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The Magnetosphere and Geomagnetic Micropulsations with Special Reference to Micropulsation Studies in Sri Lanka

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Abstract : This paper presents the physics of the magnetosphere in relation to geomagnetic micropulsations and summarises the significant results of the studies conducted and work in progress on geomagnetic micropulsations in Sri Lanka.

1. Introduction

About twenty five years ago, it was generally thought that interplanetary space was empty apart from sporadic gusts of wind composed of clouds of gas ejected from the sun and travelling outwards from the sun. Magnetic disturbances and auroral displays observed on the earth were explained in terms of these gusts of wind.

However, in the early 1950s, it came to be realised that the tails of comets could not be explained in terms of the pressure of light radiation from the sun as was the view then held. Calculations and certain experimental observations indicated that there must exist a continuous stream of ionised hydrogen atoms and electrons streaming out of the sun — a sort of solar wind. It was this wind blowing on the comets which formed their tail. It also became apparent that this solar wind must be continuously blowing on the earth system with its atmosphere and magnetic field. The actuality of the solar wind was directly verified in 1962 through observations from space probes. It was also observed that the earth's magnetic field was distorted in a most remarkable way by the solar wind (Figure 5) and that the earth's magnetic field occupied a clear-cut comet shaped region of space with the solar wind flowing round it like a high speed wind flowing round an obstacle. The comet shaped region occupied by the earth's magnetic field is called the *magnetosphere* (although it is not a sphere).

The magnetosphere is shaken by irregularities and gusts in the solar wind and this gives rise to the small fluctuations in the earth's magnetic field observed at ground stations. These fluctuations which often have a definite periodicity are called *geomagnetic micropulsations*.

2. The plasma state

Matter in space is largely in the state of an ionised gas, called the plasma state. The plasma state of matter is very different from the solid, liquid and gaseous states that we are more familiar with. An understanding of the plasma state, especially its behaviour in a magnetic field, is a prerequisite for understanding the magnetosphere.

One of the basic properties of an ionised gas is its tendency towards electrical neutrality.[11] If over a large volume, the number density of electrons deviates appreciably from the number density of positive ions, then comparatively large electrostatic forces result which yield a potential energy per particle that is very much larger than the mean random thermal kinetic energy. The principle of equipartition of energy does not allow such a deviation to exist and consequently any deviation from electrical neutrality would usually die down quickly.

A simple calculation helps to give a working definition of a plasma. Suppose the number density of electrons and positive ions in a gas are n_e and n_i respectively, and that each ion carries a charge e. The charge density in the gas would be $(n_i - n_e)e$. For simplicity let it be assumed that the charge distribution gives an electric field only in the x direction and that the associated electrical potential ϕ is given by Poisson's equation according to $\partial^2\phi/\partial x^2 = -(n_i - n_e)\, e/\varepsilon_0$ where the usual notation of SI units has been used. If the electric field (i.e. $-\partial\phi/\partial x$) is considered to be zero at a centre of symmetry at $x = 0$ and if we fix $\phi = 0$ at $x = 0$, then assuming that n_i and n_e do not vary with distance, the expression for ϕ is : $\phi = (n_i - n_e)\, ex^2/2\epsilon_0$. This means that if a particle with charge e moves in the x direction through a distance d from the centre its potential energy will change by an amount $\triangle W = | n_i - n_e |\, ed^2/2\varepsilon_0$. The value of d which makes $\triangle W = \frac{1}{2}kT$, where T is the temperature of the gas in degrees Kelvin and k is Boltzmann's constant would be $d = [kT/ | n_i - n_e | e^2]^{\frac{1}{2}}$. When the relevant values of the constants are put in, one obtains $d = 6.9\,(T/ | n_i - n_e |)^{\frac{1}{2}}$ cm where n_i and n_e are expressed in particles per cm^3. This value of d is called the " Debye shielding distance". Physically, d would be the distance over which a given deviation from electrical neutrality can be maintained. The principle of equipartition of energy will not allow such a deviation to exist over a greater distance without it dying down almost immediately. If d is much smaller than other characteristic lengths of the problem then the ionised gas is called a plasma.

3. Disturbances in a plasma in the presence of a magnetic field

From the definition of a plasma, it is clear that for phenomena varying slowly compared with the decay time of any charge density that may develop in the medium, it can be stipulated that the charge density is zero and hence also the rate of change of charge density. Then, since in basic electromagnetic theory the displacement current $\dot{D}$ comes from a rate of change of charge density, it follows that in slowly varying phenomena in a plasma, $\dot{D}$ can be neglected. When considering the behaviour of a plasma in a magnetic field, if attention is limited to slow variations where $\dot{D}$ can be neglected, the subject is called *magnetohydrodynamics* or MHD. If fast variations are considered where $\dot{D}$ cannot be neglected, such as for radiowaves passing through the ionosphere, the subject is called *magneto-ionic theory*.

4. Elements of magnetohydrodynamics (MHD)

In MHD, the plasma behaves essentially like an electrically conducting fluid moving in the presence of a magnetic field. As a result of the motion, electric currents are induced in the fluid and these electric currents produce magnetic fields of their own which modify the ambient field. At the same time, electric charges travelling in a magnetic field are subjected to the Lorentz force, and this modifies the motion of the plasma. Thus one visualises constant interaction between field and motion. It would be clear that the interaction must become unimportant for very rapid field variations because of inertia, and hence, once again, it must be stressed that the subject of MHD is restricted to relatively slowly varying phenomena.

The fundamental equations governing MHD are :-

$$\frac{\partial \rho}{\partial t} + \text{div}\,(\rho v) = 0 \tag{1}$$

$$j = \sigma[E + \mu_0(v \wedge H)] \tag{2}$$

$$\text{Curl}\, H = j \tag{3}$$

$$\text{Curl}\, E = -\mu_0 \dot{H} \tag{4}$$

$$\text{div}\, H = 0 \tag{5}$$

$$\text{div}\, D = 0 \tag{6}$$

where ρ is the mass density of the medium, v the velocity of the medium, j the current density, σ the electrical conductivity and E, H and D are the field vectors which have their usual significance. Equation (1) is merely the law of conservation of mass. Equation (2) incorporates the Lorentz force on charged particles moving in a magnetic field. Equations (3) to (6) are Maxwell's equations neglecting the displacement current. Combining (2) and (4) and then substituting for j from (3) it is easy to show that :-

$$\dot{H} = \text{Curl}\,(v \wedge H) + \frac{1}{\mu_0 \sigma} \nabla^2 H.$$

$\dot{H}$ is seen to be a sum of two parts. Let us consider them separately. If $\dot{H} = \text{Curl}\,(v \wedge H)$, then from (4) and (2) it follows that $j = 0$, which would mean that there is no relative motion between the conducting neutral medium and the magnetic lines of force. In other words, the magnetic lines of force are frozen into the medium and carried with the medium. If L is a typical linear dimension of the medium a typical relaxation time for the transport of H lines by this process would be L/v. On the other hand, if we consider the second part separately and put $\dot{H} = (1/\mu_0\sigma)\nabla^2 H$ we have a typical diffusion equation with a diffusion coefficient $\alpha = 1/\mu_0\sigma$ which tells us that any applied magnetic field inhomogeneity will tend to become homogeneous by lines of force slipping through the medium with a time constant of the order of $L^2\mu_0\sigma$. In the general situation, both these effects are present; that is, lines of force are partially carried with the medium, but there is also some slipping of the lines of force through the medium.

