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THE SOURCE OF ATMOSPHERIC ELECTRIFICATION

By

Willis L. Webb

ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

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ABSTRACT

Synoptic rocket exploration of the stratospheric circulation has revealed the presence of hemispheric tidal circulations which are indicated to be in part characterized by systematic vertical motions in low latitudes of the sunlit hemisphere. These vertical motions are powered by meridional oscillations in the stratospheric circulation produced by solar heating of the stratopause region, and serve as the energy source of electrical current systems which are postulated to result from an impressed electromotive force which is produced by charged particle mobility differences in the lower ionosphere as the tidal circulations tend to force these particles across the earth's magnetic field. These dynamo currents are variable with geometry and time variabilities of the tidal circulations as well as variability in the solar-induced conductivity of the E region. The semiconducting lower atmosphere and highly conducting earth's surface occupy the near field of the lower side of this current system with a resulting complex tropospheric electrical structure. Low impedance electric current paths along magnetic field lines result in development of currents in the exosphere which are driven and controlled by the electrical structure of the primary dynamo circuit and exert a control of their own through interaction with the solar wind. The basic physical process which provides the required electromotive force for maintenance of the earth's atmospheric environment electrical structure is thus indicated to center in thermally driven tidal motions in the lower ionosphere, with locally observed structure such as the fair-weather electric field, thunderstorms, lightning discharges, aurora, airglow, electrojets, radiation belts, etc., playing supporting roles.

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1. Introduction

The electrical structure of the earth remains today one of the most intriguing problems faced by the geo-scientist. The earth's permanent magnetic field is generally believed to result from electrical phenomena in the earth's interior, and certain small variations in that magnetic field have been demonstrated to be related to direct electromagnetic interaction of the earth system with the local solar environment. In addition, some systematic variations are believed to have their origin in motions of the weak ionospheric plasma through the permanent magnetic field. Electrical manifestations of this comprehensive magnetoelectrodynamic system are commonly noted in thunderstorm electrification, the fair-weather electric field and current, aurora, airglow and numerous other facets of an obviously complex system. The certainty that these puzzling phenomena (as viewed individually) must fit into a satisfying global electrical structure has led to inspection of new information on the physical structure of the atmosphere for clues which will serve to bind the currently fragmented picture together.

In October 1959 a new system for synoptic exploration of the earth's upper atmosphere using small rocket vehicles was initiated to extend the region of meteorological study to higher altitudes (Webb et al., 1966). This Meteorological Rocket Network (MRN) has expanded the atmospheric volume which is currently subject to meteorological scrutiny from limitations of the order of 30 km peak altitude to a current synoptic data ceiling of the order of 80 km. A number of very important findings have resulted from MRN synoptic exploration of the upper atmosphere, the most notable of which (for our current purposes) is the discovery of large diurnal variations of the temperature (Beyers and Miers, 1965), wind (Miers, 1965) and ozone (Randhawa, 1967) fields of the stratopause region. Solar ultraviolet heating of the ozonosphere is indicated by the data to be concentrated in middle and low latitudes in a relatively thin layer in the 45 to 50 km altitude region and the transport of this diurnal heat pulse downward and upward from the stratopause level is then accomplished by secondary physical processes. Consideration of this new information has led to the realization that circulation systems exist in the atmosphere above 40 km altitude which exert a profound influence on upper atmospheric structure by dynamic altering of physical processes and by mixing and transport of atmospheric constituents of the upper atmosphere.

An important result of these synoptic meteorological studies of the upper atmosphere concerns the fact that vertical motions of considerable magnitude in specific locales are indicated by the data. Upward motions in the summer high-latitude nighttime sky which are indicated by the data imply the presence of downward motions in polar regions and in middle and low latitudes of both hemispheres on a diurnal basis (Webb, 1966b). Downward motions are indicated to be located in the sunlit hemisphere from early morning until early afternoon with maximum intensity in low latitudes. Such vertical motions exert pronounced influences on the electrical structure of the atmosphere because they transport charged particles of the atmosphere vertically through regions where differing mobilities of the positive and negative charge carriers produce electromotive forces. Charge separation caused by this basic mechanism is indicated to occur in a predictable fashion in the mesosphere and lower ionosphere, and such a separated charge can be shown to result in electric fields and currents which modify the "normal" ionosphere (Martyn, 1959; Beynon and Brown, 1959; Fejer, 1953; Yuen and Roelofs, 1967; Chandra and Rangaswamy, 1967) in accord with the observed global electromagnetic structure. Some of the more relevant observations are listed below.

Short-term variations in surface observations of the earth's magnetic field have been analyzed extensively (Chapman and Bartels, 1940; Matsushita, 1965). These studies indicate the following general features:

a. Occurrence of magnetic disturbances is directly correlated with sunspot activity.

b. Occurrence of magnetic disturbances is maximum at equinox and minimum at solstice times.

c. Occurrence of magnetic disturbances is minimum in mid-morning and maximum just after midnight local time.

d. A systematic diurnal variation occurs in the magnetic field intensity with an amplitude of several tens of gammas.

It is generally assumed that these short-term variations in the magnetic field are caused by electric currents which flow in the global shell centered near the 100 km level and are the result of atmospheric tidal motions (Stewart, 1883; Chapman and Bartels, 1940; Chapman, 1954). Lack of adequate environmental data has prevented verification of these "dynamo" theories, and in general there is question about the adequacy of the tidal motions used in these initial estimates. Dynamo currents clearly do exist in the upper atmosphere, but their structure and origin remain open to question (Kato, 1956).

Available data indicate the existence of a characteristic electric field over the surface of the earth, except in storm areas (Chalmers, 1957; Imyanitov and Shifrin, 1962). Observational data on the earth's fair-weather electrical structure provide the following general information for the tropospheric situation:

a. The fair-weather electric field exhibits a negative gradient (electrical potential increases with height).

b. Intensity is variable with location and time with an average value in the 100 volt per meter range at the earth's surface.

c. An electric current of approximately 1400 amperes flows to the earth (Kraakevik, 1961).

d. A net negative charge of approximately 450,000 coulombs appears to reside in the earth's surface.

Integration of the known troposphere field gradient data indicates that the ionosphere is at a potential difference of the order of 300,000 volts above the potential of the earth's surface.

A most popular theory relative to the atmospheric fair-weather electric field pictures thunderstorms as the generators which, through the energy available in gravitational separation of precipitation, provide a steady overall potential difference between the ionosphere and the earth's surface (Wilson, 1920). The fair-weather electric current is then pictured as a uniform leak between highly conducting ionospheric and earth's surface spherical condenser plates. The current flowing in the fair-weather electric field is such that in a matter of a few tens of minutes the stored charges on the earth's surface would be effectively eliminated, so it is necessary to show that the generating mechanism is in continuous operation. Thunderstorm activity on the global scale has been shown to be at least generally capable of providing the return current required to keep the fair-weather electric field current flowing (Brooks, 1925; Gish and Wait, 1950; Stergis et al., 1957). Thunderstorms have not been shown, however, to provide the organized electrification required to produce the earth's fair-weather electric field, and there is even the suspicion that they might not produce any electrification at all if the fair-weather electric field did not already exist. These considerations lead to the view that the observational evidence of electrification in the earth's troposphere allows the possibility that these phenomena are developed directly by some basic electrification mechanism, and that local electrical effects associated with thunderstorms, duststorms, air pollution, etc., simply represent local modifications of the general electrical structure of the earth's atmospheric system.

Electric currents flow in the surface layers of the earth (Barlow, 1849; Gish and Rooney, 1937; Chapman and Bartels, 1940; Redding, 1967). Complex conductivities in land surface areas assure complications in the global field of telluric currents, but the following generalizations appear to be characteristic of average conditions:

a. Telluric currents of 10^{-10} amperes per square meter are representative of surface currents through land areas under undisturbed conditions.

b. A strong diurnal variation is evidenced, with the current flow toward the equator in the daytime.

c. Certain earth current variations are coincident with certain magnetic field variations.

d. The range of diurnal variation is greatest in summer. The question of whether these currents represent transport of charge through the earth's surface to some external circuit or are simply induction currents caused by ionospheric currents has been considered at some length in the literature without resolution.

Auroral activity is observed in a nearly circular band of approximately 23 degrees magnetic colatitude in both hemispheres (Chamberlain, 1961; Chapman and Bartels, 1940; Parker, 1959; Hines and Reid, 1965; Barcus and Brown, 1966; Bates, 1966; Barcus and Rosenberg, 1966; Piddington, 1967; Feldstein and Starkov, 1967). Auroral phenomena appear to be manifestations of electrical activity which are in part controlled by the earth's magnetic field. Principal characteristics are:

a. The base of auroral activity exhibits a maximum occurrence at approximately 100 km altitude.

b. Many magnetic field disturbances are directly related to auroral occurrences and fluctuations (Nichols, 1959; Feldstein and Starkov, 1967).

c. Auroral activity in both hemispheres varies similarly with the sunspot cycle (Chivers and Hargreaves, 1966).

d. Auroral activity is maximum at equinox times and minimum at solstice times.

e. Auroral activity generally exhibits a maximum just after midnight and a minimum just before noon local time.

Auroras are observed visually and through scattering of electromagnetic energy, with the two observational systems giving differences in details but general agreement (Montalbetti, 1965; Blevis and Collins, 1965) relative to the physical characteristics of the phenomena. The visual observations appear to deal principally with phenomena occurring along the magnetic field, while the radio observations appear to deal principally with a layer of enhanced electron concentration centered in the 100 km altitude region and frequently extending significantly above and below that level. Various concepts of the physical processes associated with auroral activity have been published (Wulf, 1953; Vestine, 1954; Cole, 1960; Chamberlain, 1956). Auroral activity is located in the correct position to be the precipitation ground for Van Allen (1959) outer belt particles, but the energy in the trapped particles is apparently inadequate for continued auroral generation.

Airglow represents characteristic optical line emissions from the ambient constituents of the upper atmosphere which result from their being in an excited state (Chamberlain, 1961; Greenspan and Woodman, 1967). The nightglow is quite striking when viewed under the proper conditions (Glenn, 1962; Carpenter et al., 1962; Hennes and Dunkelman, 1966). Principal features of the airglow include:

a. It is global in distribution, although the daytime intensity is not known with certainty because of interference by scattered sunlight.

b. It is inhomogeneous, with detail structure which appears to drift with the wind.

c. It is centered near the 100 km level and generally extends well below and above that level.

Airglow in the nighttime is generally regarded as residue from daytime solar ultraviolet excitation, although the nighttime distribution does not necessarily support such a concept.

Thunderstorms generally occupy less than one percent of the earth's surface areas and exhibit gross spatial and temporal variations (Chalmers, 1957; Smith, 1958; Coroniti, 1965). Their electrical characteristics are complex, with the most distinctive feature centering around the lightning flash. Thunderstorms are characterized very generally by:

a. Globally approximately 2000 thunderstorms are in continuous operation with an estimated lightning frequency of approximately 10 cloud-to-ground strokes per second (Vorpahl, 1967).

b. Maximum occurrence is in early evening.

c. An average of the order of 10^2 coulombs of charge is transferred vertically over an average altitude range from the surface to 10 km by each system of strokes.

d. A majority of lightning discharges result in transfer of negative charge to the earth.

