

Appendix. Theory of Magnetic Storms

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A Personal Preface

At a meeting in Stockholm in 1956 I made some introductory remarks before discussing the subject of magnetic storms and trapped particles. I think these remarks still apply.

Magnetic storms and aurorae are very complicated phenomena. Every theorist has a bias, and that is very good because it gives one a guide line for arranging observed facts in a "logical" way. But it is important to realize that this bias exists. It reveals itself most at the very beginning, namely when we idealize a complicated experimental picture and replace nature by a simple model. It is in this first step where we choose *some* facts and disregard others. Then we usually say that our theory explains the facts, and the rest yield simply to a "slight extension" of our theory. Certainly I am no exception to this rule but I try hard to remember that I am biased, and I hope that this little bit of philosophy will put *all* magnetic storm theories in their proper perspective.

To examine the origin of my own bias I must confess to the good fortune of having been exposed to Alfvén and his work on the motion of guiding centers, and also to Vestine with his emphasis on the ionospheric character of the sudden commencement. I have also been exposed to the papers of many Japanese workers, by Nagata and his students, and by Kato and his students, on the reverse sudden commencement and on pulsations; and I have taken these publications to heart. I therefore have essentially the same bias as expressed earlier in this symposium by Fukushima; namely, I believe that a proper theory of magnetic storms should try to explain the reverse sudden commencement and the peculiar features of the sudden commencement and the initial phase, including the enhancement at equatorial noon.

Introduction

The present paper is the outgrowth of an

earlier one (Singer, 1957)¹⁾ which attempted to give what was at that time a new model of magnetic storms and aurorae. In this attempt the paper was not altogether successful. A number of concepts which were then put forward are still the subject of some controversy and certainly not generally accepted. A few have turned out to be incorrect and we shall take the opportunity here to point them out. One feature, however, has become widely accepted and forms the main part of the present paper, namely the hypothesis that particles may exist in a trapped condition in the earth's magnetic field, *i.e.* in the absence of an atmosphere and other removal mechanisms particles in bound orbits would remain there indefinitely. While trapped, they gyrate and drift and set up a current which was identified with the ring current responsible for the main phase of magnetic storms.

Dessler and Parker (1959)²⁾ have correctly pointed out that both the drift and the diamagnetic effects of the particles must be taken into account in calculating the distortion of the magnetic field, although they have preferred to speak about field stresses rather than currents. (They have, however, misread my 1957 paper and apparently did not realize that I had considered the effects due to particles of all pitch angles, not just particles in the equatorial plane.)

Recently Akasofu and Chapman (1961)³⁾ have taken up the much more involved problem of calculating the magnetic effects of a complete particle distribution, and in particular have investigated the sea level magnetic effects. Our recent work (Apel, Singer and Wentworth, 1961)⁴⁾ was developed independently but basically agree with theirs on fundamentals. We were interested in the magnetic field distortion in the equatorial plane in order to compare the theory with the results of various space probes, and in the inverse problem: to reconstruct the particle distribution from the "magnetic signa-

ture" which they generate. Thus our papers are in some respects complementary.

However, we do not embrace their future extension of the theory which leads to steady-state neutral lines of zero field. In addition, we have also approached the rather difficult problem of the nonlinear effects, *i.e.* the modification to be introduced when the distorted field instead of a dipole field is used in the calculation.

Objections to Ring Current

Several criticisms have been raised during the past years against this type of ring current theory. We shall discuss each one in turn.

1. Hydromagnetic effects connected with ring currents

It was first pointed out by Parker (1958)⁵⁾ that a ring current set up at a distance of several earth radii will not make its effects felt at sea level for a period of some hundred years. This estimate was based on the calculation of the diffusion of a magnetic field in a rigid conductor but, as Hines (1959)⁶⁾ has observed, neglected the hydromagnetic term. (The earth's magnetosphere was deduced to be almost completely ionized but this was based on an incorrect application of Saha's formula.)

