MAGNETIC WAVES OF SOLAR ACTIVITY

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Abstract. An asymptotic solution of generation equations for the solar mean magnetic field is given and studied. The variation of rotational angular velocity with depth is taken from helioseismological data. Average helicity is prescribed according to the mixing length theory. It is shown that three dynamo waves of the magnetic field are excited. The first wave is generated at the surface layer and concentrates at latitudes of about 60°. Its activity becomes apparent in the poleward migration of the zone of polar faculae formation. The second more powerful wave of the field is excited in the center of the convection zone and its activity shows up in a sunspot cycle. The third wave which is similar to the first wave, is generated at the bottom of the convection zone and attenuates towards the surface. Its activity may appear as a three-fold reversal of the solar magnetic field.

1. Introduction

According to a standard conception the general mean magnetic field of the Sun displays itself as a poloidal component, observed at the latitudes higher 40° and a subphotospheric toroidal component, migrating equatorwards from middle latitudes in the form of the Maunder butterfly diagram (Parker, 1979). It has been understood that solar activity shows up, mainly, at mean and low latitudes.

Studies of the magnetic field in polar faculae, their latitudinal distribution with the phase of the cycle, the relationship between polar faculae and ephemeral and active regions and X-bright points (Sheely, 1976; Golub et al., 1977, 1979; Martin and Harvey, 1979; Makarov and Makarova, 1984, 1986, 1987), latitude distribution of the coronal brightness variation in the 5303 A line (Leroy and Noens, 1983; Makarov et al., 1987), of the magnetic neutral line migration during 1904–1982 (Makarov and Sivaraman, 1983; Makarov et al., 1985a) and latitude distribution of prominences in a cycle (de Jager, 1959) enabled us to make a conclusion that the activity of a toroidal component of the solar magnetic field manifests itself at all the latitudes of the Sun. The epoch of the completion of the solar magnetic field reversal should be considered as the beginning of a global solar activity process (Makarov et al., 1985b, 1987). At this time at the latitudes from 40° to 70° the first wave of the magnetic field toroidal component

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The values $\gamma_0$ are determined at the Hamiltonian stationary points from (6). We shall select the values of $\gamma_0$ that have $\text{Re} \gamma_0 = 0$, i.e., correspond to the fields non-decaying with time. Thus, $\gamma_0 = (3/8) (1 \pm \sqrt{3} i)$. The corresponding coordinates $(\partial S/\partial r, \partial S/\partial \theta, r, \theta)$ of a Hamiltonian stationary point are

$$
\left(-\frac{\sqrt{3}}{8} + \frac{i}{8}\right) x_m \sin \theta_m \Omega_\theta, \left(\frac{\sqrt{3}}{8} + \frac{i}{8}\right) r_m^2 x_m \sin \theta_m \Omega_r, r_m, \theta_m \right).
$$

They yield the linear approximation $S = S_r \Delta r + S_\theta \Delta \theta$ as Taylor’s series expansion in $\Delta r = r - r_m$, $\Delta \theta = \theta - \theta_m$ at the maximum point $(r_m, \theta_m)$.

In the vicinity of the $\Gamma$ maximum the radial component $\Omega_r$ of the rotational angular velocity seems to exceed the latitudinal $\Omega_r/\Omega_m^{-1}$. This supposition is confirmed by theories of differential solar rotation (Durney, 1985; Tassoul, 1978) and helioseismological data (Figure 1). That is why let us consider a $\Omega = \Omega(r)$ case for the sake of simplification.

The linear approximation is not sufficient for taking into account the boundary conditions. It is necessary to find the quadratic terms of series expansion of $S$. Let us differentiate (6) twice by $r$, by $\theta$, and by $r$ and $\theta$. We shall derive three equations that at the maximum $\Gamma$ will have the form

$$
2 S_{rr}^2 + (3 r^{-2}_m) (S_{\theta r} - S_\theta r^{-2}_m) = -2 (S_{\theta r}^2 r^{-2}_m) (r^{-2}_1),
$$

$$
2 S_{r \theta}^2 + (3 r^{-2}_m) S_{\theta \theta}^2 = 2 (S_{\theta r}^2 r^{-2}_m) (\theta^{-2}_1),
$$

$$
2 S_{rr} S_{\theta r} + (3 S_{\theta \theta} r^{-1}_m) (S_{\theta r} - S_\theta r^{-1}_m) = 0
$$

(coefficients of third derivatives are eliminated).

