SOLAR CYCLE VARIATIONS OF CORONAL NEUTRAL LINES
and POLAR REGIONS ACTIVITY

V.I. Makarov, V.V. Makarova
Kislovodsk Station of the Pulkovo Observatory
Kislovodsk 357741, USSR

S. Koutchmy
AFGL/NSO/SP, Sunspot, New Mexico 88349
(on leave from Institut d'astrophysique, CNRS-Paris)

and

K.R. Sivaraman
Indian Institute of Astrophysics
Bangalore, 560 034, India

ABSTRACT:

Observations of the corona, of prominences, of polar faculae and of large scale magnetic fields show solar activity over all latitudes, in contrast with sunspot activity, which is limited to mid-latitudes. The global behaviour of the solar activity is considered here thanks to the analysis of chromospheric synoptic maps which include the location of Hα and Ca II K prominences. The process of "migration" of neutral lines during the cycle (supposed to represent the large scale coronal magnetic field) is shown. After subsequent averaging of the maps, a discrete number of latitude zones is found: not more than 10, the most probable number being 3 or 5. This suggests the occurence of dominant modes (l=3 and l=5) of the large scale coronal magnetic field and inferred coronal structures for different epochs of the solar cycle. We suggest the geoactivity of coronal streamers could be related to the modes, noticing the dipole (l=1) mode is almost absent. A more detailed analysis points to the importance of the poleward migration of neutral lines (with $v \approx 5$ to 40 m sec^{-1}). The non-symmetric behaviour of the N and S hemisphere as well as the erratic behaviour of the corresponding sunspot activity in each hemisphere is emphasized which reflects the behaviour of both the radial component and the toroidal component of the field.

The activity of polar regions is considered in the light of analysis performed over a series of observations of white light polar faculae. Correlations are established with Ca II K polar faculae, ephemeral active regions, X-ray and He-10830 bright/dark points in polar regions. This analysis is extended to different epochs, including epochs of enhanced polar activity of 530.3nm emissions and of 13.5mm wavelength brightnesses. A fair correlation of white light polar faculae with X-ray bright points is shown for 2 selected days of overlapping observations (10 Oct and 23 Aug 1973). This suggests they are two manifestations of the same phenomena, namely the migration of magnetic field "elements" of the current sunspot cycle and the appearance of magnetic "elements" belonging to the new following sunspot cycle. Further, a latitude distribution diagram of polar faculae activity (up to 10^3 elements could be present simultaneously) covering 4 solar cycles is presented. The solar cycle behaviour of this polar faculae cycle suggests the occurence of 2 interlaced "waves" of solar magnetic activity. The polar faculae cycle is possibly a mirror image of the sunspot cycle 4-5 years later provided that the N and S hemisphere are considered separately; the correlation coefficient of polar faculae with sunspot number then reaches values up to 0.80 when a shift of 5.8 to 6.2 years is used. This allows the prediction of the level of activity of sunspot cycles.

1 INTRODUCTION

The classical description of the solar cycle, which implies a general solar magnetic field, involves the tranformation of the poloidal field, under the influences of the differential rotation, in a toroidal field emerging at low latitudes in the form of sunspot "dipoles" with a recurrence of 11 years (the so called Babcock-Leighton model), corresponding to a 22 years magnetic cycle.

However, observations of the solar corona, of prominences, of polar faculae and of large scale solar magnetic fields, show that activity is present at all latitudes. Considerable efforts were made during the last years to produce a synoptic view of the solar cycle using different tracers (Makarov et al. 1983-1987; Legrand and Simon, 1982; Leroy and Noens, 1983; Koutchmy et al. 1984) and many works are in progress on this subject (see Wilson, 1987 for ex.). Here, we concentrate our presentation on aspects relevant to the coronal physics, emphasizing aspects of polar activity presumably connected with the study of coronal holes and also, aspects connected with the details of the solar dynamo, including predictions of the level of sunspot activity for the forthcoming cycle.

2 EVOLUTION OF MAGNETIC NEUTRAL LINES AND SPECIFICITY OF POLAR REVERSALS

It is well known that solar filaments and prominences are good tracers of the large scale magnetic field, in the sense that they can be used as indicators of the polarity inversion line (McIntosh, 1972). Makarov and Sivaraman (1983) uses observations in Hα and K Ca II to produce neutral lines maps extended over more than 80 years. Over each synoptic map, for each whole rotation, the average position of the inversion line (+/- or -/+) was determined as a function of time. The resulting maps can be considered as representative of the time evolution of the axi-symmetric component of the solar magnetic field or: l (t), when m = 0, m being the spherical harmonic order and l - the order. A more accurate description which uses actual measurements of the solar magnetic field, has been recently presented by Stenflo and Weisenhorn, 1987. Here, we present results deduced from the analysis of Hα and K Ca II observations. Figure 1 shows a map extended over 6 sunspot cycles (16 to 21) where polar reversals, both one-fold and three-fold are present, and clearly delineated.

