

## Twist of Magnetic Fields in Solar Active Regions

Hongqi Zhang<sup>1</sup>, Shudong Bao<sup>1</sup>, and Kirill M. Kuzanyan<sup>1,2</sup>

<sup>1</sup>*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*

<sup>2</sup>*Heliophysics Lab, Institute of Terrestrial Magnetism, the Ionosphere, and Radio-Wave Propagation, Troitsk, Moscow region, 142190 Russia*

Received September 18, 2001; in final form October 19, 2001

**Abstract**—We study the twist properties of photospheric magnetic fields in solar active regions using magnetographic data on 422 active regions obtained at the Huairou Solar Observing Station in 1988–1997. We calculate the mean twist (force-free field  $\alpha_f$ ) of the active regions and compare it with the mean current-helicity density of these same active regions,  $h_c = \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$ . The latitude and longitude distributions and time dependence of these quantities is analyzed. These parameters represent two different tracers of the  $\alpha$  effect in dynamo theory, so we might expect them to possess similar properties. However, apart from differences in their definitions, they also display differences associated with the technique used to recalculate the magnetographic data and with their different physical meanings. The distributions of the mean  $\alpha_f$  and  $h_c$  both show hemispherical asymmetry—negative (positive) values in the northern (southern) hemisphere—although this tendency is stronger for  $h_c$ . One reason for these differences may be the averaging procedure, when twists of opposite sign in regions with weak fields make a small contribution to the mean current-helicity density. Such transequatorial regularity is in agreement with the expectations of dynamo theory. In some active regions, the average  $\alpha_f$  and  $h_c$  do not obey this transequatorial rule. As a whole, the mean twist of the magnetic fields  $\alpha_f$  of active regions does not vary significantly with the solar cycle. Active regions that do not follow the general behavior for  $\alpha_f$  do not show any appreciable tendency to cluster at certain longitudes, in contrast to results for  $h_c$  noted in previous studies. We analyze similarities and differences in the distributions of these two quantities. We conclude that using only one of these tracers, such as  $\alpha_f$ , to search for signatures of the  $\alpha$  effect can have disadvantages, which should be taken into account in future studies. © 2002 MAIK “Nauka/Interperiodica”.

### 1. INTRODUCTION

The configuration of magnetic fields at the solar surface and their evolution are important problems in solar physics. It is believed that the magnetic field is generated by a dynamo operating near the base of the convection zone, then emerges to the solar surface. A strong twist of the photospheric magnetic field is often observed in solar active regions, which may carry information about the  $\alpha$  effect as a driver of the solar dynamo. Recently, magnetic helicity was employed to describe the twist of the magnetic fields in solar active regions. Several previous studies of the transequatorial change in sign of the magnetic current helicity have been carried out [1–5]. The longitude distribution of the magnetic helicity in solar active regions was analyzed in [6, 7]. Bao and Zhang [4] found a link between the monthly averaged sunspot number and current helicity during the 22nd solar cycle. The temporal and spatial dependences of the mean force-free coefficient are analyzed in [5].

The magnetic twist can also be indirectly inferred from chromospheric H $\alpha$  structures around sunspots [8, 9], the distribution of quiescent filaments [10], and

soft X-ray images [11]. These observations provide information on the twist of the magnetic field above the solar photosphere. The question is: what is that twists the magnetic field at the solar surface? We hope that studies of the magnetic-field twist will reveal information about the properties of solar turbulent convection, and thereby the mechanism for the generation of the solar magnetic field. Both the twist and current helicity have been independently analyzed previously.

In the present study, we compute both of these quantities using the same data and compare their spatial and temporal structures. These parameters represent two tracers of the  $\alpha$  effect in dynamo theory, so we might expect them to possess similar properties. The aim of this paper is to establish how similar or different these quantities are.

In Section 2, we describe how the  $\alpha$  effect in dynamo theory may be related to observed quantities. In Section 3, we describe the observational data and observing technique. In Sections 4–6, we report similarities and differences between the derived properties of the quantities under investigation.

## 2. THE $\alpha$ EFFECT IN DYNAMO THEORY

The  $\alpha$  effect in dynamo theory (see, for example, [12]) is an important quantity used to characterize turbulent convection in the solar convective zone. This effect is believed to enable regeneration of the magnetic field via the dynamo mechanism. The  $\alpha$  effect is estimated in [13] to be

$$\alpha_{\text{ef}} = -\frac{\tau}{3} \langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle, \quad (1)$$

where  $\tau$  is the turbulent correlation time and  $\mathbf{v}$  is the velocity of turbulent fluctuations. There are no reliable estimates of this effect based on observations. Therefore, the  $\alpha$  effect has been extensively studied theoretically. Some authors have suggested that the dynamo quantity  $\alpha_{\text{ef}}$  increases with magnetic-field strength (for example, [14, 15]).

An expression for  $\alpha_{\text{ef}}$  in terms of the current helicity [see formula (9) below] was derived using a first-order smoothing approximation in [16] and without this approximation in [17]. Using this (or a similar) relationship, some properties of the solar dynamo mechanism can be traced using photospheric vector magnetograms. It has been suggested that the  $\alpha$  effect in solar dynamo theory is connected with the current helicity of the fluctuating magnetic field [16–17]. Under certain assumptions, we have

$$\alpha_{\text{ef}} = -\frac{\eta}{\langle \mathbf{B} \rangle^2} \langle \mathbf{B}' \cdot \nabla \times \mathbf{B}' \rangle, \quad (2)$$

where  $\eta$  is the molecular magnetic diffusivity,  $\langle \mathbf{B} \rangle$  the mean field, and  $\mathbf{B}'$  the fluctuating field. The magnetic fields in active regions are believed to be made up primarily of the fluctuating field, with the magnetic fluctuations being statistically stationary. Other assumptions are discussed in the references presented above. There is no explicit criterion for identifying observed active-region fields as mean or fluctuating in the sense of mean-field dynamo theory [18], but we suggest that the  $\alpha$  effect has a definite correlation with the twist and current helicity of the magnetic fields in active regions. Thus, the current-helicity distribution contains some qualitative statistical information on the  $\alpha$  effect in dynamo theory. While the relationship between the current helicity and the dynamo  $\alpha$  effect is a complex problem, we expect that functions of the helicity density and twist have positive correlations with the  $\alpha$  effect. We also note that other opinions have been expressed in some studies, such as [19], which is dedicated to the generation of magnetic helicity under the action of solar turbulent convection [19].

