V. LARGE-SCALE STRUCTURE AND DYNAMICS

GLOBAL EVOLUTION OF PHOTOSPHERIC MAGNETIC FIELDS

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ABSTRACT

The main features concerning the evolution of the large scale photospheric magnetic fields derived from synoptic maps as well as from H-alpha synoptic charts are reviewed. The significance of a variety of observations that indicate the presence of a high latitude component as a counterpart to the sunspot phenomenon at lower latitudes is reviewed. It is argued that these two components describe the global magnetic field on the sun. It is demonstrated that this scenario is able to link many phenomena observed on the sun (coronal emission, ephemeral active regions, geomagnetic activity, torsional oscillations, polar faculae and global modes in the magnetic field pattern) with the global magnetic activity.

1. INTRODUCTION

Since the discovery of magnetic fields in sunspots by Hale (1908) solar magnetic fields have been an area of investigation both with countinously improving observing techniques as well as methods of theoretical modelling. The important role of the magnetic fields in every aspect of solar activity and variability has now been fully recognised. Although most of the flux observed on the sun appears in the form of tiny fragments associated with strong fields, these structures organise themselves into large scale global patterns that evolve over the time scale of the solar cycle. Magnetic fields on the sun manifest themselves on several length scales and change on several time scales.

i. Large scale fields with mean field values in the neighbourhood of 1 gauss and time scale of the order of a few rotation periods of the sun.

ii. Intermediate scale fields which occur in the form of sunspots with high values of fields ($\sim$2000 gauss).

iii. Small scale structures which have sizes of a few arc seconds (even sub-arc size elements are present) with strong fields residing

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in them.

In this review, we shall be concerned with the first type, namely, the large scale fields.

The existence of solar magnetic fields outside of sunspots was first detected by H.W.Babcock and H.D.Babcock (1955). Their magnetograms of the sun showed the following features:

I. Solar magnetic field consists of regions of strong (10^3 Gauss) as well as regions of weak diffuse fields (~ 1 Gauss).

II. The regions of strong fields are related with active regions and the sunspots, while the regions of weak fields consist of large unipolar structures.

III. At the boundaries of unipolar regions where the radial component of the magnetic field is zero, prominences are observed. Over the solar disc these appear as H-alpha dark filaments.

IV. The poles have a weak but significant measurable fields all the time and the polarity of these fields at the poles reversed near the epoch of the maximum activity (1957-1959).

Following this, Babcock (1961) enunciated his classical model of the solar cycle. But a more fundamental problem which remains unsolved pertains to the origin and support of the solar magnetic field or the solar dynamo. Different theoretical groups at work on this have constructed several models. Although none of them is satisfactory, enough observations do not also exist today which can pick out or eliminate any of the models in preference to others with any confidence.

Further progress in the studies of solar magnetism is marked by the commencement of regular observations of the photospheric magnetic fields at the Mt.Wilson Observatory in 1959 (Howard 1967; Howard et al. 1967), at the Crimean Astrophysical Observatory (Severny 1966), at the Kitt Peak National Observatory and Stanford Observatory in 1976 and at Sayan Observatory at Sibizmir (Grigoriev et al. 1983). The main features that emerged from the synoptic maps constructed from the Mt.Wilson magnetograms for the period 1959-1980 (Bumba and Howard 1965; Howard and LaBonte, 1981) are the following:

I. Active regions break up into fragments of weak fields that coalesce to form global patterns of unipolar magnetic field regions. These slowly expand, are stretched by differential rotation and drift polewards forming the polar fields.

II. The solar equator is not the polarity division line for the background fields as in the case with sunspots.

III. The sunspot latitudes are characterised by fields of the preceding polarity while, the polar fields are composed by field flows of the following polarity which migrate towards the poles with a velocity of ~ 10 m sec^{-1}.

