A DYNAMO THEORY OF THE AURORA AND MAGNETIC DISTURBANCE*

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[*Manuscript received April* 4, 1960]

Summary

A model of an aurora regarded as a plane slab of highly ionized air parallel to the geomagnetic field within the ionosphere is examined. The model is stable in the presence of a wind of neutral molecules which, blowing the slab across the geomagnetic field, generates an electric polarization field perpendicular to its faces and a current along its length. This current is concentrated in a small height range and is chiefly due to electron drift.

The aurora moves normal to itself with a speed of the same order as the wind speed, while the drift carries its luminosity and ionization pattern along its length at a speed an order of magnitude greater. Measurement of these speeds will permit determinations of collision frequencies of ions and electrons within the aurora.

Assuming, in the equatorial vicinity of the auroral zone, an equatorwards wind in the evening and a polewards wind in the night and morning hours it is possible to explain the major movements of the aurora and associated bay type magnetic disturbances. It is suggested that the magnetic disturbance indices K and K_p are indicators of wind speed. A likely mechanism of maintenance of luminosity and ionization in the aurora is outlined. The general features of magnetic disturbance current systems within the auroral zone are briefly considered in relation to the theory and it is suggested that auroras are visible manifestations of the current flow.

Qualitative speculation on a possible source of energy for winds in the polar dynamo region leads to a unified account of the Van Allen radiation belts, auroras, and some (low latitude) airglow.

I. Introduction

Two parameters are required to define the atmospheric dynamo problem, namely, the conductivity of the ionosphere and the velocity of the wind. The quiet daily variations in the geomagnetic field can be explained in terms of the conductivity of the quiet ionosphere in conjunction with the velocity of wind inferred from atmospheric tidal oscillations (Baker and Martyn 1953). To define a model for the explanation of geomagnetic disturbance one has, in the absence of other criteria, the choice of specifying a disturbed conductivity pattern (Obayashi and Jacobs 1957) and/or a disturbed wind velocity (Maeda 1957).

The present paper does not attempt to explain the world-wide distribution of magnetic disturbance, but rather considers a highly probable local situation. A model of the aurora is defined and its properties examined. These are compared with observational data, especially on large-scale movements of the aurora and associated magnetic disturbance.

* Preliminary accounts of this work were presented at ANZAAS, Perth, August 1959, and at the Antarctic Symposium, Buenos Aires, November 1959.

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Although a one-to-one correspondence has not been established between the luminosity, magnetic, and radar observations of the aurora, these are here treated as aspects of the one phenomenon (Bond 1960) supposed as having the form of the common auroral "arcs" and "bands". These are typically long (thousands of kilometres) compared to their vertical extent (tens to hundreds of kilometres) and to their thicknesses (a few kilometres).

II. Theory

The current density at any point in an ionized gas is given by

$$\mathbf{j}=\sigma_0\mathbf{E}_{||}+\sigma_1\mathbf{E}_{\perp}+\sigma_2(\mathbf{H}\times\mathbf{E}_{\perp})/H, \qquad \ldots\ldots\ldots\ldots \quad (1)$$

where $\mathbf{E}$ is the electric field and $||$ and $\perp$ indicate components parallel and perpendicular to the magnetic field $\mathbf{H}$. σ_0, σ_1, σ_2 are the direct (parallel to $\mathbf{H}$), Pedersen (transverse), and Hall conductivities respectively.

In a lightly ionized gas

$$\begin{aligned}\sigma_0&=Ne^2(1/m_i\nu_i+1/m_e\nu_e),\\ \sigma_1&=Ne^2(t_i+t_e),\\ \sigma_2&=-Ne^2(h_i-h_e),\end{aligned}$$

where N=electron density, e=charge on electron,

$$\begin{aligned}t_{e,i}&=\nu_{e,i}/m_{e,i}(\nu^2_{e,i}+\omega^2_{e,i}),\\ h_{e,i}&=\omega_{e,i}/m_{e,i}(\nu^2_{e,i}+\omega^2_{e,i})\,;\end{aligned}$$

where $\nu_{e,i}$, $\omega_{e,i}$, and $m_{e,i}$ are the collision frequencies (with neutral particles), gyro frequencies, and masses of electrons and ions respectively. The assumption is made that the mobilities t and h are independent of ionization density N.

In general σ_0 is much larger than σ_1 or σ_2; however, our first considerations are restricted to situations in which $\mathbf{E}_{||}$ is zero. Later (in Section III (*b*)) limited consideration is given to the effects of a non-zero $\mathbf{E}_{||}$.

(*a*) *The Model*

(i) *The Steady State*.—Clemmow, Johnson, and Weekes (1955) have examined the motion of a cylindrical irregularity in an ionized medium. We investigate another elementary model now proposed. As with Clemmow, Johnson, and Weekes, dissipative effects such as diffusion and recombination are neglected here.