Nevertheless, some of Parker's point remains; and as Piddington has emphasized recently, none of the ring current theories are hydromagnetic, in the sense that they all use the Biot-Savart law to calculate the sea level effects of the ring current and therefore neglect the possible effects of the intervening plasma.

The objection, while entirely correct, may not be a fatal one. The concept of conductivity in a medium where the mean free path is very long is not an easy one to define and may therefore not be useful to employ. Instead one may consider the propagation of magnetic pressure directly, and we have argued that the propagation time, due to diffusion, will not be in the order of minutes or hours. (It should be noted that the hydromagnetic propagation time is of the order of seconds.)

2. Is the ring current stable?

Schlüter has raised the question as to what balances the Lorentz force $j \times B$. (In the

case of the Chapman-Ferraro current it was the centrifugal force.) The reply quoted in the paper by Singer (1957)¹⁾ is incorrect and should be withdrawn. The correct reply is that the Lorentz force is balanced by the mutual repulsion between the earth's dipole-like magnetic field and the gyrating particle which is represented as a small dipole.

3. Is a ring current required?

A point first raised by Gold is whether any kind of ring current is at all adequate to explain the large longitudinal differences during the main phase of a storm. We felt that Gold's objection is partly valid. Rather than abandon the ring current hypothesis, we have suggested the following explanation (Singer, 1957)¹⁾; namely that along with the ring current there would have to be superimposed an ionospheric current system which leads to the observed longitudinal dependence of magnetic field.*

Recently this subject has been developed further by Fejer (1961)⁸⁾ who treats the case of an asymmetric ring current. The excess current in the portion of the ring closes through the polar ionosphere, with currents flowing from the ring to the ionosphere along the magnetic field lines. In conjunction with this polar cap current, large Hall currents are set up which flow at lower latitudes and are responsible for many of the accompanying magnetic field changes. It seems to us that Fejer's approach is most likely to lead to a solution of the real problem (as opposed to the idealized problem which we are discussing here).

The Sudden Commencement (SC)

It is generally agreed that the extremely rapid rise of magnetic field, denoted by the "sudden commencement", indicates that the phenomenon propagating from the sun has a well defined boundary or sharp edge (Fig. 1). The idea of a shock wave was suggested by

* This view is supported by the recent observation of Kellogg and Winckler (1961)⁷⁾ that the cosmic ray cut-offs are affected at the time of sudden commencement. This would suggest that the ring current is set up just after the sudden commencement (not eight hours later) and that as far as the magnetic effects at sea level are concerned, they may be produced by a superposition of a ring current and an ionospheric current system.

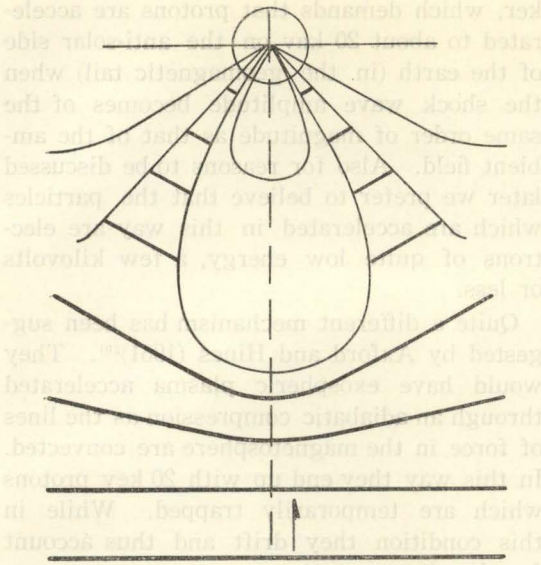


Fig. 1. Position of the shock front in the Earth's dipole field at successive intervals; the shock advances upwards in the figure, is stopped in the vicinity of the equator but can advance into the auroral zones where the field does not oppose its motion.

