

I-5-8. Interaction of Trapped Radiation and the DS Current System

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The swollen atmosphere above electric currents in the ionosphere creates (by atmospheric scattering) a reservoir of geomagnetically trapped particles with lower than usual mirror points. Mirror points may be further lowered by kinking of $F_m = \text{constant}$ surfaces produced by electric currents and hydromagnetic waves. Geomagnetically trapped particles may also be precipitated into the atmosphere by collision with (Doppler shifted) hydromagnetic waves. Auroral luminosity may be created thereby and also by King and Roach's mechanism in conjunction with joule heating by ionospheric electric current. Some auroral statistics are qualitatively explained using an average DS current system.

Introduction

Whatever are the physical processes of capturing and organising solar energy in the magnetosphere it is possible still to examine some inter-relationships of magnetic disturbance, polar ionospheric phenomena and trapped radiation. This paper will report a preliminary investigation of mechanisms arising out of geomagnetic disturbance by which geomagnetically trapped particles may be precipitated into the atmosphere. Some consequences to the polar ionosphere will be discussed. The kind of trapped particle of concern here is that characterised by two adiabatic invariants

(i) $\mu = v_{\perp}^2 / F$, where v_{\perp} is the component of its velocity perpendicular to F ,

(ii) $I = \int_{m_s}^{m_n} \sqrt{1 - F/F_m} dl$ (c.f. Vestine and Sibley, 1960) where l is length measured along the line of force in which the particle spirals and m_n, s are mirror points which of course are on surfaces $F_m = \text{constant}$.

Three mechanisms will now be discussed which should contribute heavily to the precipitation of trapped particles into the atmosphere, particularly in polar regions.

§1. Joule heating of the upper atmosphere

It has been shown elsewhere (Cole, this conference) that joule heating by geomagnetic disturbance electric currents in the ionosphere may cause large increases in scale height at altitudes above about 130 km. At latitudes and longitudes where the DS current (see Figure 1) is most intense, scale heights can be multiplied several fold. Large bulges in

the atmosphere must exist at the auroral zones, so that, e.g., the pressure at 200 km altitude there may commonly be that at about 120 km in lower latitudes. The density at great heights (up to and beyond 1000 km) above the auroral zone would be increased considerably during geomagnetic disturbance — thus causing general lowering of mirror points of geomagnetically trapped particles. In their finite lifetime at these heights (c. f. Welch and Whitaker, 1959) the particles can contribute to the general auroral luminosity. Also they create a reservoir of particles which can be drawn upon by the processes 2 and 3 below.

King and Roach (1961) have offered an explanation of subvisual red (6300 Å) auroras in terms of increased recombination due to

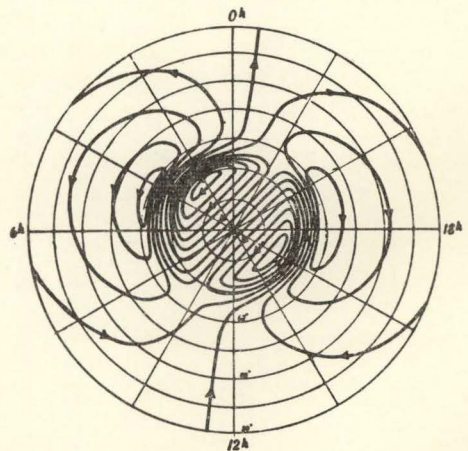


Fig. 1. Taken from Fukushima and Oguti (1953). Average DS current system for equinoctial period. Electric current of 1.5×10^5 amp is supposed to flow between adjacent stream lines.

increase of F-region temperature. They suggest the heating is due to the precipitation of Van Allen radiation. However Fig. 1 of King and Roach shows that considerable magnetic disturbance (100 γ –300 γ) was going on at the time of their observation of red auroral luminosity. This is moderate disturbance of the size normally found in the auroral zone. It is evident from the work of the writer (Cole, 1961a, 1961b) that F region temperatures may easily be doubled under such conditions. The mechanism of King and Roach together with the joule heating discussed by the writer may be responsible for a large proportion of 6300 Å emission normally observed in auroral regions.

