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THEORY OF AURORAL ELECTROJETS

by

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November 7, 1962

UNPUBLISHED PRELIMINARY DATA

To be submitted to

JOURNAL OF GEOPHYSICAL RESEARCH

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ABSTRACT

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Two mechanisms are described for the formation of electrojet currents in the auroral zone. Both mechanisms require the existence of magnetospheric convection in which only particles of relatively low energy participate. It is essential to both mechanisms that particles of one sign (positively or negatively charged) should predominate among the energetic ones that do not participate in the convection of the magnetosphere.

In the first mechanism the convection of the magnetosphere is taken to be of tidal origin and is driven by the electric polarization fields associated with the dynamo current systems.

In the second mechanism the convection is assumed to be the co-rotation of the magnetosphere with the earth, as modified by the solar wind that distorts the geomagnetic field.

In both mechanisms the ionospheric currents are a consequence of the relative motion between the less energetic particles that almost fully participate in magnetospheric convection and the more energetic particles whose

adiabatic drift motion across the magnetic field is only slightly perturbed by the electric fields associated with the convection of the magnetosphere.

If the latter particles are assumed to be the trapped energetic protons observed by Explorer XII (Davis and Williamson 1962) during magnetically quiet days, then either mechanism predicts variations of the order of $\pm$ 50 γ in the horizontal component of the geomagnetic field at auroral latitudes.

1. Introduction

It is generally believed that the quiet day variations Sq of the geomagnetic field are due to tidal motions and are caused by "atmospheric dynamo" action. The atmospheric dynamo theory has been on the whole successful in explaining the Sq variations at moderate latitudes and the enhancement of these variations in the vicinity of the magnetic dip equator (Hirono 1952, Baker and Martyn 1952, Fejer 1953). The intense ionospheric currents, inferred from the enhanced equatorial variations, are said to form the equatorial electrojet.

A similar but more variable enhancement of the diurnal magnetic variations is known to occur in the auroral zones during magnetically disturbed periods. These additional diurnal changes of the magnetic field, which are most striking in the auroral zone but extend to other latitudes as well, are known as the Ds variations. The ionospheric currents which are thought to cause the large Ds variations in the auroral zone are said to form the auroral electrojets. Recently Nagata and Kokubun (1962) have shown that even during magnetically quiet days there is a similar enhancement of the diurnal magnetic variations in the auroral zone.

Since the discovery of the trapped particle belt there have been many attempts to link it with the auroral electrojet currents. Chamberlain, Kern and Vestine (1960) have postulated that the electrojets are caused by the precipitation of previously trapped energetic particles of different sign at slightly different latitudes. Fejer (1961) has suggested that the ionospheric currents may be caused by a temporary asymmetry in the belt of trapped particles, that leads to charge separation in the magnetosphere. Kern (1961, 1962) has advocated an essentially similar mechanism. In any of these mechanisms the electric fields that cause the flow of ionospheric currents must necessarily also cause a convection of the magnetosphere.

An entirely different point of view is taken by Axford and Hines (1961). They regard the convection as the result of viscous interaction between the solar wind and the magnetosphere; the current system is according to them a consequence of magnetospheric convection.

In the opinion of the present author none of the above explanations is entirely satisfactory. Thus Axford and Hines (1961) do not give enough details about the nature or extent of the viscous interaction between the solar wind and the magnetosphere. Charge separation of trapped particles, as suggested by Fejer (1961) and Kern (1961, 1962) is a transient phenomenon that can only produce transient current systems, if the trapped particles are not monoenergetic; after some hours the adiabatic drift of the trapped particles establishes a steady state in which no further charge separation occurs. While such transient current systems may account for some of the observed charges in the geomagnetic field, the Ds magnetic variations appear to be of a rather steady nature and may persist for several days.

In this paper two new mechanisms are described for the formation of electrojet currents in the auroral zone. Both mechanisms require the existence of magnetospheric convection in which only particles of relatively low energy participate. It is essential to both mechanisms that particles of one sign (positively or negatively charged) should predominate among the energetic ones that do not participate in the convection of the magnetosphere.

In the first mechanism, the convection of the magnetosphere is taken to be of tidal origin and is driven by the electric polarization fields (Martyn, 1947) associated with the dynamo current.

In the second mechanism, the convection is assumed to be the co-rotation of the magnetosphere with the earth, as modified by the solar wind that distorts the geomagnetic field.

In both mechanisms the ionospheric currents are a consequence of the relative motion between the less energetic particles that almost fully participate in magnetospheric convection and the more energetic particles whose adiabatic drift motion across the magnetic field is only slightly perturbed by the electric fields associated with the convection of the magnetosphere.

The two mechanisms outlined above are described in Sections 2 and 3 of this paper. The choice of sequence in the description has nothing to do with the relative importance of the two mechanisms and is merely a matter of convenience. The discussion of these two mechanisms in two separate sections is moreover also rather artificial (although convenient) since the tidal motions and the co-rotation of the magnetosphere occur simultaneously rather than in isolation and the ionospheric currents caused by both these motions of the magnetosphere are influenced (though not to the same extent) by the distortion of the geomagnetic field due to the solar wind.

2. Ionospheric Currents of Tidal Origin in the Auroral Zone

Tidal motions of the atmosphere at ionospheric height are known to result in ionospheric currents. It is usual in theoretical treatments to assume that these currents flow in a relatively thin ionospheric shell between about 80 and 150 km, as a result of symmetry about the equator. Above 150 km the strongly anisotropic conductivity constrains the currents to flow along the field lines. Moreover, the entire current system must be free of divergence in the steady state and therefore no currents can flow at heights above about 150 km, if the motions of neutral air are symmetrical with respect to the magnetic equator. Within the ionospheric shell the current density $\underset{\sim}{J}$ must be nearly horizontal and is related to the horizontal component of the electric field $\underset{\sim}{E}$ by an equation of the form

$$J_x = \tilde{\sigma}_{xx} E_x + \tilde{\sigma}_{xy} E_y$$
$$J_y = -\tilde{\sigma}_{xy} E_x + \tilde{\sigma}_{yy} E_y$$