## 3. HELICITY AT THE SOLAR SURFACE

### 3.1. Expressions for the Helicity and Twist

With  $\mathbf{B}$  denoting the magnetic induction, the density of the current helicity is defined to be

$$h_c = \mathbf{B} \cdot \nabla \times \mathbf{B}. \quad (3)$$

Separating  $h_c$  into two parts determined by the parallel ( $\parallel$ ) and perpendicular ( $\perp$ ) components of the magnetic field to the line of sight, we can write

$$h_c = \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel} + \mathbf{B}_{\perp} \cdot (\nabla \times \mathbf{B})_{\perp}. \quad (4)$$

We can assume that the field is force-free within a single active region (see, for example, [20]). We then have for the force-free magnetic field

$$\nabla \times \mathbf{B} = \alpha_f \mathbf{B}, \quad (5)$$

where the constant  $\alpha_f$  can be calculated as

$$\alpha_f = \frac{\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}}{B_{\parallel}^2}. \quad (6)$$

Thus,

$$h_c = \alpha_f B^2 = \left( \frac{B^2}{B_{\parallel}^2} \right) \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}, \quad (7)$$

where  $B$  is the absolute value of the magnetic field. Note that  $\alpha_f$  has only dimensions of inverse length and not explicitly of magnetic-field strength.

### 3.2. Observational Estimates of the Current Helicity and Twist

Existing solar vector magnetographs can be used to measure the three components of the photospheric magnetic field  $\mathbf{B} = \{B_x, B_y, B_z\}$ . Let  $B_z$  be the component of the magnetic field along the line of sight and  $B_x$  and  $B_y$  be vertical (transverse) components of the magnetic field relative to the line of sight. Since active regions are usually not located near the center of the solar disk, the effect of projection becomes important for magnetic fields in active regions but is not the main problem in analyses of the magnetic-field configurations of active regions at relatively high latitudes. Most of the active regions were observed at latitudes  $\pm 30^\circ$ .

The current-helicity parameters  $h_z$  (part of the current helicity  $h_c$ ) and  $\alpha_f$  can be calculated from observed photospheric vector magnetograms:

$$h_z = \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel} = B_z \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right), \quad (8)$$

and

$$\alpha_f = \frac{\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}}{B_{\parallel}^2} = \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right) / B_z. \quad (9)$$

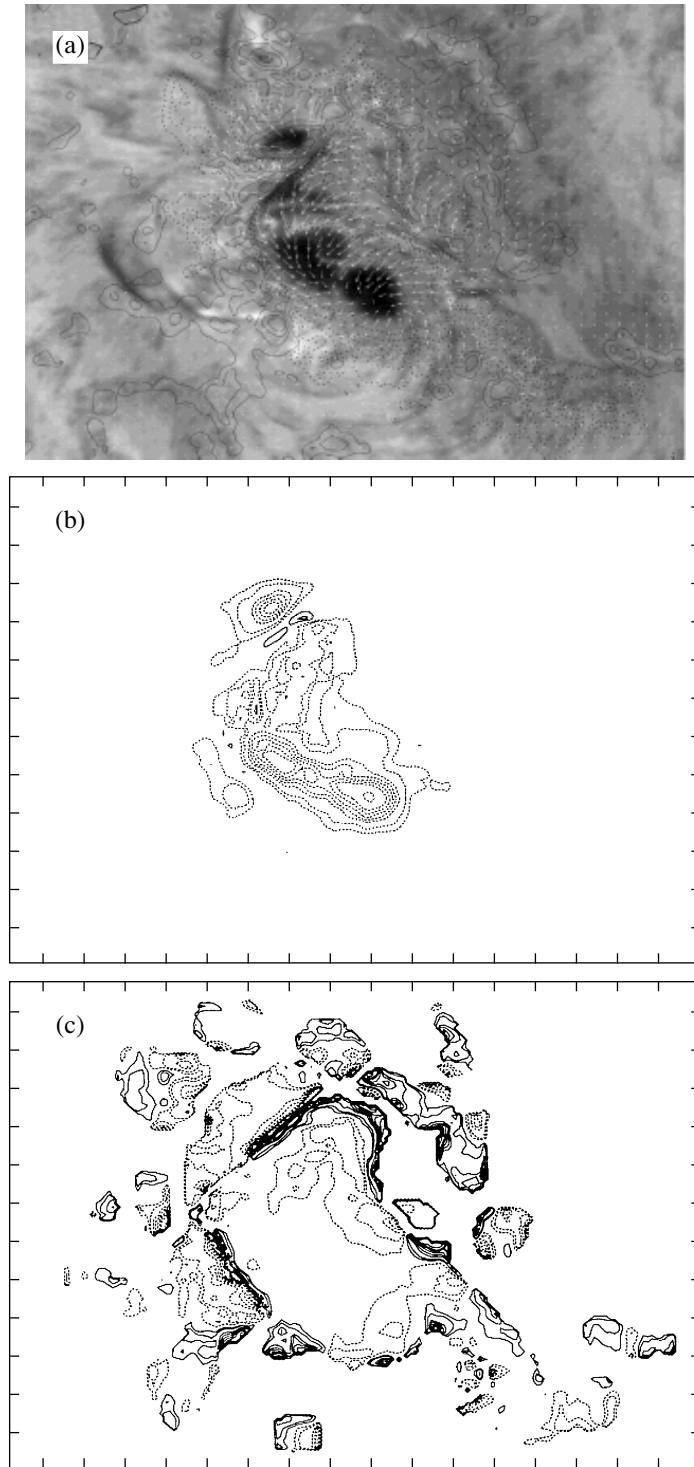


**Fig. 1.** (a) Vector magnetogram for the active region NOAA 6659 at 05:29 UT on June 9, 1991. The solid (dashed) contours indicate positive (negative) values of the longitudinal magnetic field of  $\pm 20, 160, 640, 1280, 1920, 2240, 2560$  and  $2880$  G. (b) Electric-current helicity parameter  $\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$ . The solid (dashed) contours indicate positive (negative) regions of the current-helicity distribution of  $\pm 0.25, 0.5, 1.0, 1.25, 1.5, 1.75, 2.0, 2.5 (\times 10^{-1} \text{ G}^2/\text{m})$ . (c) Force-free field  $\alpha_f$  in areas where the longitudinal field is larger than  $100$  G. The solid (dashed) contours indicate positive (negative) values of the  $\alpha_f$  distribution of  $\pm 0.5, 1.0, 2, 2.5, 3.0, 3.5, 4.0, 5.0 (\times 10^{-7} \text{ m}^{-1})$ . North is up and East is to the left.

