PROBING SIGNATURES OF THE ALPHA-EFFECT IN SOLAR CONVECTION ZONE

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Abstract. An attempt to extract maximum information on signatures of the alpha-effect from current helicity and twist density calculations in the solar photosphere is carried out. Possible interpretation of the results for developing the dynamo theory is discussed. The analysis shows that the surface magnetic current helicity is mainly negative/positive in the northern/southern hemispheres of the Sun. This indicates the actual alpha-effect at the photospheric level to be positive/negative, respectively. However, at the bottom of the convection zone we may assume this effect to change the sign to negative/positive. We reveal some quantities related to the alpha-effect and discuss its spatial and temporal distribution.

It is also found that there is a minor number of active regions where the the sign of the alpha-effect is indicated opposite to the one in the most of active regions. Such exceptional acive regions with respect to current helicity are seen to localise at certain active longitudes. We compare the determined regularities with theoretical predictions of the alpha-effect distribution in the solar convection zone.

1. Introduction

The role of the alpha-effect is very important for the mean-field dynamo theory. This effect along with the differential rotation provides regeneration of magnetic fields in astrophysical bodies from mechanical turbulent convective motions of cosmic plasmas. For the solar convection zone, the differential rotation is quite well studied by means of helioseismology (e.g., Schou et al. 1998), while knowledge of the alpha-effect is still very little because it cannot be quantitatively observed directly.

The alpha-effect was introduced by Steenbeck, Krause and Rädler (1966) as a quantity linked with the mean kinetic helicity of turbulent motions. Further theoretical advances of Keinings (1983), Seehafer (1994a), and Gruzinov and Diamond (1995) opened an opportunity to gain knowledge on the alpha-effect studying the current helicity of the solar magnetic fields. This became possible with the present level of observational resolution on the basis of recent systematic studies of magnetic fields (Canfield and Pevtsov 1994, 1995), also carried out by Beijing Astronomical Observatory team at Huairou Solar Observing Station (Bao and Zhang 1998; Zhang and Bao 1998, 1999; Bao et al. 1999). Therefore, the studies of strong magnetic fields in the solar active regions provide very useful information on the magnetic fields at the bottom of the convection zone, and thus they can be used as signatures of the alpha-effect.

The theoretical problem is how to extract such information. The main difficulty is that the values of the magnetic current helicity of small scale fields are highly dispersed over the solar photospheric level in Active Regions (ARs). The dynamo theory interpretation of the data on the alpha-effect in the solar photosphere should take into account the knowledge of convection processes which link the photosphere with the bulk of the Solar Convection Zone (SCZ). The dynamo is believed to operate in the depth of the SCZ, even perhaps at the bottom or beneath (the so-called overshoot layer).

2. Alpha-effect and Turbulent Dynamo Action

2.1. Parker's dynamo. The role of the α- and Ω-effects

In the simplest dynamo models of magnetic field generation there are two main factors which provide positive feedback between the toroidal and poloidal components of the magnetic field: the so-called α- and Ω-effects. They cause regeneration of magnetic fields from mechanical energy of turbulent convective motions of plasma in the SCZ. The magnetic field manifestations calculated in such models appear in the form of a traveling wave which possesses the main properties of the observable magnetic activity of the Sun. The dynamo waves are seen over the butterfly-diagrams of sunspot migration and over other tracers and solar indices.

On the mathematical viewpoint the Parker's dynamo equations (Parker 1955) have the following form:

$$\hat{\mathrm{L}}A = \alpha B \tag{1}$$

$$\hat{\mathrm{L}}B = -D\cos\theta\,\frac{\partial\Omega}{\partial r}\,\frac{\partial A}{\partial\theta} \tag{2}$$

where A, B are azimuthal components of the large-scale mean magnetic potential and field, differential operator $\hat{\mathrm{L}} = \partial/\partial t - \partial^2/\partial\theta^2$, α is the alpha-effect (rescaled), Ω the angular velocity, D the dimensionless dynamo number, the regeneration rate, generally large parameter for supercritical oscillatory dynamos. Latitude θ is measured from the equator.

The large-scale mean fields are introduced to represent statistical properties of MHD processes in turbulent media. They are quantities averaged over large enough spatial and temporal scales. The scale should be in accord with our interest for studies of the large scale phenomena. This approach is based on the ideas of mean field dynamo theory (Krause and Rädler 1980).

Unfortunately, as concerned with available observations, there is no distinct scales over the Sun apart of its radius. However, this is often too large for observable temporally-spatial structures of the solar magnetic fields. Therefore, below we consider a few smaller scales regarding to the observable structures of turbulence in the SCZ.

The equations above are significantly one dimensional case which is a rough simplification of a multidimensional one. However, as it was found in many numerical experiments (Moss et al. 1990; Brandenburg 1994), also supported by asymptotic analysis of, e.g., Kuzanyan and Sokoloff (1995, 1996), this simplification does not crucially change the general behavior of the solution. One can see that the solution of eqs. (2) has a form of a traveling dynamo wave (Parker's migratory dynamo). In order to obtain the equatorward waves one can show that quantity $\alpha\, \partial\Omega/\partial r$ should be negative in the Northern and positive in the Southern hemisphere of the Sun.