IV. The total magnetic flux on the sun changes only by a factor of 3 from the minimum to the maximum epochs of activity.

2. DYNAMICAL FEATURES OF EVOLUTION

During the last few years, considerable information concerning the dynamics of large scale fields have been derived both from the full disc magnetogram as well as the H-alpha synoptic charts. The latter form a good proxy for the magnetograms. The H-alpha filaments which are neutral dividing lines between two regions of opposite polarity can be used as a good tool to study the dynamical features associated with the evolution of global magnetic field pattern (McIntosh 1979; Makarov et al. 1983). The migration of the filament bands is represented most conveniently by plotting their mean latitude positions rotation wise, on a latitude - time diagram Fig.1 (Makarov et al. 1983). On this diagram the filament bands are seen to migrate polewards continously at speeds of $\sim$5 m sec^{-1}. Topka et al. (1982) demostrated that the poleward drift of the filament bands (and hence of the unipolar regions) is not by diffusion, but the surface magnetic fields are transported to the poles by poleward meridional flows. Also, it is seen that these unipolar regions always migrate poleward and at no time show an equatorward drift (Makarov, 1984). The polemost filament shows a dramatic increase in its poleward motion attaining speeds of 15-40 m sec^{-1} simultaneous with the steep rise in sunspot activity. The speed of the poleward migration seems to be related

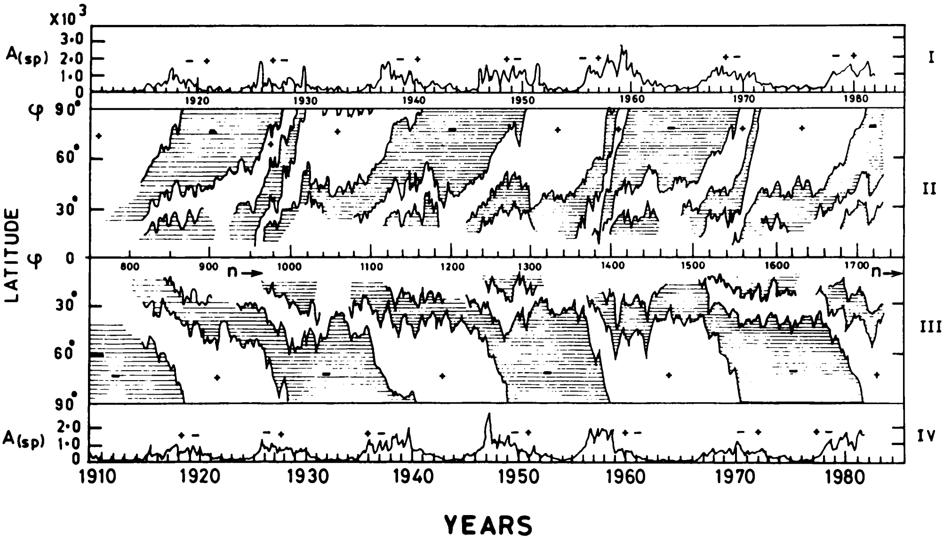

Figure 1. Boxes II and III show the migration trajectories of the neutral lines of the large scale magnetic field form $H\alpha$ synoptic charts for the period 1910–1982. + and – stand for the polarity signs of the magnetic field in the conventional way. n is the number of the Carrington rotation. Boxes I and IV show the plots of daily sunspot areas $A_{(sp)}$ in millionths of the visible hemisphere.

with the strength of the cycle concerned. The polemost filament reaches the pole first and causes the reversal of the polar field. The polemost filament in both the hemispheres do not reach the respective poles simultaneously and in such situations the polar reversal at one of the poles takes place earlier than at the other. The sun exhibits the same polarity on both the poles (monopole) till such time, the polemost filament in the second hemisphere has reached the pole and causes the reversal there. This is the picture when a single fold reversal takes place in both the hemispheres (eg. years 1920, 1940, 1950 and 1980 in Fig.1). There are instances when a three fold reversal occurs in either of the hemispheres. In such cases all the three filament bands (Fig.1) travel to the respective poles one after the other and cause a three fold reversal. Such three fold reversals took place in the northern hemisphere alone in 1930, 1960 and 1970 and in the southern hemisphere alone in 1885 and 1910 (Fig.2). The phenomenon of a three fold reversal in both the hemispheres has not been observed any time during the last 115 years (Fig.2).

