THE ROLE OF MERIDIONAL CIRCULATION IN GENERATING THE 22-YEAR SOLAR CYCLE

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ABSTRACT

The role of meridional circulation in generating the 22-year cycle of solar magnetic fields and sunspots has been analysed. The proposed model is based on the study of cyclic evolution of local and large-scale fields: direction and duration of their heliolatitude drift, and phase ratio of their maximum intensities. It is shown that the drift from the equator to the poles occurs for 16-17 years, as well as the backward drift from the poles to the equator at the base of the convection zone. Thus, the total cycle of the meridional circulation of solar magnetic fields is 32-34 years.

1. INTRODUCTION

Present-day helioseismological observations [1-10] make it possible to measure the magnitude and direction of the meridional flows of matter in the solar convection zone with a sufficiently high accuracy. These observations point clearly to the existence of poleward meridional flows of the solar matter in both hemispheres. The type of the meridional drift of solar magnetic fields differs for the system of large-scale, apparently diffuse, magnetic fields (LSMF) [1, 11-13] and the system of local magnetic fields (LMF) that manifest themselves as intensive small-scale field elements. The cyclic behaviour of LMF is observed in the mid-latitude zone in the form of the well-known 11-year sunspot cycle (Maunder butterflies in the time-latitude diagram) and the 22-year Hale magnetic cycle. The total LSMF cycle is ~22 years, but it is shifted by ~5-5.5 years ahead of the LMF cycle (13, 14]. Unlike the LMF that move during the 11-year cycle from the latitudes of ~40°-45° to the equator, the LSMF drift has opposite direction (from the equator to the poles and takes ~16-17 years [15-20, 1, 12, 13].

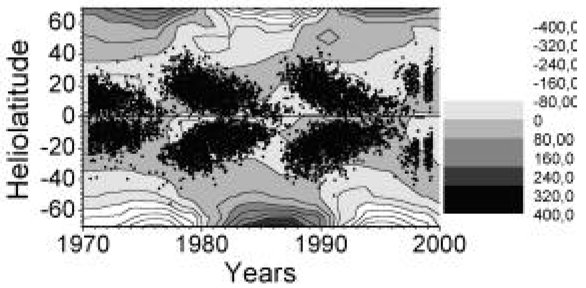

Fig. 1. The time-latitude diagram for the LSMF radial component smoothed over 40 CR with a superimposed Maunder butterflies.

2. MAIN FEATURES OF THE MERIDIONAL DRIFT OF LOCAL AND LARGE-SCALE MAGNETIC FIELDS

In our previous works [21-24, 13] we have already considered the meridional drift of magnetic fields over a long time interval. The study was based on the photospheric synoptic maps for 1960-2000 obtained with different magnetographs and the maps of magnetic fields reconstructed from Hα data for 1915-2000. Three groups of the time-latitude diagrams were used in the analysis: the diagrams for the directly measured longitudinal magnetic field, for the radial (B_r) and meridional (B_J) field components computed by a special method, and for B_r^2 and B_J^2 proportional to the energy of the respective field components. The trait of the time-latitude diagram for B_r and B_J is that averaging daily values over a Carrington rotation mainly filters out the local magnetic fields. As a result, the large-scale fields prevail on the diagrams. On the contrary, the rotation-mean values of B_r^2 and B_J^2 involve both LMF and LSMF. So, the respective diagrams display evolution of the energy sources of both components with the local fields dominating B_r^2 in the mid-latitude region. For details of calculating B_r and B_J and plotting the time-latitude diagrams see [25-27, 21, 13].

Fig. 1 represents the time-latitude diagram for the LSMF radial component smoothed over 40 Carrington rotations (CR) to eliminate all LSMF variations with periods less than 3 years (in particular, quasi-biennial variations). The diagram is supplemented with the Maunder butterflies for sunspots. It turned out that:

1. The large-scale and local magnetic fields drift in opposite directions, the former moving from the equator to high latitudes and the latter, from mid latitudes to the equator.

2. The tilt of the LMF butterfly pattern towards the time axis that corresponds to the drift velocity of ~5° per year is virtually the same all along the drift trajectory.

