SOLAR TURBULENT DYNAMO NEAR CONVECTIVE OVERSHOOT LAYER AND RADIATIVE TACHOCLINE

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In order to extend the abilities of the $\alpha\Omega$-dynamo model to explain the observed regularities and anomalies of the solar magnetic activity, the magnetic quenching of the α-effect were included in the model, and newest helioseismically determined inner rotation of the Sun has been used. Allowance for the radial inhomogeneity of turbulent velocity in derivations of the helicity parameter resulted in a change of sign of the α-effect from positive to negative in the northern hemisphere near the bottom of the solar convection zone (SCZ). The change of sign is very important for direction of Parker's dynamo-waves propagation and for parity of excited magnetic fields. The period of the dynamo-wave calculated with taking into account the magnetic α-quenching is about seven years, that agrees by order of magnitude with the observed mean duration of the sunspot cycles. Using the modern helioseismology data to define dynamo-parameters, we conclude that north–south asymmetry should exist in the meridional field. The calculated configuration of the net meridional field is likely to explain the magnetic anomaly of polar fields (the apparent magnetic "monopole") observed near the maxima of solar cycles.

INTRODUCTION

One of the most important problems in the solar physics is to understand the origin of the Sun's magnetic cycle. Currently, it is widely believed that the solar cycle results from a turbulent hydromagnetic dynamo. Majority of detailed mathematical models of the solar dynamo are based on the mean-field theory for large-scale fields of turbulent fluids [20, 34, 35, 45, 46]. Mean-field equations in this approach are obtained by averaging over the fluctuating, or small-scale, magnetic, b, and velocity, v, fields. A "dynamo machine" on the Sun is assumed to operate to the convection zone, where the velocity field can be separated into two components of different spatial scales: i) large-scale velocity $\vec{V}$ which corresponds to solar rotation, and ii) small-scale turbulent convection $\vec{v}$. The motions on different scales are not independent and their interaction results in a non-uniform global rotation, $\vec{V}(r,\theta) = r\sin\theta\,\Omega(\vec{r},\theta)\,\vec{i}_\varphi$, and helical (cyclonic) convection characterized by a parameter of mean turbulence helicity, $\alpha(r,\theta) = \alpha_0(r)\cos\theta \approx -\frac{\tau}{3}\langle\vec{v}\cdot\nabla\times\vec{v}\rangle\cos\theta$. Here, $\Omega(\vec{r},\theta)$ is the angular velocity; τ is the characteristic time of the turbulent pulsations; the angular brackets $\langle\ \ \rangle$ denote averaging over scales larger than the characteristic scale of the rms turbulent velocity $v = \sqrt{\langle\vec{v}^2\rangle}$; r, θ, and φ are radius, polar angle (colatitude), and longitude of usual spherical coordinate system whose origin is at the centre of a sphere of solar radius R; $\vec{i}_\varphi$ is the azimuthal unit vector. (The heliolatitude θ^* often used by observers is $90^\circ - \theta$).

The turbulence helicity was introduced by Steenbeck, Krause & Rädler [46]. They called the ability of the mean kinetic helicity $h_k = \langle\vec{v}\cdot\nabla\times\vec{v}\rangle$ to excite the electromotive force along the large-scale magnetic field the "α-effect". An expression for the α-effect was also derived in terms of the mean current helicity of the fluctuating magnetic field $h_c = \langle\vec{b}\cdot\nabla\times\vec{b}\rangle$ [13, 42], and the mean twist $\alpha_f = h_c/b$ of the magnetic fields of active regions [50]. The radius and colatitude dependence of the helicity parameter, $\alpha(r,\theta)$, in the solar convection zone (SCZ) cannot be directly obtained from observations. Krause [19] assumed that the α-parameter is proportional to $\cos\theta$ and changes its sign about the equatorial plane ($\theta = \pi/2$). This assumption agrees with observations of magnetic helicity [36, 42], and such an angular dependence is generally accepted nowadays. Early studies of the turbulent helicity as a function of solar radius were performed by means of analytical calculations [47] and numerical simulations [51]. Stix [47] had obtained a positive convex profile for $\alpha(r)$, while in numerical studies by Yoshimura [51] evidence was found that in the northern hemisphere the helicity parameter changes its sign from positive in the near-surface part of the SCZ to negative near the bottom of the SCZ. Later on, this radial behaviour of the mean turbulent helicity has been confirmed by analytical calculations of Krivodubskij [22, 23] and Krivodubskij & Schultz [25] using physical parameters of the SCZ models. In addition, one can obtain alternative estimates of the helicity parameter by using a tracer method, which is based on the idea that surface active regions contain information on the MHD flows at the locations where they arise and pass through [32]. Studies of the tilt of bipolar sunspot groups (magnetic twist) [29, 41] and current helicity calculations in the photosphere [1, 28, 36, 42] further confirm that the α-effect changes its sign in solar interior.

