GENERATION OF THE MAGNETOHYDRODYNAMIC WAVES IN SUNSPOT: THE HEATING OF THE CHROMOSPHERE ABOVE THE SUNSPOTS.

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ABSTRACT: The chromosphere is heated by the absorption of the weak magnetoacoustic waves.

СОЗДАНИЕ МАГНЕТОГИДРОДИНАМИЧЕСКИХ ВОЛН В СОЛНЕЧНОМ ПЯТНЕ. НАГРЕВ ХРОМОСФЕРЫ НАД СОЛНЕЧНЫМИ ПЯТНАМИ. Хромосфера нагревается поглощением слабых магнетоакустических волн.

VZNIK MAGNETOHYDRODINAMICKÝCH VĹN V SLNEČNEJ ŠKVRNE. ZOHRIEVANIE CHROMOSFÉRY NAD SLNEČNÝMI ŠKVRNAMI. Zohrievanie chromosféry vzniká absorpciou slabých magnetoakustických vĺn.

Let us suppose that the sunspot is a magnetic flux tube with homogeneous field strength H, and the magnetic lines of forces are perpendicular to the surface of the Sun (Fig. 1). The magnetic energy density, $E_m = \frac{H^2}{8\pi}$ in this case doesn't depend on the depth. The kinetic energy density, $E_k = \frac{\rho v^2}{2}$ depends on the depth according to the model of the convective zone [1]. In the region where $E_k > E_m$, the motion of the convective elements mixes the magnetic field lines because they are frozen in the matter. In the region where $E_k < E_m$, the magnetic field stops the motion and the expansion of the convective elements. The region where $E_k \approx E_m$ can be called as "critical zone". The depth of the critical zone is the depth of the sunspot if the spot is supposed to be the region where the convection is stopped by the magnetic field. The depths of the spots at several magnetic field strengths are given in Table 1. According to Table 1, the depths of the sunspots are not very large in comparison with their horizontal dimensions if the field strenght is not larger than 3000 gauss. It is interesting that the depth of the spot is comparable with the depth of the convectove zone in the case of 3500 gauss. Perhaps it is in

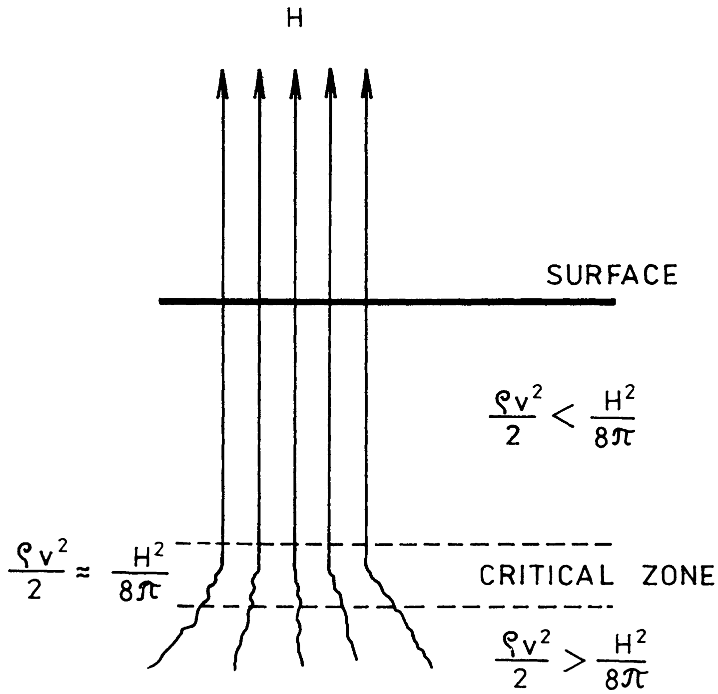

Fig. 1: Scheme of sunspot.

connection with the existence of a maximal field strength of the spots.

Table 1

The dept of the sunspots as the function of magnetic indication.

H (gauss)	Depth (km)
1000	3000
2000	7000
3000	10000
3500	100000(?)