Severe modifications of the tropospheric electric structure are observed in the vicinity of thunderstorms, but an organized transport of charge is not obvious except in the lightning discharge path, and even there the situation is highly variable.

Whistlers are electromagnetic signals of a few thousand cycles per second frequency which have been identified as being of lightning origin and are known to travel between hemispheres along magnetic field lines (Helliwell and Morgan, 1959; Gendrin, 1961; Liemohn and Scarf, 1964; Gurnett and Shawhan, 1966; Carpenter, 1966; Angerami and Carpenter, 1966). Whistlers are probably a special extreme case of a general class of events which involve propagation and transport along magnetic field lines (Gallet, 1959; Gringauz et al., 1961; Krasovskii et al., 1961). Whistlers have been observed to:

a. Travel from one hemisphere to the other in times of the order of one second.

b. Oscillate between hemispheres as many as twenty times.

c. Occur most frequently at night, possibly as a result of D region absorption in the daytime.

In all cases the whistler mode of propagation implies tubular enhancements of electron densities along field lines to guide the waves, and, in the lower-frequency case studies by Gallet the flow of discrete packets of electrons along the field lines is indicated.

Using the information which has been briefly reviewed above, the following pages will be devoted to development of a comprehensive picture of the electrical structure of the atmosphere from the earth's surface layers to distances of roughly ten earth's radii.

2. Diurnal Circulations

Diurnal variations in the temperature (Beyers and Miers, 1965) and wind (Miers, 1965) fields of the stratospheric circulation of the order of 15^{o} and 30 mps respectively were discovered through application of the sensitive measuring systems of the Meteorological Rocket Network. The diurnal variation of the wind field has been shown to be a general characteristic of MRN data (Reed et al., 1966). These measurements came as a surprise since theoretical considerations of solar ultraviolet absorption by ozone had led to the conclusion that the diurnal temperature variation would be smaller, of the order of 4^{o} (Craig, 1950; Leovy, 1964). These new data would then indicate that solar heating of the ozonosphere is confined to a much thinner region of the upper stratosphere than had previously been assumed or that other heat transport processes exist, with a resulting need for an experimental reexamination of ozone structure and dynamic equilibrium in the upper stratosphere and lower mesosphere. This was done for the ozone case by Randhawa (1967), and significant differences from theoretical expectations were found, with a greater concentration and a pronounced diurnal variation in ozone concentration in the stratopause region where a maximum ozone concentration was found to occur during nighttime hours.

The above information has been combined with geometric and theoretical considerations to arrive at a global picture of the tidal circulations of the stratospheric circulations (Webb, 1966b). Principal features of this model are a heat wave oriented latitudinally, with a trough near sunrise and a crest near 2 P.M. Winds of the stratopause level are accelerated by the resulting propagating ridge of high pressure, away from the equator in the increasing temperature sector and back toward the equator during the late afternoon and nighttime. At equinox times the tidal circulation winds are zonal westerly around the high latitude ends of the heated ridge in the sunlit hemisphere in both the Northern and Southern Hemispheres.

The situation is materially altered as the solar aspect angle changes toward solstice time. The ridge of high pressure (heated, expanded air) quickly includes the polar region of the developing summer season so that the zonal portion of the tidal circulation of that hemisphere can no longer be westerly on the sunlit side of the summer pole, but must be easterly in the nighttime sky and forms the Stratospheric Tidal Jet (STJ) (Webb, 1966b) indicated in Figure 1. In the winter hemisphere, on the other hand, the westerly zonal portion of the tidal circulation can be expected to move to lower latitudes. It is evident from stratospheric circulation data acquired by synoptic sounding that these events have a marked impact on the general circulation (Webb, 1966a).

Consideration of the physics of ozonospheric absorption of solar ultraviolet radiation indicates that observed diurnal variations should have an altitude dependence with solar aspect. Deposit of heat from a uniform source into a near exponential atmosphere of spherical form should be at lowest altitudes at the subsolar point and should be found at higher altitudes at the limb of this interaction. Thus, the observed altitude of the tidal circulation at the stratopause (45-50 km) in low latitudes would indicate that the local tidal effects in polar regions should be found at higher altitudes. These considerations are based on the assumption of a uniform absorbing medium, which is obviously in error, but should at least give a first order approximation to the actual geographic distribution of the tidal circulations. The stratospheric circulation in the mesopause region of high latitudes in the summer solstice period (the STJ) has been investigated by Morris (1967) with the discovery that maximum winds of the summer easterly stratospheric circulation are to be found at that point in space and time. Since it is relatively certain that the meridional temperature gradient at that time and location is negative in the upper mesosphere, these data provide strong evidence that the flow in that region is nongeostrophic. That is, the STJ appears from these data to be a nonequilibrium, highly divergent flow of the summer high latitude nighttime mesopause region which has its energy source in asymmetries in the middle and low latitude tidal oscillatory motions of the stratopause region.

The global tidal circulations discussed above imply vertical motions of gross dimensions in the mesosphere and ionosphere. The import of such

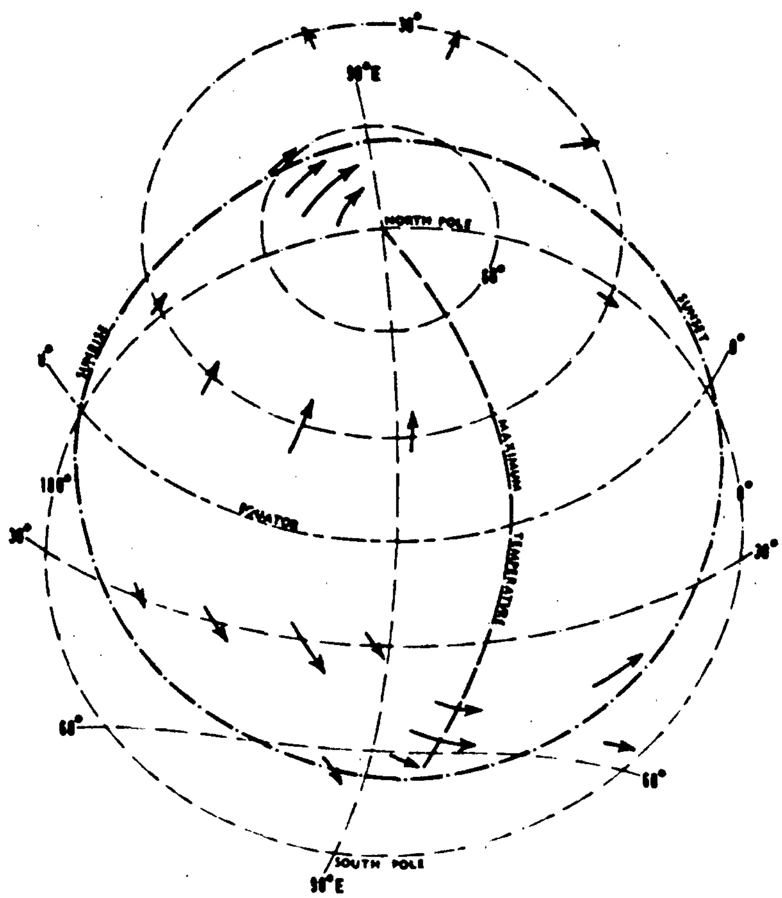

Figure 1. Diurnal tidal circulation of the summer solstice Northern Hemisphere mesosphere projected on the stratopause which is represented by an equidistant projection centered on 42 degrees north latitude and 103 degrees west longitude.

motions on the physical, chemical and electrical structures of the upper atmosphere may be significant, so their spatial and temporal characteristics will be considered in more detail here. The implication of vertical upward motions in the nighttime sky of the summer high latitude mesopause region has long been available from noctilucent cloud observations (Vestine, 1934; Ludlam, 1957; Webb, 1965; Fogle and Haurwitz, 1966). Consideration of the known physical characteristics of these clouds leads to the conclusion that minimum upward motions of the order of tens of centimeters per second are required in the summer high latitude nighttime sky, with speeds in the meter per second range compatible with available data. Mesospheric air is mixed by these tidal circulations, and a portion of the air involved in those circulations is injected across the mesopause into the lower ionosphere in high latitudes of the summer hemisphere. Using order of magnitude values of one meter per second vertical speed, .01 of the mesopause hemispheric area involved in the STJ and a mesopause density of 2×10^{-5} kg m^{-3}, the mesospheric mass transported across the mesopause boundary by this tidal circulation is evaluated to be of the order of 10^6 kg per second. Obviously this mass must return downward across the mesopause surface at some other location.

It is well known that the mesopause region of the winter polar regions is quite warm relative to the temperatures expected from radiational processes. Various mechanisms have been suggested to account for this anomalous thermal distribution, with only compressional heating from downward motions possessing the requisite power capability. A downward flow of the order of centimeters per second would be adequate to provide the observed heating if adiabatic conditions prevail. The area of the winter hemisphere in which this source of heat appears to occur is of the order of one tenth of the total hemispheric area, and simple calculation of the mass of that downward transport across the mesopause indicates that it must be of the order of one tenth of the 10^6 kg per second which is postulated to move upward across the mesopause in the STJ. In view of the gross approximations which we are forced to make in these estimates, the downward mass transport over the winter pole could be a more significant fraction of the upward mass transport of the STJ at the mesopause level.

Consideration of earth rotational effects on the stratospheric tidal circulations indicates that special features of these circulations should be expected in equatorial regions. Reversal in direction of the horizontal component of the Coriolis force means that the hemispheric tidal circulations will separate over the rotational equator. Divergence associated with this rotational separation results in transport of stratospheric mass out of equatorial regions along the leading edge of the heat wave from sunrise to 2 P.M., with a maximum in late morning. Observations indicate that tidal motions near 30° latitude are constrained to roughly the 40-60 km altitude range, and rough estimates of the mass outflow across thirty degree latitude north and south boundaries indicate that about four percent of the mass of that sector is removed during the eight-hour heating period. As has been pointed out (Webb, 1966b), the mass deficit of stratopause equatorial regions can be replaced in three principal ways:

a. Convergence of the horizontal wind field as reflected by a decrease in zonal wind velocity during the heating period. The data indicate that such a mechanism is operating.

b. Subsidence of the entire upper atmosphere, in which case the 60 km level would lower by approximately 3 km.

c. Development of vertical downward circulation which would transport the required mass into the region.

The four percent mass deficit mentioned above is of the order of 10^{14} kg, which, over the eight-hour period, yields a mass transport of approximately 10^{10} kg per second. Clearly, then, the mass injected into the lower ionosphere by the STJ is a very small amount compared to the mass involved in this equatorial oscillation. It seems probable that all of the mechanisms mentioned above are involved in relaxation of equatorial mass losses during the morning hours of the heat wave. Downward-directed winds are then to be expected in the mesosphere and lower ionosphere at low latitudes on the sunlit side of the globe on each side of the equator with maxima as illustrated in Figure 2, while an upward-directed circulation will occur between 2 P.M. and sunrise. It is important to note that these tidal circulations do not reach below the stratopause level and that they should evidence an exponential increase with height, with a scale height of roughly eight kilometers, except as modified by convergence and divergence.