3. The local magnetic fields have maximum intensity in a narrow latitudinal band of 20°-25° at the maximum of the 11-year cycle, while the large-scale fields are most intensive in the polar regions at the cycle minimum. The LMF and SLMF maxima are shifted about one another by either half or one and a half 11-year cycles depending on what LSMF sign is chosen.

4. Unlike LMF, the LSMF are seen to drift at variable velocity. It takes them about 2-3 years to travel from the equator to the latitudes of 20°-25°. In the latitude zone from 25° to 50°, the drift velocity drops abruptly down to 1-2 m/s, so that the fields pass the interval of 25° for 15 years. Then the velocity of the poleward drift grows rapidly again, and the remaining distance of ~40° is traversed for about a year. Thus, the total way of LSMF from the equator to the pole takes about 16-18 years: from the maximum of one 11-year cycle of LMF to the minimum following after a cycle and a half. In general, the observed pattern of the LSMF meridional drift agrees with the latitudinal distribution of the plasma velocity in the solar convection zone as inferred from helioseismological studies [10].

5. Two modes have been isolated in the observed poleward meridional drift of large-scale solar magnetic fields: the drift lasting 16-17 years for the radial field component B_r smoothed over 40 CR and the drift lasting 2-3 years for B_r in the range of periods from 8 to 40 CR (quasi-biennial component). Both modes have constant but different drift velocities. These modes differ also by their contribution in different phases of the 11-year cycle. The change of polarity of the drifting magnetic fields suggests that the slow drift is related to the 22-year magnetic cycle of LSMF and the fast drift, to quasi-biennial oscillations. The variable velocity of the LSMF meridional drift in different latitudinal zones is, possibly, the result of superposition of the two above-mentioned drift modes. The shift velocity of the sunspot fomation zone on the butterfly diagram for LMF is equal to the velocity of the slow LSMF drift on the time-latitude diagram.

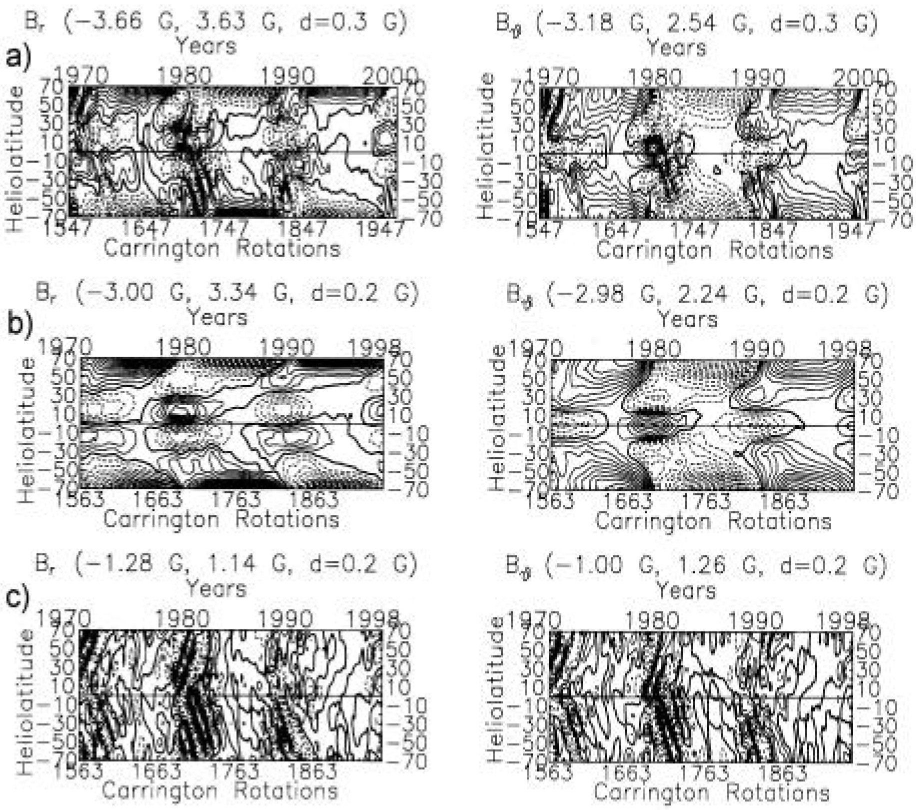

Fig.2. The time-latitude diagrams for the rotation-averaged LSMF radial (B_r) and meridional (B_J) components.

