Currents of non-uniformities in solar atmosphere

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Non-uniformities of plasma and magnetic field are known to cause electric currents in plasma. Electron density gradient causes diffusion current, electron temperature gradient — thermocurrent, gradient of magnetic field module — gradient current, curvature of magnetic field lines — centrifugal current. Being independent of electric field, the currents of non-uniformities may act as extraneous to cause charge separation and electric field in plasma. In cosmos, the currents of non-uniformities were observed; in particular, gradient and centrifugal currents — in magnetosphere, diffusion one — in a comet coma and in artificial plasma cloud. On present work, the gradient current was investigated more fully than earlier. Two unknown components, parallel and perpendicular to magnetic field were found. The equation for gradient current density was obtained. We compared the theoretical densities of currents of non-uniformities (with usage of electron pressure and corresponding gradients) with measured current densities (calculated as rotor of magnetic field) for sun photosphere. It follows from the comparison that the currents of non-uniformities play important, may be main, role in measured local current in photosphere. It is necessary to consider in electromagnetic models.

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Introduction

It is commonly believed that magnetic field of Sun is generated by convective motions of plasma inside the star. The field, together with the electric currents being the source of the field, rises to upper layers of Sun, its atmosphere. There, the field gives birth the observed phenomena of solar activity such as spots, active regions, flares, and mass ejections. The region of generation and the region of observation very differ on the plasma parameters, in particular on plasma density. This leads to a difference in the values of electron magnetization, $\beta = \omega/\nu$. (Here ω is the gyromagnetic frequency, ν is the frequency of isotropization collisions.) In convective zone of the Sun (region of generation) $\beta \approx 0$, at the photosphere level $\beta \approx 1$, at chromosphere β amounts to hundreds, and it is still larger in corona. Because of very different magnetization one should apply different approaches for modeling electrical processes in these media. Inside the Sun the conductivity may be regarded as scalar; the conductivity current be collinear to electric field. This is namely the basis of standard magmeto-hydrodynamics (MHD) models. In the star atmosphere the plasma is anisotropic. In this case, the conductivity current has tree components, — parallel (magnetic field-aligned) current, Hall current, and perpendicular (Pederson) current. It is obvious that the standard MHD model being applied to the anisotropic plasma of star atmosphere cannot bring a true result. To take into account the anisotropy, the simplest approach now is used: the current is assumed to be parallel to the magnetic field (free-force approach).

Plasma of solar atmosphere is very non-uniform medium; this appears in gradients of density, temperature and non-uniform magnetic fields. In such the plasma, currents of non-uniformities — diffusion, thermocurrent, and gradient current — may play an essential role. At present we may see the tendency to take partly into account these currents. Electromagnetic plasma models have been published with having applied Hall current [1, 2], diffusion current [3], thermocurrent [4], and with applying a number of currents [5, 6].

Distribution of magnetic fields and currents in solar atmosphere is a hot point of solar physics. The current density in photosphere may be deduced by means of magnetic field rotor; or the presence of the currents may be found on deviation of the field from so-called potential field. Structure of magnetic field in solar atmosphere may be revealed on soft X-rays and Hα images, and on extrapolation of the field being measured on photosphere level.

It is known that vertical magnetic field-aligned currents with the value up to 10^{12} A flow upward and downward in a sunspot [7]. It turned out that these currents, being close together, are an universal property of the spot, and moreover they cover a large share of an active region [8, 9, 10, 11, 12, 13, 14]. A little is known on nature of the currents. In electromagnetic models they are simply postulated as initial conditions [15, 16].

It was found that twisted magnetic flux tubes represent typical phenomenon. Another observation relatively the tubes — they expand slightly with increasing the height in atmosphere [9, 10, 11, 17, 18]. It follows from Maxwell equations that both the phenomena arise because of electric currents being present in the tube. The twist arises due to longitudinal currents, the absence of tube expanding appears due to currents embracing the tube, — this is akin to a solenoid current encircling the magnetic field of constant diameter.

It is difficult to study horizontal currents by a direct

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method, by means of calculating the magnetic field rotor. Sparse papers show that these currents take place in active regions [19]. Accurate analysis of magnetic field strength at some heights over photosphere was fulfilled in [20]. The field in temperature minimum zone was found being noticeably larger than in middle photosphere. This points out at existence of horizontal currents in there.

Studying the currents in active regions is of particular interest in the context of flare activity. There are theoretical and experimental evidences that solar flares are energized by the magnetic field in active region. At one of first theory [21, 22], a loop of electric current plays main role in a flare. A part of the loop is situated beneath photosphere, and another part — in solar atmosphere. The loop carries the current up to 10^{12} A. The flare begins when suddenly disruption of the current happens in atmospheric part of the loop. In the place of disruption a large electrical voltage, say 10^{10} V, appears. On theory, the place of energy release has the dissipation factor $\mathbf{j} \cdot \mathbf{E}$ (a scalar product) being positive. It is important that the place of energy release has very smaller volume than the place where the magnetic energy was stored.