Given a homogeneous, unbounded, weakly ionized neutral gas with ionization density N (ions) in the presence of uniform and steady orthogonal electric and magnetic fields $\mathbf{E}^0$, $\mathbf{H}$, is there a steady state solution for which an infinite plane slab parallel to H and of ionization density N' (ions) persists in the gas without change of form?

The unit normal ($\mathbf{n}$) outward from the slab makes an angle α with $\mathbf{E}^0$. Rectangular axes $0(x, y, z)$ with unit vectors $\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$, have the directions of $\mathbf{E}^0\times\mathbf{H}$, $\mathbf{E}^0$, and $\mathbf{H}$ respectively (see Fig. 1). The superscript 0 is used for quantities in the undisturbed state in the absence of the slab and the superscript p

for the incremental quantities resulting from polarization charge. The total electric field is $\mathbf{E}^0+\mathbf{E}^p$. The geometry of the model will make $\mathbf{E}^p$ orthogonal to $\mathbf{H}$. Drift velocities of electrons (negative ions are neglected) and positive ions (assumed singly charged) are given, respectively, by

$$\mathbf{v}_e=-e\left(t_e\mathbf{E}_\perp+h_e\frac{\mathbf{H}\times\mathbf{E}_\perp}{H}\right), \quad \ldots\ldots\ldots\ldots \quad (2a)$$

$$\mathbf{v}_i=e\left(t_i\mathbf{E}_\perp-h_i\frac{\mathbf{H}\times\mathbf{E}_\perp}{H}\right). \quad \ldots\ldots\ldots\ldots \quad (2b)$$

A prime is used to indicate quantities inside the slab. Then, if $\mathbf{V}$ denotes the velocity of the faces of the slab, the condition that the electronic and positive

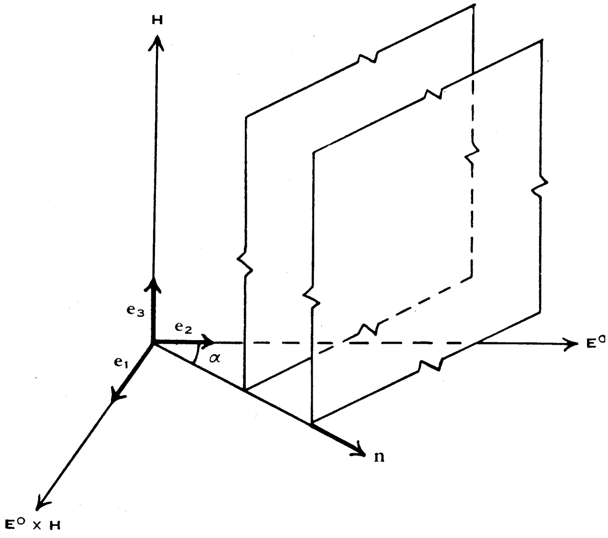

Fig. 1.—Gas between the parallel planes differs in electron density from that of its surroundings. Magnetic field $\mathbf{H}$ is parallel to the planes and orthogonal to $\mathbf{E}^0$ (an applied electric field). $\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$ are unit vectors in the direction of $\mathbf{E}^0\times\mathbf{H}$, $\mathbf{E}^\circ$, and $\mathbf{H}$, and $\mathbf{n}$ is an outward unit normal to the parallel planes.

ion currents should separately be continuous yields two relations which must be satisfied on the surface of the slab, namely,

$$\mathbf{n}.(\mathbf{v}_e^0+\mathbf{v}_e^p-\mathbf{V})N=\mathbf{n}.(\mathbf{v}_e^0+\mathbf{v}_e^{p'}-\mathbf{V})N', \quad \ldots\ldots \quad (3a)$$

$$\mathbf{n}.(\mathbf{v}_i^0+\mathbf{v}_i^p-\mathbf{V})N=\mathbf{n}.(\mathbf{v}_i^0+\mathbf{v}_i^{p'}-\mathbf{V})N'. \quad \ldots\ldots \quad (3b)$$

From equations (2) and (3) it follows that

$$\mathbf{V}.\mathbf{n}=\frac{[\omega_e/\nu_e+\omega_i/\nu_i]eE^0\sin\alpha}{\{(\nu_e^2+\omega_e^2)/\nu_e\}m_e+\{(\nu_i^2+\omega_i^2)/\nu_i\}m_i}. \quad \ldots\ldots\ldots\ldots \quad (4)$$

It is thus shown that a steady state is possible in which the slab does not change form and that this state is independent of electron density either inside or outside the slab.