Anomalies in latitudinal distributions of electron densities of the ionosphere in equatorial regions have been reported in the F-region from data obtained by ground based ionosounders (Rawer, 1952; Hanson, 1965) and above the peak of electron density with topside satellite probing equipment (Krishnamurthy, 1966). These data have the general character of enhanced electron density (the parameter measured) in magnetic equatorial latitudes (Appleton, 1946), centrally over the equator to 15 degrees north and south in topside altitudes of 300 to 1000 km and separately in each hemisphere at about 15 degrees latitude at approximately 140 km altitude in the F-region (Brace, et al., 1967; Chandra and Rangaswamy, 1967). The temporal variations are diurnal in nature with maximum effects during daylight hours at midafternoon in low latitudes. In addition, marked reductions in electron density are noted in the topside data poleward from approximately 20 degrees magnetic latitudes. These anomalous electron densities are less than an order of magnitude, although they may locally be considerably larger, as in the case of the equatorial and polar electrojets (Chapman, 1951, 1954) which operate near the 100 km level within a few degrees of the magnetic equator and in the auroral zone, respectively.

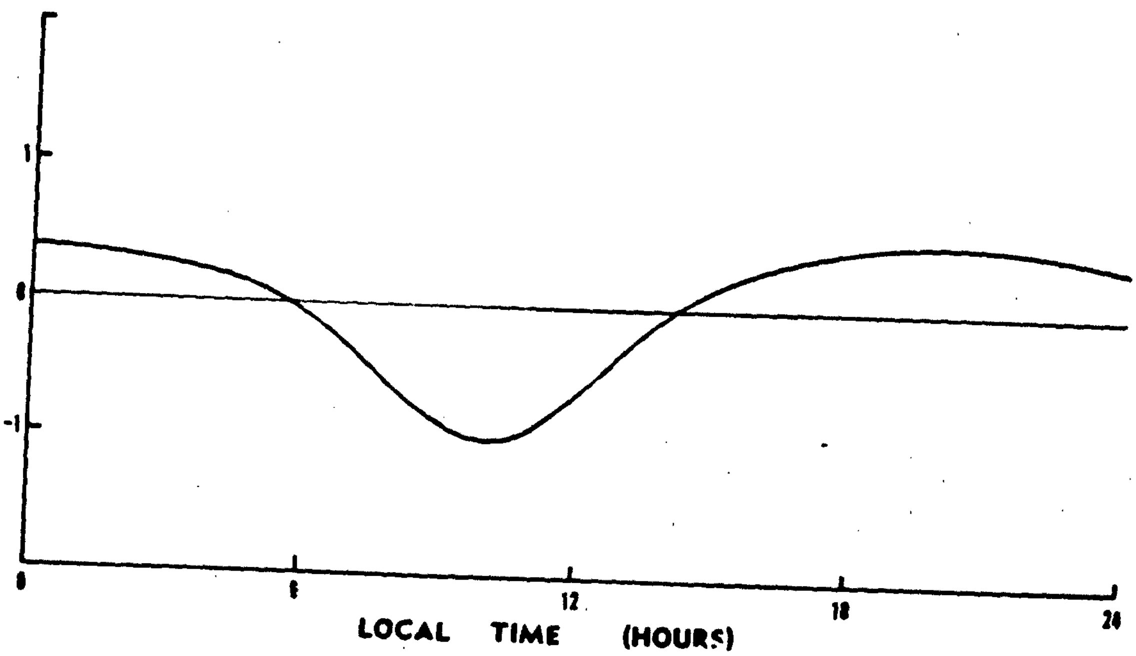

Figure 2. Diurnal character of vertical motions across the mesopause surface at 15 degrees latitude. The ordinate has been normalized to a nondimensional unity at the peak of the day-time downward motion.

While these variations are generally considered to be tidal in origin as a result of their diurnal occurrence, the details of the physical processes involved are complex (Axford, 1963; Dougherty, 1961; Hanson and Moffett, 1966). The excess electrons are usually postulated to be held in equatorial regions by electric fields which have their origin in the D and E regions. Ionospheric plasma fountains with downward motions in the F region of greater than 10 mps have been postulated to explain these diurnal electron density variations (Martyn, 1945).

It must be noted here that the very smooth picture of the tidal circulation presented above has imposed on it a large amount of detail structure. These small scale features appear to be generated by a variety of physical processes, ranging from synoptic scale disturbances to turbulent eddies as well as the full spectrum of mechanical body wave perturbations. It is emphasized that a great amount of variability is a characteristic feature of all upper atmospheric data of sufficient resolution, and these considerations of uniformity which have been used here for clarity must not be allowed to mislead the investigator as to the true state of the medium.

3. Electrical processes

Motion of a gas containing a mixture of electrons and ions through a magnetic field will result in production of an electromotive force oriented in the direction of flow as a result of differing mobilities of the charge carriers. Fejer (1965) has stated the general relation

$$q(\vec{E} + \vec{w} \times \vec{B}) + m\vec{g} + m\nu\vec{v} - \frac{\vec{\nabla} p}{n} = 0 \tag{1}$$

where $\vec{E}$ is the electric field, $\vec{w}$ the velocity of the charged ($q = 1.6 \times 10^{-19}$ coulombs) particles, $\vec{B}$ the magnetic field, m the mass of the particles, $\vec{g}$ the gravity, ν the collision frequency, $\vec{v}$ the velocity of the charged particles relative to the neutral gas and $\frac{\vec{\nabla} p}{n}$ is the pressure gradient of the charged molecules of n particles per cubic meter. He derived the vertical component solution for the case of a vertical wind exerting a force (F) through collisions between neutral and charged molecules to obtain the charged particle speed (v) relative to the neutral gas:

$$v = -\frac{F}{m}\left(\frac{\omega}{\nu^2 + \omega^2}\right) \tag{2}$$

where ω is the gyrofrequency for the particular charged particles involved. The gyrofrequency is given by $\omega = \frac{qB}{m}$, which indicates that the gyrofrequency of electrons will be significantly greater than that for the ions as a result of the difference in mass (9.1×10^{-31} kg for electrons and greater than 1.67×10^{-27} kg for ions).

Collision frequencies are significantly different for ions and electrons. An expression for the collision frequency of the simple electron population has been derived by Nicolet (1953) to be

$$\nu_e = 5.4 \times 10^{-10} N \, T_e^{1/2} \tag{3}$$

where N is the number density of the gas and T_e is the temperature of the electron gas. Chapman (1956) has derived the expression

$$\nu_i = 2.6 \times 10^{-9} N \, m^{1/2} \tag{4}$$

for the collision frequency of ions. In both cases the collision frequency decreases with increasing altitude in accord with the usual density scale height. Collision frequency dependence of electrons on their possible non-gaussian temperature distribution in the ionosphere and ions on the mass of the parent molecule results in complex and relatively uncertain profiles in the upper atmosphere. Estimates of representative profiles are illustrated in Figure 3, the arrows of which indicate the points at which gyro and collision frequencies are equal according to Fejer (1965).

These are important altitudes for our purposes since they indicate the regions in which control is shifted from the magnetic field mode above to the dynamic mode below. Thus at higher altitudes the individual charged particles would essentially be held in place by the magnetic field if a wind tended to transport them across the field, while at lower altitudes collisions would disrupt the gyro motions and the charged particles would be carried along with the wind. These considerations would then indicate that in the 70-150 km altitude region particularly, electrons would be restrained in their vertical motion with the neutral gas of the tidal circulation while their partner positive ions would move with the neutral gas. The force producing this separation will increase with decreasing height as a result of an increasing collision frequency until the collision frequency becomes high enough to carry

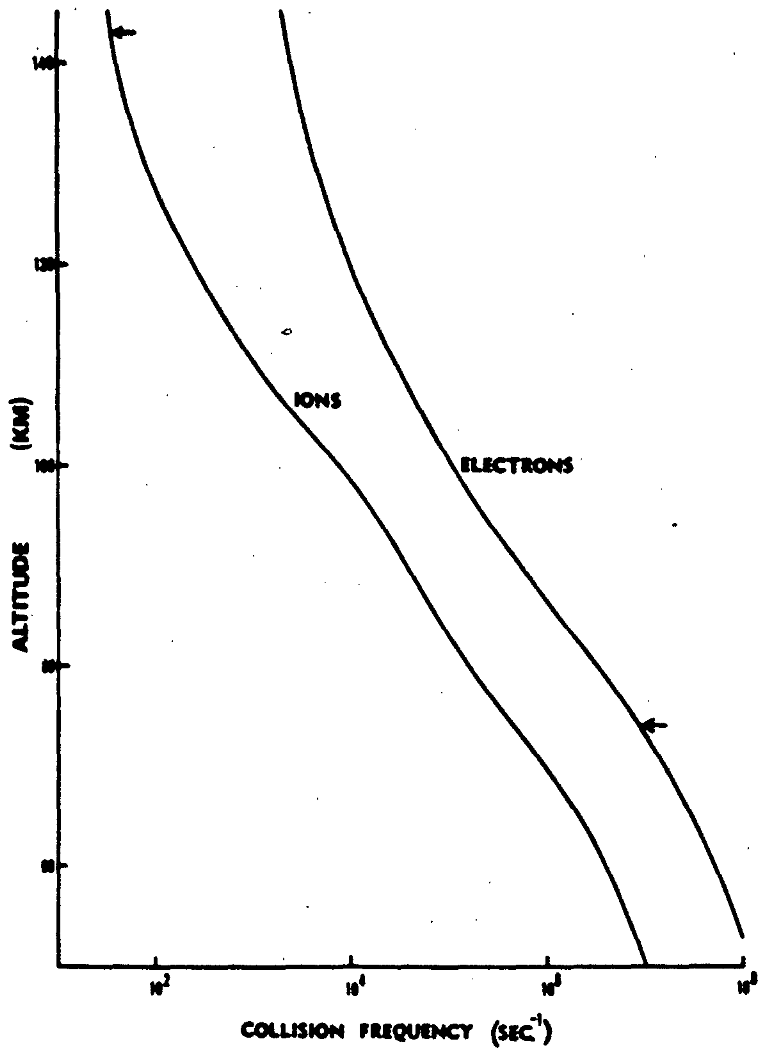

Figure 3. Typical collision frequencies versus altitude for ions and electrons. Arrows indicate the approximate gyrofrequencies for electrons and oxygen molecules of unit charge.

the electrons along with the wind also. The current which would result from this impressed electromotive force, if no limiting resistance were involved, can be obtained by evaluating the difference in relative speeds ($\vec{v}$) of the electrons and an equal number of positive ions from Equation 2 and using their difference as a measure of the rate of charge separation. The gravitational and pressure gradient terms of Equations 1 and 2 can be considered negligible in the 50-150 km region. In the special open circuit case where the electrons, as a result of magnetic field constraints, have a speed of $-\vec{v}$ relative to the flow and the motion of positive ions is controlled by collisions, the vertical electric field ($\vec{E}$) required to prevent further charge separation (that is, to force the positive ions also to move upstream with a speed of v) can be calculated approximately from the relation

$$q\vec{E} = m\nu\vec{v}, \tag{5}$$

where the gravitational and pressure gradient terms are considered negligible and the effects of charge motions in the horizontal are neglected for the moment. If a return current path is available such a velocity of separation (w) of the positive ions and electrons yields the current density ($\vec{J}$)

$$\vec{J} = nq\vec{w} \tag{6}$$

In general in the atmosphere a circuit is neither open nor closed. The presence of mobile charge carriers affords the atmosphere a certain conductivity through a unit cross section which is defined by the field form of Ohm's law

$$\vec{J} = \sigma\vec{E} \tag{7}$$

where $\vec{J}$ is the current density produced by an electric field $\vec{E}$ and σ is the conductivity in mhos per meter through a column of one square meter cross section. The resistivity (ohm meters) is thus the reciprocal of the conductivity. The specific conductivity for a direct current in an ionized gas such as the atmosphere is given by (Hanson, 1965):

$$\sigma = \frac{nq^2}{m_e \nu_e} \quad \frac{nq^2}{m_i \nu_i} \tag{8}$$

This equation yields the value to be used if there is no magnetic field or along the field lines.

