STATISTICAL MODEL OF SMALL SCALE DISCRETE STRUCTURE OF MAGNETOPLASMA IN ACTIVE REGIONS OF THE SUN

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Abstract. A possible statistical model of the solar magnetoplasma in solar active regions consisting of a totality of small-scale current vortex plasma elements ('subgranules') is discussed. Some results are given which naturally follow from such a model: the small value of effective conductivity in the macro-structures of the plasma (hence, the possibility of a greater mobility and changeability of field and plasma for a short time), the formation of filamentary-structural elements, the oscillating regime of the magnetoplasma in an active region. A principal scheme is given of the experiment on a solar magnetograph with very high resolution, which is able to reveal discrete fields of the subgranules. The dispersion equation is derived for macro-magnetic oscillations of the statistical ensemble of magnetized subgranules. The possibility is noted to reveal macro-magnetic oscillations and waves during observations of low-frequency modulation in the solar radio-emission. It is shown that at solar radioburst propagation in the corona, (according to the model under consideration, some regularly located plasma inhomogeneities should be present in the active region) Bragg's diffraction takes place. Typical properties of complex radiobursts may be received (extreme narrowness of the band, short lifetime, directivity).

Recent observations of magnetic fields on the Sun have shown (Severny, 1965; Beckers, 1968), that the solar magnetoplasma (where $8\pi/H^2 \times (P + \frac{1}{2}\varrho u_\perp^2) \ll 1$) is characterized by a small-scale ($\simeq 3$–5×10^7 cm) structure. This fundamental property of the solar magnetoplasma inherent in the terrestrial and cosmic plasma as well, determines the main macroscopic characteristics of solar activity phenomena. With a large scale characteristic of solar phenomena, the great dynamic behavior of the activity in the magnetized plasma is incompatible with the practically infinite conductivity of the solar atmosphere. The stable filamentary structure of the cosmic plasma, where a longitudinal section is much greater than a transverse one, cannot be explained with the theory of stability of a laboratory plasma (Kadomzev, 1963).

A number of other peculiarities are observed in solar activity phenomena, and for their explanation some independent hypothesis is necessary. These peculiarities are: variations of the magnetic flux balance in an active region; the problem of transport of energy, field and matter in the magnetized solar plasma; special features of the spectra of flares and prominences; a long time-scale generation of subthermal particles in active regions; two component structure of magnetic fields in the spots, and others.

In our paper (Mogilevsky, 1968) an attempt has been made to show that the above mentioned properties of the solar magnetoplasma may result from the observed fine structure of the field and plasma. We try to give a description of the magnetoplasma as a statistical ensemble of discrete small-scale elements.

In theoretical works by Ermakov (1969, 1970) some static properties of individual

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plasma clouds with current vortices have been considered. He has theoretically proved the possibility of the existence of discrete excited elements of plasma with their own magnetic fields in the potential field, those are known as 'subgranules' or 'gyrons'. The analytical presentation of field and plasma during the process of the streamlining of the element (without a boundary discontinuity) has been obtained for a spheroid. The geometry of the element may be different as well. Such a solution for the stable subgranules is possible, when there is minimum energy of a system with a current vortex, i.e. a spontaneous appearance of subgranules may occur. However, aside from a 'diamagnetic' model, a model with a field discontinuity on the surface, i.e. that with the boundary current, is possible. A stable axi-symmetric subgranule of that type may be estimated. At least two types of subgranule models possibly exist: a mixed model and such a type of model in which a transformation of a 'diamagnetic' one into a 'paramagnetic' and that of the reverse action, may occur. The determination of models is done on the basis of corresponding experimental data.