Years Cycles	1856–1878 10 – 11	1879–1901 12 – 13	1902–1923 14 – 15	1924–1944 16 – 17	1945–1964 18 – 19	1965–1985 20 – 21	1986– 22 –
N	↓	↑ ↓	↑ ↓	↑↓↑ ↓	↑ ↓↑↓	↑↓↑ ↓	
S	↑	↓↑↓ ↑	↓↑↓ ↑	↓ ↑	↓ ↑	↓ ↑	

Figure 2. Hale's 22-year cycles and the reversal of the sun's magnetic field in the odd and even 11-year cycles in the northern and southern hemispheres. Three vertical arrows in one group (↑↓↑) represent a three-fold reversal, while a single vertical arrow (↑ or ↓) represents a one-fold reversal.

3. FORMATION OF UNIPOLAR MAGNETIC REGIONS

Both the magnetogram data as well as the H-alpha synoptic charts show that the polar magnetic fields during any cycle are built up and maintained by the continous arrival of discrete f-polarity regions. These regions originate in active region latitudes and migrate towards the poles. This picture can be illustrated better with the help of Fig.1 for any cycle particularly in the southern hemisphere where the single fold reversal make the illustration easier. During cycle 20 (1964-1974) the following part of active centres in the southern hemisphere was of south polarity (-), whereas the polarity at the pole was positive (+) from 1960 to 1971, while the reversal took place. Fig.1 shows something more than this. It can be seen that these negative unipolar regions were formed at latitudes > 30° from as early as 1957, although their poleward migration started only as late as 1966-1967. Thus, the zone of negative polarity that formed in cycle 19 determined the polarity of the high latitude field in cycle 20 during the period 1970-1981. This picture would lead to the interpretation that this zone with the new fields (-) was formed out of the p-polarity of the active regions starting with 1957 as, these regions could not have been formed out of the regions of cycle 20, which are yet to appear on the sun at least at these latitudes (> 30°). It may be that the f-polarity regions of cycle 20 aded fresh unipolar regions to those already formed from the p-polarity of the earlier cycle. This process is most obvious for cycle 18 (1944-1954) in Fig.1.

4. EVOLUTION OF FIELDS AT HIGH LATITUDES

The solar cycle has been defined traditionally from the spot counts or areas of spots as the interval between two successive minima giving an average value of ~11 years. But a number of observations show that the activity begins at high latitudes soon after the reversal of the polar fields and a few years before the first appearance of the spots of the new cycle. These observations are the following:

i. Coronal emission observation in the 5303A line.
ii. Ephemeral active regions (ERs).
iii. Geomagnetic activity.
iv. Torsional oscillations.
v. Polar faculae
vi. Global modes in the magnetic field pattern.

4.1. Coronal Emission in 5303A line

It is known that the coronal emission intensity in 5303A line is a good index of the magnetic field. In the 1950s the coronal observers (Waldmeier 1957; Trellis 1963) noticed in their data that a zone of enhanced emission in 5303A line makes its appearance at high latitudes in each hemisphere several years before the commencement of the "classical" sunspot cycle. This is in addition to the strong emission component present during the years of the sunspot cycle that always mathes with the butterfly diagram of sunspots. The high latitude bands are brought out conspicuously when the standard deviation of the coronal emission σ_{5303} is used as the emission index rather than the mere average emission values. This index is very useful for detecting particularly the newly emerging magnetic flux regions. The plot of the isovalues of the quantity $\sigma_{5303} - \overline{\sigma}_{5303}$ ($\overline{\sigma}_{5303}$ is the latitude average of σ_{5303} over 20° intervals) for years 1944-1974 shows the two components clearly, when freed of the background emission (Leroy and Noens, 1983). The high latitude components appear immediately after the polar reversals and drift towards the poles (Fig.3) (Makarov et al. 1987a). The two latitude components partly overlap in time and thereby extend the duration of the coronal activity to 16-18 years. Results of Altrock (1988) for cycle 21 and of Bumba et al. (1989) for the period 1965-1986 show the two latitude components in each hemisphere. The latter data even suggest a possible connection between the two components unlike the results of Leroy and Noens (1983).