3. STUDY OF LSMF MERIDIONAL DRIFT USING TIME-LATITUDE DIAGRAMS AND CORRELOGRAMS

Fig. 2 shows the time-latitude diagrams for the rotation-averaged LSMF radial (B_r) and meridional (B_J) components smoothed over 8 (*à*) and 40 (*b*) CR and a diagram for the periods ranging from 8 to 40 CR (quasi-biennial component) (c). Smoothing over 8 CR was performed to remove noise and visualize better the meridional drift of magnetic fields. Smoothing over 40 CR eliminates the LSMF quasi-biennial oscillation, leaving only the component associated with the 11-year cycle. The B_r and B_J values smoothed over 8 and 40 CR, as well as the quasi-biennial components were calculated for the heliolatitudes from –70° to +70° at 10° intervals [13].

associated with the slow cyclic meridional circulation of matter at a constant speed of about 1-3 m/s and another, with generation of quasi-biennial oscillations of magnetic fields by a certain, as yet unknown, mechanism.

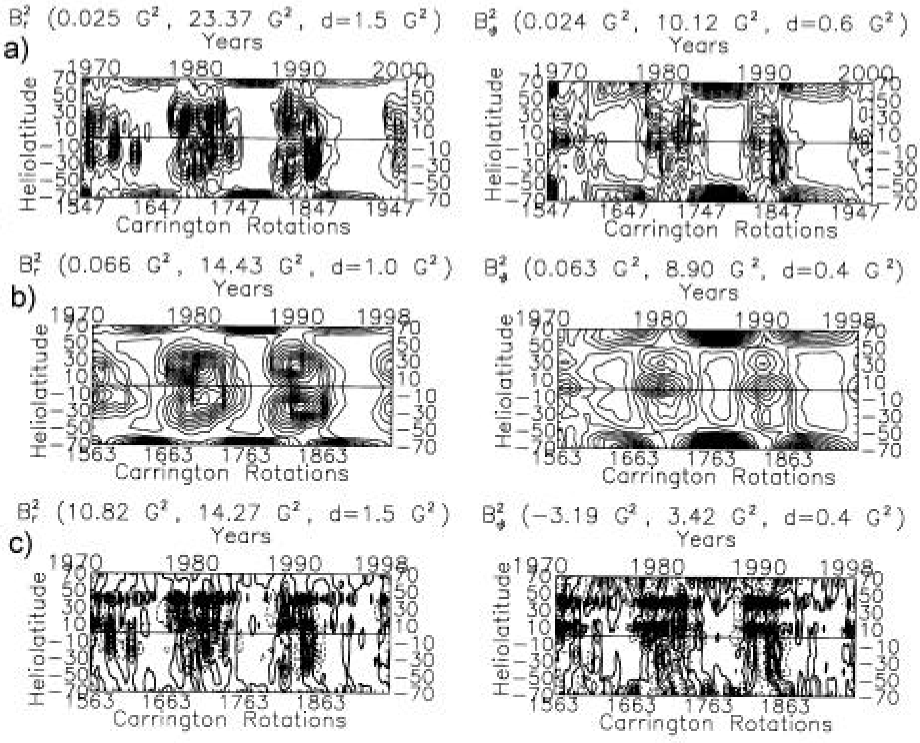

Fig. 3. The time-latitude diagrams for the rotation-averaged values of B_r^2 *and* B_J^2.

In Fig. 2, one can readily see the modes of the LSMF poleward meridional drift mentioned above: a 16-17-year drift for B_r smoothed over 40 CR (Fig. 2b) and a 2-3-year drift for B_r in the interval of periods from 8 to 40 CR (Fig. 2c). The upper panel (Fig. 2a) represents a superposition of both modes. The fast drift appears as “tongues” of the magnetic field of one sign stretched towards high latitudes. These tongues are best pronounced in immediate proximity to the maximum of the 11-year cycle. Unlike the slow LSMF drift at a rate of about 2-3 m/s covering the entire region from the equator to the poles, the fast drift at a rate of about 20 m/s is confined to the magnetic field neutral line that separates the mid-latitude zone (LMF) from the polar one (LSMF). Penetration of the fast-drift tongues to the polar regions is associated with pronounced quasi-biennial oscillations of LSMF. The slow drift at a speed of about 1-3 m/s prevails in the declining phase, at the minimum, and in the early growth phase of solar activity. We are, obviously, dealing with two different types of the meridional drift of magnetic fields controlled by two different mechanisms. One of them is

