HYPERSONIC PULSING REGIMES OF MAGNETIC FIELD EMERGE FROM LOWER LAYERS OF THE CONVECTIVE ZONE UP TO THE PHOTOSPHERE OF THE SUN

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1. Introduction

Oscillations of an isolated thin magnetic tube at various depths of the convective zone and in the atmosphere of the Sun are investigated in the present work in the approximation of ideal magnetic gas-dynamics ([1]). These oscillations are the source of generation of acoustic waves whose transition in weak shock waves provides anomalous heating of the solar atmosphere.

The modes of small-amplitude linear oscillations at various depths of the convective zone are investigated. The loss of stability of equilibrium of the magnetic tube, which is initially at rest in the convective zone, as well as the nonlinear large-scale oscillations of the tube and tube emergence into the solar atmosphere are independently investigated.

The results obtained are fundamental for research of sunspot generation and physics of solar activity; they are important for analysis of generation and time evolution of global magnetic structures, solar wind, and some other astrophysical phenomena [2].

2. Mathematical statement of the problem

In this work, radial oscillations of a thin magnetic tube located in the equatorial plane of the Sun (Fig.1a) are investigated. The zeroth harmonic of oscillations is studied, at which only the magnetic tube radius varies (Fig. 1b).

The full set of equations of ideal magnetic gas dynamics [1, 3] is shown below:

$$2\pi r\rho\Sigma = M_0 = \text{const}\,, \tag{1}$$

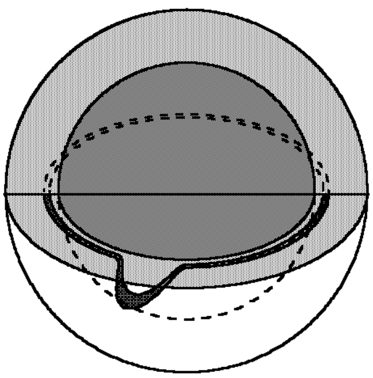

Figure 1a. Location of a thin magnetic tube in the equatorial plane of the Sun.

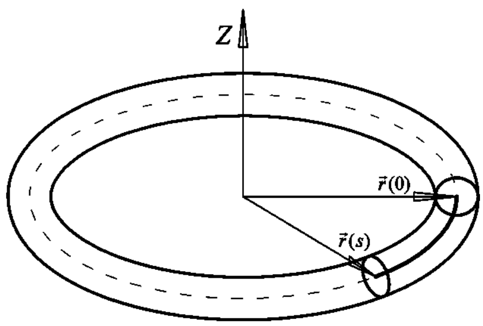

Figure 1b. System of coordinates for calculations.

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Abstract

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$$\frac{\mathrm{d}r}{\mathrm{d}t} = \upsilon , \quad (2)$$

$$(\rho_i + k\rho_e)\frac{\mathrm{d}\upsilon}{\mathrm{d}t} = (\rho - \rho_e)g - \frac{1}{4\pi}\frac{H^2}{r} , \quad (3)$$

$$\frac{p}{\rho^{\gamma}} = \frac{p_0}{\rho_0^{\gamma}} = \mathrm{const} , \quad (4)$$

$$H\Sigma = H_0\Sigma_0 = \mathrm{const} , \quad (5)$$

$$p_i + \frac{H^2}{8\pi} = p_e , \quad (6)$$

$$p = \frac{R_0}{\mu}\rho T . \quad (7)$$

Equation (1) formulates the law of mass conservation in the magnetic tube. Equations (2) and (3) describe the tube motion under the influence of the archimedean force and tension of magnetic field lines. The velocity of the tube is supposed to be essentially subsonic, and the influence of the ambient medium on the tube motion is expressed in terms of additional mass in (3) [4]. Equation (4) is the adiabatic energy law. Equation (5) is the law of conservation of magnetic flux over the tube cross section. All parameters depend only on the radius of the tube curvature - r. Equation (6) determines the equality of the ambient gas pressure p_e to the internal pressure in the magnetic tube, which consists of the gas pressure p_i and the pressure of the magnetic field. The dependences of $p_e(r)$, $g(r)$, $\rho_e(r)$ on r are determined by the chosen model of the solar convective zone [5], and they are necessary to close the system of equations.

System (1)-(7) is dimensionless, and the units of plasma parameters in the tube are shown below:

$[r_0] = 10^{10}$ cm	$[g_0] = 1.327\cdot10^6$ cm/s^2	$[p_0] = 10^5$ dyn/cm^3	$[T_0] = 10^4$ K
$[\rho_0] = 10^{-6}$ g/cm^3	$[t_0] = (r_0/g_0)^{1/2}$	$[\upsilon_0] = g_0\cdot t_0$	

3. Liner oscillations of the magnetic tube at various depths of the convective zone of the Sun. Relaxation zone and zone of solar Dynamo

The equilibrium position of the magnetic tube can be achieved by imposing the following limitation on gas density and magnetic field strength:

$$(\rho - \rho_e)g = \frac{1}{4\pi}\frac{H^2}{r} . \quad (8)$$

In equilibrium, the force of magnetic field tension counterbalances the archimedean buoyancy force. In equilibrium, the magnetic field strength corresponding to (6), (7), (8) and (3) uniquely determines the plasma density, pressure and temperature.