It can be supposed that in the critical zone magnetohydrodynamic waves are generated, the energy of convective turbulent motions transforms into the energy of magnetohydrodynamic waves.

Let us analyse the processes taking place in the critical zone. Because in the critical zone the density of the magnetic energy is comparable with the density of the kinetic energy of the convective motion, the influence of the magnetic field to the convection has to be taken into consideration. The energy of the convective element can approximately be given by the following eguation:

$$\frac{m\, v(x)}{} = \int_0^x K(x)dx - \frac{H^2}{8\pi}\frac{m}{\rho} \quad , \qquad (1)$$

where m is the mass and v(x) the velocity of the element, K(x) is the upward force. Using this equation in [2] have been calculated models of the convective zone at several magnetic field strength. In Fig. 2 the characteristic velocities $\bar{v}$ of the convective motions are given at 1000, 2000 and 3000 gauss respectively.

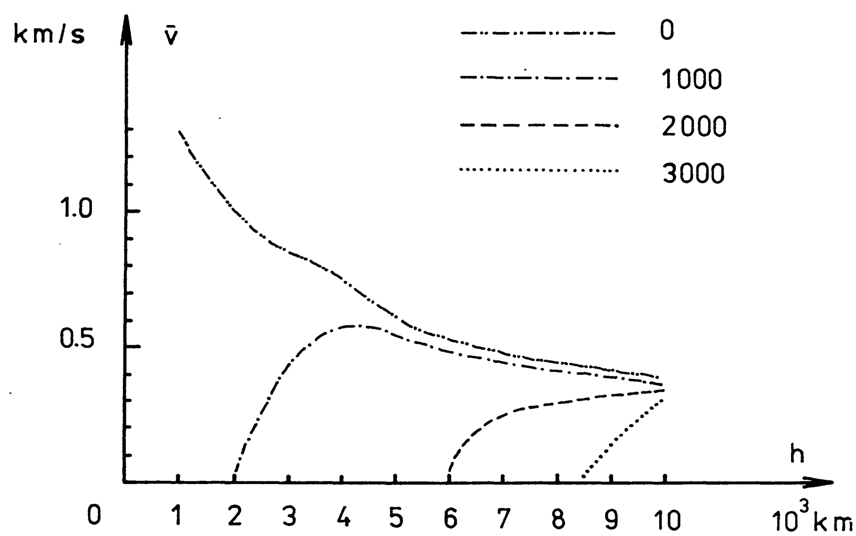

Fig. 2: The characteristic velocities $\bar{v}$ of the convective motions are given at 1000, 2000 and 3000 gauss respectively.

Kulsrud [3] calculated the emission coefficients of various types of magnetohydrodynamic waves. If the magnetic field strength is larger than 500 gauss, the emission coefficients for Alfvén waves and slow magnetoacoustic waves are the same and the emission coefficient for fast magnetoacoustic waves is negligible small. The emission coefficient for Alfvén and slow magnetoacoustic waves are [2]:

$$S_{Alf} = S_{sl} = 5{,}2 \cdot 10^6 \, f_1(M_H)\, \frac{\rho \bar{v}^3}{P} \quad , \qquad (2)$$

where $M_H = \frac{\bar{v}}{V_A}$, P is the pressure and f_1 is a numerically given function.

According to [2] and [3], if there is no magnetic field: sound waves, if the magnetic field strength is 50 - 100 gauss: fast magnetoacoustic waves and if the magnetic field strength 1000-3000 gauss: Alfvén and slow magneto-acoustic waves are generated respectively.

The emission coefficients of Alfvén and slow magnetoacoustic waves as functions of the depth are presented in Fig. 3 at several magnetic field strength.