Figs. 3a,b,c represent the time-latitude diagrams for the rotation-averaged values of B_r^2 and B_J^2 similar to the diagrams for B_r and B_J in Fig. 2. As seen from Fig. 3, the cyclic behaviour of B_r^2 smoothed over 8 or 40 rotations in the mid-latitude region resembles very much the behaviour of the butterfly diagram for sunspots. When superposed, both diagrams are seen to coincide almost perfectly. Contrary to B_r^2, which mainly reflects the evolution of toroidal fields (or, to be more exact, the evolution of the LMF generation region), the B_J^2 diagram shows the cyclic evolution of poloidal fields; therefore it bears virtually no resemblance to the butterfly diagram. Thus, the time-latitude diagrams for the rotation-averaged B_r and B_J components display the LSMF behaviour, while the corresponding diagram for B_r^2 illustrates variations of the LMF generation region. The B_J^2 component manifests the behaviour of the global fields, since it is dominated by lower-order multipoles (mainly, dipole).

To study the LSMF meridional drift, we have calculated the cross-correlation functions (CCF) for the B_r and B_J components and the B_r^2 and B_J^2 values characterizing their energy for the time interval from 1969 to 1999. Then, we considered correlation of the values of the corresponding magnetic field parameter at each of the 14 northern and southern heliolatitudes with the similar values at the equator with a shift of one data series relative to another by ±100 CR. The resulting cross-correlation values were used to plot the correlation diagrams (correlograms) within the shift step-time reference frame.

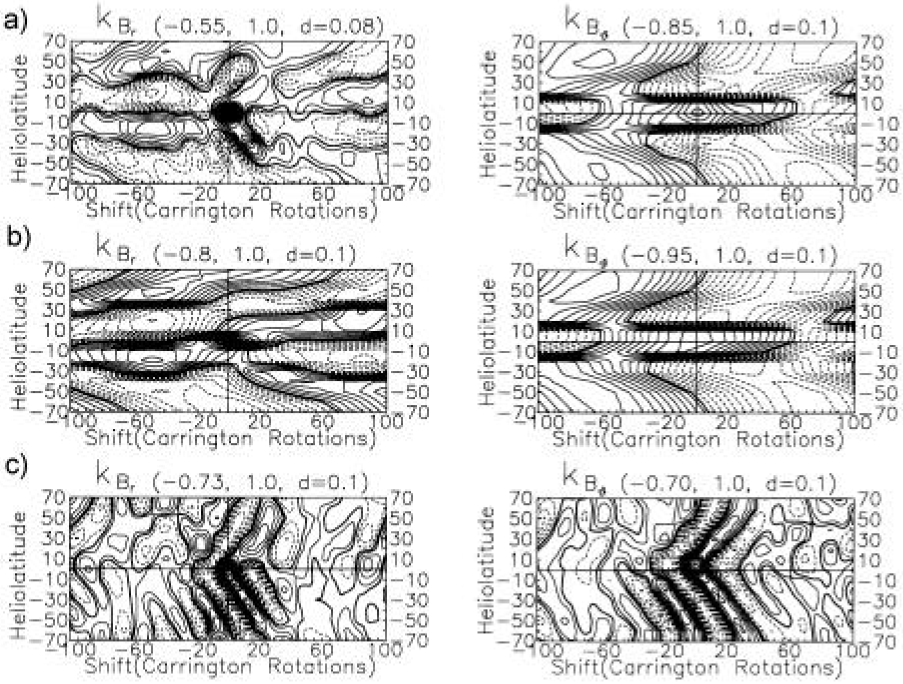

Fig. 4. Cross-correlation of B_r *and* B_J *at the equator with their respective values at the other 14 selected heliolatitudes spaced by 10°in the northern and southern hemispheres for the time interval of 1969-1999.*