Figure 2 shows the result for cycle 20 and 21 when an average over 10° in latitude is considered. It shows that the l number (here we define l as the number of neutral lines when m = 0 is considered) vary from l = 3 to l = 5; surprisingly, l = 1 (pure dipole field) is observed seldom. During the phase of minimum sunspot activity we observe l = 3 at the surface; however, far from the surface under the pressure of the solar wind and because slow reconnections occur in the low corona, we can conjecture that the large scale coronal structure become more simple and forms the helio-sheet as shown on Figure 3a. During the phase of sunspot maximum, l = 5 and a more divergent coronal structure should dominate, see Figure 3b.

The results presented in Figure 1 show 3 kinds of behaviour of neutral lines which are better illustrated on Figure 4, giving more details as observed during the sunspot cycle 19. The first phenomenon is the polar drift occuring between the interval of a new sunspot maximum and the polar reversal; the displacements of neutral lines correspond to motion of 5 to 40 $m.sec^{-1}$. After the polar reversal, neutral lines are drifting very slowly: 0.5 $m.sec^{-1}$ and then "oscillations" of the position of the neutral lines are observed. Therefore, short displacements toward the equator are also observed. We notice that when a 3-fold polar reversal is observed, the drifts correspond to larger motions, 20 to 40 $m.sec^{-1}$ and that during 0.5 to 1.0 year the same polarity can exist for both poles. Additionally, independent behavior of the polar reversal for each pole is probably connected with the asymmetry of the sunspot activity observed later on, when each hemisphere is compared.

Finally, magnetic field measurements (see, for example Leroy in this volume) in prominences, including those on polar crown filaments, shed more light on the connection between the poloidal field and the toroidal field, if we assume the magnetic field lines are closed. These results need however a more detailed analysis which is beyond the present work.

3 ACTIVITY OF POLAR REGIONS

After the polar reversal, regions above latitudes 40° show different kinds of activity: polar faculae, bright x-ray points, dark