There is an analogous situation in hydrodynamics in the viscous flow of fluids. We distinguish between streamline flow and turbulent flow. In streamline flow, the streamlines are stationary and the fluid slips through the streamlines easily. In turbulent motion, the streamlines tend to be carried with the fluid. A characteristic number called Reynolds number given by $R = Lv\rho\eta^{-1}$ determines when turbulent motion is important.

In MHD, there is a similar number which could be called the magnetic Reynolds number, given by $R_M = Lv\mu_0\sigma$ which determines whether transport of magnetic lines with the medium dominates or whether the slipping of lines through the medium dominates. If $R_M >> 1$, then transport dominates and the magnetic lines are effectively frozen into the medium ; if $R_M << 1$ then magnetic lines diffuse easily through the medium. The condition $R_M >> 1$ is very rare under laboratory conditions. However, in space, on a cosmic scale, L can be very large and the condition $R_M >> 1$ is easily satisfied, and in fact this is the situation that is usually met.

The freezing in of magnetic lines of force into a plasma introduces stresses within the plasma medium. Since the magnetic energy per unit volume in a magnetic field is $\mu_0 H^2/2$ (SI units), the principle of virtual work leads to the result that a magnetic field subjects the plasma to a tensional stress of μ_0/H^2 in the direction of the lines of force and simultaneously to a hydrostatic pressure of $\mu_0 H^2/2$ in addition to the normal gas kinetic pressure produced by the random thermal motion of the gas particles. In other words, one looks on the lines of magnetic force as taut-strings embedded in the plasma medium which subject the medium to a tension, whilst at the same time, they also cause an increase in the hydrostatic pressure of the medium. This picture is most helpful in understanding qualitatively the various types of low frequency mechanical waves that can travel through a plasma in a magnetic field.

5. Waves in a plasma in a uniform magnetic field

When parts of a plasma medium are displaced, restoring forces of two types can come into play. There is the normal type of pressure force involved through compressions and rarefactions of the medium. If this is the only type of restoring force involved, then we have pure *sonic waves*. On the other hand, any movement of the plasma medium at right angles to a line of magnetic force will carry the line of force with it and cause a magnetic restoring force to act. If the restoring forces operating are purely magnetic in origin, they are called *hydro-magnetic waves.* Often, both types of restoring force are involved and the resulting wave is then called a *magneto-sonic wave*.

If the movements of the medium are in the same direction as the lines of force, then there is no distortion of the magnetic field. Only gas kinetic pressure forces arising out of the compressions and rarefactions of the medium are involved and we have pure sonic waves propagated parallel to the lines of force with the usual velocity of sound, given by $C_S = (\gamma P/\rho)^{\frac{1}{2}}$ where γ, P and ρ have their usual significance. If the movements of the medium are at right angles to the lines of force, we can have two situations. In one, there are no pressure fluctuations involved, for example, when there is a twist of a bundle of lines of force. The restoring forces involved are then purely magnetic in origin and are due to lines of force acting like stretched strings. The velocity of these twist waves travelling along lines of force would by analogy with the velocity of transverse waves along a stretched string, be given by $V_A = (\mu_0 H_0^2/\rho)^{\frac{1}{2}}$ where H_0 is the strength of the ambient magnetic field. These are the pure hydromagnetic waves, which are also called Alfvén waves, after Alfvén who first visualised their existence. In the second situation, the movement of the medium at right angles to the lines of force causes pressure fluctuations in the medium caused both by gas kinetic compressions and rarefactions and by magnetic field strength variations produced by lines of force moving towards and away from each other. It can be shown easily that the velocity of such pure longitudinal magneto-sonic waves travelling at right angles to the lines of force is $(C_S^2 + V_A^2)^{\frac{1}{2}}$. These are the simplest cases. When the direction of propagation is not along lines of force or at right angles, the situation is complicated but, as will be explained below, two basic modes could be distinguished.

Three basic vectors characterise the type of wave that is propagated through the plasma. They are H_0 the ambient magnetic field vector ; k the propagation vector of the wave, which is in the direction of propagation of the wave ; and v the particle velocity in the medium associated with the wave. Now, any v can be resolved perpendicular to the plane (H_0 , k) and parallel to it, and this enables us to recognise two basic modes : (a) v perpendicular to the plane (H_0, k) called the transverse mode and (b) v coplanar with (H_0, k). Suppose the angle between the direction of propagation of the wave front (i.e. k) and H_0 is ϕ. The phase velocity in case (a) is $V = V_A \cos \phi$ and the wave is essentially a transverse Alfvén wave largely guided by the field lines but with its wave front inclined to the field lines. The phase velocity V in case (b) can be shown to be the roots of the equation $V^4 - V^2 (V_A{}^2 + C_S{}^2) + V_A{}^2 C_S{}^2 \cos^2 \phi = 0$ which for a given ϕ gives two real roots for V^2 which correspond to a fast wave and a slower wave. In the magnetosphere, conditions are such that $V_A >> C_S$ and the faster mode corresponds to the magnetosonic wave described earlier, with $V = (V_A{}^2 + C_S{}^2)^{1/2}$ when $\phi = 90°$ and which degenerates into the pure Alfvén mode with $V = V_A$ when $\phi = 0$. For intermediate values of ϕ, V takes on values between these two extremes. This mode is only weakly guided by the field lines when $V_A >> C_S$ and is more or less isotropic. The slow wave corresponds to the pure sonic wave with phase velocity $V = C_S$ when $\phi = 0°$. In this mode, the phase velocity rapidly reduces to 0 as ϕ increases from 0 to 90°. Hence the slow wave is strongly guided by the field lines. Thus for a given ϕ, in general there would be three types of waves: (1) the transverse Alfvén mode (2) the fast magnetosonic mode and (3) the slow sonic mode. A polar diagram of the phase velocities of these three types of waves takes the form shown in Figure 1.