It is believed that the solar axisymmetric global (large-scale) magnetic field $\vec{B}$ incorporates two constituents: one component, hidden in deep layers and stretched along the solar parallels, is a strong toroidal (azimuthal) field, $\vec{B}_{\mathrm{T}}$, and the second component is a relative weak poloidal (meridional) field, $\vec{B}_{\mathrm{P}}$. The observed regularities of solar magnetic activity can be attributed to the poloidal and toroidal magnetic fields, which are coupled and evidently generated by a common process.

The mean-field dynamo theory provides very plausible explanation for the solar magnetic cycle [34, 35, 45]. In the deep highly conducting layers of the SCZ a strong toroidal field is generated by differential rotation stretching a weak poloidal field (the Ω-effect). The helical turbulent convection plays a crucial role in the closing of solar dynamo-cycle. Namely, helicity generates a new poloidal field, with the magnetic polarity opposite to that of the previous cycle, by twisting the toroidal field-lines (the α-effect). The inductive effect by the differential rotation is much stronger as compared to the α-effect. Therefore, contribution of the helical convection to the generation of the toroidal field can be neglected (the $\alpha\Omega$-dynamo approach). The turbulent viscosity $\nu_{\mathrm{T}} \approx (1/3)\, v\, l \approx (1/3)\tau v^2$ (l is the mixing length of the turbulent motions) is decisive in the dissipation of the large-scale magnetic fields since this coefficient is several orders of magnitude larger than the value of microscopic magnetic viscosity $\nu_m = c^2/4\pi\sigma$ (σ is the microscopic conductivity).

When generation and turbulent dissipation of magnetic flux are balanced, the cycling $\alpha\Omega$-dynamo can be described by two induction equations [20, 34, 35]. Parker [34] has shown that the solutions of these equations are two travelling dynamo waves. The radial gradient of the angular velocity, $\partial\Omega/\partial r$, together with the helical convection, α, produces the meridional migration of dynamo waves, while the latitudinal gradient of the angular velocity, $\partial\Omega/\partial\theta$, causes the radial migration. The majority of current studies primarily take into account the radial shear in the angular velocity. Then, the direction of the meridional migration depends on the sign of the product $\alpha \cdot \partial\Omega/\partial r$ [51]. This quantity has to be negative in the northern hemisphere for the dynamo wave to propagate toward the equator, $\alpha \cdot \partial\Omega/\partial r < 0$; and, on the contrary, magnetic waves drift towards the poles under the condition that $\alpha \cdot \partial\Omega/\partial r > 0$.

CONVECTIVE OVERSHOOT LAYER AND RADIATIVE TACHOCLINE

For the $\alpha\Omega$-process to be effective, it is necessary for the magnetic flux tubes to be kept in the region of the field generation in the SCZ for a long time. However, due to fast buoyant rise of magnetic fields it is generally difficult to ensure their significant amplification and storage during a time comparable to the solar cycle period. The *convective overshoot layer*, just beneath the base of the SCZ, where the sinking convective bubbles penetrate a fraction of a scale height into the stable radiative interior [38, 43] is of particular interest for the problem of magnetic buoyancy. In this layer the thermal stratification is weakly subadiabatic, which is necessary to counteract magnetic buoyancy [6]. Furthermore, the strong positive gradient in the turbulent velocity at the bottom of the SCZ and in the overshoot layer results in the intensive diamagnetic downward transport [21, 40] on the one hand, and on the other it produces the negative α-effect [22, 23, 25, 39] needed for equatorward propagation of the dynamo waves at mid to low latitudes.