The Ω-effect is mainly associated with the gradient of angular velocity $G = \partial\Omega/\partial r$ which can be studied from helioseismology data (see, Basu 1997; Kosovichev et al. 1997; Schou et al. 1998) and appears positive in the deep enough convection zone over most of low latitudes in both of the hemispheres. This is perhaps different in the radiative transfer zone or over high latitudes. The dynamo might work in a thin layer at the bottom of the convection zone, where the differential rotation is strong but the alpha-effect is assumed to exist due to turbulent convective motion.

In contrast with the Ω-effect, the α-effect which is responsible for regeneration of the poliodal field from the toroidal one, can be associated with mean kinetic helicity of turbulent motion (e.g., Krause and Rädler 1980) as

$$\alpha_{ef} = -\frac{\tau}{3}\,\langle h_k \rangle\,, \tag{3}$$

where τ is the turbulent correlation time (characteristic convection time), $h_k = \mathbf{v}\cdot\nabla\times\mathbf{v}$ denotes the kinetic helicity, and $\mathbf{v}$ the small scale velocity. Unfortunately, α_{ef} is not available for direct determination. Therefore, various theoretical and numerical attempts have been carried out to estimate this factor.

Krause (1967) gave an estimate of the kinetic alpha-effect in terms of rotation Ω, convection velocity $v_c(r,\theta)$, and density distribution functions $\rho(r,\theta)$ based on the ideas of the mixing length theory with account of Coriolis forces. This reads the following

$$\alpha_{ef} = -\frac{16}{15}\,\tau^2\, v_c^2\ \mathbf{\Omega}\cdot\nabla\log(\rho v_c). \tag{4}$$

One can conclude that under quite general assumptions on the convection in the SCZ the α-effect is proportional to the factor $\sin\theta$.

There is no confidence on the sign of the alpha-effect in the SCZ. The observations of the global magnetic activity are not sensible to this sign but to the sign of the product of the α- and Ω-effects. In order to obtain the observable equatorward migration of the main dynamo wave we should provide the differential rotation and the α-effect to possess opposite signs somewhere in low latitudes of the Northern hemisphere. Two realizations of such condition are possible. In the earlier studies the most or researchers assumed that $G < 0$, and $\alpha > 0$. Later taking into account some results of helioseismology studies of the internal rotation of the Sun they changed their mind to $G > 0$, $\alpha < 0$. There are different ideas on how the alpha-effect is distributed over the depth of the SCZ and how it relates to the domain where the maximum generation takes place. There is an extensive discussion on the thickness of the generation layer in the convection zone (cf., Moss et al. 1990; Brandenburg 1994). This concept of the generation layer is based on the idea of the overshoot layer dynamo (e.g., Skaley and Stix 1991; Rüdiger and Brandenburg 1995). The effective kinetic alpha-effect versus the magnetic field strength was studied in the complete system of the MHD equations by, e.g., Brandenburg and Donner (1997).

Glatzmaier (1985) found numerical evidence that the alpha-effect changes sign with depth. This is linked with that the upward flows diverge in top layers of the convective zone but the downward ones in the bottom. Correspondingly, the upward/downward flows converge in the bottom/top of the SCZ. Although, in a MHD system with extremely high Reynolds numbers like in the SCZ the convection is significantly turbulent, and one can hardly see such prominent divergent/convergent flows at all. Krivodubskij and Schultz (1993) and Krivodubskiy (1998) developed a theory of the alpha-effect distribution over the depth of the SCZ which is large closely below the surface, and zero at the certain level near the bottom of the SCZ. Below this level it changes sign to the opposite one. This is consistent with recent numerical studies of Brummell et al. (1998).

Schlichtenmaier and Stix (1995) considered a phase shift between the toroidal and the poloidal fields in the framework of dynamo models. This quantity can be an independent tracer of particular signs of the α- and Ω-effects. This work needs to be developed to further comparison with available solar indices. The location of the main magnetic field generation in the SCZ and the actual values of signs and magnitudes of the α- and Ω-effects still remain unclear. This puzzle causes serious problems in application of the dynamo theory to the solar case.

In the light of what is said above one can see, that alternative estimates of the alpha-effect would significantly benefit the solution of the dynamo problem. In solar ARs there are strong magnetic fields which arise mainly from the depth of the SCZ. These fields contain information on the MHD flow at the locations where they arise from and through (cf., Melrose 1991). The tilt of sunspots (Longcope et al. 1998; Canfield and Pevtsov 1997; Pevtsov and Canfield 1998; Seehafer 1990) and the magnetic current helicity (Seehafer 1990; Pevtsov et al. 1994, 1995) could be useful tracers of this factor. This paper is dedicated to analysis of the magnetic current helicity and twist measurements as tracers of the alpha-effect in the SCZ.