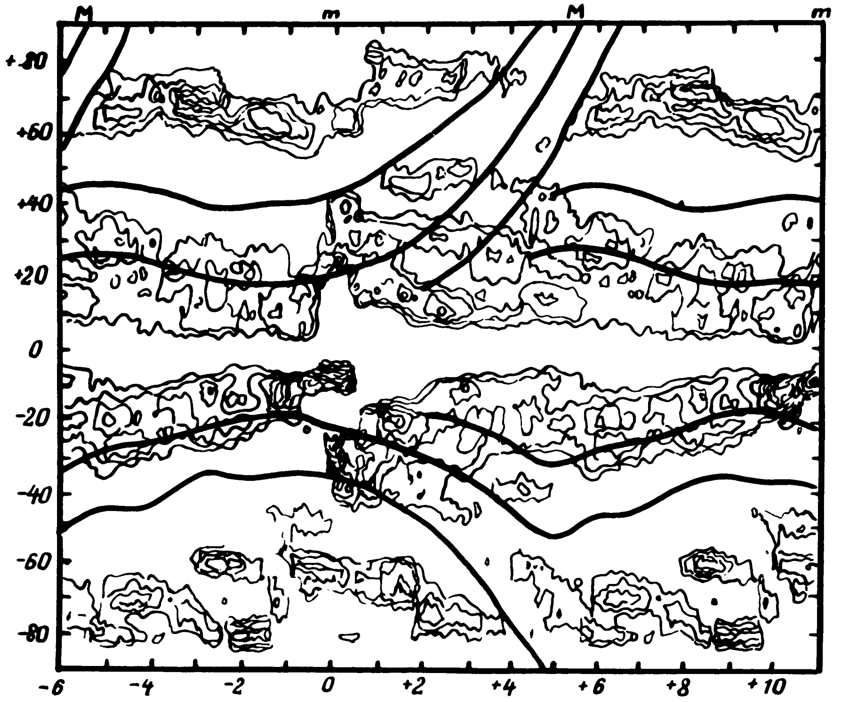

Figure 3. Map of isovalues of the quantity $\sigma_{5303} - \bar{\sigma}_{5303}$ (Leroy and Noens, 1983). σ_{5303} is the standard deviation of the coronal intensity at each latitude over periods of about 1 year, and $\bar{\sigma}_{5303}$ is the latitude average of σ over 20° intervals. The thick lines are the migration trajectories of neutral filament bands for cycle 20 (Makarov, Leroy, and Noens, 1987a). m is the minimum epoch of the solar cycle, M the maximum epoch. The vertical axis gives the solar latitude in degrees.

4.2. Ephemeral Active Regions (ERs)

The properties of ERs and their evolution in relation to the solar cycle have been studied by Martin and Harvey (1979) for the 20th cycle. The ERs occur in the form of tiny bipoles. They identified a high latitude band of ERs in 1973 and 1975 in each hemisphere. Their important finding is the detection of a significant number of ERs contained in the high latitude bands that exhibited a polarity orientation dictated by Hale's law appropriate to the next cycle (cycle 21) rather than to cycle 20, while the low latitude ERs showed the polarity of cycle 20. Thus the ERs belonging to two successive cycles coexist for more than 3 years, with the high latitude component leading the low latitude component. These findings have been confirmed from further analysis of subsequent data for cycle 21 by K.Harvey (Wilson 1988).

4.3. Geomagnetic Activity

Another evidence for the high latitude component of activity is provided by Legrand and Simon (1981) who formulated a pattern for the global solar activity of 16-18 years duration from their study of geomagnetic activity in relation to the solar cycle. They noticed geomagnetic activity related to the solar cycle arises from two components: one, the high speed wind streams originating from the coronal holes at high latitudes and the other, related to the sunspot activity. The high latitude component makes its appearance shortly after the polar field reversal and coexists with the low latitude component of activity with an overlap of 6-7 years, thereby extending the duration of solar cycle to 16-18 years.

