# MAUNDER CONVECTION MODE ON THE SUN AND LONG SOLAR ACTIVITY MINIMA*

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**Abstract.** A model of velocity field oscillations in the solar convective zone is suggested. The system of convective equations is investigated for a thin rotating spherical envelope when the rotation velocity is depended on the coordinates. It is shown that two different structures of convective cells (longitudinal, or latitudinal) can exist in the envelope depending on gradients values of the rotation velocity and Prandtl number.

It is supposed that two different regimes of convection (stationary and autofluctuating) are possible in the envelope when the angular velocity gradients are determined by the convection itself. In the case of autofluctuating regime the alternation of longitudinal and latitudinal structure of convection is realized.

If one assumes that on the Sun there exists an autooscillating convection regime, then the periods of the existence of latitudinal convection structure may be associated with long periods of activity minima since according to Cowling's theorem, the action of the axisymmetric magnetic field generation mechanism is impossible under conditions of axisymmetric velocity structures.

In recent years attention has been payed to rather unusual phenomena proceeding on the Sun. They manifest themselves in the fact that long periods of anomalously low solar activity take place. The most investigated of such minima is the last one, the so-called Maunder minimum, which was accompanied by various unusual phenomena in the terrestrial and solar atmospheres and in the interplanetary space. But the Maunder minimum manifested itself first of all in almost a complete disappearance of spots from the surface of the Sun. For seventy years of the minimum (1645–1715) there were less spots than for one 'normal' 11-year solar cycle (Eddy, 1976).

The most convincing proof of the reality of this phenomenon was obtained from the study of the amount of isotope $C^{14}$ in tree rings, that is produced in interaction between a flux of highenergy cosmic rays and the matter of the Earth's atmosphere. From these data it is seen that during the whole period of the Maunder minimum the cosmic ray intensity was anomalously large (see, e.g., Kocharov *et al.*, 1979). This points to some interplanetary magnetic field variations which make it possible for cosmic rays to penetrate more freely into interplanetary space. This was observed not only in the Maunder but also in some other earlier solar activity minima. As can be seen from radio-carbon data, the time distribution of these minima is extremely inhomogeneous. In particular, the last two solar activity minima (Maunder and Spörer) took place with about a two hundred-year interval, whereas after the Maunder minimum it is already alsmost three hundred years that normal 11-year cycles without any essential lowering of solar activity are observed.

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The question of the causes of this phenomenon remains open. In a number of papers it is supposed that the activity minima are due to a sharp decrease in the peaks of 11-year activity which is caused by the position of the minima of hypothetic 80-year and 170-year periodicities of solar activity (see, for example, Link, 1978). However, the analysis of statistical properties of solar activity does not confirm such an assumption (Willis and Tulunay, 1979).

Leighton (1969) suggested that during Maunder minimum the toroidal magnetic fields were too weak in the solar subphotosphere zone so they could not emerge. The active regions were absent on the photosphere and for this reason the dynamo mechanism did not operate.

Rusmaikin and Zel'dovich (1980) assumed that in the period of long activity minima the magnetic fields in the convective zone were able to suppres the-$\alpha$-effect, and as a consequence the action of the dynamo mechanism on the Sun ceased.

Another explanation was given by Yoshimura (1978). He assumed that for the periods of long activity minima the convection mechanism was switched off, for which reason the magnetic fields were not generated any longer. According to this model the solar rotation differentiality must increase in the period of activity minimum, since the restraining effect of magnetic fields on differential rotation disappeared. It should be noted however that differentiality of solar rotation is most likely to be due to the presence of convection (Gilman, 1975), therefore the convection having being switched off, the differential rotation would rather damp than be amplified. Besides, according to Dearborn and Neuman (1978), not only switching off but even a small decrease in efficiency of convective heat transfer would have led to catastrophic changes in the climate on the Earth. Proceeding from what has been said above, one should assume that convective heat transfer does exist also in the periods of long activity minima and its efficiency changes quite little, if at all. In our opinion long solar activity minima are caused by changes in the structure of hydrodynamic flows in the convective zone (Dogiel and Syrovatskii, 1977, 1979a). In the periods of minima the convection structure is such that it proves to be inefficient for magnetic field generation. Parker (1976) suggested that such a convection mode should be called Maunder mode.