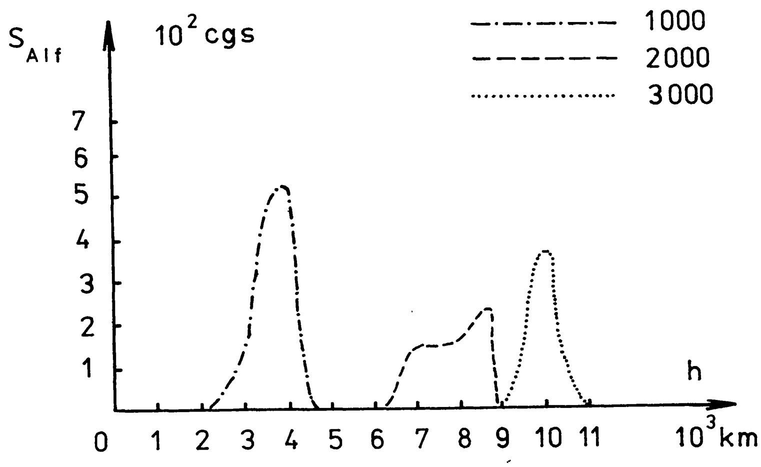

Fig. 3: The emission coefficients of Alfvén and slow magnetoacoustic waves as functions of the depth are presented.

The Alfvén and slow magnetoacoustic waves propagate practicaly along the field lines. Taking into consideration the reflexion of the waves, has been calculated the fluxes of Alfvén and slow magnetoacoustic waves at the surface of the Sun [2] at several magnetic field strengths (Table 2). It should be noted that the flux decreases with the growth of the field strength.

Table 2

The fluxes of Alfvén and slow magnetoacoustic waves.

H(gauss)	Flux(erg/cm^{2}s)
1000	10^9
2000	4.10^8
3000	3.10^8

This calculations show that the flux of magnetohydrodynamic waves emitted from sunspots is larger than the flux emitted from active regions and at least an order of magnitude larger than the flux emitted from undisturbed regions.

Knowing the fluxes of magnetohydrodynamic waves emitted from sunspots we can construct models of the solar chromosphere above the sunspots.