In general, such the scenario proves be true in later observations. The sites of flares are linked with the places where the currents are concentrated at photosphere level, in other words, — with the places of non-potential magnetic field [20, 23, 24]. Some studies show that flare is coupled with two magnetic field loops [9, 25, 26] or with several loops from which only two play main role [11, 17]. Both loops carry electric currents, in particular parallel currents. One, a high-lying loop, exists long before the flare. Certainly this loop accumulates magnetic energy. The onset of the flare correlates with the emergence of a smaller low-lying loop. There are observations that the flare begins in the place where the loops interact — X-ray source may be seen here. Then the flare process spreads along the loops attaining their footpoints. The flare energy is about 5–10% of stored magnetic energy; the high-lying loop is seen to survive after the flare. Maximal magnetic field strength was noticed in peak of the flare [10, 20]. The magnetic fields and electric currents often appear to simplify their structure after the flare [27].

Magnetic fields are everywhere observed in galaxies. In spirals, orientation of the field are often (not always) parallel to arms: the field is of the values 3–10 μG [28]. As mentioned for a long time, magnetization is very high for all kinds of interstellar medium. Electron magnetization in cold interstellar gas, zone H1, ($T = 30 - 70°K$, hydrogen concentration is of 20–40 cm^{-3}) amounts to 10^7, electron magnetization in coronal ionized gas is of 10^{11} [29]. Magnetic field with the strength of 22 mG was found in the corona of the circumstellar disk of young stellar object at the distance 40 a.u. from the object [30]. Even in that, most dense medium, magnetization is not smaller than 200.

In contrast to stars, magnetic field in intragalactic medium is observed in the same place where being generated. Because the magnetization is very high there, the electromagnetic theory should be from the very outset formulated on base of anisotropic conductivity. This relates fully to the magnetic field in clusters of galaxies.

In Earth magnetosphere, at the latitude of some ten thousand kilometers, a ring current flows; it was directly detected in flyby of rocket [31]. Magnetic storm arises when a cloud of coronal plasma enters inside Earth's magnetic field and this causes increase in this magnetosphere current. It is well known that the magnetosphere current represents, on its nature, a sum of gradient and centrifugal currents. Notice, the magnetization in the magnetosphere is very high. The same conditions — the gradient of magnetic field module, the curvature of magnetic lines, and high magnetization take place in stellar atmosphere. Hence, one should expect that the gradient and centrifugal currents are present there; and the task arises — how much large are the currents and what is their role in electromagnetic phenomena?

Plasma currents arising from non-uniformities

A current of charged particles arises due to fields, non-uniformity, and anisotropy of medium [32]. Let us list the currents what were detected in cosmic plasmas:

1. Conductivity current. It is caused by electric field.

2. Diffusion current. It is due to gradient of charged particle density.

3. Thermocurrent. This current is also named as "thermodiffusion" current, "thermoelectric effect" and "Nernst effect" [4]. This current is due to gradient of charged particle temperature provided that collision frequency has some dependence of velocity of charged particles [33]. In the absence of magnetic field the nature of diffusion and thermocurrents are quite similar to diffusion and thermodiffusion in gas. In presence of magnetic field both the currents (more precisely their Hall components) are often called as "diamagnetic effect" because this effect leads to weakening of magnetic field in spatially restricted plasma. In cosmic conditions diamagnetic effect was confidently observed in comet coma [34] and in the plasma cloud made by explosion of metal in ionosphere [35].

4. Gradient current. It arises when the module of magnetic field changes in space.

5. Centrifugal current. It arises in magnetic field with curved lines.

These currents arise due to non-uniformities of potential, plasma, and magnetic field. We will name these currents as the currents of non-uniformities.

In some cases, another currents may be essential, for example, the current of entrainment of electrons by photons and currents caused by waves.

A current in plasma is calculated in different ways depending of the parameter λ/l, λ is the free path (or giroradius) of the particle, l is the typical plasma dimension. For the case of finite λ/l, each the current must

be calculated for given plasma geometry, magnetic field, etc. For tokomaks, the current dependent of plasma and temperature gradients, — named "bootstrap current", has been calculated [36]. In cosmic plasma the relation $\lambda/l \approx 0$ takes place as a rule. In this case the currents are roughly defined by local plasma conditions and universal equations may be obtained for density of different currents. But in some cases the currents are non-local: the current associated with particles accelerated in flares, for example.