The overshoot layer seems to be very thin and its radial thickness, d_{over}, is about $(0.004\text{–}0.005)\,R$ [4]. The problem of generation of magnetic fields in such a thin layer encounters several problems [39]. Therefore, the region of dynamo is expected to extend deep into the inner part of the Sun and it may cover *radiative tachocline* – a transition layer in which the rotation changes from being differential inside the SCZ to almost uniform rotation in the radiative interior [44]. Although theoretical predictions for this layer with strong radial shear in the angular velocity have been confirmed by early helioseismology inversions, the thickness of the tachocline d_{tach} is not yet confidently determined and remains a matter of debate. The forward modelling inversion techniques give a value of d_{tach} in the range from $\approx 0.09R$ [18] to $\approx 0.04R$ [7]. The very thin tachocline $d_{\mathrm{tach}} \approx (0.01\text{–}0.02)\,R$ is also possible [10]. However, it may be a radial gradient of angular velocity, $\partial\Omega/\partial r$, which reaches its maximum value in the tachocline, that creates favourable conditions for the excitation of strong toroidal fields. According to recent helioseismology inversions [2, 5], the tachocline has one more significant property which is encouraging for dynamo models. It consists of two different parts, one at low latitudes where $\partial\Omega/\partial r > 0$ and another at high latitudes where $\partial\Omega/\partial r < 0$. This feature is most important for theoretical explanation of the observed north–south Sun's magnetic asymmetry since the parity of the dynamo-excited field depends on the sign of $\partial\Omega/\partial r$. Moreover, the tachocline region is prolate: these two parts of tachocline are located in different depths and have different thicknesses [2]. Dikparti & Gilman [8, 9] had shown that the global hydrodynamic instability in the overshoot part of tachocline may produce a specific α-effect. Together with the Ω-effect and the meridional circulation, this α-effect constitutes the $\alpha\Omega$-flux-transport dynamo in tachocline. Therefore, *the most favourable and promising place for the $\alpha\Omega$-dynamo should be the region which includes deepest layers of the SCZ, the convective overshoot layer and the tachocline.*

Many aspects of the observed regularities of solar cyclicity have been considerably clarified in theoretical studies, mean-field modelling and numerical simulations based on the $\alpha\Omega$-dynamo mechanism. These studies usually include magnetic helicity, anisotropic dynamo coefficients, meridional circulation as well as helioseismically determined solar rotation (see a recent review by Ossendrijver [33]). At the same time, several serious difficulties still remain to be solved by the solar dynamo models. The main problems are: the storage of the strong fields in deep generation zone; penetration of these strong fields to the surface solely at mid to low latitudes (at the "royal zone"); the latitudinal distribution of sunspots over the cycle (butterfly diagram); duration of the dynamo cycle; the north–south magnetic asymmetry observed near the solar-activity maxima. There are expectations that these problems could be solved by including the downward magnetic transport and magnetic quenching effects as well as the modern helioseismically determined solar rotation in the dynamo models.

In the paper [26] (this issue) we showed that two negative magnetic buoyancy phenomena (turbulent diamagnetism and $\nabla\rho$-effect) may be the most plausible reason why the polar deep-rooted azimuthal field could not become apparent at the surface as sunspots at high latitudes. At the same time, at mid to low latitudes the upward $\nabla\rho$-effect can facilitate strong magnetic fields to emerge through the surface at the sunspot belt. Here we study some remaining uncertainties of the solar global magnetism, namely, we consider the problems connected with the period of solar dynamo-cycle and the parity of poloidal magnetic field.

SIGN CHANGE OF TURBULENCE HELICITY PARAMETER

The influence of rotation on turbulence leads to a strongly anisotropic α-effect, while the increasing magnetic field causes the generation to saturate due to the α-quenching [37]. A complete α-tensor has five non-zero components in spherical coordinates. Only the azimuthal $\alpha_{\phi\phi}$ component, denoted here as $\alpha(r,\omega,\theta) = \alpha_0(r,\omega)\cos\theta$, is important for the $\alpha\Omega$-dynamo. According to Rüdiger & Kitchatinov [37], the coefficient $\alpha_0(r,\omega)$ takes the form:

