NEW RESULTS CONCERNING THE GLOBAL SOLAR CYCLE

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Abstract. We derive the poleward migration trajectory diagram of the filament bands for the years 1915–1982 from the H-alpha synoptic charts. We find that the global solar activity commences soon after the polar field reversal in the form of two components in each hemisphere. The first component we identify with the polar faculae that appear at latitudes 40–70° and migrate polewards. The second and the more powerful component representing the sunspots shows up at $\sim 40°$ latitudes 5–6 years later and drifts equatorward giving rise to the butterfly diagram. Thus the global solar activity is described by the faculae and the sunspots that occur at different latitude belts and displaced in time by 5–6 years. This gives rise to the prolonged duration for the global solar activity lasting for 16–18 years as against the 11 years which has come about based only on the spots. The two components match with the pattern of the coronal emission in 5303 Å line. Finally, we show that the two components of activity also match with the pattern of excess shear associated with the torsional oscillations on the Sun and this provides a link between the torsional oscillations and the magnetic activity.

1. Introduction

According to the classical picture, the magnetic field on the Sun manifests as a poloidal component observed above latitudes 40° and a toroidal component that emerges at mid-latitudes in the form of sunspot 'dipoles' and migrates towards the equator. However, during the last decade the studies of the magnetic field in polar faculae, their latitude distribution with the phase of the cycle (Sheeley, 1976; Makarov, Makarova, and Sivaraman, 1987), of the ephemeral active regions and X-ray bright points (Martin and Harvey, 1979; Golub *et al.*, 1977), of the latitude distribution of the coronal brightness in 5303 Å line (Leroy and Noens, 1983; Makarov, Leroy, and Noens, 1987), of the migration of the magnetic neutral line (Makarov and Sivaraman, 1983, 1986) and of the latitude distribution of prominences in a solar cycle (Waldmeier, 1960) show that the activity is present over all latitudes on the Sun. The synoptic view of the solar cycle derived using the H-alpha filament as tracers (Makarov and Sivaraman, 1983, 1986) show that the epoch of the reversal of the polar magnetic field heralds the beginning of the global solar activity processes. Starting from this epoch, the first component or the first wave (the term 'wave' is used here rather in a loose sense to illustrate the progressive nature of the phenomenon) of the global magnetic activity begins to show up at latitudes from 40 to 70° as polar faculae migrating polewards. The second and the more powerful wave is the sunspot activity that starts when the first wave is already at its peak and drifts towards the equator – i.e., the butterfly diagram. The polar faculae,

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the ephemeral active regions and X-ray bright points belong to a class of activity distinctly different from the sunspots in terms of their physical and morphological properties.

In this paper we present the new results of our study of the polar faculae for 4 cycles (1940–1985) and show how the traditional concept of the solar cycle has remained incomplete without inclusion of this component. The polar faculae populate the higher latitude zones on the Sun and their evolution over the course of the solar cycle appears as a mirror image of the butterfly diagram, but displaced in time by 5 to 6 years. This displacement in time streches the duration of the solar activity to 16–18 years as against the traditional value of ~ 11 years. We also show how the addition of the polar faculae on the sunspot butterfly diagram can explain its similarity with the pattern of the 5303 Å coronal brightness distribution published by Leroy and Noens (1983) over the solar cycle. The notion of an extended solar cycle has been suggested independently by different solar groups working with different parameters of solar activity, like coronal emission brightness in 5303 Å line (Leroy and Noens, 1983), torsional oscillations (Howard and LaBonte, 1980; Snodgrass, 1987b), solar wind streams (Legrand and Simon, 1981), etc., Wilson *et al.* (1988) have brought together many of the periodic phenomena (butterfly diagram, coronal brightness, ephemeral active regions, and torsional shear pattern) and have attempted to show the manifestation of the extended cycle in all of them. But the plots of polar faculae demonstrate the extended cycle better than any other indicator so far examined. Lastly, we are able to relate the polar faculae with the high latitude component of the enhanced shear derived by Snodgrass (1987b) that is associated with the torsional oscillations. This finding of ours taken along with the spatial correspondence of the excess shear zone at low latitudes with the butterfly diagram already established by Snodgrass (1987b) makes the picture connecting the torsional oscillations with the activity cycle fairly complete. With the arrival of more data on the pattern of torsional oscillations, their correspondence with the polar faculae and the butterfly diagram should become unambiguously clear.

2. Global Pattern of Large-Scale Magnetic Field in the Period 1904–1984

We have constructed H-alpha synoptic charts covering the period 1904–1984 using the Kodaikanal data for the years 1904–1964 (Makarov and Sivaraman, 1986), McIntosh's (1979) data for the years 1964–1973, *Solar Geophysical Data* for the years 1973–1978, and *Solnechnye Dannye* for the years 1978–1984. The way we have constructed these H-alpha synoptic charts, the accuracies involved and their good agreement with the Mt. Wilson magnetograms are described in detail elsewhere (Makarov and Sivaraman, 1983). This method permits an accuracy of 10° for the mean filament band position for each rotation. From these H-alpha synoptic charts we have derived the filament trajectory curves for the period 1915–1982 that show the epochs of the polar reversals in the two hemispheres. These results are presented in Figure 1 and the salient features are:

2.1. A comparison of the results in Figure 1 for cycles 20 and 21 with those of

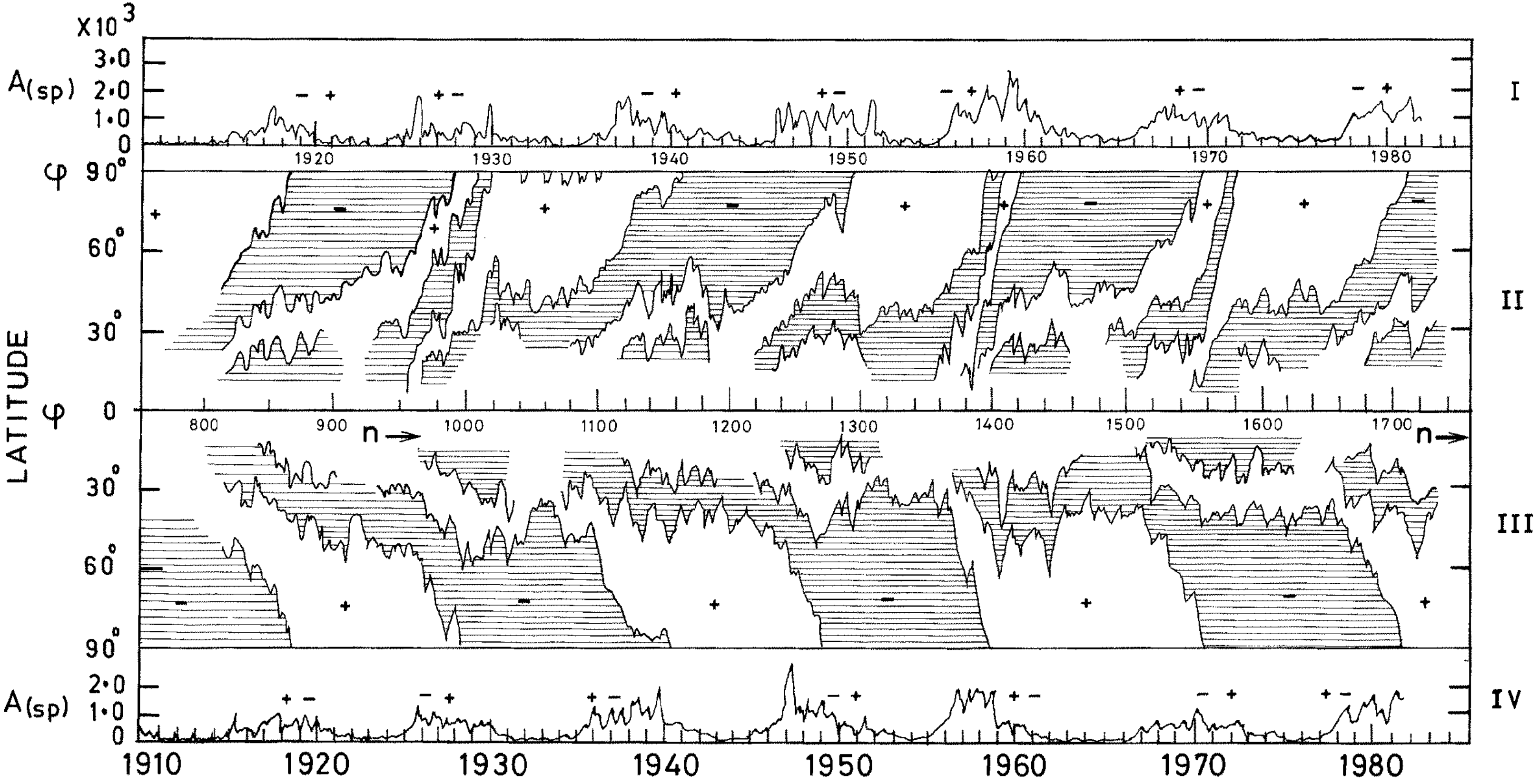

Fig. 1. Boxes II and III show the migration trajectories of magnetic neutral lines (filament bands) derived from H-alpha synoptic charts in the northern and southern hemispheres for the period 1010–1982. Dashed areas correspond to negative polarities and clear areas to positive polarities. Boxes I and IV: The continuous curve represents the run of mean daily areas of sunspots average over one rotation with 3-point smoothing. *A* (Sp) are the areas of sunspots in millionths of the visible hemisphere.

Howard and LaBonte (1981) shows that the zonal boundaries from H-alpha charts exactly match with the boundary division of polarity of the magnetic field. Also, the migration of the filament neutral lines agrees well with the migration of the large-scale magnetic fields seen in the diagram of Howard and LaBonte (1981).

2.2. The large scale magnetic field shows latitude zonal structure. We see that the dominant mode number l (here we define l as the number of neutral lines present when $m = 0$) vary from $l = 3$ to $l = 5$. Surprisingly $l = 1$ (i.e., pure dipole field) is seldom observed on the Sun. At the surface, during the sunspot maximum $l = 5$ appears common although higher modes in l are also noticed at times.