Both of these parameters likewise do not provide any real information on the horizontal component of the electric current in current-helicity calculations. The horizontal component of the electric current can sometimes make an important contribution to the total helicity in the photosphere, since the force-free field approximation fails throughout the solar convective zone. However, this approximation is believed to be acceptable for small enough areas in an active region.

The instruments and data-reduction technique have been discussed in previous papers [21, 4]. We resolved the  $180^\circ$  ambiguity in the transverse field and computed it using the techniques described in these papers.

To calculate the helicity parameters, we used only selected domains of the active regions and took into account only pixels far from magnetic neutral lines (e.g., [3]). For this purpose, we applied selection criteria to the magnetic-field components and current [4]. Namely, in order to reduce the influence of noise, which in the original magnetograms does not normally exceed 20 G for the line-of-sight (longitudinal) field  $B_{\parallel}$  and 100 G for the transverse field  $B_{\perp}$ , we removed pixels in which the observed fields were lower than these values before calculating  $h_c$  and  $\alpha_f$  and further neglected these pixels in the averaging. The resulting noise in  $J_z$  was calculated to be about 1 mA/m<sup>2</sup>, and the accuracy in  $\alpha_f$  and  $h_c$  was about 20–25%. Thus, we removed pixels in the vicinity of magnetic neutral lines when determining the averages.

It is interesting that, although the intensity distributions of  $h_z$  and  $\alpha_f$  are different, as a rule these parameters have the same signs in the same areas of the active regions [7]. To best illustrate the basic properties of the current helicity parameters  $h_z$  and  $\alpha_f$ , we present a vector magnetogram of the active region NOAA 6659 on June 9, 1991, and the corresponding values of  $h_z$  and  $\alpha_f$  calculated using this magnetogram (Fig. 1). We find that the distributions of the current helicity  $h_z$  and twist  $\alpha_f$  are similar to those obtained in [7]. This means that the distributions of these parameters over the active region are relatively similar, even if the intensities of the current-helicity parameters in an active region are normally spread over a relatively wide range, as for NOAA 6659 (see Fig. 2).

### 3.3. Statistical Reduction of the Twist and Current-Helicity Data

To study the statistical properties of the current helicity, we calculated the mean helicity parameters of the active regions. Assuming a force-free field using

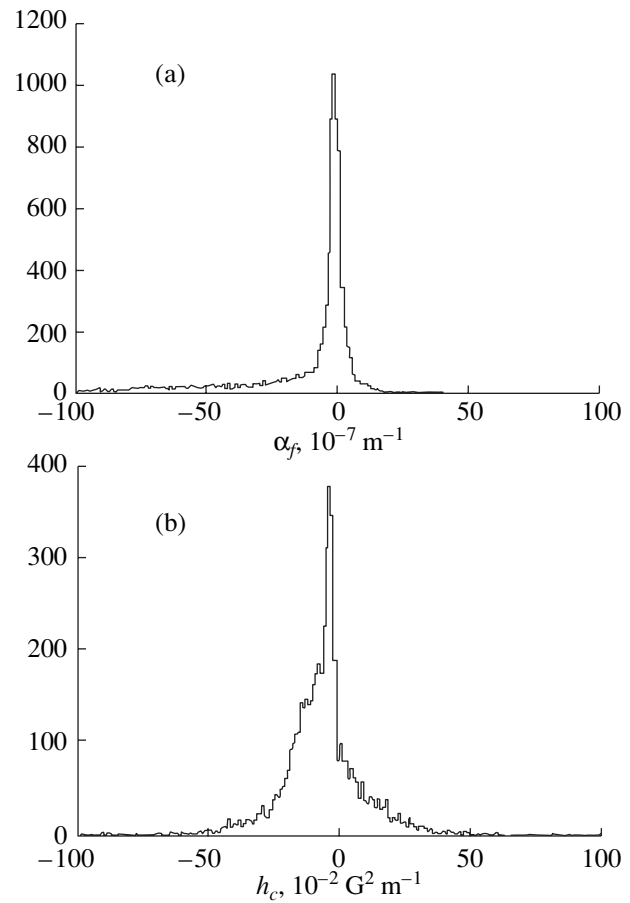


**Fig. 2.** Distributions of the (a) twist  $\alpha_f$  ( $10^{-7} \text{ m}^{-1}$ ) and (b) current-helicity density  $h_c$  ( $10^{-2} \text{ G}^2/\text{m}$ ) for pixels in the magnetogram of NOAA 6659 at 05:29 UT on June 9, 1991.

(8), we can obtain the mean value  $\langle \alpha_f \rangle$  for the active regions, where the angular brackets denote a spatial average. Neglecting the contribution of the transverse component of the electric current, taking into account relation (7), we calculate the mean density of the current helicity in the photosphere  $\langle h_c \rangle$ .

Both  $\langle \alpha_f \rangle$  and  $\langle h_c \rangle$  have been used earlier in studies of the helicity properties of active regions, although they were analyzed separately from each other. In the current study, we computed  $\langle \alpha_f \rangle$  and  $\langle h_c \rangle$  using the same data and compared their spatial and temporal structures.

We used photospheric vector magnetograms of solar active regions obtained with the vector magnetograph of the Huairou Solar Observing Station. The data cover the period 1988–1997 and include most large active regions present in these ten years. We computed  $\langle \alpha_f \rangle$  and  $\langle h_c \rangle$  as described above (see, for example, [3, 4]) for 422 active regions (one magnetogram per region). For the sake of simplicity, we omit the angular brackets  $\langle \rangle$  below.

