

of trapping. Thus the particles cannot escape by going through the region of field reversal, though their pitch angle distribution is modified in this region.

Singer, S. F.: Comment on the present question by Smith: Our recent work (with Apel and Wentworth, J. G. R. 1961) parallels that of Akasofu and Chapman in many respects. (Our work was done independently but later.) We agree on fundamentals but have considered different aspects of the problem. The ring current should be treated in a self-consistent manner, we believe. But instead, we have used a perturbation method. We find convergence and do not get reversed field gradients in the perturbed field (= dipole field + field due to trapped particles) nor do we get a reversal in the sign of the field.

Sultz, R. J.: You commented that this calculation did not produce a reversal of the earth's magnetic field (neutral line). Has this reversal been achieved in other model calculations?

Chapman: Except in one case, all our calculations were first approximations, in that *the change* in the dipole field caused by the presence of the particles was ignored in calculating their motions, current and field. Hence their field is proportional to the maximum energy density in our model belt, and if this density is sufficiently great, there would be field reversal.

Gold, T.: The iteration process of which one step was shown would seem to be unsuitable for the calculation of the case of an actual reversal of the field. The method will converge, though progressively more slowly with stronger currents, so long as there is no actual reversal; but a self-consistent calculation rather than an iteration will be required in the case of a current strength that causes a reversal.

Chapman: Your remark about convergence may well be true, though to me this does not seem obvious. But I do think that we should (and will) make new calculations starting with a field already reversed by a stronger belt, and try to achieve self consistency at least approximately. The reversal is caused by the main part of the belt, and in the center of the belt its field would be little altered if the innermost particles were removed.

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I-3-3. A Comprehensive model of Auroral and Geomagnetic Disturbances*

W. I. AXFORD, J. A. FEJER and C. O. HINES

Defence Research Board, Ottawa, Canada

We present here a theoretical model which is able to account in a simple way for many characteristics of auroral and related phenomena. It is based on a specific picture of motions in the earth's magnetosphere, falling within the limited class of permissible motions (T. Gold, J.G.R., 64, 1219, '59)¹⁾, and applied to a model of the magnetosphere

which incorporates a 'geomagnetic tail' for the field lines that rise at high latitudes (F. S. Johnson, J. G. R., 65, 3049, '60²⁾; J. H. Piddington, J. G. R., 65, 93, '60³⁾). The motions include a rotation of the inner portions of the magnetosphere, and a related counter-rotation in the tail region near the equatorial plane, enforced by the earth's rotation (*cf.* Johnson, loc. cit.; see Fig. 1).

* No manuscript has been received and the preprint is reprinted.

The particular motions that we now intro-

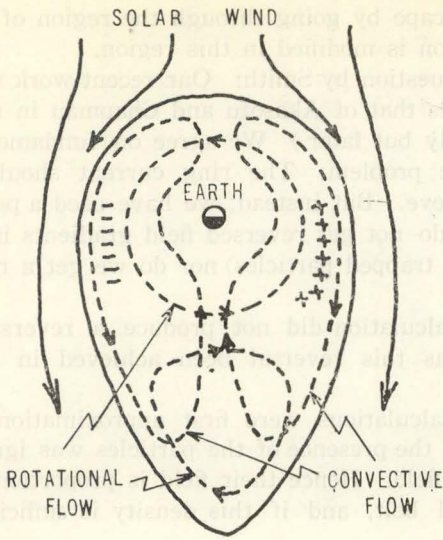


Fig. 1.

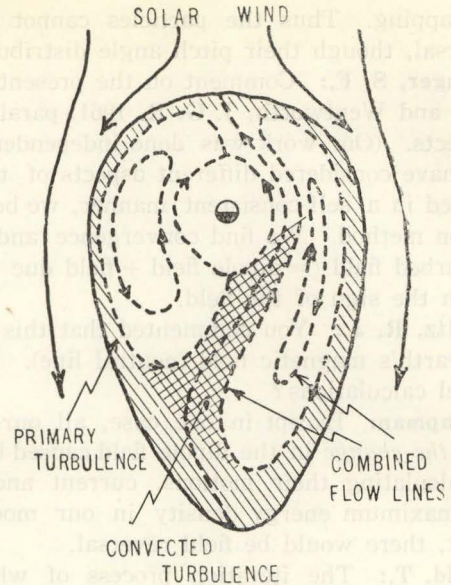


Fig. 2.