The introduced notation is

$$
\theta^{-2}_1 = -\Gamma_{\theta \theta} \Gamma^{-1}_m, \quad r^{-2}_1 = -\Gamma_{rr} \Gamma^{-1}_m
$$

and it is supposed that $\alpha = \alpha(r) \alpha(\theta)$, so that $\Gamma_{r \theta} = 0$.

System (7) has four independent solutions. Of these four one should choose the one, that yields an exponentially attenuating field outside the generation area. Thus, the boundary conditions are taken into account using the simplest method.

Let us restrict ourselves to a quadratic approximation of $S$ in $\Delta r, \Delta \theta$ and determine $\sigma$ and $\gamma_1$. For the purpose let us equalize the coefficients with equal powers $\varepsilon$ in (1) in the second approximation. Then we obtain an inhomogeneous linear system relative to $a_1, b_1$ with a zero-determinant (6). The compatibility condition of the system with account for (5) yields

$$
\left(\frac{3i}{r_m^2}\right) S_{\theta \theta} \Delta \theta \frac{\partial \sigma}{\partial \theta} + 2i S_{rr} \Delta r \frac{\partial \sigma}{\partial r} +
$$

$$
+ \left(\frac{3i}{2r_m^2} S_{\theta \theta} + i S_{rr} - \frac{i S_{\theta}}{r_m^2} \left(\cot \theta_m + \frac{\alpha_{\theta}}{\alpha_m} - \gamma_1\right)\right) \sigma = 0.
$$
is described (Parker, 1979; Zeldovich et al., 1983) by the equations

\[
\left( \gamma - \frac{\partial^2}{\partial r^2} - \frac{\sin \theta}{r^2} \frac{\partial}{\partial \theta} \left( \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \right) \right) a = R_\alpha \omega b ,
\]

\[
\left( \gamma - \frac{\partial^2}{\partial r^2} - \frac{\sin \theta}{r^2} \frac{\partial}{\partial \theta} \right) b = R_\Omega \sin \theta \left( \frac{\partial \Omega}{\partial r} \frac{\partial a}{\partial \theta} - \frac{\partial \Omega}{\partial \theta} \frac{\partial a}{\partial r} \right) .
\]

(1)

The dimensionless numbers \( R_\alpha = R_\odot \alpha_0 \nu^{-1} \) and \( R_\Omega = R_\odot |\nabla \Omega|_0 \nu^{-1} \) determine the intensity of the mean helicity \( \alpha \) and differential rotation \( \nabla \Omega \) with the characteristic values of \( \alpha_0 \) and \( |\nabla \Omega|_0 \). The imaginary and real parts of \( \gamma \) are the frequency and growth rate of the field, respectively. The components with the dimensionless complex-valued functions \( a = a(r, \theta) \) and \( b = b(r, \theta) \) through the relation

\[
(B_r, B_\theta, B_\phi) = \frac{B_\theta e^{\gamma t}}{r \sin \theta} \left( \frac{1}{r} \frac{\partial a}{\partial \theta}, - \frac{\partial a}{\partial r}, b \right) .
\]

(2)

The dynamo number \( D = R_\alpha R_\Omega \) is of the order \( 10^4 \)\textendash\( 10^5 \) for the Sun. Hence, the asymptotic method is applicable, which generalizes the known WKBJ method (Maslov and Fedorjuk, 1981) with a small parameter \( \varepsilon = D^{-1/3} \), which is a ratio of the wavelength for the generated field to the solar radius. We seek for a solution in the form of power expansion so that the basic terms of Equation (1) have the same order:

\[
\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} R_\alpha(a_0 + a_1 \varepsilon + \ldots) \\ \varepsilon^{-2}(b_0 + b_1 \varepsilon + \ldots) \end{bmatrix} e^{(t/\varepsilon)s} ,
\]

(3)

\[
\gamma = \varepsilon^{-2}(\gamma_0 + \gamma_1 \varepsilon + \ldots) .
\]

(4)