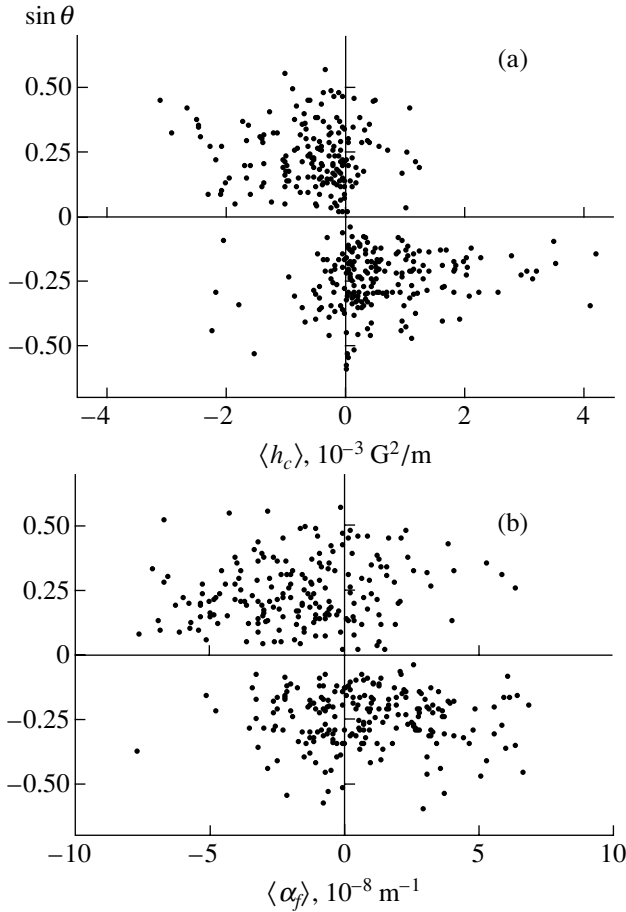


**Fig. 3.** Latitude distributions of the (a) mean current-helicity density  $\langle \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel} \rangle$  and (b) the mean twist  $\langle \alpha_f \rangle$  for 422 active regions. Each point represents a single active region.

#### 4. LATITUDE DISTRIBUTION OF THE TWIST AND CURRENT HELICITY. INFLUENCE OF THE PROJECTION EFFECT ON THE MAGNETIC-FIELD ESTIMATES

Figure 3 shows the latitude distributions of  $\alpha_f$  and  $h_c$ . Although the definitions of the two helicity parameters differ, they show similar behavior—the magnetic fields in opposite hemispheres are mainly twisted in opposite directions. Figure 4 presents the distributions of  $\alpha_f$  and  $h_c$  averaged over latitude intervals with representative numbers of observational data points. Figure 5 shows histograms of  $h_c$  and  $\alpha_f$  for the active regions.

For  $h_c = \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$ , 84% of the active regions in the northern hemisphere and 81% in the southern hemisphere have negative and positive mean current-helicity densities, respectively. The percentage of active regions following this tendency is lower for  $\alpha_f$ . Only 74% (62%) of active regions in the northern (southern) hemisphere show this tendency. This is

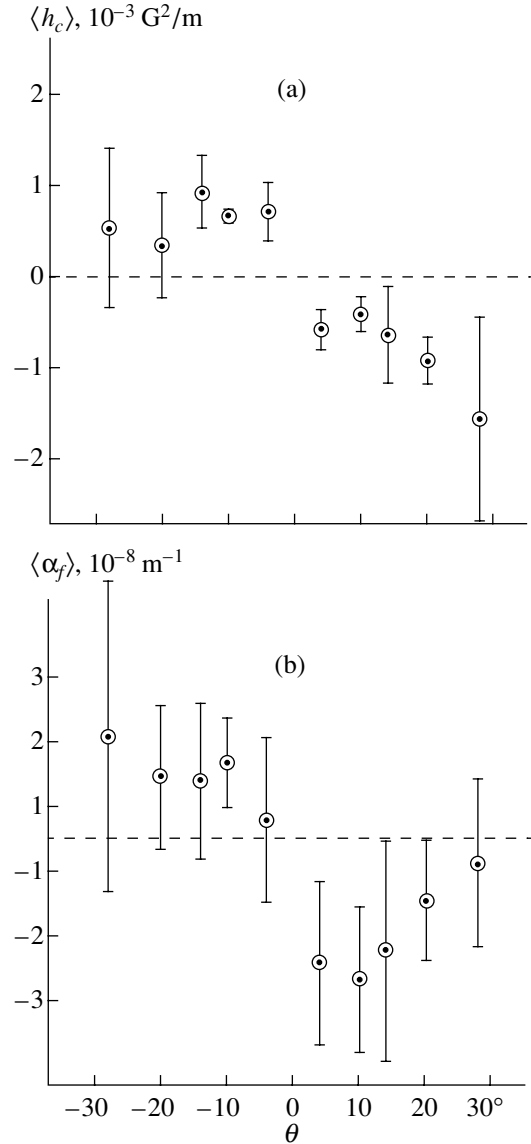


**Fig. 4.** Values of the (a) mean current-helicity density  $\langle \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel} \rangle$  and (b) twist density  $\langle \alpha_f \rangle$  averaged over latitude intervals with representative numbers of observations. We used five intervals between latitudes of  $0^\circ$ ,  $8^\circ$ ,  $12^\circ$ ,  $16^\circ$ ,  $24^\circ$ , and  $32^\circ$  in each hemisphere. The vertical bars show 95% confidence intervals.

consistent with the results of [2], although our definition of  $\alpha_f$  is slightly different from that used by Pevtsov *et al.* [2]. With few exceptions, most of the active regions were observed in the range  $\pm 30^\circ$ . The maxima of the mean current-helicity density occur near  $\sin \theta = \pm 0.25$ , where  $\theta$  (the solar latitude) is about  $\pm 15^\circ$ , in agreement with [22]. However, these patterns could be a consequence of our selection of the active regions for study, as well as of the fact that the current-helicity parameters were probably

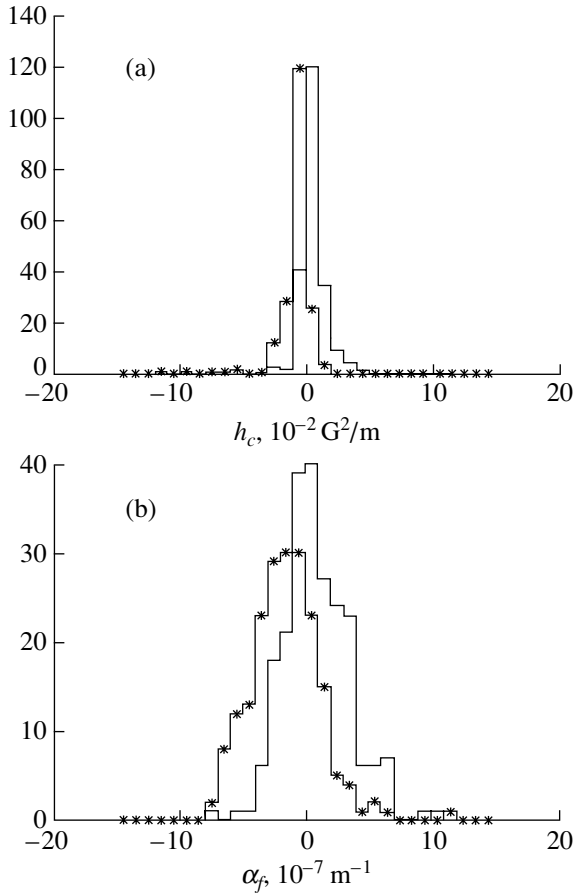


**Fig. 5.** Histograms of the distributions of the mean (a) current-helicity density  $h_c$  ( $\text{G}^2/\text{m}$ ) and (b)  $\alpha_f$  ( $\text{m}^{-1}$ ) for the 422 active regions. The distributions with (without) asterisks show the current-helicity parameters in the northern (southern) hemispheres.

analyzed over regions of strong magnetic fields, which are usually present at such latitudes.

