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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part I

# I-3-4. A Mechanism to Establish the Magnetic Storm Ring Current[+]

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It is shown how hydromagnetic waves generated by the impact of solar plasma on the geomagnetic field may form shock waves in the magnetosphere and provide a means of creating the geomagnetic storm, main-phase, diamagnetic ring current. These shock waves should develop on the night side of the earth and heat the ambient protons (which constitute the normal protonosphere) to approximately the hydromagnetic-wave velocity (of the order of 500 km/sec). The transfer of hydromagnetic wave energy to the protons stresses the geomagnetic field and produces the geomagnetic-storm main phase; *i.e.*, the kilovolt-energy protons form a diamagnetic current. The bombardment of the upper atomosphere by energetic hydrogen atoms from the decaying ring current and the possible change in the decay time-constant of the ring current through the sunspot cycle are discussed.

## § 1. Introduction

The main phase of a geomagnetic storm is the period of the storm during which the geomagnetic field strength is below the normal undisturbed value at low and temperate latitudes. The hypothesis, first put forth by *Singer* (1957)[1], that the main phase decrease is due to energetic protons trapped in the geomagnetic field is now generally accepted. It was initially assumed that these protons were from solar plasma injected into the geomagnetic field (*Singer*, 1957[1]; *Dessler* and *Parker*, 1959[2]). Two independent arguments were put forth which indicated that the main phase is brought about by kilovolt energy protons in a broad belt somewhere in the vicinity of four earth radii ($4R_E$) from the center of the earth (*Dessler* and *Parker*, 1959)[2]. The approximate position of $4R_E$ was inferred from (1) the observed decrease of the vertical intensity at magnetic latitudes of about 60° and (2) the observed 1 to 3 day main-phase recovery time, *i.e.*, the time for the ring current to decay. This location for the main-phase ring current is consistent with the magnetic storm observations of Explorer VI (*Smith* and *Rosen*, 1960)[3].

Zodiacal light measurements (*Blackwell* and *Ingham*, 1950)[4] and our interpretation of the Explorer VI radiation measurements (*Arnoldy*, *Hoffman* and *Winckler*, 1960[5]; *Fan*, *Meyer* and *Simpson*, 1960[6]; *Rosen*, *Farley* and *Sonett*, 1960[7]) indicate that the solar wind is much weaker than previously thought, so that it does not penetrate the geomagnetic field to as close as $4R_E$ geocentric distance. For example, if the solar wind had pushed in as close as $4R_E$ during the magnetic storm of August 15–18, 1959, when our interpretation of Explorer VI data indicated a diamagnetic ring current as $4R_E$, the Van Allen radiation beyond approximately this distance could not have remained trapped (see *Dessler* and *Karplus* (1951)[8] for a fuller discussion of this point). However, the radiation detectors indicated the presence of trapped radiation all the way out to apogee (about $7R_E$). Thus, we doubt now that the particles at $4R_E$, which produce the geomagnetic-storm main phase, are of direct solar origin. We must look elsewhere for the origin of the trapped particles; an attractive alternative to direct injection is to assume that charged particles already present in the geomagnetic field (*i.e.*, the particles which constitute the protonosphere) are accelerated in the vicinity of $4R_E$ and beyond.

The depression of the horizontal component of the geomagnetic field at the surface of the earth is proportional to the total energy of the trapped particles, and about $10^{15}$ joules of trapped particle energy is needed to give

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[+] A more detailed version of this work is scheduled to appear in the November 1961 issue of the Journal of Geophysical Research.

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the typical 100 $\gamma$ reduction of a big storm. The proton density at $4R_E$ is of the order of $10^2$ protons/cm$^3$ (*Smith*, 1960[9]; *Johnson*, 1961[10]), so that the total energy requirement suggests an individual proton must be accelerated or heated to an energy of the order of 1 kev (500 km/sec), 1 kev energy during the active phase of the storm. In this paper, it is suggested that the heating is hydromagnetic in nature, in a manner similar to the heating of the solar corona.