§ 2. Breakdown of conditions of adiabatic invariance

The collision of trapped particles with Doppler shifted hydromagnetic waves in the exosphere is considered. This supplements the considerations of Welch and Whitaker (1959) and Wentzel (1960). When the time or space changes in magnetic field are shorter than the gyroperiod or gyroradius of the trapped particle the conditions for adiabatic invariance no longer apply. Under these conditions the mirror points of a trapped particle may change in height as well as latitude and longitude.

Consider a hydromagnetic or low frequency (ν) electromagnetic wave travelling along the geomagnetic field with phase speed V . A particle of velocity v and pitch angle α collides with it. The Doppler shifted frequency encountered by the particle is

$$\nu^* = (1 - v \cos \alpha / V) \nu \tag{1}$$

This approximation of the more general relativistic equation is sufficiently accurate for electrons of energies up to 100 keV and protons of energies up to 100 MeV. The phase

speeds of low frequency electromagnetic waves are dispersed about the Alfvén speed (V_A) (Cole, 1961). Let us put $V = V_A$. Since very likely $v/V_A \gg 1$ in the exosphere for the Van Allen particles considered, it follows that breakdown of adiabatic invariance for electrons (e) and ions (i) occurs when

$$\nu_{e,i} > \frac{V_A}{v_{\parallel,e,i}} \frac{\omega_{e,i}}{2\pi} \tag{2}$$

where $v_{\parallel} = v \cos \alpha$.

Table I shows values of minimum values $\nu_{min,e,i}$ at which breakdown occurs for various field strengths and distances (Sonett et al., 1960) from the earth in the equatorial plane taking estimates of n suggested by the work of Pope (1961). A value of $v_{\parallel}/c = .2$ is assumed (i.e. approximately 10 keV electrons, 20 MeV protons).

It is apparent that an association of kilocycle noise and the atmospheric red oxygen line (6300 Å) (Ellis, 1959) and between auroral coruscations and magnetic micropulsations (Campbell and Rees, 1961) may be due to the release of trapped particles into the atmosphere.

§ 3. Distortion of the surfaces $F_m = \text{constant}$

Consider the distortion produced in the $F_m = \text{constant}$ surfaces by a filament of high current concentration of the DS system (c.f. Cole, 1960) situated at a height somewhere between 90 km and 150 km altitude.

To compensate for a change ΔF in magnetic field produced by the current filament, height in the geomagnetic field may be changed by an amount $\Delta R = R(\Delta F)/3F$ where R is the distance from the centre of the earth. The filament (assumed to be at a height of 100 km) will then kink the surfaces $F = \text{constant}$ by amounts

$$\Delta R_i = \frac{100 RA}{3rF} \tag{3}$$

Table I.

R	4	5	6	7	8	9-12
n	100	20	10	5	5	5
H	5×10^{-3}	2×10^{-3}	10^{-3}	10^{-3}	5×10^{-4}	10^{-4}
$\nu_{min,e}$ (c/s)	2×10^3	7×10^2	5×10^2	5×10^2	2×10^2	5
$\nu_{min,i}$ (c/s)	1	3×10^{-1}	3×10^{-1}	3×10^{-1}	10^{-1}	2×10^{-3}

Table I—Values of $\nu_{min,e,i}$ for model (R, n, H) where R is radial distance from earth (in earth radii) from centre of earth in equatorial plane.

where A =amplitude of magnetic disturbance at ground under the filament, r =distance from filament in km. Subject to the invariance of I the mirror points of trapped particles will change also by heights ΔR_i . Putting $A = 10^3 \gamma$ (a high value), ΔR_i decreases linearly from 140 km at 150 km altitude to 7 km at 1000 km altitude. Thus the effect of a steady filament causing leakage of geomagnetically trapped particles is large within a few hundred kilometres of it and complementary to the following effect.