Fig. 4 shows the correlograms for B_r and B_J smoothed over 8 and 40 CR, as well as for their quasi-biennial oscillations in the range of the periods from 8 to 40 CR. The figures in brackets above the panels denote (in the order of sequence) the minimum and maximum correlation coefficients and the step between the contours in the panel. The zonal structure of LSMF and its poleward meridional drift are distinctly seen in the Figure. As in Fig. 2, one can readily identify two drift modes with the time scales of about 16-17 years for the B_r and B_J components smoothed over 8 and 40 CR and about 2-3 years for quasi-biennial components. Note that the correlograms for B_r smoothed over 8 CR display both drift modes (the fast drift being mainly confined to the latitudinal zone of ±50°). The similar diagrams for B_J reveal the slow drift mode alone at mid-latitudes, the fast drift being only present in the high-latitude region (>50°). Thus, the main contribution to B_J in the mid-latitude zone is made by the poloidal component responsible for the magnetic field 11-year variations, while the toroidal component responsible for quasi-biennial oscillations is more noticeable in B_r. In general, quasi-biennial oscillations of the large-scale solar magnetic fields associated with the fast drift exist in both field components (Fig. 4c), however in B_r, they are mainly pronounced at mid latitudes, and in B_J, both at mid and at higher latitudes.

In contrast to B_r and B_J (Fig. 4), which characterise the LSMF behaviour, the correlograms for B_r^2 and B_J^2 (Fig. 5) are more complicated. At mid latitudes dominated by the LMF energy, the correlograms for B_r^2 illustrate the behaviour of the local field sources (generation zones), and the B_J^2 correlograms reveal the effect of large-scale poloidal fields connecting the magnetic fields in the northern and southern hemispheres. In the polar zones, both B_r^2 and B_J^2 manifest the behaviour of the global magnetic fields. The diagrams for both components indicate to positive correlation of their respective variations throughout the mid-latitude zone up to 50°-60°. Note that if B_J^2 varies almost synchronously at all latitudes from 50°N to 50°S, the variation of B_r^2 in both hemispheres reveals a noticeable cyclic shift of the zone of the correlation maximum from ~60° towards the equator for the time equal to ~35-40 CR (~2.5-3 years). This shift, obviously, corresponds to the lower return branch of the meridional circulation loop for quasi-biennial oscillations. The fast shift of the correlation maximum from 50°N to 50°S for the time equal to ~10 CR on the B_J^2 correlograms is likely due to the North-South asymmetry of solar magnetic fields. This, probably, accounts for a year's delay of the field reversal at the South Pole relative to that at the North Pole.

In the mid-latitude zone, the variations of B_r^2 at different heliolatitudes correlate with each other. The same is true for the B_J^2 variations. However, the