2.2. Magnetic and Current helicities. Observations of the solar photosphere.

The helicity of magnetic fields may be characterized by several different parameters. The density of magnetic helicity can be defined as

$$h_m = \mathbf{A} \cdot \mathbf{B} \,, \tag{5}$$

where $\mathbf{A}$ is a vector potential of magnetic field $\mathbf{B}$ (Moffatt 1978). In general, h_m determines the number of linkages of magnetic field lines. The total magnetic helicity in domain $\mathcal{D}$ is

$$H_m = \iiint\limits_{\mathcal{D}} h_m \, dV \,. \tag{6}$$

If space is divided into a number of flux tubes, the helicity integral contains contributions from the internal structure of flux tubes, such as twist and kink, and from external relations between flux tubes, i.e., knotting and linking.

Let us consider an isolated magnetic system ($B_n = \mathbf{B} \cdot \hat{\mathbf{n}} \,|_\sigma = 0$). Then variation of magnetic helicity with time is readily derived from the Maxwell equations, and can be written in the form

$$\frac{dH_m}{dt} = -2 \iiint\limits_{\mathcal{D}} \eta \, \mathbf{J} \cdot \mathbf{B} \, dV \,, \tag{7}$$

here η is the resistivity and $\mathbf{J}$ is the electric current density. For the ideal MHD ($\eta = 0$), the magnetic helicity is apparently conserved. Equation (7) can be rewritten as

$$\frac{dH_m}{dt} = -\frac{2\eta}{\mu_0} H_c \,, \tag{8}$$

$$H_c = \iiint\limits_{\mathcal{D}} h_c \, dV \,, \quad h_c = \mu_0 \, \mathbf{J} \cdot \mathbf{B} \,, \tag{9}$$

where μ_0 is the vacuum permeability, H_c is the total current helicity, and h_c is the current helicity density.

Therefore,

$$h_c = \mathbf{B} \cdot \nabla \times \mathbf{B}. \tag{10}$$

Separating h_c into two parts — parallel ($\|$) and perpendicular ($\perp$) to the line of sight — one can write

$$h_c = \mathbf{B}_\| \cdot (\nabla \times \mathbf{B})_\| + \mathbf{B}_\perp \cdot (\nabla \times \mathbf{B})_\perp \,. \tag{11}$$

The both parts of helicity h_c can be linked with each other in the framework of the force-free field theory (see Section 3.1 below).

Unfortunately, because we have magnetic measurements at a single height in the solar atmosphere, we can determine only the first part of current helicity density, i.e., $h_c^{||} = \mathbf{B}_{||} \cdot (\nabla \times \mathbf{B})_{||}$ (see Bao and Zhang 1998). This quantity may be expressed by

$$h_c^{||} = \mu_0 \, B_z J_z \; = \mu_0 \, B_z \cdot (\nabla \times \mathbf{B})_z \, , \tag{12}$$

where

$$J_z = \frac{1}{\mu_0} \left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right) . \tag{13}$$

Then we may calculate the twist factor

$$\alpha_f = \frac{h_c^{||}}{B_z^2} = \mu_0 \frac{J_z}{B_z} \, . \tag{14}$$

Here B_z, B_x and B_y are the vertical and horizontal components of magnetic fields in local Cartesian coordinates (with the z-axis upwards), which are derived from both the observed line-of-sight field $\mathbf{B}_{||}$ and transverse field $\mathbf{B}_{\perp}$ (Venkatakrishnan et al. 1988).

We choose formula (12) to calculate the current helicity in our approach, taking into account that only the vertical component of the electric current enters the solar upper atmosphere and determines its helicity. We assume the value $\mu_0 B_z J_z$ to contribute the main impact to the value of the current helicity. The database of active regions used in our study of the current helicity were obtained with the Solar Magnetic Field Telescope (SMFT), a vector video magnetograph system installed at Huairou Solar Observing Station (HSOS) of Beijing Astronomical Observatory. We have considered data for 422 ARs taken within the period of 10 years (1988–1997). They are a quite representative sampling of the total solar surface activity, where there were about 3,000 ARs for the time considered.

Important issues of the studies are criteria of selection of pixels in the magnetograms for calculation of helicity parameters $h_c^{||}$ and α_f. In order to reduce the level of noise which does not normally exceed in determination of the line-of-sight (longitudinal) field $B_{||}$ the level of 20 G, and for the transverse field $B_{\perp}$ 100 G, the pixels where the fields observed is lower such levels were eliminated for calculation of parameters h_c and α_f and further ignored for averaging procedures. Correspondingly, the noise level for J_z was calculated of about 1 mA m^{-2}. Further details of the observational technique and data reduction are described by Bao and Zhang (1998).

