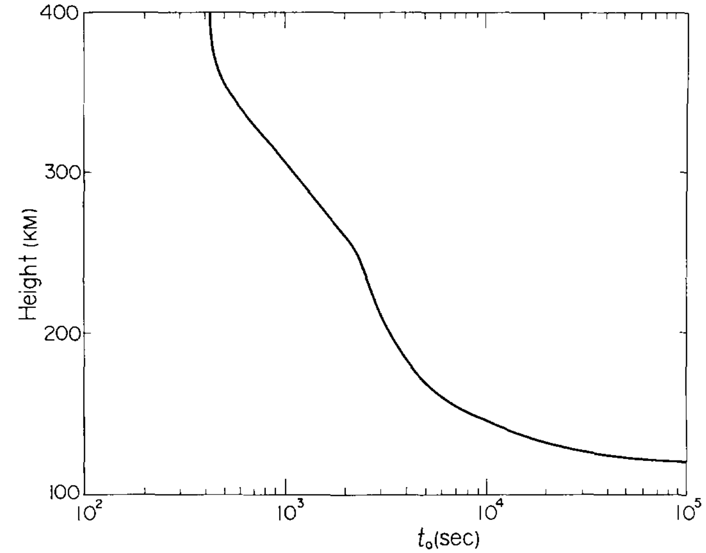


Fig. 13. Time constant tending to the stationary state in plasma (t_0) when an electric field is applied.

sphere or further outer regions. This produces $\mathbf{J} = [\sigma]\,\mathbf{E}$ which in turn induces $\mathbf{V}$ by $\mathbf{J} \times \mathbf{B}_0$ as in (22). Then, $(\mathbf{V} \times \mathbf{B}_0)$ transforms $\mathbf{E}$ and $\mathbf{J} = [\sigma]\,(\mathbf{E} + \mathbf{V} \times \mathbf{B}_0)$. Polarization field or induction $\partial \mathbf{B}/\partial t$ further complicates the situation, and hampers us in tracing exactly the chain of the cause and effect. We only point out that on a transient stage a fluctuating component in $\mathbf{J}_\perp$ and $\mathbf{V}_\perp$ appears which depends on σ_2 (PIDDINGTON, 1955). In the course of this process the system generates joule heat which may damp out any free motion in the magnetosphere in less than 10 sec (COLE, 1963). It is worth while to reexamine a convective motion of the magnetosphere (GOLD, 1959, 1962; AXFORD and HINES, 1961) along this line.

6. Concluding Remarks

We have reviewed various studies made, and presented those to be made in the field of electrodynamics of the ionosphere. Important future problems in electrodynamics of the ionosphere will be summarized as follows.

Though well established in principle, we now face a new situation in the dynamo theory: that the ionosphere of both hemispheres are electrically connected by high conductive field lines; the condition, $J_z = 0$ is approximately valid, but the total effect of vertical current flowing from one hemisphere to the other is important. The horizontal current system deduced from the measured $\Delta\mathbf{H}$ on the ground may not correspond to reality. We do not yet know much about effects of non-periodic wind upon the ionosphere or the magnetosphere. This presents new problems.

The drift $\mathbf{V}_d$ has proved to be a powerful candidate in interpreting variations of the ionosphere. This interchanges ionization contained in tubes of the geomagnetic field line. We should consider not only this motion at right angles to $\mathbf{B}_0$ but those parallel to $\mathbf{B}_0$ as diffusion.

With increasing height or increasing period of the phenomena, $(\mathbf{J} \times \mathbf{B}_0)$ becomes increasingly important. The motion and $\mathbf{J}$ interacts with each other.

The ionosphere is connected to the magnetosphere by lines of the geomagnetic field force. This connection produces various reactions between both hemispheres.

We stress the importance of measuring the electrical state of the ionosphere and of higher region. Although some experiments have been attempted to detect $\mathbf{J}$ in the dynamo region (Singer *et al.*, 1951; Cahill *et al.*, 1959; Burrows *et al.*, 1964), we are not yet satisfied with the result. Further systematic rocket measurement of the neutral wind in the dynamo region e.g. sodium vapour experiment is highly desirable. These experiments are of paramount importance for the dynamo theory. One of the interesting new methods is to obtain $\mathbf{E}'$ from the movements of irregularities; the data of measurement of this movement is abundant since IGY, and timely for the analysis.

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