MERIDIONAL DRIFTS OF LARGE-SCALE SOLAR MAGNETIC FIELDS AND MERIDIONAL CIRCULATION

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ABSTRACT

The meridional drifts of local (LF) and large-scale (LSMF) solar magnetic fields has been studied for the time interval 1960-2000. The LSMF meridional drift velocity has been considered as a function of latitude. Two modes have been discovered in the meridional poleward drift of LSMF with the typical equator-to-pole travel times of 16-18 and 2-3 years. It is shown that the variation in the square values of the solar field radial component on the time-latitude diagrams coincides with the equatorward drift of local magnetic fields (LF). A shift by 5-5.5 years is observed in the intensity maxima of the global and local fields. It is shown that the total period of meridional circulation of solar plasma in the convection zone is ~22 years, i.e. is equal to the Hale magnetic cycle.

INTRODUCTION

Up-to-date helioseismological studies [1-5] provide us with rather accurate data on the intensity and direction of meridional fluxes in the solar convection zone down to ~0.8 R_0 (where R_0 is the solar radius). These data prove unambiguously that poleward meridional flows of matter exist in both solar hemispheres. Their velocity obviously depends on the latitude, being maximum (~20-25 m/s) at mid latitudes (λ~20°-40°) and minimum (about 1-3 m/s) [5] in the equatorial and polar regions.

A meridional drift was also revealed when studying solar magnetic fields. The nature and direction of the drift differ for the systems of large-scale magnetic fields (LSMF), which are apparently diffusive [6-9], and local fields (LF). The local fields are mainly closed, differentially rotating fields that prevail in the photosphere. This field system manifests itself in the mid-latitude zone as the well-known 11-year sunspot cycle (butterfly diagram in the time-latitude diagram) and the 22-year Hale magnetic cycle. The system of global magnetic fields (GMF) comprises open fields with quasi-solid rotation, which determine the structure of the heliosphere [10-12]. The system of large-scale magnetic fields (LSMF) is likely to be intermediate between the local and global fields. A full magnetic cycle of both GMF and LSMF is equal to ~22 years and is shifted with respect to the sunspot cycle leading it by ~5-5.5 years (i.e., half an 11-year solar cycle) [9, 12]. Some authors [7-9, 13-20] argue that, unlike the local sunspot fields, moving from the latitude of ~40°-45° to the equator during an 11-year cycle, the LSMF meridional drift is directed from the equator to the poles and takes ~16-18 years (3/4 of the 22-year magnetic cycle). Contrary to the LF and LSMF, the GMF does not display any meridional drift at all [10].

COMPARISON OF THE DRIFT OF LOCAL AND LARGE-SCALE MAGNETIC FIELDS

In this study, we consider the meridional drift of large-scale magnetic fields (LSMF) over a long time interval. We have used both the digitized synoptic charts of photospheric magnetic fields from different magnetographs for the past 40 years (1960-2000) reduced to a single format and the magnetic charts recostructed from Hα filament observations for 85 years (1915-2000) [21]. Since the field intensity is absent on the reconstructed charts, the contribution of strong local fields to the reconstructed magnetic fields is significantly reduced, which makes them convenient for the analysis of the meridional drift. [22, 23

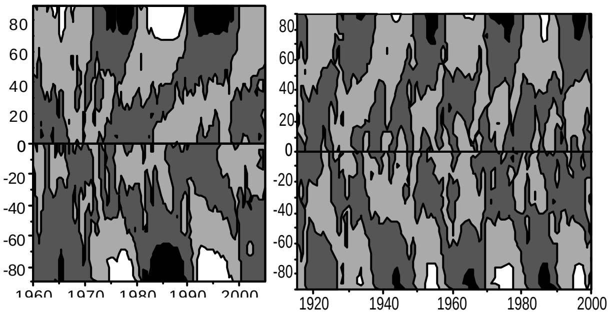

Figure 1. Time-latitude diagram of the radial magnetic field calculated under potential approximation from magnetographic data (left) and Há data (right).