Figure 6 shows the relation between  $h_c$  and  $\alpha_f$ . In about 40% of the active regions, the mean  $h_c$  and  $\alpha_f$  have opposite signs. The magnitude of the magnetic field acts as a weight factor when averaging the current-helicity density  $h_c$  over a given active region. This may explain the different properties of  $h_c$  and  $\alpha_f$ . Figure 6b shows the latitude dependence of the correlation of  $h_c$  and  $\alpha_f$  upon averaging in latitude. The correlation decreases with increasing heliocentric distance; for example, the correlation is about 70% near the disk center and about 50% near latitude  $\pm 25^\circ$ . This difference can be ascribed to the influence of the effect of projection on estimations of the magnetic field, which is more important at higher latitudes and for larger inclinations of the field to the solar surface. There is also a slight difference between the two hemispheres.

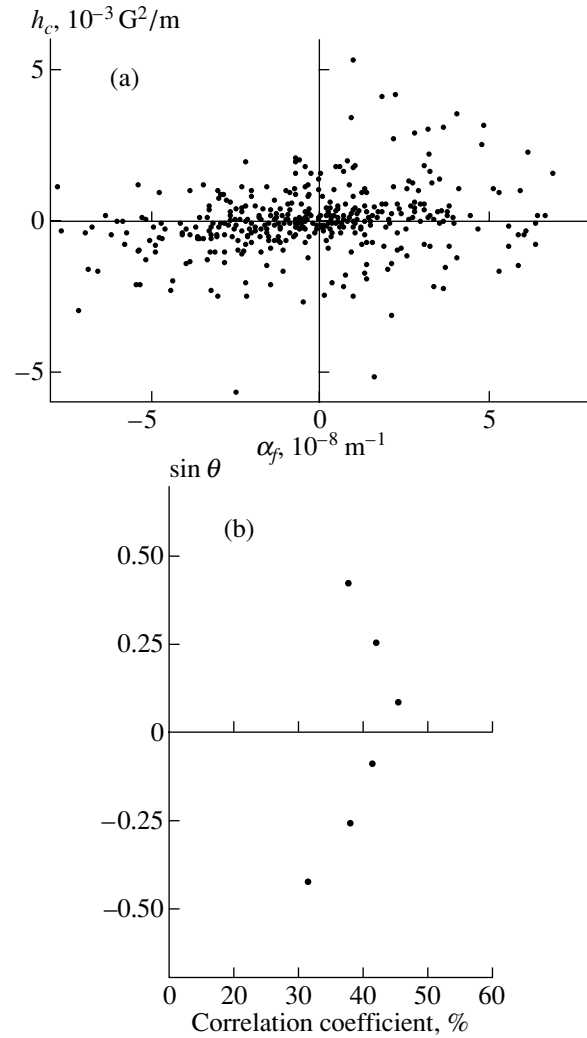


**Fig. 6.** (a) Relationship between the mean current-helicity parameters  $\alpha_f$  and  $\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$  for 422 active regions. (b) Relationship between the correlation coefficient for  $h_c$  and  $\alpha$  and the latitude after averaging over the sine of the latitude in steps of 0.05.

## 5. EVOLUTION OF THE MEAN HELICITY DENSITY

Figure 7a shows the time variations of  $h_c$ . The data show appreciable scatter in 1989–1993 and much lower values in 1994–1997. Accordingly, the solar activity was much higher in 1988–1993 and lower in 1994–1997. The relation between the mean current-helicity density and the number of sunspots was briefly analyzed in [4]. Comparing our Fig. 7a with Fig. 3 of [4], we find that the amplitude of  $\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$  changes with time. This implies that the current-helicity density of active regions depends on the phase of the solar magnetic cycle. This may be due to the fact that the magnetic-field strength varies with the solar cycle, with  $h_c$  somehow being proportional to the magnetic field.