3. Magnetic helicity and the alpha-effect

3.1. The force-free field factor

Relatively small domains of the solar atmosphere under certain assumptions can be considered within the framework of the force-free field theory. This theory provides description of magnetic fields for which the following relation is valid (Woltjer 1958)

$$\nabla \times \mathbf{B} = \alpha_f \mathbf{B}, \tag{15}$$

where α_f is a scalar function of position. Assuming that solar ARs are such domains, we can calculate this coefficient from the observational data. Thus we have

$$\alpha_f = \frac{(\nabla \times \mathbf{B})_{||}}{\mathbf{B}_{||}}, \qquad \text{and} \qquad h_c = \frac{B^2}{B_{||}^2}\left(\mathbf{B}_{||} \cdot (\nabla \times \mathbf{B})_{||}\right) = \alpha_f B^2. \tag{16}$$

There is, however, no reason to believe that the magnetic field at photospheric level is force-free. In this case a part of the current helicity density, $h_c^{||} = \mathbf{B}_{||} \cdot (\nabla \times \mathbf{B})_{||}$, can still be calculated, and ratio α_f can also be formally calculated using formula (14).

3.2. Keinings-Seehafer Formula (KSF)

As it was found by Keinings (1983) and Seehafer (1994a, 1994b, 1995, 1996), see also Rädler and Seehafer (1990), Gruzinov and Diamond (1995), that under certain assumptions on the turbulent plasma motion the alpha-effect can be expressed in terms of the magnetic current helicity:

$$\alpha_{ef} = -\eta \frac{\langle \mathbf{b}' \cdot \nabla \times \mathbf{b}' \rangle}{(\langle \mathbf{B} \rangle)^2} \approx -\eta \frac{\langle h_c \rangle}{(\langle \mathbf{B} \rangle)^2}. \tag{17}$$

Here we assume $\mathbf{B} = \langle \mathbf{B} \rangle + \mathbf{b}'$, where $\langle \mathbf{B} \rangle$ denotes the mean magnetic field, $\mathbf{b}'$ the small scale one. The main assumption made here is that fluctuations of the magnetic field are considered statistically stationary and homogeneous on the scales of averaging, which are small compared to the scales of the mean field variations. This is a quite natural assumption. Notice, that following Seehafer's papers cited above we do not require this condition in a strict sence on the scales of the entire SCZ, which would not be a correct assumption as there is an anisotropy of turbulence due to rotation.

However, we do not assume that the turbulence is homogeneous and isotropic. Notice that estimates of the α-effect in terms of magnetic and kinetic helicities are considered by e.g., Pouquiet et al. (1976) and Field et al. (1999), as well as by Gruzinov and Diamond (1995).

Another important assumption which we made in formula (17) is that introducing the mean current helicity $\langle h_c \rangle$ we neglect the helicity of the mean field $\langle \mathbf{B} \rangle \cdot \nabla \times \langle \mathbf{B} \rangle$ and treat further the average helicity of the observable magnetic field $\langle h_c \rangle$ as helicity of the small scale fields in formula (17). This assumption is reasonable as the magnitude of large-scale fields in the depth of the Sun is believed to be small compared with the magnitude of small scale fields, and so the impact of helicity of the mean field was estimated small by other studies, e.g., Rädler and Seehafer (1990).

This formulation of the alpha-effect is alternative but complementary to another one which uses terms of kinetic helicity (3). This opens a prospective to use the magnetic current helicity data calculated from observable magnetograms (e.g., Abramenko et al. 1996; Bao and Zhang 1998) for probing the alpha-effect at the solar surface.

In formula (17) η is the molecular magnetic diffusivity. We assume this to be a not very much changing function of position over a given AR. This assumption is definitely crude for the whole SCZ. The value of the alpha-effect used for the dynamo theory is based on estimates in the depth of the SCZ. However, it is believed that the signatures of the alpha-effect at the solar surface can also be useful for revealing the structure of the alpha-effect at the locations further deeper in the solar interior where the dynamo operates. The convection processes cause the active regions to represent a certain fraction of the whole MHD flow and, therefore, the magnetic fields from the deep interior of the SCZ (e.g., Melrose 1991). Thus, we may assume that the α-effect along with current helicity and magnetic helicity are conserved for turbulent convective motions in the SCZ (Berger and Field 1984). Therefore, the surface values of these quantities are likely to be positively correlated with their values in the depth of the SCZ.

The main problem for realization the idea of probing the alpha-effect is quantity $\langle \mathbf{B} \rangle$. Normally in ARs this value is negligible as compared with the current values of B. Perhaps at the present state the observational resolution does not allow one to reveal this quantity reliably.

The analysis of observational data show that the Keinings-Seehafer formula (17) can be used only for observational data taken at large spatial scales, over which the flow is believed to possess some of the mean field properties. This scale should be of order the size of a giant cell. However, the typical time of turbulent motion of such objects is of order one month (Hoyng 1992) while the most of available observations are taken for a few consequent days. One can see from analysis of magnetograms that α_f is highly dispersed over the solar photosphere (e.g., Zhang and Bao 1998). The available data of magnetograms enable us to calculate this factor provided appropriate reliability only over a small fraction of the area of ARs. Therefore, we can hardly use Keinings-Seehafer formula directly, but treat it as an instrument for estimates.

On the contrary with the alpha-effect, the force-free field coefficient α_f can be calculated from available observations over a certain part of area of ARs and is probably the most reliable signature the alpha-effect in the SCZ. Another important signature is twist and, therefore, the current helicity h_c, studied for our collection of magnetograms by, e.g., Bao and Zhang (1998), Zhang and Bao (1998, 1999), and Bao et al. (1999).