It is widely believed that the solar corona is heated by the dissipation of hydromagnetic or sound shock waves. The particle collision frequency is negligibly small in the corona compared with the shock wave rise time. No quantitative theory has been put forth to describe energy dissipation in a collisionless shock. However, observations clearly show that the corona is being continuously heated*; we will assume that the earth's protonosphere is heated by a shock dissipation mechanism similar to that operating in the solar corona.

## § 2. The Model

To illustrate how hydromagnetic shocks may generate a proton ring current, we note that the outer geomagnetic field is distorted by the solar wind, perhaps in a teardrop shape, as suggested by *Johnson* (1960)[10]. The essential feature is that the geomagnetic field is unsymmetrical, extending farther from the earth on the night side than on the day side. Experimental evidence indicates that, at a time of unusually low magnetic activity, the boundary between the solar wind and the geomagnetic field near local noon occurs at about $14R_E$ (*Sonett, Judge, Sims,* and *Kelso,* 1960)[11].

It has been pointed out that large-amplitude hydromagnetic waves can be generated by the impact of solar plasma on the geomagnetic field (*Dessler*, 1958[12]; *Dessler* and *Parker*, 1959[2]). The hydromagnetic waves are generated by the impact of the solar wind on the geomagnetic field, so that their source extends completely around the sunward side. The breadth of the source indicates that, even on the night side, there will be no significant diminuation of wave amplitude resulting from geometrical attenuation. The geomagnetic field strength is approximately doubled at the interface on the sunward side by solar wind pressure. On the night side, the field is more nearly dipolar so that the geocentric distance at which $\Delta B/B=1$ will be less on the night side than the day side for a given wave amplitude $\Delta B$. For example, if $\Delta B/B=1$ at $6R_E$ on the sunward side, then $\Delta B/B$ will again equal unity at approximately $6/(2)^{1/3}=4.8R_E$ on the nighttime side. Beyond this distance, $\Delta B/B>1$ since $B$ falls off roughly as $1/r^3$; closer to the earth, $\Delta B/B<1$ since $B$ rapidly gets stronger. This model is then analogous to the solar corona, where hydromagnetic waves move outward from the sun into a region of monotonically decreasing field strength until $\Delta B/B\geq 1$. We expect that hydromagnetic heating increases rapidly with $\Delta B/B$, so that it is toward the night side that the strongest hydromagnetic heating of the protonosphere should occur.

## § 3. Hydromagnetic Heating

The theory of the hydromagnetic heating of a tenuous ionized gas has been developed because of its importance in maintaining the solar corona. The heating of a tenuous gas through dissipation of passing hydromagnetic waves is based on the tendency of hydromagnetic waves both longitudinal and transverse to steepen their fronts. The rate of steepening of hydromagnetic waves depends upon their relative amplitude and the compressibility of the medium. The rate of steepening is significant when the wave amplitude $\Delta B$ approaches $B$, and when the medium is highly compressible, *i. e.*, when the gas pressure $p\ll B^2/(2\mu_0)$. The steepening increases until limited by dissipation. The dissipation increases as the square of the gradient when there are collisions, (*i.e.*, when viscosity and resistivity are properties of the medium). In the absence of collisional dissipation, dynamical instabilities must take over the dissipative process. The overall heating is self-regulating, raising the speed of sound to a value comparable to the velocity amplitude of the wave, at which level the steepening is limited by declining compressibility.

A compressional wave, whether it propagates parallel or perpendicular to a magnetic

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* The reader is referred to a review of the development of coronal heating theories in the appendix of a recent paper (*Parker*, 1960)[11].

field, tends to steepen its front because, among other things, the speed of propagation is higher in the compression than in the rarefaction. The theory of the steepening of a longitudinal wave (an acoustical wave) in a field free gas, or in the presence of a uniform magnetic field in the direction of propagation, may be found in the literature (*Lighthill*, 1956[13]; *Taylor* and *Maccoll*, 1943[14]) for a polytrope gas, for which $p \propto \rho^{\alpha}$, where $\alpha$ is the polytrope index for the gas. The steepening time for a compressional wave propagating across a magnetic field has been given by *Petschek* (1958)[15].