The convection structure in the rotating spherical shell has been investigated in many papers. First of all the action of rotation on convective motions was shown to lead to the fact that convective cells try to stretch along the rotation axis (Cowling, 1953; Chandrasekhar, 1961). Under the conditions of a spherical shell rotating at a constant angular velocity in the initial state, such a longitudinal structure of motion convection leads to rotation momentum redistribution as a result of which angular velocity gradients appear (Busse, 1972). The results of numerical calculations show that such a stationary state can be achieved in which there remains only one convective mode characterized by the spherical function $Y_l^l(\vartheta, \varphi) = P_l^l(\cos\vartheta)e^{il\varphi}$ (Durney, 1970). There forms a longitudinal structure of convective cells stretching from pole to pole.

The longitudinal structure of motions turns out to be effective for the dynamo mechanism to be realized in a rotating shell. The time development of magnetic fields

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in such a shell that models the behaviour of magnetic fields on the Sun was investigated in numerical calculations (Yoshimura, 1975).

Usually the convective structure is investigated under the condition of rigid rotation. The only nonlinear term taken into account in the problem is an averaged term of convection modes interaction. It is responsible for the appearance of angular velocity gradients in the shell. Thus, the development of convection proceeds under condition of differential and not rigid rotation. Interaction of convective motions with shear flow (differential rotation) can lead to changes in the convective structure. To take into account this effect, we have solved the problem in which we have sought the most unstable convection mode (i.e. the mode excited at the lowest difference of temperatures between the internal and external spheres) under condition of differential rotation. The angular velocity was set up in the form

$$\Omega(\vartheta) = \Omega_0(1 + p\cos^2\vartheta), \tag{1}$$

where $\Omega_0 = \text{const.}$, $p = \text{const.}$ and $\vartheta$ is the latitude.

We have solved a set of equations for dimensionless fluctuations of velocity $\mathbf{v}$, temperature $\theta$, and pressure $p'$ at a given difference of temperatures $\Delta T = \text{const.}$ between the internal and external spheres and against the background of the established temperature distribution

$$\nabla^2 T_0 = 0\,. \tag{2}$$

From the noncompressibility condition, $\mathbf{v}$ is presented in the form (Chandrasekhar, 1961)

$$\mathbf{v} = \operatorname{rot}\operatorname{rot}\mathbf{r}\,v + \operatorname{rot}\mathbf{r}\,w\,. \tag{3}$$

Then for $v$, $w$, and $\theta$ we have the equations (Busse, 1971)

$$\left[L^2\left(\nabla^2 - \frac{\partial}{\partial t}\right) + \lambda\mathbf{k}\times\mathbf{r}\cdot\nabla\right]\nabla^2 v + \lambda Q w - \frac{1}{r_0}RL^2\theta = \\ = \bar{\mathbf{r}}\operatorname{rot}\operatorname{rot}[\mathbf{u}\times\nabla\times\mathbf{v} + \mathbf{v}\times\nabla\times\mathbf{u}]\,, \tag{4}$$

$$\left[L^2\left(\nabla^2 - \frac{\partial}{\partial t}\right) + \lambda\mathbf{k}\times\mathbf{r}\cdot\nabla\right] w - \lambda Q v = \\ = \mathbf{r}\operatorname{rot}[\mathbf{u}\times\nabla\times\mathbf{v} + \mathbf{v}\times\nabla\times\mathbf{u}]\,, \tag{5}$$

$$\nabla^2\theta + Pr\frac{\partial}{\partial t}\theta + \frac{L^2 v}{r_0} = Pr(\mathbf{u}\nabla)\theta\,, \tag{6}$$

with the boundary conditions

$$v = \frac{\partial^2 v}{\partial r^2} = \frac{\partial w}{\partial r} = \theta = 0\,, \qquad r = r_0\,, \quad r_0 + h\,. \tag{7}$$