Indeed, assuming in the limit of small scale turbulent motion inside a given AR, and that the energy of the mean field $(\langle \mathbf{B} \rangle)^2$ is roughly proportional to the energy of the observable field $\mathbf{B}^2$ (but much smaller in absolute values), the mean force free coefficient α_f is somehow related to the alpha-effect with the opposite sign according to Keinings-Seehafer formula (17), cf., Seehafer (1995):

$$\alpha_{ef} \sim - \left\langle \frac{h_c}{B^2} \right\rangle = - \langle \alpha_f \rangle \,. \tag{18}$$

Notice that if instead of large volumes of the size of a giant cell ($\sim 10^5$ km) we consider smaller volumes of the size of supergranula ($1 - 2 \cdot 10^4$ km) the level of noise and uncertainty caused by the observational resolution does not allow us to reveal any significant spatially-temporal dependence as values of α_f are very highly dispersed for such scales (see, Zhang and Bao 1998, 1999). This quantity is appeared to be very different from one to another location. Due to turbulent fluctuations there is no regularity in its distribution. Furthermore, in this case we are reluctant to consider any temporal evolution as the typical time of turbulent motion of supergranula is of order of one day while the most of available magnetograms of ARs of our collection are taken within just a few consequent days, and very rarely a few magnetograms per day are available.

The further smaller scale is the size of granula ($\sim 10^3$ km) which is at the limit of spatial resolution of observational data. The turnover turbulence time is now of order a few minutes, and neither spatial, nor temporal behavior of α_f over such structures is available for now.

4. Spatially-temporal average of mean $\langle \alpha_f \rangle$

The averaging procedure employed in order to reveal mean-field properties of the observable magnetic fields should operate with large enough structures. They should not exceed the order of giant cell scales: distances of order 10^5 km and times of order one or a few months ($10^6 - 10^7$ s).

Proper spatially-temporal averaging procedure is necessary to reveal the properties of the global alpha-effect. The most of active regions which contain areas with strong magnetic fields contain also weak field domains (e.g., Zhang and Bao 1998, 1999). Considering such small enough regions as well as some active elements separately from each other would not yield any valuable result due to high dispersion of the quantities. Averaging over the scales smaller than the size of supergranula ($1 - 2 \cdot 10^4$ km) and the times less than at least one Carrington rotation would cause very low spatially-temporal resolution and would not give any regularly changing quantity upon averaging. Therefore, we must use intermediate scales which are consistent with the main actual scales of turbulence in the solar convection zone.

We worked with the data calculated by Bao and Zhang (1998), Zhang and Bao (1998, 1999). First the data on α_f were spatially averaged over a given magnetogram (which is comparable with the size of an AR) of order 10^5 km. Then the data were sorted by time with periods of 27 days (almost Carrington rotations). Spatially they were sorted by latitudinal belts of 5 degrees solar latitude, which corresponds to about $6 \cdot 10^4$ km (comparable with scales of an AR). After that averaging the data became a rather sparse array which still needs to be interpolated and extrapolated in order to reveal a physically consistent function. The results obtained seem to be optimally consistent with available observations.

The properties of the spatial and temporal structure of mean $\langle h_c \rangle$ are described in Bao and Zhang (1998). We can see below that factor $\langle \alpha_f \rangle$ has sometimes similar but still quite different properties from the ones of current helicity density (see Zhang et al. 2000).

5. Properties of the helicity and α_f distribution

There are a few phenomena which are revealed by analysis of observational data by Bao and Zhang (1998), Zhang and Bao(1998, 1999), and Bao et al. (1999). Magnetic, current and kinetic helicities and the alpha-effect contain one inverse length less than magnetic energy. Therefore, they are dissipated slower than the energy during Taylor relaxation. They may be more sensitive to the fine structure of the magnetic fields rather than just energetic level tracers like sunspots. They reveal temporally-spatial properties of the solar magnetic fields like short period oscillations (semi-biennial variations, cf., Benevolenskaya 1998, 1999) likely linked with North-South Asymmetry of the magnetic filed manifestation at the solar surface (e.g., Zhang et al., 2000).

5.1. Latitudinal distribution of mean $\langle \alpha_f \rangle$. Antisymmetry over latitudes

The temporal average of the α_f indicates that this is an antisymmetric function of latitude. Indeed, from Figure 1 you can see that this function is almost zero at the equator and have almost constantly different signs in different hemispheres (cf., Bao and Zhang 1998; Zhang and Bao 1998). The mean force-free alpha coefficient is mainly negative in the Northern and positive in the Southern hemisphere. Correspondingly, the alpha-effect should be positive/negative in the Northern/Southern hemispheres. Polynomial and running average approximations of this quantity show that this function behaves in a similar way to sine of latitude (Fig. 1). Such behavior is related to ones predicted by theories (Krause 1967; Zeldovich et al. 1983). Indeed, we may expect the alpha-effect to possess such structure as it is influenced by Coriolis forces.