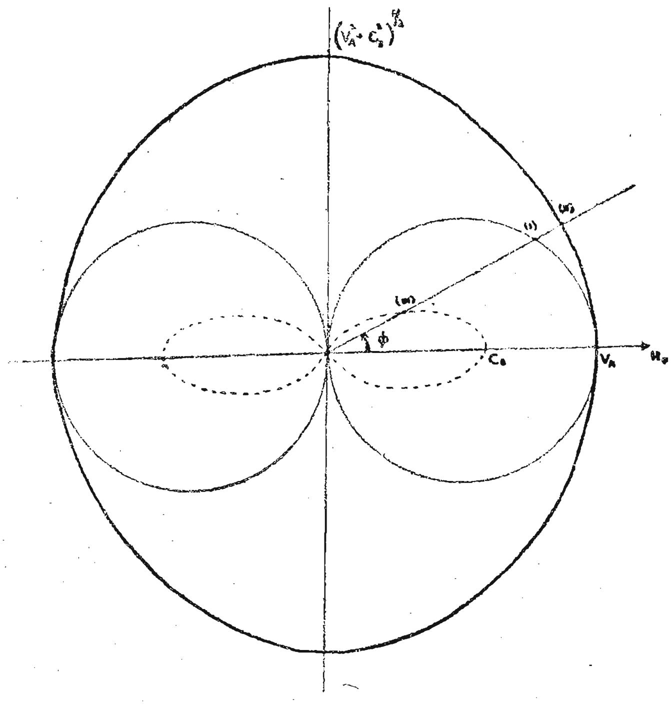


FIGURE 1. A polar diagram of the phase velocities of the three modes of propagation.

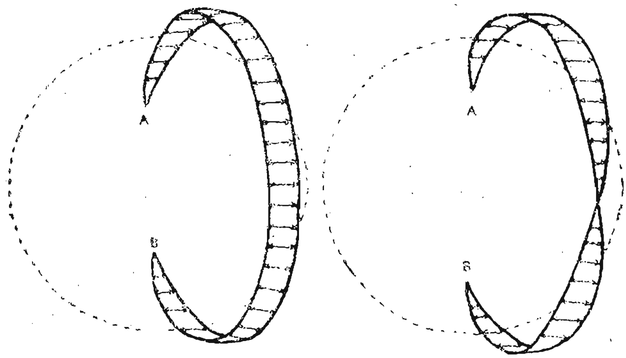
Type (3) waves are largely controlled by gas kinetic pressure fluctuations and would therefore be unimportant where ion collisions in the plasma are rare like in the magnetosphere. They are likely to become important only in the lower ionosphere. Hence in the main magnetosphere we need distinguish only two main types of waves : the transverse Alfvén mode, guided along field lines and the fast magnetosonic mode, which is more or less isotropic. In a uniform plasma which is uniformly magnetised, these two modes are independent. But non-uniformity causes coupling between the two modes and this gives rise to elliptically polarised waves, because in one mode v is perpendicular to the plane (H_0, k) and in the other mode it is parallel to this plane. This elliptical polarisation of the wave could be left handed or right handed with respect to the field lines. The heavy positive ions in the plasma would gyrate round the field lines in a left handed sense, thus qualitatively one would expect that the field lines would exert a bigger control on the mode with a left handed polarisation. Hence since it is the transverse Alfvén mode that is strongly controlled by the field lines, in the magnetosphere where the magnetic field is not uniform, the coupling of the two modes would make the Alfvén mode show left handed polarisation with respect to the field lines whereas the magneto-sonic mode which is only weakly controlled by the field lines would show signs of right handed polarisation.

6. A plasma in a dipole field

Let us consider an idealised situation where the earth is associated with a dipole magnetic field and is surrounded by a spherically symmetric plasma. Certain basic types of waves can be visualised in such a plasma. Consider a magnetic shell, that is, a family of field lines dropping into a particular latitude and having all longitudes. In the earth model, it could be considered that the lines of force are effectively anchored to the base of the ionosphere. One can visualise standing waves set up on these field lines such that the particle velocities are always on the surface of the shell (Figure 2). If all the field lines of a shell move together, then these movements constitute a twisting of the entire shell. The waves will be of the Alfvén type and be confined to a torroid. Hence Alfvén type waves in a dipole field are often called torroidal waves. As in the case of a stretched sonometer wire, the period of the fundamental mode of these torroidal waves in a magnetic shell would be twice the travel time of an Alfvén wave moving along the field line from the conjugate points A and B of a field line. The period of the second harmonic would be half this period. These eigen periods would clearly depend on the length of the field line and the actual plasma density distribution along the line, and hence they would vary with the latitude of intersection of the shell with the earth's surface.

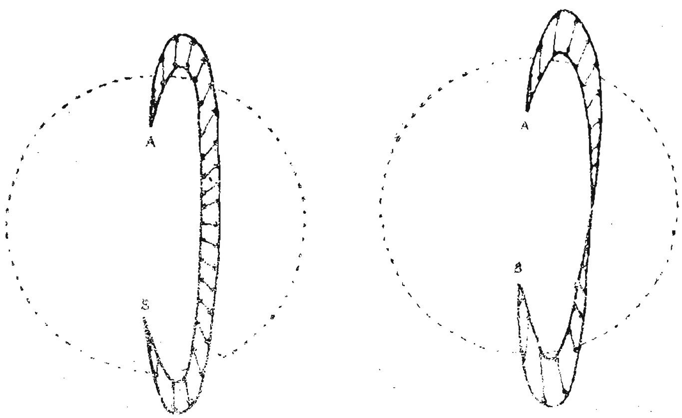
One can also visualise oscillations where the particle movements are at right angles to the surface of a shell (Figure 3). Here, the magnetic lines move in the meridian plane and move closer or away from lines in neighbouring shells, giving rise to magneto-sonic type waves. These are also called poloidal waves because the particle movements are essentially towards or away from a pole. These poloidal waves move across the field lines and spread to fill the entire plasma rather than being selectively guided by the field lines as in the torroidal mode. The fundamental period for standing waves of this type in the idealised earth model would be like that of a resonance tube closed at one end ; that is, four times the time taken for the magneto-sonic wave in the fast mode to travel from the ionosphere to the upper boundary of the plasma.

