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SOME EFFECTS OF HYDROMAGNETIC WAVES IN THE SOLAR ATMOSPHERE

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ABSTRACT

A hitherto undisclosed source of absorption of hydromagnetic waves, due to the presence of neutral atoms, is investigated quantitatively. In the chromosphere the rate of absorption due to this effect may be 10^{10} times greater than that due to ordinary viscosity.

General solar heating, due to hydromagnetic waves caused by granules, is investigated and order-of-magnitude agreement with observational data is found.

The new effect is discussed in connexion with heating near sunspots and with flares.

1. THE RATE OF ABSORPTION OF HYDROMAGNETIC WAVES

It has been shown [1, 2] that heating of gas by crossed electric and magnetic fields depends on the composite conductivity $\sigma_3 = \sigma_1 + \sigma_2^2/\sigma_1$, where σ_1 and σ_2 are the direct and Hall conductivities respectively. In a fully ionized gas like the solar corona σ_3 is very large and the rate of dissipation of electromagnetic energy very low.*

However, when neutral atoms are present in comparable numbers, even though the electron collision frequency is hardly affected (because of the small collision section of the atoms compared with ions), the value of σ_3 decreases by a large factor and the absorption increases correspondingly. The effect has been discussed in connexion with non-spot solar heating and with galactic hydromagnetic waves [3, 4].

When electrons collide much more frequently with ions than with atoms a partially ionized gas may be treated as a fully ionized gas co-existing with a neutral atom gas. The latter is only effective in exerting a viscous drag on the former which moves under the influence of the electromagnetic field. For the shear waves with which we are concerned gas

* When the hydromagnetic waves are strong and irregular and some of the ions are moving much faster than the average, substantial dissipation of energy may occur by another process discussed below.

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pressure gradients may be neglected and the momentum equations of the gases are

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}-\mathbf{v}')\frac{\eta}{\tau} + \frac{V^2}{H_0^2}(\mathbf{H}_0 \times \operatorname{curl} \mathbf{H}) = 0$$

and

$$\frac{\partial \mathbf{v}}{\partial t} = (\mathbf{v}-\mathbf{v}')\frac{1}{\tau},$$

where $\mathbf{v}$ and $\mathbf{v}'$ are the velocities of the plasma and neutral atom gases, η is the ratio of the mass densities of neutral atoms to plasma, τ is the collision period of a neutral atom with a heavy ion and $\mathbf{H}$ the magnetic field with a steady component $\mathbf{H}_0$; V is the hydromagnetic velocity $H_0(4\pi\rho)^{-\frac{1}{2}}$ where ρ is the density of the ion plasma alone. These equations are combined with the field equations for a moving fully-ionized gas (reference [1], Eq. (17)):

$$\nabla^2\mathbf{H} - \sigma_2/\sigma_1 \frac{\partial}{\partial z} \operatorname{curl} \mathbf{H} = 4\pi\sigma_3\left[\frac{\partial \mathbf{H}}{\partial t} - \operatorname{curl}(\mathbf{v}\times\mathbf{H})\right],$$

where the z-axis coincides with $\mathbf{H}_0$.

The absorption coefficient of hydromagnetic waves described by these three equations takes a simple form when the wave angular frequency $\omega \ll \tau^{-1}$. We have

$$\kappa = \frac{\omega^2\tau\eta}{2SV(1+\eta)^{\frac{1}{2}}}, \tag{1}$$

where SV is the wave velocity, S having a value of $\cos\psi$ or unity for the 'ordinary' (O) and 'extraordinary' (E) waves respectively [5], ψ being the angle between $\mathbf{H}_0$ and the direction of wave propagation. In the middle chromosphere in a magnetic field of 100 gauss and with equal numbers of atoms and heavy ions this absorption rate is about 10^{10} times that due to ordinary Joule heating (neglecting neutral atoms) and much greater than that due to ordinary viscous effects.

Earlier theories of coronal heating, flares, etc., invoked large induction electric fields to provide acceleration. These theories have been shown untenable because the magnetic field is frozen into the plasma. It is not frozen into the neutral atoms, however, and its movement relative to this gas may result in a large induced electric field; hundreds of volts/cm is possible. It is this field which, according to the present theory, is responsible for the various phenomena. The movement of the ion plasma may be regarded as a Hall drift under the influence of the electric field. Rapid relative motion of the two gases results in collisions which cause heating, excitation and ionization with subsequent emission of quanta up to X-ray energies.