Substituting (3) and (4) into (1) and equalizing the coefficients with equal powers of \( \varepsilon \) we shall obtain as the first approximation a uniform system relative to \( \alpha_0 \) and \( b_0 \). The solution of the system is determined by some function \( \sigma \) (Maslov and Fedorjuk, 1981; Sokoloff et al., 1983):

\[
a_0, b_0 = (\alpha, \gamma_0 + (\nabla S)^2) \sigma .
\]

(5)

The solution exists if the determinant of the system is equal to zero:

\[
\gamma_0 + (\nabla S)^2 = \left[ i\alpha \sin \theta \left( \frac{\partial \Omega}{\partial r} \frac{\partial S}{\partial \theta} - \frac{\partial \Omega}{\partial \theta} \frac{\partial S}{\partial r} \right) \right]^{1/2} = 0 .
\]

(6)

The Hamiltonian of this equation has stationary points at the maximum of the function \( \Gamma(r, \theta) = |ar \sin \theta \nabla \Omega| \), that describes a distribution of a local dynamo number. Let us designate partial derivatives at the maximum \( \Gamma \), as \( \Omega_r, \Gamma_{\theta r}, S_{\theta} \), etc., and values of functions and coordinates mark with the 'm' index. For convenience let \( \Gamma_m = 2 \), which corresponds to the amplitude \( \sim \sqrt{2} \) for the profiles of the dimensionless functions \( \alpha(r, \theta) \) and \( \nabla \Omega(r, \theta) \).
of the global solar activity begins to show up predominantly as polar faculae, migrating polewards. From a comparison of polar faculae and ephemeralig regions and X-bright points one can make a conclusion that these events manifest a special class of solar activity, differing from sunspots and emerging in the surface layer (Makarov and Makarova, 1987). This activity shows up all over the Sun, but concentrates at latitudes of about 60° and is in the antiphase with sunspot activity.

The second more powerful equatorwards wave of the toroidal component becomes evident in the sunspot migration near the maximum activity of the first wave.

The direction of the magnetic field toroidal component in polar faculae (the first activity wave) is opposite to that of the field in sunspots in the first half of the polar faculae cycle, but coincides with the direction of the toroidal component in sunspots in the second half of the polar faculae cycle (the second activity wave). The latitude-time diagram for polar faculae is similar to that of the Maunder butterflies for sunspots (Makarov and Makarova, 1986).

The radial component of magnetic fields of active regions migrates poleward at the beginning of activity and sometimes manifests a threefold polarity reversal of the magnetic field at an interval of 1 to 2 years (Makarov and Sivaraman, 1983).

The modern dynamo-theory suggests that the mean field be generated in the convection zone due to differential rotation $\nabla \Omega$ and action of mean helicity $\alpha$ of random motions. The theory explains conditions which are necessary for excitation of the field, the wave character of the field and its reversals (Parker, 1979; Zeldovich et al., 1983). However, all theoretical models have so far explained only a simple pattern without account for the toroidal component activity in solar polar zones (Yoshimura, 1975; Stix, 1976; Ruzmaikin, 1985). It has been due to the absence of observational data on the distribution of sources of the field generation $\nabla \Omega$ and $\alpha$ and on the distribution of the mean field over the entire solar disc.

The present paper reports an attempt to construct a more realistic picture of field generation using the distribution $\Omega (r)$ inside the Sun as obtained from helioseismological data (Christensen-Dalsgaard and Gough, 1984; Duvall et al., 1984; Gough, 1985), and the mean helicity $\alpha (r)$, as calculated on the base of the mixing length theory (Krivodubskij, 1984). Application of the asymptotic method of the WKBJ type (Maslov and Fedorjuk, 1981) enables us to derive an analytical solution of the equations. The principal observational properties of the global process of solar activity can be interpreted in terms of three dynamo-waves generated under the accepted law of rotation.

