

## Motions in the Magnetosphere of the Earth

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*Abstract*—The conditions determining the dynamical behavior of the ionized gas in the outer atmosphere of the earth are discussed. It is proposed to call this region in which the magnetic field of the earth dominates the 'magnetosphere.' Observations by Van Allen and others indicate that this zone reaches out to between 5 and 10 earth radii, depending on the degree of magnetic disturbance.

It is shown that the existence of an insulating layer at the base of this region, namely the non-ionized atmosphere, completely changes the type of control exerted by the magnetic field, allowing a class of motions to occur freely without the need to overcome any magnetic forces. The extent to which such motions may occur is discussed, and some of the indications from airglow and magnetic observations are mentioned.

The theory predicts that, at the level of the  $F_2$  layer and above, most motions will show strict symmetry between the two base points of a magnetic line of force.

It has now become possible to investigate the region above the ionosphere in which the magnetic field of the earth has a dominant control over the motions of gas and fast charged particles. This region is known to extend out to a distance of the order of 10 earth radii; it may appropriately be called the magnetosphere. Even though at present only the most rudimentary information is available about the behavior of this region, it is of interest to investigate the laws that dictate the motion of material there.

It is customary in magnetohydrodynamics to consider the approximation of arbitrarily high electrical conductivity. In those circumstances the concept of lines of force obtains a new meaning. The Faraday concept was a representation only of the direction of the field at each point in space; no meaning was attached to the identity of each line. In a perfectly conducting fluid the particles that are at one time on a line of force remain on one throughout the motion; each line has thus an identity, established through the identity possessed by a set of fluid particles. This concept has proved extremely valuable for discovering the relation between flow and deformation of a magnetic field in magnetohydrodynamics.

This identity of lines of force loses meaning as soon as insulating surfaces or volumes play a part. Thus a conducting disk spinning between the poles of a conducting magnet experiences no magnetic torque so long as there are insulating sheets, however thin, separating it from the pole pieces. The lines of force are not drawn around by the disk, for, not possessing identity, the field need not change in order to allow each area in any of the conductors to remain linked with the same quantity of magnetic flux. If contact is made, as by filling the space with a conducting liquid, the situation is changed entirely, for now all lines are identifiable everywhere, and they must therefore be wound up in the motion, resulting in a decelerating torque through the Maxwell stresses in the deformed field.

The earth's field in the magnetosphere is embedded in a good conductor, namely the tenuous ionized gas known to exist there. In this region it is permissible to consider gas and field locked to each other, for sufficiently rapid motions. But the atmosphere acts as an insulating sheet separating all this region from the conducting earth, and no currents of any significance can flow between the ground and the lower surface of the ionosphere. (The atmospheric convection of charge is insignificant in its magnetic effects.) No identity of lines exists therefore across the

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atmosphere, and consequently there are no magnetic forces resulting from a certain class of ionospheric and magnetospheric motions.

For example, in the particular case of axial symmetry, no torque would result from a relative rotation between earth and magnetospheric material. (This is quite different from the case of the sun, where no insulating layer intervenes.) In the general case no magnetic forces can result for any motion that leaves the shape of the field in the magnetosphere unchanged as well as its position relative to the surface of the earth. The field within the atmosphere, where no currents can flow, must then necessarily also remain unchanged, and no new forces can arise. There exists a class of motions that will not change any fields, namely those in which each arch of a line of force, from one to the other base at the bottom of the ionosphere, moves to the position previously occupied by another such arch. In general, this involves deformation of the material, but, allowing that, any line of force with the material that it is threading can be moved to any other position. The entire medium can thus be stirred up without requiring any magnetohydrodynamical work.

Although this motion leaves all fields unchanged, it is still controlled by the field. Thus, for example, if in the northern hemisphere a patch of ionospheric material was found to be moving in a certain way, there must be a corresponding motion at the conjugate point in the field in the southern hemisphere, and the two areas would have to remain conjugate throughout the subsequent motion.

An entirely equivalent way of regarding this motion would be to take coordinates fixed with respect to the earth, and to consider the electric fields associated with a motion of the magnetospheric material across the field.  $d\mathbf{B}/dt = \text{curl } \mathbf{E} = 0$  everywhere in that case. But an electric field  $\mathbf{E} = (1/c)\mathbf{V} \times \mathbf{B}$  exists then which, for just the case of the class of motions of material described, results in no currents but only in surface charges at the insulating layer. In this description a particular class of motions of the conducting medium in the fixed magnetic field is thus permitted, and is associated with electric fields derived from surface charges.