The total current is the vector sum of currents of the different kinds, each for electrons and ions:

$$\mathbf{j} = \mathbf{j}_E + \mathbf{j}_D + \mathbf{j}_T + \mathbf{j}_{\nabla B} + \mathbf{j}_R +$$
$$+ \text{ similar currents for ions } + \text{ another currents. (1)}$$

Here $\mathbf{j}_E$, $\mathbf{j}_D$, $\mathbf{j}_T$, $\mathbf{j}_{\nabla B}$, and $\mathbf{j}_R$ designates the density of conductivity, diffusion, thermocurrent, gradient, and centrifugal current, accordingly. It is natural, that the density of the total current simultaneously satisfies to Maxwell equation thereby making it possible measuring the current through magnetic field rotor.

From the available literature it appears that equations for density of the conductivity, diffusion, and thermocurrents are known for a wide range of plasma parameters [33, 37]. At the presence of a magnetic field each the current has three components. For example, components of the conductivity current are directed on the mutually perpendicular vectors $\mathbf{E}_\parallel$, $\mathbf{E}_\perp$, and $\mathbf{E} \times \mathbf{B}$ — parallel, perpendicular, and Hall component, respectively. The components of diffusion and thermocurrent have same names.

The gradient of magnetic field module, ∇B, is an axial vector. Generally, it can be oriented with any way concerning the magnetic field in the point. This allows decomposing the gradient into two components $\nabla_\parallel B$ and $\nabla_\perp B$, being parallel and perpendicular to the magnetic field, Fig. 1(a). The mutually perpendicular vectors $\nabla_\parallel B$, $\nabla_\perp B$, and $\mathbf{B} \times \nabla B$ define the coordinate axes Z, X, and Y, respectively. When speaking about the gradient current, one keeps in mind its component, which being directed at the vector $\mathbf{B} \times \nabla B$, see Ref. [38], for example. The formula for this "Hall" component is deduced and applied for a case of infinite magnetization — collisionless plasma. The origin of this component is presented on Fig. 2(b). The Hall gradient current is well known on observations of electric phenomena in plasmas. As mention above, this current creates, together with the centrifugal current, the ring current in magnetosphere. It is likely assume, that there are not one, but three components of the gradient current. Two unknown components will be considered as directed on the vectors $\nabla_\parallel B$ and $\nabla_\perp B$ and be named as parallel and perpendicular components, respectively.

Parallel component of gradient current

Let us show that the parallel component of the gradient current does exist, and estimate its value. In the beginning of the consideration we will follow to historically developed scheme, for example, see [38].

In magnetic field a charged particle gyrates. This movement may be characterized by a magnetic moment

$$\mu = mV_\perp^2/2B = \varepsilon_\perp/B. \quad (2)$$

Here $V_\perp$ is the perpendicular (to the field) component of velocity, $\varepsilon_\perp$ is the perpendicular kinetic energy, m is the mass of the particle.

For researching the parallel component it is convenient to take the field in which the gradient is parallel to the field itself, Fig. 1(b) and Fig. 3. As known, in this field the particle undergoes to the mean Lorentz force

$$\langle f \rangle = -\mu \nabla B. \quad (3)$$

Irrespective of the sign of the charge the force is directed to weaker field, see Fig. 3.

As the particle gyrates, the parallel component of velocity increases, and the perpendicular one decreases. Total velocity of the particle remains, because kinetic energy of the particle does not change in interaction with a magnetic field. Thus there is ejection of the charged particles and thereby all the plasma into the weaker field area. The ejection of plasma is essential for very and fully ionized plasma, — this is chromosphere and corona as applied to the Sun. The magnetic field with $\nabla B \parallel \mathbf{B}$ is used in the devices for magnetic confinement of plasma — magnetic bottles. Here we complete citing the historical consideration.

Let's continue the consideration to show that the longitudinal Lorentz force causes an electric current. We will consider weakly ionized plasma, i.e., in which the electron-neutral and ion-neutral collisions prevail over the collisions between the charged particles. Also assume a large, but finite magnetization — that is a large enough magnetic field.

Let observe the motion of the particle between successive collisions. After a collision all the directions of the velocity are equiprobable; the mean parallel velocity is zero. Due to action of parallel Lorentz force there is acceleration

$$a = \langle f \rangle/m = \mu \nabla B/m = -V_\perp^2 \nabla B/2B. \quad (4)$$

Because the electron velocity is larger than the ions, it is seen from Eq. (4) that there is the preferred flow of electrons, that is a current. To evaluate this current, collisions should be involved. Due to the parallel Lorentz force, directional velocity arises between collisions. As result of next collision, this directional velocity again disappears. To the time $t = 1/\nu$ (mean time between collisions), the directional velocity attains the value

$$a/\nu = -\mu \nabla B/m\nu. \quad (5)$$

The mean (drift) velocity may be written as the half of that:

$$V_{dr} = -\mu\nabla B/2m\nu. \qquad (6)$$

For current density the standard formula may be written:

$$\mathbf{j} = qN\mathbf{V}_{dr}. \qquad (7)$$

Here q is the charge, N is the concentration of charged particles of given sort. Substituting the need parameters in Eq. (7), the parallel current density may be expressed, on module

$$j_{\parallel} = \frac{qP\nabla B}{2\nu mB}. \qquad (8)$$

Here $mV_{\perp}^2 N/2 \equiv P_{\perp} = P$, $P_{\perp}$ is the perpendicular pressure, P is the pressure of the charged particles.