where the subscript x indicates the south component, and the subscript y indicates the east components of the electric field $\underset{\sim}{E}$ and the current density $\underset{\sim}{J}$, and where $\tilde{\sigma}_{xx}$, $\tilde{\sigma}_{xy}$ and $\tilde{\sigma}_{yy}$ are functions of the electron and ion number densities and collision frequencies (Baker and Martyn, 1952, Fejer 1953). The electric field is taken to be the sum of the polarization and the dynamo fields. The latter is defined as the electric field that would be seen by an observer moving with the neutral air in the absence of any polarization charges while the former is the electric field due to the polarization charges. The electrostatic potential due to polarization charges is then determined by the condition that the divergence of the height-integrated current density in the ionospheric shell must vanish in the steady state. The differential equation for the electrostatic potential (as a function of the geographical coordinates) that results from the above condition, has been solved numerically (Fejer 1953) under certain simplifying assumptions about the wind system and the ionospheric conductivities.

The above résumé of the dynamo theory shows its basic assumption that the currents well above 150 km, in the magnetosphere, flow along the field lines and are free of divergence and that in the symmetrical case these currents vanish. This is not obviously true if there are many energetic trapped particles present in the magnetosphere as the considerations in this section will show. A modification of the tidal current system by the presence of trapped particles in the magnetosphere is therefore bound to occur.

The coupling between the tidal motions and the trapped particle belt is provided by the polarization electric field that is carried into the magnetosphere by the magnetic lines of force that are also lines of equal potential. The resulting electric field in the magnetosphere causes a convection (Fejer 1961) that may be described (Gold 1959) as an interchange of the tubes of force. This interchange takes place in such a manner that the low energy particles that at a given time occupy a tube of force, continue at all future time to occupy a tube of force of equal flux content. The magnetic field is not changed by this interchange motion. These conclusions are in accord with the frozen field concept and follow logically if it is assumed that the drift velocity of low energy particles, perpendicular to the magnetic field, is given by $\mathbf{E}\times\mathbf{B}/B^2$ where $\mathbf{E}$ is the electric field and $\mathbf{B}$ is the magnetic induction. The low energy particles thus take part fully, by definition, in the convection of the magnetosphere.

The same drift velocity that is imparted to the low energy particles by the magnetospheric convection, is also imparted to particles of higher energy, but does not dominate the motions of the latter in a direction perpendicular to the magnetic field. For example a particle with about 40 kev energy, trapped on a field line that intersects the auroral zone, drifts round the earth in less than four hours as a result of the dipole nature of the earth's magnetic field. The velocity of this drift, westerly for ions and easterly for electrons, is about twenty times greater than the drift velocity of tidal origin. Moreover, the direction of the tidal drift changes its sense in the course of the drift around the earth of a high energy particle and only causes a temporary displacement to field lines emerging from the surface of the earth at slightly higher or slightly lower latitude. An undistorted dipole field is assumed throughout the present section.

For low energy particles the drift velocity, due to the dipole nature of the earth's magnetic field, may be neglected in comparison with the drift velocity of tidal origin. The particles with energies less than, say, a few electron volts therefore take part fully in the magnetospheric convection.

It is convenient to divide the particles of the magnetosphere into two groups: energetic particles with energies greater than, say, 40 kev, that are not taking part in the convection of the magnetosphere and are hardly affected by it, and low energy particles that take part fully in the convection. Such a division into two groups is clearly an idealization, but this should not affect the validity of the following arguments.

If the number density of the positively charged energetic trapped particles were everywhere equal to the density of the negatively charged ones in the magnetosphere then these energetic particles would have no influence on the dynamo current system and the associated convection of the magnetosphere. If, however, energetic trapped particles of one sign were present in much larger numbers than particles of the other sign, then a convection of the low energy particles could give rise to a type charge separation that is essentially different from the type proposed by Kern (1961, 1962) and Fejer (1961). In the process proposed by those two authors, charge separation results from the adiabatic motion of energetic trapped particles alone. In the process to be described here the motion leading to charge separation is that of the low energy particles, moving under the influence of an electric field that is nearly perpendicular to the magnetic field. In the former process a temporary asymmetry in the distribution of trapped particles or, as Kern (1962) expresses it, a separation of surfaces of constant number density from surfaces of constant integral invariant was the prerequisite. In the process to be described here an overall lack of neutrality in the belt of energetic trapped particles coupled with a drift of low energy ionization across the surfaces of constant number density of energetic particles is the prerequisite. While the former process tends to lead to temporary current systems, the process proposed here leads to steady current systems, if the drifts of ionization are of a steady nature.

It will be assumed in this paper that the number density of energetic protons is far greater than the number density of electrons in the same energy range. This is borne out by observations made with proton counters carried by the Explorer XII satellite which showed that the measured fluxes of protons and electrons, with energies greater than about 100 kev, are of the same order of magnitude. The assumed belt of energetic trapped particles has thus a net positive charge and, as has already been pointed out, this net positive charge plays a vital part in the following arguments.

In the absence of magnetospheric convection the positive space charge of the energetic charged particles is neutralized by a corresponding negative space charge of low energy particles. If, however, there is a magnetospheric convection associated with the dynamo currents then this neutralization will tend to be upset by the low energy particles drifting through the belt of trapped energetic protons. Neutralization will nevertheless be maintained by currents flowing along the field lines to and from the ionosphere, as illustrated by Figure 1.

Figure 1 shows a meridional cross section of the proton belt. The magnetosphere is assumed to convect outward, as indicated by the arrows, over a considerable range of longitudes. The convection only affects the low energy particles whose outward moving excess negative space charge causes an accumulation of negative charge on the outside and positive charge on the inside of the belt. Electric fields are soon established by the accumulating space charge and a discharge occurs along the field lines and through a short ionospheric path across the auroral zone as indicated in Figure 1. The electric fields which drive these ionospheric currents also cause the simultaneous flow of much larger Hall currents (Hirono 1952, Baker and Martyn 1952, Fejer 1953) that are approximately free of divergence. These Hall currents, which flow in an easterly or westerly direction must contribute to the auroral electrojets; if they alone were to cause the electrojet currents which are known to be easterly between approximately midday and midnight and then reverse their direction, then the above simple reasoning would require an outward tidal drift of the magnetosphere between about midday and midnight and a reversal of direction at about midnight at auroral latitudes.

