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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-1A-2. Hydromagnetic Radiation of the Sun and Its Effect at the Earth

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A theory is put forward to account for the steady background of geomagnetic disturbance. Hydromagnetic radiation continually spilt out of the sun or generated in the inner corona is suggested to be responsible for the bulk of geomagnetic disturbance. The transit time of disturbance from sun to earth is determined by the Alfvén speed in the space between. The theory suggests that the density of interplanetary gas (assumed fully ionised) is between 10 and 10^{-1} proton-electron paris per cm^3.

A characteristic wavelength equal to the dimensions of the sun would explain cosmic ray modulation in the manner suggested by Elliot[1]. Such waves would be of period 10 minutes. The waves can cause corpuscular bombardment of comets and planets.

The earth environment acts as a hydromagnetic lens to radiation of period less than 10 seconds and concentrates its energy to the central polar region ($<80°$ latitude). Waves of longer period create winds of variable speed and direction about the earth.

The earth's outer atmosphere constitutes an inhomogeneity in the path of the large hydromagnetic waves, and currents that would normally flow uninhibited in interplanetary space create a space charge distribution in the lower ionosphere. This can cause currents in the E regions contributing to geomagnetic disturbance.

Generation of Hydromagnetic Disturbance.

Hydromagnetic waves emitted by the sun or its inner corona are suggested to account for the bulk of geomagnetic disturbance.

Consider the hydromagnetic thermal emission of ionised gases. Elsewhere the author (Cole, 1961a[2]) has shown that, in a fully ionised gas, electrohydromagnetic waves of frequency (ν) less than the plasma frequency (ν_p) have speeds dispersed about the Alfvén speed (V_A) whilst at higher frequencies phase speeds are dispersed about that of light (c). Consider the ideal situation in which the hydromagnetic block ($\nu<\nu_p$) is undispersed with speed V_A and the high frequency block ($\nu>\nu_p$) is undispersed with velocity c. Apply Planck's law for black body radiation at temperature T remembering that the refractive index in the range $\nu<\nu_p$ is c/V_A. It follows that in the interesting special case when $h\nu_p/kT\ll 1$ and $V_A/c\ll 1$,

$$\rho_2/\rho_1=(\pi kTV_A/h\nu_p c)^3\cdot(\pi/5)-(V_A/c)^3 \qquad (1)$$

where

$$\rho_1=\int_0^{\nu_p}\rho(\nu)d\nu\ ,$$

$$\rho_2=\int_{\nu_p}^{\infty}\rho(\nu)d\nu\ ,$$

$\rho(\nu)d\nu$=energy density of radiation in frequency range ν to $\nu+d\nu$.

Put $\nu_p=e(n/\pi m)^{1/2}$ and $V_A=H/(4\pi nM)^{1/2}$, where n=electron density; e, m=charge, mass of electron; H=resident magnetic field, and M=mass of proton. Then $\rho_1>\rho_2$ when

$$\frac{k^2T^2}{h^2e^2}\pi m\gg n>\frac{\pi}{2}\left(\frac{\pi}{5}\right)^{1/3}\frac{km^{1/2}}{heM^{1/2}c}HT\ , \qquad (2)$$

i.e. $$10^{13}T^2\gg n\geq 5\cdot 10^7 HT\ . \qquad (3)$$

Suppose that the sunspot cycle time of 11 years represents the time for a hydromagnetic disturbance to move from the centre of the sun to its surface and back. This would imply magnetic fields internal to the sun of strength of order 10^3 gauss. The average density of the sun is of order 10^{24} protons and electrons per cm^3 and interior temperatures of order 10^7 degrees K may be general. Thus, *on the assumption that the dispersion characteristics of interior solar material are grossly similar to those of a fully ionised gas*, it follows that the energy in the hydromag-

netic block of thermal radiation is very much larger than that in the complementary block. This suggests that hydromagnetic energy plays an important role in the internal structure of this star.

Putting into (3) likely values of $H=10^3$ and $T=10^7$ degrees K we see that in the integration ρ_1 the upper limit ν_p could be decreased by a factor 10^5 without destroying the inequality $\rho_1>\rho_2$. This would also markedly improve the left hand inequality in (3).

Some of this hydromagnetic radiation may spill out of the sun to cause the magnetic features on its disc (Babcock and Babcock, 1952[3]) and in its corona. Some may propagate through the corona to the earth. On the assumption that the inner corona is the sole generator of hydromagnetic waves for geomagnetic disturbance one must invoke non-thermal processes for it may be shown that thermal emission is inadequate. The existence of non-thermal processes in the inner corona can be taken for granted in view of the changes observed in its complex structure.