Gold; however, the mechanism of formation of this shock wave in terms of collisions (Gold, 1955⁹); Singer, 1957¹¹) must be withdrawn. The subject of formation of collision-free shock waves has received a great deal of theoretical attention in recent years but the various investigators are not at all in agreement on, for example, what constitutes the organizing length or thickness of the shock wave (*cf.* Morawetz and Grad, 1961¹⁰); Colgate, 1957¹¹); and Petschek, 1958¹²).

Disagreement exists also concerning the propagation of the shock wave in the magnetosphere of the earth. Some view the sudden commencement as a simple compression of the magnetic field, very similar to the original proposal by Chapman and Ferraro; for example Dessler and Parker (1959)²) adopt this view in treating the SC in terms of a one-dimensional propagation of the wave through the magnetosphere. Their treatment, of course, is highly idealized and one should not expect that it would explain many of the detailed features of the sudden commencement. First of all, the *reverse* sudden commencement (SC*) cannot be explained in this manner (Nagata and Abe, 1955¹³); Fukushima 1951¹⁴), nor the enhancement of the SC in

daylight and at the equator (Sugiura, 1953¹⁵); Vestine, 1954¹⁶); H. Maeda and M. Yamamoto, 1961¹⁷); Nishida and Jacobs, 1961¹⁸). These two features had prompted us to develop a rather *ad hoc* picture of the propagation of the shock wave energy along the lines of force into the auroral zone, the wave accelerating the plasma there to high energies (Fig. 1). It was noted that the diamagnetic effect of the plasma heated by the shock would decrease the field in its immediate vicinity and give rise to the SC*. Looked at in another way, one can speak about the gas pressure, which has suddenly been increased, as pushing out the lines of force near the auroral zone and therefore decreasing the field there (Singer, 1957)¹¹.

However, this view is also much too simple and intuitive. I wish to retain perhaps only the main idea, namely, that the reverse sudden commencement is produced as the shock wave energy moves into the auroral horns and that this process then sets up or enhances the ionospheric current system which is responsible for the SC*, perhaps by producing an EMF through charge separation, or simply by enhancing the conductivity in the auroral zone as was suggested by Nagata. The equatorial and daylight enhancements follow from the well-known properties of ionospheric conductivity.

A quite different proposal has been put forward by Piddington who develops the interaction between a shock wave and the magnetosphere in terms of a "twist wave" which he feels account for the main features of polar magnetic storms.

The propagation problem of an MHD wave in the earth's magnetic field is an exceedingly difficult one. In the first place, it is a three-dimensional problem. Many modes are possible, the medium is anisotropic, birefringent, and inhomogeneous over a relatively small scale. In addition, the wave often has a large amplitude and does not have the Alfvén velocity.

It is evident that there is no universal agreement on how an interplanetary shock wave interacts with the earth's magnetic field. An *a priori* discussion is quite difficult and uncertain, and we have preferred to use the observational evidence to give a clue to what is happening in the magnetosphere.

Setting up of the Ring Current

It is important to know how the particles responsible for the ring current are brought into the magnetic field. Our earlier view (Singer, 1957)¹⁾ was that protons from the solar corpuscular stream, having a streaming kinetic energy of 20 kev, are injected into trapped orbits in the geomagnetic field by way of scattering from perturbations. This view was essentially adopted also by Dessler and Parker (1959)²⁾, and Akasofu and Chapman (1961)³⁾. We now consider this hypothesis to be unsatisfactory since it is quite difficult to calculate this injection process in detail. A new departure has been suggested by Dessler, Hanson and Parker (1961)¹⁹⁾, who point out that the main phase ring current particles may be locally accelerated. This resembles the suggestion (see Fig. 1) that the shock wave accelerates particles in the auroral zone to be dumped into the ionosphere, but that a certain number remain trapped. We prefer this point of view to the particular mechanism of Dessler, Hanson and Par-

ker, which demands that protons are accelerated to about 20 kev on the anti-solar side of the earth (in the geomagnetic tail) when the shock wave amplitude becomes of the same order of magnitude as that of the ambient field. Also for reasons to be discussed later we prefer to believe that the particles which are accelerated in this way are electrons of quite low energy, a few kilovolts or less.