4.4. Torsional Oscillations (TO)

The torsional oscillation refer to the alternating latitude bands of faster than average and slower than average rotation present on the sun discovered by Howard and LaBonte (1980) from the Mt.Wilson velocity data. According to them, the torsional waves (two per hemisphere) start from either pole once in 11 years before the sunspot maximum and travel to the equator in the course of 18-22 years. The epoch of appearance of sunspots at $\pm 40°$ latitudes coincides with the arrival of the faster band of the torsional wave at these latitudes and the TO merge with the butterfly diagram then on. The TO is considered as a signal representing the propagation of magnetic activity on the sun. If the time of travel of TO from the pole to the equator on the solar hemisphere represents the duration of the solar cycle, then the latter turns out to be $\sim$18 years. Such an extended duration although, hypothesised independently by Legrand and Simon (1981) from the solar wind stream studies and by Martin and Harvey (1979) from the ERs, this concept gained strength only after the TO came to be known.

4.5. Polar Faculae

After every polar reversal, regions above ±40° latitudes show polar faculae. These can be seen in white light images of the sun as well as in the Ca II K line spectroheliograms. The number of polar faculae present on the sun follow a cyclic variation with the period of 11 years which differ in phase with the sunspot numbers by ~90° (Sheeley 1976). The most significant results that have emerged from a study of the evolution of polar faculae are the following:

i. The faculae appear a few months after the polar revrsal. During the deep solar minimum periods, about 900 faculae can be identified on the solar disc and over a third of these occur as bipoles, some of them aligned in the E-W direction. The unipolar faculae have a polarity identical to that of the background field, while in the case of the bipolar faculae the preceding polarity is identical to that of the background field. The polarity orientation of these bipoles is opposite to that of the spots of the same cycle (Hale's law), but identical to the polarity orientation for bipolar spots of the next following cycle for the hemisphere concerned (Makarov and Makarova 1984, 1987). In other words, while faculae of the (N+1) cycle make their appearance at high latitudes, the activity of the preceding cycle (N) is still present at lower latitudes in the sunspot phase. This is similar to the behaviour of ephemeral active regions.

ii. The faculae appear first at latitude zones 40°-60° and the zones of appearance migrate slowly and reach high latitudes 70°-80° as the cycle progresses (Fig.4) (Makarov and Sivaraman 1986; Makarov et al. 1987b).

iii. The new cycle shows up first as faculae at high latitudes and leads the sunspot phenomenon by 5-6 years. Each of these has a duration of 11 years, but occur at separate latitudes and displaced from each other in time by 5-6 years within a 22 year magnetic cycle (Fig.4). Thus the conventional solar cycle, which is defined as the duration of the butterfly patterns based on the spot number counts, describes only that part of the activity relating to the cycle that occurs within the ±40° latitude zones; whereas, if the activity at latitudes > 40° is also taken into account then the solar activity cycle starts from the appearence of the faculae and lasts till the end of the butterfly diagram. The duration of this global cycle turns out to be 16-18 years (Makarov and Sivaraman 1989).

If we now compare the coronal emission pattern as that of Leroy and Noens (1983) with the faculae distribution, the match appears good. The high latitude component of the coronal emission coincides spatially with the faculae and the low latitude component with the butterfly diagram.

In the case of the torsional oscillations (TO), the analysis of Howard and LaBonte (1980) that led to the inference of a pole to equator travelling wave pattern with k=2 contained a mathematical artifact and the pattern when freed of the artifact consists of