Let's compare the parallel currents for electrons and ions assuming their temperatures being same. Transport cross sections for the ion-atom collisions exceed them for the electron-atom ones by some times. Accepting, nevertheless, for simplification, these cross sections being identical, we receive from Eq. (8) the approximate dependence of the parallel current on the mass of the particle

$$j_{\parallel} \propto 1/\nu m \propto m^{-1/2} \qquad (9)$$

The density of the electron current is very greater than the ion's. This feature is explicitly shown on Fig. 3. The dependence expressed by Eq. (9) is same as that for conductivity current.

Algorithm for calculating the current density

As mentioned, the density of the Hall gradient current was deduced for a case of collisionless plasma [38]. In such the calculations a drift approach is generally used. This approach has some limitations. Now it is considered more reliable to use an algorithm suitable for arbitrary magnetization β. Equation for the collisionless plasma may be received as the limit $\beta \to \infty$ [39]. In the present work we will follow such a way.

We took the algorithm what widely exploited for finding the drift velocity in homogeneous ionized medium with applied uniform electric and magnetic fields, but we used this algorithm when non-uniform magnetic field is applied. (In the case of non-homogeneous medium — there are gradients of density or temperature — another, more complex algorithm should be applied.)

Directly after a collision all the directions of the scattered particle are equiprobable, — the collision makes the mean velocity to equal zero. Then the particle interacts with the field, — electric, magnetic or both. This interaction brings asymmetry in the movement of the particle. To the time of next (second) collision the particle has
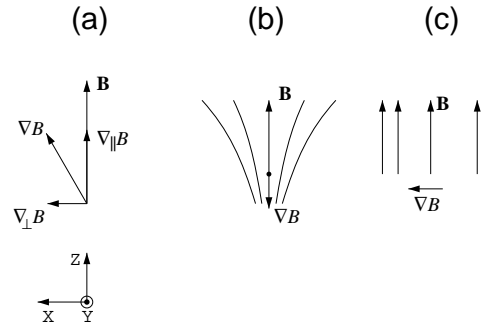

FIG. 1: Coordinate system and magnetic fields being used for calculating. (a) arbitrary disposition of vectors ∇B and **B**. Vector ∇B may be decomposed at parallel and perpendicular components, which defines, in this work, the axes Z and X respectively. Vector $\mathbf{B}\times\nabla B$ defines the axis Y. (b) non-uniform magnetic field with $\nabla B \parallel \mathbf{B}$. It was used for calculating the parallel component of gradient current, see also Fig. 3. (c) non-uniform magnetic field with $\nabla B \perp \mathbf{B}$. It was used for calculating the perpendicular and Hall components of gradient current, see also Fig. 2.

received some average shift in space. Let **r** be the radius-vector of the particle in the moment of the next collision relatively the first. Then the average shift between the subsequent collisions is

$$\langle\mathbf{r}\rangle = \sum \mathbf{r}_i/n_{coll}. \qquad (10)$$

Here n_{coll} is the number of the collisions has been included in the calculation.

As a result of the second collision, the directions of the velocity become again isotropic. Assuming stationarity, the velocity distribution function does not depend on time. Thus the movement after the second collision will occur in same a way as after the first. Hence, it is well enough to take into account the movement of the particle between the first and second collisions. Inelastic collisions may be omitted in the calculation because they are already taken into account in the velocity distribution function. Thus, average (drift) velocity, which the particles get in the applied field, is

$$\mathbf{V}_{dr} = \langle\mathbf{r}\rangle\nu. \qquad (11)$$

As the drift velocity becomes known, Eq. (7) gives the current density.

It follows from above, that the calculation of the drift velocity reduces to calculating the vector $\langle\mathbf{r}\rangle$. Several methods — Monte Carlo, regular, and combined — were used to yield an identical result. The regular method as being fastest has been described below.

The solid angle 4π, in which the particle equiprobably scatters, is divided into small angles Ω_i. The vector of initial velocity is the average on the angle Ω_i:

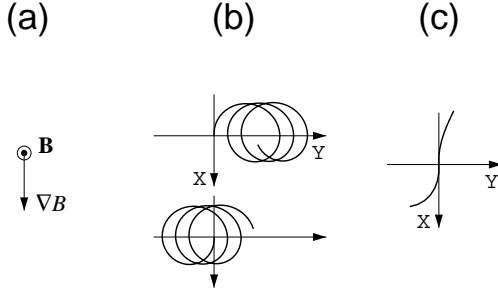$$\mathbf{V}_i(0) = V(0)\langle\mathbf{\Omega}_i\rangle. \qquad (12)$$

