ELECTRIC FIELD MODIFICATION OF PRECIPITATION SPECTRA

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Summary

The superposition of a parallel electric field along the direction of the Earth's magnetic field results in a change in the precipitation into the ionosphere. The extent of the total additional ionization caused is dependent not only on the number of magnetospheric electrons displaced, but also on the details of energy and pitch distributions as they enter the denser lower atmosphere. The dependence of precipitated pitch distribution on the original spiralling field line and on the superimposed field is found.

I. Introduction

Consideration is given here to further aspects of the effects of the superposition of a longitudinal electric field along the direction of the Earth's magnetic field. In particular, a determination is made of the modifications to the orientations of those electrons which, as a result of such superimposed fields, are precipitated into the ionosphere from a spiralling orbit in the magnetosphere.

The application of a parallel electric field results in a change in the spiralling–mirroring domains of trapped particles and also in the consequent change in the extent of precipitation from the magnetosphere into the ionosphere. These effects have been studied previously (Catchpoole 1966*a*) and results presented indicating their dependence on the field line of spiralling θ_0 and on the equatorial ratio of longitudinal to transverse particle velocities $(u/v)_0$, as well as, of course, on the magnitude of the applied electric field itself. θ_0 is the colatitude of surface intersection of the field line while specification of the other parameter is equivalent to that of the particle's equatorial pitch angle α_0 as used here.

Besides affecting the extent of the precipitation of magnetospheric particles, the superimposed parallel electric field envisaged will also alter the energy spectra and the orientations of these particles. The object of the calculations reported in this paper has been to determine the relationship between the applied electric field and these distributions upon precipitation. As before, an arbitrary dividing altitude of 600 km is supposed between a region of spiralling (or magnetosphere) and one of precipitation out of trapping (or ionosphere). Other general concepts of the earlier work are also retained, such as the existence of a differential dynamo effect to produce a conjugate potential difference as a source for the applied field. The present considerations relate to the motion of electrons only although corresponding results will apply to protons in the conjugate hemisphere or to other charged particles (Catchpoole 1966*b*).

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The interest here is, then, in the distribution of electrons as they cross the magnetosphere–ionosphere interface under the acceleration of a parallel electric field. In particular, pitch angle distributions are considered. These are of importance in the subsequent motion and effects of the precipitated component in the ionosphere. Of special significance is the further ionization caused by the dumped particles, brought about by collisional ionization or otherwise. The pitch distribution of the particles on entering the denser lower region determines the effective ionization paths. It will also in this way be one of the factors controlling the height distribution of the resultant additional ionization.

II. Change in Pitch Angle

As a first step, the relation is found between the reference pitch angle α_0 of a spiralling electron as it crosses the equatorial plane and that pitch angle α_p which it has acquired by the time it crosses the arbitrary precipitation level of 600 km. This relation will involve both the magnetic fields and also the particle's energies at these two points of its orbit. The required dependence on any superimposed electric field is inherent in that field's effects on particle energy.

Using the first adiabatic invariant of particle motion (Longmire 1963), the magnetic moment μ due to the circular motion of the charged particle in the magnetic fields B can be equated at the equatorial plane (subscript 0) and at the precipitation level (subscript p) as

$$\mu = B_p/v_p^2 = B_0/v_0^2, \tag{1}$$

where v is the transverse component of the electron velocity. From the conservation of energy,

$$\tfrac{1}{2}m(u_0^2+v_0^2) = \tfrac{1}{2}m(u_p^2+v_p^2)-\tfrac{1}{2}eV,$$

where V is the potential difference between conjugate points producing the parallel electric field of interest. As illustrated here, the sign is such that this corresponds to a field direction which results in increased precipitation. The energy of an electron as it is precipitated is

$$\epsilon_p = \epsilon_0+\tfrac{1}{2}eV. \tag{2}$$

Taking these two conditions together gives the required relation between the particle's pitch angles at precipitation α_p and at the equatorial plane α_0 as

$$\sin\alpha_p = \sin\alpha_0\,(\epsilon_0/\epsilon_p)^{\frac{1}{2}}\,(B_p/B_0)^{\frac{1}{2}}. \tag{3}$$

This has been evaluated and graphs of α_p against α_0 are shown in Figure 1. These are for various values of the electric field parameter $k = V/\epsilon_p$. (This is to be distinguished from the parameter c used in the earlier work referred to above.) For clarity, only the graphs for $k = 0$ and $k = 1$ are drawn in full for field lines from $\theta_0 = 20°$ to $\theta_0 = 70°$. With no superimposed electric field, a particle's pitch angle is increased by the time it is precipitated. This reflects the deceleration due to the convergence of the magnetic field lines. As the superimposed field is increased, α_p approaches the values α_0 and then finally values of k are reached for which $\alpha_p < \alpha_0$.