The above qualitative arguments could be made more quantitative by the assumption of an atmospheric wind system and the subsequent calculation of the resulting ionospheric current system. This has already been carried out in the absence of trapped energetic protons (e.g., Fejer 1953) by numerical solution of the relevant differential equation. The differential equation was obtained from the condition that the divergence of the height-integrated current density $\underset{\sim}{j}$ within the ionospheric shell vanishes (Fejer's equation 15 which leads to equations 17 and 18). In the presence of trapped energetic protons div $\underset{\sim}{j}$ does not vanish on the ionospheric shell on account of the currents pouring in and out along the lines of force which are indicated in Figure 1. If Q is the space charge of the energetic particles per unit area of the earth's surface, after projection along the lines of force, then

$$\operatorname{div} j = \frac{\partial}{\partial\theta}(j_x \sin\theta) + \frac{\partial j_y}{\partial\varphi} = -\frac{\partial}{\partial\theta}(Q v_x \sin\theta) - \frac{\partial}{\partial\varphi}(Q v_y) \tag{1}$$

where x indicates the south component, y the east component, θ the co-latitude, φ a suitably defined longitude and where v_x and v_y are the velocity components of magnetospheric motion projected to the earth's surface along the field lines. It is easily shown that

$$v_x = -E_{py}/B \sin\chi \tag{2}$$

$$v_y = E_{px}/B \sin\chi \tag{3}$$

where E_{px}, E_{py} are the components of the polarization field. B is the magnetic induction and χ the inclination of the geomagnetic field. Equation (1) is the differential equation that must be solved numerically after v_x and v_y are substituted from equations (2) and (3) and the values of j_x, j_y, E_{px}, E_{py} given by Fejer's (1953) equations (13) and (14) are used. The space charge density Q is determined by the assumed belt of trapped protons.

It would be desirable to obtain such complete numerical solutions; in this paper, however, merely the approximate strength and location of the electrojet currents predicted by the present theory are obtained.

In the present approximation the derivatives with respect to φ are neglected in equation (1) in comparison with the derivatives with respect to θ. The height integrated additional current density Δj_x due to the belt of trapped protons is then approximately equal to

$$\Delta j_x = -Q v_x = E_{py} Q / B \sin \chi \tag{4}$$

and the corresponding Hall current density j_H is about four times larger (c.f. Figure 3 of Fejer 1953).

In the calculation of Q the geomagnetic field was taken to be that of a dipole. The flux distribution and the pitch angle distribution of trapped protons given by Akasofu, Cain and Chapman (1962) was assumed. The particles were assumed to have exponential energy spectra similar to those measured by Davis and Williamson (1962). The spectral distribution was taken to be proportional to exp $(-\mathcal{E}/\mathcal{E}_o)$ for energies $\mathcal{E}$ greater than 80 kev where $\mathcal{E}_o$ was assumed to be given by $\mathcal{E}_o = 400 \exp \; 0{\cdot}55(2{\cdot}8 - R_e)$ and where R_e is the equatorial distance of the field line in earth radii. This expression is an arbitrary extrapolation which fits the spectral measurement of Davis and Williamson. The spectra were arbitrarily cut off at the lower limit of $\mathcal{E}_t = 80$ kev, on the assumption that protons of lower energy would be rapidly removed by charge exchange. It is then easily shown that the equatorial number densities given by Akasofu, Cain and Chapman (1962) (which were calculated on the assumption of monoenergetic particles with an energy $\mathcal{E}_c = 500$ kev) must be modified by a factor $(\pi \mathcal{E}_c/\mathcal{E}_o)^{\frac{1}{2}} \exp(\mathcal{E}_1/\mathcal{E}_o)\left[1 - \mathrm{erf}(\mathcal{E}_t/\mathcal{E}_o)^{\frac{1}{2}}\right]$ where $\mathcal{E}_1 = 100$ kev is the threshold level of the particle detector used by Davis and Williamson.

The resulting equatorial number density n_e is shown by Figure 2 as a function of the equatorial distance R_e. The number density on a field line, for which the equatorial number density is n_e, is given, at a point with geomagnetic colatitude θ, by

$$n = n_e \sin^6\theta \left(4\cos^2\theta + \sin^2\theta\right)^{-\frac{1}{2}} \tag{5}$$

if the pitch angle distribution of Akasofu, Cain and Chapman, for which the number density is inversely proportional to the magnetic induction B, is assumed.

Let the number of energetic protons in a shell, such that the field lines within it cut the earth's surface between the colatitudes θ_o and $\theta_o + \delta\theta_o$, be calculated. The area on the earth's surface under such a shell, projected along the field lines on one of the hemispheres, is given by $2\pi R^2 \sin\theta_o \, \delta\theta_o$ where R is the radius of the earth. The cross sectional area of the shell at ground level, measured in a direction normal to the field lines, is therefore $2\pi R^2 \sin\theta_o \sin\chi \, \delta\theta_o$ where χ is the angle of inclination. The magnetic flux along the shell must be constant and therefore the cross sectional area must vary as $B^{-1} \propto \sin^6\theta \left(4\cos^2\theta + \sin^2\theta\right)^{-\frac{1}{2}}$.

Therefore the cross section at an arbitrary colatitude θ along the shell is given by $\delta A = 2\pi R^2 \sin^{-5}\theta_o \sin\chi \left(4\cos^2\theta_o + \sin^2\theta_o\right)^{\frac{1}{2}} \sin^6\theta \left(4\cos^2\theta + \sin^2\theta\right)^{-\frac{1}{2}} \delta\theta_o$.