$$\alpha_0(r,\omega) \approx -\frac{\tau}{3}\langle\vec{v}\cdot\nabla\times\vec{v}\rangle \approx -\left(\frac{1}{2}\right) l^2\Omega\,\Psi^v(\omega)\nabla\ln(\rho^{S(\omega)}v) = -\left(\frac{1}{2}\right) l^2\Omega\left[\Psi^\rho(\omega)\left(\frac{\nabla\rho}{\rho}\right) + \Psi^v(\omega)\left(\frac{\nabla v}{v}\right)\right], \quad (1)$$

where $\omega = 2\tau\Omega$ is the Coriolis number, $S(\omega) = \Psi^\rho(\omega)/\Psi^v(\omega)$ is the weight factor which characterizes the relative contribution of the radial gradient of density in the convective α-effect. Functions $\Psi^\rho(\omega)$ and $\Psi^v(\omega)$, introduced by Rüdiger & Kitchatinov [37], take into account the influence of rotation on the density and turbulent velocity contributions to the α-effect. In the case of slow rotation, $\omega \approx 0.01-0.5$, typical for upper convection layers, these functions assume constant values close to $\Psi^\rho = 3\Psi^v = 4/5$. In contrary, under the fast rotation in the deep layers, $\omega \approx 5$–20, these functions assume values $\Psi^\rho = 3\Psi^v = 2\pi/\omega$. The parameter α_0, calculated from equation (1), is positive in the most volume of the SCZ.

However, in the deep convective layers the strong positive radial gradient in turbulent velocity yields negative contribution to total α-effect, $\alpha_0^v(r,\omega) \approx -\left(\frac{1}{2}\right) l^2\Omega\Psi^v(\omega)\left(\frac{\nabla v}{v}\right)$, which dominates the positive contribution of the density inhomogeneity, $\alpha_0^\rho(r,\omega) \approx -\left(\frac{1}{2}\right) l^2\Omega\Psi^\rho(\omega)\left(\frac{\nabla\rho}{\rho}\right)$. Our evaluation [23, 25] on the basis of physical parameters from the SCZ model by Stix [48] indicates that with increasing depth the total value of α_0 changes its sign from positive to negative at $z \approx 160\,000$ km ($r \approx 0.77\,R$). Finally, the helicity parameter reaches its negative peak value, $\alpha_0 \approx -5\cdot 10^3$ cm/s, not far from the overshoot layer, while the mean negative amplitude (averaged over the negative values region), $\overline{\alpha_0(r,\omega)}$, amounts to $\approx -2\cdot 10^3$ cm/s (Fig. 1). As a result, the sharp radial gradient in turbulent velocity near the bottom of the SCZ favours formation of the negative α-effect layer which has thickness $\approx 30\,000$–$40\,000$ km.

Thus, our analytical calculation shows that the α-effect is in agreement with the pioneering idea of Yoshimura [51] who was the first to consider the numerical dynamo model with two layers in which the α-effect had opposite signs. It also agrees with the estimations of the α-effect based on the current helicity calculations [28, 42]. It is very likely that namely the deep negative α-effect layer is responsible for observed behaviour of the surface large-scale magnetic patterns. The helioseismic inversions give $\partial\Omega/\partial r > 0$ for the near equatorial region [12], then condition $\alpha\cdot\partial\Omega/\partial r > 0$ evidences that here dynamo waves propagate toward to equator producing the sunspots migration as the solar cycle progresses. Since at high latitudes $\partial\Omega/\partial r < 0$, then $\alpha\cdot\partial\Omega/\partial r > 0$, and so excited dynamo waves must move toward the poles. Apparently, these waves cause the observed polar drift of the background magnetic fields (*e.g.*, [30, 31]).