2. HEATING AWAY FROM SUNSPOTS

Alfvén [6] has suggested that some of the energy of the photospheric solar granules may be transferred upwards by shear waves and contribute to coronal heating. The available supply of kinetic energy is about 10^7 erg $cm^{-2} sec^{-1}$ which may be 100 times or more that needed to maintain the corona in non-spot regions. The previous difficulty met by this theory was that the rate of absorption of wave energy appeared to be too low to cause much heating. It is now found that in a limited region where $\eta \sim 1$ this difficulty is overcome.

Upward transfer of energy must be by wave motion, the three possible waves being the O, E and S hydromagnetic waves (see reference [7]), the fourth wave, the space-charge electric wave, is not likely to be important at these frequencies. The O and E waves are the shear waves discussed above; the S wave is mainly longitudinal and approximates a sound wave in very weak fields. In a weak magnetic field, say 5 gauss, the velocities of these waves at the photosphere are about 0·2, 0·2, 10 km sec^{-1} respectively, which gives a measure of the relative effectiveness in energy transfer. Thus most of the energy is transferred initially by a sound wave as in the theory of Biermann [8] and others.

As the wave approaches a level of about 1500 km it tends to be strongly absorbed in the absence of a magnetic field. However, the field increases the coherence of the wave and also causes the weak shear waves to attain the same velocity as the strong S wave. There will then be a tendency to share the available energy equally between the waves as they have some electromagnetic vectors in common. At higher levels the O and E waves are slowly absorbed and also partially reflected due to a decreasing refractive index of the medium. According to the theory it is the energy provided by the absorption of these waves which heats part of the solar atmosphere.

A quantitative examination [3] suggests that a significant proportion of the original energy, in the frequency band $0{\cdot}1 < \omega < 0{\cdot}3$, may reach a level of 6000 km where $\eta \sim 1$. Waves of much lower frequency tend to be mainly reflected, those of much higher frequency to be absorbed at lower levels. At the level where $\eta \sim 1$ the ion and atom densities are about 3×10^{-9} cm^{-3} and $\tau \sim 1$ sec. Waves of frequency 0·2 rad sec^{-1} in a field of 5 gauss have an absorption coefficient of about 10^{-9} cm^{-1}. In a layer a few thousand km thick the energy released might be about 10^5 erg $cm^{-2} sec^{-1}$, perhaps sufficient to replenish the quiet or non-spot corona. At lower levels the heating per gas particle falls rapidly and in the corona itself the total heating is very small because of the dearth of neutral atoms.

A prediction of the neutral atom theory is that heating occurs, not in the body of the hot corona itself, but in the surface layers of the chromosphere and of prominence material. There is some evidence that this is the case.

3. HEATING NEAR SUNSPOTS AND FLARES

Current ideas of the origin, maintenance and decay of a sunspot magnetic field [9] suggest that there is irregular motion below the photosphere. The rate of development of a spot group indicates an upward motion of at least 0·03 km sec^{-1} from a depth of 20,000 km and more localized eddies may move much faster. These movements are communicated to the magnetic field and result in the formation of transverse and longitudinal hydromagnetic waves. The waves will tend to travel up the magnetic field and emerge either through the spot itself or through a non-spot region penetrated by a spot magnetic field.

Several varieties of hydromagnetic disturbance may travel up a cylindrical bundle of sunspot lines of force. Perhaps the most important form of shear wave is torsional, since this causes less disturbance (and so is less absorbed) in the surrounding medium than do waves involving lateral movement or expansion and contraction of the bundle. Torsional oscillations may be initiated by contact of the field with a vortex element in the gas at low levels. Longitudinal (S) waves may also be present and rise to the surface.

The Poynting flux of energy is given by

$$P = (H_o H_p v)/8\pi, \tag{2}$$

where H_p is the perturbation magnetic field and v the gas perturbation velocity given by

$$v = \frac{H_p}{H_o} \cdot V = \frac{H_p}{(4\pi\rho)^{\frac{1}{2}}}. \tag{3}$$

The total flux over a bundle of area A is $\int H_o H_p v \, dA/8\pi$ and, since $\int H_o \, dA$ is constant we have, for a uniformly expanding bundle, $H_p v = \text{const.}$ Hence $v \propto \rho^{-\frac{1}{4}}$ so that the disturbance becomes more violent as it rises.

A disturbance rising from a depth of 20,000 km to the photosphere experiences a density drop of $\sim 10^3$ so that an initial disturbance of say 0·1 km sec^{-1} becomes one of 0·6 km sec^{-1}. If the steady magnetic field is 2000 gauss, then $H_p \sim 70$ gauss and $P \sim 3 \times 10^8$ erg cm^{-2} sec^{-1}. This flow of energy, when absorbed by the process described above, may account at least in part for the very hot ($> 10^7$ °K), high-pressure regions whose existence above sunspots is inferred from both optical [10] and radio [11] observations.