The meridional length of a section of the shell contained between the colatitudes θ and $\theta + d\theta$ is $ds = R \sin^{-2}\theta_o \sin\theta \left(4\cos^2\theta + \sin^2\theta\right)^{\frac{1}{2}} d\theta$ so that the total number of particles in the shell is given by

$$\int n \, \delta A \, ds = 2\pi R^3 \sin\chi \sin^{-7}\theta_o \left(4\cos^2\theta_o + \sin^2\theta_o\right)^{\frac{1}{2}} n_e \, \delta\theta_o \int_{\theta_o}^{\pi-\theta_o} \sin^{13}\theta \left(4\cos^2\theta + \sin^2\theta\right)^{-\frac{1}{2}} d\theta .$$

The number of particles per unit projected area on the earth's surface is obtained after division of the above expression by twice the projected area $2\pi R^2 \sin\theta_o \, \delta\theta_o$ in one of the hemispheres and the space charge Q of the particles per unit projected area is therefore given by

$$Q = e\, n_e R \sin\lambda \sin^{-8}\theta_0 (4\cos^2\theta_0 + \sin^2\theta_0)^{\frac{1}{2}} \int_{\theta_0}^{\pi/2} \sin^{13}\theta (4\cos^2\theta + \sin^2\theta)^{-\frac{1}{2}} \tag{6}$$

where e is the charge of a proton. For values of θ_0 between 0 and $\pi/4$ the values of the integral on the right of equation (6) is almost independent of θ_0 and is very nearly equal to 1/3.

If the corresponding value of Q is substituted into equation (4) and B is replaced by $B_e(4\cos^2\theta_0 + \sin^2\theta_0)^{\frac{1}{2}}$ then the following result for j_x is obtained:

$$j_x = (E_{py}/B_e)(e\, n_e R/3 \sin^8\theta_0) \tag{7}$$

In accordance with our previous assumptions the height integrated Hall current density j_H is about four times greater than the value given by (7). The solid line in Figure 3 shows the distribution with latitude of $j_H = 4j_x$, computed from the number density distribution of Figure 2 on the assumption that $E_{py}/B_e = 100$ m/sec ; this corresponds to a drift velocity of about 50 m/sec. at F-region heights. The highest current density in Figure 3 occurs at a geomagnetic latitude of about 66°, which is close to the center of the auroral zone.

The largest change in the horizontal component of the magnetic field on the ground caused by the current system of Figure 3 is about 44γ. This is much less than the field changes observed during magnetic storms in the auroral zone.

It should be emphasized that the current densities derived here are very critically dependent on the assumptions about the spatial distribution and energy spectrum of trapped protons. If, for example, the exponential spectra are cut off at a slightly lower energy than 80 kev, then the maximum in the current density in Figure 3 is enhanced and shifted to a higher latitude as shown by the dashed line for which $\mathcal{E}_t$ = 60 kev; the corresponding change in the horizontal component of the magnetic field is increased to 66 γ . It would be very desirable to extend the measured spectra to lower energies; a more accurate prediction of the current densities would then be possible. It is of interest to point out here that the auroral current densities derived by Nagata and Kokubun (1962) from quiet day magnetic data are about the same as those shown by Figure 3.

The proton fluxes and spectra used in the computation of Figure 3 were measured during a magnetically quiet day. Measurements made by Explorer XII show an enhancement by a factor of 3-4 in the number of protons between 2.5 and 4.5 earth radii, with energies between 100 kev and 400 kev, during a magnetic storm in September 1961, about 17 hours after sudden commencement (Davis 1962). The number of energetic protons between 5 and 6 earth radii did not change substantially. It thus appears that the electrojet current densities predicted by the theory would be considerably higher during magnetic storms than during magnetically quiet days.

In the absence of measured proton energy spectra which extend to energies well below 100 kev and in the absence of reliable experimental data on the phase and amplitude of magnetospheric convection a reliable experimental test of the purely tidal theory of auroral electrojet is hardly possible. It should nevertheless be pointed out that the polarization electric field proposed by Martyn (1955) has just the opposite phase to that required by a purely tidal theory if the majority of the trapped particles are assumed to be positively charged. While Martyn's suggestion is not based on direct experimental evidence and the phase of the actual polarization field may therefore differ considerably from that proposed by him, there is at present certainly no clear evidence in favor of a purely tidal theory of the electrojets. Ionospheric currents of tidal origin must, however, make a substantial contribution to the electrojet current system.

3. Ionospheric currents in the auroral zone due to the distortion of the geomagnetic field by the solar wind.

It was shown in the last section how the relative drift of low energy plasma through the belt of high energy trapped particles in the magnetosphere causes ionospheric currents. The low energy plasma may be said to be frozen into the field lines and convect with them while the high energy plasma is not. In the mechanism of the last section the electric polarization field of the dynamo theory caused a convection of the tubes of force and the ionization frozen into them. In the present section the tidal polarization field will be ignored but two other important effects that were ignored in the last section will be taken into account: the distortion of the geomagnetic field by the solar wind and the rotation of the earth and its magnetosphere.

Let the presence of the belt of energetic trapped particles be ignored at first. The neutral atmosphere is taken to rotate with the earth at least up to and including ionospheric heights. A polarization field is then established that makes the lines of force of the magnetosphere and the low energy plasma frozen into them convect in such a way that the feet of the lines of force in the ionosphere (at a height of about 150 km) rotate with the neutral atmosphere, which, in turn, rotates with the earth. At great heights the low energy plasma does not, however, rotate solidly with the earth, on account of the distortion of the geomagnetic field by the solar wind, which compresses the field more strongly on the day side than on the night side. As a consequence, the low energy plasma that on the day side is at a given distance from the center of the earth in the equatorial plane, will be at a greater distance from the center of the earth after the earth's rotation takes it to the night side.