Superimposed on the general magnetic bay disturbance suggested by Figure 1 are magnetic fluctuations of periods of a few minutes to an hour and of amplitude (a) 100γ - 1000γ at the auroral zone. In general the larger the magnetic bay the larger a . Such fluctuations must propagate upward and outwards as hydromagnetic waves. The energy of the extraordinary (E) wave travels along the geomagnetic field lines on which it originates. Thus if φ is the cross section of the tube of force so defined and ΔF_B the amplitude of disturbance, then, in the absence of damping, $(\Delta F_B)^2 V_A \varphi = \text{constant}$. It follows that ΔF_B approximately constant for propagation from the E region to 1000 km altitude. For a likely value of $\Delta F_B \approx 1000 \gamma$ fluctuations of mirror point height of $\Delta R_B \approx 70$ km are produced by the wave. In the exosphere we may say $\Delta F_B \propto \rho^{1/4}$. Thus disturbance of size 1000γ at the auroral zones would propagate to the equatorial plane with amplitude $\sim 10 \gamma$. Fluctuations of this size have been observed in the outer geomagnetic field (Sonett et al., 1960).

Since the energy of the ordinary (O) hydromagnetic wave is propagated in all directions its amplitude is given by $(\Delta F_0)^2 V_A r^2 = \text{constant}$. Thus in general $\Delta F_B > \Delta F_0$ at large distances from the source.

§ 4. Discussion

We have seen how the swelling of the atmosphere over the DS current system could assist the production of luminosity firstly by the mechanism of King and Roach and secondly by progressive lowering of mirror points of trapped particles due to atmospheric scattering.

Hydromagnetic waves emitted upwards from DS current filaments could cause the

release of Van Allen radiation as suggested above. These processes could be initiated externally, viz. electric field generated in the exosphere (c.f. Cole, 1961d) could heat the ionosphere. Hydromagnetic waves generated in the exosphere could then cause precipitation of trapped particles. *Nevertheless the same inter-relationship of DS system and depletion of trapped radiation would exist.*

Elsewhere (Cole, 1960) the writer has suggested that the DS current system has considerable filamentary structure. Hydromagnetic waves emitted upwards from these filaments would cause release of Van Allen radiation on the lines of force connected to the filament, thus producing an aurora of the same form as the filament.

The swelling of the atmosphere over the DS current system should be greatest over the high current portion of the morning cells (see Fig. 1). Fig. 2 shows schematically the diurnal variation of auroral occurrence to be expected using Fig. 1 and the above physical principles. This explains the diurnal variations reported by Isayev (1940), Bond and Jacka (1959), and others.

One would expect auroral zone type blackout to have the greatest probability of occurrence with greatest magnetic disturbance, i. e. in association with the dense current region of the morning cell of DS. This is Observed (Zaborshchikov and Fedakina, 1958).

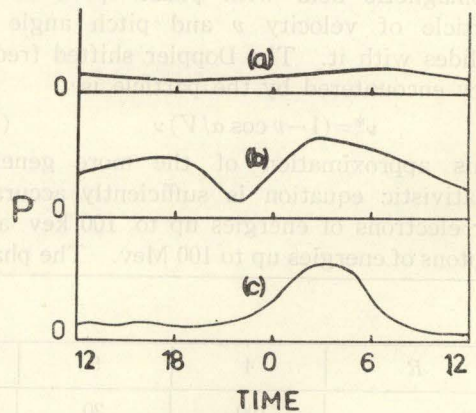


Fig. 2. Schematic representation of diurnal variation of probability (P) auroral occurrence to be expected using physical principles in the text.
 Curve (a): $\geq 75^\circ$ magnetic latitude (λ).
 Curve (b): $75^\circ \geq \lambda \geq 67^\circ$.
 Curve (c): $\lambda \leq 67^\circ$.

"Auroral type" airglow (c. f. Sandford, 1959) associated with the low-latitude current flow of the DS system must be expected from the processes outlined above.

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Discussion

Hines, C. O.: Do you take seriously the occurrence of spirals which is often claimed for irregular ionospheric features? Lest my question be misinterpreted, let me say that I believe the considerations which have been presented here are pertinent to the problem, but do not suffice to explain in sufficient detail even that area of the problem that has been discussed here. In particular, at a time when I was a sceptic, I went carefully over some of the evidence claimed to exhibit spirals, and I could find no point on which I could object to the evidence. I therefore believe in certain spirals at least, end now, of course, with Axford, claim an explanation for one of them.