Hanson (1965) has given Equation 9 relating the electrical parameters of a gaseous medium such as the ionosphere to obtain the conductivity in a direction perpendicular to a magnetic field for the direct current case (the Pederson conductivity):

$$\sigma' = \frac{n^2 \nu_e}{m_e(\nu_e^2 + \omega_e^2)} \quad \frac{n^2 \nu_i}{m_i(\nu_i^2 + \omega_i^2)} \tag{9}$$

In the presence of combined magnetic and electric fields a force is exerted on ambient charged particles which is normal to the plane of the field vectors in the direction of $\vec{E} \times \vec{B}$ (the Hall conductivity). In the absence of a difference in mobilities of the charged particles the positive and negative particles will simply be displaced together, but in general in the lower ionosphere the ions are effectively immobilized while the electrons are highly mobile and an electric current is thus generated in the $-\vec{E} \times \vec{B}$ direction. The conductivity for such a current is given by the relation (Hanson, 1965):

$$\sigma'' = \frac{n^2 \omega_e}{m_e(\nu_e^2 + \omega_e^2)} \quad \frac{n^2 \omega_i}{m_i(\nu_i^2 + \omega_i^2)} \tag{10}$$

The above considerations form the principal basis for interaction between the neutral diurnal circulation systems of the upper atmosphere and the earth's electrical structure. There are other modes of interaction indicated by Equation 1, and in specific cases they may play a dominant role. For our purposes here we will center our attention on the electodynamic processes of interaction characterized by asymmetries in the Pederson and Hall conductivities.

4. Electrical Structure

The electrical structure of the atmosphere varies with time and space in a complex fashion, and thus can only be represented in a limited fashion by a particular model or set of data. While the general features of electron structure are adequately portrayed by the theory of Chapman layer formation (Chapman, 1931), it is apparent that important detail features can only be explained by significant deviations from this assumed radiational equilibrium under static conditions (Rawer, 1952; Belrose, 1965a, Belrose, 1965b; Heikkila and Axford, 1965; Martyn, 1959; Appleton, 1959; Gibbons and Waynick, 1959; Maeda and Sato, 1959; Nichols, 1959; Herman, 1966). It is thus desirable to make gross generalizations relative to the general electrical structure to obtain a first look at the nature of important physical processes which may occur, and then to compare the expected results of these processes with modifications of the static electrical structure which are known to exist. This procedure is reasonable as long as it is clearly remembered that a uniformity has been assumed which does not exist.

The vertical distributions of specific, Pederson and Hall conductivities for a mean midlatitude noontime atmospheric model are illustrated in Figure 4. Sea water has a conductivity of a few mhos per meter (variable with temperature and salinity) which, as a result of the large oceanic area, determines the general electrical characteristics of the earth at sea level Topsoil conductivity falls in the range 10^{-1} - 10^{-3} marked A in Figure 4, and thus land areas present a greater and more variable resistance to the flow of an electric current. It should be noted, however, that a smaller columnar resistance may be obtained over a particular earth-atmosphere columnar path over land as a result of low resistance surface elevations (mountains) serving to effectively short out some of the very high resistance path of the lower atmosphere.

The very low conductivity of the lower atmosphere ($\sim 2 \times 10^{-14}$ mhos per meter) results from the high collision frequency (and thus low mobility) produced by high air density and the small number of charged particles. The conductivity increases rapidly with altitude from surface values to the order of 10^{-9} mhos per meter at the base of the D region, partly as a result of an increase in number density of charged particles. Above about 50 km the presence of free electrons becomes important as a result of gross differences in mass and collision cross sections of the charge carriers so that the conductivity becomes nonisotropic, with a component structure which is illustrated in the upper portions of Figure 4. At low latitudes the specific conductivity (σ_0) is most applicable meridionally, the Pederson conductivity (σ') is most applicable vertically and the Hall conductivity (σ'') is most applicable zonally.

Vertical motions produced by the tidal circulations described in Section 2 will, in low latitudes of the morning and early afternoon sunlit hemisphere, result in electrical charge separation in the vertical direction with positive charges forced downward by collision between those ions

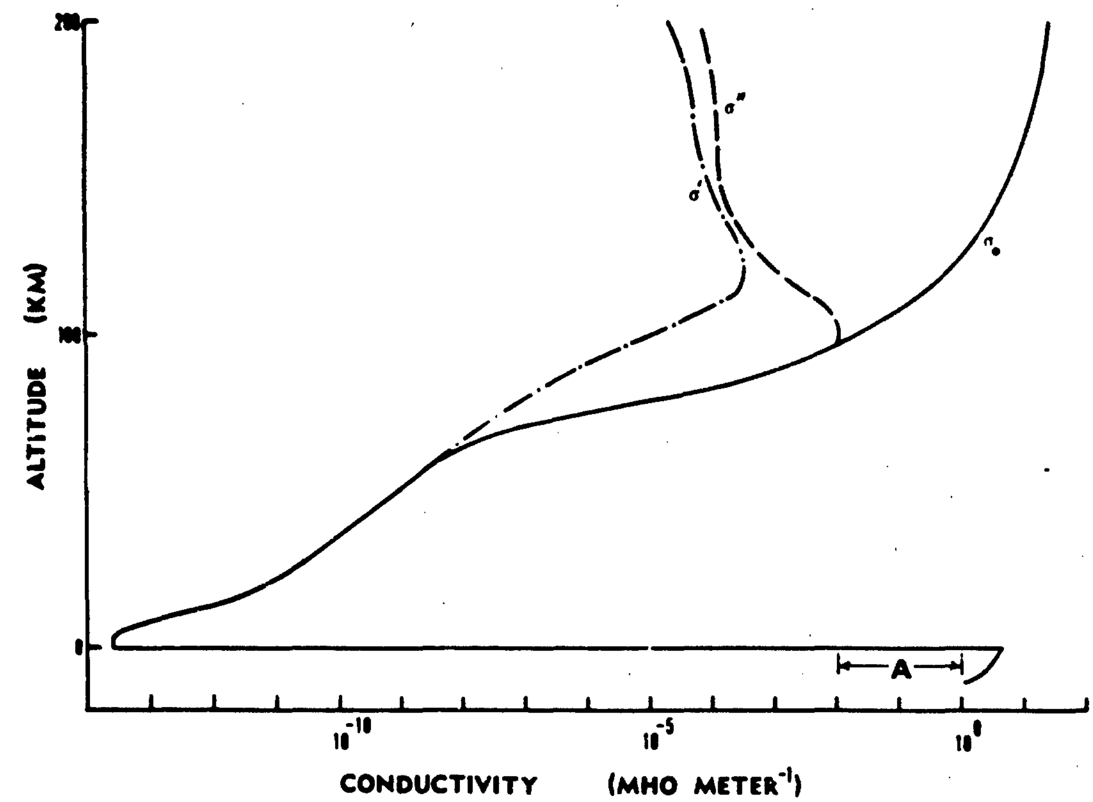

Figure 4. Vertical distribution of the specific (σ_0), Pederson (σ') and Hall (σ'') conductivities for typical midlatitude noon conditions after Cole and Pierce (1965) from the surface of the ocean to 100 km and Hanson (1965) from 100 km upward. The symbol A refers to the range of variable conductivity of the earth's surface layers.

and molecules of the neutral flow when that flow is downward. Using the open circuit approximation of Equation 5 (in the absence of an effective return circuit path) with vertical speeds of one meter per second at 80 km and 10 mps at 100 km acting on ions of molecular weight 30 a vertical upward-directed equilibrium electrical field of the order of .066 volts per meter at the 80 km level is obtained, decreasing in strength below and above that level with a value of .015 at the 100 km level as is illustrated by the E_v curve of Figure 5. The charge separation process will produce an opposing electric field which will rigidly maintain a positive space charge in the stratopause region and a negative space charge in the ionosphere during the morning and early afternoon. This region of separated charge will exhibit a diurnal structure under control of the tidal circulation which continuously rotates around the earth at a speed of approximately 460 mps at 15 degrees latitude.

The same reasoning may be applied to evaluate the electrical structure which will result from the tidal upward flow which is indicated to occur (Figure 2) as the heat wave recedes locally from 2 P.M. until sunrise. Using vertical circulation values of .4 of the morning values (from mass continuity considerations) for the late afternoon period from 2 P.M. to sunset, mean values of E_v will be approximately one fourth the noontime values illustrated in Figure 5, with the principal additional difference being that the direction of the resulting electric field will be reversed. The efficiency of this source of electric field generation will decrease during the evening as a result of the diurnal decrease in electron density.

The general circulation will also produce electrical charge separation through horizontal application of the process indicated in Equation 5. This mode will be globally asymmetric in that it will be most effective in the sunlit hemisphere as a result of the enhanced concentrations of electrons and positive ions. This time assuming that the electrons of the 80 km region will remain essentially with the magnetic field while the ions will be carried along with the wind (a short circuit), nominal values of 10^9 electron-positive ion pairs per cubic meter, and a wind speed of 100 mps normal to the magnetic field, a current density (J) is obtained from Equation 6 to be of the order of 1.6×10^{-8} a m^{-2} in the direction of the wind. Using the same wind speed, a positive ion-electron concentration of 10^{10} at 90 km yields 1.6×10^{-6} a m^{-2}. This latter value would remain essentially unchanged with height up to approximately the 140 km level, where the collision frequency is inadequate to carry the positive ions across the magnetic field and the charge separation process would stop. In the case of a west wind, which corresponds to the winter season in the monsoonal circulation, the circulation-produced current will be in the same direction as the tidally produced current, so the current produced by the general circulation of winter will enhance the dynamo current in the morning circuit and decrease the intensity of the evening circuit. An east wind, typical of the summer season, will tend to move positive ions westward, and thus the current the summer general circulation produces will oppose that produced by the morning tidal circulation