The energetic trapped protons observed by Davis and Williamson (1962) are relatively little affected by the electric fields in the magnetosphere which are associated with its rotation and daily expansion and contraction. The adiabatic motion of these protons, most of which remain close to the equatorial plane, makes them follow lines of approximately constant magnetic induction in the equatorial plane. This means that the particles will be closer to the center of the earth on the night side, where the compression caused by the solar wind is less intense than on the day side. The behavior of the energetic protons is therefore exactly opposite to the behavior of the low energy particles. Consequently there is again a relative drift of low energy ionization through the belt of trapped protons in the equatorial plane. This drift is outward between midday and midnight and inward between midnight and midday if the orbital velocity of the earth is neglected in comparison with the velocity of the solar wind. The continued neutralization of the energetic protons therefore results in a current system of the type indicated by Figure 1 between midday and midnight. The corresponding Hall currents contribute to the auroral electrojets; their phase agrees approximately with the phase of electrojet currents inferred from the magnetic variations.

It is desirable to make the above consideration more quantitative by a very rough model of the compressed geomagnetic field. It is therefore assumed that on the noon meridian half-plane the magnetic field is that which would exist inside a spherical cavity whose radius is r_d times that of the earth. It is further assumed that at the center of this hypothetical cavity there is a magnetic dipole whose magnetic moment is equal to that of the earth; the currents that are assumed to flow on the surface of this cavity exactly cancel, outside the sphere, the field of the center dipole. The field inside such a cavity has been calculated by Wentworth and Tepley (1962).

Similarly it is assumed that on the midnight meridian half-plane the magnetic field is that which would exist inside a similar sphere whose radius is, however, r_n times that of the earth.

The above representation of the distortion of the earth's magnetic field by the solar wind is admittedly very crude but it should give results of the right order of magnitude. Using this representation and Wentworth's and Tepley's (1962) equations, the latitude λ_n of the foot of a field line in the midnight meridian half-plane was calculated as a function of the latitude λ_d of the foot of a corresponding field line in the noon meridian half-plane. The assumed correspondence was such that an energetic trapped proton in the equatorial plane, that would start from one of the above field lines, would at some stage in the course of its adiabatic motion pass through the other field line. Figure 4 shows $\lambda_d - \lambda_n$ as a function of λ_n for this rather crude model. The angle $\lambda_d - \lambda_n$ indicates thus the maximum change that occurs in the geomagnetic latitude of the projection (to the earth's surface along the distorted geomagnetic field lines) of an energetic trapped proton, in the course of its adiabatic motion. The curves in Figure 4 were calculated from the parametric representation

$$\cos^2\lambda_d = r_d^2\,(r_d^3 - 3p^3)\,p^{-1}\,(r_d^3 - 1)^{-1}\,(r_d^3 - 2p^3)^{-2/3} \tag{8}$$

$$\cos^2\lambda_n = r_n^2\,(r_n^3 - 3p^3)\,p^{-1}\,(r_n^3 - 1)^{-1}\,(r_n^3 - 2p^3)^{-2/3} \tag{9}$$

where r_d and r_n are radii of the "noon" and "midnight equivalent spheres," measured in earth radii and where p is the parameter. This representation follows from Wentworth's equations (1) and (2). The parameter p may be interpreted as the distance in earth radii from the center, where the undistorted equatorial dipole field would have the same value as the distorted field has along the orbit of a trapped energetic particle. In Figure 4 the pairs of values $r_d = 7$, $r_n = 14$; $r_d = 9$, $r_n = 18$; $r_d = 11$, $r_n = 22$ were used.

After projection along the field lines to the earth's surface, the relative motion of the high energy particles against the low energy background results in a daily excursion $R(\lambda_d - \lambda_n)$. If the movement were assumed to be harmonic then the maximum relative velocity in the north-south direction measured after projection to the surface of the earth, would be $\pi R(\lambda_d - \lambda_n)/T$ where T is the length of the solar day. For $\lambda_d - \lambda_n = 10°$, which occurs for $\lambda_h \sim 66^\circ$ for the $r_d = 9$, $r_n = 18$ curve, the maximum relative velocity would be 41 m/sec. This value is not very different and certainly not significantly smaller than the drift velocities of tidal origin. At lower latitudes the tidal drifts probably predominate while at higher latitudes the drifts considered in this section are more important. The current density caused by the mechanism described in this section can be calculated again by using equation (4), so that the magnitude of the Hall current density is given approximately by $4\ Q\ v_x$ where $v_{x_{max}} = \pi R(\lambda_d - \lambda_n)/T$.

It should be emphasized here that the current system discussed in this section does not have its greatest intensity at the same geomagnetic latitudes on the night side as on the day side, since the projection of the same adiabatically moving proton along the field lines is at different latitudes on the day and on the night sides. Observations of the auroral electrojets (Harang 1946) tend to show this type of asymmetry. It is interesting to point out that a similar behavior of hydrogen emission in the aurora is observed, and an explanation along similar lines has been suggested by Reid and Rees (1960).

The distortion in the geomagnetic field also affects the calculation of Q, the space charge of the energetic trapped particles, per unit area of the earth's surface. A dipole field was assumed in the calculation of the quantity Q in the previous section. No attempt is made here to recalculate Q for the distorted geomagnetic field in view of the rough nature of the present approximations to the distorted field. It is hoped that the preceding arguments, even in the absence of any detailed calculations, show that the contribution to the auroral electrojet currents of the mechanism described in the present section is somewhat greater at latitudes higher than, say, 65° and somewhat smaller at lower latitudes than the current densities shown in Figure 3. The phase of the current system is determined by the direction of the solar wind with respect to the earth and therefore depends on the ratio of the earth's orbital velocity to the solar wind velocity. If the earth's orbital velocity is very much smaller than the velocity of the solar wind then the predicted electrojet current is eastward between midday and midnight and reverses its direction at midnight.

Conclusions:

It has been shown that if the presence of the energetic trapped protons observed by Davis and Williamson (1962) is assumed then the additional assumption either of the existence of atmospheric tidal motions or of the existence of a distortion in the geomagnetic field, caused by the solar wind, necessarily leads to intense east-west ionospheric currents in the auroral zone. The quiet day observations of the magnetic field, as described by Nagata and Kokubun (1962), indicate the presence of electrojet currents of about the same order of magnitude as predicted by either of the two present mechanisms for the energetic trapped proton belt of Davis and Williamson (1962). Exact predictions of the current system are not possible in the absence of information on the energy spectra of the protons with energies below 100 kev, and in the absence of more information about the change of the proton belt during magnetic storms. A more accurate knowledge of tidal air motions and of the distorted magnetic field would also be required.