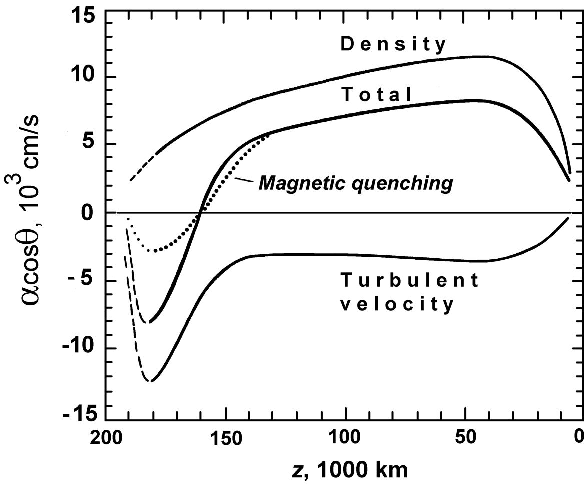

Figure 1. The depth-dependence of the helicity parameters, α_0, α_0^ρ, α_0^v, and the magnetic quenching of the α-effect, $\alpha(\beta_S) = \alpha_0\Psi_\alpha(\beta_S)$ (dotted curve in the low part of the SCZ). The total α-effect, α_0, is positive in the bulk of the SCZ but reverses to negative close to its bottom. The mean amplitude of magnetically quenched (suppressed) helicity parameter averaged over the layer of its negative values, $|\,\overline{\alpha_0\Psi_\alpha(\beta)}\,|$, is about 10^3 cm/s

MAGNETIC QUENCHING OF THE α-EFFECT AND PERIOD OF THE SOLAR DYNAMO CYCLE

In the $\alpha\Omega$-dynamo approximation, the period of Parker's magnetic wave

$$T = 2\pi/\{(1/2)\sin\theta\,|\alpha\cdot\partial\Omega/\partial r|\ (r/\lambda)\}^{1/2} \tag{2}$$

is assumed to be a cycle period (λ is the meridional dimension of the dynamo region at model calculations). However, the magnitude of T calculated in the kinematic approach is about one year [47, 49], which is much less than the observed solar cycle duration. Apparently, the correct value of the dynamo cycle's period can be expected when one involves the nonlinear dynamo approach and takes the meridional circulation into account.

The increasing magnetic field will primarily suppress the α-effect, which is more ordered and weak when compared to the Ω-effect. According to this concept, the magnetic feedback on the α-effect could be described by the relation

$$\alpha(\beta) = \alpha_0\Psi_\alpha(\beta), \tag{3}$$

where α_0 is the "nonmagnetic" value of the helicity parameter (1), $\beta = B/B_{\rm eq}$ is the parameter of normalized field, $B_{\rm eq} \approx (4\pi\rho)^{1/2}v$ is the equipartition magnetic strength, ρ is the fluid density, and $\Psi_\alpha(\beta)$ is a quenching (saturation) function of magnetic intensity normalized to unity at $\beta = 0$. Rüdiger and Kitchatinov [37] derived the quenching function

$$\Psi_\alpha(\beta) = \frac{15}{32\beta^4}\left[1 - \frac{4\beta^2}{3(1+\beta^2)^2} - \frac{1-\beta^2}{\beta}\ \mathrm{arctg}\ \beta\right]. \tag{4}$$

Owing to the magnetic antibuoyancy effects the rather strong steady-state toroidal fields, $B_S = \beta_S B_{\rm eq} \approx$ 3000–4000 G ($\beta_S \approx 0.7$–0.9) can be kept near bottom of the SCZ [26, 27]. Our calculations have shown that these magnetic fields cause essential α-quenching [23]. The values of the α-quenching function $\Psi_\alpha(\beta_S)$ in deep layers are about 0.3–0.4 (Fig. 2). This magnetic saturation leads to the reduction of negative peak of helicity parameter to $\alpha(\beta_S) = \alpha_0\Psi_\alpha(\beta_S) \approx -2\cdot 10^3$ cm/s (Fig. 1). The corresponding mean magnitude, $|\,\overline{\alpha(\beta_S)}\,|$, decreases to $\approx 10^3$ cm/s, which is much smaller than its kinematic value.

Recent helioseismically determined solar rotation gives smaller values of $\partial\Omega/\partial r$ than those from earlier measurements. Using the rotation velocity inferred for the epoch near the maximum of the 23rd cycle [12], we have found the estimation $\partial\Omega/\partial r \approx 2.5\cdot 10^{-18}$ rad/s cm at latitude $\theta^* \approx 30°$ for negative α-effect layer ($r \approx 5.2\cdot 10^{10}$ cm, $\Delta r \approx 3\cdot 10^9$ cm, $\Delta\Omega \approx 8\cdot 10^{-9}$ rad/s). If we use the averaged quenched negative helicity parameter in this low-latitude region, $\alpha^* = \overline{\alpha(\beta_S)}\cos\theta \approx -5\cdot 10^2$ cm/s, the estimation with equation (2) leads to increase of the dynamo-cycle period to about seven years, that by order of magnitude agrees with the observed mean duration of the sunspot cycles.