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Here $h$ is the shell thickness, $r_0$ is its internal radius, $\nu$ and $k$ are coefficients of viscosity and heat conductivity, $\alpha$ is a volume expansion coefficient, $g_0$ is gravity acceleration, $\lambda = (2\Omega_0 h^2)/\nu$ is Taylor number, $R = (\alpha g_0 \Delta T h^3)/k\nu$ is Rayleigh number, $Pr = \nu/k$ is Prandtl number, $\mathbf{u} = [\omega \mathbf{r}]$ is shear velocity, where $\omega = (p\lambda \cos^2 \vartheta)/2$, $\mathbf{k}$ is the direction of rotation,

$$L^2 = -\frac{1}{\sin\vartheta}\frac{\partial}{\partial\vartheta}\sin\vartheta\frac{\partial}{\partial\vartheta} - \frac{1}{\sin^2\vartheta}\frac{\partial^2}{\partial\varphi^2}, \tag{8}$$

$$Q = \mathbf{k}\nabla - \tfrac{1}{2}(L^2\mathbf{k}\nabla + \mathbf{k}\nabla L^2). \tag{9}$$

In the thin-shell approximation, $h/r_0 \ll 1$,

$$\mathbf{r}\,\mathrm{rot}\,\mathrm{rot}(\mathbf{u}\times\nabla\times\mathbf{v} + \mathbf{v}\times\nabla\times\mathbf{u}) \approx \frac{p\lambda}{2}\frac{\partial}{\partial\varphi}(L^2\cos^2\vartheta\,\nabla^2 v), \tag{10}$$

$$\mathbf{r}\,\mathrm{rot}(\mathbf{u}\times\nabla\times\mathbf{v} + \mathbf{v}\times\nabla\times\mathbf{u}) \approx -\frac{p\lambda}{2}\frac{1}{\sin\vartheta}\frac{\partial}{\partial\vartheta}\left(\sin\vartheta\cos^2\vartheta\frac{\partial}{\partial r}L^2 v\right). \tag{11}$$

The unknown quantities $v$, $w$, and $\theta$ are presented in the form of a series of the spherical functions $Y_l^m(\vartheta, \varphi) = P_l^m(\cos\vartheta)e^{im\varphi}$. The time dependence $t$ is sought in the form $e^{i\sigma t}$. The problem is investigated within the stability limit, i.e. $\sigma$ has only real values. The problem is reduced to obtaining the mode excited at the lowest temperature difference. In other words, from the conditions of the minimal Rayleigh number it is necessary to find the values of $l$ and $m$.

The solution of the problems (3)–(7) is sought for in the approximation of slow rotation at $\lambda \ll 1$ and small perturbation amplitudes. All the unknown quantities are presented in power series of $\lambda$:

$$R = \sum_n R_n\lambda^n, \qquad \sigma = \sum_n \sigma_n\lambda^n, \qquad v = \sum_n v_n\lambda^n, \quad \text{etc.} \tag{12}$$

We start by considering the order $\lambda^0$ (Busse, 1972):

$$v_0 = \sin(\pi\Delta r)P_l^m(\cos\vartheta)e^{im\varphi}, \tag{13}$$

$$\Delta r = \frac{r - r_0}{h},$$

$$\theta_0 = r_0\frac{\nabla^4 v_0}{R_0}, \tag{14}$$

$$R_0 = \frac{\left[\pi^2 + \dfrac{l(l+1)}{r_0^2}\right]^3}{\dfrac{l(l+1)}{r_0^2}}, \tag{15}$$

$$\sigma_0 = w_0 = 0. \tag{16}$$

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From the condition of the minimum of $R_0$ one can find the value of $l$,

$$\frac{l(l+1)}{r_0^2} = \frac{\pi^2}{2} . \tag{17}$$

In the first approximation in $\lambda$

$$v_1 = \sin(\pi \Delta r) e^{im\varphi} (K_1 P_{l+2}^m + K_2 P_l^m + K_3 P_{l-2}^m) , \tag{18}$$

