INTRODUCTION

The structure and dynamics of the solar photosphere are very important for better understanding of basic solar phenomena such as atmospheric energy transport, turbulent diffusion of magnetic field or chaotic excitation of solar oscillations. The degree of photospheric gas ionization is quite small [1, 2]. It means that electrically charged particles in the photosphere can be considered as passive contaminants embedded in motions of the gas. Results of observations clearly show that the photospheric passive contaminants embedded in motions of the gas.

Results of observations clearly show that the photospheric charged particles in the photosphere can be considered as ionization is quite small [1, 2]. It means that electrically charged particles in the photosphere can be considered as passive contaminants embedded in motions of the gas. Results of observations clearly show that the photospheric passive contaminants embedded in motions of the gas.

In this report we consider possibility of formation of small-scale plasma structures in the turbulent flows of photospheric gas on the Sun and analyse dependence of their spectrum and intensity on height and the magnetic field strength. It was shown that in the height range 150–350 km the slope of the structure spectrum decreases with increasing the altitude. Under the weak magnetic field (B=±5 G), the intensity of plasma structures is unchanged with height. The increase in the magnetic field strength results in a rise in the structure intensity and in a decrease in the spectral slope.

PACS: 94.05.–a; 96.60.Mz; 47.27.–i

BASIC EQUATIONS AND RELATIONS

To describe turbulent mixing in the solar photosphere (which is a slow process) a three-fluid model can be used. Since the charged particles are passive contaminants, they have no influence on motions of neutral gas and the gas velocity field u(x, t) may be treated as a known function of position and time. The gas in the photosphere can be regarded as incompressible, \( \nabla u = 0 \). The behaviour of charged particles embedded in the gas flow can be described by the following set of equations [5]:

\[
\begin{align*}
\frac{\partial N_i}{\partial t} + \nabla (N_i \mathbf{v}_i) &= 0, \\
\tau_i^{-1} (\mathbf{v}_i - \mathbf{u}) &= q_i \mathbf{E} / m_i + \Omega_i (\mathbf{v}_i \times \mathbf{B}) - \mathbf{v}_i \cdot \nabla N_i,
\end{align*}
\]

where the variables are chosen as density \( N_i \) and velocity \( \mathbf{v}_i \) for each species \( s = \{ \text{ion}, \text{e} \} \), \( \tau_i \) is a characteristic time of charged particle collisions with neutrals, \( q_i = q_i B m_i c \) is the gyrofrequency, \( v_T \) is the thermal velocity, \( m_i \) is the particle mass, \( \mathbf{b} = \mathbf{B}/B \) is the unit vector along the magnetic field \( \mathbf{B} \), \( E \) is the electric field.

The way of derivation of \( \Psi(k, \omega) \), the spatiotemporal spectrum of \( \delta N = N_i / N_0 \) from Eqs. (1), (2) is described in [5]. Length-scales of random gas motions were restricted to the inertial range of turbulence. In this range turbulence is homogeneous and isotropic one with known statistical properties. The spectrum tensor of the field \( \mathbf{u} \) [4, 5, 8] is:

\[
\Phi_{\alpha \beta}(k, \omega) = D_{\alpha \beta}(k) \pi(k) E(k) \left[ 4 \pi^2 (1 + \omega \tau_i^2) \right]^{-1}, \quad k_0 < k < k_0 s,
\]

where \( D_{\alpha \beta} = \delta_{\alpha \beta} - k x_k / k^2 \) is the projection operator, \( \tau_i(k) = (k^2 + \epsilon / k^{1.5})^{-1} \) is the decay time of eddy with a length-scale \( k^2 \), \( E(k) = \epsilon k^{3 / 2} / 50 \) is the energy spectrum function, \( k_0 > 1 \) is the basic energy input scale, \( \epsilon(k) = (\nu L_0)^{1 / 3} k^{2 / 3} \) is the Kolmogorov dissipation wavenumber, \( \nu \) is the kinematic viscosity of the gas, \( \epsilon \) is the rate of turbulent energy dissipation per unit mass, the Kolmogorov constant \( C_1 \) is around 1.5 [9].

