the average current in the auroral jet in an equinoctial season (Fukushima and Oguti 1953).

As regards polarization—it would require very special geometry to reduce the applied field by an order of magnitude. In any case in the above theory E is the vector sum of all electric fields, no matter how they arise.

Hines, C. O.: The rate of heating can be deduced by a method that does not depend on absolute conductivities, but only the ratio R of integrated Pederson to integrated Hall conductivities, if it is believed that the velocity of auroral motions represents $E \times B/B^2$. From this relation $|E|$ can be calculated. The magnetic measurements yield current flow. This, if multiplied by R, yields the dissipative component of the currents—the Pederson current—which in turn, when multiplied by $|E|$, yields the dissipation rate. Axford and I have done this, and derive a value which is down by only one order of magnitude from the value quoted by Cole. I do not think we can argue over one order of magnitude in such calculations.

Chamberlain, J. W.: (Regarding comments by Dr. Hines) I think auroral motions should not be used to derive the magnitude of a driving electric field, as though the velocities represented the transport velocity of atmospheric electrons. Auroral motions, both visible and on radar, are clearly not equivalent to electron motions in the atmosphere.

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I-3-6. Interchange and Rotation of the Earth Field Lines*

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I plan to discuss two theoretical points concerning the structure of the magnetosphere of the earth. One is connected with the possible motions of the thermal gas and their effects on the orbits of energetic particles, and the other is concerned with the structure of the outer atmosphere that results from the combined effects of gravitation, magnetic field and rotation.

I have discussed elsewhere (in the Journal of Geophysical Research) the possibility that the thermal gas in the magnetosphere may take part in large scale motions without any magnetic work being done or any magnetic fields being changed. This turned out to be the consequence of the insulation of the lower atomosphere which prevents any substantial vertical current through it. The patterns of motion in this class are all of the kind that might be described as an interchange of tubes of force. The rule is merely that all the gas that was at one time on a common line of force will at all future times be found on a common line of force, though not necessarily occupying the same part of space. The wide class of interchange motions that can occur have effects on the orbits of more energetic particles. Hines and Axford have discussed one class of interchange motions which they expect to occur as a consequence of the streaming solar plasma interacting with the magnetosphere. They discussed the manner in which energetic particles, in that case electrons of 5 to 50 kev, get distributed and in part precipitated in the auroral zone.

The interchange motion is associated with electric fields. It is through these fields that energetic particles have their orbits affected. One can see no good reason why interchange motions and their associated electric fields should not be very significant and indeed the

* The discussion of this paper is printed in page 204.

dominant cause of a transportation of particles in the radiation belts from one level to another.

To see the nature of the effect it is easier to consider it in terms of interchange motion than in terms of the associated electric field, although the points of view are of course equivalent. Consider for example the motion of an energetic particle in the radiation belt in the equatorial plane. The gradient drift impresses on it a motion in longitude which is faster the higher the particle energy. If now in the course of this longitude drift the particle goes through a region in which the background gas is expanding outwards as a consequence of the interchange motion, then the energetic particle will have impressed on it the same radial component of velocity for the time that it is in that region. If elsewhere it encounters a down-going region, it will similarly be moved inwards. The more energetic the particle the shorter it will be in any one region during its gradient drift, and the smaller will therefore be the radial displacement that it will suffer.

It can be shown that if the interchange motion is a steady one during the interval of time that it takes a particle to encircle the earth, then the increments in the radial distance gained and lost on the way around will just cancel exactly. Another way of saying this is that the electric fields for a steady pattern of motion will be timed independent, and a constant electric field can only give a deformation to the orbit of the fast particle, but it cannot progressively move it in or out.

The situation however is quite different if the interchange motions change in the time that it takes a particle to encircle the earth. It is very probable that this is a common circumstance during a magnetic storm when very fast motions will be set up. It is therefore during a magnetic storm that one should expect a drastic redistribution of energetic particles to occur, in which in general the lowest energies should be the most affected. Calculating the effect statistically in a fluctuating velocity field, one concludes that the radial increment of distance that a particle suffers in a given time goes like $E^{-1/2}$ where E is the energy of the particle. It can thus be understood how low energy particles can be drastically redistributed in a region in which high energy particles show stable orbits, and such effects have indeed been observed.

Now we come to the effect of rotation on the outer parts of the magnetosphere. If any ionized gas exists in the equatorial plane beyond 6.8 earth radii and if at that distance the earth's magnetic field still enforces complete co-rotation, then the centrifugal force will win over gravity. An inverse pressure gradient would then be set up and the pressure and density would continue to increase outwards. Somewhere this regime must cease, for certainly co-rotation cannot persist indefinitely far outwards. The present indications are that the earth's field dominates out to a distance of 10 or 15 radii and co-rotation of any gas therefore goes out that far.

This gas will be prevented from escaping altogether by the magnetic field. One can thus calculate, on the basis of extremely simple assumptions, the atmospheric structure that would result. In the polar direction one has the usual change of pressure with height that one has in the absence of rotation. In the equatorial plane, however, one has a decrease which is exponential close to the earth, which however then reaches a minimum and has a subsequent increase limited only by the outer boundary of the co-rotating region. Prof. T. P. Mitchell at Cornell and I have looked into this problem and we conclude that a doughnut shaped subsidiary atomosphere must be expected to surround a rotating planet at a distance beyond that of the stand-still orbit. In the case of the earth that is at 6.8 radii.

Similar considerations apply of course to the sun and to the other planets, and interesting consequences can be suggested for this doughnut atmosphere. In particular there is an interesting effect on dust particles which will be drawn to the central plane of such a doughnut atmosphere by dissipation and which would have permanently stable orbits, in which the rate of gain of angular momentum from gas friction with the doughnut atmosphere would just balance the rate of loss by the Poynting-Robertson effect. We are at the present time considering whether Saturn's rings can be attributed to such an effect.