Cole, K. D.: My main purpose was to draw out a relationship between elemental magnetic disturbance and elemental aurora. This is a basic physical consideration. Starting from raw observations one may produce instantaneous pictures of (say) an equivalent current system that would explain the magnetic disturbance or one may select merely the time of maximum of occurrence of this disturbance and produce curves which are the spirals you spoke of. There can be no fundamental between these two ways of presenting the data. The conflict comes only in subsequent interpretation. Physics must explain the relationship between the elemental phenomena—statistics and geometry should explain the rest.

Hultqvist, B. K. G.: There is a feature in the reasoning presented to Dr. Cole which I may have misunderstood and would like to ask about. In most cases people try to explain the various features of a magnetic storm by means of trapped radiation. You presume the magnetic storm and discusses the interaction of it on the conditions in the equatorial plane. So as I understand, it is not a theory of magnetic storms.

Cole: The mechanisms I have discussed involve interaction between the ionosphere and magnetosphere. Of course the energy for the processes must originally come from the sun but having started disturbance in the ionosphere reactions of the ionosphere on the magnetosphere through the mechanisms I have discussed should take place.

Parkinson, W. D.: I have one comment on Dr. Hultqvist's remark. It seems to me that what Dr. Cole has suggested is a positive feedback mechanism which would make storm phenomena increase from a small beginning.

Also I have a question. You mentioned 1000 gammas disturbance, and a frequency of 3×10^{-1} cycles. Do you need these together, because even in the auroral zone you do not get such large changes as quickly?

Cole: No; these figures are used for two independent mechanisms.

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I-5-9. The Origin of Irregularities in the *F* Region

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In the absence of any accepted explanation for the origin of *F* layer irregularities, a new mechanism is suggested. This is in essence a feedback mechanism involving trapped energetic electrons from the Van Allen Belts and whistlers. It is argued that *F* region irregularities in electron density should extend a long way up lines of force and they will be identified with the magnetospheric ducts which are supposed to transmit *VLF*. The mechanism proposed would in fact cause ionisation at conjugate points, and this provides one possible test. The release of trapped electrons, other than by collisions, has to be considered. To defeat the trapping mechanism, the adiabatic invariant must be changed and this requires an electric field, which varies appreciably in a gyroperiod of the electrons. At a few earth radii this can be *VLF*. The suggestion is then that the enhancement of *VLF* in a duct accelerates the release of energetic electrons, some of whose energy goes into ionisation in the *F* layer, which is tied to the lines of force, and therefore enhances the duct.

Some quantitative considerations can be given. The effect of whistlers on electrons is very similar to the effect of hydromagnetic waves on protons, discussed by Dragt (1961). The change in v_{\perp} can be written as an integral which is almost a Fourier integral of the electric field, the frequency being Doppler

shifted from the gyrofrequency by v_{\parallel} . Assuming this integral can be treated as a Fourier integral, it is now pointed out that the other Fourier components of the whistler have no effect on the electron, and in particular their phases are not important. Then the change in v_{\parallel} is the same as would have resulted from the lightning stroke, if there had been no dispersion, and this is easy to calculate, if the numbers are known. A field of *E* volts/metre lasting for τ microseconds gives an electron an impulsive velocity of 2×10^7 cms/sec. At a distance of 100 km from a lightning stroke *E* might be 0.5 and $\tau=20$, giving 2×10^8 cms/sec. Heppner's (1961) observations of whistlers from a satellite suggest a higher value that a whistler can change the pitch angle of a not quite relativistic electron by about half a degree. The result can be described as a random walk in pitch angle, as in Dragt's case, and this again can be regarded as a diffusion of the distribution in pitch angle, resulting in a flow of particles into the loss cone. For small pitch angles this diffusion must approximately balance the loss by collisions. Since the probability of loss by collisions varies very rapidly with height and hence with pitch angle, the intensity of trapped electrons must increase very rapidly with height, in the region where collisions are important, that is the *F* region and somewhat higher. The result is that many collisions between belt electrons and air