If $\mathbf{E}^0$ is due to a wind of velocity $-U\mathbf{e}_1$ and δ is the angle between $-U\mathbf{e}_1$ and $\mathbf{n}$, then $\sin\delta = -\cos\alpha$. Then, in a frame of reference moving with the wind,

$$\mathbf{V}.\mathbf{n} = \frac{-(\omega_e/\nu_e+\omega_i/\nu_i)\ U\cos\delta}{\omega_e/\nu_e+\nu_e/\omega_e+\omega_i/\nu_i+\nu_i/\omega_i}. \qquad \text{(5)}$$

Now in the ionosphere $\omega_e/\nu_e > \omega_i/\nu_i$, hence*

$$\mathbf{V}.\mathbf{n} \approx -U\cos\delta/(1+\nu_e\nu_i/\omega_e\omega_i). \qquad \text{(6)}$$

In a frame of reference in which the wind velocity is $\mathbf{U}$ (i.e. a rest frame on the ground) the velocity of the faces is given by

$$V_s = \mathbf{n}.(\mathbf{U}+\mathbf{V}). \qquad \text{(7)}$$

The ratio $V_s/\mathbf{U}.\mathbf{n}$ is plotted in Figure 2 as a function of ω_e/ν_e, assuming with Baker and Martyn (1953) that $(\omega_e/\nu_e).(\nu_i/\omega_i) = 1650$.

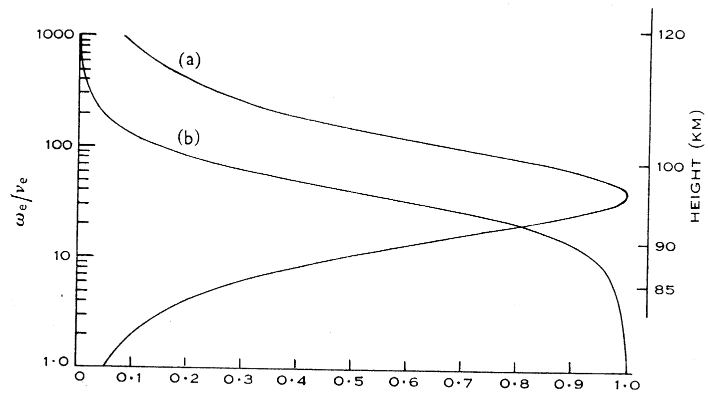

Fig. 2.—Curve (*a*), $(\sigma_2/\sigma_1)/(\sigma_2/\sigma_1)_{\text{max.}}$ as a function of ω_e/ν_e. Note: $(\sigma_2/\sigma_1)_{\text{max.}} \approx 20$. Curve (*b*), $V_s/\mathbf{U}.\mathbf{n}$ as a function of ω_e/ν_e. Height scale is approximate.

(ii) *Current Flow.*—We now investigate the current flowing in the slab. The polarization field will be entirely internal and normal to the slab faces. The rate of accumulation of electrons on a face of the slab is

$$\partial n_e/\partial t = eN'\mathbf{n}.(\mathbf{v}_e^0+\mathbf{v}_e^{p'}-\mathbf{V}) - eN\mathbf{n}.(\mathbf{v}_e^0-\mathbf{V}),$$

whilst the rate of accumulation of positive charge on a face is

$$\partial n_i/\partial t = eN'\mathbf{n}.(\mathbf{v}_i^0+\mathbf{v}_i^{p'}-\mathbf{V}) - eN\mathbf{n}.(\mathbf{v}_i^0-\mathbf{V}).$$

Thus the rate of charge (q) accumulation is

$$\partial q/\partial t = eN'\mathbf{n}.(\mathbf{v}_i^0-\mathbf{v}_e^0+\mathbf{v}_i^{p'}-\mathbf{v}_e^{p'}) - eN\mathbf{n}.(\mathbf{v}_i^0-\mathbf{v}_e^0).$$

* After completion of this work a recent paper by Clemmow and Johnson (1959) came to hand. Equation (**6**) is almost identical with their equation (**61**) for the velocity of propagation of an irregularity.

Now the polarization field $\mathbf{E}^{p'}$ is $-4\pi q\mathbf{n}$, hence

$$(-1/4\pi)\partial E^{p'}/\partial t=(N'-N)e^2(t_i+t_e)E^0\cos\alpha+N'e^2(t_i+t_e)E^{p'}$$
$$+(N'-N)e^2(h_i-h_e)E^0\sin\alpha.$$

Thus,

$$E^{p'}=\frac{N-N'}{N'}E^0\left(\cos\alpha+\frac{h_i-h_e}{t_i-t_e}\sin\alpha\right)[1-\exp\{-4\pi N'e^2(t_i+t_e)t\}].$$