Since there is a class of motions in the mag-

netosphere not impeded by the magnetic field, we must inquire what forces exist to cause or to dissipate them. Also we shall want to understand the consequences that such motions have on a variety of observable phenomena.

In the presence of conducting gas exerting a significant pressure, it is necessary to inquire into the magnetohydrostatic balance. If a certain distribution of gas were contained in the region occupied by the field at one time there may now be the possibility of a rearrangement of all this gas such that the total energy of the system is lowered, and one that can be carried out without the need to overcome any magnetic forces. Provided that a pattern of motion exists from the initial to the lowest energy configuration, such that the energy decreases monotonically, the system will carry out such a motion. This is quite analogous to thermal convection in a gravitating compressible medium; only in the present case the forces are derived from the magnetic field whose gradient implies an outward force on the gas which according to its energy content acts as a diamagnet. Also there is now a new restriction on the pattern of motion that can take place, namely the one that involves no magnetic work being done.

In a gravitating compressible fluid there is a certain gradient of the temperature with height, the adiabatic gradient, at which no change in the energy of the system results from any convection. A slower decrease of the temperature with height than the adiabatic gradient leads to stability; a faster decrease leads to convective instability. In the magnetohydrostatic case we wish to find the analogous division into a stable and an unstable regime. We shall at first neglect the effects of gravitational forces on any gas, and consider the magnetic forces only. This procedure is equivalent to considering a gas content of the magnetosphere which is entirely at a temperature much in excess of that of escape in the absence of magnetic fields. Such a condition may be approximately fulfilled by the ionized gas in the magnetosphere. Also we shall make the approximation that the gas pressures existing in the region are insufficient to alter the magnetic configurations significantly; the thermal energy density is assumed to be small compared with the magnetic energy density  $H^2/8\pi$ . This condition may in fact be vio-

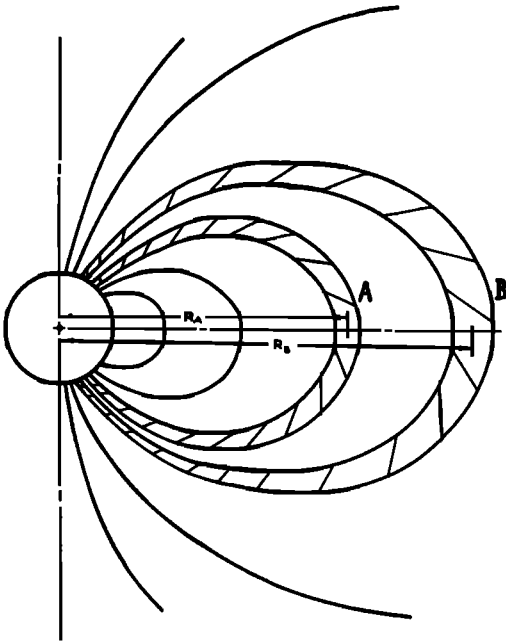


FIG. 1

lated, especially during periods of magnetic disturbance. Also, we shall restrict the discussion to a dipole field only.

To derive the adiabatic gradient in the magnetohydrostatic case, we consider the change in the pressure or energy density of the gas that fills a magnetic tube of force  $A$  (Fig. 1) when the tube is moved so as to occupy the position of the tube of force  $B$ . We take the approximation that the volume of the earth is small compared with the regions under consideration, and we are then helped by the fact that the lines of force of a dipole field are all similar to one another except for scale.