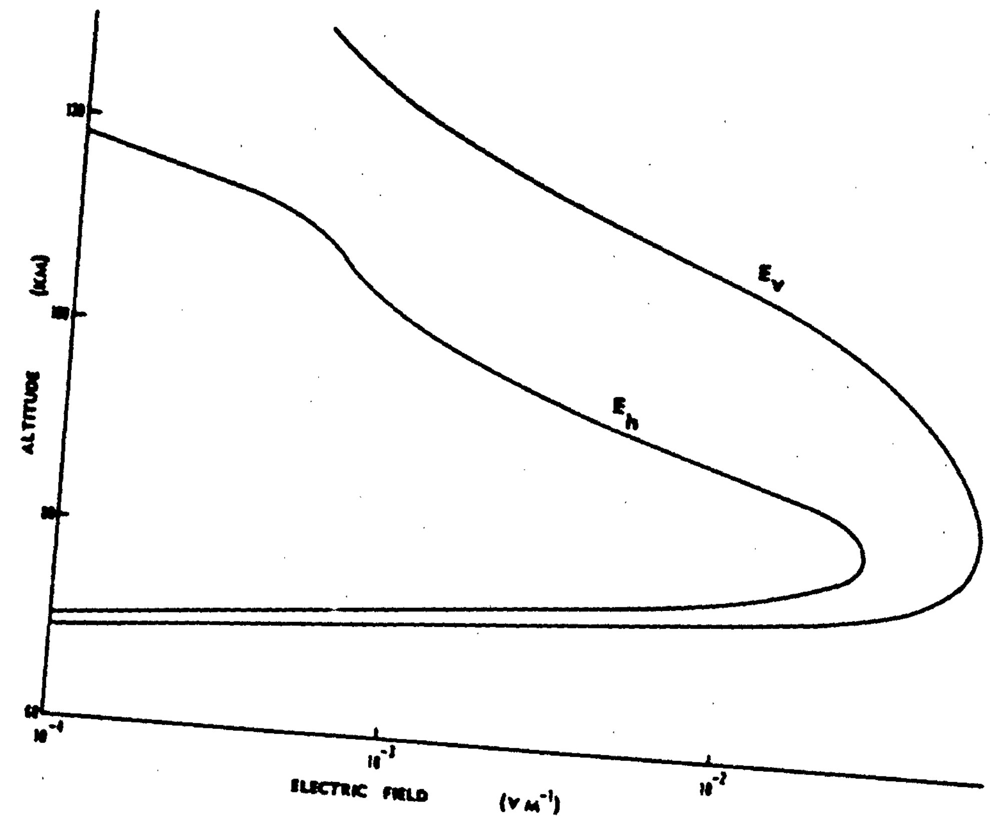

Figure 5. Vertical distribution of the negative electric field (E_v) generated by a noontime downward motion of the tidal circulation of one meter per second at 15 degrees latitude and the zonal electric field (E_h) produced by the Hall effect associated with E_v.

and enhance the evening current. This mode of electrical structure generation will then introduce an annual variation into the intensity of the dynamo current circuits and will tend to shift the time of day in which the maximum electrical intensity is reached.

A final mode of generation of electrical structure concerns the cross product of the general circulation and the magnetic field. This force will be vertical so that the circuit will be largely open and the equilibrium electric field will be given approximately by

$$\vec{E} = \vec{v} \times \vec{B} \tag{11}$$

Using 100 mps and .34 x 10^{-4} webers per square meter, an equilibrium electric field of .0034 volts per meter is obtained. This electric field will have the same orientation as the tidally produced field during morning hours at low latitudes when the circulation is easterly, but will diminish that tidally produced electric field in the case of winter westerlies.

Juxtaposition of electric and magnetic fields in an ionized gas will result in imposition of forces on charged particles in a direction normal to the plane of the field vectors in the direction of the cross product of the electric and the magnetic vectors (Fejer, 1965). In the D and E regions the ions are immobilized (relative to motions through the gas) by collisions so that the electrons are the principal carriers of this "Hall" current. The speed of electron motion (unhampered by collisions) constituting such a current is given by Equation 12

$$v = \frac{\vec{E} \times \vec{B}}{B^2} \tag{12}$$

Using values of B = .34 x 10^{-4} webers per square meter directed northward and E = .066 volts per meter (Figure 5) directed upward as obtained during the morning hours (Figure 2), a westward velocity of electron motion of approximately 2 x 10^3 mps is obtained for the 80 km altitude.

The horizontal motion of electrons described above involves motion across the magnetic field and will result in development of additional electrical forces. The second term of Equation 1 indicates an upward force on the electrons participating in the westward Hall current. The electric field required to stop charge separation (an open circuit) from this mechanism is approximately .068 volts per meter directed upward for the 80 km case described above. This process will then augment the vertical electric field generated by the downward tidal motions by an approximate factor of two, which will in turn strengthen the Hall current. This open-ended process is limited by electrical resistance to the Hall current flow which, through collision processes, exerts a force equal to mvv. At 80 km this circuit impedance results in a back emf which is of the same order as the additional Hall emf which is gained by the $\vec{v} \times \vec{B}$ process. It is probable that the current indicated in Figure 5 for that level is approximately correct. At 100 km, however, the back emf is an order of magnitude less than the $\vec{v} \times \vec{B}$ gain, so the 10^{-5} a m^{-2} indicated in Figure 5 is probably low, possibly by as much as an order of magnitude.

The current density carried by such a system can be calculated by use of Equation 6, which yields an 80 km value of 2.6×10^{-7} a m^{-2} when a concentration of 10^9 electrons per cubic meter is used with the motion derived above. Now the electric field associated with such an electric current can be calculated from Equation 7, using a value of 10^{-5} mhos per meter obtained from Figure 4. This calculation yields an eastward-directed horizontal electric field at 80 km of .026 volts per meter which, over a longitudinal span of 1.5×10^7 meters over which the downward flow occurs, indicates a potential difference of 384,000 volts between sunrise and early afternoon along the longitude circle at 15 degrees latitude. Similar calculations at other altitudes indicate that the vertical distribution of the midday Hall current of low latitudes is of the type illustrated in Figure 6. The circulation-generated dynamo current will reverse direction seasonally with the monsoon and should have an apparent influence on the upper E region electrical structure where the tidally produced structure is small and at other locations where the dominant tidally produced electrical structure is reduced. These considerations lead to the conclusion that in a longitudinal belt at low latitudes ($\sim$ 15 degrees) there will be a region of electromotive force (emf) generation with a potential difference of the order of 4×10^5 volts at the base of the E region between the early morning sector and the early afternoon sector (Figure 7) for each meter per second of vertical downwind of the tidal circulation at 80 km altitude. The direction of this potential gradient is such that the early morning sector (B) is depressed in potential relative to the early afternoon sector (A).

In the afternoon and evening the tidally generated electric fields which generate the Hall currents will reverse direction and be oriented downward. The Hall current will then flow westward after 2 P.M. The electron density of the E region decreases throughout this period to make the Hall current generating process ineffective during the late nighttime (smaller than noontime by two orders of magnitude). It is clear, then, that the sunset dynamo circuit is weaker than the morning circuit.

Flow of these dynamo currents in the E region ($\sim$ 100 km) of the atmosphere will result in development of a diurnal pattern of electrical potential distribution in that region. The above analysis indicates that

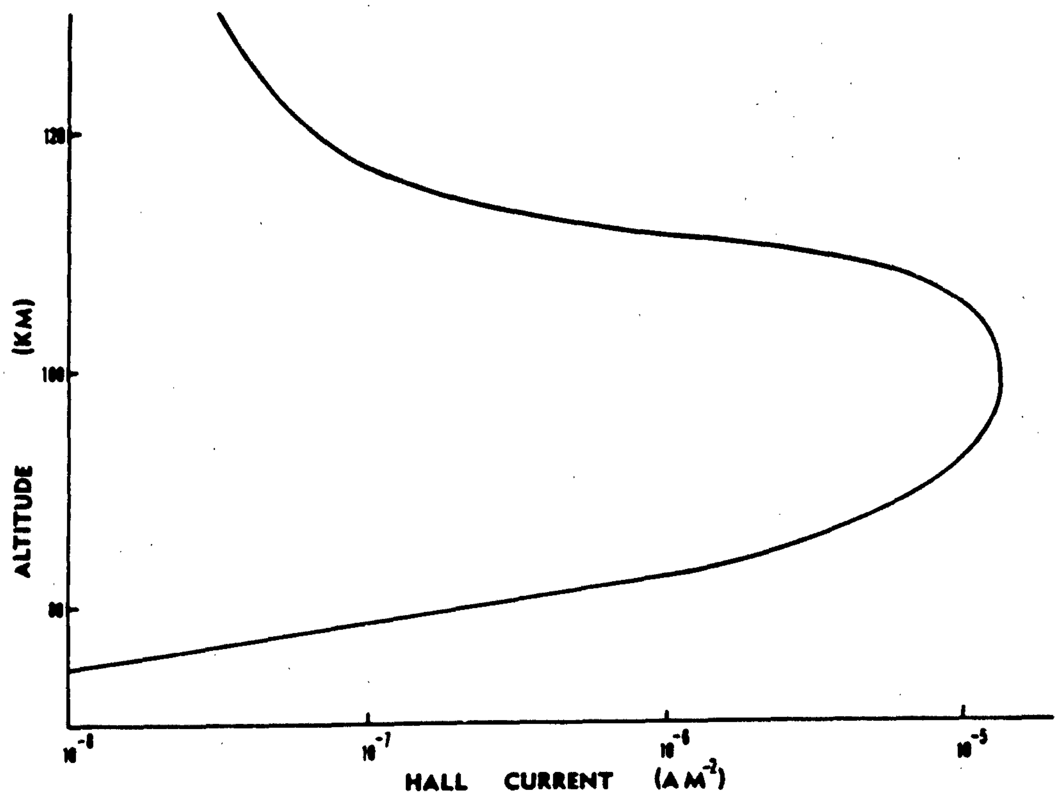

Figure 6. Hall current produced in low latitudes by a tidal downward motion of one meter per second at 80 km altitude as the heat wave approaches. The direction of current flow is to the east.