Let us resolve the total current density $\mathbf{j}$ into two components, $\mathbf{j}_n$ normal to the slab and $\mathbf{j}_p$ parallel to the slab in the direction $\mathbf{n}\times\mathbf{H}$. It follows, since $\mathbf{j}=N_e(\mathbf{v}_i-\mathbf{v}_e)$, that

$$j'_n=\sigma_1E^0\cos\alpha-\sigma_2E^0\sin\alpha$$
$$+\sigma'_1\frac{N'-N}{N'}E^0\left(\cos\alpha-\frac{\sigma_2}{\sigma_1}\sin\alpha\right)\exp(-4\pi\sigma'_1t), \quad \ldots\ldots \quad \mathbf{(8a)}$$

$$j'_p=-\sigma'_3E^0\sin\alpha-\sigma_2E^0\cos\alpha+\frac{\sigma_2^2}{\sigma_1}E^0\sin\alpha$$
$$-\sigma'_2\frac{N'-N}{N'}E^0\left(\cos\alpha-\frac{\sigma_2}{\sigma_1}\sin\alpha\right)\exp(-4\pi\sigma'_1t), \quad \ldots \quad \mathbf{(8b)}$$

$$j_n=\sigma_1E^0\cos\alpha-\sigma_2E^0\sin\alpha, \quad \ldots\ldots \quad \mathbf{(8c)}$$

$$j_p=-\sigma_1E^0\sin\alpha-\sigma_2E^0\cos\alpha, \quad \ldots\ldots \quad \mathbf{(8d)}$$

where

$$\sigma_3=\sigma_1+\sigma_2^2/\sigma_1.$$

Thus the exponential time constant for approaching the steady state is $1/4\pi\sigma'_1$. If $\mathbf{E}^0$ arises from a wind with speed U of neutral particles in the direction opposite to $\mathbf{e}_1$, the internal current in the steady state is given by

$$j'_n=\sigma_1UH\sin\delta+\sigma_2UH\cos\delta, \quad \ldots\ldots \quad \mathbf{(9a)}$$

$$j'_p=\sigma'_3UH\cos\delta-\sigma_2UH\sin\delta-\frac{\sigma_2^2}{\sigma_1}UH\cos\delta, \quad \ldots\ldots \quad \mathbf{(9b)}$$

and the polarization field by

$$E^{p'}=\frac{N-N'}{N'}UH\left(\sin\delta+\frac{\sigma_2}{\sigma_1}\cos\delta\right). \quad \ldots\ldots \quad \mathbf{(10)}$$

This polarization field has a maximum (in the case of $N\to0$) of

$$|E^{p'}|_{\max.}=UH\sqrt{(\sigma_3/\sigma_1)} \quad \ldots\ldots \quad \mathbf{(11)}$$

when $\delta=\frac{1}{2}\pi-\tan^{-1}\sigma_2/\sigma_1$. Clearly $|E^{p'}|_{\max.}$ may be much greater than UH, the maximum electrostatic field derivable from the movement of an isotropic conductor across a magnetic field (Alfvén 1950).

(*b*) *Acceleration of Charged Particles*

Under the influence of an electric field $\mathbf{E}$ and magnetic field $\mathbf{H}$, charged particles move in trochoidal paths between collisions. The energies of the particles continually oscillate by virtue of movement to and fro along $\mathbf{E}$. It may be shown from the equations of Chapman and Cowling (1953, p. 324) that in the absence of collisions the distance d travelled to and fro by a particle of mass m and charge e is $2(v/\omega+eE/m\omega^2)$ where ω is its gyro frequency and v its speed prior to the application of E. In the field $|E^{p'}|_{\text{max.}}$ given by equation (**11**),

$$d=2\left(\frac{v}{\omega}+\frac{eUH}{m\omega^2}\sqrt{\frac{\sigma_3}{\sigma_1}}\right). \qquad \textbf{(12)}$$

Thus the maximum change in energy of the particle over a half cycle is

$$\Delta\xi=2|\pm mvU\sqrt{(\sigma_3/\sigma_1)}+mU^2(\sigma_3/\sigma_1)|, \qquad \textbf{(13)}$$

the sign + or − being used accordingly as the charge of the particle is positive or negative. Except for gas particles of initially very high velocities and for even moderate values of U, equation (**13**) becomes

$$\Delta\xi\approx 2mU^2(\sigma_3/\sigma_1). \qquad \textbf{(14)}$$

In an isotropic gas $\sigma_3/\sigma_1=1$, of course. In a lightly ionized tenuous gas (e.g. ionospheric F region) $\sigma_3/\sigma_1\approx 1$. In the ionospheric E region σ_3/σ_1 may reach a value of about 400 (Baker and Martyn 1953). In stellar atmospheres values greater than 10^{10} are common (Piddington 1954).

In the dynamo region of the Earth's atmosphere significant values of U may arise through the action of a neutral particle wind; the effects of such winds are considered in later sections. In stellar atmospheres U may attain significant values through the action of radiation pressure of the Milne kind (Milne 1926).

It appears likely that the movement of the Earth's exosphere through the interplanetary magnetic field or the solar system through a galactic magnetic field may produce significant electrostatic fields which would manifest themselves as anisotropies in cosmic ray intensities. Such fields may also accelerate individual charged dust particles.