The magnetic field strength declines with distance as  $1/R^3$ , where  $R$  is the distance from the center. The motion of a tube of force from  $A$  to  $B$  therefore implies an expansion such that the cross-sectional area of  $B$  is  $(R_B/R_A)^3$  times as great as that of the same tube at  $A$ . The volume of the tube has therefore increased as  $(R_B/R_A)^4$ , for the length has increased in proportion to  $R$ . If the tube of force at  $A$  contained a gas having an energy density characterized by the pressure  $p = nkT$  (where  $n$  is the number density of molecules,  $k$  is Boltzmann's constant, and  $T$  is the absolute tempera-

ture), then the pressure would be decreased by the expansion into the position  $B$  according to the gas law applicable. Let us take a monatomic gas whose ratio of the specific heat is  $5/3$ , and consider an adiabatic expansion. This may be a good approximation in some cases in the magnetosphere. We have  $pV^{5/3} = \text{constant}$ .  $V = aR^4$ , where  $a$  is a constant.  $p(aR^4)^{3/5} = \text{constant}$ . Hence  $p = nkT = \text{constant} \times R^{-20/5}$ . In the isothermal case where  $pV = \text{constant}$  the result would be that the pressure would diminish with radius as  $R^{-4}$ .

The law that corresponds to the adiabatic gradient for the magnetohydrostatics of a monatomic gas in a dipole field is therefore a decrease of the energy density with increasing radius according to  $R^{-20/5}$ . It is to be noted that in this case, unlike the situation in the gravitational case, it is only the energy density, or the product  $nT$ , that enters, not  $n$  and  $T$  separately. It is therefore not a temperature gradient that can be defined as the one of limiting stability, but a gradient of the gas energy density; a little hot or a lot of cold gas has similar effects.

If a non-colliding particle flux is considered instead of a hot gas the considerations lose their simplicity. It is then necessary to specify the distribution of pitch angles of the particle motions in the field in order to follow the consequences of an interchange motion. (The adiabatic law is probably not changed very much for any pitch angle but may become as steep as  $R^{-6}$ .)

If in the actual case the energy density falls off with increasing radius more slowly than  $R^{-4}$  the system will be stable against thermal convection; more energy is required to compress the down-going tubes of force than is available from the expansion of the rising ones. For gradients of the energy density that lie between  $R^{-4}$  and  $R^{-20/5}$  a thermal convection can take place at a rate at which heat can be exchanged between rising and falling masses; at  $R^{-4}$  the process would need to be strictly isothermal and the rate of movement therefore very low. For gradients steeper than  $R^{-20/5}$  the system is unstable against fast adiabatic convection. A motion will then take place in which the lower tubes of force expand and move into the place previously occupied by upper ones, and vice

versa. Within the approximations made, the magnetic field is nowhere and at no time changed in the process. These motions might have been described, as mentioned earlier, in terms of a fixed magnetic field and motions permitted as a consequence of electric fields derived from charges.

The most important description of the magnetosphere that future experimentation will give us will be a definition of the regions that are convectively stable or unstable. The present knowledge of the Van Allen flux is by itself not adequate to provide this information, for the principal thermal energy content of the region very probably resides in a lower particle energy than has been counted up till now. The total energy content that has to be associated with magnetic disturbance on the earth is greatly in excess of the energy content implied by the measured Van Allen flux.

It is very improbable, however, that the total very density diminishes as rapidly with increasing radius, measured in the equatorial plane, as  $R^{-2}$  (or even as fast as  $R^{-1}$ ) in all that region in which the Van Allen flux increases with  $R$ . A large part of the magnetosphere is therefore likely to be magnetohydrostatically stable. There are two regions where instability might be suspected: one is a region beyond 6 or 7 earth radii where the Van Allen flux generally decreases and where the gas density no doubt has to merge into the ambient one in the solar system; the other is a region very close to the earth where the diurnal heating of the outer atmosphere by the sun may provide large amounts of hot and partly ionized gas whose energy content falls off very rapidly with distance, owing to the exponential fall-off in the atmospheric density.

The disturbances impressed on the system from outside associated with magnetic storms clearly involve forces other than those discussed here. It is probable, however, that also in the motions taking place then those representing an interchange of lines of force will dominate since just for those no magnetic forces need to be overcome. The inward and outward transportation of gas masses and also of particle fluxes at such times may occur much more freely than it would in the absence of an insulating atmosphere and therefore of this type

of motion. A better understanding of the processes of magnetic storms and auroras and of the Van Allen radiation zone would all require better estimates of the interchange motions than can be made at present. Such motions may show themselves directly in the bodily movement of auroral rays, especially in latitude; in the geographical movements of foci of magnetic disturbance; or in high-level ionospheric winds. In all cases these movements will be characterized by a symmetry in the two magnetically defined hemispheres, and this symmetry may be demonstrable in a variety of observations.