Notice, that the level of antisymmetry of this function may significantly depend on the technique of calculation and inferring of the h_c and α_f data from available magnetograms. The criteria of selection of pixels in the magnetograms refereed in Section 2.2 (see also Bao and Zhang 1998) and the averaging procedure above make the data appropriate to reveal such regularity.

5.2. Longitudinal distribution of mean $\langle\alpha_f\rangle$. Active longitudes and deep interior origin of the ARs. Anomalous sign (reversed sign) average helicity phenomenon

Some longitudes have ARs which persist over long time periods. Some of them often possess the twist (current helicity) opposite to what is seen over the most ARs in a given hemisphere. Such ARs are ARs with anomalous twist (Zhang and Bao 1998, 1999) which is a signature that the alpha-effect in such regions is mainly of opposite sign with respect to the others. The number of such ARs is relatively small, it does not often exceed 30% level for both of parameters $\langle\alpha_f\rangle$ and $\langle h_c\rangle$ for the studied sampling of magnetographic data.

Such ARs often correspond to some specific active longitudes, and they rotate mostly with the radiative transfer interior of the Sun. One can suggest that such ARs capture the flow from very deep layers of the SCZ, where the alpha-effect has probably the sign opposite to the one at the surface (Krivodubskij and Schultz 1993; Krivodubskiy 1998; Brummell et al. 1998). Under this assumption we can interpret the phenomenon of such reversed sign helicity ARs as an evidence of that the alpha effect changes its sign in deep interior of the SCZ. Such depth is normally associated with the so-called overshoot layer (e.g., Glatzmaier 1985) where the solar dynamo is believed to operate.

According to the models the alpha-effect changes sign with the depth. Hence, we can conclude that the alpha-effect in the overshoot layer is negative/positive in the Northern/Southern hemispheres. The acceptance of such explanation would explain at least in part the so-called 'Solar dynamo dilemma' (Parker 1987) concerning the consistency of the signs of the α- and Ω-effects with the direction of the solar dynamo wave propagation.

5.3. Temporal variations of mean $\langle\alpha_f\rangle$

Temporal dependence of mean $\langle\alpha_f\rangle$ as a signature of the alpha-effect has similarities with the temporal dependence of the current helicity density obtained by Bao and Zhang (1998). Upon smoothing this reveals a short-term period of about 2–3 years (Fig. 2). One could try to interpret this period as the period of exchange of a part of magnetic energy between the Northern and Southern hemispheres of the Sun. Such oscillations may be likely linked with energetic magnetic activity and can be considered in the framework of interaction between odd and even, as well and mixed parity modes of generated magnetic fields (e.g., Sokoloff et al. 1995; Tobias 1997; Knobloch et al. 1998).

The dependence of $\langle\alpha_f\rangle$ on time could be compared with available observations of the solar magnetic activity versus other indices and theoretical predictions. Thus, over the time of one solar magnetic half-cycle (1988–1997) the magnetic current helicity is noticed to be modulated by an oscillation with one remarkable period of about 3 years (Bao and Zhang 1998). The detailed analysis of the latter results and the results presented in Fig. 2 revealed that both quantities $\langle h_c\rangle$ and $\langle\alpha_f\rangle$ oscillate with a short period of about $2 - 3$ years. On the contrary to that of the current helicity, the alpha-factor α_f is not noticed to have remarkable oscillations with longer periods. The dependence of the alpha-effect on the magnetic field is rather complicated. There is a simplified treatment of this problem, considering a simple quenching of the alpha-effect.

Under certain assumptions such properties of the temporal behavior may be in agreement with theoretical studies. Indeed, let us assume that the alpha-effect depends on the magnetic field amplitude as the simplest form of quenching given by series $\alpha(B^2) \simeq \alpha_0 - \alpha_2 B^2 + \alpha_4 B^4 + \dots$ (α_0, α_2, and α_4 constants). If we imagine the signature of the alpha-effect α_f has such form then $h_c \sim \alpha(B^2)\,B^2$. If the period of oscillation of B is 22 yr., then α would have a period of 11 yr and 5.5 yr, and h_c 5.5 and 2.75 yr etc., correspondingly. This is, however, not clear how such oscillations interact with each other and whether they are reliably to explain a short term oscillation with period of about 2–3 yr. Such treatment is based on some imaginations and should account that the alpha-effect was suggested to be quenched by the small scale rather than large scale fields (e.g., Vainstein and Cataneo 1992; Gruzinov and Diamond 1994). There are different theories concerning the dependence of the alpha-effect on the magnetic fields, e.g., Kleeorin and Ruzmaikin (1982), Kulsrud and Anderson (1992), Rüdiger and Kitchatinov (1993), Cataneo and Hughes (1996).