To obtain \( \Psi(k, \omega) \) the only electric field \( \mathbf{E} \) considered was that required to prevent charge separation (due to \( \mathbf{E} \) electrons tend to follow ions). In addition a contribution of the mode interaction in the process of plasma structure generation was taking into account through the coefficient of turbulent diffusion \( D_T \). For the structures with length-scales smaller than \( L_0 = N_0 / \sqrt{N_i} \), the length-scale of \( \sqrt{N_i} \), the following expression was derived [5]

\[
\Psi(k, \omega) = \left[ 4 \pi^2 (1 + \omega \tau_i^2) (1 + \omega \tau_i^2) \right]^{-1} \tau_i^{-1} Q(k) \left[ \frac{L_0}{k} \right]^{-1},
\]

where \( \tau_i = (D_0 k^2 + K k^2)^{-1} = (D_A k^2 + \epsilon k^{1.5})^{-1} \), \( D_A \) is the ambipolar diffusion coefficient, \( Q(k) = (|\mathbf{n} k^2| / \langle L_0 k^2 \rangle + (|\mathbf{b} k^2| / \langle L_0 k^2 \rangle)^2) C_1 k^{1 / 3} \), \( \mathbf{n} = N_0 n_i / V_0 \) is the unit along
\[ \nabla N_{\text{eff}} k_{3} = (eD_{3})^{3/4} \] is the Obukhov-Corrsin wavenumber known in the theory of passive scalar turbulent convection [9], in the present case it define the structure length-scale at which \( K_{x}=D_{x} \).

From Eq.(4) we can obtain the spatial spectrum of \( \delta N \)

\[ P_{x}(k) = \int_{-\infty}^{\infty} \Psi(k) d\omega = [4\pi(1 + \tau_{z}/\tau_{x})]^{1/2} \tau_{z} Q(k) . \quad (5) \]

Unlike [5] the inequality \( D_{x} \neq \nu \) was taken into account in the present case. Using Eq.(5) a mean-square level of \( \delta N \) in the range \( (k_{1}, k_{2}) \) may be calculated

\[ \langle \delta N^{2} \rangle = \int P_{x}(k) d\Phi = S((k_{1}/k_{2})^{1/3} - S((k_{1}/k_{2})^{1/3}) , \quad (6) \]

where

\[ S(x) = \frac{3}{8} \int L_{0}^{-1/2} x^{-1/2} (3 + \nu / \nu_{0}) x - 2/3 + \frac{3}{8} L_{0}^{-1/2} [\arctg x^{1/2} - (1 + \nu / \nu_{0}) / 2]^{1/2} \arctg (x(1 + \nu / \nu_{0}) / 2)^{1/2} + \frac{3}{8} \tau_{z} \Omega_{x}^{1/2} (2\ln(x(1 + \nu) - 1 + \nu) \ln(x(1 + \nu) / 2 + x(1 + \nu))) \]

here \( \nu = \nu_{x} / D_{x} \) is the diffusion Prandtl number.

The 1D spectrum of plasma structures in the turbulent photospheric flow that may be measured along \( z \)-direction may be obtained from Eq.(5) too:

\[ P_{x}(k_{z}) = \int_{0}^{L_{0}} k_{d} d\Phi = \alpha_{2} / 2 \int_{k_{z}}^{L_{0}} F(k) k^{-2} d\Phi . \quad (7) \]

where \( f(k_{z}, k_{x}, \theta) = k_{z}^{2} k_{x}^{2} \cos^{2} \theta + 2 k_{z}^{2} \sin^{2} \theta, \theta_{1} \) is the angle between \( n \) and \( b \), \( \theta_{2} \) between \( z \) and \( b \), \( k_{1}^{2} = k_{x}^{2} - k_{z}^{2}, k_{0}^{2} = k_{z}^{2} + k_{x}^{2}, f(k) = (1 + \nu / \nu_{0}) / 2 \int_{k_{z}}^{L_{0}} F(k) k^{-2} d\Phi \).

Eqs. (6), (7) give an opportunity to estimate changeability of small-scale plasma structures with changing the height and the magnetic field strength.