Another region of instability may arise in the absence of external disturbance if the external ambient pressure falls and so leaves the gas pressure gradient greater than the critical one in the region where the changeover from terrestrial to interplanetary gas conditions takes place. This is a region that is expected to be generally outside the auroral region, and the lines of force involved would therefore be those that emanate close to the poles. Those would then be liable to an interchange motion in which gas energy is transported farther out (perhaps effectively lost from the earth) until the pressure gradient is restored to the stable value. This motion may represent a major source of loss of gas and particle fluxes from the vicinity of the earth.

The possibility of an inner convection zone driven by the diurnal heating of the outer atmosphere deserves further consideration. The proportion of the energy content in a tube of force that may be due to diurnally heated gas must be greatest in those tubes of force that emanate in an equatorial zone. Not only is the solar heating more intense there, but also the lines of force involved do not go through large regions whose stability would counteract the effects of the diurnal heating at a lower level. If a diurnally convecting zone exists we should expect it to be confined to the lines of force that emerge within a certain distance of the equator.

In trying to decide what the size or the limiting latitude of such a zone might be, one could proceed either by calculation, using what evidence there is of the gas content and diurnal heating at high levels in the atmosphere, or by search for observational facts that would be

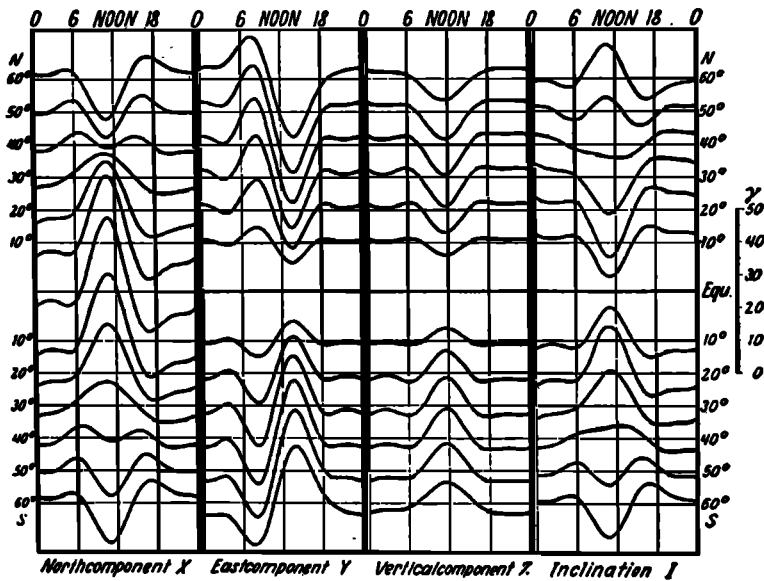


FIG. 2.—Diurnal changes of the earth's magnetic field at different magnetic latitudes. [After Chapman and Bartels, 1940.] Sunspot minimum year 1902. Approximately  $40^\circ$  latitude is seen to be the division between the low-latitude and the high-latitude behavior.

accounted for by such a limited region of convection. The data now available for the high-level atmospheric energy content and its diurnal variation are quite inadequate for the first method, and it is therefore necessary to concentrate on the second. Several phenomena suggest that a region in the vicinity of  $40^\circ$  latitude is associated with a substantial change in the magnetospheric conditions. The diurnal variations of the earth's field at magnetically undisturbed times show a completely different behavior between low- and high-latitude regions with the changeover in the neighborhood of  $40^\circ$  (Fig. 2). At the low latitudes the behavior of the field corresponds to a compression at noon, whereas it is an expansion at that time at the high latitudes. Also in the region of  $40^\circ$  latitude is a zone of enhanced airglow, and there are strong suggestions that the phenomenon of airglow is under some sort of magnetic control. Lastly the minimum detected in the Van Allen radiation zones separating the inner from the outer belt is defined by the line of force at about  $40^\circ$  [Van Allen and Frank, 1959].