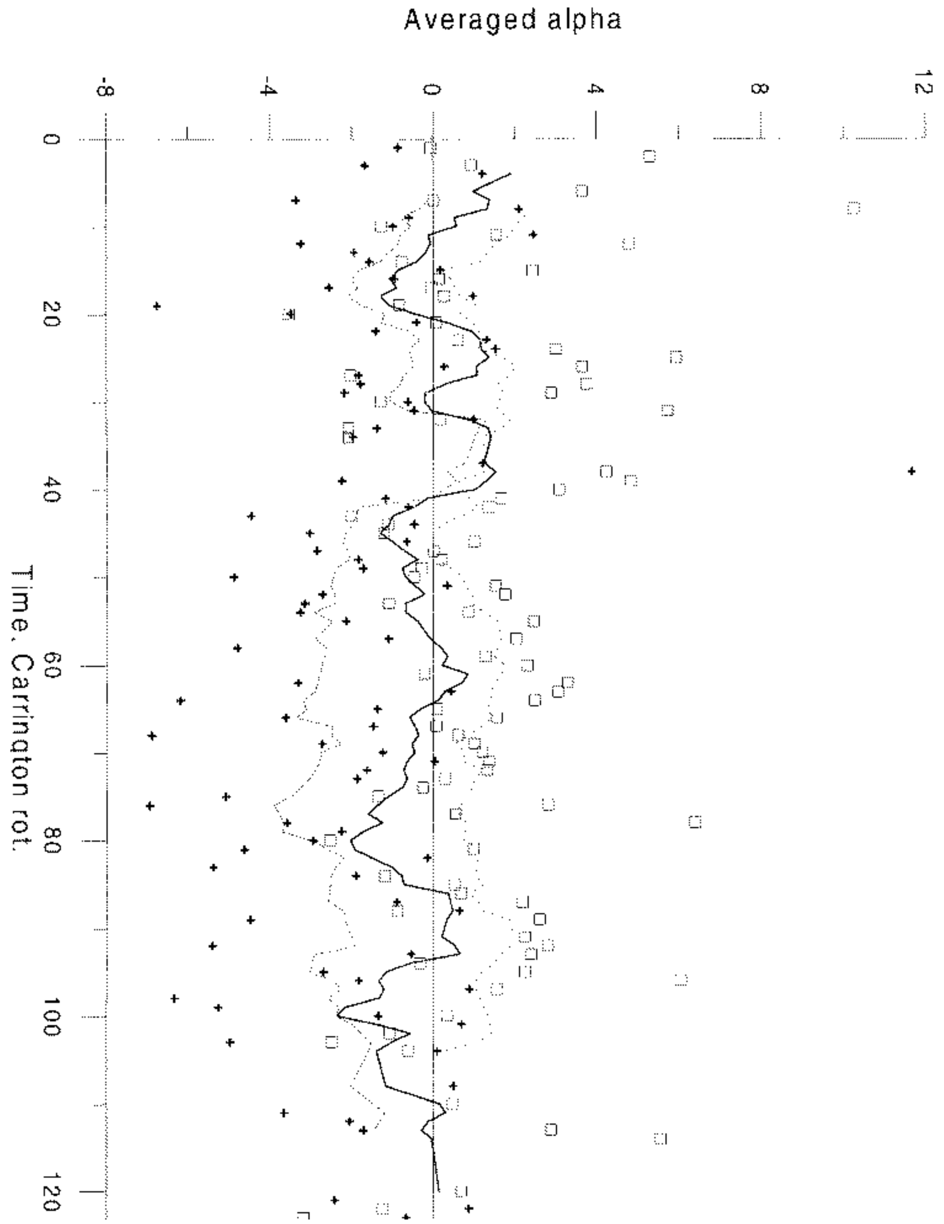

Figure 1. Five point running average interpolation of the mean value $\langle \alpha_f \rangle$ averaged over the total time 1987–1996 versus latitude (dotted line). Averages over ARs sorted by specific 5-degree latitudinal intervals are shown by asterisks. The polynomial interpolation of order 3 is shown as a dash-and-dotted line. This distribution is similar to sine function of latitude.