It will be appreciated that in the poloidal mode, the entire plasma resonates and the same period should be seen at all points. Oscillations in this mode should therefore not be latitude dependent.



Fundamental 2nd Harmonic
Torroidal Mode

FIGURE 2. Standing wave patterns in the torroidal mode.



Fundamental 2nd Harmonic
Poloidal Mode

FIGURE 3. Standing wave patterns in the poloidal mode.

These are the simplest modes. More complicated types of standing wave modes can be visualised where, for example, waves could be guided along field lines and yet be localised in longitude giving rise to what are called guided poloidal type oscillations. Obviously, very complex situations could arise. However, the simple picture presented above suffices to obtain a basic understanding of some of the oscillations that occur in the actual earth's magnetosphere.

7. The atmosphere above the earth's surface

Up to an altitude of about a 100 km, the atmosphere could be regarded as an unionised gas. From 100 km upwards, the atmosphere is appreciably ionised and we enter the region called the ionosphere. Collisions of ions with neutral molecules is frequent in the lower region of the ionosphere, but are less frequent in the upper regions. Beyond an altitude of about 600 km, the mean collision interval is larger than 600 s and the medium begins to behave like a plasma with geomagnetic field lines frozen into it and supporting hydromagnetic and magneto-sonic waves of the type described in the foregoing sections.

A uniform atmosphere settling under gravity does so with its mass density ρ decreasing exponentially with height. On the other hand, the earth's dipole field H_0 decreases with altitude as the inverse third power of the distance from the earth's centre. Under such circumstances, the Alfvén wave velocity $V_A = (\mu_0 H_0^2/\rho)^{\frac{1}{2}}$ would decrease with altitude.

In the actual atmosphere, however, there are two regions where ρ decreases much more rapidly than exponentially, causing V_A to increase with altitude. The first of these regions is between an altitude of 1,500 km and 3,000 km. In this region there is a very rapid decrease in ρ because the proportion of heavy ions compared with hydrogen decreases rapidly with height due to differential settling under gravity. At a height of about 3,000 km the plasma virtually consists entirely of hydrogen and there is again an exponential decrease in ρ, causing V_A to decrease with altitude again.

The second region begins at an altitude of about 12,000 km, which is about 2 earth radii above the earth's surface and extends up to an altitude of about 5 earth radii above the earth's surface. In this region, collisions are so rare that ions spiralling round lines of force and mirroring between conjugate points begin to build up the great radiation belts called the Van Allen radiation belts. As these particles spiral and mirror along lines of force, they also drift laterally because the earth's magnetic field decreases with altitude. This gives rise to an effective "ring current" which flows round the earth. The centre of gravity of this ring current is at an altitude of about 20,000 km which is about 3 earth radii above the surface of the earth. By Lenz's law, this ring current flows in a direction which would produce a magnetic field which opposes the cause that gave rise to it, namely the decrease in H_0 with altitude. Hence, the magnetic field of the ring current would decrease the earth's field within it and enhance the earth's field outside it. The total pressure in the plasma is, as was shown earlier, $P+\mu_0 H_0^2/2$. This means that for pressure balance, an increase in H_0 can occur only at the expense of P and hence of ρ the density of the plasma. Thus, as one crosses the region of the radiation belts there is a sudden drop in ρ. This boundary region is called the *plasmapause*. Typically, the density within the plasmapause is some 20 times higher than the density outside. Hence there is an increase in the Alfvén wave velocity V_A with altitude in this region. The region within the plasmapause is sometimes called the plasmasphere, and the plasmapause marks the outerboundary of the relatively dense plasma which rotates with the earth.

The Alfvén wave velocity V_A varies with altitude roughly as indicated in Figure 4.

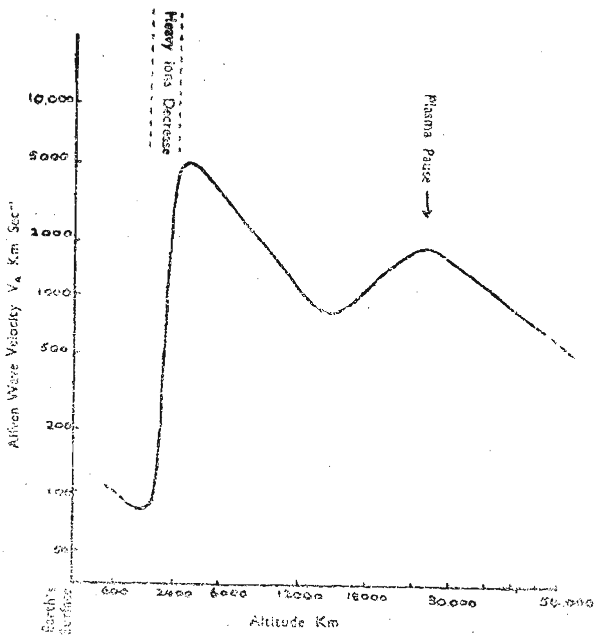


FIGURE 4. Variation of Alfvén wave velocity with altitude.

8. The actual magnetic field of the earth

The dipole magnetic field of the earth has an internal origin. It is distorted by three main external sources which are : (1) ionospheric currents, (2) ring currents, and (3) the solar wind.

At the earth's surface, ionospheric currents are much closer than the other disturbing sources, and variations in the earth's magnetic field detected at the earth's surface are ultimately due to ionospheric currents. Outside the ionosphere in the region of the plasmapause, ring currents dominate. Beyond the plasmapause, rocket and satellite observations have revealed that the earth's field is distorted in a most remarkable way, due to the interaction of the solar wind with the earth's magnetosphere.

The solar wind is a stream of plasma which flows radially out of the sun through the solar system. Its existence was directly verified in 1962 by the Mariner 2 probe to Venus, and was shown to consist of protons and electrons. It has a quiescent bulk velocity of about 275 km/s near the earth's orbit. The sonic velocity in the solar wind is only about 20 km/s, which means that the solar wind is highly supersonic with a mach number of over 10. This supersonic wind hits the earth system.

As described earlier, the earth's magnetic field traps a plasma round it in the great radiation belts. If there was no solar wind, the earth's magnetic field would be largely dipolar, with a small distortion due to the ring currents of the radiation belts. By Lenz's Law, the supersonic highly conducting solar wind cannot penetrate into this earth plasma which contains the earth's magnetic field. It must flow round it. In other words, the solar wind sees the earth plasma as an obstacle in its path.