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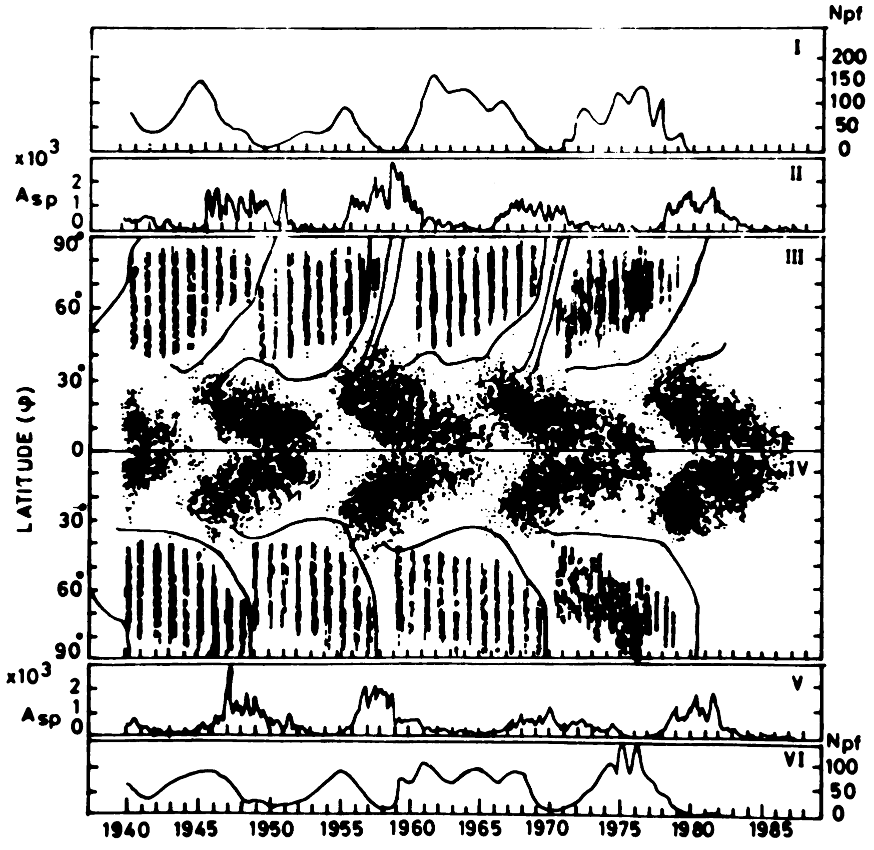

Figure 4. Boxes III and IV show the latitude distribution of polar faculae and sunspots (butterfly diagram) during 1940–1985. The superposed lines are the migration trajectories of filaments reproduced from Figure 1 after smoothing, to show the epochs of polar reversals. Boxes II and V show the sunspot areas A_{sp} as in Figure 1. Boxes I and VI show the counts (N_{pf}) of polar faculae in the north and south hemispheres.

a relative polar spin up near solar maximum and a separate single wave that runs from mid to low latitudes during the rest of the cycle (Snodgrass 1985, 1987). The torsional shear (which is the derivative of the net torsional pattern with respect to the latitude) increase and decrease regions at low latitudes match well with the butterfly diagram of sunspots (Snodgrass 1987). The high latitude shear increase zone which has no counterpart in Snodgrass's (1987) interpretation, is seen to match well with the polar faculae regions (Makarov and Sivaraman, 1989).

4.6. Global Modes in the Magnetic Field Pattern

The discovery of the resonant global wave pattern in the magnetic fields of the sun by Stenflo and coworkers has provided a new area from where encouraging results have come out regarding the global