At this stage the accelerating force of the parallel electric field has overcome the net retardation due to the magnetic gradient. The dependence of these effects on the particular field line of spiralling θ_0 is seen from the figure.

Beyond a certain critical equatorial pitch α_{0c}, the spiralling electrons are unable to reach the precipitation level. As an increasing pitch approaches this value, the slope of the curves shown generally increases as the longitudinal velocity of the particle is decreased near the precipitation point by line convergence. The change in curvature seen for some of the $\theta_0 = 70°$ curves is due to the predominance of the parallel electric field on a field line of small magnetic gradient. This change would also, of course, appear on curves for lower θ_0 and progressively larger k. Such curves as those illustrated thus indicate the regions of predominant electric or magnetic field effects noted before (Catchpoole 1966*b*).

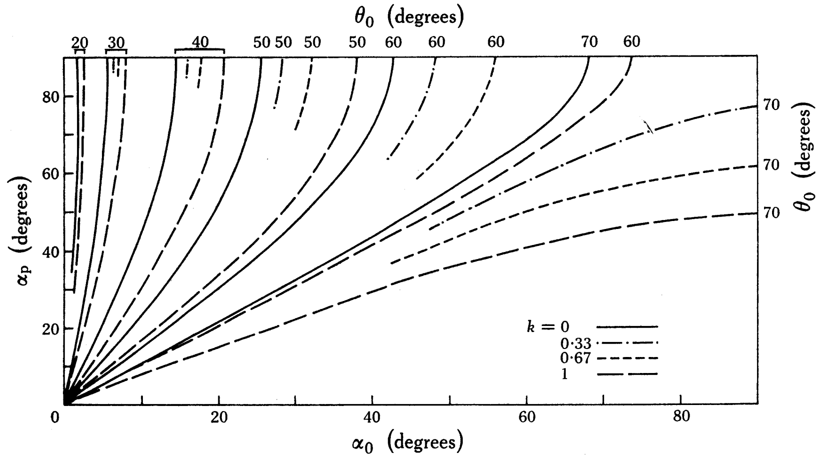

Fig. 1.—Showing the relationship between the precipitated pitch angle α_p and the corresponding equatorial plane pitch angle α_0. This is a function of the field line of spiralling θ_0 and of the magnitude of the superimposed parallel electric field (indicated by the parameter k).

Supposing some initial equatorial pitch distribution, the relative total precipitation can also be found by reading the appropriate critical angles from this figure. In this way, the increased precipitation due to a certain superimposed electric field is determined. However, these particular results are not repeated here, as they are the same as those found previously by a similar procedure.

III. Distribution of Precipitation with Pitch Angle

The main results of the present calculation are shown in Figure 2. This illustrates the way in which precipitated electrons are distributed in pitch angle at the time of entering the ionosphere together with the dependence of such distribution on the superimposed electric field. The curves are derived from a magnetospheric distribution which is isotropic in the equatorial plane. The value which is graphed as a function of precipitation angle is the ratio $N(\alpha_p)$. This is a relative population per unit of pitch angle which is referred to that of $\alpha_0 = 90°$ in the isotropic equatorial distribution.

For a given precipitated pitch, Figure 1 was used to find the corresponding equatorial pitch for like parameters. The change in pitch angle interval which the equivalent increment of equatorial population now occupies is taken into account by using the slopes of the curves in Figure 1.

Figures 2(*a*)–2(*e*) are for the field lines of indicated colatitude and the set of curves in each case indicates the effects of increasing superimposed electric fields. It can be seen how the initial near-symmetry of distribution about a median pitch