The problem of the mechanism and place of generation of individual subgranular decay has not yet been formulated. However the properties of a statistical ensemble of interacting 'collisionless' subgranules in the external homogeneous (or quasi-homogeneous) potential field **H** may be discussed. For the description of that anisotropic statistical ensemble a distribution function $f(q, v)$ in phase space (q, v) may be obtained from Vlasov's (1966) kinetic equation for space-limited structures:

$$\frac{\partial f}{\partial t} + \operatorname{div}_q vf + \operatorname{div}_v \langle \dot{v} \rangle f = 0 \tag{1}$$

together with an integral equation

$$\iint f(q, v, t)\, dq\, dv = F(\theta_m, \varphi_m, H), \tag{2}$$

where θ is the parameter of the energy of sporadic subgranular movement (the 'magnetic temperature');

$\varphi_m(q) = \int f(q, v)\, dv$ is the space concentration of subgranules.

In the most simple axi-symmetric case (Z is the axis of symmetry) the distribution function is:

$$f = A\varphi_m(z - ut) \exp\left(-\frac{\varepsilon_m}{\theta_m} + \alpha I \right), \tag{3}$$

$$I = r\left(u + \frac{e}{mc} A_\varphi \right) \tag{4}$$

where A and α are constants, ε_m is the density of the subgranular kinetic energy, A_φ is the component of the vector potential of the magnetic field, e and m are the total charge of polarization and subgranular mass, u is the macrovelocity of the ensemble. Knowing the distribution function macro properties of that plasma may be determined.

So, for example, the transference of the magnetic field in the active region from the photosphere into the chromosphere and the corona may be the result of subgranular diffusion. It is possible to estimate the value of the effective conductivity in the macro volume ($V \gg V_s$ the subgranular volume)

$$G_{ef} = G_o R_m^{-1} \tag{5}$$

R_m is Reinold's magnetic number (for the solar atmosphere it is $\gtrsim 10^4$–10^5). Physically it means that the conductivity is sharply reduced in the macro volume due to the frequent scattering of electrons in the external subgranular fields, while the common values of the plasma conductivity inside the subgranules are not changed. The sharp difference between turbulent and molecular viscosity may be an analog to the above-mentioned effect. Hence, during macro events in the solar magnetoplasma with discrete magnetized subgranules, the time scale of the field dynamics will be essentially different from that which it should be according to the classical values of the plasma conductivity. It is shown in (Mogilevsky 1968) that if the subgranular model considered is used, the above mentioned characteristic properties of the solar magnetoplasma may be explained (at least qualitatively) from a *unified point of view*. In our work (Mogilevsky *et al.*, 1968) the data and our explanation of the observed quasi-pi-component of Zeeman's splitting in the sunspot umbras testify to the correctness of the model. The two component model of the field and the plasma of the spots proves the truth of that idea as well (Mogilevsky *et al.*, 1968; Obridko, 1968).

At present the urgent necessity appears to be to obtain direct experimental data not only about the existence of discrete small-scale structures, but to determine characteristic parameters of a subgranule. There are great difficulties in carrying out field measurements for elements, the characteristic dimensions of which are of the order of the spatial resolution of modern solar telescopes. However, we may try to undertake such a task, using a special method of observation by means of our solar magnetograph. As a matter of fact the idea of statistical Fourier spectrometry may be used. Instead of the usual optical light modulator with an ADP crystal, a light modulator employing photo elasticity is used. In the water or crystal of the modulator a frequency-operated ultrasonic space grating is generated by a piezocrystal. The phase difference Γ of the wave λ with an optical path in the modulator $1' = 1\Delta n$, where Δn is the difference arising from the refraction constant, due to photo elasticity (it depends on the modulation wave phase), will be

$$\Gamma = \frac{2\pi}{\lambda} 1\Delta n(t). \tag{6}$$

Evidently, it is possible to select such a condition in the modulator, when the maximum $\Gamma_m = \lambda/4$. Then along the entrance slit of the magnetograph a modifying polarizing 'mosaic' will appear. A number of strips and their dimensions may be changed by frequency variations in the modulator. For example for the ultrasonic frequency $\Omega = 10^7$ cps the strip width (resolving capacity) of the IZMIRAN tower telescope is $0\overset{''}{.}1$. If the magnetic field along the whole entrance slit is homogeneous, the magnitude of a magnetic field signal would not depend on the modulator frequency. If the slit crosses, for example, N discrete magnetic elements, then the strongest signal will be when $N = 2K(d/\Lambda)$, where d is the modulator height Λ is the length of the ultrasound wave, and K is a constant. Thus, the light is modulated in even harmonics Ω, it is changed in amplitude, and the number of strips in the modulator corresponds to the magnetic element number on the slit. Using Fourier analysis for the field intensity change during the frequency variation of Ω modulation, a motion about the average picture of the field distribution within the limits of similar discrete subgranules is formed. The disturbing influence of the atmosphere (vibration) may be reduced by the following:

(a) by means of putting into operation the phase detecting of the magnetic field signal, synchronized with the frequency of the modulator Ω and carrying out measurements on both frequencies of modulation (2Ω and 4Ω).

(b) carrying out some additional measurements (synchronous with the magnetograph) on the same spectrograph in a neighboring nonmagnetic line of the atmosphere scintillations with leading in its spectrum (through the reverse Fourier filter) in the magnetograph channel.

The estimations show sufficient effectiveness of such a method.

Important information about properties of the considered statistical model of the magnetoplasma may be obtained from the analysis of its wave characteristics. Since a definite value of the magnetic moment $\boldsymbol{\mu}$ is connected with discrete subgranules, some space regulation of the magnetic moments arises in the quasihomogeneous external potential magnetic field $\mathbf{H}_0$. This effect is broken by disturbances of individual subgranules. These disturbances may be of a non-coherent character, then they determine the macromagnetic noise (numerically it is characterized by parameter θ_m). They also may be of a coherent character as well, resulting in macromagnetic waves. For their description a mathematical formalism of a phenomenological description of spin waves may be used (Achiezer *et al.*, 1967). In our case the magnetic energy ω is in a single volume $V_0 > V_s$

$$\omega = F\left(\boldsymbol{\mu}, \frac{\partial \bar{\mu}}{\partial q}\right) + \frac{1}{8\pi}(\bar{H}^m)^2 - \bar{\mu}\bar{H}_0, \tag{7}$$

where F is potential energy of subgranular interaction, $\bar{H}^m = \langle \sum_i \bar{H}_i^e \rangle$ is the magnetic field of the subgranular ensemble, averaging in Volume V_0, $\bar{\mu}$ is the average magnetic moment in a volume V_0. The time variations of the magnetic moment are described by a vector equation

$$\frac{\partial \bar{\mu}}{\partial t} = C[\bar{\mu} \times \tilde{H}], \tag{8}$$

where C is a constant proportionality factor, and the effective magnetic field $\tilde{H}$ is determined by a functional derivative

$$\tilde{H} = -\frac{\partial \omega}{\partial \mu}. \tag{9}$$

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Equation (8) may be linearized, if the following approximate expressions are used for the magnetic moment $\bar{\mu}$ and the field $\bar{H}^m$

$$\begin{aligned}\bar{\mu}(q,t) &= \bar{\mu}_0 + \bar{m}(q,t),\\ \bar{H}^m(q,t) &= \bar{H}^m_0 + \bar{h}(q,t),\end{aligned} \tag{10}$$

where $\bar{\mu}_0$ and $\bar{H}^m_0$ are the corresponding equilibrium values, around them occur regular variations of the moment and the magnetoplasma field, considered here. Then from (8) we shall obtain a linearized equation

$$\frac{\partial\bar{\mu}}{\partial t} = C[\bar{\mu}_0 \times \tilde{H}], \tag{11}$$

where

$$\tilde{H} = \bar{h} - \beta\bar{m} + \alpha\Delta\bar{m}, \tag{12}$$

β and α are constants.