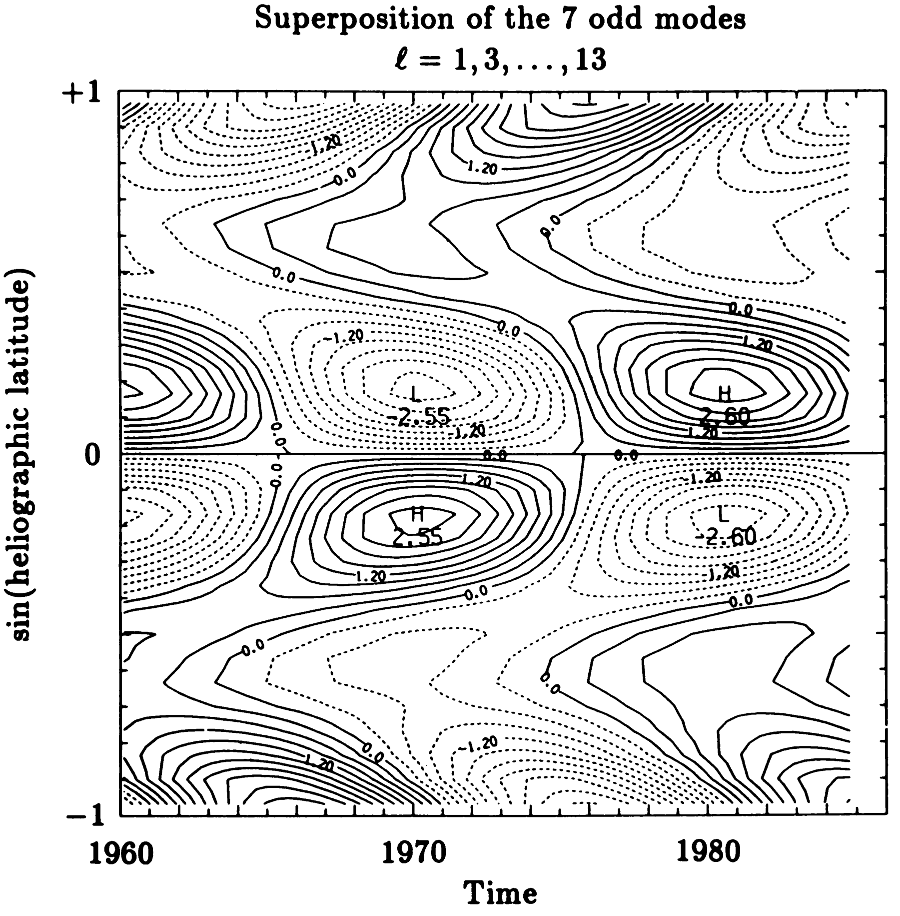

Figure 5. Synthetic evolutionary diagram computed as the superposition of 7 discrete harmonic modes (with purely sinusoidal time variations), with only odd values of $l (l = 1, 3, \ldots, 13)$. (Reproduction of Fig. 4 of Stenflo (1988). By courtesy of Stenflo and Kluwer Academic Publishers.)

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evolution of photospheric magnetic fields. The power spectrum of the spherical harmonic coefficients for the zonal modes of the radial magnetic field shows the presence of a set of discrete resonant frequencies (Stenflo and Vogel, 1986; Stenflo and Güdel, 1988; Stenflo, 1988). The harmonic modes can be characterised by their degree ℓ and order m. The rotationally symmetric modes (with m=0) obey a parity selection rule: the modes with odd parity (odd values of ℓ) are dominated by power that correspond to a period of 22 years for all values of ℓ; while the even parity modes show power at higher frequencies that vary with value of ℓ, with no trace of the 22 year cycle. Gokhale et al. (1989) have obtained similar results from their analysis of 80 years of sunspot data. The zonal magnetic field pattern averaged over all longitudes shows the evolution of the field in the solar latitude-time domain (Stenflo, 1988). The main features are:

i. The polarities reverse sign every 11-years both at high and low latitudes.

ii. On the high latitude zones, the magnetic field pattern drift steeply towards the poles and

iii. On the low latitude zones, the field shows drift towards the equator in the course of the 11-year cycle, which is the butterfly diagram.

Stenflo (1988) has constructed synthetic contours by approximating the true power spectrum by δ - functions, one for each value of ℓ. The resulting pattern derived by superposing 14 discrete modes reproduces the observed zonal pattern well. The pattern can be considerably refined by separating out the antisymmetric component (i.e. by a superposition of only 7 odd modes; ℓ = 1, 3, ... 13), which brings out the equatorial and poleward drifts of the magnetic patterns and the 22-year periodicity most conspicuously (Fig.5). This picture of the evolution of the magnetic fields totally agrees with the composite global field pattern with the polar faculae and the sunspot butterfly diagram shown in Fig.4. The similarity of the polarity distribution of the two components and the polarity reversals also match exactly.