FIG. 2: The mechanism of perpendicular and Hall components of gradient current. (a) the magnetic field being used for calculating. The field growths downwards; the gyroradius decreases downwards. (b) the origin of drift velocity for large magnetization (strong field, sparse plasma). (c) the case of small magnetization. First collision occurs in the center of coordinate. The motion of positive particle being scattered up and down is shown; the trajectories have the length being equal to free path. Mean shift between collisions is defined as center of gravity for the locations of next collision. As obvious from panel (b), for large β the mean Y coordinate of second collision is positive — this is well-known case of Hall gradient current in collisionless plasma. To the contrary, it is seen from panel (c) that the mean Y coordinate for small β is negative. As consequence, the Hall component has different signs for small and large β, see also Eq. (13). From panel (c) it is seen that a net shift along axis X is present, at its negative direction. This means that the perpendicular component indeed takes place. With increasing β, as seen from panel (b), the mean X coordinate of second collision tends fast to zero. This well corresponds to behavior of the perpendicular (diagonal) terms in matrix of Eq. (13).

Here $V(0)$ is the module of initial velocity (for its choice see below), $\langle \mathbf{\Omega}_i \rangle$ is the mean normal to the area Ω_i. In this method the concept of weight of scattered particle is used. The weight at the moment immediately after the collision is supposed $W_i(0) = \Omega_i/4\pi$, what corresponds to natural normalization $\sum W_i(0) = 1$. When the particle is moving on a trajectory there is reduction of the weight due to collisions. During time Δt the weight diminishes by

$$\Delta W(t) = W'(t)\Delta t = -W(0)\exp(-t\nu)\Delta t.$$

The code builds the trajectory of the particle moving in given field. For each the time interval the value $|\Delta W_i(t)|\mathbf{r}_i(t)$ is added to $\langle \mathbf{r} \rangle$. The calculation for given scattered particle expires when its weight becomes less than a little value defined beforehand. Finally,

$$\langle \mathbf{r} \rangle = \sum |\Delta W_i(t)|\mathbf{r}_i(t).$$

This equation has the same meaning as Eq. 10. The sum is taken on the directions of scattered particles, on intervals of time and, if required, on the module of the initial velocity.

The computation was made for Maxwellian distribution function of charged particles on velocities. Bulk of
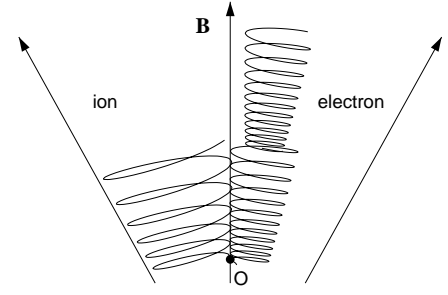

FIG. 3: The mechanism of parallel gradient current. The motion of electron and ion in the magnetic field with $\nabla B \parallel \mathbf{B}$ is shown between the collisions. The particles were assumed to have same energies. For clearness, the ion mass is taken by factor 4 larger than that of electron one. Hence, the ratio of gyroradiuses is of 2. The particles scattered in point "O" in the direction perpendicular to the field. First, a trajectory represents a circle; it turns out into a spiral due to parallel Lorentz force acting upwards. The trajectories of both particles are depicted for the time being equal to ion collision time. As for electron, it underwent two collisions for this time. (Assuming the cross sections are same.) As seen, the electron has shifted at weaker field direction by two times larger than the ion. Hence, the drift velocity is inversely proportional to the root of mass; see Eq. (13).

the computation has been made for the monoenergetic particles with the initial velocity equal to the thermal velocity

$$V(0) = V_T \equiv (8kT/\pi m)^{1/2}.$$

Additional computation has been made in which the initial velocity varied around V_T; the initial weight was multiplied by a normalized factor. It presented the fraction of the particles with the given velocity module in the Maxwellian distribution. The both computations — with fixed and varying velocity module — gave the same result.

Code execution yields in numerical data of the drift velocity, being computed for the different magnetization β. The code was used for calculation of drift velocity in the fields:

The non-uniform magnetic field for a case $\nabla B \parallel \mathbf{B}$, Fig. 1(b) and Fig. 3.

The non-uniform magnetic field for a case $\nabla B \perp \mathbf{B}$, Fig. 1(c) and Fig. 2.

Uniform electric and magnetic fields for a case $\mathbf{E} \parallel \mathbf{B}$.

Uniform electric and magnetic fields for a case $\mathbf{E} \perp \mathbf{B}$.

The last two cases served for the aim of control. They gave the numerical values which corresponds to a well-known equation of tree-components conductivity current.