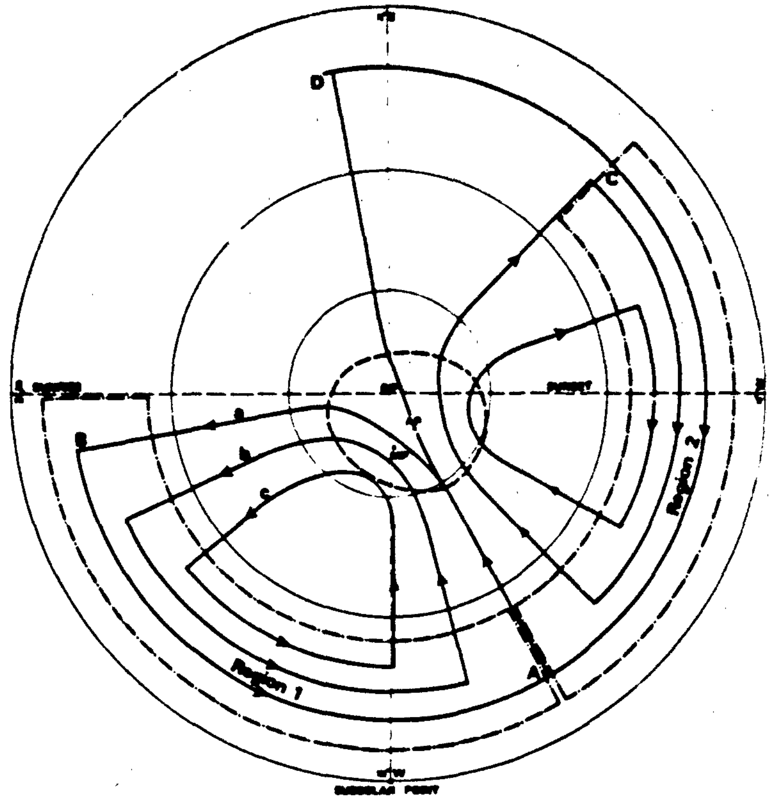

Figure 7. Equatorial projection of the dynamo current system. Regions 1 and 2 (enclosed by dash-dot curves) represent regions of electromotive force generated by vertical tidal motions. Positions of the rotational (RP), magnetic (MP) and auroral (AP) poles for the Northern Hemisphere are indicated. The point of highest electric potential is at A. The dashed circular curve represents the centerline of the auroral zone.

the maximum potential will be located geographically near the point marked A in Figure 7 (near 2 P.M. at low latitudes). Minimum potential should be located near the point of Figure 7 marked B. Significant diurnal differences will be induced in the hemispheric dynamo currents at equinox times as a result of asymmetries between the rotational and magnetic axes, and as a result of equatorial separation of the vertical tidal circulations over the rotational equator there will be a reduced potential between the low latitude emf regions of the two hemispheres. More substantial hemispheric differences will develop as the subsolar point moves away from the equator, with the summer hemisphere being favored with a stronger tidal circulation and enhanced electron concentrations, and thus with a stronger dynamo current and greater potential differences. All of these factors indicate that potentials in equatorial regions will be different between hemispheres for similar geomagnetic latitudes and make it probable that trans-equatorial currents will flow between the hemispheric emf zones, probably from the summer toward the winter hemisphere.

Such currents will flow along magnetic field lines, so the specific conductivity (solid line) of Figure 4 would be applicable. These currents would start near the 100 km level of one hemisphere on a magnetic field line, progress upward in a divergent field to cross the magnetic equator at a few hundred (and/or thousand) kilometers altitude, and converge back to the 100 km level at the same low latitudes of the other magnetic hemisphere. This low latitude interhemispheric dynamo current circuit is in the location of the inner Van Allen radiation belt (Van Allen, 1959) and presumably provides the basic energy for that phenomenon. The inner radiation belt electric current path then serves to smooth inequalities in the hemispheric tidally produced emf regions. There should be marked diurnal variations in the basic currents flowing in the region of the inner radiation belt. Some of the electrons and ions taking part in these exospheric currents will, as a result of their favored initial trajectory angles and thermal energies, be trapped in the magnetic field for short or long periods. These trapped particles will drift longitudinally (electrons drifting to the east and positive ions to the west) along L-shells (Heikkila and Axford, 1965) to envelope the entire low latitude global region in a few tens of minutes in the case of particles with energies in the millions of electron volts. Thus, the daytime dynamo regions supply the inner Van Allen radiation belt with ions and electrons which then interact with the nighttime upper atmosphere of middle and low latitudes as they drift around the globe, resulting in enhanced ionization and heating in low and middle latitudes of the nighttime D and E regions and forming a ring current in the upper ionosphere which will serve to reduce the meridional component of the earth's magnetic field.

In order for these hemispheric generators of dynamo currents in the 100 km E region to be effective it is necessary that there be return current paths in the E region. Such paths will be minimum resistance paths from the high to low potential regions. The very low conductivity which results from a high collision frequency of positive ions in the D region will limit electrical currents which could constitute return flows at altitudes below the emf zone, and rigidity of the magnetic field will preclude an effective electron current flow above. Positive and negative ions will move in opposite directions as a result of this horizontal electric field in the 100 to 140 km region, and this current flow will serve to weaken the tidally generated emf. An important return current path is available in the meridional direction, where at least part of the path can be traversed at an enhanced conductivity (the specific conductivity) along the magnetic field lines. At the magnetic equator the meridional conductivity would be essentially that indicated by the solid curve of Figure 4, decreasing with increasing magnetic latitude until in polar regions the conductivity will be reduced to essentially the Pederson values which are representative of those regions.

Estimated columnar resistivities along three legs of three selected paths in Region 1 illustrated in Figure 7 are tabulated in Table 1. Also listed are the fractional parts of the total path resistance which are contained in the separate path segments. These values indicate that gross lateral differences in potential exist in the E region on a global scale. Assuming that the dynamo current is conservative (no convergence or divergence) along the path "a", the potential will fall from its

Table 1. Columnar resistivities (R) and fractional parts (F) for paths a, b and c of Figure 7. Resistance units are 10^{-0} ohms.

	a		b		c	
	R	F	R	F	R	F
Poleward	1.2	.31	1.2	.33	1.0	.5
Auroral	.7	.25	.5	.20		
Equatorward	.9	.44	.9	.47	1.0	.5
Total	2.8		2.6		2.0	

highest value at point A (say 10^6 volts) to .69 (see Table 1) of that value ($.69 \times 10^6$ volts) at the auroral zone. Across the auroral zone the IR drop will result in a potential fall of an additional .25 of the total to $.44 \times 10^6$ volts, and over the equatorward leg of path a the potential would fall to its lowest value at B. The sunlit hemisphere of the E region is thus always at an elevated potential relative to the nighttime region, with a maximum in low latitudes near 2 P.M., while the hemispheric minimum is located near 4 A.M. in low latitudes. It is clear that such a structure in the potential field of the base of the ionosphere will have important implications for the boundary regions above and below the D and E regions in which this basic phenomenon is located.

The mode of interaction between the ionospheric dynamo current and the earth's magnetosphere is illustrated in Figures 8 and 9. The situation is illustrated for the equinox case with the sun's rays roughly normal to the plane containing the rotational and magnetic vectors. In Figure 8 the subsolar point is located over 160 degrees west longitude, and in Figure 9 it is over 20 degrees east longitude, just twelve hours later. The projections of the dynamo current circuits of each hemisphere are idealistically represented by dashed curves. It is obvious that the electric potential of the dynamo current ($\sim$ 100 km altitude) considered above will not generally be equal at each end of any high latitude geomagnetic equipotential line even if the interhemispheric inner Van Allen radiation belt currents do maintain the hemispheric emf zones at essentially equal potential. In the case illustrated in Figure 8 the Northern Hemisphere magnetic field lines at sunrise (on the left) will be at a higher electric potential (in auroral zones of the order of 10^4 volts for each meter per second of downward tidal wind) than will the Southern Hemisphere ends of those magnetic field lines (for example, compare B and B'). These voltages are quite large when considered in the light of the impedance of the magnetic field line paths, which might have a total columnar resistance of the order of 10^5 ohms per square meter at 70 degrees geomagnetic latitude. Large currents of the order of 10^{-1} amperes per square meter can be expected to flow from one hemisphere to the other along the magnetic field lines (Mozer and Bruston, 1966; Blake et al., 1966; Somayajulu, 1964), limited principally by the reduced conductivity of the field lines in the upper atmosphere near the dynamo level and the mechanics of individual charge motion in the exosphere along the magnetic field lines.

It is informative to look at the situation twelve hours later as is illustrated in Figure 9. In this case the Northern Hemisphere ends of the magnetic field line ending at B are at a lower electric potential than those same field lines at B' in the Southern Hemisphere. These considerations indicate that there is a diurnal variation in all of the phenomena that result from this interhemispheric electrical difference which basically is a result of asymmetries between the rotational and magnetic axes. That is, the exospheric current will flow from B to B' in Figure 8, and it will flow from B' to B in the case illustrated in Figure 9.

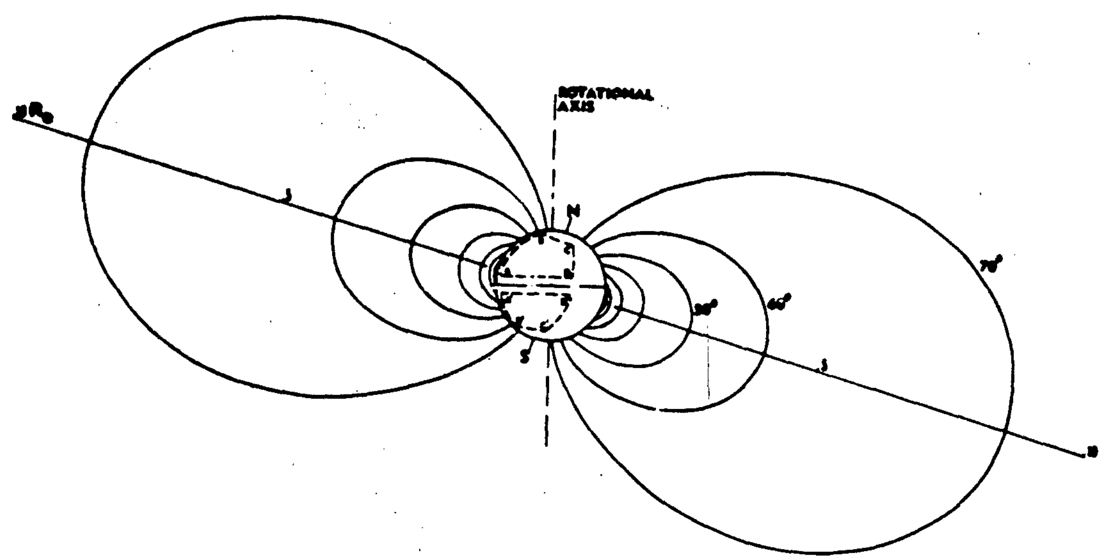

Figure 8. Equinoctial cross section of the earth's geomagnetic field when the sun is over 160 degrees west longitude. The dashed curves represent projections of hemispheric circuit elements of the tidally generated dynamo current.

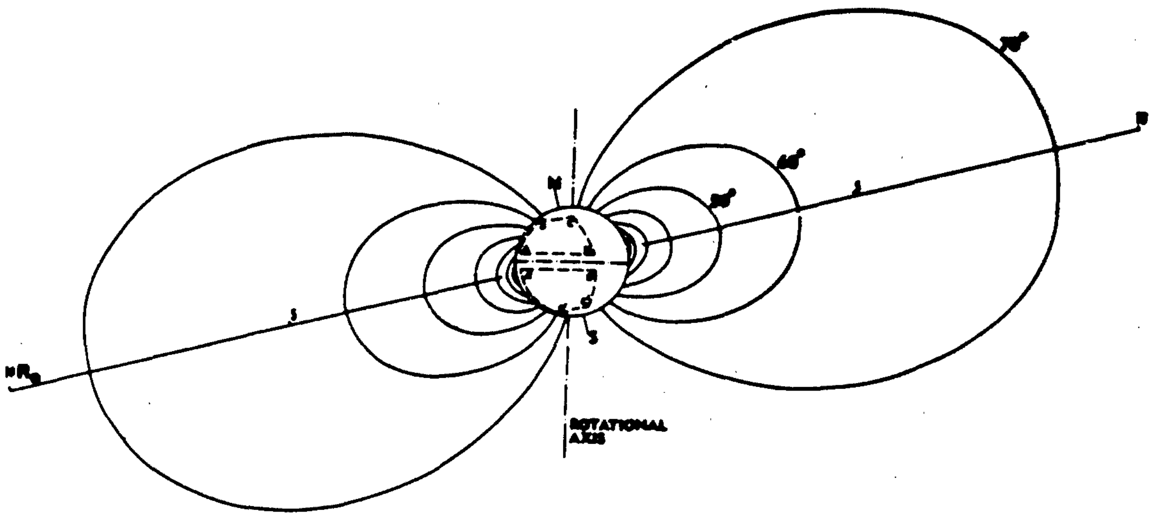

Figure 9. The same situation illustrated in Figure 8 except that the sun is over 20 degrees east longitude.