2.3. All filament bands – the polemost ones, as well as those at lower latitudes – start their poleward migration with small speeds ranging from 5 to 20 m s^{-1} synchronously with the rising phase of the cycle as reckoned from the sunspot number counts or sunspot area. Around the peak of activity, these filament bands, moving polewards

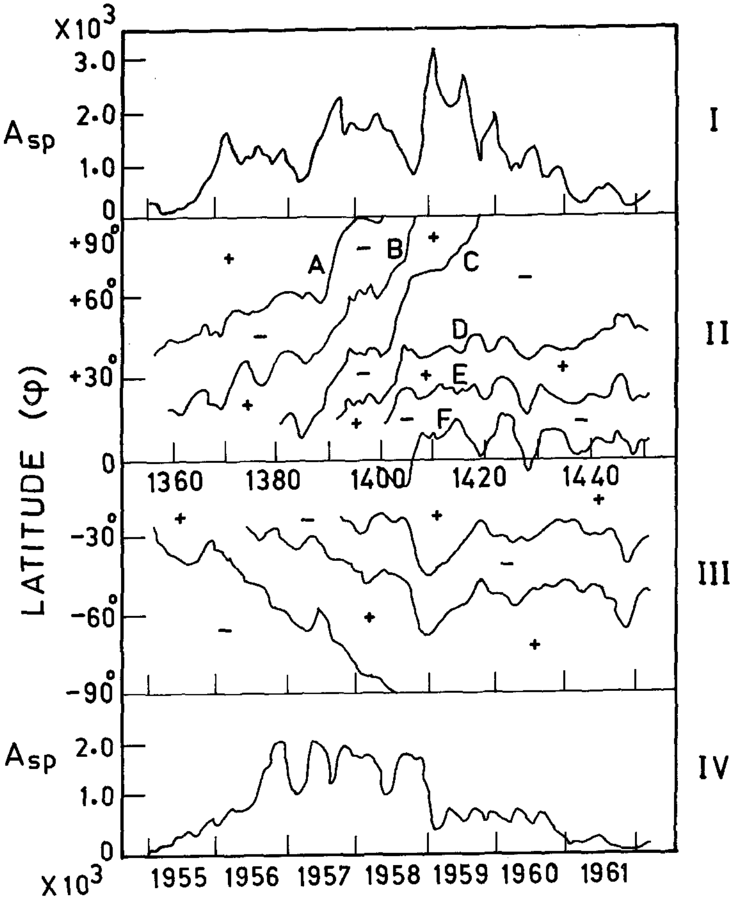

Fig. 2. Boxes II and III: Details of the migration processes of the neutral lines in cycle 19 (1954–1962) in the two hemispheres. *A*, *B*, *C* are the three filament bands that effected a threefold reversal in 1957–1959 in the norhtern hemisphere. *A* is the polemost filament. *D*, *E*, *F* are the low latitude filament bands. Boxes I and IV are the sunspot areas *A*(Sp) as in Figure 1.

slowly till then, show sudden acceleration and start moving with velocities as much as 40 m s^{-1}. In the 19th cycle (1954–1962) in the northern hemisphere where there are three filament bands (A, B, C in Figure 2), all three are accelerated simultaneously in time, the polemost filament band A reaching the pole first, the immediately lower band B reaching next, and so on. In a cycle where there is only a single polar reversal (cycle 18), the polemost filament band reaches the pole only in the declining phase of the cycle, whereas in a three-fold reversal (cycle 19), the polemost band A reaches the pole before the activity is at its peak, while by the time the third and the last filament C reaches the pole, the activity is already on the decline. This poleward drift of filaments has also been noticed by Topka *et al.* (1982) from their analysis of the H-alpha synoptic charts for the period 1964–1980 and this is in perfect agreement with our results for the same period. A similar poleward transport of fields has been noticed by Howard and LaBonte (1981) from their analysis of the Mt. Wilson magnetograms.

2.4. Even after the polar reversal, the filament bands for the next reversal (D, E, F in Figure 2) are still only at low latitudes meandering with a quasi-oscillatory motion at about 20–30°. But they start the poleward drift synchronously with the increase in the sunspot number. At no stage do the neutral lines associated with the large scale magnetic field regions show an equatorward drift. It should be noted here that the filaments connected with active regions or sunspots do not fall in this category.

Our conclusions are further confirmed by Figure 3 which we have constructed through a different approach (Makarov, Tavastsherna, and Sivaraman, 1986). We have calculated the distribution of the dominant polarity area over every 10° latitude zone. This is defined as

$$A_\psi(t) = \frac{S^+ - S^-}{S^+ + S^-} ,$$

where S^+ or S^- represents the area of '+' or '−' polarity over a 10° latitude zone on the H-alpha synoptic charts. In Figure 3 we represent these areas over the entire surface of the Sun. The formation of new zones of magnetic field in sunspot latitudes and their poleward drift are seen clearly. It must be noticed that, there are no regular equatorward migrations of large scale unipolar magnetic field.

But according to the classical picture of Waldmeier (1960, his Figure 7) the high-latitude zone prominences migrate polewards and low-latitude zone prominences migrate equatorwards in the course of the solar cycle. Although the former, has a much lower resolution and precision than ours it is identical to the poleward migration seen in our synoptic charts. The equatorward migration in his figure is that of the filaments associated with the active regions which just reflects the butterfly diagram of sunspots. This equatorward migration, however, will not be seen in our charts, as we depict only the movements of the large-scale unipolar magnetic regions and not those of the localized active regions like the spots.