As the hydromagnetic waves travel from the photosphere to the mid-chromosphere where $\eta \sim 1$ there is a further large increase in gas velocity to about 200 km sec^{-1}. The energy abstracted from the wave due to a collision between a heavy ion and an atom may be as high as 200 eV which is of the right order to account for the very high gas temperatures, emission of X-rays, violent movement of material and other observed and inferred effects. It may be noted that the perturbation magnetic field, H_p, associated with this very substantial gas velocity is small, only about 2 gauss in a total field of the order 1000 gauss.

Hydromagnetic waves with perturbation velocities of 10 km sec^{-1} at the photosphere will have perturbation magnetic fields of about 1000 gauss. These waves might be observable but should cause no very obvious effects at this level. However, on rising to a level where $\eta \sim 1$, the density has dropped to about 10^{-15} and the perturbation velocity risen to about 1000 km sec^{-1}. The results are likely to be catastrophic: there will in particular be violent heating of the surface layer of the chromospheric neutral atom gas. The heating is due to the violent beating of this gas by magnetic lines of force to which the ions are attached. If the waves are of angular frequency comparable with the neutral atom collision frequency then collision energies of thousands of electron volts are developed.

The mechanism is proposed as an explanation of the origin of flares.

A comparison of the observed properties of flares [12] with those anticipated from the mechanism shows fair agreement. In particular, flares grow near sunspots from pre-existent 'normal' bright hydrogen flocculi. Such flocculi constitute the surface layer of the neutral atom chromosphere and are bright because they are heated by the recurrent weak hydromagnetic disturbances. On occasions the heated surface layer may be on prominence material or on the underside of chromospheric clouds ('Hydrogen bombs'). The structure of flares is also related to the magnetic field distribution; the relationship is complex but sometimes the flares seem to extend along lines of force. Such effects are consistent with an origin in hydromagnetic waves, which are controlled by the field.

4. HYDROMAGNETIC WAVES IN THE CORONA

While the neutral atom mechanism may be adequate near the surface of the chromosphere (visible in line emission) it hardly seems capable of maintaining the corona, since the kinetic energy of the particles of hot gas would be dissipated in raising the gas to high coronal levels against the gravitational field. However, there are several factors which, with the aid of neutral atom heating, are likely to provide the observed hot gas at high levels.

There is considerable turbulence in the corona, particularly in the neighbourhood of sunspots. This would cause some mixing and raising of the gases. Strong hydromagnetic waves, and in particular shock hydromagnetic waves, instead of causing the gas only to oscillate back and forth, make it slide along the magnetic field and so provide electromagnetic energy to raise the gas to high levels.

There is another effect or perhaps series of effects which depends on the presence of a proportion of ions with velocities much greater than the average. The neutral atom mechanism should release such particles which will rise to 10^5 km or so without loosing a great proportion of their initial kinetic energy. When those particles have energies corresponding to a gas 'temperature' of less than 10^8 °K their collision periods are minutes or less and comparable with the wave periods. Under those circumstances the heating or accelerating mechanism may be described as a viscosity effect, the ordinary viscosity being enhanced by the presence of the fast particles.

We may use an expression for viscous absorption derived by van de Hulst [13] replacing the kinematic viscosity by the expression $\eta_F v_F^2 \tau_F$ where η_F is the proportion of fast particles in the total mass of gas, v_F is their velocity and τ_F their collision period. The absorption coefficient κ_F due to the viscous effects of those particles may then be compared with that due to neutral atoms (Eq. (1)) and we find

$$\frac{\kappa_F}{\kappa} = K\left(\frac{v_F}{v}\right)^2 . \frac{\eta_F}{\eta} . \frac{\tau_F}{\tau}, \tag{4}$$

where K is a constant of order unity and it is assumed $\eta \ll 1$. The expressions for κ and κ_F are similar as, in a way, are the mechanisms. In one case the particles causing absorption (neutral atoms) remain at rest while the ions are accelerated by the wave, in the other case the absorbing particles (fast ions) move rapidly from one part of the wave to another where the relative velocities are high. In either case a subsequent collision causes substantial loss of wave energy. In the corona in a magnetic field of 10–100 gauss and with say 10 % of ions at a 'temperature' of 10^7 °K the value of κ_F/κ does not fall far short of unity and allowing for the decreased density the heating effect may be important.