On the basis of these data, we have constructed the time-latitude diagrams for the magnetic fields averaged over a Carrington rotation (Fig. 1). Figure 2 illustrates the time-latitude diagram for large-scale magnetic fields with the superimposed butterfly diagram for sunspots. For details of calculating B_r and plotting the time-latitude diagrams see [9, 10, 24, 25]. The dark gray strips in the figures turning into black at the poles correspond to N polarity (H>0) and light gray strips turning to white at the poles, to S polarity of the magnetic field (H<0). As should be expected, the poleward meridional drift is much better pronounced in the diagrams based on the reconstructed Hα charts than on magnetographic data (Fig. 1).

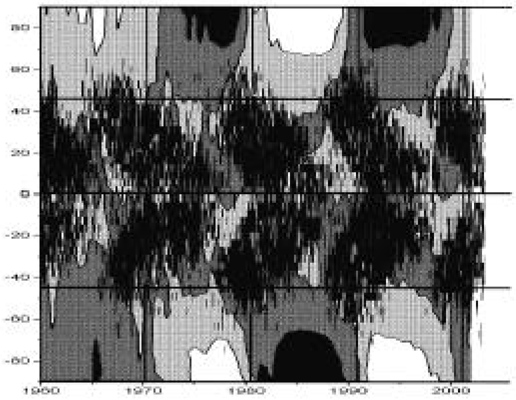

Figure 2. Time-latitude diagram of the large-scale magnetic field with a superimposed Maunder butterfly pattern.

In order to specify the drift parameters, the field distribution in the time-latitude diagram (see Fig. 1, north hemisphere) was approximated in [19] by the function:

$$B_r / s\,(J) = \sum_w A_w(J)\exp(iw(t + j\,(J))) \qquad (1)$$

$$\sum_w A_w^2 = 1, \qquad (2)$$

where σ(θ) is the standard distribution. The amplitude $A_\omega(\theta)$, frequency ω, and phase φ (θ) were determined for each latitude by Fourier expansion.

Figure 3 represents the LSMF meridional drift velocity as a function of latitude, according to the model described above. The figure reveals two regions of fast drift. The drift velocity increases from nearly zero at the equator to the maximum value of 13 m/s in the vicinity of 20°. Approximately the same velocities were obtained in [7, 15, 26]. At higher latitudes in the range of 33°-53°, the drift velocity is as small as 1-3 m/s, and then it increases abruptly up to 25 m/s near the pole.

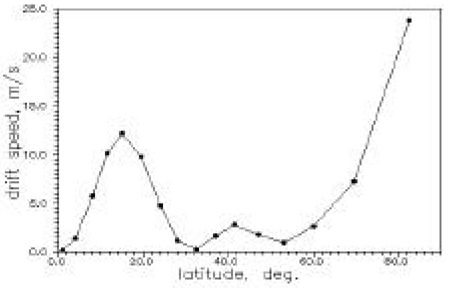

Figure 3. LSMF meridional drift velocity as a function of heliolatitude according to model (1)

The comparison of our LSMF diagrams with the butterfly diagram infers the following conclusions:

1. The large-scale and local magnetic fields drift in anti-phase, the former moving from the equator to higher latitudes and the latter, in the opposite direction. In each cycle of activity, the local fields arise a short time before the reversal of the large-scale fields and complete their motion towards the equator 12-13 years later, at the instant of the next reversal. A narrow latitudinal interval, where the strips of the poleward and equatorward drifts intersect, lies in the vicinity of 20°.

2. The inclination of the butterfly diagram to the time axis, corresponding to the drift about 5° per year, is virtually the same along the whole way from mid-latitudes to the equator and is well approximated by linear equation. Thus, the equatorward drift of sunspots (LF) lasts for 10–11 years - from the minimum of one 11-year cycle to the minimum of another. The central part of the butterfly diagram (greatest sunspot number) coincides with the maximum of the LF cycle and falls on the latitude (20°), where the local and large-scale field strips intersect.