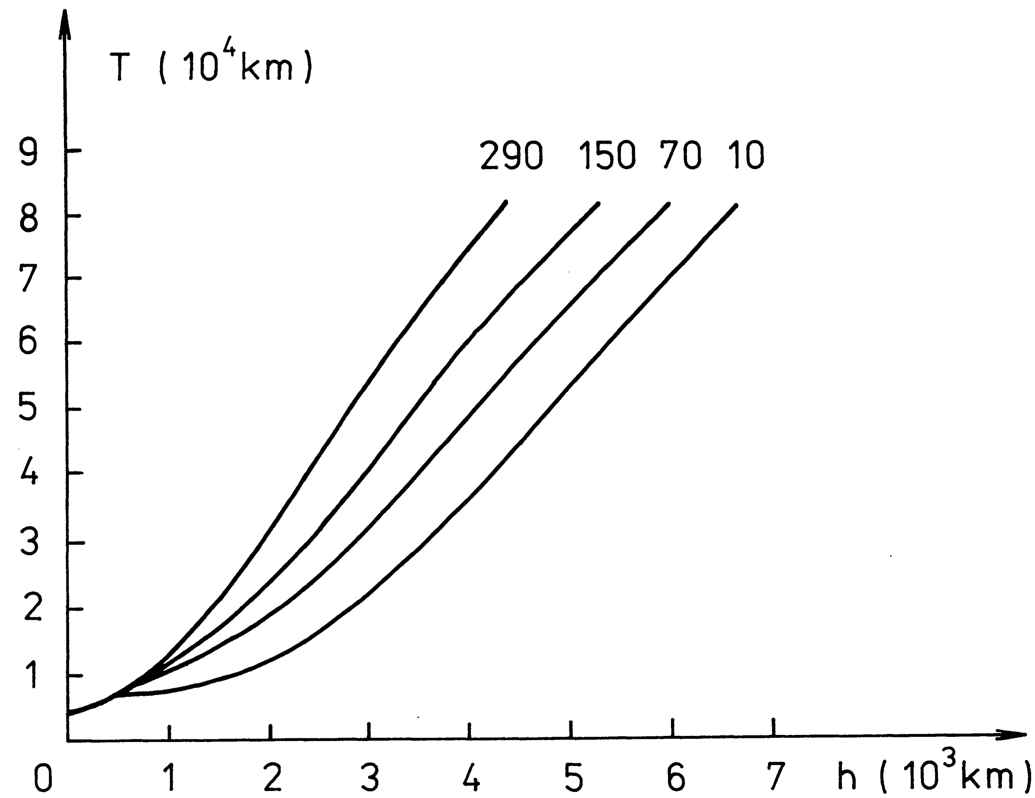

Fig. 4: The temperature T as a function of height in the chromosphere.

The radiative emission coefficien $\mathcal{E}_e$ of the solar matter in the chromosphere has been calculated by Cox and Daltabuit [4].

$$\mathcal{E}_e = 10^{-23}\, f(T)\, n_e\, n_H\ , \qquad (3)$$

where f(T) is a numerically given function, n_e and n_H are the electron and Hydrogen densities. According to 5 :

$$\mathcal{E}_e = 1{,}33\ 10^{24}\ F(P,T)\, \rho^2\ , \qquad (4)$$

where F(P,T) is also a numericaly given function.

The Alfvén waves don't damp in the chromosphere and therefore don't play a role in the heating of the chromosphere. Osterbrock [6] has suggested that the slow magnetoacoustic waves transform into weak shock waves in the layer of $V_A \approx V_s$ (V_A is the Alfvén and V_s is the sound velocity). The chromosphere is heated by these weak shock waves according to [3], [5] and others. The absorption coefficient for the weak magnetoacoustic shock waves my be written as follows [5]:

$$\mathcal{E}_a = \frac{1}{8}2^{1/2}t_o^{-1}\gamma^{-5/4}P^{-5/4}\varrho^{3/4}F_o^{3/2} \cdot$$

$$\cdot \left(1+\frac{1}{8}2^{1/2}F_o^{1/2}t_o^{-1}\int_0^h \gamma^{-5/4}P^{-5/4}\varrho^{3/4}dh\right)^{-3} \qquad (5)$$

where t_o is the transit time of the shock waves, γ is the ratio of specific heats, P is the gas pressure and F_o is the energy flux the shock waves at the level h=0.

Let us suppose that chromosphere is heated by the absorption of weak magnetoacoustic waves. In this case $\mathcal{E}_a = \mathcal{E}_e$, or combining equations for $\mathcal{E}_a$ and $\mathcal{E}_e$, and using the equation of state and the equation of the hydrostatic equilibrium, we get a differential equation for P 5 :

$$P'' = -\frac{(P')^2}{P} \cdot$$

$$\cdot \frac{5 + 4F(P,P')^{-1}\frac{\partial F}{\partial P}P - 12a(-PP')^{1/6}F(P,P')^{1/3}}{+\frac{\partial F}{\partial P'}F(P,P')^{-1}P'} \qquad (6)$$

The model has been calculated by this equation numerically. For the transit time of shock waves, t_o, depending on the magnetic field strength, 10, 30, ..., 290 seconds have been taken successively.

Figure 4 shows the temperature T)h) as a function of height in the chromosphere.

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Discussion

M.A. Mogilevsky:
Вы взали при оценке поток энергии МГД волн 10^8 эрг/см^2. Это на три порядка больше того, что наблюдается (к стати эти экспериментальные данные, которые показали многие наблюдатели заставили Паркера отказаться от теории охлаждения пятна потоком уходящих МГД волн).

M. Marik:
Замедленные магнетоакустические волны не замыкаются в пятне. Они нагревают

только хромосферу над пятном с слоя $V_A \approx V_S$. Одна часть потока нагревает хромосферу, другая часть выходит в корону.

J. Staude:

For comparison the theory with the observations of oscillations it would be useful to know the predicted spectrum of waves. Which period could be expected?

M. Marik:

According to the presented theoretical calculations the period of oscillation of magnetohydrodynamic waves changes from some minutes to one hour, depending on the magnetic field strength.