A transverse hydromagnetic wave propagating along a uniform magnetic field through an incompressible medium is non-dispersive. A plane wave which is exactly circularly polarized is nondispersive even when the medium is highly compressible (*Ferraro*, 1955[16]), but in any other case the wavefront tends to steepen when there is compressibility. The steepening time for transverse hydromagnetic wave has been worked out by *Montgomery* (1959)[17] for the case where the compressibility of the gas is large, $p \ll B^2/(2\mu_0)$. The steepening time for a longitudinal wave is proportional to $B/\Delta B$, whereas for the transverse wave it is proportional to $(B/\Delta B)^2$. The difference arises form the fact that in the former case the pressure change is first order in $\Delta B$, in the latter it is second order in $\Delta B$.

It follows immediately from the above work that the sufficient conditions for rapid steepening of a hydromagnetic wave propagating in a uniform magnetic field $B$ are a compressible medium and $\Delta B \sim B$. When these conditions are satisfied, the steepening time, $t_S$, may be shown to be of the order of the wave period $T$. For the case of wave propagating into the tail of the geomagnetic field, $t_S$ will be less than $T$ because: (1) $\Delta B$ must increase with radial distance if there is no dissipation. This statement follows from conservation of energy flux $(\Delta B^2/\mu_0) V_{hm}$ where $V_{hm}$ is the hydromagnetic wave velocity; since $V_{hm}$ decreases radially outward approximately as $1/r^2$; (*Dessler*, *Francis*, and *Parker*, 1960)[18] $\Delta B$ must increase directly proportional to $r$, (2) $B$ decreases as $1/r^3$. Therefore $\Delta B/B$ increases about as $r^4$. This increase in $\Delta B/B$ with radial distance is so rapid that $\Delta B/B$ will increase significantly in less than a wavelength for wave periods greater than about 30 sec. For example, between 4 and $5R_E$, $\Delta B/B$ will increase by $(5/4)^4 \approx 2.5$. The wavelength for a 30-sec period wave at 4.5 earth radii is about $10^4$ km or $1-1/2R_E$ so that, in this example, $\Delta B/B$ is more than doubled in approximately 2/3 of a wavelength.

The self regulating aspect of hydromagnetic shock heating may be seen from the following discussion. Starting with a cold gas $(p \ll B^2/2\mu_0)$, the interaction between the solar wind and the geomagnetic field produces both longitudinal and transverse hydromagnetic waves. The propagation velocity of both types of waves within most of the magnetosphere is $B/(\mu_0\rho)^{1/2}$; we would expect the energies in the two modes to be of the same order. The characteristic steepening and dissipation time is less than the individual wave period $T$, so that heating proceeds rapidly. We postulate here that the energy should go principally into the ions. The vigorous supply of hydromagnetic waves present during the active phase of the storm is sufficient to raise the ion temperature rather quickly. The heating goes on until the ion pressure becomes comparable to the field pressure and thus reduces the compressibility of the medium. This relative decrease of compressibility will increase the characteristic dissipation time. Thus, heating will diminish when $p$ becomes comparable to $B^2/(2\mu_0)$. In addition, a cooling effect occurs if $p$ should momentarily exceed $B^2/(2\mu_0)$. The field could then no longer contain the ions, which would expand (and/or escape through various dynamical instability processes) and be lost from the region. Altogether then we expect the heating to proceed to the point where $p$ is of the same order as $B^2/(2\mu_0)$, and no further. Since $\Delta B \sim B$, the speed of sound is comparable, in order of magnitude, to the velocity amplitude of the individual waves—*the Mach one effect*. With $\Delta B/B \sim 1$, we expect that the thermal velocity of the ambient ions will be raised to the hydromagnetic velocity, which is (*Dessler*, *Francis*, and *Parker*, 1960)[18] of the order of the required 500 km/sec (corresponding to about 1-kev energy) in the general vicinity of $4R_E$. The hydromagnetic wave velocity may increase by about a factor of three during a magnetic storm due to an observed decrease in the plasma density in the protonosphere (*Carpenter* 1961)[19]. Such an occurrence would change none of the arguments nor affect any of the conclusions reached in this paper. The heating is not effective much closer than about $4R_E$ because $B$ increases inward so rapidly that $\Delta B/B$ is soon much less than unity. Thus, we expect that ambient protons beyond about $4R_E$ will be heated by hydromagnetic shock waves during the active phase of a geomagnetic storm until the proton energy density approaches the local magnetic field energy density.