III. Application to the Aurora and Magnetic Disturbance

Baker and Martyn (1953) have calculated the conductivities as functions of height in a model ionosphere. It is seen from their work that the bulk of atmospheric dynamo current flows between 90 and 120 km height. Also between the same height limits Hall currents far outweigh Pedersen currents. Thus a good approximation in the dynamo region is

$$\sigma_3\approx\sigma_2.\sigma_2/\sigma_1. \qquad \textbf{(15)}$$

Weekes (1956) exhibits graphs of the mobilities of electrons and ions separately as functions of height. From these graphs it is seen that in the dynamo region the Hall current due to electrons dominates that due to ions. Hence throughout the greater part of the dynamo region we may say

$$\sigma_2\approx\sigma_{2(\text{electrons})}=\frac{Ne^2}{m_e}\,\frac{\omega_e}{\nu_e^2+\omega_e^2}.$$

Since $\omega_e/\nu_e\gg 1$ in the region considered,

$$\sigma_2\approx Ne/H. \qquad \textbf{(16)}$$

Since electrons dominate the flow of current,

$$\mathbf{j} \approx -Ne\mathbf{v}_d, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

where $\mathbf{v}_d$ represents the drift velocity of electrons.

We now identify the model described in Section II (*a*) above with an aurora immersed in the ionosphere and identify $\mathbf{U}$ with the velocity of horizontal wind perpendicular to the (near vertical) polar geomagnetic field. The current flow within an aurora is given by equations (**9**). From equations (**9b**), (**15**), (**16**), (**17**), we obtain for the drift velocity of the electrons within the auroral mode

$$v_d \approx -(\sigma_2/\sigma_1) U \cos\delta \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

in the direction $+\mathbf{n}\times\mathbf{H}$. (It is assumed that $N' \gg N$ so that the first term of equation (**9b**) is the dominant one.)

Figure 2 shows the variation of σ_2/σ_1 as a function of ω_e/ν_e and height. The ratio σ_2/σ_1 reaches a maximum value of about 20 in the dynamo region (cf. Baker and Martyn 1953). The maximum value depends on the value chosen for the ratio of collision frequencies of ions and of electrons. This point will be discussed below (Section III (*c*)).

We now identify the speed V_s given by (**7**) with the horizontal movement of an aurora normal to its length and the velocity of drift of electrons $\mathbf{v}_d$ with that along the aurora of large-scale features of the luminosity pattern and of the ionization pattern producing radio echoes. This is justified when $N' \gg N$, for $E^{p'}$ (equation (**10**)) and hence v_e (equation (**2a**)) and v_d become independent of N'. The theory predicts that for the lower portion of the ionosphere V_s is of order U and v_d of order $10U$ (see Fig. 2).

(*a*) *Auroral Movements and Magnetic Disturbance*

If we now suppose that patterns of ionization established within the auroral zone are blown by a neutral particle wind it is possible to account for a number of observations on auroral morphology. Appropriate wind speeds, generally 10–100 m/sec and sometimes more, are observed in the dynamo region (Elford 1959*a*, 1959*b*).

In the vicinity of and equatorwards of the auroral zone, auroras are oriented on the average roughly east-west. If then the wind in this region has a diurnal variation, being equatorwards in the evening and polewards later in the night and morning, one would expect a similar movement of auroras. This is observed (cf. Bond 1960). Similarly we explain the diurnal variation of latitude of arcs reported by Jacka (1953). Equations (**17**) and (**18**) also explain Robertson's (1960) observation on the occurrence of positive bays in the evening and negative bays later in the night and morning.

The drifts of auroral ionization (Unwin 1959) and luminosity patterns (Bond 1960) along the aurora with speeds an order of magnitude greater than typical wind speeds are explained by equation (**18**). The diurnal variation in ionization drift speed (Kaiser 1958) is explained by the cos δ term in (**18**).

Heppner (1954) shows that the bulk of the magnetic bay producing current does in fact flow in or near auroras. This indicates that $N \ll N'$. To estimate the magnitude of a magnetic bay we take account now of only the current flowing in visible auroras (equation (**9b**)). The currents flowing outside an aurora indicated by equations (**8c**) and (**8d**) may contribute significantly to disturbance if they occupy a great enough region. At Macquarie Island when the magnetic K-index is 6 there is a magnetic disturbance of order 500 gamma and auroras typically fill the whole sky. Thus the total effective (latitude) thickness of auroras is of order 100 km. Recent rocket measurements of electron densities in auroras give values of 10^6–10^7 per cm^3 (Jackson and Seddon 1959). If the auroral dynamo be 10 km thickness in height and at 100 km above the ground, then a disturbance at the ground of over 500 gamma is easily explicable.

It has been observed (Zaborshchikov and Fediakina 1958) that during positive magnetic bays $h_{\text{min.}}E_s$ is generally above 100 km, whilst during negative bays $h_{\text{min.}}E_s$ is generally below 100 km. Moreover, increased absorption of extraterrestrial radio waves is more associated with negative than with positive bays. These observations can be qualitatively explained by a modification of the theory which will not impair the foregoing conclusions.