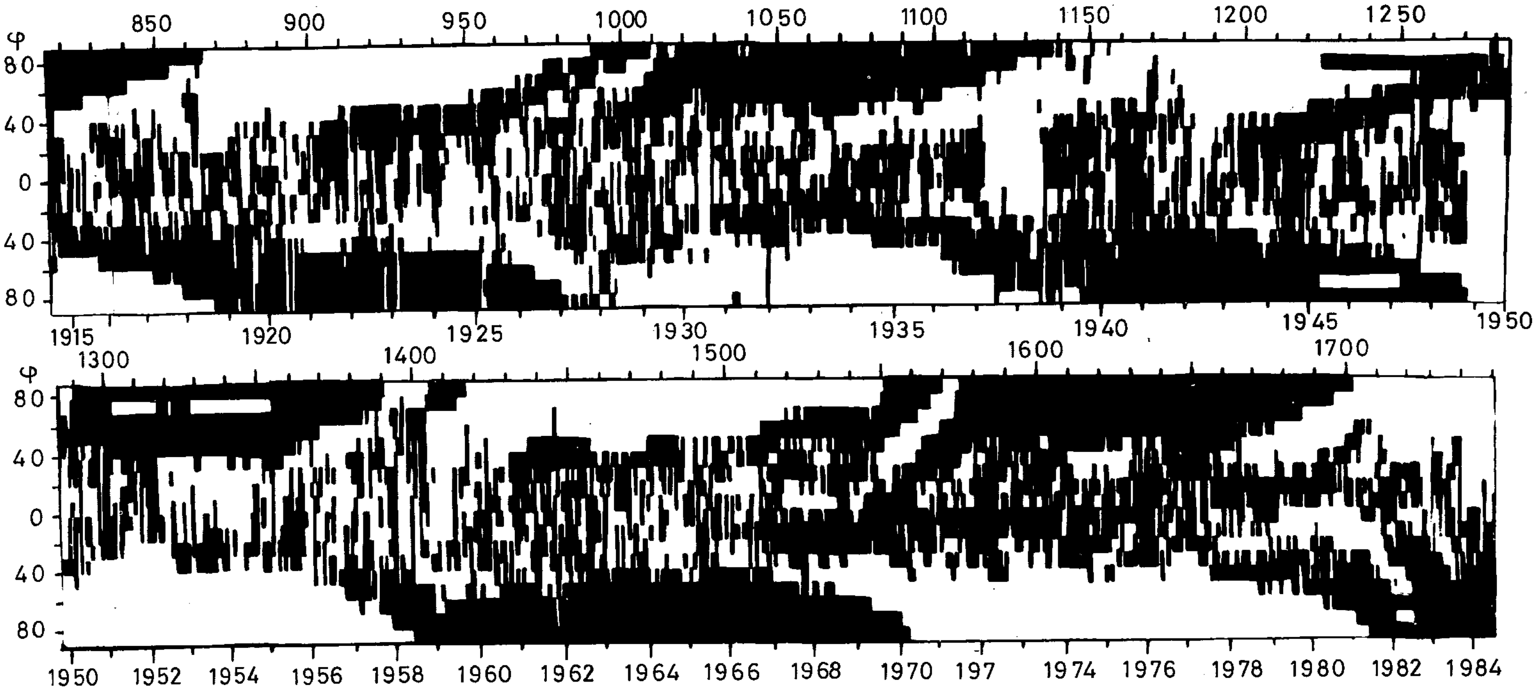

Fig. 3. The zonal structure of the solar magnetic field for the period 95–1984 derived from H-alpha synoptic charts using the average over 10° latitude strips. Dark areas correspond to positive polarities and clear areas to negative polarities. Ordinate: latitude in degrees. *Top*: zonal structure for the years 1915–1950 (Carrington rotations 820–1280). *Bottom*: zonal structure for the years 1950–1984 (Carrington rotations 1290–1750).

3. Polar Faculae as Part of the Global Activity

After every polar reversal, regions above 40° latitudes show a different kind of activity, namely, polar faculae, X-ray bright points, dark He I (10830 Å) points as well as bipolar and unipolar ephemeral active regions. The polar faculae can be seen both in white light and in the chromospheric K line images of the Sun. They show cyclic variation with a period of nearly 11 years and the numbers of polar faculae lag behind the sunspot number by approximately 90° (Sheeley, 1976). The first polar faculae appear 1 or 2 months after the reversal at the poles. They seem to possess a variety of forms and structures and occur both singly (size 1–3 arc sec) and in groups in the form of a string of bright points (size – 1 arc sec or more). The majority of them appear in pairs suggesting a bi-polar structure, and are aligned in the E–W direction with the leading member appearing brighter. A few of them occur in pairs making an angle that can vary from $+\pi/2$ to $-\pi/2$ with reference to the E–W direction. During the solar minima of 1964, 1976, 1985, faculae were observed at all latitude zones over the Sun (Makarov and Makarova, 1987). According to these authors, about 900 faculae are observed at any time over the entire solar disc. With the help of the Kitt Peak magnetograms published in *Solar Geophysical Data*, Makarov and Makarova (1984) showed that the polarity of most of the leading (westward) part of faculae is the same as that of the background field after the polar reversal. The predominant polarity of the faculae is thus opposite to that of spots of the same cycle, but is identical with the polarity of the spots of the following cycle. In this connection it is interesting to recall that although the ephemeral active regions (ERs) too show random orientations, there is a statistically significant tendency for the high latitude ERs to show an orientation appropriate to the following cycle (Martin and Harvey, 1979). Makarov, Makarova, and Sivaraman (1987) have measured the migration of the zones of appearance of the faculae using the Kodaikanal Ca II K-spectroheliograms and the Kislovodsk high contrast photoheliograms for four solar cycles (1940–1985). The faculae appear first at latitude zones 40–60° and the zones of appearance migrate slowly and reach higher latitudes (70–80°) as the cycle progresses (Figure 4). It would be of interest to compare the latitude migration of ERs if any with that of polar faculae, but Martin and Harvey (1979) feel that sufficient data on ERs do not exist to answer this question. Wilson *et al.* (1988) find that the high latitude ERs seen between 1980–1986 also do not exhibit any clearcut trends. However, they hypothesize that these solar features should show an equatorward drift similar to the torsional shear pattern.