The viscous heating effect tends to increase with temperature until limited by the fact that the fast ions do not collide often enough to transfer their energy, which oscillates between the wave and the particles, this occurs when $\tau_F \gtrsim \omega^{-1}$. Meanwhile the third effect becomes operative, the fast particles collide not only with other particles but with strong hydromagnetic waves; with the magnetic field itself. A single collision may increase the kinetic energy of the particle by many times its original value. Subsequently some particles will suffer collisions and degrade their kinetic energy to heat while others will become 'runaway' ions, suffering no collisions but, under suitable circumstances, gaining energy continously from the waves until some eventually become cosmic rays.

5. COSMIC RAYS AND RADIO BURSTS

The statistical gain of energy of ions by collisions with hydromagnetic wave packets was suggested by Fermi and reformulated by Thompson [14]. The results agree quantitatively for 'strong' waves, that is when $H_p \to H_0$ and are used to estimate the time taken to create cosmic rays in the corona.

Assume $H_p/H_0 = 0{\cdot}2$ which is an order of magnitude greater than the flare value given above and may be expected for the exceptionally powerful disturbances which release cosmic rays. Hydromagnetic waves of length say 10^5 km in the corona then cause a gain of energy by a factor of exp. 1 in about 200 secs or a factor of 10^8 in 1 hr. The necessary injection energy is about 10^4 eV.

Strong flares are accompanied and followed by an outflow of gas moving at about 10^3 km sec^{-1}. This may be the remains of the longitudinal or S-type hydromagnetic wave which would be expected to accompany, at least in some degree, the transverse O- and E-type waves which are invoked to explain the flare. This flow of gas may be necessary to release the cosmic rays from the confines of spot magnetic field. On reaching a level of about 10^6 km or so in about $\frac{1}{2}$ hr it will so have stretched and attenuated the magnetic field that the cosmic rays may escape. The gas has in effect, changed the magnetic field from a typical dipolar form to a more-or-less radial form.

Same radio bursts are thought to originate in large-scale disturbances travelling out from the sun. Some such disturbances seem to travel out at about 10^3 km sec^{-1} and others at 10^5 km sec^{-1}, starting simultaneously from the vicinity of a flare [15]. The travelling sources of bursts need not be ion clouds, they could equally well be wave-packets and on this basis they have a simple explanation.

The slow travelling disturbance is the S-wave or the remains of the S-wave, probably degenerated into a shock wave directed largely along the magnetic field until it reaches a level where the field is too weak to control it. The fast travelling disturbance is perhaps the O or E hydromagnetic wave responsible for the flare. In the low corona in a magnetic field of 1000 gauss the velocity of these waves is about 10^5 km sec^{-1}. There will be a tendency for the velocity to remain steady as the field-strength and gas density both decrease outwards.

It seems that on the basis of a mild hydromagnetic disturbance below a sunspot, a number of observed effects may be explained.

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Discussion

Schatzman: What is the direction of propagation of the flux of mechanical energy transported by the hydromagnetic waves?

Piddington: In a more or less uniform medium hydromagnetic waves may propagate freely in any direction and so transport energy freely in any direction. From a single small-scale disturbance a spherical wave would spread; from numerous granules an interference pattern would be formed.

Schatzman: What is the energy transmitted upwards in the chromosphere as a result of hydromagnetic waves compared to that transmitted by pure compression waves? As far as I know, the compression waves transport an energy sufficient for heating the chromosphere and the corona.

Piddington: Near the photosphere the speed of the shear waves is about 0·2 km/sec for a magnetic field of a few gauss. The speed of the compression waves is about 10 km/sec so that unless a particular disturbance greatly favoured the formation of shear waves these would initially play an unimportant part in energy transport. At higher levels, however, the situation is reversed.

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Biermann: As was just pointed out, the velocity of hydromagnetic waves is, outside a spot region, quite small compared with the velocity of compression waves. Would that not indicate that outside spots the old picture of pressure waves is up to the higher levels of the chromosphere, as good an approximation as one might wish to have? Up to the limit just indicated only slight modifications should be expected from the interplay of the magnetic and shearing modes.

Piddington: Pressure waves would seem to play the main part up to about 1500 km. Above that level the shear waves are more efficient at transporting energy. There is evidence that the pressure waves would disintegrate, in which case the shear waves would be all-important as a medium of energy transport.

Biermann: This depends, of course, on the local value of the magnetic field and also on the hydrogen density.

Alfvén: Would not small charged grains, instead of neutral atoms, also be able to cause a heating of the corona?

Piddington: Yes, provided the charge and density of the grains is appropriate.

Sarabhai: One of the remarkable features of cosmic ray increases associated with flares is that the flare is often quite far removed from the central meridian. On 23 February 1956, the flare was about 70° from the central meridian and generated cosmic rays up to 30–40 BeV in energy. Is the angular distribution of ejection of energetic particles of this theory compatible with the observations?

Piddington: No statement can be made on the angular distribution.