Equatorial Sections through Magnetosphere

duce, and whose consequences we study in detail, can be attributed to a viscous-like interaction between an assumed 'solar wind' and the outer portions of the magnetosphere. It may be ascribed alternatively to the effects of high-energy solar particles which enter the magnetosphere on the sunward side and then develop space charge as a consequence of their drift motion in the inhomogeneous geomagnetic field. In any event, the motions are such as to carry the outer ionization of the magnetosphere towards the region of the tail, and to establish a return path for the flow in the interior of the magnetosphere down to the region of the outer Van Allen belt. (See Fig. 1.)

Turbulence at the outer boundary of the magnetosphere is also carried into and through the interior. The ionization is energized during the inwards convection and in the regions of turbulence: The region of inwardly convecting turbulence provides a particularly strong source of energetic particles. Because of the combination of rotational and convective motions, this region occupies an oddly-shaped equatorial cross-section as depicted in Fig. 2. The motions and the turbulent regions are observable at ionospheric heights, in a pattern that may be obtained by mapping the equatorial sections downwards along geomagnetic field

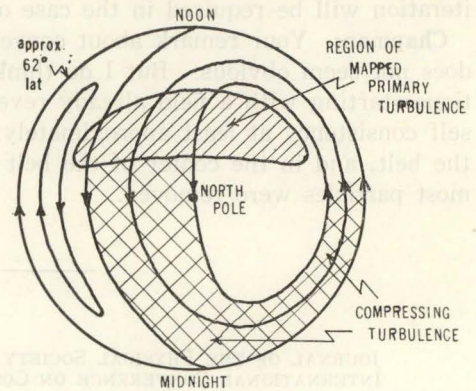


Fig. 3. Polar View of Earth

lines. Such a pattern is shown in Fig. 3, where the flow lines are drawn as for an external observer not rotating with the earth.

The detailed development of this model can be applied to account for the following observations (among others): (1) Aurorae (including radio aurorae) occur predominantly in the night-time hours. (2) Quiet auroral forms characterize pre-midnight conditions, irregular forms characterize post-midnight conditions. (3) Enhanced disturbance features (including aurorae, high-intensity *Es*, spread *F*, geomagnetic agitation, cosmic noise absorption) at high latitudes maximize along a spiral-shaped contour running from higher to lower latitudes during the late evening

and early morning hours. (4) Auroral irregularities and radio-star scintillation centers move westwards during the pre-midnight hours and eastwards during the post-midnight hours at low auroral latitudes, reversing at high auroral latitudes, while the currents of bays and of the *Ds* system flow oppositely. (5) The storm-time growth and decay of a ring current, and the recovery of the Van Allen flux to high levels following its diminution early in a storm.

Details of the model and of its application

may be found in papers now in press in the Canadian Journal of Physics: "A unifying theory of high-latitude disturbance phenomena" by W.I. Axford and C.O. Hines, and "The effects of energetic trapped particles on magnetospheric motions and ionospheric currents" by J. A. Fejer.

References

- 1) T. Gold, *J. Geophys. Res.*, **64**, (1959) 1219.
- 2) F. S. Johnson, *J. Geophys. Res.*, **65**, (1960) 3049.
- 3) J. H. Piddington, *J. Geophys. Res.*, **65**, (1960) 93.

Discussion

Alfvén, H.: As the behaviour of a plasma which enter the magnetic field of the earth is discussed, I should like to point out that this can be investigated, and has been investigated, experimentally. In Malmfors Block's experiment a plasma is shot towards the dipole field of a terrella. The penetration of the plasma in the experiment resembles very much what is observed in nature. The plasma penetrates to the terrella in rings around the poles which should be identified with the auroral zones.