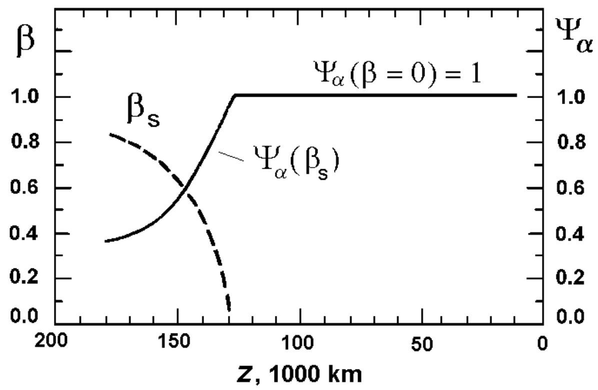

Figure 2. Distribution of the quenching function, $\Psi_\alpha(\beta_\mathrm{S})$, with depth, z, in the SCZ. The parameter of the normalized steady-state field, $\beta_\mathrm{S} = B_\mathrm{S}/B_\mathrm{eq} \approx B_\mathrm{S}/(4\pi\rho)^{1/2}v$, is also shown

One may assume that near the solar surface the poleward meridional flow may retard the low-latitude equatorward dynamo-waves, and in this way it will promote further fitting of dynamo-cycle period to observed mean duration of the sunspot cycle of about 11 years.

TIME NORTH–SOUTH MAGNETIC ASYMMETRY OF POLOIDAL FIELD

Magnetographic studies indicate that the poloidal field of the Sun can usually be described by a simple dipolar configuration that has asymmetric polarity with respect to the equator plane. However, during the last five solar-activity maxima, both magnetic poles had the same polarity: the reversals of the northern and southern polar fields occurred one to two years apart. This results in an apparent magnetic "monopole" in the solar field at the maxima epochs [11]. To account for this magnetic anomaly, some researchers have suggested that a quadrupolar harmonics of the poloidal field, magnetically symmetric mode about the equatorial plane, could be dominant at those epochs [3, 11]. The dynamo theory must prove this assumption on prevalence of quadrupolar configuration for some period.

There is a better chance to resolve this problem by dynamo models if the recent helioseismological detections for solar rotation were used. Different regimes of the internal rotation in the near equatorial and polar domains and substantial temporal and spatial angular-velocity variations near the bottom of the SCZ have been revealed by helioseismic experiments during the past seven years covering the rising phase of the 23rd solar cycle [12].

By solving the dispersion relations, Parker [35] found that the character of the excitation depends on the sign and magnitude of the parameter

$$K\lambda = \left(\alpha\,\frac{\partial\Omega}{\partial r}\,r\lambda^3/\nu_\mathrm{T}^2\right)^{1/3}. \tag{5}$$

Obviously, the conditions for exciting the global magnetic field modes (dipole or quadrupole) will be different in the domains with opposite signs of $\partial\Omega/\partial r$. Therefore, we studied the dynamo effect for these differing domains close to the tachocline and the overshoot layer, using the helioseismology data on the solar inner rotation during the rising phase and near maximum of the 23rd cycle [12], and physical parameters of the SCZ model by Stix [48]. The calculated value of the wave number of the dynamo wave at the near-equator region $K\lambda_1 \approx -7$ [24] is very close to Parker's eigenvalue $K\lambda = -7.43$ required for a dipolar configuration. Therefore, at mid to low latitudes, the $\alpha\Omega$-dynamo excites, foremost, the lowest harmonics of the poloidal field, the dipole mode. At the latitudes above 50° the radial gradient of the angular velocity changes its sign, so here the calculated wave number proves to be positive, $K\lambda_2 \approx +9.5$. Then, the quadrupole configuration dominates in the structure of the poloidal field at near pole domain [24] since $K\lambda = +7.43$ is sufficient to excite this mode. As a result, at superposition of two meridional magnetic harmonics both polar zones have the same polarity. Obtained north–south asymmetry of the net meridional field can account for the anomaly of the polar magnetism observed near the maxima of solar cycles (the apparent magnetic "monopole" of the Sun in that epochs).

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