2. Asymptotic Solution of Equations of the Solar Mean Magnetic Field

The turbulent magnetic viscosity $v_T$ varies insignificantly in the solar convection zone (Parker, 1979; Krivodubskij, 1984). Let us assume it to be constant and measure distances in solar radii $R_\odot$ and time in $R_\odot v_T^{-1}$. Then the large-scale magnetic field averaged over the azimuth in the spherical coordinate system, connected with the Sun,
Hence, $\sigma$ is determined as a homogeneous polynomial in $\Delta r$ and $\Delta \theta$ with an eigenvalue $\gamma_1$. The zero polynomial $\sigma = \text{const.}$ has $\gamma_1$ with the minimum module for the real part in comparison with other polynomials. Hence, the corresponding mode of the magnetic field is the first to be excited if the dynamo number exceeds the critical value $D_c = (-\text{Re} \gamma_1/\text{Re} \gamma_0)^3$, see Equation (4).

When $D > D_c$ the field enhances and when $D < D_c$ it decays. Let us consider a case of $D = D_c$, because the growth rate of real fields is small. In this case resolving (7) by taking into account the boundary conditions we determine

$$D_c = e^{-3} = 8(1/\sqrt{2} r_m \theta_1 + 1/\sqrt{3} r_1)^3$$
and find the main order of the solution $\varepsilon$:

$$
\begin{pmatrix}
    B_r \\
    B_\theta \\
    B_\phi 
\end{pmatrix} = B_0 I_m 
\begin{pmatrix}
  \varepsilon R_\alpha \left( \frac{i}{r} \right) \frac{\partial S}{\partial \theta} \\
  -\varepsilon R_\alpha \frac{\partial S}{\partial r} \\
  \gamma_0 + (\mathbf{\nabla} S)^2
\end{pmatrix} \frac{\exp \left( i\omega t + \frac{i}{\varepsilon} S \right)}{\varepsilon^2 r \sin \theta},
$$

where $\omega = \sqrt{3} \left( \frac{1}{\sqrt{2}} r_m \theta_1 + \frac{1}{\sqrt{3}} r_1 \right)^2$ is the frequency of the generated fields, and

$$
S = \left( \frac{\sqrt{3}}{4} + \frac{i}{4} \right) r_m \text{sign} (\alpha_m \Omega_r) \Delta \theta + \left( \frac{1}{4} + \frac{\sqrt{3}}{4} \right) \left[ \left( \frac{r_1}{2} \right)^2 \left( \frac{\Delta r}{r_1} \right)^2 + \left( \frac{r_m \theta_1}{\sqrt{6}} \right) \left( \frac{\Delta \theta}{\theta_1} \right)^2 \right].
$$

The ratio of the poloidal ($B_r, B_\theta$) to the toroidal $B_\phi$ field component is of the order $\varepsilon R_\alpha = (R_\alpha^2 / \sqrt{R_\Omega})^{1/3}$ and because in $\alpha\Omega$-dynamo $R_\Omega > R_\alpha^2$ (Zeldovich et al., 1983), the toroidal component of the magnetic field exceeds the poloidal component. It is the toroidal component of the magnetic field that provides main manifestations of activity of the solar magnetic field. The distribution of this component, in accordance with (9), is determined by the wave

$$
\exp \left( -\frac{I_m S}{\varepsilon} \right) \sin \left( \omega t + \frac{\text{Re} S}{\varepsilon} \right) \sim B_\phi.
$$

The wave migrates along $-\mathbf{\nabla} \text{Re} S$ over the surface similar to the spherical and changes its own amplitude. The maximum amplitude of the wave (min ImS) is shifted from the maximum of the $I$ source in latitude direction by an angle $\text{sign} (\alpha_m \Omega_r) \theta_1 / \sqrt{2}$. The shift of the maximum of the amplitude takes place in the same direction as that of the migrating wave. The wave migrates poleward when $\alpha_m \Omega_r > 0$ and equatorward when $\alpha_m \Omega_r < 0$. The field concentrates near the maximum of the wave amplitude. This result shows that the latitude-time diagram for the toroidal component of the generated field is similar to Maunder’s butterflies for sunspots.