The experiment has very recently been repeated with a high density plasma using the so-called thermo-nuclear technique. A similar phenomenon is observed.

According to the experiment the production of the aurora has nothing to do with the formation of a field-free region, as suggested by Akasofu-Chapman, nor is it primarily due to a pressure effect.

Hines, C.O.: These results are very interesting in their own right, but I severely doubt their applicability to the geophysical system. One feature that occurs in the geophysical case, and that is absent from the laboratory model, is the existence in the (geo-)magnetic field of a substantial low-energy plasma with high magnetic Reynolds number. This feature is central to the theory developed by Axford and myself. Until this feature can be duplicated in the laboratory, properly scaled, I would find it difficult to agree that the laboratory experiments can tell us very much about the occurrence of aurorae and auroral zones.

Ratcliffe, J. A.: Do particles of different sign reach the earth on opposite sides of the curve of deposition on the earth, according to the theory?

Hines: I should make it clear that the only deposition curve about which we hold strong opinions is that which descends from high to auroral latitudes on the late evening — earlymorning part of the earth. This is the curve along which the great majority of irregular features reach their diurnal maximum intensity, and it is a curve which we would associate with the occurrence of convecting turbulence in the magnetosphere during the compression phase. The compression itself would be capable of raising both electrons and protons to energies of some kev, and would tend then to inject electrons to somewhat greater depths. In this sense, electron precipitation may be said to be stronger than the proton precipitation on this curve—but because of differences in depth-of-penetration properties rather than differences in energy of the two types of particle. We do not know how to assess the additional energization that would be conveyed by the turbulence itself. If turbulence energizes protons sufficiently more strongly than it energizes electrons, the foregoing conclusions could be reversed. Auroral and particle observations indicate, of course, that the electron precipitation is the more important along this curve.

Our theory cannot give any clear interpretation of the second deposition curve that is observed, which rises from auroral to higher latitudes in the pre-dawn hours and

which in some ways appears to be continuous with the first. This curve, and its symmetrical counterpart in the post-sunset hours which Nikolsky and Burdo cite from geomagnetic agitation data, appears to be closely related, to $H\alpha$ emissions as reported by Montalbetti and McEwen at this meeting. The protons appear to have energies of 20–80 kev, from doppler measurements, and such protons could of course produce E -region effects. They would be essentially trapped particles, only slightly affected by the convection discussed in our current theory—they would be perturbed rather than carried by the convection—and I would prefer not to guess at the moment whether or not the perturbation is significant to their deposition.

Davis, T. N.: I wish to point out, as Dr. Hines did not have the time to do so, that this theory is the first to suggest an explanation for the fact that auroral arcs are aligned toward the sun within the polar cap, that is within colatitude 10° .

Hines: I would comment that we really show that the pattern of motions over the polar cap is so aligned. Insofar as Dr. Davis has found that arcs and motions are parallelly aligned at lower latitudes, it might be inferred that our theory would give the observed orientation of arcs at high latitudes. As yet, however, we have no theoretical explanation of the link between the two, although this question is currently under examination.

Smith, E. J.: What magnitude of solar plasma energy densities are required to produce the effects you describe?