For low frequencies (less than the ion gyrofrequency w_i) Maxwell's equations for $\bar{h}$ and $\bar{m}$ will be

$$\begin{aligned}&\operatorname{rot}\bar{h} = 0\\ &\operatorname{div}\bar{h} = 4\pi \operatorname{div}\bar{m}.\end{aligned} \tag{13}$$

In the common case, using Fourier's presentations* of vectors h and m we shall obtain

$$\begin{aligned}\bar{m} &= \int m_0 e^{i(kq - wt)} \mathrm{d}w\\ \bar{h} &= \int \bar{h}_0 e^{i(kq - wt)} \mathrm{d}w.\end{aligned} \tag{14}$$

Then the Equations (13) give

$$\begin{aligned}\bar{k} \times \bar{h} &= 0\\ \bar{k}\bar{h} &= -4\pi\bar{k}\bar{m},\end{aligned} \tag{15}$$

or

$$\bar{h}(kw) = -ik\psi(kw) \tag{16}$$

where ψ is the Fourier component of a magnetic potential. On the other hand, using (14) in (8), we obtain

$$\bar{m}_i(kw) = \chi(kw)\,\bar{h}_i(kw), \tag{17}$$

where χ is a tensor of the oscillating magnetic receptivity. Using (16) in (17), we obtain

$$\{k^2 + 4\pi k_i k_j \chi(kw)\}\,\psi(kw) = 0 \tag{18}$$

or

$$\{k^2 + 4\pi k_i k_j \chi(kw)\} = 0. \tag{19}$$

Equation (19) represents the dispersion law of macro-magnetic waves, showing the

* In our case this expression may be confined by a finite row of Fourier harmonics.

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connection between the frequency w and the wave vector k. Here it is important that for low frequencies w (where $w < w_i$) a dependence of χ (or μ) on frequency appears. And this result is important and may give the essential effects in wave propagation of the considered discrete elementary magnetoplasma (for example, the interaction between the macromagnetic and the low frequency plasma waves). Discovery and research of these low frequency oscillations ($10^{-1} < w < 10^3$ cps) in the solar plasma would give some new information about its structure.

The discrete structure of the magnetoplasma may bring up a number of interesting peculiarities in the metric and decametric radiowave propagation through the corona*. Let us assume that the subgranular structure exists in the active regions of the corona as well. Then we shall consider the radiowave propagation in frequencies $w \lesssim w_0$, where w_0 is the plasma frequency (the nature of these wave generations is not important in this case). A relatively regular space distribution of plasma clouds should be as a space diffraction grating. During the radiowave propagation with an angle to a chain of subgranules (the angle corresponds to Bragg's diffraction angle) the radioemission intensity of a wave λ in the first side maximum will be determined by an expression:

$$I_{-1} = I_0 \sin^2 \frac{\pi \Delta n l}{\lambda}, \tag{11}$$

where Δn is the difference of the refraction index in the unit path, l is the optical wave in the 'grating'. Let us take an example for 25 Mc/s (the characteristic dimensions of subgranules in the radiofrequency accepted by us) the deviation angle will $\sim 18°$ and $\sim 10\%$ of the emission will be directed to this side. A small space angle of deviation, determined by the length of a wave and 'grating' parameters causes a noticeable effect due to the static 'grating'. 'Statics of the grating' comes true because of the fact that macrowaves propagate with a velocity $V \lesssim V_A$, that is much lower than the group velocity of radiowaves in the corona. However, relatively long radio bursts may drift (to one or the other side), passing through the swinging space 'grating'. Those bursts are actually observed (Ellis, 1969; Markeev and Chernov, 1970). The narrow strip, the drift velocity and the burst duration will be more distinct for low frequencies than for high ones. This effect is actually revealed if we compare similar events on frequencies in the region of both 200 MHz and $\simeq 40$ MHz (Ellis, 1969; Markeev and Chernov, 1970).

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* As is seen from estimation, for the shorter radiowaves the effect is insignificant.

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Discussion

Sweet: What is the size of the subgranules, and how could they influence the non-radiative flux from the photosphere?

Mogilevsky: In order to determine the subgranule sizes it is necessary to assume a definite mechanism of dissipation for the current fields of subgranules. For admitted assumptions, estimations give the subgranule size value of the order of hundreds of km. It is close to the observed sizes of 'magnetic dots'.

If the magnetic field gradient exists then according to a model adopted by us the diffusion of subgranules and their macro-oscillations determine a non-radiative flux of the photosphere. This influence is determined with the variations of the plasma temperature and density which are put into the 'background' plasma by the subgranules.