The degree of concentration of the field characterizes the distance where the amplitude of the wave $B_\phi$ decreases from the maximum by a factor of $e$ as compared with the maximum. This direction is equal to $2 r_1 [1 + (\sqrt{3} r_1 / \sqrt{2} r_m \theta_1)]^{-1/2}$ in radial direction and to $2 r_m \theta_1 [1 + (\sqrt{2} r_m \theta_1 / \sqrt{3} r_1)]^{-1/2}$ in the latitude direction. The corresponding distances, at which the phase of the wave changes by $\frac{1}{2} \pi$ are by a factor of about 1.6 greater. The latter characterizes the phase speed of the wave of the toroidal component in the generated field.
3. Distribution of the Solar Magnetic Waves

For an application of the obtained solution to the solar magnetic field it is necessary to know the radial and latitude location of the maxima \( I = |\varpi \sin \theta (\partial \Omega / \partial r)| \), and some effective widths of these maxima in the radial \( r_1 \) and latitude \( \theta_1 \) directions.

Let us suppose that the maximum \( I(\theta) \sim \varpi(\theta) \sin \theta \) is located at the latitude \( 40^\circ \) and its width is \( \theta_1 = 35^\circ \) with \( \Omega = \Omega(r) \). Within the accuracy of the asymptotic solution (9) this supposition agrees with the fact that the mean helicity is determined by the Coriolis force action upon convective elements, i.e., \( \varpi(\theta) \sim \cos \theta \).

The radial distribution \( \Gamma \) is determined by the functions \( \varpi(r) \) and \( \Omega(r) \). The former is estimated by the use of the mixing length theory (Krivodubskij, 1984), the latter is derived on the base of helioseismological data (Christensen-Dalsgaard and Gough, 1984; Duvall et al., 1984; Gough, 1985). It should be noted that \( \Omega(r) \) is hard to obtain using modern helioseismological data. Hence, the dependence \( \Omega(r) \) differs significantly within the convective zone not only in different papers but even with the same authors (Duvall et al., 1984). One should also add that the magnetic field suppresses essentially the mean helicity \( \varpi \) and this leads to a variation of \( \varpi(r) \), calculated according to the mixing length theory in the absence of the magnetic field. Therefore, further we shall estimate qualitatively only the generated field and properties of their sources.

We shall use the data given by Christensen-Dalsgaard and Gough (1984) and Krivodubskij (1984), describing \( \Omega(r) \) and \( \varpi(r) \) as continuous curves. A graph of the \( r \varpi(r) (\partial \Omega / \partial r) \) dependence using these data is given in Figure 2. The source of generation of the \( \Gamma \) field has roughly 3 maxima: (a) near the surface, with \( r_m \approx 0.94 \); (b) in the mid of the convective zone, with \( r_m \approx 0.80 \); (c) at the bottom of the convective zone, with \( r_m \approx 0.73 \).

The effective width \( r_1 \) can be evaluated using parabolic approximation of corresponding domains of \( \Gamma \). After some calculations we derive \( r_1 \approx 0.05 \) and \( r_1 \approx 0.06 \), and \( r_1 \approx 0.02 \) for the surface, middle and bottom of the convective zone of \( \Gamma \) maxima.

As is seen from Figure 2 three dynamo-waves of the magnetic field near the maxima of \( \Gamma \) are excited in each solar hemisphere.

The first wave is generated in the surface layers at a depth of about 40,000 km. Since in this region \( \varpi, \Omega > 0 \), the toroidal component of the magnetic field migrates poleward and concentrates near \( \theta_1 - (1/\sqrt{2}) \theta_1 \), i.e., at a latitude near \( 65^\circ \). As is seen from the asymptotic solution (9) a distribution of the toroidal component of the magnetic field should be observed in the solar polar zone as a latitude-time diagram, that is similar to the Maunder butterflies diagram mirrored relative to the \( 40^\circ \) latitude.

The obtained qualitative features of the field behaviour are in satisfactory agreement with the observational data. Activity in the form of polar faculae, ephemeral active regions, and X-bright points is actually observed in solar polar regions. Although these events are observed at all latitudes, still the regions at \( 60^\circ \) to \( 70^\circ \) are the most active (Makarov and Makarova, 1986). Polar faculae are close bipolar structures from 3" to 50" of arc and more (Makarov and Makarova, 1984). Hence, one can expect that the depth of formation of these elements be about \( 10^4 \) km. The inclination angle of the axis
of polar faculae to a parallel varies within $-\frac{1}{2}\pi$ to $\frac{1}{2}\pi$. The polarity of the magnetic field of the leading (west) part of these structures coincides with that of the background field and keeps the same during the cycle. The zone of formation of the polar faculae migrates poleward. Thus, one can make a conclusion that these events reflect the activity of the magnetic field toroidal component. Therefore, it would be natural to expect that the first source of generation of the toroidal component of the magnetic field, located at $r_m = 0.94$, is responsible for the behaviour of a populated class of observed small-scale magnetic structures on the Sun in Figures 3 and 4.