The solar activity in any cycle thus consists of two waves in each hemisphere: the first set starts from mid latitudes (±40°) immediately after the polar reversal and migrate towards the poles which we identify with the polar faculae; the second set that starts from latitudes ±40° and proceeds towards the equator is the conventional one, connected with sunspots, that gives rise to the butterfly diagram. Thus, the new cycle shows up first as faculae at high latitudes immediately after the polar reversal and leads the spot phenomenon by 5–6 years. Each of the two waves has an 11 year duration and the two waves belonging to the same cycle occur at separate latitude zones on each

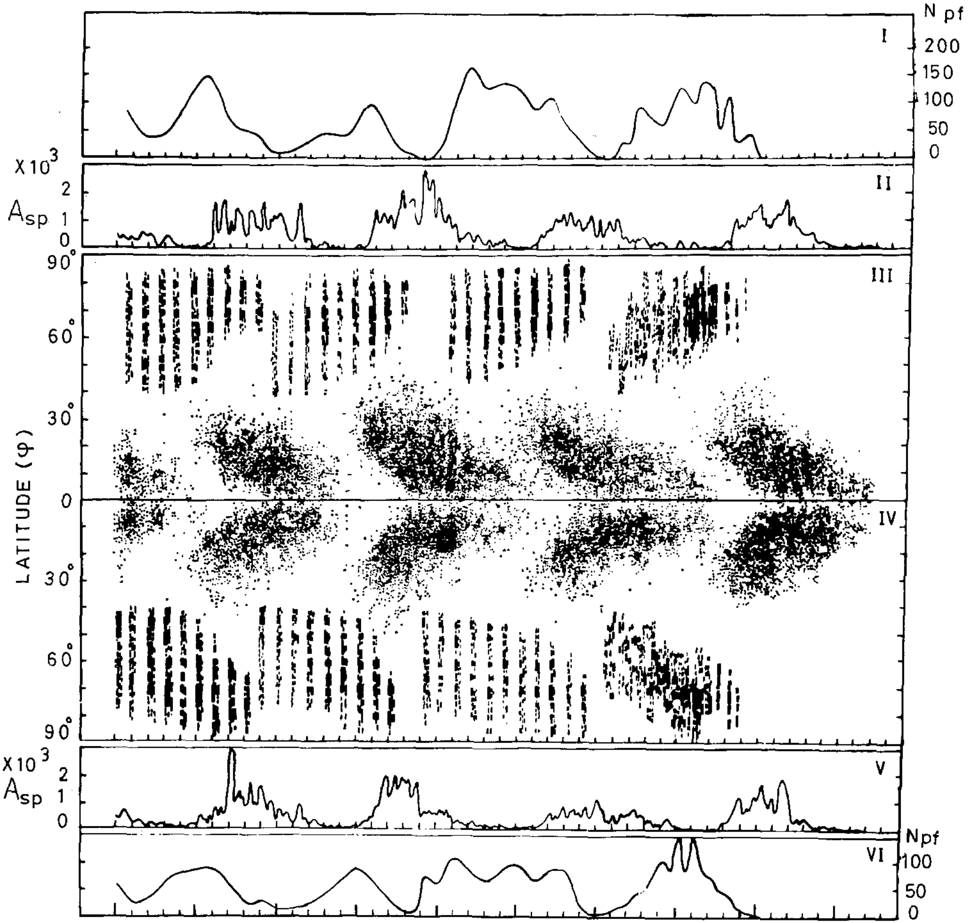

Fig. 4. Boxes III and IV show the latitude distribution of polar faculae and sunspots (butterfly diagram) during 1940–1985. Notice that the faculae make their appearance first between 40°–70° latitudes in the northern and southern hemispheres and then migrate towards the respective poles as the cycle advances. The superposed lines are the migration trajectories of filaments reproduced from Figure 1 after smoothing to show the epochs of polar reversals. Notice that the polar faculae make their appearance immediately after every polar reversal. Boxes II and V are the sunspot areas A(Sp) for these years as in Figure 1. Boxes I and VI: the continuous line represents the polar faculae counts (N_{pf}) in the northern and southern hemispheres.

hemisphere of the Sun displaced from each other in time by about 5–6 years. In other words, they are spatially separated with an overlap in their times of occurrence by 6–5 years. Thus the conventional solar cycle, which is defined as the duration of the butterfly patterns based on the spot number counts, describes only the part of the activity relating to the cycle that occurs within the ± 40° latitude zones. Whereas if we also take into account, the activity in higher latitudes zones (> 40°) justifiably belonging to the same cycle (based on similar dipole polarities) then the duration of a solar activity cycle which starts from the appearance of the faculae and ends with the ending of the butterfly diagram, turns out to be 16–18 years.