A solar wind density of 50 protons/cm$^3$ moving with a velocity of $10^3$ km/sec delivers about $4\times10^{-2}$ watt/m$^2$ to the geomagnetic field, so that over a cross section of radius $4R_E$ the energy incident is $8\times10^{13}$ joules/sec. Assuming that a significant fraction of this energy goes into hydromagnetic wave generation, there is ample wave energy during the active phase of the storm to generate the $10^{15}$ joules necessary to produce the main phase.

It is assumed that hydromagnetic heating mechanism, which forms the main phase ring current, transfers an important amount of energy only to the protons; the electron energy remains substantially unaffected by the passage of a hydromagnetic shock wave, as the hydromagnetic velocity corresponds to only 1/2 ev for an electron.

## § 4. Physical Consequences of a Proton Ring Current

### A. *High Energy Atomic Hydrogen Flux from Decaying Proton Ring Current*

On the basis of the shock-wave heating mechanism which is proposed in this paper, only the protons would be significantly affected by the shock wave dissipation. The decay of the proton ring current by charge exchange with hydrogen atoms gives rise to a flux of fast neutral hydrogen atoms (~1 kev) penetrating below the base of the exosphere. The fraction $f$ of the fast hydrogen atoms which arrive at the top of atmosphere for a current at $4R_E$ is given approximately by

$$f = \frac{\pi R_E^2}{4\pi(4R_E)^2} = 1/64\,. \qquad (4)$$

Since $10^{31}$ protons are lost in a time of the order of $10^5$ seconds, this gives rise to a flux $\phi$, of fast hydrogen atoms at the base of the exosphere of

$$\phi = \frac{10^{31}}{10^5\times 64}\times\frac{1}{4\pi R_E^2} = 3\times10^5 \text{ atoms/cm}^2\cdot\text{sec}\,. \qquad (5)$$

Observation of this flux during the main phase would be strong evidence in support of a proton ring current. These observations should be made on the night side, however, since there could be a large background hydrogen atom flux on the base of the exosphere on the day side caused by charge exchange between the solar wind and the escaping hydrogen geocorona.

### B. *Change in Ring Current Decay Time with Sunspot Cycle*

*Johnson* (1961)[9] has pointed out that the radiation source responsible for atomic hydrogen formation (~2000A) does not change appreciably through the solar cycle, whereas the radiation (~1000A) which determines the temperature of the exosphere is probably less intense during sunspot minimum than during sunspot maximum; thus, in order to match the escape and formation rates, it follows that the geocorona must be more dense near sunspot minimum than near sunspot maximum. At four earth radii this change in the hydrogen concentration amounts to a factor of about 3 (*Johnson*, 1961, p. 17[9]) over the sunspot cycle. If the ring current decays by charge exchange with the hydrogen geocorona, the time constant of this decay should be thus about 3 times shorter during sunspot minimum than during sunspot maximum (assuming that the position of the ring current does not vary appreciably over the solar cycle). An examination of existing magnetic storm magnetograms could thus provide a direct test of this hypothesis for the removal of the diamagnetic ring current.

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## *Discussion*

**Singer, S. F.**: 1. We once accepted the charge exchange hypothesis but I have begun to doubt it. It requires too many coincidences. The magnetic storm trapped particles must be protons, they must have energies ~20 kev, and the neutral hydrogen density must be right. 2. I don't see why the ring current decay would be faster at solar minimum. On the contrary, with a lower *F*-layer temperature the H-density at 4 earth radii should considerably less than at solar maximum (and higher temperature).

**Dessler, A.J.**: 1. Everything that works requires coincidences; *e.g.*, isn't it a coincidence that we have noses on which to rest spectacles? We have suggested two consequences of a proton ring current removed by charge exchange which should test our hypothesis. 2. F. S. Johnson has explained why there should be about 3 times more neutral H at $4R_E$ during sunspot minimum in Chapt. 1 of the *Satellite Environment Handbook*, Stanford Press, 1961; we accept his work as essentially correct.