The reported characteristics of Type II radio bursts (Wild, 1955[4]; Roberts, 1959[5]) are compatible with their sources having the nature of outward moving hydromagnetic disturbance. Assuming that the frequency split (Δ) observed in the fundamental (ν_p) is magnetic (c.f. Roberts, 1959[5]) we may calculate the Alfvén speed $V_A(=\nu_H m^{1/2}c/\nu_p M^{1/2})$ by equating Δ with ν_H the gyrofrequency of electrons. Using the data of Roberts' Fig. 8 one finds V_A values distributed about 1000 km/sec. These speeds are about a factor of 2 larger than source drift speeds calculated by Roberts using a model corona. In view of the uncertainties of the model one is justified at this stage in suggesting that the true drift speed (V_D) is V_A. This could be tested, for, in this case $V_D\nu_p/\Delta$ should be substantially constant.

Hydromagnetic Propagation from Sun to Earth

Studies of the delay of geomagnetic disturbance on solar associated phenomena gives speeds across the sun-earth distance distributed about 10^8 cm sec^{-1}. This speed is here equated with the average Alfvén speed in this space (c.f. Cole, 1959[6], 1960[7], 1961b[8]). If the average magnetic field in this space is 10^{-4}–10^{-3} gauss, the required average interplanetary gas density would be between 10 and 10^{-1} protons and electrons cm^{-3}. Hydromagnetic waves of amplitude a few gammas at the earth's orbit would cause a flux of about 10^{-3}–10^{-2} ergs cm^2 sec^{-1} or about 10^{-9}–10^{-8} of the solar constant. Captured by the earth with a capture cross section of 10 earth diameters (by virtue of the geomagnetic field) such a flux would explain the permanent geomagnetic disturbance (Cole, 1960[7]). At the sun this represents a flux of order 10–10^2 ergs cm^{-2} sec^{-1} which is only 10^{-4}–10^{-3} of that estimated by Piddington (1956[9]) to come up from granules alone. Elsewhere (Cole, 1961) it has been suggested that the emission of hydromagnetic waves by the inner corona may inhibit the expansion attributed to it by Parker (1958[10]).

One would expect a characteristic wavelength of about the size of the sun for emission from the inner corona. This is consistent with the heliocentric model of modulation of cosmic radiation at the earth's orbit prepared by Elliot[1] (1960). He suggests inhomogeneities of dimensions 10^{11} cm (i.e. about the size of the sun) in the solar magnetic (assumed dipole) field. Waves of this length would take times of order an hour to pass the earth. Geomagnetic disturbance with this period is common.

These waves can cause corpuscular bombardment of the planets and comets. The velocity amplitude (v) of particles in a wave of magnetic amplitude ΔH in an interplanetary field H is $V_A\Delta H/H$. Thus if $\Delta H/H=10^{-1}$ and $V_A=10^8$ cm sec^{-1}, v is 10^7 cm sec^{-1}.

Capture of Hydromagnetic Energy by the Earth

The process of earth-capture of energy of solar emitted hydromagnetic waves depends on the frequency of the waves. Firstly consider waves of dimension very much less than the earth's, i.e. of period less than 10 sec. The earth environment acts as a huge hydromagnetic lens to these. Preliminary considerations suggest that their energy finds its way to the upper atmosphere of high magnetic latitudes ($\gtrsim 80°$).

Secondly, waves of length very much greater than earth dimensions would create wind of variable direction about the earth.

Some aspects of the physics of the capture of energy from an interplanetary wind has been examined more fully elsewhere by Piddington (1960[9]) and by the author (Cole, 1961c[11]).

According to the author the interplanetary wind blowing through the outer geomagnetic field establishes an electrostatic field in the ionosphere which in turn drives electric current orthogonal to the geomagnetic field so contributing to geomagnetic disturbance.

Conclusion

The above theory is intended to indicate the very likely source of energy of the bulk of geomagnetic disturbance which is a quasi-permanent phenomenon. The theory does not preclude the possibility of other mechanisms of transport of energy from sun to earth particularly at times of unusually strong disturbance.