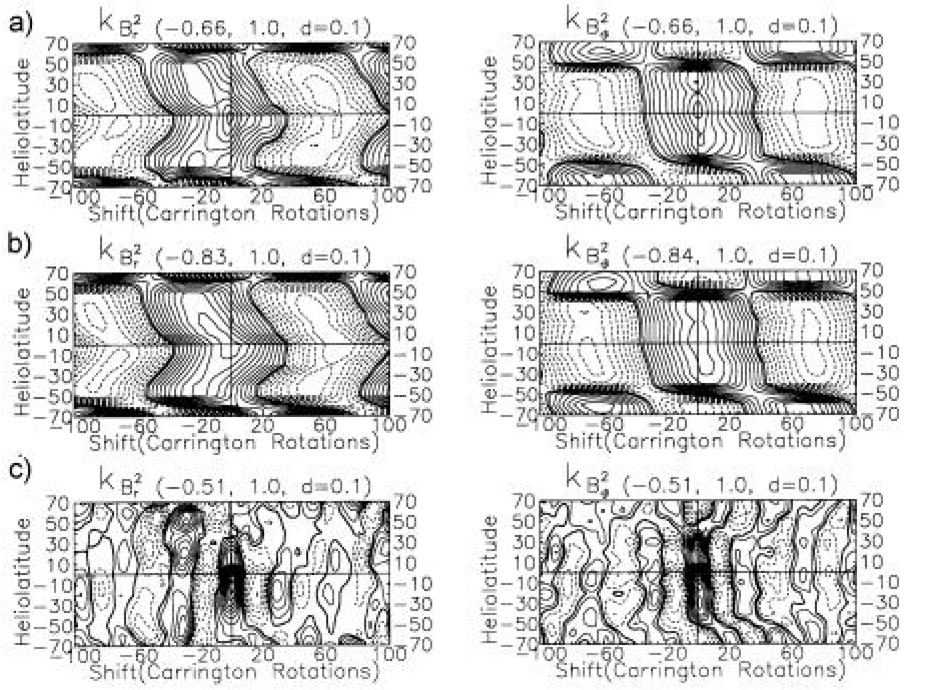

Fig. 5. Cross-correlation of B_r^2 and B_J^2 at the equator with their respective values at the other 14 selected heliolatitudes spaced by 10° in the northern and southern hemispheres for the time interval of 1969-1999

situation changes dramatically if we compare the variations at middle (low) and high latitudes. Here, both B_r^2 and B_J^2 at different latitudes vary in anti-phase, unless we shift the variation in the mid-latitude zone by ±(60-70) CR (i.e., by ~5-5,5 years) relative to the corresponding variation in the polar zone. It implies a close relationship between the LMF variations at mid latitudes and LSMF variations at higher latitudes shifted by about 5.5 years and agrees with the observed relationship between the occurrence rate and intensity of the polar plages and variations of sunspot indices at mid latitudes 5 years later [14, 28]. The relationship under discussion suggests that the global magnetic field observed in the polar regions is primary relative to the mid-latitude local fields and is associated with the meridional circulation of magnetic fields at the base of the convection zone.

Having analysed the time-latitude and correlation diagrams of the magnetic-field variation at the equator and at high latitudes, we arrive at the following conclusions:

1. If we eliminate LSMF variations with periods less than 40 CR (quasi-biennial oscillations), then the poleward drift of the B_r and B_J components occurs at a speed of about 2-3 m/s and takes 16-17 years. The drift of the B_r^2 component (characterising the toroidal field) from mid latitudes (λ<~60°) to the equator occurs for the time equal to the shift of the sunspot production zone on the Maunder butterflies, i.e., about 11-12 years.

2. The maximum correlation zone on the time-latitude diagrams for B_r^2 is shifted by about 5-5.5 years from the pole to mid latitudes.

3. The latitudinal shift of the maximum correlation zone for B_r^2 variations from ~60° to the equator occurs for about 35-40 CR (~2.5-3 years), which corresponds to the return branch of the LSMF fast drift from the equator to the poles for a time scale of about 2-3 years.

4. CONCLUSION

The poleward drift of the LSMF B_r and B_J components for 16-17 years is due to the meridional circulation of matter in the convection zone and corresponds to the upper segment of the circulation loop extending down to ~0.8 R_o. In this part of the convection zone, the kinetic energy of the meridional flow of matter exceeds significantly that of the diffuse large-scale magnetic fields, so that the latter are carried away by meridional flow to the poles. The B_r^2 diagrams display the drift of the generation region of local fields (sunspots) at the base of the convection zone from ~45°-60° to the equator for the time of about 11-12 years at a speed of about 2-3 m/s. This is virtually equal to the LSMF drift velocity at the top of the convection zone. The field is, apparently, carried from the pole to the mid latitudes by the return flow of meridional circulation for the time equal to ~5-5.5 years. At lower latitudes, just where magnetic fields are mainly generated according to the present-day dynamo theories, the situation is fundamentally different. Here, the energy of magnetic fields is much greater than the kinetic energy of the meridional flow. As a result, the dynamo wave generated in this region actually controls the return meridional flow determining its velocity. The drift velocity of the dynamo wave (manifested in the sunspot butterfly diagram) is virtually equal to the velocity of meridional shift of LSMF from the equator to the poles at the top of the convection zone. Thus, the total cycle of meridional circulation of matter in the convection zone equals about 32-34 years. It agrees with the model of meridional circulation of magnetic fields proposed by Tlatov [29]. According to this model, the return flow of the meridional circulation of magnetic fields at the bottom of the convection zone moves from the poles to the equator for the time of about 16-17 years. Along with the above-mentioned loop of meridional circulation responsible for the 22-year magnetic cycle, there may exist another, shorter loop lasting for ~5-6 years and responsible for quasi-biennial oscillations of large-scale solar magnetic fields.

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