$$\Theta_1 = \sin(\pi \Delta r) e^{im\varphi} (G_1 P_{l+2}^m + G_2 P_l^m + G_3 P_{l-2}^m) , \tag{19}$$

$$\begin{aligned} w_1 = e^{im\varphi} \Bigg\{ & \frac{C_1}{2l+5} 4p\pi(l-m+3)\cos(\pi\Delta r) P_{l+3}^m + \\ & + \frac{l-m+1}{(2l+1)\beta(l+2)} \Bigg[ \left[ \pi(1-p) + 4\pi p \left( C_1 \frac{(2l+1)(l+m+2)}{(2l+5)(l-m+1)} + C_2 \right) \right] \times \\ & \times \cos(\pi\Delta r) - \frac{l}{r_0} \sin(\pi\Delta r) - \frac{l}{r_0} \frac{\pi \operatorname{ch}\left[ \frac{\alpha(l+1)}{r_0} (\Delta r - \frac{1}{2}) \right]}{\alpha(l+1) \operatorname{sh} \frac{\alpha(l+1)}{2r_0}} \Bigg] P_{l+1}^m + \\ & + \frac{l+m}{(2l-1)\beta(l-1)} \Bigg[ \left[ \pi(1-p) + 4\pi p \left( C_2 + C_3 \frac{(l-m+1)(2l+1)}{(l+m)(2l+3)} \right) \right] \times \\ & \times \cos(\pi\Delta r) + \frac{l+1}{r_0} \frac{\pi \operatorname{ch}\left[ \frac{\alpha(l-1)}{r_0} (\Delta r - \frac{1}{2}) \right]}{\alpha(l+1) \operatorname{sh} \frac{\alpha(l+1)}{2r_0}} + \\ & + \frac{l+1}{r_0} \sin(\pi\Delta r) \Bigg] P_{l-1}^m + \\ & + C_3 \frac{4\pi p}{2l-3} (l+m-2) \cos(\pi\Delta r) P_{l-3}^m \Bigg\} , \end{aligned} \tag{20}$$

$$\alpha^2(n) = n(n+1) , \qquad \beta(n) = \frac{n(n+1)}{r_0^2} + \pi^2 , \tag{20a}$$

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$$\sigma_1 = \frac{m}{\alpha^2(l)(1+Pr)}\left[1 - \frac{p}{r_0}\frac{\alpha^2(l)}{2l+3}\left(1 + \frac{2(l+1)(l^2-m^2)}{4l^2-1}\right)(1+Pr)\right], \tag{21}$$

$$C_1 = \frac{p}{2}\frac{(l-m+1)(l-m+2)}{(2l+1)(2l+3)}, \tag{22}$$

$$C_2 = \frac{p}{2(2l+3)}\left[1 + \frac{2(l^2-m^2)}{2l-1}\right], \tag{23}$$

$$C_3 = \frac{p}{2}\frac{(l+m)(l+m+1)}{(2l+1)(2l+3)}, \tag{24}$$

$$K_1 = \frac{imC_3\beta(l+2)\beta(l)}{\left[\dfrac{\alpha^2(l+2)}{\alpha^2(l)}\beta^3(l) - \beta^3(l+2)\right]}, \tag{25}$$

$$K_2 = \frac{im}{2\alpha^2(l)}\frac{Pr}{\beta(l)(1+Pr)}, \tag{26}$$

$$K_3 = imC_3\frac{\beta(l-2)\beta(l)}{\left[\dfrac{\alpha^2(l-2)}{\alpha^2(l)}\beta^3(l) - \beta^3(l-2)\right]}, \tag{27}$$

$$G_1 = \frac{1}{r_0\beta(l+2)}\left[\alpha^2(l+2)K_1 - imPrC_1\frac{\alpha^2(l)}{\beta(l)}\right], \tag{28}$$

$$G_2 = -\frac{\beta(l)}{R_0}K_2, \tag{28a}$$

$$G_3 = \frac{1}{r_0\beta(l-2)}\left[\alpha^2(l-2)K_3 - imPrC_3\frac{\alpha^2(l)}{\beta(l)}\right]. \tag{29}$$