**CHANGEABILITY OF PHOTOSPHERIC PLASMA STRUCTURES**

To estimate changeability of the photospheric plasma structures we shall consider the case when \( n \) and \( b \) are in vertical direction, while the possible measurement direction \( z \) is horizontal. Then \( \theta_{1} = \theta_{2} = \pi / 2 \) and Eq.(7) takes the form

\[ P_{x}(k_{z}) = \alpha_{2} / 2 \int_{k_{z}}^{L_{0}} F(k) k^{-2} d\Phi . \quad (8) \]

The plasma structures are analysed near heights of 150 and 350 km. The outer scale of turbulence \( k_{0}^{-1} = L_{0} = 940 \text{ km} \) is the same for both heights [6], and we suppose that \( L_{0} = \alpha_{0} \).

The mean gas velocity on \( L_{0} \) is \( u_{0} \), and then \( \varepsilon = u_{0}^{2} / \nu_{0} \). Parameters of the photosphere taken from [1,2,6] together with the calculated values of \( k_{0}^{-1} \) and \( k_{0}^{-1} \) are presented in Table 1. Characteristics of plasma structures calculated with use of Eqs.(6), (8) and the value \( \tau_{z} \Omega_{x} \) are shown in Table 2 (\( \gamma \) is the power index when \( P_{x}(k_{z}) \) was approximated by a simple power law \( k_{z}^{-\gamma} \)).

**Table 1. Parameters of the solar photosphere**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( h=150 \text{ km} )</th>
<th>( h=350 \text{ km} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T ) (K)</td>
<td>5180</td>
<td>4670</td>
</tr>
<tr>
<td>( N_{\text{m}} ) (m(^{-3}))</td>
<td>5.05 \times 10^{22}</td>
<td>1.01 \times 10^{22}</td>
</tr>
<tr>
<td>( N_{\nu} ) (m(^{-3}))</td>
<td>6.04 \times 10^{18}</td>
<td>1.12 \times 10^{18}</td>
</tr>
<tr>
<td>( m_{0} ) (a.u.m.)</td>
<td>25</td>
<td>26.3</td>
</tr>
<tr>
<td>( u_{0} ) (km/s)</td>
<td>1.1</td>
<td>2.05</td>
</tr>
<tr>
<td>( k_{0}^{-1} ) (cm)</td>
<td>10.4</td>
<td>20</td>
</tr>
<tr>
<td>( k_{\nu}^{-1} ) (cm)</td>
<td>1.33</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Fig.1. Spectrum \( P_{x}(k_{z}) \) at \( h=150 \text{ km} \)**

**Fig.2. Spectrum \( P_{x}(k_{z}) \) at \( h=350 \text{ km} \)**
Table 2. Characteristics of plasma structures

<table>
<thead>
<tr>
<th>h, km</th>
<th>B, G</th>
<th>$\tau\Omega$</th>
<th>$&lt;\delta N^2&gt;^{1/2}$, %</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>5</td>
<td>1.98x10^{-3}</td>
<td>2.5</td>
<td>2.22</td>
</tr>
<tr>
<td>150</td>
<td>250</td>
<td>9.9x10^{-4}</td>
<td>2.6</td>
<td>1.41</td>
</tr>
<tr>
<td>350</td>
<td>5</td>
<td>9.4x10^{-5}</td>
<td>2.5</td>
<td>1.94</td>
</tr>
<tr>
<td>350</td>
<td>250</td>
<td>4.7x10^{-3}</td>
<td>2.8</td>
<td>1.23</td>
</tr>
</tbody>
</table>

CONCLUSIONS

An analytic expression for the 1D spectrum of the plasma structures in a turbulent flow of photospheric gas Eq.(7) as well as the formula for estimation of the RMS level of their intensity Eq.(6) were presented in the report.

Using the expressions it was shown that in the height range 150–350 km the slope of the structure spectrum decreases with increasing the altitude. Under the weak magnetic field ($B=5$ G), the intensity of plasma structures is unchanged with height. The increase in the magnetic field strength results in a rise in the structure intensity and in a decrease in the spectral slope.

The obtained results seem to be important for better understanding of basic solar phenomena, such as generation of the random component of magnetic field or chaotic excitation of solar oscillations.

REFERENCES