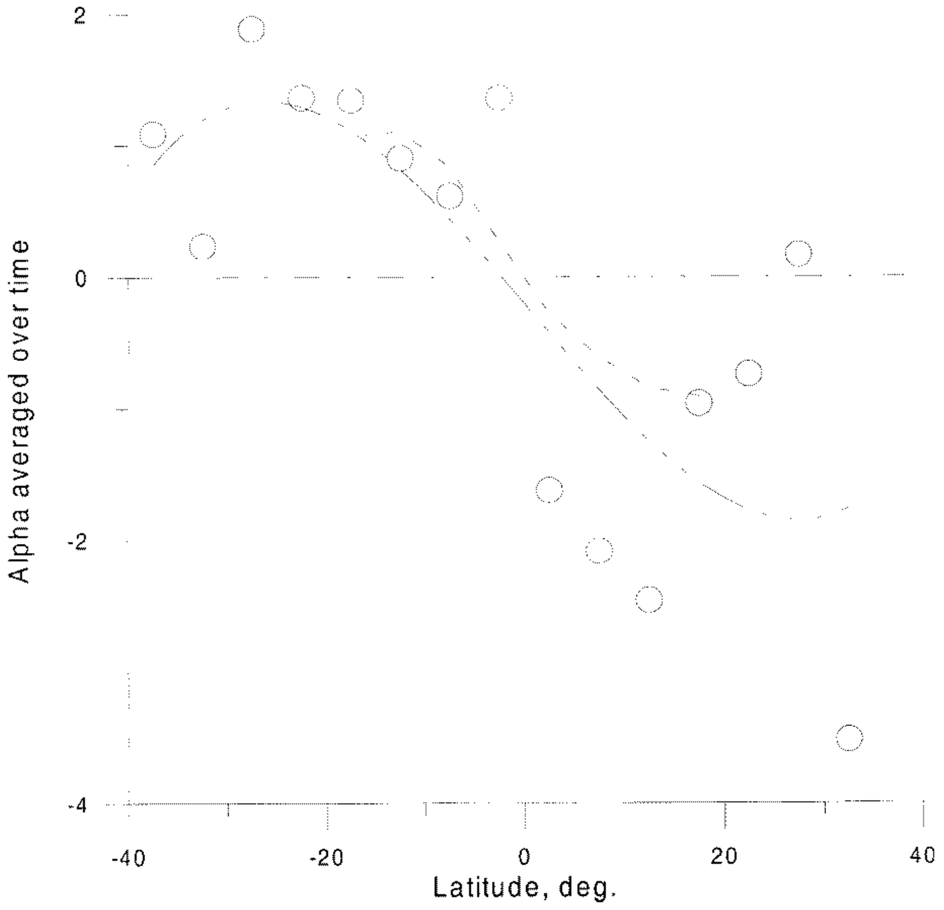

Figure 2. Five point running average interpolation of the mean value $\langle \alpha_f \rangle$ averaged over all latitudes versus time. Crosses indicate averages over individual ARs in the Northern hemisphere, and squares in the Southern. The total sum over the Northern (short dashed line), Southern (dash-and-dotted line) and both the hemispheres (solid line) are shown. Time is given in Carrington rotations numbered starting since rotation 1797 (January 1, 1988).

Thus, we can see here a signature of the so-called semi-biennial cycle. Other signatures of this cycle are also seen by other tracers (Benevolenskaya 1998, 1999; Hoyng 1993; Hoyng et al. 1994; Makarov et al. 1997). Nevertheless, to reveal the global temporal evolution of these quantities one must collect data for the following 11 yr cycle, and so we could carry out such analysis earliest in 2010. We also expect that both of the current helicity and the alpha-factor α_f may be somehow influenced by the main 11 yr cycle (cf., Ruzmaikin 1996).

6. Discussion

Thus, in our analysis we obtained that the force-free alpha-coefficient α_f is negative/positive over the Norther/Southern hemispheres at the photospheric level. Its interpretation as a signature of the α-effect for dynamo mechanism suggests the latter one to have the sign opposite to the first one. Besides that, we found that the values of the α_f slightly vary with time with typical period of 2–3 years irrelatively on the phase of the solar cycle.

We may try to consider a dynamo wave near the surface of the Sun. Although the most of dynamo models assume that the sources of the dynamo mechanism are situated in the depth of the SCZ, we could imagine a surface dynamo as a hypothetical case, which is in accord with recent modelling of the double magnetic cycle with 22 and 2–3 years periods (Benevolenskaya 1999). This hypothetical surface dynamo would require the radial gradient of angular velocity Ω to be negative near the surface of the Sun in order to obtain an equator-ward dynamo wave, which is in agreement with helioseismological studies.

We may suggest that with depth in the SCZ the alpha-effect changes its sign and becomes negative/positive, respectively. This property is in accord with theoretical treatment of, e.g., Glatzmaier (1985), Krivodubskiy (1998), and also recent numerical simulations of Brummell et al. (1998). The phenomenon of the reversed sigh helicity and twist active regions could be considered as an evidence of that.

Indeed, it is also found that there is a minor number of ARS where the the sign of the alpha-effect is indicated opposite to the one in the most of active regions. Such exceptional ARs with respect to current helicity are seen to localise at certain active longitudes, which rotate mostly with the same agnular velocity as the radiative interior of the Sun. One can suggest that such ARs capture the flow from very deep layers of the SCZ, where the alpha-effect has presumably the sign opposite to the one at the surface.

Then we must suggest that $\partial\Omega/\partial r$ is positive in the depth of the SCZ for the case of an equator-ward wave. This conclusion is in agreement with recent helioseismology results (e.g., Kosovichev 1997; Schou et al. 1998) at least in low latitudes. Therefore, we must conclude that the dynamo generation of magnetic fields may take place in the depth of the convection zone but not necessarily in the overshoot layer. This conclusion means that the direction of propagation of the hypothetical surface dynamo wave coincides with the one at the bottom of the SCZ.

We must stress that numerous assumptions made for interpretation of the mean value $\langle \alpha_f \rangle$ as a signature of the α-effect are crude and should be understood as a first theoretical outlook on the available observational data on the twist and helicity in the solar photosphere. Further progress in observational technique and new theoretical treatment of the fine structure of the magnetic field would open new perspectives for understanding the mechanism of the solar magnetic activity.

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