Equation for gradient current density

To fit the numerical data generated by the code, the empirical equation for gradient current density was de-

vised. The equation reprodices the numerical data with accuracy of 1% for a small magnetization and 5% for large one:

$$\mathbf{j}_{\nabla B} = -\frac{8qP}{\pi^2 \nu mL} \begin{pmatrix} \frac{2Z\beta^2}{(\beta^2+1)^2} & \frac{-\beta(\beta^2-1)}{(\beta^2+1)^2} & 0 \\ \frac{\beta(\beta^2-1)}{(\beta^2+1)^2} & \frac{2Z\beta^2}{(\beta^2+1)^2} & 0 \\ 0 & 0 & \frac{Z\beta^2}{\beta^2+1} \end{pmatrix} \mathbf{I}. \quad (13)$$

Here $\mathbf{I}$ is the unit vector in direction of the gradient of magnetic field module, L is the characteristic length of change of magnetic field module:

$$\mathbf{I} = \nabla B/|\nabla B|, \qquad L = B/|\nabla B|, \quad (14)$$

$$\nabla B \equiv \begin{pmatrix} \nabla_X B \\ \nabla_Y B \\ \nabla_{||} B \end{pmatrix}, \, Z \text{ is the sign of charge.}$$

It is seen from Eq. (13) that Hall component of gradient current (being long known for infinite β) has the remarkable feature: it changes the direction at $\beta = 1$. Fig. 2 shows why this occurs. This property was not known formerly.

For comparison, let's copy out from [33] the equation for the density of diffusion and thermocurrent for weakly ionized plasma, for electrons:

$$\mathbf{j}_{D,T} = \frac{qP}{\nu mL} \begin{pmatrix} \frac{Z}{\beta^2+1} & \frac{-\beta}{\beta^2+1} & 0 \\ \frac{\beta}{\beta^2+1} & \frac{Z}{\beta^2+1} & 0 \\ 0 & 0 & -Z \end{pmatrix} \mathbf{I}. \quad (15)$$

If Eq. (15) describes the diffusion current,

$$L \equiv N_e/|\nabla N_e|, \qquad \mathbf{I} \equiv \nabla N_e/|\nabla N_e|,$$

where L is the characteristic length of change of electron density and $\mathbf{I}$ is the unit vector on concentration gradient.

If Eq. (15) describes the thermocurrent,

$$L \equiv T_e/|\nabla T_e|, \qquad \mathbf{I} \equiv \nabla T_e/|\nabla T_e|,$$

where L is the characteristic length of change of electron temperature and $\mathbf{I}$ is the unit vector on temperature gradient. For the case of thermocurrent, Eq. (15) is valid when collision frequency independent (weakly dependent) of charged particle velocity.

Equation (15) will also describe the conductivity current if admit $L = \epsilon_T/qE$ and $\mathbf{I} = \mathbf{E}/E$, that is L is the length on which the electron attains the thermal energy ϵ_T in the given electric field E and $\mathbf{I}$ is the unit vector in the electric field direction.

It is seen from comparison of equations (13) and (15) that the density of gradient current at large β has the same asymptotic as that for diffusion and thermocurrent. The parallel components of all the currents are independent of β, Hall components behave as $1/\beta$, and the perpendicular components behave as $1/\beta^2$.

Equations (13) and (15), being written in the same form, allow us to evaluate and to compare the densities of different currents in the plasmas of interest.

Currents of non-uniformities as extraneous currents

A current may be classified in relation to electric field — the current independent on electric field may be extraneous. For an extraneous current, the factor of dissipation $\mathbf{j} \cdot \mathbf{E}$ is negative. It is positive for conductivity current and it is zero for Hall current — the later is nondissipative current. Due to action of extraneous current a part of the energy of charged particles turns into the energy of electric and magnetic field.

Diffusion and thermocurrents, being independent of electric field, may be extraneous currents — at proper direction of the electric field. Generators of electricity have been worked out on base of diffusion and thermocurrents.

Being also independent of electric field, gradient and centrifugal currents may also be extraneous. A place where they evince as extraneous is again the magnetosphere. Be the magnetosphere axially symmetric, the current (sum of gradient and centrifugal ones) were of constant value along its round. No electric field would arise. But as result of interaction with solar wind, the magnetosphere is an asymmetric structure. Hence the sum of two currents has different value along equatorial round of the magnetosphere. Is the total (extraneous) current unclosed? No, gradient and centrifugal currents create a charge separation, followed by electric field. Conductivity current appears. So, total current (including the tree currents) forms the closed circuit of observed magnetospheric ring current. (This circuit may be partly branched off in ionosphere.)

Currents of non-uniformities on sun photosphere and on other plasmas

Let's raise the question, — currents of what nature participate in the currents observed in atmosphere of the Sun? For the answer we will evaluate, with use of equations (13) and (15), the densities of different currents at photosphere level and compare them with the observable current density.