In reality both the tidal motions and the distortion of the magnetic field are present; the actual electrojet currents are probably caused by the simultaneous action of both mechanisms described in this paper. More temporary contributions to the electrojet currents may also be made by other mechanisms such as the charge separation proposed by Fejer (1961) and Kern (1961, 1962).

Stress has been laid in this paper on the explanation of the Ds current system. As has been pointed out by Axford and Hines (1961), any "mechanism capable of driving the Ds current system from high in the magnetosphere should lead to convective motions" of the type they have discussed. The two mechanisms proposed here must indeed lead to convective magnetospheric motions of the type discussed by Axford and Hines. The exact details of these convective motions cannot, however, be predicted until a more accurate knowledge of the distorted geomagnetic field and the other geophysical parameters already mentioned becomes available.

ACKNOWLEDGEMENTS

The author would like to acknowledge the benefit of helpful discussions with Drs. A. J. Dessler, W. B. Hanson and F. S. Johnson. This research was supported by the National Aeronautics and Space Administration under Grant NSG-269-62.

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CAPTIONS FOR FIGURES

Figure 1. Diagrammatic representation of neutralizing currents caused by the outward convection of the magnetosphere in the presence of a belt of energetic trapped protons.

Figure 2. The equatorial number density of trapped protons in the assumed model belt in the plane of the equator as a function of the distance from the center of the earth.

Figure 3. The ionospheric Hall current density below the assumed proton belt resulting from a tidal drift defined by $E_{py}/B_e = 100$ m/sec where E_{py} is the east component of the polarization field in the auroral zone and B_e is the equatorial induction of the geomagnetic field.

Figure 4. The latitude change $\lambda_d - \lambda_n$ between midday and midnight of the projection of a drifting equatorial energetic trapped proton to the earth's surface along the field lines as a function of the latitude λ_n of the midnight projection.