5. SCENARIO OF THE GLOBAL MAGNETIC FIELD PATTERN

The good agreement among the observations of different parameters, (coronal emission, polar facule, global modes, geomagnetic activity, ephemeral active regions) all of them connected with the magnetic fields can now be pooled together to evolve a working empirical model. According to this model, the global photospheric magnetic field consists of two components: the high latitude and the low latitude components (Fig.4 and Fig.6). The high latitude component is represented by the coronal emission, the polar faculae and the ephemeral active regions, which makes its appearance immediately after the polar reversal and is characterised by the poleward drift. The second and the more powerful component is represented by the sunspots that appear when the first component is already at its

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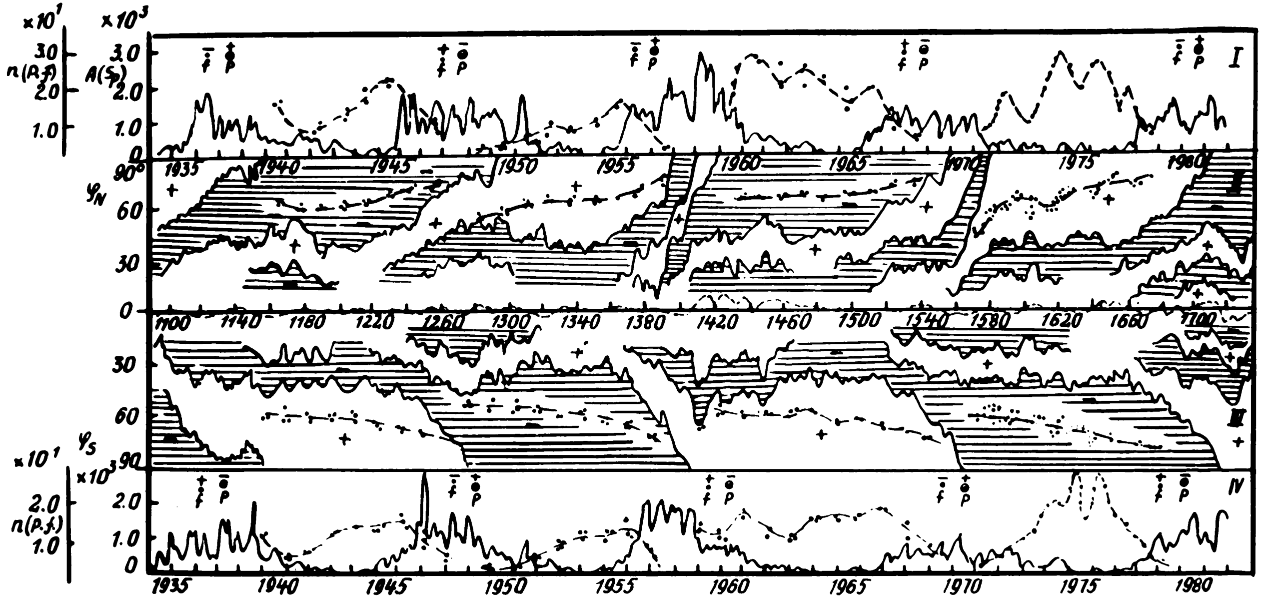

Figure 6. Global solar cycle activity during 1935–1980 as in Fig. 1. Boxes I and IV: The broken curves represent the number of polar faculae n $(p.f.)$. The solid curves represent the areas of spots $A(Sp)$ as in Fig. 1. Boxes II and III: The dots represent the latitudes of the polar faculae for the N and S hemispheres. The broken line is a free hand fit through these points. The rest is the same as in Fig. 1.

peak and has an equatorward drift which is the butterfly diagram. The theoretical support for the magnetic waves of solar activity is provided by the investigations of Makarov et al. (1987c). The two components appear on the sun at different latitude zones and with a shift in time by 5-6 years which gives the notion of the extended duration of the solar cycle. It is not known at this stage whether the two components could be connected by a common causal agency. The agreement or otherwise with the TO pattern is also unclear at this stage, due to paucity of the TO data. With the arrival of more results on TO and ephemeral active regions, the picture should become more meaningful.

Our understanding of the solar magnetism leans heavily on the empirical results derived from observations of the surface fields. Hence, it is important to be able to offer as much information based on observations as possible to provide clues in framing the global picture of the solar magnetic fields. From the theoretical side, it seems quite satisfying to note that the solar magnetic field can be described as a linear superposition of discrete global modes. This approach appears to be promising and may provide clues in our endeavour in understanding the magnetic fields and their variability on the sun and other stars too.

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