3. Unlike local magnetic fields, the large-scale fields drift at variable speed. As mentioned above, they begin to move rather rapidly from the equator and reach the latitudes of 20°-25° for 2-3 years. In the range of 25°-50°, the drift velocity drops suddenly to 1 m/s or less, and the fields pass this 25°-interval for 15 years. Then, the drift speeds up again, and the rest of the way to the pole (40°-50°) takes a year. Hence, the total travel time of LSMF from the equator to the pole is about 17-18 years, i.e., from the maximum of one 11-cycle to the minimum following the next one. The observed drift pattern agrees with the heliolatitude distribution of the solar plasma velocity in the convection zone obtained by helioseismological method [5].

4. It should be noted that the local fields have maximum intensities in the narrow band of latitudes in the vicinity of 20°, while the large-scale fields are maximum in the polar regions.

TWO MODES OF THE LSMF MERIDIONAL DRIFT

We have studied independently the behaviour of the magnetic fields with the characteristic lifetimes ≥0.6

years, ≥3 years, and in the range of 0.6-3 years [9, 28]. In each subsystem, we have obtained the radial (B_r) and meridional (B_θ) magnetic field components averaged over one rotation, as well as their square values (B_r^2 and B_θ^2), and have plotted the time-latitude diagrams for all of these values.

The B_r and B_θ diagrams analyzed independently for each magnetic field subsystem have revealed two different types of the meridional poleward drift in LSMF: a 17-18-year drift for the field subsystem with the characteristic lifetimes ≥3.0 years and a 2-3 year drift for the subsystem with the characteristic lifetimes ranging from ~0.6 to 3 years. In the first case, the average lifetime of a polarity band at a certain heliolatitude is ~11 years and in the second, ~15-20 rotations (~1.5 years). Unlike the slow (~2-3 m/s) LSMF drift covering the whole latitude zone from the equator to the pole, the fast drift (~20-25 m/s) is confined to the magnetic neutral line, which separates the mid-latitude zone (LF domain) from the polar ones (GMF domain). This type of the drift is best pronounced in the years near the solar maximum. At the decay and minimum of the solar cycle, the slow drift at a velocity of ~1-3 m/s is predominant. The existence of two modes of the poleward drift is likely to account for the observed latitudinal variations in the meridional drift velocity. Their superposition results in the velocity distribution illustrated in Fig. 3.

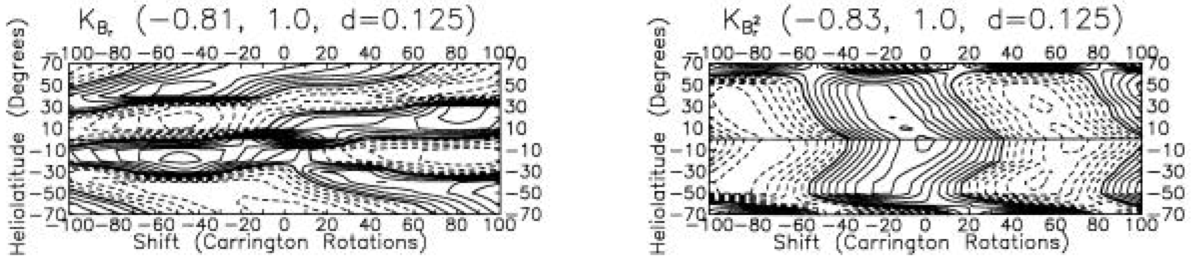

Figure 4. Cross-correlation of B_r and B_r^2 (smoothed over 40 CR) at the equator with their respective values at the other 14 selected heliolatitudes spaced by 10° in the northern and southern hemispheres for the time interval of 1970-1999. The figures in brackets above the panels denote (in the order of sequence) the minimum

As should be expected, the cyclic variation of the square radial component B_r^2 at mid latitudes for the subsystem with the characteristic lifetimes >3 years resembles very much the sunspot butterfly diagram and manifests mainly the evolution of the local field generation region. At the same time, the square meridional component B_θ^2 reflects the evolution of the poloidal field sources (GMF), and therefore, the butterfly diagram is not virtually discerned.