We consider the effect of allowing for the inclination of the Earth's magnetic field to the vertical. Figure 3 illustrates a cross section of an aurora in the magnetic meridional plane with the wind blowing equatorwards. Positive charges will gather on the leading face of the aurora and negative ones on the trailing face. Thus in this situation electrons will tend to be lifted out of the lower regions of the ionosphere so that their effect on absorption is lessened. Apparently they are lifted to a region where their horizontal drift velocity is less (namely, above the peak in drift velocity near 100 km, cf. Fig. 2). However, when the wind is polewards electrons will be depressed into lower regions where their effect on absorption is increased yet the bulk of them still occupy a region of high drift speed. This also explains Robertson's (1960) observation that negative bays are of larger amplitude in general than positive bays.

The two physically distinct components of velocity of an aurora are V_s and v_d. Since v_d is of order 10 and more times V_s, the arbitrary resolution of the movements of auroras north-south and east-west will not in general give information about V_s and v_d unless the orientation is known. However, as mentioned above, near the auroral zone the average orientation of auroras is east-west, so that on the average we may associate north-south movement with V_s and east-west movement with v_d. Now Bond (1960) exhibits a graph for the latitude of auroras as a function of K_p, whilst Unwin (1959) exhibits a graph for the drift velocity of auroral ionization as a function of K at Macquarie Island. The average values from these two sets of data are plotted in Figure 4. (The fit is achieved by choosing the same ordinate for the drift 3000 m/sec and 41° gm. co-lat. at K_p, $K=9$ and $K_p=0$ corresponding to 100 m/sec and 27° gm co-lat.) In terms of the present theory, the correspondence revealed in Figure 4 suggests that K and K_p are indicators of wind speed.

Thus, though changes in ionization density are important, it appears that the wind in the polar dynamo region is a prime factor in determining the morphology of auroras and magnetic disturbance. A source of energy for this wind will be discussed later (Section IV).

(*b*) *Luminosity of Auroras*

In the model presented in Section II the only electric field available for the acceleration of charged particles is that given by (**10**), which is orthogonal to H. The maximum energy acquired by a charged particle which does not suffer collision is given by equation (**13**). Thus a 100 m/sec wind may accelerate

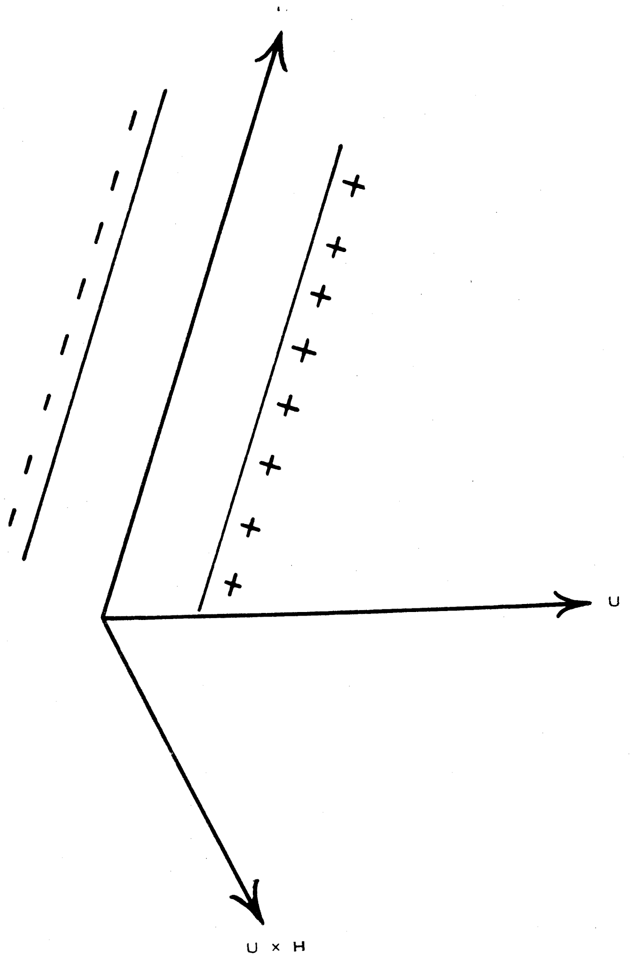

Fig. 3.—Effect of inclined magnetic field.

charged nitrogen and oxygen molecules to energies of approximately 1 eV. Under favourable circumstances this field may contribute to the luminosity of auroras.