Quite a different mechanism has been suggested by Axford and Hines (1961)²⁰⁾. They would have exospheric plasma accelerated through an adiabatic compression as the lines of force in the magnetosphere are convected. In this way they end up with 20 kev protons which are temporarily trapped. While in this condition they drift and thus account for the ring current.

Properties of Ring Current

We (with J. R. Apel and R. C. Wentworth, 1961)²¹⁾ have extended the earlier work on the drift of trapped particles so as to calculate

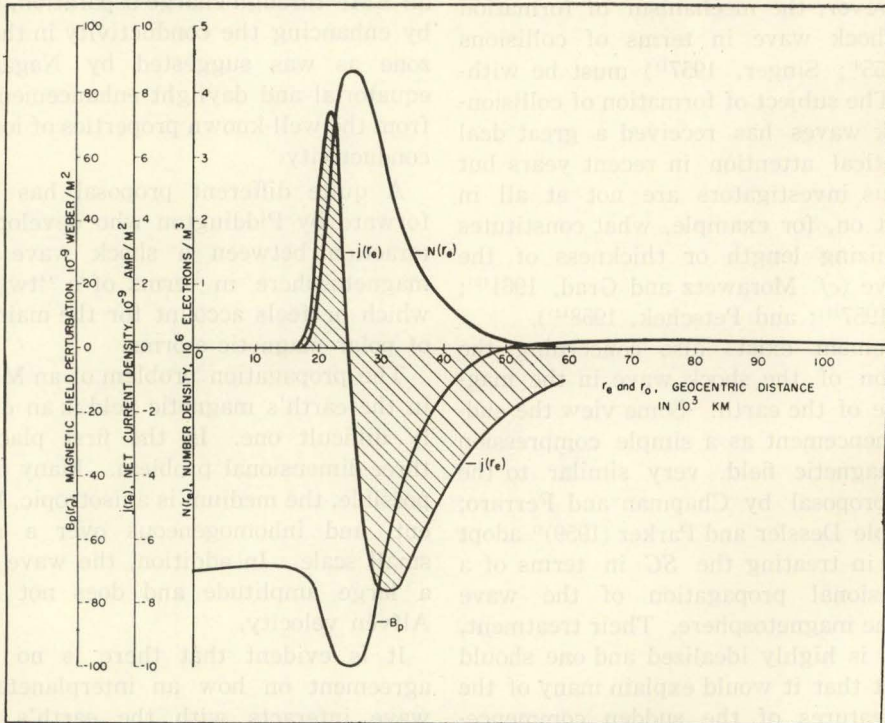


Fig. 2. The smoothly varying density model. Profiles of number density N , net current density j and magnetic field perturbation B_p in the equatorial plane. Note the small positive component in B_p beyond 50,000 km. The negative maximum in B_p occurs at the point of greatest electron density, *i.e.*, at 25,000 km.

their magnetic effects. We have first transformed their dipole moments into a magnetization current which can be added to the drift current; the latter flows from east to west. Thus the result for any particle distribution is a current system which contains an eastward component at lower altitudes and then changes to a westward component (Fig. 2). It is interesting to note that the current is proportional to the gradient of the energy density of the trapped particles and depends on nothing else. The zero current or cross-over point is reached where the gradient of energy density is zero, *i.e.* where the particles have their maximum energy density.

We have calculated "magnetic signatures" of the particles (*i.e.* the magnetic field which they generate) in the equatorial plane as a function of distance, for various trapped particle distributions. Fig. 2 shows the equivalent current system and the magnetic signature for a distribution which rises rapidly from a zero value to a maximum at r_m , and then falls off as $1/r^6$. This spatial dependence

was chosen so as to keep β constant, where β is defined as the kinetic energy density of the particles divided by the magnetic energy density.