As seen from the time-latitude diagrams for B_r and B_θ averaged over one rotation, the large-scale magnetic fields located above the local field generation region are dominating in the convection zone. In the B_r^2 and B_θ^2 diagrams, the large-scale (global) fields prevail at the poles and more intensive local fields, at mid latitudes. Thus, the meridional poleward drift of diffuse LSMF can be explained as a result of the meridional circulation of solar plasma in the convection zone, while the B_r^2 diagram reflects the cyclic evolution of the wave of generation of local fields.

We have also calculated the cross-correlation functions (CCF) for each of the 4 parameters (B_r, B_θ, B_r^2 and B_θ^2) under consideration at the equator and at the other 14 heliolatitudes for the time interval of 1970-1999 with a shift up to ±100 CR. The correlograms in [28] show two modes of the drift from the equator to the poles with the characteristic times of the order of 17-18 years and 2-3 years.

Figure 4 shows the correlograms for B_r and B_r^2 variations with periods more than 40 CR (~3 years). Similar correlograms have been obtained for B_θ and B_θ^2 variations. Unlike the correlograms for B_r and B_θ, the correlograms for B_r^2 and B_θ^2 display an essential difference between the mid-latitude and polar zones. The variations of B_r^2 and B_θ^2 display a positive correlation virtually all over the mid-latitude zone with a shift of about ±20 rotations. On the other hand, the correlation between the equatorial and high-latitude variations of B_r^2 and B_θ^2 is negative, a positive correlation being only observed when the respective variations occur with a shift of about ±(60-70) CR (i.e., ~5-5.5 years). This means that the negative correlation between the B_r^2 (or B_θ^2) values in the mid and high-latitude zones at every given moment turns into positive as variations at the poles shift by ±(60-70 CR) (i.e., ~5-5.5 years) with respect to variations in the mid-latitude zones. This points to a close connection of the magnetic field variations in the mid- and high-latitude zones. The obtained shift by ~5-5.5 years agrees with the results of [12] and may account for the apparently causal relationship between the occurrence rate and intensity of the polar faculae and mid-latitude sunspots observed about 5 years later [27]. This relationship implies that the global magnetic field in the polar region is primary with respect to the toroidal fields in the mid-latitudinal zone.

CONCLUSIONS

According to helioseismological studies (e.g., see [5]), the meridional circulation is a global phenomenon not confined to the solar surface alone. The helioseismic measurements are consistent with the presence of 2 circulation cells in each hemisphere with a poleward flow from ~1-3 m/s (slow drift from equator to pole) to ~20 m/s (fast drift from ~5° to the polar filament region) in the upper layers of the convection zone and an equatorward velocity of about 2-3 m/s (and maybe of ~20 m/s in the mid-latitude zone for the fast mode) at the base of the convection zone. The turning point for the circulation is at $r = 0.80R_0$, where R_0 is the radius of the Sun. The poleward flow consists of two modes: a slow mode with a speed of ~2-3 m/s and a drift time from the equator to the pole of about 17-18 years and a fast mode in the mid-latitude (<|±50°|) region with a speed of ~20 m/s and a drift time from the mid to high latitudes of ~2-3 years. The opposite equatorward drift of the solar plasma and magnetic field from the pole to the equator at the base of the convection zone corresponding to the lower branch of the meridional circulation contour takes ~5-5.5 years.

Hence, local fields originate in the mid-latitude region at the base of the convection zone. They arise from the magnetic field carried to mid latitudes from the polar zone by the invisible reverse meridional flow for the time equal to -5.5 years. Simultaneously, the large-scale diffuse poloidal field is generated from the toroidal one. The growth of that poloidal field results in regular reversal of GMF at the poles.

The total period of meridional circulation of solar plasma in the convection zone is ~22 years, i.e. is equal to the Hale magnetic cycle. The fast drift (~20 m/s) at mid latitudes is closely related to quasi-biennial oscillations (QBO) and its origin is still as vague as of the latter.

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