The airglow observations of Roach [1959] are of particular interest in this connection. He observes the prominent forbidden line of atomic

oxygen at 5577 angstroms and concludes that large-scale patterns of brightness appear to move over an observing station in the course of a night. He finds an indication of a region of maximum intensity at a latitude of  $38^\circ$ , and he finds a most interesting seasonal behavior in the direction of the maximum brightness that is seen from an observing station in the middle latitudes. The ratio of the intensities a little above the horizon in the north to those in the south is shown to be a quantity that has a semi-annual but no annual variation. This ratio of north to south brightness has minima at the equinoxes and maxima at the solstices, which could be interpreted by saying that the zone of maximum brightness moved to lower latitudes at the equinoxes and to higher latitudes at the solstices (Fig. 3).

Roach discusses the semiannual nature of this variation and finds it puzzling. It is clear that the airglow cannot be significantly affected by the amount of solar radiation received by the upper atmosphere on the day preceding the observation, for in that case there should be a strong annual term. A semiannual term, on the other hand, suggest that, whatever the solar influence is, it is constrained to affect the two

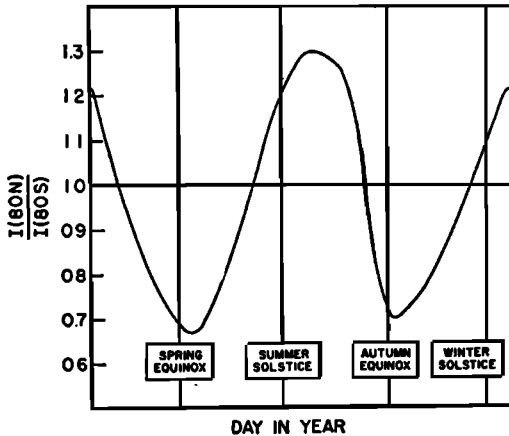


Fig. 3—Relationship of the ratio of intensity of 5577, north/south to season; from Fritz Peak, Colorado [Roach, 1959]

hemispheres in an identical manner. It is hard to think of any way in which a constraint of this sort could arise except through the magnetic field. If the behavior at one base of a line of force has to be the same as that at the other base, no solar influence can show an annual term, and a semiannual one will then be expected. The existence of a semiannual term by itself argues strongly in favor of an interpretation of airglow in which the magnetic field plays an important part even in the absence of a detailed theory of the phenomenon. The more particular suggestion that might be made within the present discussion is that the extent of the convecting region shrinks to its smallest size at the equinoxes when the sun is above the equator and therefore above the center of the zone, and the zone grows to its maximum extension at the solstices when more solar heat is applied at the higher latitudes. If this magnetospheric convection is responsible, as it might well be, for driving particle fluxes into the atmosphere, a seasonal movement in the limit of the convecting zone may show up as a seasonal movement in airglow brightness. The semiannual nature and the sign of the phenomenon are then accounted for. Alternatively it is possible that it is just the upper air density which is under magnetic control and affected by the convection zone and that the airglow brightness arising in some other way is controlled by this density. It seems very hard to suggest any interpretation not involving the

interchange motion and yet leading to a strictly semiannual behavior.

Possibilities for the investigation of such motions come from a number of fields. Ionospheric radio observations may succeed in demonstrating that, for motions at the  $F_2$  level and above, a strict symmetry exists for the points that lie on a common line of force. Stations at conjugate points in the two hemispheres are probably required for this. Similarly airglow observations and magnetic observations at conjugate points would be important.

The amount of thermal energy that can be added into a tube of force by nuclear explosion is by no means small, and this can be expected to result in an interchange motion in which the tube that is mostly affected moves so as to occupy a position far out, connecting with high magnetic latitudes. This motion would not be shown up by energetic charged particles whose drift motion in longitude is so fast that they will remain in the affected tube of force for a much shorter time only than that taken up by the interchange motion. The existence of a stable shell of fast electrons as was observed in the Argus experiments is thus in no conflict with the present considerations, but these observations place a limit on the speeds and patterns of interchange motions that may occur.

The diffusion of fast particles in captured orbits is not discussed in the present paper. It is clear, however, that the velocities of the interchange motions will be also impressed on the particle fluxes; only the motion in longitude, which is faster the higher the particle energy, will tend to average out the effects. Indeed, these effects will average out exactly when the drift of the particle once around the earth occurs in a time during which no changes in the velocities of the interchange motions have taken place. Nevertheless it is probable that these effects are the dominant ones for the eventual diffusion of any captured flux of energetic particles.

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