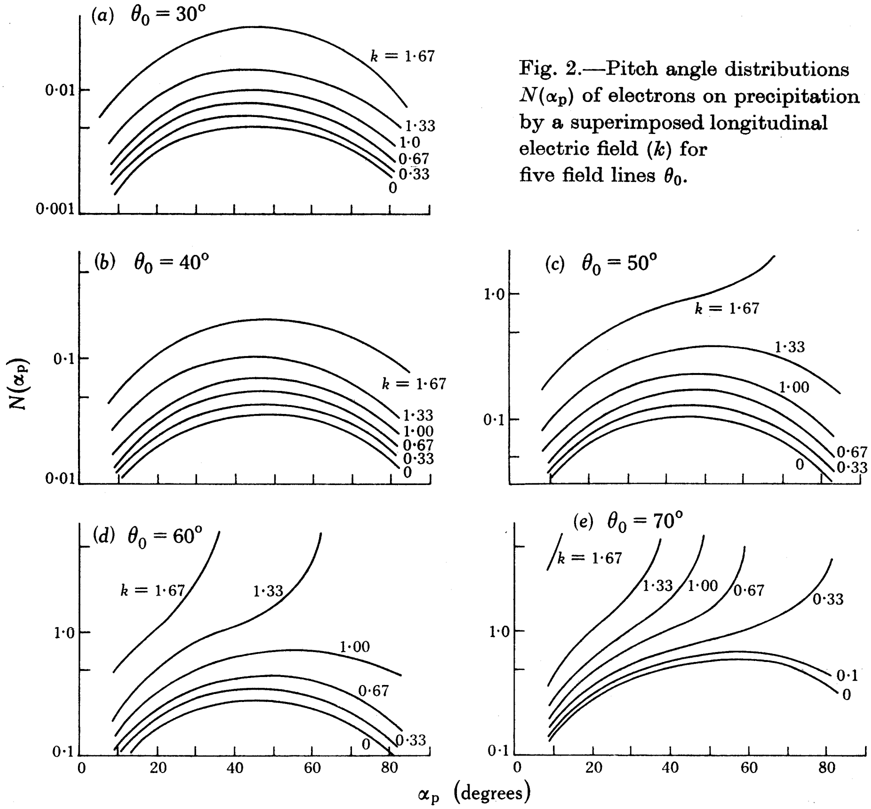

Fig. 2.—Pitch angle distributions $N(\alpha_p)$ of electrons on precipitation by a superimposed longitudinal electric field (k) for five field lines θ_0.

for the set of superimposed fields shown is progressively lost with increasing colatitude. This corresponds to the increasing effectiveness in precipitation of a field of given magnitude when applied along magnetic field lines of decreasing length. As θ_0 increases, the pattern of a greater number of electrons at the larger pitch angles (which is a feature of the assumed initial equatorial distribution) is reflected more and more in the precipitation distributions for progressively smaller applied fields.

IV. Increased Ionization with Superimposed Electric Field

A particular objective of the study of superimposed electric fields in the magnetosphere is to estimate the additional ionization which will result in the lower or ionospheric regions. The extent of this further ionization will depend both on the direct electron contribution of the precipitation itself and on the exact way in which these electrons enter the ionosphere. This latter must account for the energy spectra of the electrons (equation (2)) since further collisional ionization will depend on this. It must also account for the pitch distributions, as found above, since on these depend the available path lengths for further ionizing processes. Calculations of the complete height profile through the atmosphere of the additional ionization caused by the displaced magnetospheric electrons must similarly allow for these entry pitch distributions. Further, they must also trace the change in the distributions with altitude, allowing for the different path lengths and for the various essential atmospheric parameters such as the efficiencies of ionization for the several constituents (Seaton 1959; von Engel 1965).

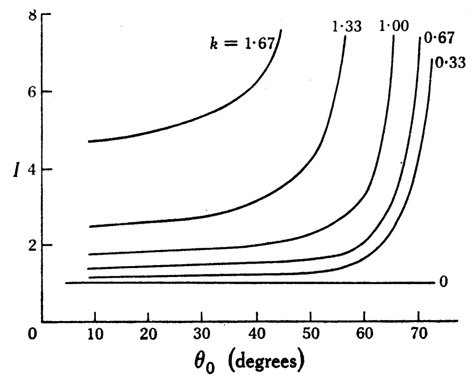

Fig. 3.—Relative increase in additional ionization at higher altitudes resulting both directly from the increased precipitation and indirectly from the changed pitch distribution of the displaced magnetospheric electrons. This ratio I is shown as a function of field line surface colatitude θ_0 for various superimposed electric fields (k).

Another important particular aspect of the study of superimposed fields is that of their effect on the conjugate point precipitation of photoelectrons which are produced in the lower denser regions of the atmosphere. Pitch angle distributions of photoelectrons entering the magnetosphere from the production hemisphere have been determined before (Catchpoole 1967). These will be equivalent to some anisotropic equatorial distribution but their re-entry distribution for the precipitation hemisphere can be found as above and from Figure 1 in terms again of geometric (θ_0) and electric (k) parameters.

A very simple illustration of these effects is shown in Figure 3 which indicates such ionization increases due to precipitation. It relates, however, only to the uppermost region of the ionosphere or the medium into which the magnetospheric particles are displaced. That is, the altitude variation of the pitch distribution, requiring the specification of a model atmosphere, is not included. Instead, the relative increase in ionization I which is shown is

$$I = I\big(\theta_0, N(\alpha_p), k\big) = \int_0^{\frac{1}{2}\pi} \big(N(\alpha_p)\sec\alpha_p\big)_k \, d\alpha_p \Big/ \int_0^{\frac{1}{2}\pi} \big(N(\alpha_p)\sec\alpha_p\big)_0 \, d\alpha_p \,. \qquad (4)$$

This accounts both for the additional precipitation due directly to the superimposed field and also for the path length variation with entry pitch angle. However, it is supposed simply that the additional ionization is directly proportional to path length. Figure 3 thus gives a first indication of the dependence of further ionization on the field line of preceding spiralling and on the magnitude of the superimposed electric field.

V. Acknowledgments

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VI. References

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