However, in a real aurora significant electric fields may develop parallel to the geomagnetic field. For conductivity is a function of height and therefore the build-up of polarization at the faces of the aurora will not be uniform at all heights. Under these conditions current must flow along **H**—this is equivalent to creating an electric field parallel to **H**. The effect of this current flow along **H** will be to delay the steady state suggested by equation (**9**). An upper limit to this electric field parallel to **H** may be obtained by assuming that in the initial stages of luminosity development all the current which flows in the direction of the normal **n** (see Fig. 1) is redirected along the geomagnetic field lines. Thus from equations (**1**) and (**8a**) (putting $t=0$, $E^0=UH$, $\delta=\frac{1}{2}\pi+\alpha$ and $N'\gg N$)

$$E_{\parallel}\approx r(\sigma_1' UH \sin\delta+\sigma_2' UH \cos\delta)/\sigma_0', \quad \ldots\ldots\ldots \quad (\mathbf{19})$$

where r is the ratio of the height extent and the latitude extent of the dynamo section of an aurora. An auroral dynamo may be 20 km in height extent and less than 1 km thick. Since in the dynamo region $(\sigma_2/\sigma_0)_{\text{max.}}$ and $(\sigma_1/\sigma_0)_{\text{max.}}$ are about 10^{-2} (Baker and Martyn 1953), it may be shown that $E_{\parallel}$ values of order 10^{-5} V/cm are obtainable from a wind of 30 m/sec. Chamberlain (1955) in a study of auroral rays concludes that an electric field of order 10^{-5} V/cm is adequate to explain their luminosity.

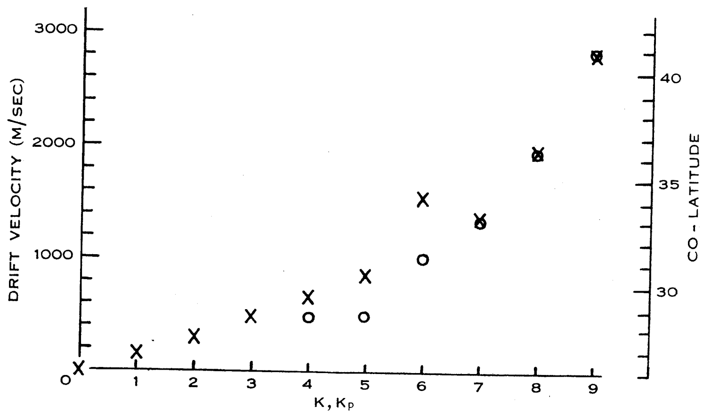

Fig. 4.—Superposition of two sets of data : (○) the EWE average drift speed of auroral ionization as a function of K-index at Macquarie Island (Unwin 1959) ; (×) the average maximum co-latitude of auroras as a function of K_p (Bond 1960).

The luminosity of an aurora appears to move with the same velocity at all heights. This observation does not conflict with the theory. The electric field causing luminosity at great heights moves with a speed dictated by the electron flow at the base of the aurora in the dynamo region. The auroral dynamo may occupy only a small height range and so only a small range of values of V_s and v_d may be effective in determining the speed of luminosity. It appears that the values of V_s and v_d associated with the bulk of " dynamo " electrons will dominate and that values of V_s and v_d associated with other electrons may contribute to diffuseness at the edges of auroral luminosity.

As mentioned above, the leakage of charge along the field lines increases the time to reach the steady state (maximum) electron drift (v_d) in an aurora. It is thus expected that the luminosity peak of an aurora should precede the associated magnetic disturbance at the ground, as has been reported by Bless *et al.* (1959).

(c) The Collision Frequencies of Ions and Electrons with Neutral Particles

From equation (**18**) it follows that $\sigma_2/\sigma_1 \approx v_d/U \cos \delta$. It can be seen from the equations of Baker and Martyn (1953) that when $\nu_i/\nu_e \gtrsim 10$ (as is presumably the case in the ionosphere), then $(\sigma_2/\sigma_1)_{\text{max.}} \approx \frac{1}{2}(\nu_i/\nu_e)$ (to within 1 per cent.). Thus

$$\frac{\nu_i}{\nu_e} \approx 2\left(\frac{v_d}{U \cos \delta}\right)_{\text{max.}} \qquad (\mathbf{20})$$

Also it may be shown that

$$\frac{V_s}{(\sigma_2/\sigma_1)\, U \cos \delta} \approx \frac{\nu_e}{\omega_e}.$$

Therefore, from equation (**18**)

$$\nu_e/\omega_e \approx V_s/v_d. \qquad (\mathbf{21})$$

Thus the collision frequencies of electrons and ions may be determined by ground-based observations of wind and auroral movements.

(d) World-wide Magnetic Disturbance

Dynamo theory of world-wide magnetic disturbance (Maeda 1957 ; Obayashi and Jacobs 1957) in its usual form argues from a diffuse continuously (spatially) varying current. It does not envisage structural discontinuities of the kind discussed here. It may be capable of explaining on a world scale average magnetic disturbance but would fail to draw out the small-scale and short-term detail.