The maximum possible value of magnetic field intensity in the tube is determined from Eq. (6):

$$H_{\max} = \sqrt{8\pi p_e} . \quad (9)$$

If the depth of tube location is less than 40 km below the photosphere, then the tube in equilibrium is unstable for all possible values of the field strength (9). The tube located in the range of depths from 40 km to $140\cdot10^3$ km below the photosphere is in stable equilibrium if the magnetic field intensity is greater than the critical value $H_{cr}(r)$ (Fig. 2). The tube equilibrium in that range of depths is unstable if the magnetic field intensity is lower than the critical value.

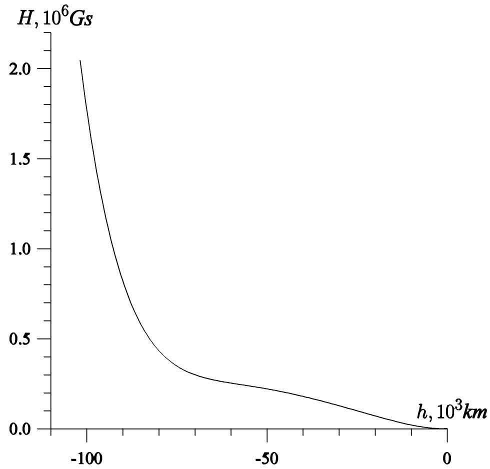

Figure 2. Critical intensity of the magnetic field versus the depth in the relaxation zone.

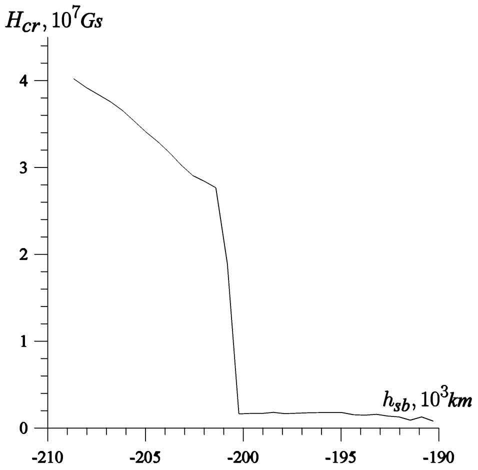

Figure 3. Critical intensity of the magnetic field versus the depth in high layers of the Dynamo zone

The second area where the tube can be in stable equilibrium is situated lower than $190 \cdot 10^3$ km below the photosphere (Fig. 3). In contrast to the previous domain, the tube here is in steady equilibrium if the magnetic field intensity is lower than the critical value $H_{cr}(r)$ depending on depth (see Fig. 3). If the magnetic field intensity is greater than the critical value, equilibrium of the magnetic tube becomes unstable, and the tube, deviating from its initial position due to a small perturbation, emerges upward with an increasing velocity due to convective-like instability development.

Lower than $209 \cdot 10^3$ km below the photosphere, the critical values of the magnetic field intensity exceed the maximum possible value determined by (9). Below this depth, there are ideal conditions for storage and generation of magnetic energy. The region below $209 \cdot 10^3$ km is termed as "the zone of action of the solar Dynamo" or, simpler, "the Dynamo zone " [6].

4. Emergence of magnetic fields from the Dynamo zone

The range of depths ($190 \cdot 10^3 \div 209 \cdot 10^3$ km) where the generated magnetic fields lose stability and float up to the photosphere if their intensity exceeds the critical level practically forms the majority of all nonstationary active solar processes [7].

The processes of the loss of stability and emergence of magnetic fields in the upper layers of the convective zone are nonlinear; therefore, their investigation requires numerical methods to solve system (1)-(7). At the initial time, the condition of equilibrium is set, the tube is assumed to be at rest; thus, only the relation between the field intensity and the critical value H_{cr} at the same depth determines the subsequent evolution of the tube.

If the initial magnetic field intensity of the tube is greater than the critical one, the tube equilibrium loses stability and the tube is floating up with an increasing velocity in the convective instability regime. Results of numerical modeling of tube emergence out of the Dynamo zone from various initial depths are shown in Fig. 4.