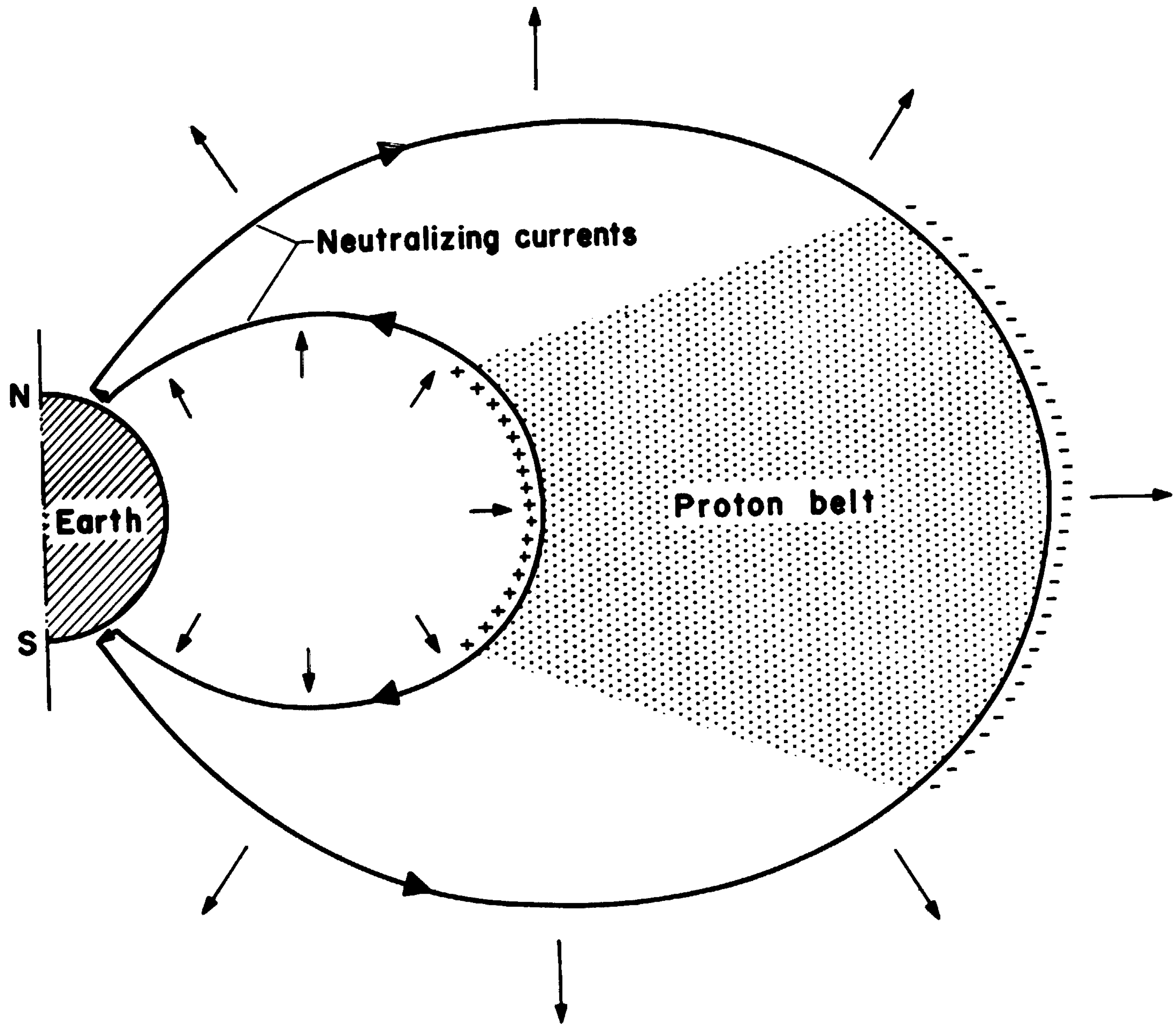


Figure 1

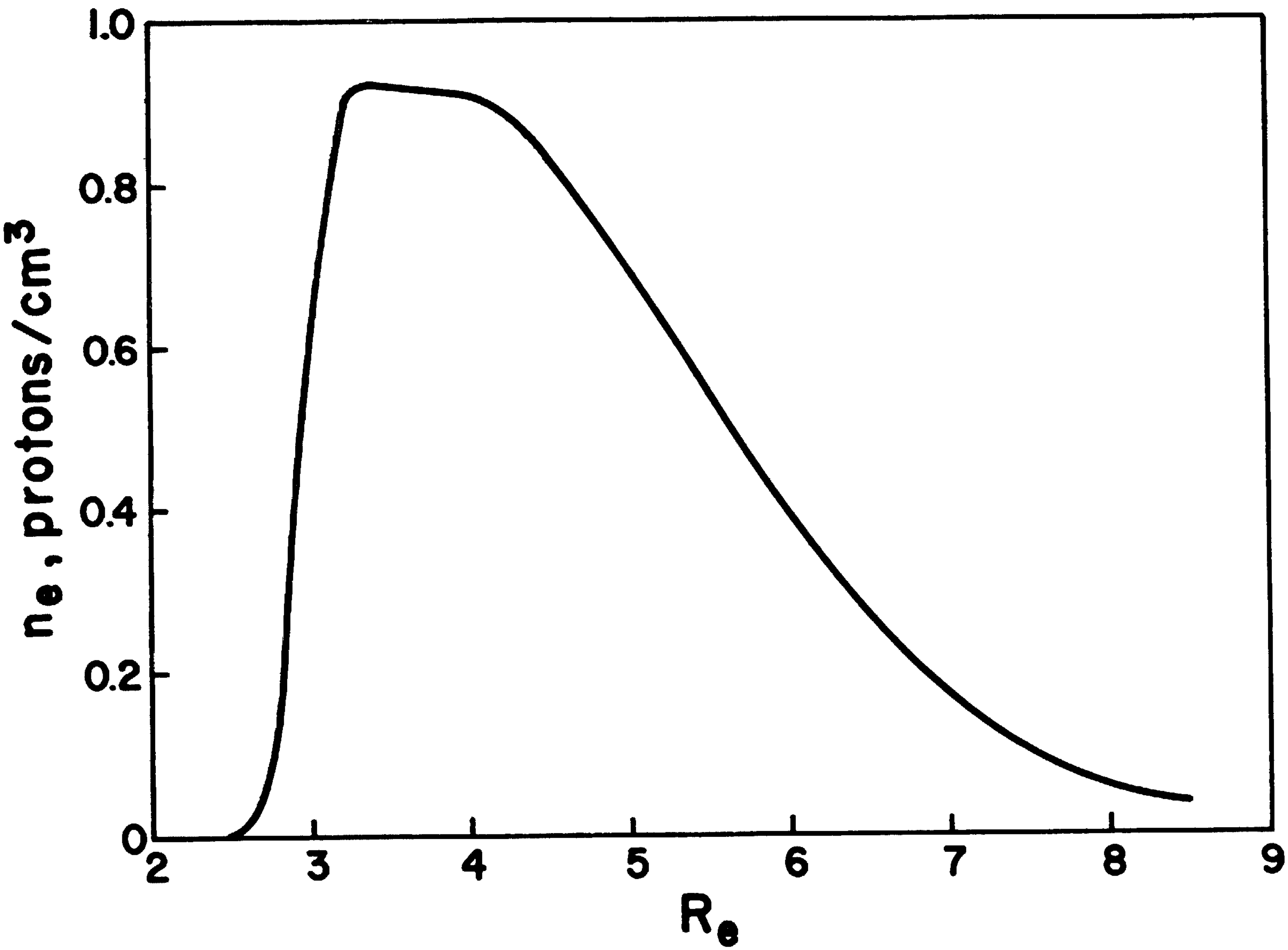


Figure 2

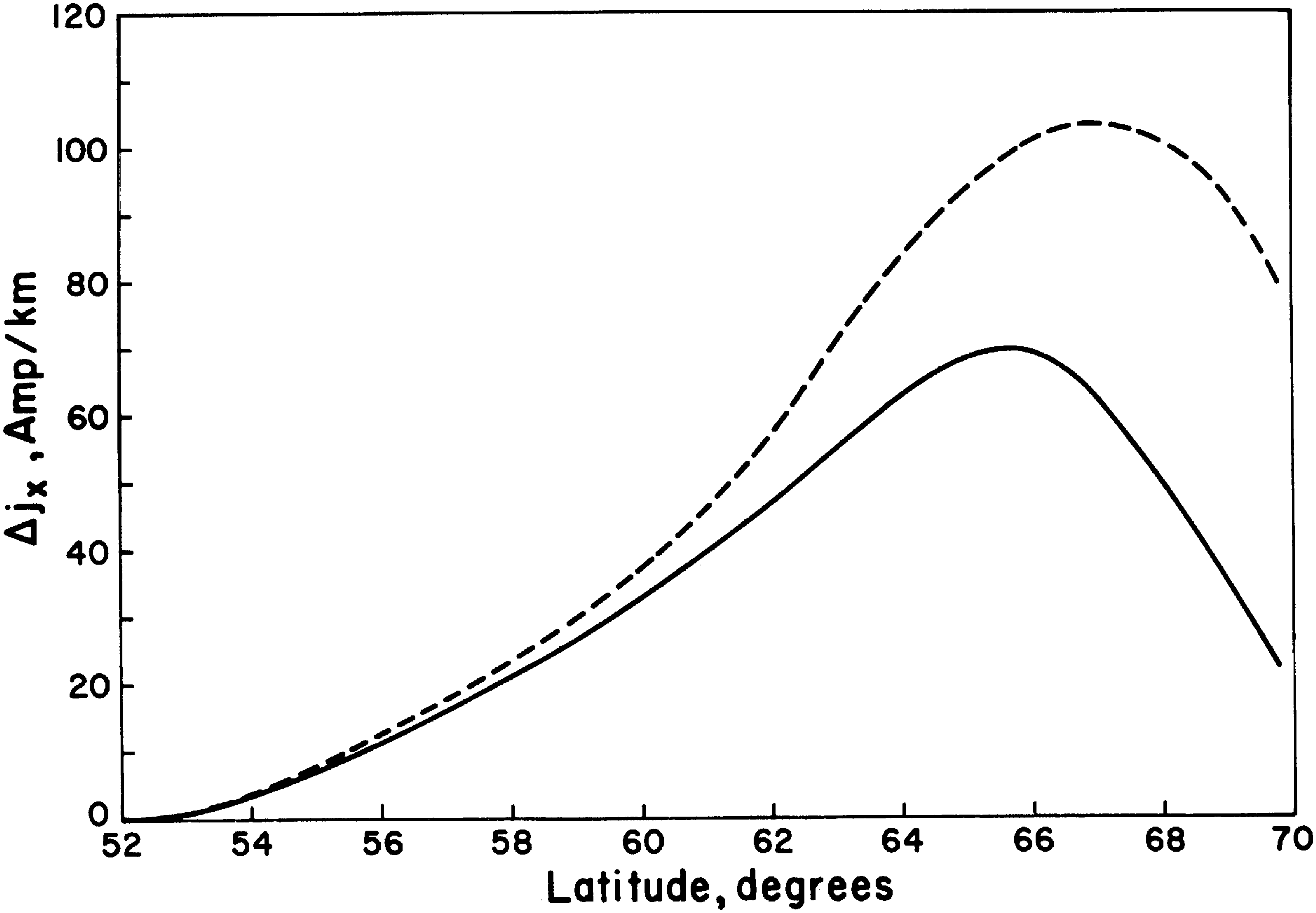
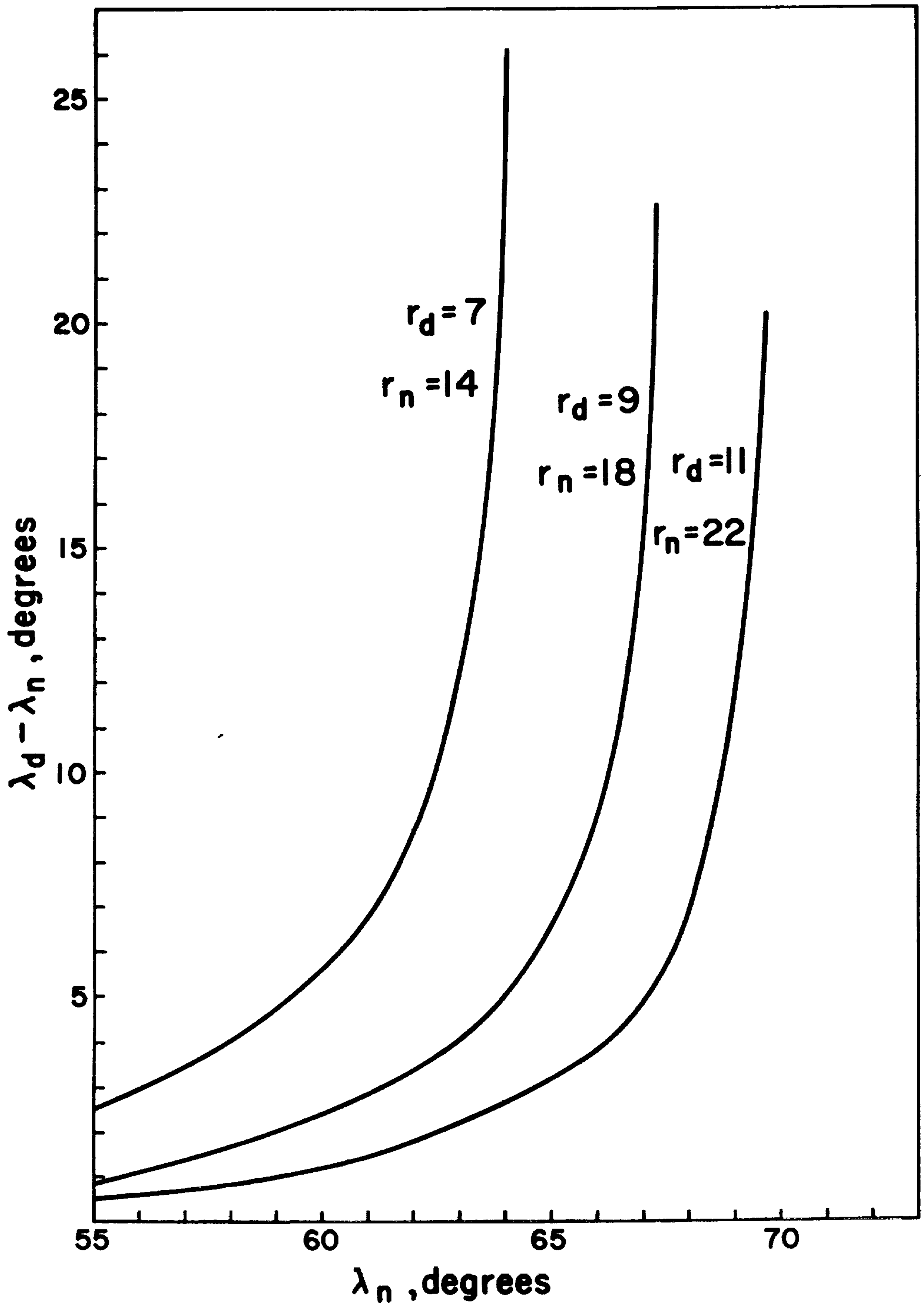

120
100
80
60
40
20
0
Δjx ,Amp/km
52
54
56
58
60
62
64
66
68
70
Latitude, degrees

Figure 3



25
20
15
10
5
55
60
65
70
$\lambda_d - \lambda_n$, degrees
λ_n , degrees
$r_d = 7$
$r_n = 14$
$r_d = 9$
$r_n = 18$
$r_d = 11$
$r_n = 22$

Figure 4