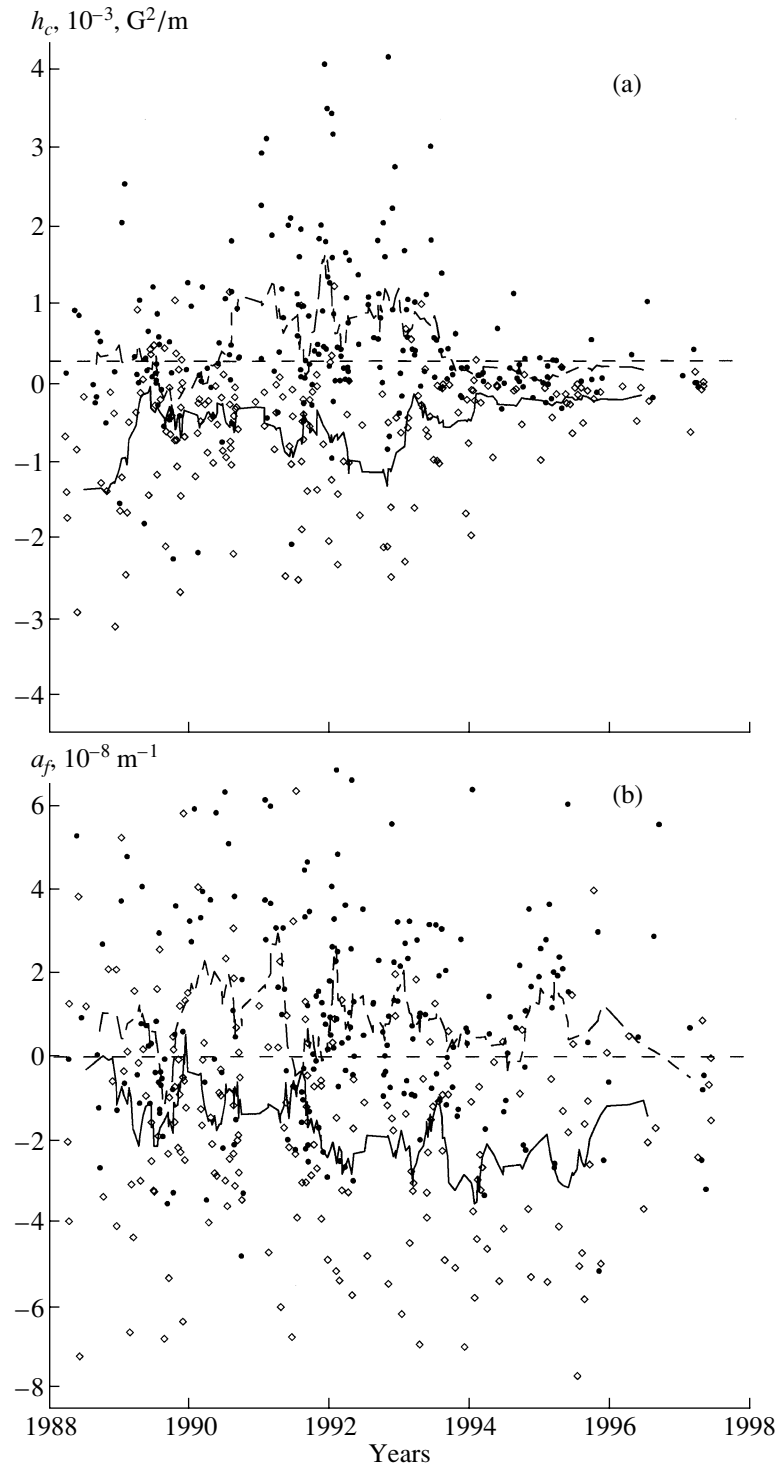


**Fig. 7.** (a) Time evolution of  $\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$ ; the vertical axis is in  $10^{-3} G^2/m$ . (b) Time evolution of  $\alpha_f$ ; the vertical axis is in  $10^{-8} m^{-1}$ . The active regions in the northern and southern hemispheres are denoted by diamonds and filled circles, respectively. The solid line the 11-point moving average over the northern (southern) hemispheres.

Figure 7b shows the evolution of  $\alpha_f$  during the same period. There is no significant difference between years of solar maximum and solar minimum. This implies that the mean twist density of active

regions does not significantly depend on the solar activity. Moreover, the parameter  $\alpha_f$  in active regions loses information about the magnetic-field strength. From a statistical point of view, it is difficult to find

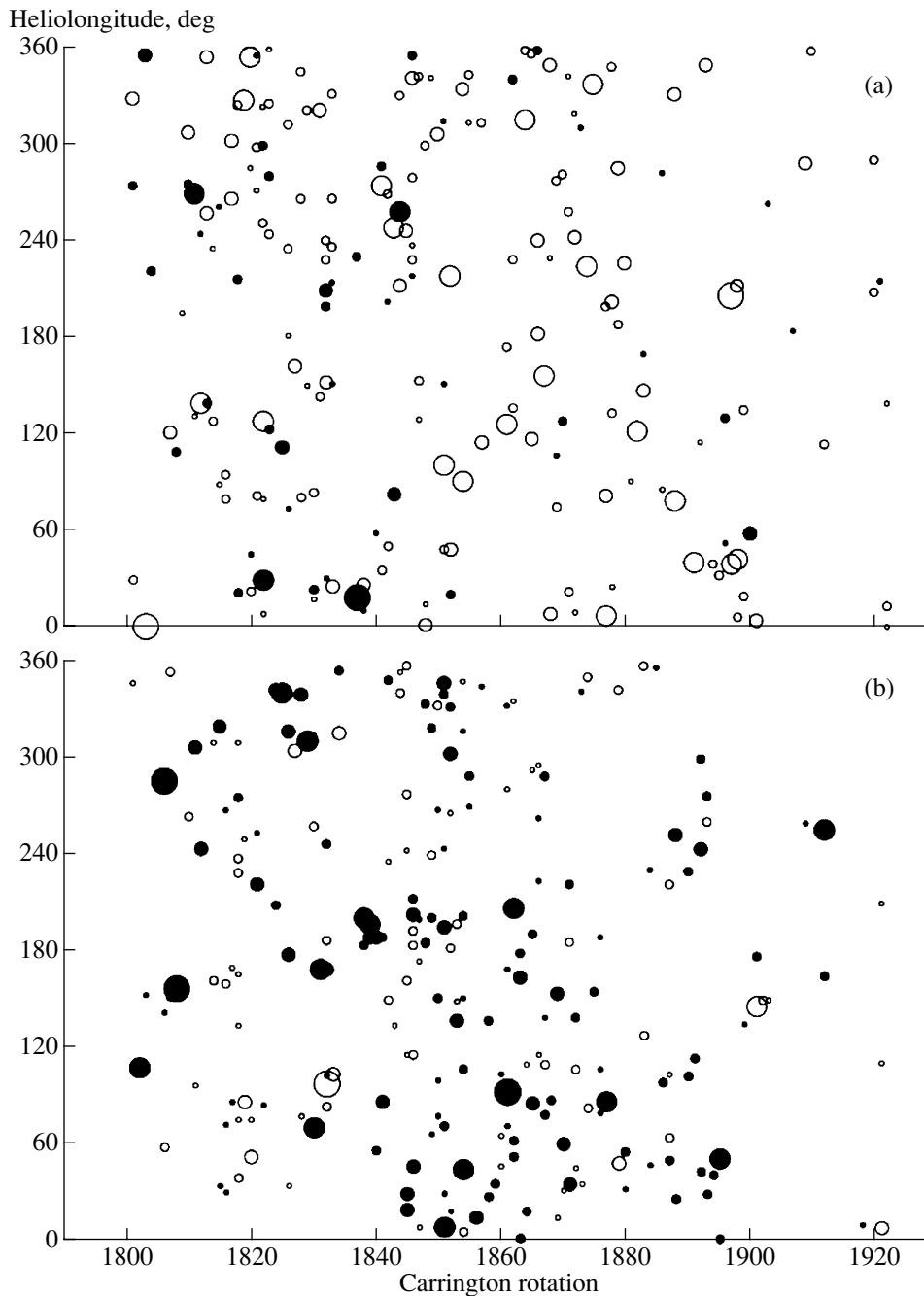


**Fig. 8.** Longitude distribution of  $\alpha_f$  as a function of time (in terms of Carrington rotations) in the (a) northern and (b) southern hemispheres. The density is indicated by the sizes of the circles: 0, 1, 3, 5, 7 ( $\times 10^{-8} \text{ m}^{-1}$ ). Black (white) circles denote positive (negative) sign values.

a clear dependence of the mean  $\alpha_f$  on the phase of the solar cycle based on the studied sample of active regions.