Acknowledgement

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6) K. D. Cole: Planet. Space Sci. **1** (1959) 319 (An error in this paper is corrected in Cole, 1961a).
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Discussion

Dungey, J.W.: Have you estimated the intensity at the earth for the thermal radiation? Have you allowed for absorption in the interplanetary gas? I think Landau damping will be important.

Cole, K.D.: I have neglected absorption. The flux required is a small fraction (10^{-4}–10^{-3}) of that normally invoked to explain coronal heating.

Lüst, R.: What is the physical idea behind, that you get more thermal radiation in the hydromagnetic frequency range than in the normal electromagnetic frequency range? I do not think that this is possible.

Cole: At the frequencies of hydromagnetic radiation (in an ionized gas containing magnetic field) there is no radiation with the speed of light.

Parker, E.N.: I believe it is a questionable procedure to replace c (the speed of light) in the Plank Law by the Alfvén speed, is it not?

Cole: I cannot at present think of any reason not to do so. At hydromagnetic frequencies the phase speed is the Alfvén speed not that of light.

Davis, L. Jr.: You speak of hydromagnetic waves propagation from the sun to the earth. Do the effects at the earth depend on the model used for the interplanetary field? If the field is irregular would not the transmission be seriously affected? What models of the interplanetary field do you assume?

Cole: A regular field is assumed for present discussion. Irregular field may be characteristic of only severe disturbance. Other mechanisms of transport of energy may operate then.

Dessler, A. J.: If comet tails are affected by the particle velocity associated with h.m. waves ($V_p = V_A h/H$), would not comet tails point toward the sun part of the time (or perpendicular to the comet-sun line for a transverse wave)?

Cole: Fluctuations in the direction of comet tails are to be expected. How much, I do not know.

Sonett, C.P.: Do you propose to heat the corona by means of hydromagnetic waves generated in the solar interior rather than by the usual Biermann and Alfvén mechanism.

Cole: The original source of energy for these processes may be hydromagnetic

radiation from the interior of the sun. The flux at the sun which could explain geomagnetic disturbance (assuming an earth capture cross section of 10 diameters) is of order 10–10^2 ergs cm^{-2} sec^{-1}. This is a small (10^{-4}–10^{-3}) of the flux invoked by various authors to explain coronal heating.

Davis: Comment made after the meeting: It seems useful to supplement the discussion following the paper with some comments of a type that could not be supplied extemporaneously. The key issues are whether the energy flux due to thermally generated waves is increased enormously above that for black body radiation if hydromagnetic or acoustic waves are present and if the resultant waves can have major astronomical or geophysical effects. In order to produce such effects, the wave must be reasonably long, hence consider only waves longer than $\lambda_m=1$ cm. Thus we can work in the Rayleigh-Jeans limit. Then the flux for all waves longer than λ_m is

$$B(\geq\lambda_m)=vkT/3\lambda^3{}_m \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1} .$$

Numerically, if $T=10^6$ °K and $V=10^7$ cm/sec, the minimum possible velocity of an acoustic or hydromagnetic wave in a medium at 10^6 °K, the energy flux is

$$B(\geq 1 \text{ cm})=4\times10^{-3} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1} .$$

The black body flux in the solar photosphere ($T=5800°K$) is 2×10^{10} erg cm^{-2} sec^{-1} sterad^{-1}. Thus there can be no astronomical or geophysical consequences of importance due to thermally generated, reasonably long hydromagnetic waves. It is not possible to get greater energy in these waves by allowing shorter waves in a region of lower velocity to propagate to a region with high velocity since refraction will limit the intensity to the thermodynamic limit. Much greater fluxes are obtained if $\nu_m(=v/\lambda_m)$ is increased, but these correspond to thermal conductivity, not to mass motions on a geophysical scale.

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II-1A-3. Infrasonic Pressure Waves Associated with Magnetic Storms

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Pressure waves with predominant periods between 20 and 80 seconds and amplitudes up to 8 dyne/cm^2 have been recorded with a quadrilateral microphone array near Washington, D. C. during intervals of high magnetic activity. These waves have a trace velocity along the earth's surface higher than the local speed of sound and show diurnal-directional properties consistent with a source on the night side of the earth. A high degree of association with large values of the planetary magnetic index K_p has been established.

Pressure fluctuations in the atmosphere were detected by condenser microphones placed on the surface of the earth so as to form a quadrilateral averaging 7.5 km on a side (Fig. 1). The output of each microphone was amplified and recorded on translucent paper tapes. A visual cross-

* A more complete description of this work has been submitted to the Journal of Geophysical Research.