It is suggested that auroras are just visible lines of the magnetic disturbance current system. This is a natural outcome of the above theory and is supported by observations as follows. At Macquarie Island (just outside the auroral zone, Bond and Jacka (1960)) the orientation of auroras is generally east-west (Bond 1960) ; at Mawson (just inside the zone) the aurora often shows large-scale curvature (as distinct from relatively small-scale convolutions and kinks which appear as a general feature of auroras in most places) (ANARE records) ; at Scott Base (well inside the zone) the aurora often takes the form of complete loops in the sky (Carter Observatory 1957, 1958) ; at Dumont d'Urville (well inside the zone) the orientation of arcs in 1954 generally lagged the orientation of the Sun-Earth line by an acute angle (Weill 1958). These observations are qualitatively what could be expected following inspection of diagrams for disturbance current systems (see Figs. 227–240 of Vestine *et al.* 1947).

The polar disturbance current system (Vestine *et al.* 1947) could be explained in terms of a wind system with a source at the centre of the " afternoon " current cells and a sink at the centre of the " morning " current cells. The lines of flow of the wind would be roughly orthogonal to the current lines, hence across the polar cap wind in the dynamo region would blow from the afternoon sector to the morning sector.

IV. Energy Source for the Wind System

Corpuscular bombardment of the Earth may be effected by a solar wind (Parker 1959) or hydromagnetic shock waves (Singer 1957) or weak hydromagnetic waves (Cole 1959). Let us consider the last mentioned. Hydromagnetic waves can deliver energy in two modes ; the extraordinary and the ordinary mode.

The extraordinary mode travels with the Alfvén speed V_A in all directions, whilst the ordinary mode travels with the phase velocity $V_A \cos \psi$, where ψ is the angle between the wave normal and the magnetic field (Piddington 1955).

In the case of hydromagnetic waves coming all the way from the Sun or being generated at the interface of the Earth's outer atmosphere and the interplanetary medium, the energy of the ordinary mode will accumulate principally in high magnetic latitudes and in the lines of force connected to them, whilst the energy of the extraordinary mode may be expected to accumulate in low magnetic latitudes and in the lines of force connected to them because of the curvature of the geomagnetic field lines. This would explain in a simple unified fashion the occurrence of the two maxima in the radiation intensity at heights above the Earth's surface (Van Allen 1959). This mechanism is without the difficulties of the actual transmission of particles. For, whereas disruption of the Earth's magnetic field must be invoked to explain how low energy extraterrestrial particles become trapped in the Earth's magnetic field, no such disruption is necessary for the capture of energy from hydromagnetic waves. The latter is merely a function of the geometry of the capturing system.

Let us consider the effect of hydromagnetic waves of all wavelengths coming either from the Sun or from interplanetary space near the Earth. Waves of length less than the scales of inhomogeneities (e.g. in density or magnetic field) in the Earth's exosphere would retain their character as waves and suffer damping and loss of energy, as demonstrated by Piddington (1959). However, waves of length greater than the scales of inhomogeneities would soon degenerate into a system of gyrating particles in the Earth's field. These particles will lose energy chiefly at their mirror points by collision ; in this way ionization is established and energy is delivered to the dynamo region. Also the polar dynamo region may receive energy from low energy cosmic rays.

One would expect an " auroral zone " associated with each of the naturally occurring radiation belts, just as a temporary " auroral zone " was associated with the man-made radiation belts of the Argus experiments (Christofilos 1959). This would account for the maximum of intensity of the airglow observed near gm. lat. 35° by Nakamura (1958) as the " auroral zone " of the inner Van Allen radiation belt. Also Sandford (1959) has observed that " the intensity of the O_I lines 5577 Å and 6300 Å in the airglow and aurora vary as similar functions of the K_p-index and therefore suggests that the increased O_I emissions in the airglow during periods of increased magnetic activity are essentially the same phenomena as aurora ". This supports the above thesis.

V. Discussion

The above theory correlates many widely dispersed observations. The application of the dynamo idea to the theory of auroras is not new ; Vestine (1954) quotes references to work up to that time. However, the present approach is new.

The theory leads to the inference that the " weather " of the polar dynamo region is under the control of corpuscular or hydromagnetic wave bombardment ; these effects dominate the effects of tidal oscillation.

The following picture of an aurora has evolved from consideration of the above theory. Some agency, probably charged particles from the outer Van Allen radiation belt or hydromagnetic waves directly from interplanetary space, establishes a wind system in the polar dynamo region. The wind blows an established pattern of ionization across the magnetic field. This generates electric fields, in the region of high electric conductivity, which drive currents and cause luminosity and maintain ionization for very much longer times than would be permitted by "quiet" ionospheric conditions.

To test the theory simultaneous observations of wind velocity (by the meteor trail drift method) and auroral orientation, movement, and height are required. These are required to check that indeed the speed of an elongated aurora normal to itself is just V_s. If this were established, the aurora would become a very valuable visible adjunct to the study of winds in the polar dynamo region.

VI. Acknowledgments

The author thanks Dr. F. Jacka, Chief Physicist, Major F. R. Bond, and Mr. G. Cowling of the Antarctic Division for stimulating discussion. To Dr. Jacka thanks are due for help in presentation of the final manuscript. Miss J. Cummings-Wright performed the numerical calculations and drew the graphs.

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