In addition, it is clear that at the time a current is flowing from B to B' in the case illustrated in Figure 8, a current will also be flowing from C' to C in the early afternoon sector. A possible current circuit is then along the 70 degree magnetic latitude field line from the Northern Hemisphere auroral zone (B) out through the earth's near space and back to the Southern Hemisphere auroral zone (B'), eastward along that auroral zone to the point C', and then back to the Northern Hemisphere auroral zone (C) along the 70 degree magnetic latitude field line which projects toward the sun in the early afternoon sector. Since we are here considering only an extreme simplification of the actual dynamo current distribution, it is clear that the longitudinal high latitude currents termed auroral electrojets (Gottlieb and Fejer, 1967; Davis and Sugiura, 1966) in the high conductivity E region of auroral zones will play important parts in the global electrical current circuits which have their origin in stratospheric tidal circulations.

The exospheric current path discussed above is representative of the principal exospheric current paths which must exist. That is, in the sunlit hemisphere over the primary dynamo circuits the potential differences between hemispheres will be maximum and the conductivities required to transport the currents will be maximum. This does not preclude the flow of currents in the nighttime exosphere but surely should result in gross diurnal changes in character of the currents. Drifts of electrons (eastward) and positive ions (westward) which become trapped (a small fraction of the particles participating in the interhemispheric currents) would populate the nighttime outer Van Allen belt, and the precipitation of these particles in the nighttime auroral zones would provide enhanced conductivity so that longitudinal currents will flow in the nighttime auroral zones, completing additional exospheric current circuits. These processes, along with the known diurnal expansion and contraction of the exosphere through the permanent magnetic field (Harris and Priester, 1962; Jacchia and Slowey, 1964) and variations in the dynamo electric potentials could be the mechanisms which result in buildup of a stored component of hard radiation (Vestine, 1954) and subsequent preferred dumping in the nighttime region. The resulting increased conductivity in nighttime auroral zones would then provide additional current paths through high latitudes from the nearest high conductivity region of the daytime sector. The division of the high latitude portion of the current circuit marked "a" in Figure 7 between the two dynamo current systems of early morning and late afternoon would then become more complex in the nighttime auroral zone, with the switch between control by the two dynamo systems occurring in the early morning hours near 2 A.M. Observational data on auroral characteristics during this period do indeed indicate a dramatic change (Davis, 1960).

Many of the observable electromagnetic phenomena exhibit semiannual variations with maximums at equinox times. An understanding of the reason for this pronounced cyclic variation is essential for any general concept of electrical and magnetic structure. The point is well illustrated in Figure 10. A cross section is presented here which roughly includes the rotational axis, the magnetic axis and the sun at solstice time in the Northern Hemisphere. The most obvious fact is that all of the high latitude magnetic pole in the Southern Hemisphere is denied the ionizing solar ultraviolet radiation during a part of the diurnal cycle, and only the lower portion of the auroral zone magnetic field lines are connected when maximum opportunity is afforded twelve hours later than the case illustrated in Figure 10. In general, lack of solar ultraviolet radiation means that the D and E regions of the ionosphere will have roughly two orders of magnitude less in electron concentration. This, coupled with the failure of the dynamo current to reach high latitudes in the winter hemisphere limits the flow of current into the higher latitude magnetic field lines of the outer Van Allen belt and thus limits the occurrence of phenomena which depend on this mode of operation. This does not necessarily mean that less total interhemispheric current flows, but simply that the current must follow other paths, or accomplish it in a way which is less efficient in generating observable auroral and high latitude magnetic phenomena. For instance, it is well known that ionospheric electron densities are noticeably high in middle latitudes of the winter hemisphere (the winter anomaly) when compared to the calculated values obtained from static solar-atmospheric interactions.

The high geomagnetic latitude mode of hemispheric interaction between the dynamo current circuits occupies the exospheric location of the outer Van Allen radiation belt (1959). Thus, the basic control and power for the outer radiation belt appears to center in high latitude potential differences of the primary dynamo current circuits. Interaction of the earth's magnetosphere with the solar wind will complicate the current system involving the outer radiation belt, particularly with regard to the high energy portion of the trapped radiation spectrum. These exospheric currents will result in gross modifications of the potential distributions along the primary dynamo circuit. For instance, if the inner radiation belt current should produce a net flow from low latitudes of one hemisphere to the other, the outer radiation belt is very likely to constitute the return path of that current. Such a current path could be illustrated by a flow from point E (Figure 8) of the Northern Hemisphere through the inner Van Allen belt to point A', meridionally to the auroral zone at B', exospherically to B and meridionally back to E. A large number of similar parallel circuits are immediately obvious.

The known presence of auroral activity in high magnetic latitudes of both hemispheres will result in significant modification of the simplified picture of the dynamo currents presented in Figure 7. Measurements of precipitating electrons (Gledhill et al., 1967) and protons (Sharp et al., 1967) in auroral zones indicate the presence of currents along the magnetic field lines of the order (10^{-3} amperes per square

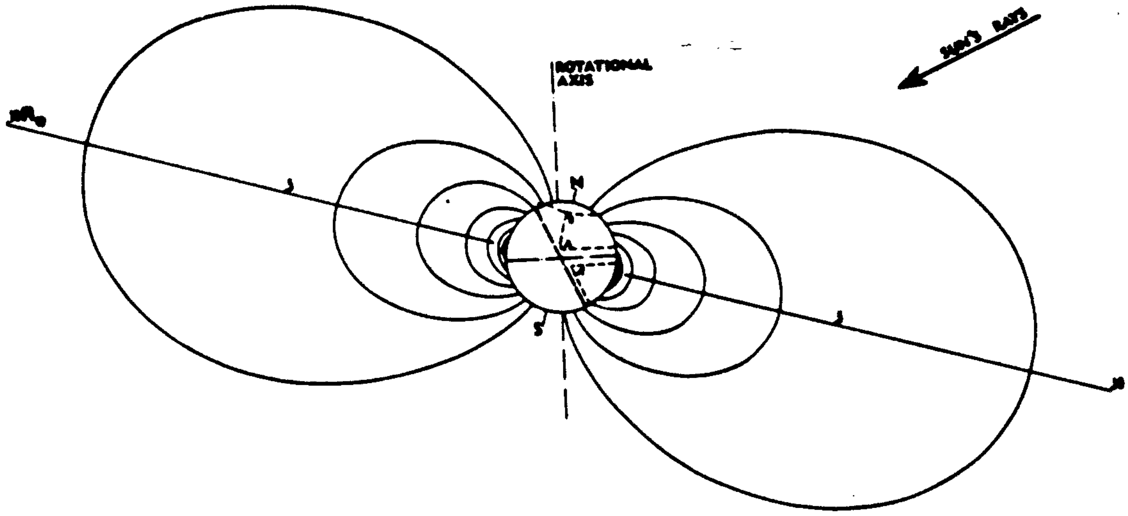

Figure 10. Cross section of the geomagnetic field in the plane of the sun's ray when the sun is over 70 degrees west longitude. The heavy dashed line marks sunrise, and the light dashed line indicates an element of the dynamo circulations and the northern auroral zone projected on the above plane.

meter) of those calculated in the dynamo current. Much larger fluxes of energetic electrons have been noted in middle latitudes (Paulikas et al., 1966), and there is reason to expect the precipitation of protons in these regions (Prag et al., 1966). Brace et al. (1967) have suggested such a source of precipitating particles for maintenance of observed high electron (and possibly ion) temperatures in the ionosphere at night, and the presence of airglow throughout the night would indicate some such energetic flux. In addition, Brace et al. (1967) have shown thermal structure of the 1000 km level which requires special sources and sinks of heat. All of these observations can be considered to be in general agreement with heating and ionization effects of important interhemispheric currents flowing along the magnetic field lines.

The electrons and positive ions in these interhemispheric current flows, particularly in the outer belt circuit, will attain high speeds in the electric potential drop (of the order of 10^4 volts for each meter per second of the tidal vertical motion) as they traverse the earth's near space along the magnetic field lines. This energy will be dissipated in collision processes as the individual charged particle mode of current flow is interchanged for the usual conduction mode. Hot electrons, ionization and photoemission will be expected results in the E and F regions along the paths near terminal points of these exospheric current circuits. Examples of observed ionospheric thermal and kinetic structure which can now possibly be ascribed to joule heating by these electric currents have been published by Harris and Priester (1962), Nagy and Walker (1967), Jacchia and Slowey (1964), Gleeson and Axford (1967), Jacchia et al., (1967), Cummings and Dessler (1967), Schilling and Sterne (1959), Becker (1967), Dalgarno et al., (1967), Banks (1967) and Cook (1967).

Superimposed on the hypothetical current pattern of the dynamo circuit which is illustrated in Figure 7 will be the above described regions of convergence and divergence in the dynamo current system which will involve comparatively large exospheric current flow into and out of the horizontal primary dynamo circuit from above. The geometry and intensity of these currents will be determined by interaction between the earth's magnetosphere and the solar wind, solar induced variations in the electrical conductivity of the dynamo region and through variations in the tidal motions which serve as the basic source of power for the dynamo current systems. The first two controls represent the well known solar influence through particulate and wave emissions incident on the electrical and magnetic structure of the earth, while the last source of control represents a new quasi-independent neutral atmosphere mode of establishing the electrical and magnetic structure of the atmosphere. Observational data point very clearly to the fact that the smooth character of the curves of Figure 7 is a gross simplification and that a principal feature of the stratospheric tidal circulation and ionospheric conductivity is a strong variability. The variability of the earth's electrodynamic structure which is known through observations of particular events is then a composite result of variable inputs from the atmospheric circulation and the solar impact on this dynamic medium.

The above described production of a Hall current system in each of the hemispheres through vertical tidal motions at low latitudes can be expected to result in certain complications in equatorial regions. This is true because the rotational and magnetic equators do not coincide, and further because the magnetic intensity along the magnetic equator is variable. Thus, when the magnetic equator is in low latitudes of the Northern Hemisphere, such as in the Indian Ocean, the electrical structure of the Northern Hemisphere would be intensified because the Hall effect will be most effective where the tidal downflow of low latitudes is most nearly normal to the magnetic field. By the same token, maximum electrical intensity should shift to the Southern Hemisphere when the magnetic equator is south of the rotational equator, as will be the case in the South American region. There should be, then, a marked diurnal variation in the interhemispheric currents.

Splitting of the tidal circulations on each side of the rotational equator may well provide a structure in which the vertical winds over the equator are quite small at the eighty kilometer level. The tidally produced electrification would then be small in that region and the other modes of electrification might become apparent. In particular, advective transport of positive ions across the magnetic field by the general circulation should first be noted. If such were the case, certain results should be clearly observed. Namely, an easterly circulation over the rotational equator should serve to diminish the characteristic eastward-directed dynamo current while a westerly circulation should enhance that current.

