

I-3-2. The Ring Current and a Neutral Line Discharge Theory of the Aurora Polaris

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The electric current intensity distribution and the magnetic field produced are calculated for a model ring current belt, centered at 6 earth radii, in the outer part of the outer radiation belt. The current, partly eastward though mainly westward, produces a pronounced dip of the magnetic field near the center of the belt, agreeing with Explorer VI observation.

During magnetic storms, protons (50~500 Kev) in the belt increase, perhaps by capture from solar streams carrying (tangled?) magnetic fields. The ring current increases, and at times reverses the earth's magnetic field near the center line of the belt. Neutral lines ($H=0$) appear, of two kinds, X and O.

Particles discharged through narrow strips close to one or more X lines produce diffuse arcs, single or multiple. Particles sporadically captured produce transient eastward electric fields along the X lines. Electrons are accelerated, a strong (but unstable) current flows along the X lines. This narrows the "escape" strips and increases the number and energy of the auroral electrons. The result is extremely thin and bright auroral curtains, with large scale folding and fine ray structure. Westward auroral electrojets are also explained.

The large decrease in the horizontal component of the earth's field during the main phase of magnetic storms is ascribed to the formation or enhancement of a geomagnetic ring current. We have made detailed numerical computations for a model radiation with center line at equatorial radius $r_e = r_{e0}$. At r_e the number density $n(r_e)$ is $n_0 \exp(-q^2(r_e - r_{e0})^2)$. The pitch-angle distribution function $F(\phi)$ is $A \sin^{\alpha+1} \phi$. Four parameters completely describe the model belt. The values chosen are $r_{e0} = 6a$ ($a =$ earth radius), $\alpha = -1/2$ and $q/a = 1.517$, together with $n_0 E$, the product of n_0 , the maximum number density (per cm^3) at the center, and E the energy (in Kev) of each particle.

The value $\alpha = -1/2$ corresponds to a pitch-

angle distribution that has a moderate excess of small pitch-angles. The value $q = 1.517a$ corresponds to a reduction of density to a tenth of the maximum value n_0 , at a radial distance a on either side of the center line of the belt — that is at $5a$ and $7a$.

Fig. 1 shows the current intensity distribution; the unit current is the value at $r_{e0} =$

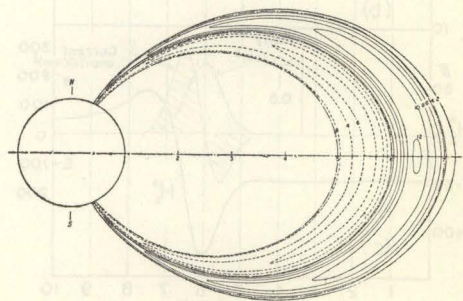


Fig. 1.

1) There engaged in a program of research sponsored by the National Bureau of Standards and the Air Force Geophysical Research Directorate.

$6a$, which is $1.66 \times 10^{-5} n_0 E$ amperes. The current flows eastward in the inner part of the belt and westward in the outer part. The resultant current is westward. The main contribution to the current comes from the diamagnetism of the trapped particles.

Fig. 2 shows the magnetic field vectors for the model belt. Within a radius $2a$ the field is nearly uniform and directed southward, parallel to the earth's dipole axis. Near and

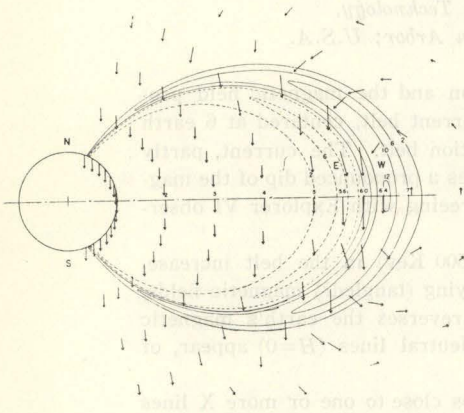


Fig. 2.

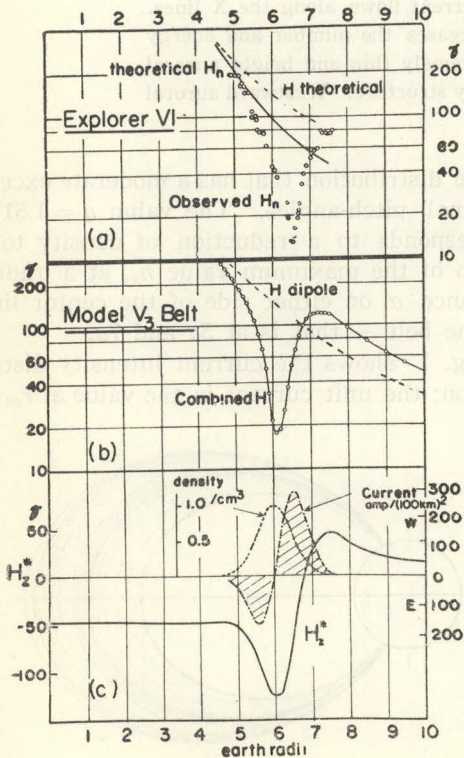


Fig. 3.

in the belt the field is notably nonuniform. It shows considerable curl in the region of most intense current, centered at about $6.5a$.