When a supersonic wind meets an obstacle, a shock pressure front must develop. Such a shock front does exist where the solar wind meets the magnetosphere. It was discovered by the IMP-1 satellite in 1963/64. The outer boundary of the magnetosphere is called the *magnetopause*. Satellite observations have revealed that there is a turbulent region between the shock front and the magnetopause to which the name *magnetosheath* has been given.

The total pressure in a plasma is $P + \mu_0 H^2/2$. Just outside the magnetopause, conditions are such that $P >> \mu_0 H^2/2$ and the magnetic field has little control over the mechanical motion of the solar wind. However, within the magnetopause $\mu_0 H^2/2 >> P$ and the motion of the plasma is completely controlled by the magnetic field.[12]

Satellite observations have also revealed a most extraordinary situation, behind the earth, in a direction away from the sun. It was found that the geomagnetic field stretches to form a long comet-like tail which extends well beyond the orbit of the moon.[8] The existence of the tail indicates that the solar wind catches geomagnetic lines of force at the magnetopause and blows them out behind the earth. This stretching of the lines would be resisted by the tensional stress $\mu_0 H^2$ in them. In the tail, the field is directed towards the sun in the northern half and away from the sun in the southern half. It has also been found that there is a well defined neutral sheet between the two halves, where as expected from the requirements of the $P+\mu_0 H^2/2$ pressure balance, the plasma density is relatively large.

A schematic drawing of the magnetosphere is shown in Figure 5.

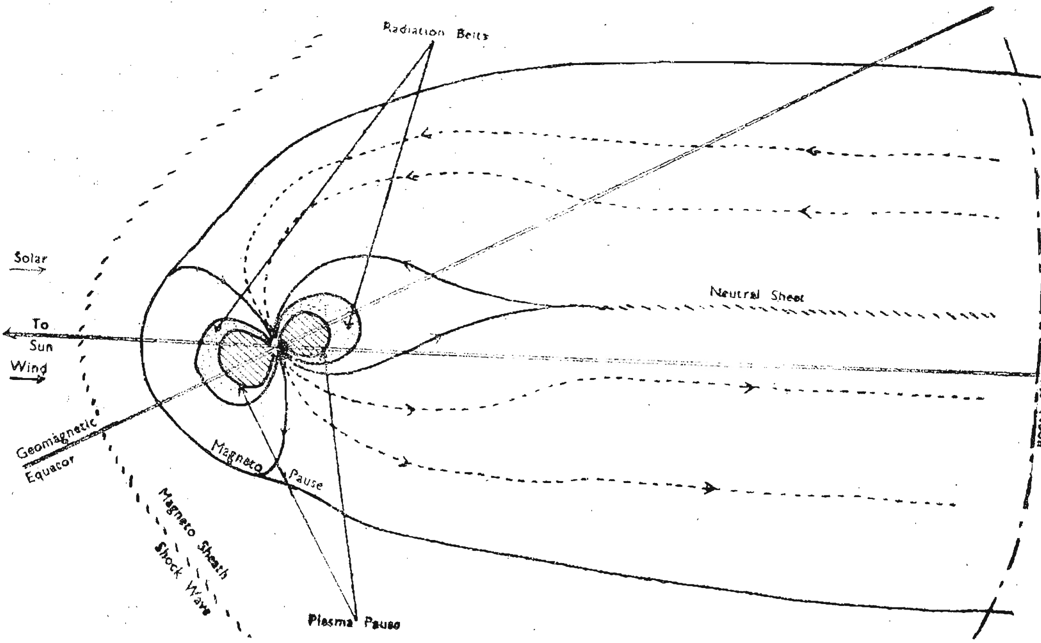


FIGURE 5. A schematic drawing of the magnetosphere.

9. Hydromagnetic waves in the magnetosphere

Observations from interplanetary space probes and satellites have revealed that there are variations in the solar wind velocity and particle density. These variations must give rise to fluctuations in pressure at the magnetopause. Also, just as much as waves are generated on the surface of a sheet of water when a wind plays on it, due to a process arising out of a phenomenon called the Kelvin-Helmholtz instability, there is an analogous instability at the magnetopause due to the solar wind flowing round it, which should generate surface hydromagnetic waves at the magnetopause. Processes such as these cause the magnetosphere to vibrate like a jelly. Complicated modes of standing waves can be set up, and these are only being gradually understood. After about ten years of research, a basic understanding is emerging although a lot more work remains to be done. This article presents only a qualitative description of some of the basic modes that could occur.

Let us first consider the surface waves generated on the magnetopause by the solar wind playing on it. From the stagnation point at the nose of the magnetosphere, the solar wind branches out towards the dawn and dusk meridians. Due to the earth's orbital velocity relative to the radial solar wind, the axis of symmetry of the magnetosphere is on an average tilted about 10 to 25° from the earth–sun line (Figure 6).[9]

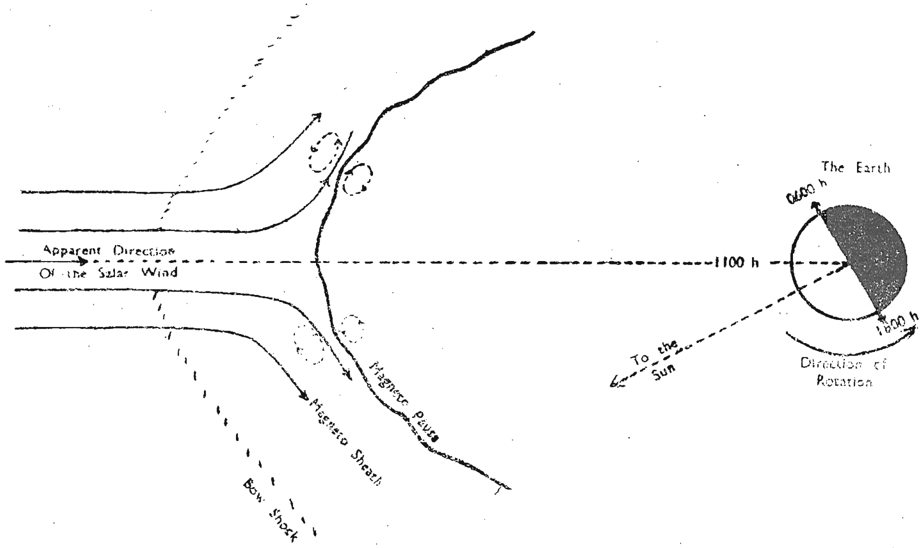


FIGURE 6. The solar wind playing on the surface of the magnetosphere.