It should be made clear that the periodicity of the solar cycle remains unchanged; the pole reversal pattern, the polar faculae or the butterfly diagram taken alone will result in the traditional 11-year cycle and the 22-year magnetic cycle. The importance is to realize that the two waves of activity that manifest in two different forms occur at separate times and at two separate regions on the Sun with an overlap within a 22-year magnetic cycle. Legrand and Simon (1981) inferred the existence of two components of solar wind streams responsible for the enhanced geomagnetic activity: one the high speed wind stream originating from high latitude coronal holes and the other from regions of conventional solar activity. From the long data they used for this study, they showed that the two components of solar activity taken together could be fitted to a solar cycle pattern with extended duration of 17 years. Further evidence in support of this accrue from the study of coronal emission pattern in 5303 Å (Leroy and Noens, 1983) and the torsional oscillation patterns (Snodgrass, 1987b). But the results from the polar faculae plots establish the concept of the prolonged duration for the solar cycle in unmistakable terms.

4. Coronal Emission in Relation to Global Magnetic Activity

The coronal emissin data in 5303 Å line in relation to the latitude zonal structure of the magnetic fields for the period 1944–1974 analysed by Leroy and Noens (1983) show the prolonged duration of the solar cycle. The relationship of this emission pattern with

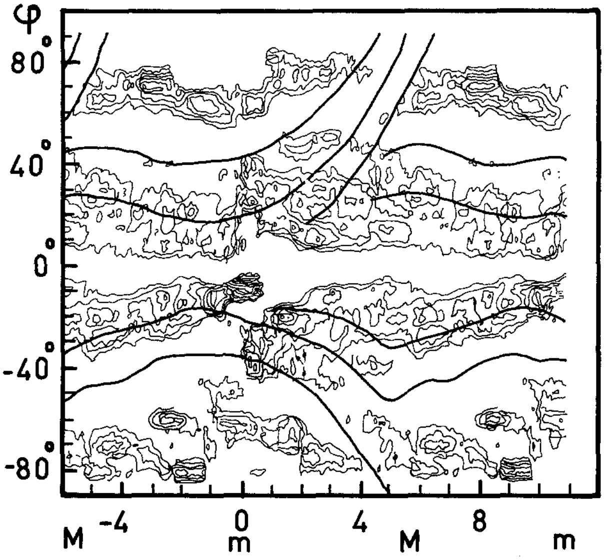

Fig. 5. The map of isovalues of the quantity $\sigma_{5303} - \bar{\sigma}_{5303}$, (Leroy and Noens, 1983). σ_{5303} is the standard deviation of coronal intensity at each latitude over periods of about 1 year and $\bar{\sigma}_{5303}$ is the latitude average of σ_{5303} over 20° intervals. Leroy and Noens (1983) have used the mean of the three values of σ_{5303} from identical phases of the cycles 18, 19, and 20 (1944–1974) to represent a typical average cycle. The thick lines are the migration trajectories of neutral filament bands for cycle 20 (Makarov, Leroy, and Noens, 1987). *m* – minimum epoch of solar cycle. *M* – Maximum epoch of solar cycle. Ordinate – solar latitude in degrees.

the two components of magnetic activity which is an important aspect became obvious when the same data were reinterpreted by Makarov, Leroy, and Noens (1987) (Figure 5). We notice that there are two broad unconnected zones of coronal emission in each hemisphere: one each around ± 60° and another each around ± 30° latitudes. The high latitude zones of 5303 Å emission make their appearance immediately after the polar reversal and continue throughout the minimum epoch with a slow and continuous poleward drift. We interpret that, this high latitude emission can be related to the magnetic activity caused by the first wave which also manifests as the high latitude faculae, both of them moving polewards in the same way. In addition, in each hemisphere, there exists a broad band of 5303 Å emission around ± 30° latitude with equatorward drift. This would correspond to the second wave of activity, namely the spots which constitute the butterfly diagram.

With regard to the migration direction, the poleward drift of the high latitude component is unmistakable in Figure 1 of Leroy and Noens (1983) and they represent this by a continuous line directed polewards in the two hemispheres although, prompted by the concept of the travelling wave of the torsional oscillations (Howard and LaBonte, 1980) they are tempted to draw in the same figure another continuous line representing the wholy equatorward drift starting from the poles although the evidence for this in their data is rather weak.