Fig. 3 shows (a) the magnetic field measurements made by the magnetometer carried by Explorer VI; (b) the field distortion produced in the equatorial plane by the model belt; and (c) the number density distribution $n(r_e)$, the corresponding current distribution $i(r_e)$ and the magnetic intensity $H(r_e)$, in the equatorial plane, for $n_0 E = 150$ (corresponding, for example, to $n_0 = 1/cc$ and $E = 150$ Kev). There is fair agreement between the observations and our computed results. Fig. 4 shows lines of force of the earth's dipole field (broken lines) and of the distorted combined field (full lines), for $n_0 E = 150$.

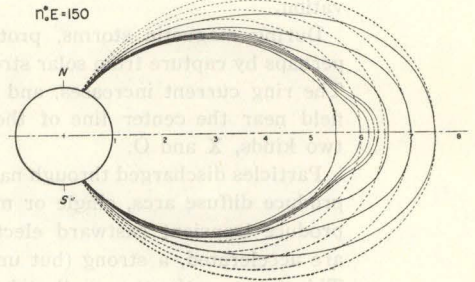


Fig. 4.

Our computations are based on the motions of trapped particles in the earth's dipole field. This gives what may be called the dipole approximation to the field of the belt. The corresponding distortion of the dipole field shown above must affect the motions of the particles, and in turn the current intensity and magnetic field produced. To estimate this non-linear effect, we computed the magnetic field again, using the field distorted by the dipole approximation for $n_0 E = 90$. Fig. 5, analogous to Fig. 3 (b), (c), but for $n_0 E = 90$, graphs the variation of the belt field H , and the combined field, along an equatorial radius, for the dipole approximation (broken lines), and for this second approximation (full line).

The difference between the two approximations is small except near the center of the belt, where the field increase is larger for the second approximation.

We believe that when the belt is sufficiently enhanced—by increase of $n_0 E$ —the

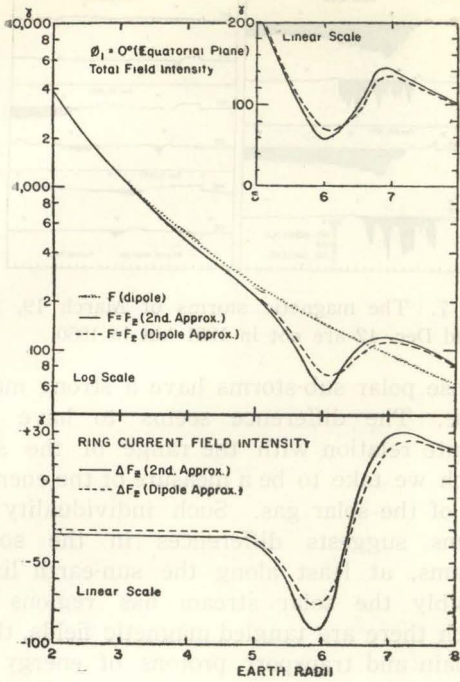


Fig. 5.

earth's field near the center of the dip can be not merely reduced but reversed. It is known that the diamagnetism can reverse the direction of the original magnetic field in the mirror machines, now extensively used to confine plasma for the study of thermo-nuclear reactions.

The reversal occurs within a narrow strip of the equatorial plane, bounded by neutral lines along which the field intensity is zero. The lines are of two kinds, X and O. The magnetic lines of force cross on X lines and encircle O lines. The line of force that passes through the X neutral line is connected with the earth. If the number density distribution is irregular and has more than one maximum, there may be more than one strip of reversed field, and corresponding pairs of neutral lines, X and O. Further, owing to the eastward current on the sunward side of the earth, at the surface of the hollow in the solar stream, the reversal of the field is most likely to occur on the night side of the earth. Fig. 6a graphs such a complicated field distribution; Fig. 6b shows the corresponding field lines in a meridian plane, and Fig. 6c shows a schematic pattern of the stages of reversal in the equatorial