The turbulent magnetic field in the magnetosphere carried by the solar wind, is preferentially directed towards the dawn and dusk meridians. Surface waves on the magnetopause will, like waves on the sea, have an approximately elliptical motion, the rotation being in the opposite sense on the dawn side and the dusk side from the stagnation point. The earth's magnetic field lines, which would come out of the plane of the paper in the diagram of Figure 6, being frozen into the magnetospheric plasma, will participate in this elliptical motion of the plasma on the magnetopause, and hence generate elliptically polarised Alfvén waves along the field lines which are near the magnetopause. Looking in the direction of the magnetic lines, the polarisation would be left handed on the dawn side and right handed on the dusk side, with the line of change being at about the 11.00 h meridian. Observations made from the Explorer 33 satellite in 1970 support this picture. The field lines excited by this mechanism are on the outermost magnetic shell. The eigen period of the fundamental mode for standing waves (Figure 2) on these lines is about 10 to 15 min. These field lines dip into the earth at high latitudes and large, long period oscillations of the earth's magnetic field (called Pc 5 type micropulsations) observed at ground stations in high latitudes (68 to 70°) would appear to correspond to these oscillations.

The variations in pressure on the magnetopause caused by variations in velocity and density in the solar wind, should generate poloidal oscillations especially in the central regions of the sunlit magnetopause. The Alfvén wave velocity variation with altitude show two maxima (Figure 4). In these regions, the gradient of the refractive index for these waves change rapidly. Such regions form boundaries for hydromagnetic waves, where a fraction of any incident energy will be reflected. Thus, for hydromagnetic waves the magnetosphere gets divided up into a number of cavities in which the waves could form standing wave patterns. For example, the region between the plasmapause and the magnetopause would behave like a resonance tube closed at one end. The region between the Alfvén velocity maximum at about 2,000 km and the plasmapause would behave like a resonance tube with nodes at both ends. Eigen periods corresponding to standing waves in these work out to be between 20 and 150 s and these would appear to correspond to Pc2, Pc3 and Pc4 type geomagnetic micropulsations which are observed at ground stations, mostly during day-light hours (Section 10).

This is a very simplified picture. There is strong coupling between the poloidal and torroidal modes in the inhomogeneous field of the earth in the magnetosphere and hence oscillations of one type will generate the other and *vice versa*. The actual situation is therefore complicated.

At night-time, especially towards midnight, sharp pulses of damped oscillations called Pi2 type micropulsations are observed in the geomagnetic field. These oscillations would appear to be connected with an impulsive type of phenomenon in the geomagnetic tail. A possibility that has been suggested is the reconnection of oppositely directed field lines across the neutral sheet. This forms a situation like that of a stretched catapult. The reconnected lines snap back like the strings of a catapult and in doing so catapult the plasma in the neutral sheet between them towards the earth giving rise to, amongst other things, an impulsive stimulation of the resonating cavities on the night side of the magnetosphere.

So far, only standing waves in the magnetosphere have been considered. These have slow periods and wavelengths of the order of the linear dimensions of the magnetosphere. When the wavelength of hydromagnetic waves is very small compared with magnetospheric dimensions there is the possibility of travelling hydromagnetic waves in the magnetosphere. These waves have periodicities of the order of 0.2 to 5 s. Such periodicities are detected in geomagnetic micropulsations and are called Pc1 type oscillations. It is interesting to note that in the outer magnetosphere the magnetic field strengths are such that the period of gyration of protons in these fields is also of the same order of magnitude as these oscillations. One can then imagine a resonance interaction between Alfvén waves with these periods travelling along the outermost field lines and showing a left handed elliptical polarisation, as explained earlier, and the gyrating protons. By a process called "Landau Damping" the hydromagnetic wave can lose energy to the resonant particles, and the reverse can also happen through a mechanism called the cyclotron resonance mechanism. These processes could cause pulses of oscillations to run up and down the field lines after being repeatedly reflected at conjugate points (e.g. A and B in Figures 2 and 3), where a field line dips into the ionosphere. At each reflection, a part of the wave will get reflected and a part will get transmitted to the earth. Pc1 micropulsations are indeed observed at conjugate points at high latitudes where the outermost field lines dip into the ionosphere. Further, the repetitive time of pulses of oscillations corresponds to the expected time taken for an Alfvén type oscillation to travel up and down the appropriate field line. These Pc1 oscillations are also observed at other latitudes because a part of the energy gets conducted to these latitudes by means of current patterns induced in the ionosphere by the oscillation of the field lines.

10. Geomagnetic micropulsations observed at the earth's surface

Geomagnetic micropulsations are small fluctuations with periods between about 0.2 s and 600 s that are observed to occur in the earth's magnetic field recorded at the earth's surface. The amplitude of these fluctuations vary from a fraction of a γ to about 10 γ where a γ is equivalent to 10^{-5} oersted. The quiescent strength of the earth's magnetic field in equatorial regions like Sri Lanka is about 0.4 oersted or 40,000 γ. Hence it will be realised that these fluctuations are relatively small and that special sensitive techniques have to be used to record them.

These geomagnetic micropulsations are sometimes continuous in character and are called Pc type oscillations (P for pulsation, c for continuous). Pc type oscillations occur largely during day-time. Night-time micropulsations are, more often than not, impulsive in character and are like heavily damped oscillations. Such oscillations are called P_i type oscillations (i for impulsive). By international agreement, geomagnetic micropulsations are classified according to period as follows :-

Type of oscillation	Period range seconds
Pc1	0.2—5
Pc2	5—10
Pc3	10—45
Pc4	45—150
Pc5	150—600
Pi1	1—40
Pi2	40—150

The need for electrical neutrality in a plasma requires that, for slowly varying phenomena like geomagnetic micropulsations, the electrical charge density in a plasma be taken as zero. As pointed out earlier, this also requires that the displacement current $\dot{D}$ in the plasma be taken as zero, and the fundamental equations governing plasma oscillations would be as stated in equations (1) to (6) in Section 4. It will be seen from equation (3) of Section 4 that the magnetic field variations in a plasma corresponding to the periods considered here must originate through fluctuating current densities only, and not through changes in the displacement current $\dot{D}$ as well, as is the case in the usual electromagnetic wave theory.

In the magnetospheric plasma, four main regions where current densities are likely to be generated can be identified. They are : (1) the magnetopause where surface currents would be induced due to interaction with the solar wind, (2) the plasmapause which is the region of the ring current produced by the great radiation belts, (3) the neutral sheet in the geomagnetic tail of the magnetosphere and (4) the ionosphere. The magnetic effects of these currents would drop off roughly in inverse proportion to the distance from the current sheet. The nearest current sheet to the earth's surface is the ionosphere which is at least a few hundred times nearer than the next nearest current sheet at the plasmapause.