The temperature and density of the tube plasma decrease due to adiabatic extension of the emerging tube. There exists a special depth where the tube acceleration changes its sign and the tube begins to break, which depends on the initial parameters of the tube. The total buoyancy force is equal to zero at the point where the force changes its sign. This point plays the role of

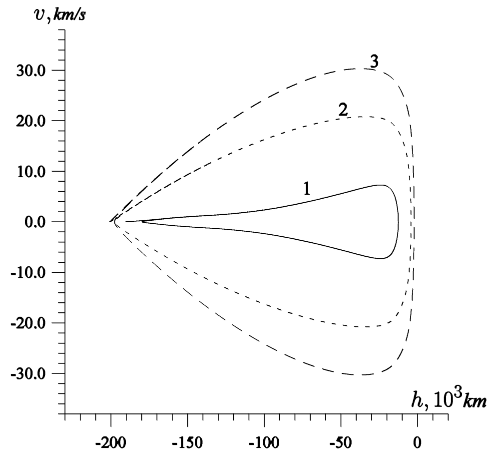

Figure 4. Tube emergence out of the Dynamo zone from various initial depths: ***1*** – $190 \cdot 10^3$ km; *2* – $200 \cdot 10^3$ km; ***3*** – $201 \cdot 10^3$ km

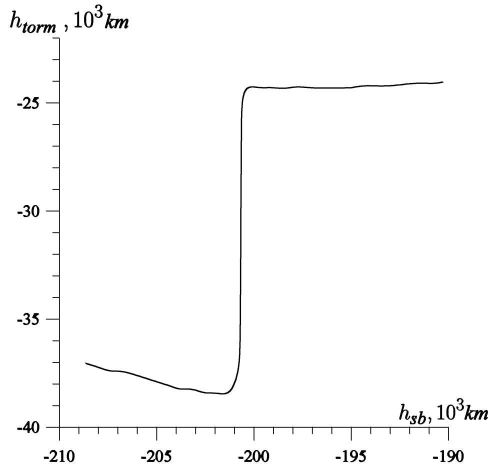

Figure 5. New position of the equilibrium point as a function of initial positions within the Dynamo zone

new equilibrium during emerging of the tube. The velocity of emergence is maximal at this point. As a result of tube breaking, the velocity of emergence changes its sign, and the tube passes through the point of maximum altitude and begins to move in the opposite direction. Since dissipative processes are omitted, the tube returns to the initial position (Fig. 4).

The initial position within the Dynamo zone (Fig. 5) unequivocally determines the new position of the equilibrium point due to imposing of the stability loss condition: $H(t=0) = H_{cr}(r)$**.** The new equilibrium positions are grouped in a narrow layer ($23 \cdot 10^3$km $\div$ $38 \cdot 10^3$km). The velocities of emergence of the magnetic tube at these depths are maximal, and the velocity can reach up to 40 km/s (Fig. 4). The velocity of emergence of the magnetic tube remains subsonic for all variants considered. Near the photosphere, the velocities of the magnetic tube,

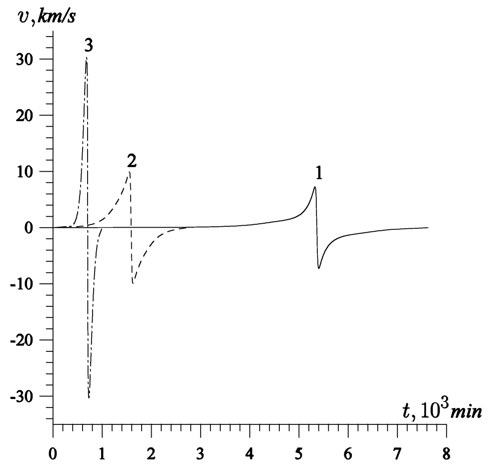

Figure 6. Velocity of emergence of the magnetic tube versus time.

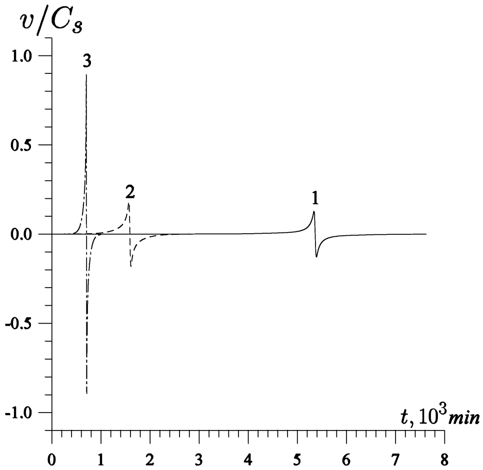

Figure 7. Velocities of the magnetic tube, measured in Mach numbers, versus time.