The second maximum of $\Gamma$, with $r_m = 0.8$, is located in the region, where $\alpha_m \Omega_r < 0$, that is why the nearby generated wave of the field migrates equatorward. The activity of this magnetic field shows up at the latitudes lower 40° in the solar cycle. Spörer’s law reflects migration of the wave of the toroidal field. Expansion and the following narrowing of the sunspot zone (the Maunder butterfly diagram) reflect the growth of the amplitude of this field on the way of the wave $\theta_m + (1/\sqrt{2}) \theta_1$ and the decrease of the amplitude in further migration. So, the magnetic field concentrates near the 15° latitude. This is in agreement with the estimation of the position of the maximum of the observed
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Fig. 3. A latitude-time distribution for the standard deviation of the green coronal line 5303 Å intensity according to Leroy and Noens (1983). The time is reckoned from the minimum (m) to the maximum (M) of the sunspot activity. The heavy lines mark the averaged (over 1944–1974) positions for polarity division lines of the large-scale magnetic field.

field (Yoshimura, 1976) and the maximum of the sunspot activity at the latitudes from 10° to 20° in dependence on the power of the cycle (Figure 4).

From a comparison of the corresponding values \( r_m, r_1, \theta_1 \), and an expression for \( \omega = 2\pi/T \) it is seen that two waves of the field considered above have similar periods, but their amplitudes on the surface are different. The amplitude of the second wave is larger than that of the first wave, because the field generated with \( r_m = 0.8 \), is formed in the domain of a higher maximum of and damps comparatively slowly towards the surface due to a large value of \( r_1 \) (see (9)). The first wave of the field, generated with \( r_m = 0.94 \), cannot grow to the critical value, necessary for sunspot formation, and its activity shows up in magnetic structures of the polar faculae type with a smaller strength of the field in comparison with sunspots.

The distance between the maxima of \( \Gamma \) is about 0.14 ∼ 3\( r_1 \). This value is close to a distance where the wave phase changes to \( \frac{1}{2} \pi \) (see the end of Section 1). Therefore, a phase shift of the order of \( \frac{1}{2} \pi \) (about several years) should take place between the two waves of activity. Observations confirm the existence of this shift and this leads to a longer duration of the global process of solar activity to 17 years (Legrand and Simon, 1981; Makarov et al., 1985b).

The third wave of the field is generated, with \( r_m = 0.73 \) at the bottom of the convective zone at a depth of about 200,000 km. This wave as a wave determining the polar faculae
Fig. 4. The number of polar faculae (broken curves) and the sunspot area averaged over three solar rotations and given in units of $10^{-6}$ of the area of the hemisphere (heavy curves) versus time are presented for the (a) northern and (c) southern hemispheres. (b) A latitude–time diagram for polar faculae and sunspots in the period 1970–1985.

activity, migrates poleward and concentrates at latitudes near $65^\circ$. But its period is smaller by a factor of several times. It can be seen from a comparison of corresponding $r_1$, and the expression for $\omega$. The wave has a comparatively small $r_1$ and is generated at a deeper layer than the others. Therefore, it concentrates more vigorously along the latitude and attenuates significantly towards the surface (see Section 2), notwithstanding a comparatively large height of the corresponding maximum $\Gamma$. A significant decay of this wave towards the surface prevents us from detecting it against the background of the other two waves. But this wave can have a sufficiently large amplitude in the mid of the convection zone and, thus, it influences the source of the second wave due to a predominant influence of the magnetic field on the mean helicity (Ruzmaikin, 1985). This can affect the sunspot activity, which is associated with the variation of the magnetic neutral line migration. While the period of this wave is several years, its action can be observed at high latitudes at the maximum of sunspot activity as a polyfold reversal of the magnetic field and fluctuations during unifold reversals.

References