The electron concentration is taken from [40]. From these data, the characteristic length of change of electron density at vertical has been calculated; it turned out to be 70 km. From the same data, the characteristic length of change of electron temperature on vertical at photosphere level was obtained to be about 600 km. The electron density changes faster than the temperature. Such the relationship is expected for weakly (partly) ionized plasma: on Saha equation, a small change in temperature leads to larger change in degree of ionization, following in large change in the electron density.

For evaluating the gradient current density with use Eq. (13) we need know the typical length of change of magnetic field module. Magnetic field in solar atmosphere is known to be very structural, it rather consists of small-scale magnetic elements — magnetic flux tubes [41]. The cross size of the magnetic elements

at photospheric level is smaller than the resolution of magnetometers. Hence it is impossible building tree-dimensional structure of the magnetic field and defining the length of change of magnetic field module from it. There are methods what allow us to learn more about the magnetic field at smaller scales than the resolution limit.

The procedure of inversion of Stokes profiles is applied to the polarization of magnetic lines in single resolution elements [42]. Inversion of Stokes profiles reveals that two different magnetic components coexist in one resolution element with the size of 0".3–1".0 = 220–750 km. A large fraction of the field strengths was measured being in kG regime. A fraction of observed Stokes profiles requires opposite polarities in the resolution element. Such the method being especially applied to the different lines or to the lines in visible and infrared range allows evaluating the mean unsigned flux density and the longitudinal component of the magnetic field. Then, filling factor (being one – several percents) and character size of the magnetic elements may be obtained [43].

The next data on characteristic size (diameter) of small-scale magnetic elements in quiet photosphere may be found in literature: 75 km [43], 96–118 km [44], 100–200 km [45], 40–220 km [46], 100 km [47], 50–100 km [48], 140 km [49].

Electron magnetization β being calculated for the effective field 1 kG is given on Tab. I.

Another method for revealing the magnetic structures includes imaging the Sun in molecular G-band [44], in the wings of strong spectral lines such as Hα and Ca II H and K [45]. It was stated that the mean equivalent diameter of the magnetic structures is of 100–300 km, at the limit of resolution of ground-based solar telescopes.

Summing these data, we may say that the characteristic diameter of small-scale magnetic elements in quiet photosphere is of 75–300 km. Obviously, for the characteristic length of change of magnetic field module the associated radius, 40–150 km, should be taken.

Evidently, there is mechanical balance on horizontal of the magnetic structures with surrounding plasma [50]. Gas pressure and magnetic pressure, being defined at the same photospheric level, must anticorrelate in accordance with equation $P_{gas} + B^2/8\pi = $ const. In such the case, the typical length of plasma density on horizontal should be the same as the characteristic length of change of magnetic field module that is 40–150 km. This well agrees with the typical length of plasma density on vertical, 70 km.

The given data allows us to evaluate the densities of different currents on photospheric level. Because the magnetization is close to 1, the matrix elements in equations (13) and (15) is of order 1 also. Hence, for our aim, either component of some current density may be presented by reduced equation

$$j \approx qP/\nu mL, \tag{16}$$

where the length L accounts for 70, 600, and 40–150 km

TABLE I: Electron magnetization β and densities (in mA/m^2) of currents of non-uniformities at photosphere levels of quiet sun evaluated on equations (13) and (15).

H (km)	β	j_D	j_T	$j_{\nabla B}$
−40	0.41	6.7	0.6	3.3–13
−30	0.55	3.5	0.3	1.7–7
−17	0.69	1.55	0.14	0.8–3
0	0.82	0.7	0.06	0.35–1.4
22	0.97	0.4	0.05	0.2–0.8

TABLE II: Densities of vertical current measured at rotor of magnetic field at photosphere level.

j_z (mA/m^2)	Resolution	Reference
Active regions		
$\pm 2, \ldots \pm 20$	2"/pixel	[12]
$\pm 7.5, \ldots \pm 12$	3" × 2"	[23]
$\pm 1.2, \pm 2.4$	4"	[10]
$\pm 6, \ldots \pm 24$	2" × 2"	[17]
$-30, +50$	1.1"	[14]
$\pm 20, \ldots \pm 70$		[19]
± 7		[13]
$\pm 2.4, \ldots \pm 20$		[9]
Quiet photosphera		
$\pm 0.1, \ldots \pm 0.2$	4"	[52]

for diffusion, thermocurrent, and gradient current, accordingly.

The densities of currents of non-uniformities, being calculated at Eq. (16) for these lengths are given on Tab. I.

Now, of concern to us is observable currents in sun photosphere. The only current what can be measured in there is magnetic field-aligned current in areas of strong vertical field. Here $\nabla B \parallel \mathbf{B}$. In active regions including sunspots this current may be measured with enough accuracy on rotor of cross-to-sight magnetic field. See Tab. II for the data. It is seen that the better the resolution, the larger is the measured value of current density. This correlation was many discussed in literature. (This particularity in measurements appears because the current/magnetic field structures have sizes smaller than the resolution; and the currents in close structures can have opposite direction.)