In the linear theory, both currents and magnetic effects are strictly proportional to β ; therefore scaling can be done very easily. However, separate calculations must be carried out for each value of r_m . One quantity that can be obtained easily is the magnetic change at the center of the dipole (which is nearly the same as that at sea level provided the trapped particle distribution exists as some distance above sea level).

A very useful model calculation is shown in Fig. 3. Here a sharp distribution has been assumed which rises discontinuously to a maximum value at r_m and falls off again with constant β . Here the eastward current is a current sheet flowing at the inner surface of the particle distribution. For this type of distribution, the effects of variations in the position of the discontinuity can be calculated easily and are shown in Fig. 4.

A particularly useful model for calculation

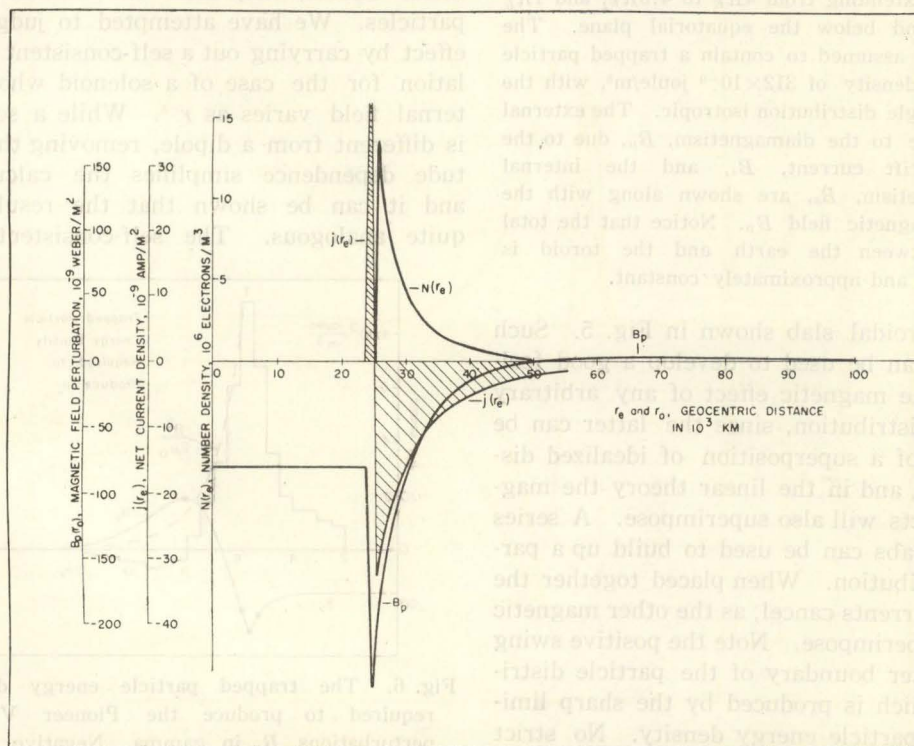


Fig. 3. The discontinuous density model. The particle concentration drops sharply to zero at 25,000 km, leading to the eastward surface current indicated by the spike in j . For the sake of clarity, the discontinuities are shown slightly separated.

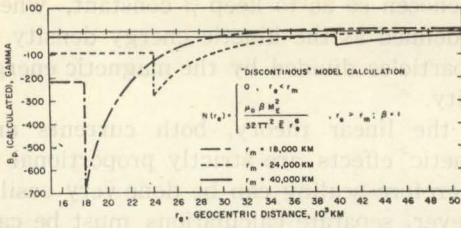


Fig. 4. Field perturbations from the discontinuous model. The detailed shapes are not reproduced without a detailed knowledge of the number density distribution.