## 6. LONGITUDE DISTRIBUTIONS OF $\alpha_f$ AND $h_c$

Figure 8 shows the longitudinal distribution of  $\alpha_f$  as a function of time (measured in solar rotation

periods) in both hemispheres. The regions where the sign of  $\alpha_f$  does not follow the transequatorial rule are distributed quite uniformly in longitude. On the other hand, Zhang and Bao [7] found a tendency for active regions with opposite signs of  $h_c$  to cluster at certain longitudes. Note, however, that Canfield and Pevtsov [6] also analyzed the longitudinal distribution of  $\alpha_f$  and found some tendency for active regions whose

helicity distribution did not follow the transequatorial rule to cluster at certain longitudes over many rotations.

## 7. DISCUSSION

Various properties of the twist of the photospheric magnetic field can be derived from magnetograms of active regions. The twist of the magnetic field is linked with the magnetic (current) helicity. Because the total helicity  $\mathbf{B} \cdot (\nabla \times \mathbf{B})$  cannot be obtained using photospheric magnetographs, the study of  $\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$  and  $\mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}/B_{\parallel}^2$  (i.e.,  $\alpha_f$ ) becomes important and necessary. By analyzing the helicity parameters in detail, we find that they not only obey the transequatorial rule [i.e., the mean current helicity and twist density of active regions usually have negative (positive) sign in the northern (southern) hemisphere] but also contain slightly different information on the twist properties of the magnetic field.

We see in (4) that  $\alpha_f$  describes the degree of the twist of the magnetic field. It is normally believed that the twist of magnetic lines of force is due to the action of the Coriolis force, differential rotation, etc., as magnetic lines of force rise from the base of the convection zone and form active regions at the solar surface. If the magnetic field is generated by solar-dynamo action and the magnitude of the photospheric large-scale magnetic field depends on the phase of the solar activity cycle, the mean intensity of the electric current-helicity density should contain some information about both the twist and strength of the magnetic field. However,  $\alpha_f$  is related to the twist of the magnetic field of active regions and does not depend on the intensity of the field, so the calculated value of  $\alpha_f$  probably contains information primarily on the Coriolis force and differential rotation, which do not significantly change with the phase of the solar cycle.

On the other hand, in about 30% of the total number of active regions in each hemisphere, the sign of  $\alpha_f$  is opposite to that of the majority of active regions in that hemisphere. In such active regions, the mean twist of the magnetic field differs from that determined by the Coriolis force. This probably reflects some statistical effects associated with the redistribution of solar magnetic fields, although this difference could also be partially due to the averaging procedure when twists of opposite sign for regions of weak field make a small contribution to the mean current-helicity density. Our results show that the two different helicity quantities  $\alpha_f$  and  $h_c$  have different properties. The transequatorial rule is stronger for the  $h_c$  than for the  $\alpha_f$  distribution.

The  $h_c$  distribution shows a clear dependence on the level of solar activity (phase of the solar cycle), while  $\alpha_f$  does not. The active regions with reversed sign of  $h_c$  (disobeying the transequatorial rule) cluster at certain longitudes. We can clearly see indications of such reverse-sign longitudes for  $h_c$ , but not for  $\alpha_f$ . One possibility is that  $\alpha_f$  has lost information about the magnetic-field strength and contains mainly information on the magnetic shear near magnetic neutral lines, as discussed in [23, 7].

Although some properties of the helicity in solar active regions are discussed above, we should also point out that some differences between the distributions for  $\alpha_f$  and  $h_c$  could be due to uncertainties in the observational data and reduction technique, as well as other factors, such as the effect of projecting the vector magnetic field onto the solar surface and errors in the measurements of the transverse magnetic field. However, it is hardly likely that such factors could cause about 40% of the active regions to have opposite signs for  $h_c$  and  $\alpha_f$  (cf. Fig. 6a).

The basic agreement between the transverse magnetic fields determined from Huairou magnetograms and the fine structures in H $\alpha$  and H $\beta$  filtergrams has been confirmed by a number of studies [24, 25]. The influence of errors in the transverse field measurements on the difference in the current helicities calculated using the Huairou and Mees datasets was recently analyzed in [26]. It was found that this is probably not important for determining the signs of the current helicity in most active regions. However, it is not clear if such measurement errors contribute a systematic bias to the statistical properties of the current helicity of active regions. We also note that resolving the 180° ambiguity in the highly sheared transverse magnetic field in areas near magnetic neutral lines in active regions is associated with certain difficulties, which will be analyzed in forthcoming papers.

Thus, in this paper, we have studied the distributions of observational tracers of the  $\alpha$  effect. Allowing for the qualifications about the applicability of the Keenings–Seehafer formula noted above, this is the first measurement of the  $\alpha$  effect. Knowledge of the latitude and spatial distributions of the  $\alpha$  effect is very important from the point of view of dynamo theory. If this theory is to explain Maunder butterfly diagrams, the dynamo waves [27] must propagate toward the equator at low latitudes. For this reason, the sign of the product of the radial gradient of the differential rotation and the  $\alpha$  effect should be negative (positive) in the northern (southern) hemispheres. Earlier, insufficient knowledge of the value of the  $\alpha$  effect led to uncertainty and created grounds for speculation about the direction of propagation of the dynamo wave.

Here, we suggest the following interpretation of the results of dynamo theory. The values of  $\alpha_f$  and  $h_c$  are mainly negative (positive) in the northern (southern) hemispheres. These quantities are linked with the magnetic fields near the Solar surface. We expect these quantities to change sign deep in the solar convective zone (see, e.g., [28, 29]) so that they become positive (negative) in the northern (southern) hemispheres. Then, according to the Kainigs–Seehafer formula (2), the sign of the  $\alpha$  effect near the convection-zone base is negative/positive in the northern/southern hemispheres. Taking into account the positive radial gradient of differential rotation (e.g., [30]) this leads to dynamo waves [27] propagating toward the equator, as required to explain Maunder butterfly diagrams.