Just such effects have been observed by Cahill (1959) in measurements of the equatorial electrojet (Chapman, 1951); Maynard and Cahill, 1965; Balsley, 1965; Sugiura and Cain, 1966; Gassmann and Wagner, 1966; Ogbuehi et al., 1967) with a rocket-borne magnetometer. On 17 August 1957 at 1359 165th meridian time at 159 degrees west longitude and 3 degrees north latitude a weak westward-flowing current was observed with the base at 104 km. On 18 October 1957 at 1356 near the same location a strong eastward-flowing current was observed at approximately 97 km, and on 19 October 1957 at 0907 a much stronger eastward-flowing electrojet was noted, based just above 90 km. These data would indicate that the monsoonal circulation is indeed significant in this region, since it is known that the upper atmospheric circulation has easterly winds at that location in August and westerly winds in October (Webb, 1965, Figure 4.21). The equatorial high altitude circulation exhibits a semiannual variation, with easterly winds during the period from mid-May to mid-August and mid-November to mid-February, and westerly winds during the intervening periods. Cahill's results would then indicate that the circulation transport mode of charge separation is effective but is smaller than the tidal mode, except immediately above the equator so that the circulation mode simply modulates the total electrical structure in other regions, making the total intensity of the dynamo current circuit greatest where the circulation is westerly. The strength of the tidal mode may vary in some special mode, so the electrical structure resulting from these two processes may well vary in a more complex fashion than is indicated here.

The role of thunderstorms in atmospheric electrification has been the subject of considerable discussion over the years. They have been assigned roles which range from the original source of electromagnetic force for all electrification effects in the lower atmosphere to a strictly passive role in the earth's electrical structure. There is no firm evidence to support differentiation between these two extremes. It is true that, whatever the cause or purpose of thunderstorm electrification, the physical processes and particularly the lightning discharges associated with these storms provide a low impedance path across the lower atmosphere and thus provide a partial short across the lower troposphere where maximum atmospheric impedance to vertical flow of electric current exists. Using approximations of continuous lightning discharge paths across the lower 10 km of the atmosphere, the columnar resistance is reduced from a nominal value of 5×10^{16} ohms per square meter to the order of 5×10^{15} ohms per square meter, and may well be further reduced at higher altitudes (Cole, Hill and Pierce, 1966). Thunderstorms thus provide a process which results in the earth's surface assuming an electrical potential almost equal to that of the ionospheric dynamo current region above the thunderstorms and providing an additional current path for return flow of the dynamo currents.

Thunderstorms exhibit a maximum occurrence in low latitudes at about 1900 local time over land and shortly after midnight over oceans. The thunderstorm short-circuits are then postulated to tie the earth's surface in those regions to the dynamo circuit potentials above those regions. Negative charge is known to be transported downward by lightning discharges in an amount approximately equal to the positive charge which is constantly transported downward by diffusion to the earth's surface by the fair-weather electric field. This particular leg of the dynamo electrical circuit carries a total current of approximately 1500 amperes, which is of the order of one percent of the current carried by the primary dynamo circuit. Tropospheric electrification is thus indicated to be a result of the dynamo electrification, possibly locally in particular cases supporting or opposing the operation of the primary dynamo emf but always responsive to it.

The picture of tropospheric electrification drawn above attributes the observed effects to the dynamics of a current system, which means that the current collected by the earth in fair-weather regions must flow through the crust of the earth to the thunderstorm locations in which the current flows back upward into the ionosphere. Measurements of telluric currents in the earth's crust do indeed indicate a systematic flow of electric current from the poles toward the equator during the afternoon and from the equator toward the poles at night (Chapman and Bartels, 1940). This would indicate that the early evening maximum in thunderstorm occurrence is of prime importance in establishing the difference in potential between the E region and the earth's surface.

The thermal structure of a medium is modified by the flow of an electrical current (Cole, 1962; Kato, 1962). In the direct current case the power dissipated by the current is given by

$$H = I^2R \tag{13}$$

in joules per cubic meter per second. In the primary dynamo circuit where the Hall current is generated the peak current of 10^{-5} amperes per square meter (Figure 6) with an impedance of 10^2 ohm meters (Figure 4) will yield a heat deposit of approximately 10^{-7}, or one erg per cubic meter per second. This energy input, if translated principally into heat, would result in very high temperatures for the ambient air molecules. Clearly the energy supplied by flow of the dynamo current is adequate to supply the heat required by the observed thermal structure of the thermosphere (Nicolet, 1961) as well as the kinetic energy of the particles taking part in the exospheric currents and all photoelectric effects observed in the upper atmosphere.

Exospheric electric currents will be characterized by two modes of electric energy dissipation. First will be standard I^2R conversion of Equation 13 to thermal energy in the upper atmosphere immediately above the 100 km level, although the sharp reduction of resistivity with altitude along the magnetic field lines will significantly reduce the heat deposited by these currents. The exponential decrease in heat capacity of the upper atmosphere with height will far exceed the divergence of the magnetic field lines, however, so that as long as the charged particles experience sufficient collisions to exchange their energy to the neutral molecules as thermal energy the temperature of the upper atmosphere should increase with height. When the trajectories of the charged particles are free of collisions they will accumulate a speed consistent with the difference in potential between the ends of the magnetic field lines along which they are traveling. It is important to note that the dynamo current will not be a steady current, but will be characterized by a high degree of variability. These variations in electric field strength can provide for acceleration of these charged particles which enter the exosphere with sufficient thermal energy in addition to their static acceleration in the electric field to become a part of the hard trapped radiation.

5. Conclusions.

The earth's general electrical structure is found to have its basic origin in charge separation in the lower ionosphere which is produced by differential transport of the charge carriers by low latitude vertical winds of the stratospheric tidal circulations. Vertical electric fields are generated in the E region in low latitudes of each hemisphere which, in conjunction with the earth's permanent magnetic field, power Hall current circuits which flow longitudinally toward the early afternoon sector and have their principal return paths through high latitudes. These primary dynamo currents produce gross structure in the horizontal electrical potential distribution of the E region which is not symmetrical between the magnetic hemispheres, with a resulting development of interhemispheric currents along magnetic field lines and provide the basic particle fields and power sources which form the radiation belts. The inner radiation belt currents serve to equalize hemispheric differences between the emf regions and the outer radiation belt currents serve to equalize differences in potential between auroral zones. A third electrical circuit is formed between the lower ionosphere and the earth's surface by a relative short circuit effected by thunderstorms and their lightning discharges which connect the earth's surface to the negative potential of the nighttime dynamo circuit so that a small part of the dynamo currents flows in the fair-weather electric field circuit.

This electrical structure generating mechanism serves as the source of the following atmospheric phenomena:

a. Airglow, which is powered by electrical phenomena associated with flow of the primary dynamo currents and their exospheric components and interaction of these systems with the neutral atmosphere.

b. Auroral activity, which in part represents current flows between hemispheres along high latitude magnetic field lines as a result of differences in potential developed by the E region dynamo currents in polar regions. Charged particles collected from the solar wind are also sorted and precipitated as well as accelerated under the special influence of these geoatmospheric internal electric fields.

c. Thunderstorm electrification, where the lightning discharge paths provide an effective short circuit connecting the earth's surface with the primary dynamo circuit in its low potential region.

d. Fair-weather electric field, which represents the difference between the average potential of the atmosphere and the surface potential established as indicated in c above.

e. Fair-weather electric current, which conducts approximately 1500 amperes to the earth continuously as an auxiliary return path of the primary dynamo circuit.

f. Telluric currents, which flow in the earth's surface to complete the global circuit which includes the fair-weather electric current and current flow through thunderstorm lightning paths.

g. Magnetic disturbances at the earth's surface, which are the result of variations in current intensities in the primary dynamo circuits caused by variations in the tidal circulation, E region conductivity and solar particle collection. In addition, modifications of the exospheric magnetic fields must be expected as a result of the currents flowing in circuits located in vertical meridional planes.

The electron density of the upper ionosphere and the exosphere is controlled by the electrical structure of the E region. The charged particles of the exosphere and nighttime ionosphere are generally in transit under the direction of the electric fields of the primary dynamo circuits. It is necessary to this concept that these exospheric currents exhibit a diurnal reversal in the direction of flow. Such reversals will not modify the trapped components of these currents other than possibly to accelerate them as a result of the variations in the electric fields associated with variations in the dynamo emfs. These internal variations in the dynamo circuits will in addition be modulated by solar interaction through charged particle capture by the outer belt. However, the tender point for solar control of this system is in the E region through solar radiation induced variations in the conductivity.

The thermal structure of the upper atmosphere is concluded to be strongly dependent on the electrical structure. A dominant heat source is centered in the primary dynamo circuit at approximately 100 km altitude in the sunlit hemisphere, with smaller currents flowing in the nighttime E region. The peak energy input of approximately one erg per square meter per second appears to be adequate to produce the observed thermospheric daytime temperatures of the order of 2000° C. and nighttime temperatures of several hundred degrees and to have the correct distribution in space and time. Heat will be supplied below and above the dynamo circuit by electrical interaction between the primary dynamo current and the lower atmosphere and by interhemispheric currents which pass through the upper ionosphere to and from the exosphere. The heat of the dynamo current will be lost by being transported downward by conduction and upward by convection and conduction in addition to the losses through electromagnetic and particle emissions.

This initial look at the comprehensive electrical structure of the earth's atmosphere has clarified some aspects of atmospheric physical processes. It has pointed the way toward investigations which should serve to illuminate some of the points which, for experimental or theoretical reasons, remain as difficulties in clear understanding of the earth's electrical structure. Progress has come from the application of synoptic principles, emphasizing the fact that in a complex system such as the earth's atmosphere, isolated investigations depend on sheer luck for success.

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13. ABSTRACT

Synoptic rocket exploration of the stratospheric circulation has revealed the presence of hemispheric tidal circulations which are indicated to be in part characterized by systematic vertical motions in low latitudes of the sunlit hemisphere. These vertical motions are powered by meridional oscillations in the stratospheric circulation produced by solar heating of the stratopause region, and serve as the energy source of electrical current systems which are postulated to result from an impressed electromotive force which is produced by charged particle mobility differences in the lower ionosphere as the tidal circulations tend to force these particles across the earth's magnetic field. These dynamo currents are variable with geometry and time variabilities of the tidal circulations as well as variability in the solar-induced conductivity of the E region. The semiconducting lower atmosphere and highly conducting earth's surface occupy the near field of the lower side of this current system with a resulting complex tropospheric electrical structure. Low impedance electric current paths along magnetic field lines result in development of currents in the exosphere which are driven and controlled by the electrical structure of the primary dynamo circuit and exert a control of their own through interaction with the solar wind. The basic physical process which provides the required electromotive force for maintenance of the earth's atmospheric environment electrical structure is thus indicated to center in thermally driven tidal motions in the lower ionosphere, with locally observed structure such as the fair-weather electric field, thunderstorms, lightning discharges, aurora, airglow, electrojets, radiation belts, etc., playing supporting roles.

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7. Aurora						
8. Exosphere						
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