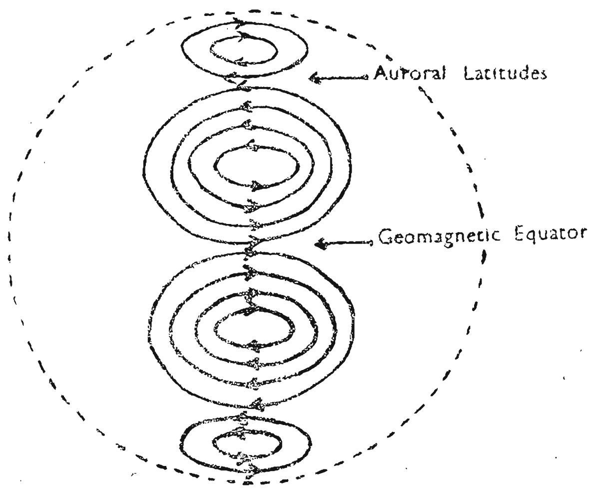


FIGURE 7. Ionospheric current pattern giving rise to geomagnetic micropulsations.

Hydromagnetic waves in the magnetosphere impinging on the ionosphere must produce fluctuating current systems in the ionosphere like the wall currents in a wave guide. In equatorial regions and mid-latitudes at least, it should be the induction effects of these current systems in the ionosphere, together with the image currents they induce in the earth, that are observed as geomagnetic micropulsations. It can be concluded, therefore, that hydromagnetic waves with the same periodicities as observed in geomagnetic micropulsations must be present in the magnetosphere. It is, however, not easy to infer the nature of the hydromagnetic waves incident on the ionosphere from a study of the geomagnetic micropulsations recorded at the earth's surface. Various attempts have been made with model ionospheres to evaluate transmission coefficients for hydromagnetic waves falling on them. These calculations are, as yet, not very convincing. Furthermore, the induced earth currents could vary drastically depending on the locality where observations are being made, and these earth currents could seriously distort the observed micropulsations, especially their polarisation. These factors indicate that geomagnetic micropulsations must be interpreted with caution.

By analysing the distribution pattern of simultaneous signals from recorders distributed at various points on the earth's surface, Jacobs and Sinno[4] suggested as early as 1960 that an ionospheric current pattern of the type indicated in Figure 7 seemed to be the agency responsible for at least the long period micropulsations observed at the earth's surface.

The current pattern induced in the ionosphere due to the tidal motion of the atmosphere, called the Sq. current pattern is also similar.[5] This sort of pattern, where there are big loops of current on either side of the geomagnetic equator which join up over the equator to produce a sort of equatorial jet current seems to be a natural pattern for the ionosphere. In the case of the Sq. current pattern caused by tidal motion, the current jet over the equator is very marked at midday longitudes, and is called the equatorial electrojet.

11. Research on geomagnetic micropulsations in Sri Lanka

Geomagnetic micropulsations can be studied by measuring the small currents or electromotive forces induced by them in suitably designed coils, or by measuring the currents induced by them in the earth's crust near the surface (telluric currents).

Investigations on geomagnetic micropulsations using the first technique were initiated at the Physics Department of the University of Ceylon, Colombo in 1963 (on the author's suggestion) by P. C. B. Fernando and the author.[5] Measurements of telluric currents were initiated at the Vidyodaya University of Ceylon by P. C. B. Fernando and A. Perera in 1968.[3]

Experimental details are given in the relevant papers ; this paper briefly indicates the significant results of investigations conducted in Sri Lanka. When these investigations were begun in 1963, the magnetosphere was little understood. The solar wind had only been recently discovered and there was virtually no information on geomagnetic micropulsations from equatorial regions. Records from high and middle latitudes had indicated that the dominant period of micropulsations in high (auroral) latitudes was about 55 to 60 s and that this dominant period decreased as the latitude decreased.

Fernando and Kannangara[2] showed that the main characteristics of Pc3 and Pc4 type micropulsations recorded in Colombo during the period 20 April to 23 May 1964 were :-

(i) The total micropulsation activity has a mean diurnal variation that builds up to a maximum just before local noon. There also occurs a slight enhancement of activity around local midnight.

(ii) The total activity shows a strong positive correlation with Kp (a world wide magnetic disturbance index).

(iii) The observed activity in the Pc3 and Pc4 band micropulsations is mainly confined to periods lying between 30 and 60 s with peak activities at (38 ± 5) s and (60 ± 5) s.

(iv) The 60 s peak is the dominant one and is highly stable, occurring both in day and night signals. It is also composed of the larger amplitude signals.

(v) The 38 s peak is constituted from smaller amplitude signals and is enhanced under day-time conditions and particularly under magnetic storm conditions.

(vi) The midnight pulsations form a rather broad spectrum with no pronounced peaks at 38 or 60 s but a broad peak at (55 ± 10) s. These are found to consist mainly of damped oscillations of the Pi type.

(vii) Apart from perhaps some sporadic bursts of activity, there is no indication of a general resonance at a period of the order of 20 s as had been reported by many mid-latitude stations.

The dominant period and some other characteristics of the micropulsations recorded by Fernando and Kannangara were in fact more similar to the micropulsations found in auroral latitudes rather than in middle latitudes. This observation lent support to the view put forward by Jacobs and Sinno described previously (Section 10). The ionospheric current loop which flows over equatorial regions would continue round to auroral latitudes and hence similar micropulsations should be seen both at equatorial and auroral latitudes.

Kannangara and Fernando,[7] made a detailed analysis of night-time Pi2 micropulsations from continuous records of micropulsations taken over a whole year in Colombo from 17 October 1964 to 16 October 1965. The main characteristics of these night-time Pi2 pulsations were :-

(i) Pi2 events are most prominent, especially about midnight, during the equinoxes.

(ii) The rate of occurrence of Pi2 events increases almost linearly with Kp up to a Kp level of at least 5.

(iii) The dominant periodicity of Pi2 events shows a definite Kp dependence, the median shifting smoothly from a value of about 100 s at the $Kp = 0$ level to about 45 s at the $Kp = 5$ level.

(iv) Pi2 oscillations tend to have longer periods when they occur at, or immediately before, midnight and to have shorter periods when they occur at predawn.