We see that both  $h_c$  and  $\alpha_f$  are equally important for identifying signatures of the solar  $\alpha$  effect. We conclude that approaches based only on one of these tracers, such as  $\alpha_f$ , even one having the same dimensions as the  $\alpha$  effect, could have some shortcomings. Therefore, both of these tracers of the  $\alpha$  effect should be taken into consideration in future studies. The parameter  $h_c$  is relevant for investigations of the sign of the  $\alpha$  effect, while  $\alpha_f$  is more suitable as an indicator of the magnitude of the  $\alpha$  effect. Nevertheless, the use of data only for  $\alpha_f$  [5] can reveal the main structure of the  $\alpha$  effect in the solar convective zone.

## 8. CONCLUSION

Thus, the main results of the paper are the following.

(1) The average  $\alpha_f$  and  $h_c = \mathbf{B}_{\parallel} \cdot (\nabla \times \mathbf{B})_{\parallel}$  both provide information on the twist of magnetic-field lines. The difference is that  $\alpha_f$  does not contain information on the magnetic-field strength, while  $h_c$  does.

(2)  $\alpha_f$  and  $h_c$  show similar latitude and longitude distributions. However, the distribution of the mean current-helicity density  $h_c$  of active regions shows a stronger transequatorial regularity than does that of  $\alpha_f$ . The distribution of active regions that do not follow the transequatorial rule for the sign of  $\alpha_f$  is more uniform in longitude than the corresponding distribution for  $h_c$  and reveals no clustering at particular longitudes. This transequatorial sign rule for  $\alpha_f$  and  $h_c$  corresponds to the general expectations of dynamo theory.

(3) About 40% of the active regions have  $\alpha_f$  and  $h_c$  with opposite signs. This may be due to the fact that  $h_c$  depends on the magnetic-field strength as a weight factor.

## 9. ACKNOWLEDGMENTS

We wish to thank Dr. T.J. Wang for useful discussions and help with the computer programs. This research was supported by the Chinese Academy of Sciences and the National Science Foundation of China. KMK would like to thank the Chinese Academy of Sciences and National Science Foundation of China for supporting his visit to Beijing Astronomical Observatory, as well as also the staff of the Huairou Solar Observing Station for providing good conditions during his stay in China. This work was partially supported by the Russian Foundation for Basic Research (project nos. 99-02-18346 and 00-02-17854), a Young Researchers' Grant from the Russian Academy of Sciences, and NATO (grant PST.CLG.976557). We thank Dr. V. Obridko and the anonymous referee for helpful comments and suggestions.

## REFERENCES

1. N. Seehafer, *Sol. Phys.* **125**, 219 (1990).
2. A. A. Pevtsov, R. C. Canfield, and T. R. Metcalfe, *Astrophys. J. Lett.* **440**, L109 (1995).
3. V. I. Abramenko, T. J. Wang, and V. B. Yurchishin, *Sol. Phys.* **168**, 75 (1996).
4. S. D. Bao and H. Q. Zhang, *Astrophys. J.* **496**, L43 (1998).
5. K. M. Kuzanyan, H. Zhang, and S. Bao, *Sol. Phys.* **191**, 231 (2000).
6. R. C. Canfield and A. A. Pevtsov, in *Synoptic Solar Physics*, Ed. by K. S. Balasubramaniyam, J. W. Harvey, and D. M. Rabin, *ASP Conf. Ser.* **140**, 131 (1998).
7. H. Zhang and S. Bao, *Astrophys. J.* **519**, 876 (1999).
8. G. E. Hale, *Nature* **119**, 708 (1927).
9. R. S. Richardson, *Astrophys. J.* **93**, 24 (1941).
10. S. F. Martin, R. Bilimoria, and P. W. Tracada, in *Solar Surface Magnetism*, Eds. C. J. Rutten and C. J. Schrijver (Kluwer, Dordrecht, 1994), p. 303.
11. D. M. Rust and A. Kumar, *Astrophys. J. Lett.* **464**, L199 (1996).
12. F. Krause and K. H. Rädler, *Mean-Field Magnetohydrodynamics and Dynamo Theory* (Akademie-Verlag, Berlin, 1980).
13. F. Krause, *Habilitationsschrift* (Univ. Jena, 1967); *The Turbulent Dynamo*, NCAR Technical Note TN/IA-60 (1971).
14. A. Brandenburg and K. J. Donner, *Mon. Not. R. Astron. Soc.* **288**, L29 (1997).
15. A. Brandenburg, S. H. Saar, and C. R. Turpin, *Astrophys. J. Lett.* **498**, L51 (1998).
16. R. K. Keinigs, *Phys. Fluids* **26**, 2558 (1983).
17. N. Seehafer, *Europhys. Lett.* **27**, 353 (1994).
18. N. Seehafer, in *New Perspectives on Solar Prominences (IAU Coll. 167)*, Eds. D. Webb, D. Rust, and B. Schmieder, *ASP Conf. Ser.* **150**, 407 (1998).
19. D. W. Longcope, G. H. Fisher, and A. A. Pevtsov, *Astrophys. J.* **507**, 417 (1998).

20. L. Woltjer, Proc. Nat. Acad. Sci. **44**, 489 (1958).
21. T. J. Wang, A. A. Xu, and H. Q. Zhang, Sol. Phys. **155**, 99 (1994).
22. J. B. Zirker, S. F. Martin, K. Harvey, and V. Gaizauskas, Sol. Phys. **175**, 27 (1997).
23. H. Zhang and S. Bao, Astron. Astrophys. **339**, 880 (1998).
24. H. Q. Zhang, G. Ai, T. Sakurai, and H. Kurokawa, Sol. Phys. **136**, 269 (1991).
25. H. Q. Zhang, Sol. Phys. **154**, 207 (1994).
26. S. D. Bao, A. A. Pevtsov, T. J. Wang, and H. Q. Zhang, Sol. Phys. **195**, 75 (2000).
27. E. N. Parker, Astrophys. J. **122**, 293 (1955).
28. H. Yoshimura, Astrophys. J. **247**, 1102 (1981).
29. N. H. Brummell, N. E. Hurlburt, and J. Toomre, Astrophys. J. **493**, 955 (1998).
30. J. Schou, H. M. Antia, S. Basu, *et al.*, Astrophys. J. **505**, 390 (1998).

*Translated by H. Zhang*