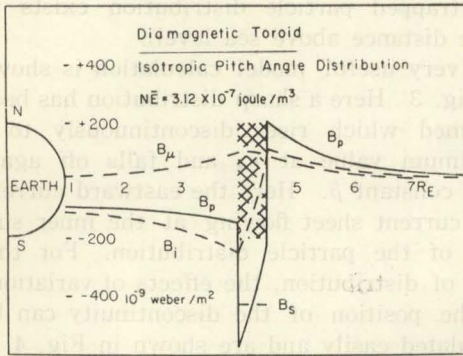


Fig. 5. The fields due to a finite diamagnetic toroid extending from $4R_E$ to $4.5R_E$, and $1R_E$ above and below the equatorial plane. The toroid is assumed to contain a trapped particle energy density of 312×10^{-9} joule/m³, with the pitch angle distribution isotropic. The external field due to the diamagnetism, B_μ , due to the pure drift current, B_i , and the internal diamagnetism, B_s , are shown along with the total magnetic field B_p . Notice that the total field between the earth and the toroid is negative and approximately constant.

is the toroidal slab shown in Fig. 5. Such a model can be used to develop a good feeling for the magnetic effect of any arbitrary particle distribution, since the latter can be made up of a superposition of idealized distributions, and in the linear theory the magnetic effects will also superimpose. A series of such slabs can be used to build up a particle distribution. When placed together the surface currents cancel, as the other magnetic effects superimpose. Note the positive swing at the outer boundary of the particle distribution which is produced by the sharp limitation in particle energy density. No strict physical reality should be assigned to it.

We are now ready to attack the inverse problem, namely to deduce the particle dis-

tribution from an observed magnetic signature. This problem is unique only if one knows the magnetic field at every point in space. However, with certain assumptions on the reasonableness of the particle distribution we can proceed as follows: Fig. 6 shows the magnetic signature obtained in Pioneer V, which is fairly close to an equatorial signature; it also shows the particle energy density which we have deduced from the signature. No significance should be attached to the region of negative energy density which simply indicate the inaccuracy of the method. It should be noted that the maximum energy density is of the order of 50 keV per cm³ and that this density can be made up as desired, for example by having one 50 keV particle per cm³ or fifty 1 keV particles/cm³. Unfortunately, the magnetic signature tells us nothing about the nature of the individual particles.

Non-linear Problem

It is clear that the magnetic effects produced by the trapped particles disturb the geomagnetic field sufficiently to cause non-linear effects, *i.e.*, alter the motion of the particles. We have attempted to judge this effect by carrying out a self-consistent calculation for the case of a solenoid whose external field varies as r^{-3} . While a solenoid is different from a dipole, removing the latitude dependence simplifies the calculation and it can be shown that the results are quite analogous. The self-consistent field

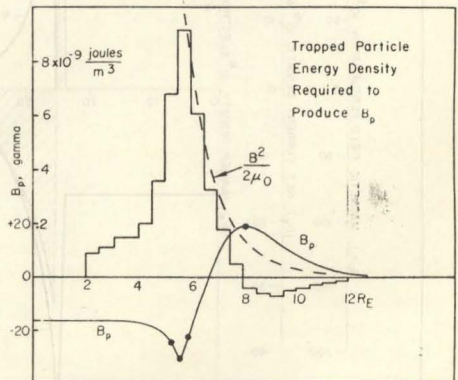


Fig. 6. The trapped particle energy density required to produce the Pioneer V field perturbations, B_p in gamma. Negative values of NE result from small inaccuracies in the calculation. The required energy density does not exceed the field density $B^2/2\mu_0$.

shown in Fig. 7 has a positive gradient over a small radial interval between 25,000 and 31,000 km. However, it should be noted that since the total field has decreased, the particle energy density should be decreased as well in order to keep the pressure ratio constant. We conclude that in a truly self-consistent case, the field gradient would never be positive; the particles drift and generate an opposing field which would reduce the gradient to zero at most.