In the second approximation

$$R_2 = \frac{m^2}{2\alpha^2(l)}\frac{Pr^2}{(1+Pr)^2} + \frac{\alpha^2(l)\zeta(l+1)}{2\beta(l+1)}\left\{\pi^2\left[1 + 2p(\zeta(l+2) + \frac{1}{2l+3}\times\right.\right.$$

$$\left.\times\left[1 - \frac{2(l^2-m^2)}{2l-1}\right]\right) - p\right] + \frac{l(l+2)}{r_0^2}\times$$

$$\left.\times\left[1 + \frac{2\pi^2 r_0}{\alpha(l+1)\beta(l+1)}\,\mathrm{cth}\,\frac{\alpha(l+1)}{2r_0}\right]\right\} + \frac{\alpha^2(l)\zeta(l)}{2\beta(l-1)}\times$$

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$$\times \left\{ \pi^2 \left[ 1 + 2p(\zeta(l-1) + \frac{1}{2l+3} \left[ 1 + 2p(\zeta(l-1) + \frac{1}{2l+3} \times \right.\right.\right.$$

$$\left.\left.\left. \times \left[ 1 + \frac{2(l^2-m^2)}{2l-1} \right] - p \right] + \frac{(l^2-1)}{r_0} \quad \frac{1 + 2\pi^2 r_0 \operatorname{cth} \dfrac{\alpha(l-1)}{2r_0}}{\alpha(l-1)\beta(l-1)} \right] \right\} +$$

$$+ p^2 \frac{\pi^2}{4} \alpha^2(l)[(l+4)\zeta(l+3)\zeta(l+2)\zeta(l+1) -$$

$$- (l-3)\zeta(l-2)\zeta(l)\zeta(l-1)] -$$

$$- p \frac{\pi^2}{2} \left[ 1 + 2p \left[ \zeta(l+2) + \frac{1}{2l+3} \left( 1 + \frac{2(l^2-m^2)}{2l-1} \right) \right] - p \right] \times$$

$$\times \frac{(l+1)^2}{\beta(l+1)} \zeta(l+1) \left[ (l+1)\zeta(l+2) - \frac{(l+2)}{2l+3} \left( 1 + \frac{2(l^2-m^2)}{2l-1} \right) \right] +$$

$$+ p \frac{\pi^2}{2} \left[ 1 + 2p \left[ \zeta(l-1) + \frac{1}{2l+3} \left( 1 + \frac{2(l^2-m^2)}{2l-1} \right) \right] - p \right] \times$$

$$\times \frac{l^2}{\beta(l-1)} \zeta(l) \left[ l\zeta(l-1) - \frac{(l-1)}{2l-3} \left( 1 + \frac{2(l^2-m^2)}{2l-1} \right) \right] -$$

$$- \frac{m^2p^2}{8} \alpha^2(l)\beta(l) \left\{ \zeta(l+2)\zeta(l+1) \left[ \frac{\beta^2(l+2)}{\xi(l+2)} + Pr \frac{\beta(l)}{\beta(l+2)} \times \right.\right.$$

$$\left. \times \left[ \frac{\alpha^2(l+2)}{\alpha^2(l)} \frac{\beta(l+2)(\beta(l)}{\xi(l+2)} - \frac{Pr}{\beta(l)} \right] \right] - \zeta(l)\zeta(l-1) \left[ \frac{\beta^2(l-2)}{\zeta(l-2)} + \right.$$

$$\left.\left. + Pr \frac{\beta(l)}{\beta(l-2)} \left[ \frac{\alpha^2(l-2)}{\alpha^2(l)} \frac{\beta(l-2)\beta(l)}{\xi(l-2)} - Pr \frac{1}{\beta(l)} \right] \right] \right\}, \tag{30}$$

$$\zeta(n) = \frac{n^2-m^2}{(2n-1)(2n+1)}, \tag{31}$$

$$\xi(n) = \frac{\alpha^2(n)}{\alpha^2(l)} \beta^3(l) - \beta^3(n). \tag{32}$$

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From expression (30) one can obtain the value of $m$ by determining the minimum possible Rayleigh number $R$. Investigation of expression (30) show that at sufficiently low values of the number $p$, $|p| < p_{cr}$ ($p_{cr}$ is some critical value) the most dangerous is the mode with $m = l$. It has the form of longitudinal cells extended along meridians. It should be noted that as has been said above, angular velocity gradients are produced just at such a convection structure. At a realization of this cell structure the decisive factor is the presence of Coriolis forces.