The initial depths of emergence: *1* – $190 \cdot 10^3$ km; *2* – $200 \cdot 10^3$km; *3* – $201 \cdot 10^3$ km

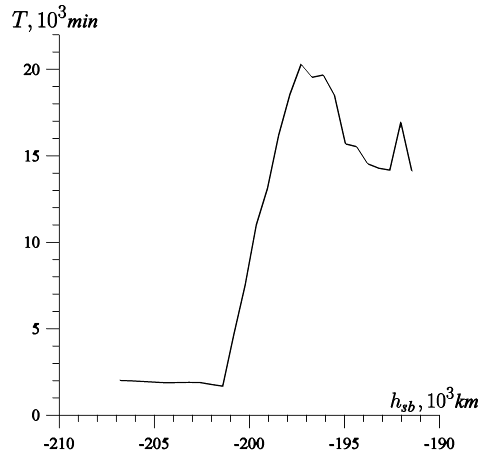

Figure 8. Full period of oscillations versus the initial depth of emergence.

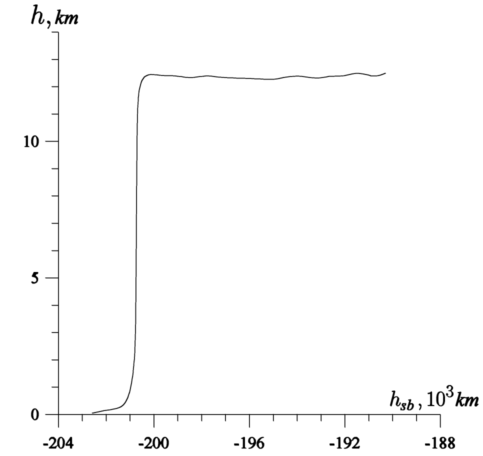

Figure 9. Direct transition of magnetic fields from the Dynamo zone into the solar atmosphere versus the initial depth of emergence.

measured in Mach numbers, increase nonlinearly. The magnetic tube generates acoustic waves, which penetrate through the photosphere in the solar atmosphere and transform into weak shock waves in the solar chromosphere [8].

The motion between the start position and the equilibrium point is characterised by a low velocity relative to rapid acceleration and by changing of the motion direction near the point of equilibrium (Figs. 6 and 7). The oscillations have the character of separated overshoots. The duration of overshoot motion is obviously less than the period of oscillations of the magnetic tube, and its characteristic scale is 60 minutes (1 hour) instead of the full period of oscillations whose scale is of the order of several days (Fig. 8). The depth of the maximal ascent, measured from the photosphere, increases with decreasing initial depth within the Dynamo zone. Below the depth of $203 \cdot 10^3$km, a direct transition of magnetic fields from the Dynamo zone into the

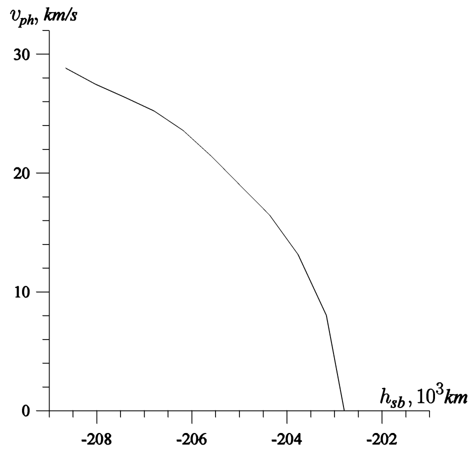

Figure 10. Velocity of emergence of magnetic fields at the photosphere level versus the initial depth of emergence within the Dynamo zone.

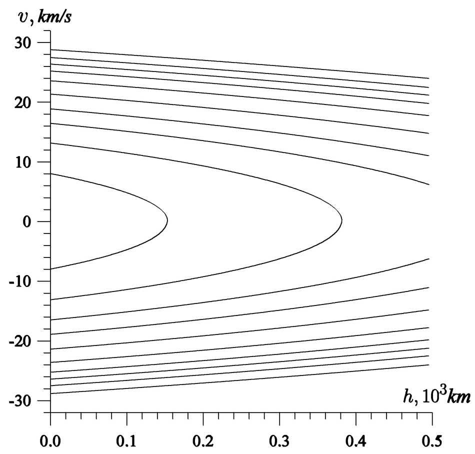

Figure 11. Magnetic tube velocity distributions over the altitude within the limits of the solar chromosphere.

solar atmosphere occurs (Fig. 9) [7]. The velocity of emergence of magnetic fields at the photosphere level increases nonlinearly up to hypersonic values (M ~ 4, Fig. 10) with increasing initial depth within the Dynamo zone. Figure 11 shows the magnetic tube velocity distributions over the altitude within the limits of the solar chromosphere. If the Mach number of the tube exceeds 2, then the velocity of emergence within the solar photosphere depends weakly on the altitude. This circumstance allows us to explain the formation of coronal jets (transients) at large altitudes within the solar atmosphere [9, 10].

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