Neutral Lines

For the reason above, we cannot agree with the further extension of the theory by Akasofu and Chapman (1961)³⁾, in which they argue that by introducing a sufficiently high energy density of trapped particles, it is possible to reverse the magnetic field in direction; therefore, there must exist within the magnetosphere lines along which the field is essentially zero. In the steady state situation, our results indicate that it is not even possible to reverse the field gradient. This lack of reversal was invoked by Singer in the earlier paper where it was assumed that the maximum particle density which a magnetic field may contain is determined by having the resulting drift current reduce the ambient field gradient to zero.

It follows, therefore, that if the field gradi-

ent cannot be reversed, neither can the magnetic field and it must fall off monotonically with increasing distance. In our view it is possible for transient effects to exist which may produce neutral field lines for very short times. By this means, it is possible to preserve the scattering property of a neutral or zero field line which is what is really wanted by Akasofu and Chapman.

Decay of Ring Current

An important problem is connected with the decay of the main phase of the magnetic storm. At the surface of the earth, one may deduce that the field produced per particle depends linearly on the energy per particle, or that the total field perturbation at sea level is proportional to the total kinetic energy present in the ring current. Thus in order for the field to decay, this energy must be dissipated in some fashion; it is not enough to convert it to other regions of the field, or to transfer it to other particles.

We originally assumed that the protons are removed by scattering from magnetic inhomogeneities and are lost to the atmosphere or to space. More recently several investigators have considered charge exchange as a means of removing the fast protons (Stuart, 1959²²⁾; Dessler and Parker, 1959²⁾; Singer and Wentworth, 1959²¹⁾). However the problem is not at all a simple one; in order that charge exchange remove fast protons, one requires the presence of neutral hydrogen in sufficient amounts. The density of hydrogen falls off in a fashion which may be derived from a theory of the exosphere (Öpik and Singer, 1959²³⁾, 1961²⁴⁾) and its absolute value is given by a normalization based on the observations of the solar Lyman- α line (Purcell and Tousey, 1960²⁵⁾). (In our view the analysis based on night time Lyman- α (Johnson, 1959²⁶⁾) is less reliable.)

We have calculated the effect of charge exchange on the trapped protons and show in Fig. 8 the proton concentration and sea level horizontal field at various times during the magnetic storm, as the protons are removed by charge exchange with neutral hydrogen. It is apparent that charge exchange is too slow a process for removing protons at 6 to 8 earth radii to account for the main phase decay. Thus, the drawback of the

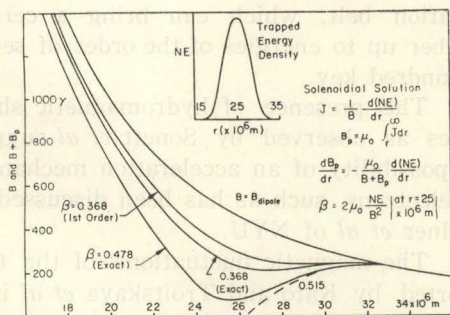


Fig. 7. Magnetic field perturbation of particles trapped in an axially-infinite, cylindrically symmetric geometry. The energy density has the profile shown, with a maximum at 25,000 km. The quantity β is the kinetic to magnetic energy density ratio evaluated at 25,000 km. Three values of β are shown for the self-consistent field, while the first order field corresponding to $\beta=0.368$ is illustrated for comparison. Note that the value of β which results in a demagnetization of the dipole field lies between 0.478 and 0.515.

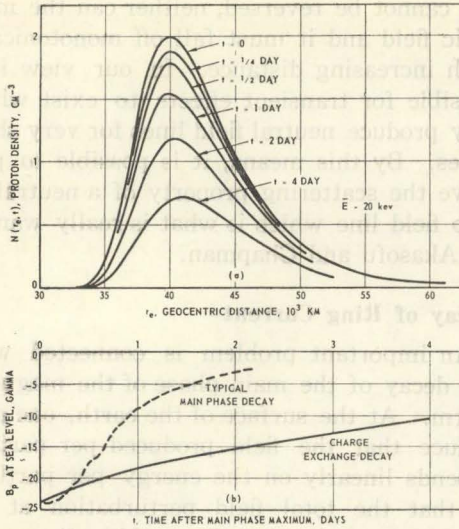


Fig. 8a. Decay of a proton belt centered at 40,000 km by charge exchange with neutral hydrogen. Fig. 8b. The time variation in the sea-level equatorial magnetic field perturbation for removal of the belt above by charge exchange.

charge exchange hypothesis is that it can only operate at low enough altitudes, on the order of three or four earth radii, where there is sufficient hydrogen concentration.