It is difficult to measure transverse magnetic field in quiet sun photosphere and to calculate vertical current there. Nevertheless, the estimation of the quiet sun currents was made with use of chromospheric fine structures seen in Hα images with comparison of theoretical chromospheric field obtained by potential extrapolation of the observed, line-of-sight photospheric field [51, 52]. In area of unipolar vertical magnetic field, there were found the currents $(1-8) \times 10^9$A being directed upwards or downwards, with the density of 0.1–0.2 mA/m^2 [52]. This density seems to be underestimated when the low resolution in this work is considered. The structure of currents in unipolar hill of vertical field in quiet regions resembles

the current structure in a sunspot.

We want to compare the measured currents with the currents of non-uniformities; in this comparison the currents must fall to region with same conditions — quiet photosphere and, separately, active regions.

Quiet photosphere. Let us compare the density of currents of non-uniformities presented in Tab. I with only measured current presented in Tab. II. We may see that the measured current is smaller (even with regard to its underestimation) than the diffusion and gradient ones. From this it follows that the currents of non-uniformities are present in quiet photosphere and play important role in there.

Active regions. It is known that both magnetic fields and gradients (of concentration, temperature, and magnetic field module) are larger in active photosphere than in quiet one. Hence, we may anticipate, that the currents of non-uniformities in active regions are larger than in quiet photosphere. Again, we see that the currents of non-uniformities participate in the photosphere currents and play essential role.

To discuss the problem further, let us take in mind the directions of the currents. Because $\nabla B \parallel \mathbf{B}$, as the result of given work there is the parallel gradient current there; it consists of electrons moving upwards, to weaker magnetic field region. There is the parallel diffusion current there, it also consists of electrons moving upwards, to smaller electron concentration. Thus, both currents act together. They act as the extraneous current and give a charge separation following with macroscopic electric field and conductivity current. The later is of opposite direction to the extraneous current. It may be proposed that there is difference of extraneous and conductivity currents; this difference is directed upwards or downwards.

In Earth polar ionosphere, there are seen phenomena being considered as of similar nature to paired vertical currents on solar atmosphere. These are U-shape structures consisting of two magnetic field-aligned currents of opposite directions on distance of some hundred kilometers from each other [53]. It is appropriate mention here that both solar and ionospheric vertical currents are closed in area where electron magnetization is near 1.

Phenomena accompanying the magnetic field-aligned gradient current are observed in laboratory plasma. The plasma facility described in [54] has a magnetic field with axial symmetry. The plasma source is located where the field is maximal. In the center of the plasma volume the magnetic field is weakest; and the negative potential about $-300\,\mathrm{V}$ has been measured there. On frame of the given work it is possible to assume that parallel gradient plus diffusion currents cause the charge separation in the plasma; the negative potential evidences it. Also, a through current $\approx 1\,\mathrm{kA}$ streaming along magnetic lines is observed in the plasma. The direction of this current corresponds to movement of electrons towards weaker magnetic field and, at the same time, towards weaker electron density. The through current is presumably the gradient plus diffusion current, being partly canceled by the conductivity current of opposite direction.

In the plasmas of interest the cross-magnetic field currents are observed: 1) the current in photosphere which closes the vertical currents inside a sunspot and inside the hill of vertical field in quiet region, 2) the current in lower ionosphere what closes magnetic field-aligned currents in U-shape aurora structure, 3) equatorial electrojet in lower ionosphere at the height 90–110 km. Presumably, cross components (these are perpendicular and Hall ones) of gradient, centrifugal, diffusion, and also of conductivity current include to these observable currents. Notice again that magnetization of electrons is near 1 in the areas of these transverse-magnetic field currents.

Extraneous currents (gradient, centrifugal, diffusion, and thermocurrent) when being coupled with conductivity current may be considered of to generate the magnetic fields in objects without convective motions — in stars of classes Am, Ap.

Summary

Results of this paper may be summarized as the follows.

1. We gathered the observations of electrical currents in cosmic plasmas paying attention to the cases when nature of the current is known. By this is meant that the value of measured current agrees sufficiently with the current calculated on a theoretical equation (for a current of some type). The nature of the ring current in magnetosphere is well known — this is gradient plus centrifugal current. The current in comet coma and in artificial plasma cloud consists of diffusion and thermocurrent. These four currents are the current of non-uniformities.

2. In the paper the gradient current was investigated more fully than earlier. Two unknown components of the current were found. An equation for gradient current density was obtained. The equation embraces tree possible components of the gradient current.

3. It was proposed that the currents of non-uniformities present on solar atmosphere. It was checked for photosphere. The measured vertical currents was compared with the currents of non-uniformities; the later were calculated at theoretical equations. Theoretical values turned out to be the same or larger than the measured ones.

4. Hence it follows that the currents of non-uniformities indeed present in atmosphere of the star; the currents should be included into theoretical models.

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