**Smith, R.**: 1. Your model proposes shock waves with $\Delta B/B \simeq 1$ in the vicinity of the ring current, *i.e.*, the amplitude of the disturbances is comparable to the earth's field. Won't the existence of such large disturbances affect the stability of the ring current? 2. Although the Explorer VI did not fly through the region in which you expect the shocks to appear, wouldn't you expect the disturbances to propagate to other longitudes so that they would be observed? There is no evidence of such large disturbances in the Explorer VI data. The only large transient variations which were observed are correlated with bay like distubances in the auroral zone.

**Dessler**: 1. No, the disturbances create the trapped particle ring current. While some of the heated protons may be lost in the ionosphere, the remaining particles will form the ring current. 2. The variations you observed, if they are hydromagnetic waves, may well be the disturbances we require.

**Hines, C. O.**: Do you have any objection to the shock process operating farther out in the tail, with subsequent convection inwards? It would avoid the difficulty raised by Smith *apropos* the shortage of observed shocks.

**Dessler:** 1. I do not understand the shock dissipation mechanism sufficiently well to object to your suggestion that the shock heating process operates farther out in the tail. 2. I do not consider the comments made by Smith have raised any difficulties. Perhaps only a few shocks are necessary to form the ring current.

**Gold, T.:** Only the *a-c* part of the energy content of the solar stream is used in your case for generating the effect. This must be less than the *d-c* energy content, and could be a great deal less. In that case there would be a shortage of energy.

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# I-3-5. Variation of Upper Atmosphere Densities with Solar Activity

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When an electric field ($\boldsymbol{E}$) exists orthogonal to a magnetic field ($\boldsymbol{F}$) in ionised gas the current $j=\sigma_4 E$ where $\sigma_4^2=\sigma_1^2+\sigma_2^2$ where $\sigma_1, \sigma_2$ are the Pedersen, Hall conductivities. The joule heating $Q=j^2/\sigma_3$, where $\sigma_3=\sigma_1+\sigma_2^2/\sigma_1$ is the Cowling conductivity, is usefully expressed as $Q=\sigma_1 E^2$.

For study of geomagnetic disturbance, geomagnetic field lines in and above the ionosphere are regarded as equipotentials of the electric field. Hence $j$ has a broad peak from about 110 km to 150 km altitude and $Q$ has a broad peak from about 130 km to 170 km.

The decay time of air motion across the geomagnetic field is $\tau_v=\rho/\sigma_1 F^2$ where $\rho$ is the density. Thus above about 130 km convection across the geomagnetic field is largely inhibited. The joule heating of the atmosphere due to disturbance currents peaks where $\sigma_1$ peaks, *i.e.* about 150 km. This heat source makes the air expand upwards along the magnetic field. Thus the scale heights above 130 km are greater over the auroral zones than at other latitudes. From $\nabla p=\boldsymbol{j}\times\boldsymbol{F}$ it follows that for moderate magnetic disturbance a pressure at 200 km altitude in the auroral zone equal to that at 120 km in other latitudes may be maintained.

Over the whole globe scale heights above 100 km increase and decrease with geomagnetic disturbance due to joule heating of disturbance currents. This affords a simple explanation of the correlation of orbital acceleration of satellites and *Kp*.

## § 1. Introduction

It will be shown that density scale heights in the upper atmosphere above about 100 km height increase and decrease with solar activity. This is a consequence of joule heating by those electric currents flowing in the ionosphere which cause geomagnetic disturbance. Moreover it will be shown that Lorentz forces associated with these currents are capable of supporting pressures at altitudes in excess of about 130 km over the auroral zone many times those at similar altitudes in other latitudes.

## § 2. Magnetic Disturbance in Upper Atmosphere

For the purpose of study of magnetic disturbance in the upper atmosphere from the lowest inosphere upwards, the lines of force of the geomagnetic field ($\boldsymbol{F}$) are considered to be equipotentials of the electric field. This is justified on the grounds that the