One should therefore observe a dependence of the decay on the location of the ring current. It makes a difference also whether appreciable amounts of hydrogen atoms exist in bound orbits. This point is still in controversy, our view being that their number must be quite small (see Öpik and Singer, 1961)²⁴). A further drawback of the charge exchange hypothesis is that it operates only on protons having an energy between 10 and 50 keV; it becomes much too slow at higher energies.

In order for charge exchange to be the dominant removal mechanism, one must show that other mechanisms are not as important. In one calculation, we have compared charge exchange with Coulomb scattering for 20 keV protons (Singer, 1960)²⁷ and show that charge exchange is about 100 times faster. It must, however be realized that this rate depends on the ratio of neutral to ionized hydrogen, the ionized hydrogen being the dominant exospheric constituent and providing most of the Coulomb scattering centers.

We also asked the following question: What is the *fastest* way in which particles

can be removed from a trapped distribution? Imagine a process of continuous stirring of pitch angles, by whatever mechanism one desires, for example by magnetic fluctuations. This problem has been investigated earlier (Singer, 1957)¹ with the following conclusions. The shortest removal time is given by the bounce time divided by the fraction of the solid angle contained within the loss cone. For particles trapped at 6-8 earth radii, with a velocity of the order of 10^8 cm/sec, this time turns out to be *of the order of one day*. This process works for electrons equally well as for protons; we have found no mechanism for removing particles which operates faster.

Nature of Ring Current Particles: Protons or Electrons?

We would now like to postulate that the magnetic ring current particles are probably low energy electrons of the order of a few keV, or even less.

While our main impetus for this hypothesis comes from the consideration of how the particles are removed and how the ring current decays, we can give additional arguments in favor of the existence of such electrons.

1. The observations of auroral electrons of the order of 5-10 keV by MacIlwain.
2. The fact that evidently acceleration processes exist for electrons in the outer radiation belt, which can bring a certain number up to energies of the order of several hundred keV.
3. The presence of hydromagnetic shock waves as observed by Sonett *et al* suggest the possibility of an acceleration mechanism for electrons, such as has been discussed by Gardner *et al* of NYU.

4. The magnetic fluctuations of the type reported by Kato and Troitskaya *et al* indicate that there is sufficient energy in the form of magnetic fluctuations to be able to produce acceleration of particles in a Fermi process. One may look at this problem thermodynamically and argue that if in a closed system there are hydromagnetic waves and particles, then inevitably the particles will be accelerated until equipartition is reached. However, the box is not quite closed, and the particles escape before they are able to reach such high energies, so that an energy spectrum results.

Proposed Observations

Direct observations with particle detectors are perhaps the best way to decide whether low energy electrons or 20 kev protons are responsible for the magnetic storm ring current. Magnetic observations are also quite important. With a satellite in an eccentric orbit one may study the decay of a ring current. One may want to verify the conclusion of Kellogg who shows that the ring current moves inward as it decays. On the other hand, if it is made up of electrons and they are dispersed by magnetospheric convection, one might expect the current to move outward. If charge exchange acting on protons is the dominant removal mechanism, then again the ring current will move outward in a characteristic fashion.

It is also evident that the question whether the SC current flows in the ionosphere is a fairly direct one, which can be settled by an appropriate experiment suggested as far back as 1953. Measurements in a satellite and comparison with sea level data can establish whether the current flows below or above the satellite.

Acknowledgement

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