5. Global Solar Activity and Torsional Oscillations

Torsional oscillations (TO), first noticed by Howard and LaBonte (1980) refer to their observations of the alternating latitude zones of faster and slower rotation present on the Sun. The torsional waves (two per hemisphere) start from either poles once every 11 years and travel to the equator in the course of 22 years. In his new analysis of the same Doppler data, Snodgrass (1985, 1987b) showed that the earlier inference of a pole to equator travelling wave pattern with $k = 2$ (Howard and LaBonte, 1980) could be a mathematical artifact and that the pattern may actually consist of a relative polar spinup near solar maximum and a separate single wave that runs from mid latitude to low latitude during the rest of the cycle. Snodgrass (1987b) also derived from the Mt. Wilson data the torsional shear which is the derivative of the net torsional pattern with respect to latitude. He has superposed this torsional shear pattern onto the butterfly diagram of sunspots for cycles 20 and 21 (his Figure 2 of 1987b reproduced here as Figure 6) and demonstrated the coincidences of the low latitude shear increase region with the zone of activity in the butterfly diagram and the low latitude shear decrease region with that in between the adjacent butterflies. But the high-latitude shear increase zone has no magnetic counterpart in his figure. It can be seen from a comparison of Figures 4 and 6 that the high-latitude shear increase regions coincide with the polar faculae regions of our plot in both the hemispheres to a reasonable degree. Similarly the regions of high latitude shear decrease fall more or less in between the two adjacent regions of polar faculae (around the year 1970), just as this region falls in between the two adjacent butterflies at low latitudes. It can also be seen from Figure 6 that the high-

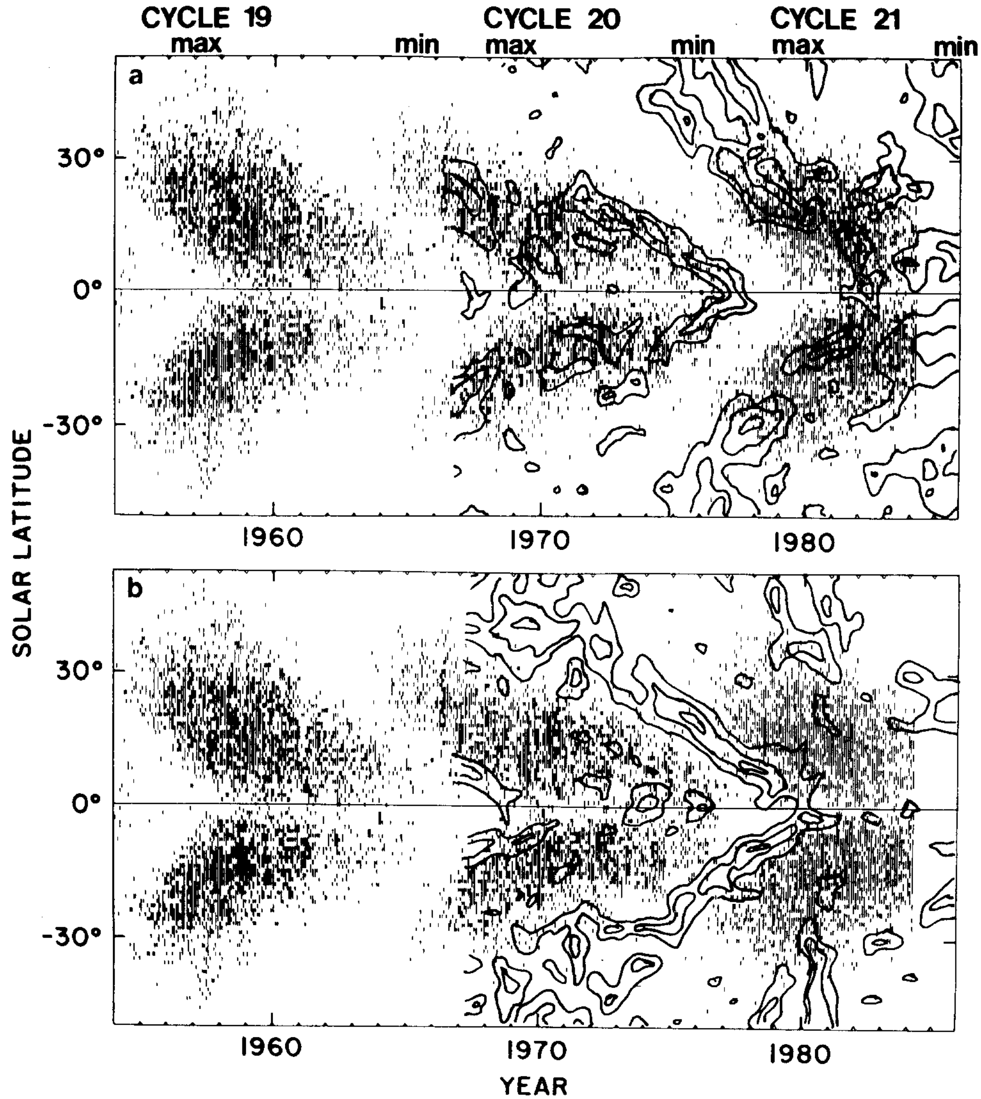

Fig. 6. Relation of the torsional shear oscillation to the sunspot butterfly diagram derived from Mount Wilson data: (a) Shear increase pattern and the butterfly diagram and (b) shear decrease pattern and the butterfly diagram. Contour intervals are $\pm 0.5, 1.0 \ldots 3.0 \times 10^{-4}$ m s^{-1} km^{-1} (Reproduction of Figure 2 of Snodgrass (1987b). (By courtesy of H. B. Snodgrass.)