Hines: Like everyone else, we must have an influx of energy at a rate at least sufficient to account for the dissipation that is implicit in the ionospheric currents of the D_s system. We estimate this at 10^{11} watts, or 10^{18} erg/sec. If we assume that this energy comes from the energy flux impinging on the magnetosphere, and give the latter a capture cross-section of 10^{20} cm² (which corresponds to a geomagnetic cavity about 10 earth radii across), we need an energy flux in the solar plasma of 10^{-2} erg/cm²/sec. If the solar plasma is approaching at a speed of 10^8 cm/sec, then we need an energy density in the plasma of 10^{-10} erg/cm³. With a proton mass of 10^{-24} gram, this corresponds to 10^{-2} protons/cm³. In fact, of course, nothing like all of the incident plasma energy will be converted into magnetospheric motions and dissipated in the ionospheric currents, so the actual plasma densities required will be greater than this value by a large but unknown factor. If the factor is, say, 10^3 , then the required energy flux is of the order 10 erg/cm²/sec, the required energy density 10^{-7} erg/cm³ and the number density 10/cm³. Such a number density, proceeding at the speed 10^8 cm/sec, also leads to a cut-off of the geomagnetic field at a distance which would place the ‘eyes’ of the D_s system at the appropriate latitude. It is interesting to note also that Sonett’s estimate of the energy flux contained in hydro-magnetic shock waves near the magnetospheric face is intermediate between the foregoing estimates of 10 erg/cm²/sec plasma energy and 10^{-2} erg/cm²/sec required for deposition into ionospheric currents, and it is for this reason that we consider such shock waves to be a likely means of coupling the solar plasma energy into magnetospheric circulation.

Bridge, H. S.: Have you estimated the extent of the “tear dropping” of the earth’s field required by this model?

Hines: We have not explored this question, nor is it a very critical one for our model. F. S. Johnson and D. B. Beard have considered the extent of the tail, and I recall distances of many tens of earth radii being discussed.

I personally prefer to think of a tail limited to within a geocentric distance of 20 earth radii or so, but I cannot argue strongly for this.

Gold, T.: The Terrella experiment referred to by Prof. Alfvén does not represent the essential conditions for the actual case. Long magnetic time constants allowing the convection of tubes of force and insulating interface are required. To understand the proper scaling of the experiment would seem to be much harder than to under-

stand the actual case. I find the essential considerations presented by Dr. Hines completely compelling.

Singer, S. F.: (1) Could you clarify the role of the neutral atmosphere in the processes of rotation and convection? (2) Could you perhaps represent the motion of lines of force (and magnetospheric material) by EMF's in the ionosphere?

Hines: The neutral atmosphere below the ionosphere serves to set the lower ionosphere into rotation, and hydromagnetic forces then ensure rotation throughout the rest of the ionosphere. Had the neutral atmosphere been conducting, the rotation would have been enforced by hydromagnetic forces right from ground level on up. With regard to the convection: the non-conducting nature of the neutral atmosphere below the ionosphere is essential to permit convection. If this atmosphere had been sufficiently highly conducting, then hydromagnetic forces could link the ionosphere with the conducting Earth, and then forces would have essentially prevented convection. As it is, polarization charges can accumulate in the ionosphere, and these cannot be dissipated sufficiently rapidly via ionospheric conduction to prevent the existence of polarization fields. From the classical point of view, it is these fields that are essential to the convection process — the convection velocity is simply $E \times B/B^2$ — and their continued existence is therefore vital. Short-circuiting through a highly conducting lower atmosphere, and/or through Earth, would have resulted in markedly decreased polarization fields and hence a much slower, if not negligible convection. This perhaps answers the second question: a hydromagnetic description of events can always be replaced by an exactly equivalent classical description, and in such a description the convection is indeed associated with an electric field. The choice of description is largely a matter of taste, although one could also argue on a causality basis for one or other of the descriptions. Axford and I prefer the hydromagnetic description for this reason, in that we tend to think of the motions in the outer magnetosphere as being fundamental and the polarization fields as being generated as a consequence, although our full paper presents the story both ways. In a generation mechanism such as Fejer describes in his full paper, the charge separation is fundamental and the motions would then be induced.

A further comment about the role of the neutral atmosphere. Within the ionosphere, the motion of the neutral constituents is important in determining the currents that will flow. Since this motion can be affected by collisions with the convecting ionization, the current flow in our model cannot be determined simply from the polarization field alone. This provides a partial explanation of the fact that observed *D_s* systems tend to be aligned at an angle to the sun-earth line whereas the polarization fields have a sort of symmetry. This point is discussed in the full Axford-Hines paper.