If $|p| > p_{cr}$, there exists an axisymmetric latitudinal structure of convective cells which are toroids ($m = 0$), whose axis coincide with the rotation axis. The decisive factor in the formation of such a structure of motions is the presence of shear flow (differential rotation). An analogous result was obtained in the problem of convection in a plane sheet in the presence of shear flow. In this case convective cells stretch along the direction of shear velocity (Kuo, 1963; Deardorff, 1965).

Let us try to imagine how the time development of convection structure may proceed when angular velocity gradients are created by the convection itself.

As long as latitudinal gradients of angular velocity are small or absent, the convection structure is longitudinal. Redistributing the momentum in the shell, convective motions create angular velocity gradients. These gradients can grow until the momentum transfer by convection is compensated by opposite momentum transfer due to viscosity which tries to level the angular velocity.

As a result the state is achieved when the longitudinal convection structure exists against the background of stationary angular velocity gradients characterised by the value $p_{st}$. Such a state is possible if $|p_{st}| < p_{cr}$.

In case $|p_{st}| > p_{cr}$ the increase of angular velocity gradients created by the longitudinal convection structure proceeds only up to the value $p_{cr}$ after which the convection structure changes from longitudinal to latitudinal. The latitudinal convection structure is not able to maintain the angular velocity gradients that caused its appearance, and therefore the gradients are decreased due to viscosity, and the system goes back to the state with the longitudinal structure of convection. So, an autooscillating convection regime with alternating latitudinal and longitudinal structure of convective cells is realized. The lifetime of longitudinal convection structure is the time of angular velocity gradient increase, the lifetime of latitudinal convection structure is the time of dissipation of these gradients.

If one assumes that on the Sun there exists an autooscillating convective regime, then the periods of the existence of latitudinal convection structure may be associated with long periods of activity minima since according to Cowling's theorem the action of axis-symmetric magnetic field generation mechanism is impossible under the conditions of axis-symmetric structure of motions. A high solar activity corresponds to the periods of the existence of a longitudinal structure of motion.

It should be noted that the alternation of longitudinal and latitudinal structure of convection cells could be happened irregularly due to the nonlinear interaction of different modes of motion (Dogiel and Syrovatskii, 1979b; Dogiel, 1980).

The behaviour of convection structure in time could be investigated with the help of

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numerical methods. Up to now there have been several investigations of this kind. Durney (1970) has investigated the system of convective equations for a rotating envelope when nonlinear interactions of motion modes was presented only in equations for a large scale modes. It was shown that the stationary case was realised in this case and the structure of convection was pure longitudinal.

Recently Gilman (1978, 1980) has carried out more complex calculations for convection in a rotating envelope. He included in the equations from 16 to 24 longitudinal wave numbers and nonlinear interaction was present for all of these modes. As a result the stationary structure of convection was also realised for investigated range of parameters of the envelope but the structure of the motion was more tangled. It was discovered that mainly longitudinal convection was realised in the equatorial zone and mainly latitudinal convection was realised near the poles of envelope. We think that the question of the existence of a range of parameters where the latitudinal structure of the convection could sometimes be realised in the whole envelope that is necessary for an autofluctuating regime, is open. As it is possible to see from the paper of Gilman (1980) the inclusion of different new effects in the problem of convection in a rotating envelope can drastically change the convection picture. In this situation we think that the realisation of an autofluctuating regime is possible and further special investigations are necessary. It seems that in more real situations we have mixture of longitudinal and latitudinal convective modes in the rotating envelope. The autofluctuating regime in this case one can imagine himself as a alternating of an amplitudes increase of longitudinal and latitudinal convective modes and accordingly the increase and decrease of the efficiency of a magnetic field generation.

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