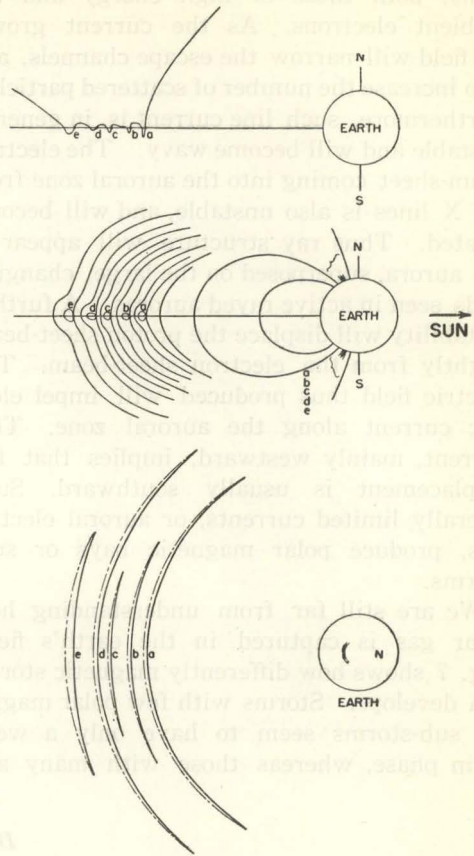


Fig. 6.

plane.

Chapman and Kendall have shown that the pitch angles of particles that pass near the X neutral line are scattered. There the guiding center approximation and the constancy of the dipole movements cease to be valid. Thus the pitch angle distribution of the particles that pass near the X line changes, and ensures a continuous supply of particles with pitch-angle less than 3° , which can contribute to the thin ribbon-like auroral luminosity. When there is more than one X line, there will be more than one auroral arc.

If a new cloud of solar gas is captured, the protons will tend to spread westward and the electrons eastward; thus an eastward electric field may rise in the cloud. When this electric field appears in a region containing X-type neutral lines, these provide an unimpeded channel for electric current flow. Elsewhere the magnetic field prevents current flow. The electric field will accelerate elec-

trons, both those of high energy and the ambient electrons. As the current grows, its field will narrow the escape channels, and also increase the number of scattered particles. Furthermore, such line current is, in general, unstable and will become wavy. The electron beam-sheet coming into the auroral zone from the X lines is also unstable, and will become pleated. Thus ray structure will appear in the aurora, superposed on the large, changing folds seen in active rayed auroras. A further instability will displace the proton sheet-beam slightly from the electron sheet-beam. The electric field thus produced will impel electric current along the auroral zone. This current, mainly westward, implies that the displacement is usually southward. Such laterally limited currents, or auroral electrojets, produce polar magnetic bays or sub-storms.

We are still far from understanding how solar gas is captured in the earth's field. Fig. 7 shows how differently magnetic storms can develop. Storms with few polar magnetic sub-storms seem to have only a weak main phase, whereas those with many and

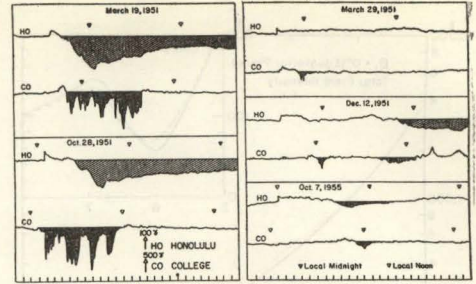


Fig. 7. The magnetic storms of March 19, 29, and Dec. 12 are not in 1951 but in 1950.

intense polar sub-storms have a strong main phase. The difference seems to have no definite relation with the range of the *ssc*, which we take to be a measure of the energy flux of the solar gas. Such individuality of storms suggests differences in the solar streams, at least along the sun-earth line. Possibly the solar stream has regions in which there are tangled magnetic fields, that enchain and transport protons of energy 50 to 500 Kev. Such protons may become trapped in the earth's field from time to time.

Discussion

Smith, E. J.: A comment: The agreement between your calculations and the Explorer VI magnetometer data is most likely to be accidental. As I understand it the calculations were done for points in the geomagnetic equatorial plane. However, the Explorer VI orbit is inclined so that in general points of observation are not located in that plane. In particular the deviation from the geomagnetic field shown in the amplitude data appears to be largely the effect of the *rotation* of the disturbance field vector as the space craft moves along the trajectory.

A question: Your calculations result in a reversal of the gradient in the earth's magnetic field. Doesn't this violate a basic assumption that the current is driven, in part, by the field gradient? Can you reverse the gradient and still expect the particles to remain trapped?

Chapman, S.: As regards your comment, the part of your diagram shown in Fig. 3 indicated not only the actually measured component but also what this component was expected to be if the field were not disturbed. This seemed to imply that the difference shown, which agrees generally with our calculations, was not due to the rotation of the *magnetometer*. Near the equatorial plane the *field vector* should be nearly normal to the plane and should *not* rotate. However, we may hope that future satellites will measure the complete field and no ambiguity in comparison will then arise.

As regards your question, it is true that a part of the current is due to the *field* gradient, but it is only a small part. The major part is due to the *pressure* gradient. Whether particles can remain trapped in a region of reversed field gradient is now being investigated as part of a general study of their motions near a neutral line. The field reversal is confined to a limited volume, which is surrounded by a region

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*

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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-