and the low-latitude components would look detached except for the outermost contour encompassing them. If this is true, then the low latitude components of the shear increase would correspond to the butterfly diagram (Snodgrass, 1987b) whereas the high-latitude components, according to us, would correspond to the polar faculae. This is better seen in the southern hemisphere. Another fact in support of the latter identification is provided by Figure 3 of Snodgrass (1987a), reproduced here as Figure 7, where he has schematically represented the latitude belts of enhanced and decreased

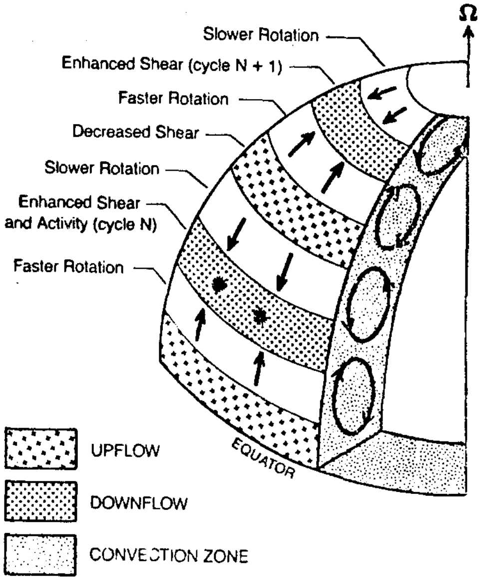

Fig. 7. Schematic diagram showing the surface motions, zones of enhanced and decreased shear at solar maximum for cycle N (sunspots in active zone) along with the emergence at high latitude of cycle $N + 1$. The bands on the surface indicate the various predicted large scale motions produced by the rolls shown as ovals in the convention zone (not needed for the discussions in this paper). (Reproduction of Figure 3 of Snodgrass (1987a). By courtesy of H. B. Snodgrass and the *Astrophysical Journal.*)

shears. At the epoch of the activity (cycle N) at equatorial latitudes, the zone of excess shear at high latitude corresponds to that of cycle ($N + 1$). This is exactly what we notice in the case of polar faculae too from polarity considerations. The polar faculae appearing immediately after a polar reversal has a polarity corresponding to the next following cycle ($N + 1$) even while the activity belonging to cycle 'N' is in full swing at sunspot latitudes.

6. Discussion

The pattern of the general magnetic field brought out from our studies of the H-alpha synoptic charts and the polar faculae complement each other and present a global picture of the solar activity. Probably the polar faculae and the sunspot are manifestations of two periodic classes of activity which differ in their size scales, and epochs of their appearance. Our synoptic charts show that the exact epoch of the polar reversal marks the beginning of activity of a new cycle. Along with this, the polar faculae make their appearance and as we have shown, the polar faculae and the sunspots coexist over a large part of the activity cycle, and this gives rise to the prolonged duration of 16–18 years for the solar cycle. The possibility of such an extended cycle was suggested by Leroy and Noens (1983) based on the coronal emission data. The linking of their coronal emission data with the filament migration trajectories by Makarov, Leroy, and Noens (1987) brought out clearly the relation between the two belts of emission and the two waves of magnetic activity. Howard and LaBonte (1980) noted from their TO data that two solar cycles are present on the Sun at any time and Snodgrass (1987b) brought out the extended cycle concept from this data. But the plot of polar faculae on the butterfly diagram brings out clearly the prolonged duration of the cycle.

The poleward motion of unipolar regions established by us uses data over 7 cycles and thus seems to be beyond any doubt. Also, Topka *et al.* (1982) using the synoptic charts of McIntosh (1979) arrived at the same results as ours. The two studies were independent and the two groups did not know of each others' results till they appeared in publications. Our data are quite similar to McIntosh's data. All these show that the large-scale unipolar regions on the Sun drift poleward. Use of any other diagnostic indicator should lead to the same conclusion, as is borne out by our studies on the polar faculae covering four cycles. The coronal emission (Makarov, Leroy, and Noens, 1987) also fits in well with our picture of global solar activity. We feel it is the paucity of data on ERs and torsional oscillations that stands in the way of arriving at a clear picture concerning the behaviour of their latitude components, namely whether they show only an equatorward drift or both a poleward as well as equatorward drifts. In the case of ERs Martin and Harvey (1979) state that it is the lack of sufficient data that precluded them from making a convincing conclusion on this aspect.

Finally, our interpretation of two waves of activity has enabled us to relate the magnetic activity with the torsional oscillations. The pattern of torsional shear on the Sun agrees with the properties of the two waves of magnetic activity brought out through our analysis. This agreement between the two kinds of observations can be considered fair enough at least for the present time. The data on the torsional oscillations when freed of the artifact, show up as two components (Figure 1 of Snodgrass, 1985) and at least in the southern hemisphere, the high latitude component shows a poleward drift. By now, data on the torsional oscillations would have piled up for almost another cycle and should be of help in understanding whether the TOs show wholly an equatorward drift or have two components, one with a poleward drift and the second one with an equatorial drift. Since all these physical features should bear a relationship with the magnetic activity, all of them should fall in line and yield a single consistent pattern.

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