Perhaps the most interesting result of this analysis was the spectacular increase shown in Pi2 activity at the equinoxes. It was pointed out that the neutral sheet of the magnetosphere points directly at the earth only at the equinoxes. This can be deduced easily if it is realised that the schematic picture of the magnetosphere shown in Figure 5 corresponds to summer in the northern hemisphere. A convincing mechanism which would cause an enhanced Pi2 activity at the equinoxes has not yet been worked out.

Polarisation studies of micropulsations were made by the author in Colombo from records taken during the period April to December 1971.[6] The following polarisation characteristics were observed :-

(i) The magnetic vector of the micropulsations lies almost entirely in the plane of the magnetic meridian.

(ii) The magnetic vector is almost horizontal for signals with periods <60 s at all times.

(iii) As the period increases, the magnetic vector becomes more inclined to the horizontal. This increase in inclination as the period increases is very gradual at night-time and $\Delta Z/\Delta H$ is still ~ 0.2 at a period of 600 s. During the day-time, $\Delta Z/\Delta H$ increases much more as the period increases and has a value of about 0.6 at a period of 600 s. (ΔZ = vertical compodent, ΔH = horizontal component).

(iv) The building of $\Delta Z/\Delta H$ for long period signals during day-time seems to follow the build-up and decay of the E region of ionisation in the ionosphere.

(v) The equatorial electrojet current does not have a first-order effect on the polarisation of micropulsations.

(vi) The polarisation characteristics do not show a first-order seasonal dependence.

(vii) In a periodic signal with both H and Z components, when H increases in a S$\rightarrow$N sense, Z increases in a vertically downward sense and *vice versa*.

The author has shown that all these polarisation characteristics observed in Colombo could be explained in terms of a current pattern in the ionosphere of the type shown in Figure 7 as being the agency responsible for the micropulsations observed at the earth's surface. For equatorial stations like Colombo, the ionospheric currents inducing the micropulsations would be currents flowing in the E $\rightleftharpoons$ W direction over the region of the geomagnetic equator. During day-time these currents would be in the E region and at night-time when the E region disappears the current would rise to the F region. The magnetic disturbance recorded at the earth's surface would be the resultant magnetic effect of this ionospheric current and its image current in the conducting earth. If the earth was a perfect conductor, the image current would be a current of the same strength as the ionospheric current and situated as far below the surface of the earth as the ionospheric current is above it. However, the earth is not a perfect conductor, and from considerations of skin depth of penetration of electromagnetc signals into a surface with finite conductivity, it was deduced that the effective image current would be situated deeper in the earth than the mirror image position, and also the depth of the image in the earth would increase as the periodic time of the signal increases. A surface observer then becomes asymmetrically placed with respect to the ionospheric current and its image, and hence depending on the degree of asymmetry, a Z component must appear in the micropulsation signal when the observing station is not directly on the geomagnetic equator. The bigger the asymmetry, the bigger would be the Z component. Thus, the increase in $\triangle Z/\triangle H$ as the period increases and the reason for the increase being not so marked at night-time is understandable, because a shift of the ionospheric current to the much higher altitudes of the F region would reduce the asymmetry. Hence a very satisfactory explanation of the polarisation characteristics observed in Colombo could possibly be made. Incidentaly, the sense of polarisation of the signals indicated that the ionospheric current sheet was north of Colombo, and indeed the geomagnetic equator passes through Sri Lanka in the region of Vavuniya, which is about 150 miles north of Colombo.

An obvious check on these results would be to make polarisation studies north of the geomagnetic equator and on it. This is being done presently by K. Kunaratnam of the University of Sri Lanka, Colombo Campus. He is taking recordings in Jaffna and Vavuniya; the former is located north of the geomagnetic equator, and the latter is more or less on the geomagnetic equator. Preliminary results reported by Kunaratnam give striking confirmation of the interpretation given above. The sense of polarisation of the signals recorded in Jaffna is opposite to that of the signals recorded in Colombo, and the signals recorded in Vavuniya have no vertical component at all. Mathematical support for the model used by the author has been given by Park.[10]

It was not possible to record the fast Pc 1 micropulsations at the Colombo Campus. However, the telluric current recorder set up at the Vidyodaya University, Nugegoda was capable of recording these signals. Fernando[1] presented an analysis of 117 Pc 1 events recorded at Nugegoda. Pc1 oscillations often appear as short emissions which repeat themselves at regular intervals, giving the appearance of a string of pearls on the recorder chart. Hence these events are often called pearl events. The main features of the pearl events observed by Fernando were:

(i) Pearls occur in the day-time with peak occurrences between 1030 and 1100, 1230 and 1300 and 1530 and 1630 h local time.

(ii) The most probable: (a) duration of a pearl event is about 10 min, (b) number of emissions (bursts) per event is between 5 and 10, (c) duration of an emission is between 40 and 50 s, (d) time interval between two successive events is 10 min to 1h.

(iii) During the day-light hours the mean wave period t_m remains substantially constant while the mean repetition period between successive emissions T_m reaches a minimum at 1230 local time.

(iv) The most probable mean wave period t_m is between 1.0 and 1.5 s.

(v) The most probable T_m/t_m ratio is 40 ± 10 for all events, 50 ± 10 for events with $t_m < 2$ s and 35 ± 10 for events with $t_m \geq 2$ s. The T_m/t_m ratio of noon signals is almost half that of the afternoon and morning signals.

Fernando interprets this last observation of the halving of T_m (t_m is substantially constant) for noon signals as being due to the feeding in of energy from Pc1 signals to both the northern and southern loops of the equatorial electrojet current system in the ionosphere through conjugate points in the northern and southern zones.

Normally, the repetition period T_m between two successive Pc1 emissions would correspond to the time taken for a packet of hydromagnetic waves to travel along the outer field lines of the magnetosphere from one conjugate point to the other and back again. When the equatorial electroject current system which is created by the tidal motion of the ionosphere is fully developed, Fernando considers that at each "bounce" of the hydromagnetic wave packet at a conjugate point in the northern hemisphere and in the southern hemisphere respectively, energy is fed into the appropriate current loop in the ionosphere and gets carried into the equatorial regions. Hence in equatorial regions T_m becomes halved at noon when the equatorial electroject current system is fully developed. The Vidyodaya results thus appear to be another pointer to the important role played by ionospheric current systems in the generation and propagation of geomagnetic micropulsations of all periods from Pc1 pulsations to Pc5 pulsations observed at the earth's surface.

This account reveals that with very modest equipment and very meagre resources, Sri Lanka has made a small but significant contribution to this fascinating field of research.

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