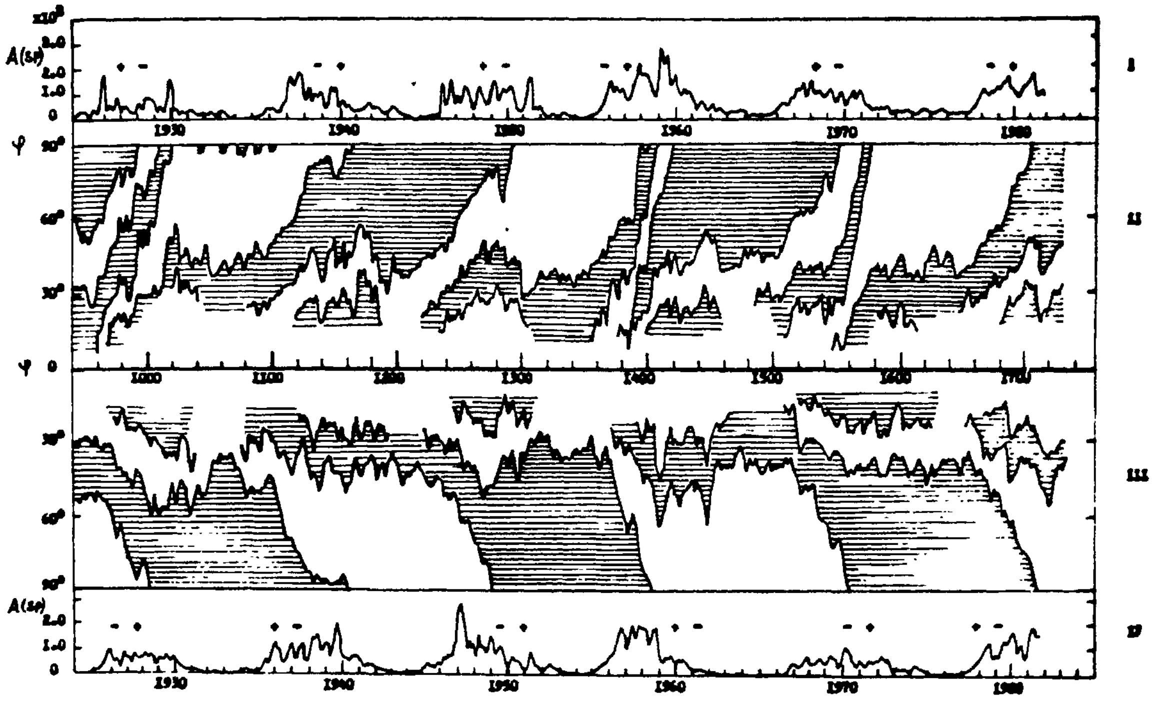

Figure 1. Parts II and III show the distribution of magnetic neutal lines inferred from observations of prominences during the period from 1925 until 1982. Dashed area corresponds to negative polarities and white area to positive ones as inferred from the comparison with magnetographic data.

Parts I and IV show the overall variations of sunspot area separately for the N and the S hemisphere; the signs + or - correspond to f or p spots of the corresponding cycle.

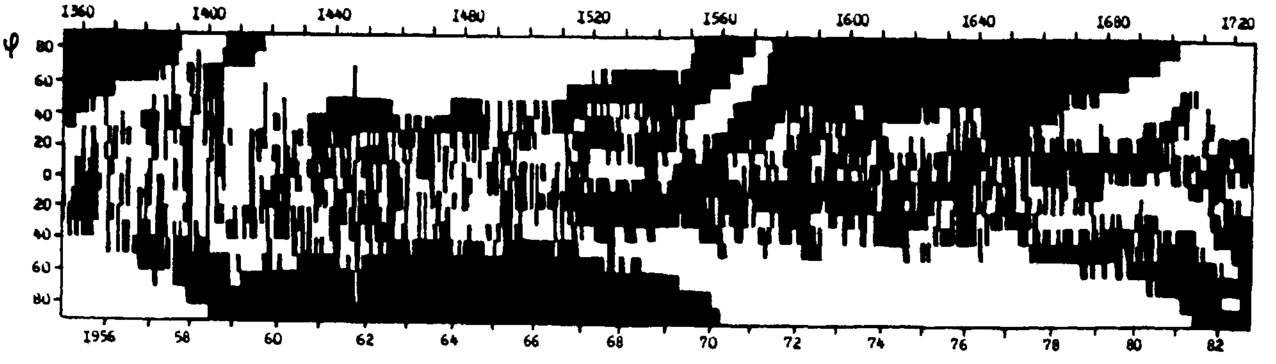

Figure 2. The zonal structure of the solar magnetic field for the period of 1955-1982 inferred from Hα synoptic maps using an average over 10° in latitude. Dark corresponds to positive polarities and white to negative one; carrington rotation are also indicated.

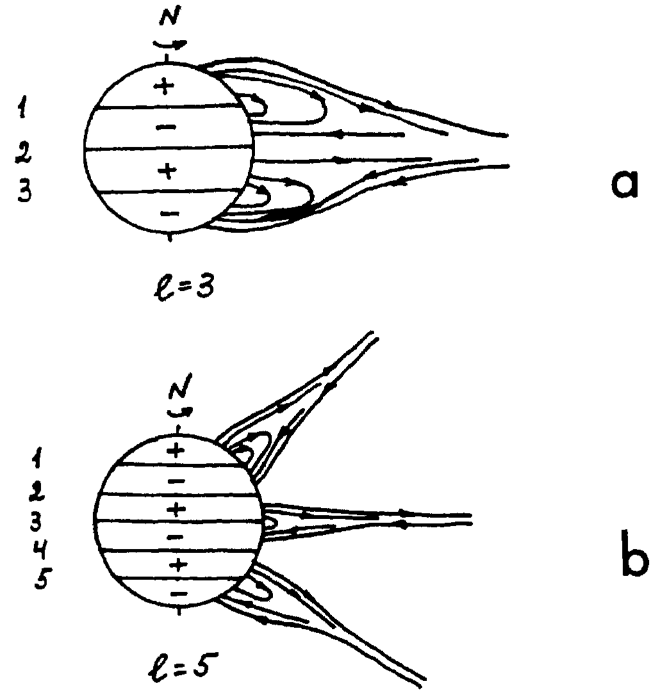

Figure 3. Inferred structure of the corona for different values of the latitude zonal number l: a-during sunspot minimum; b-during sunspot maximum.

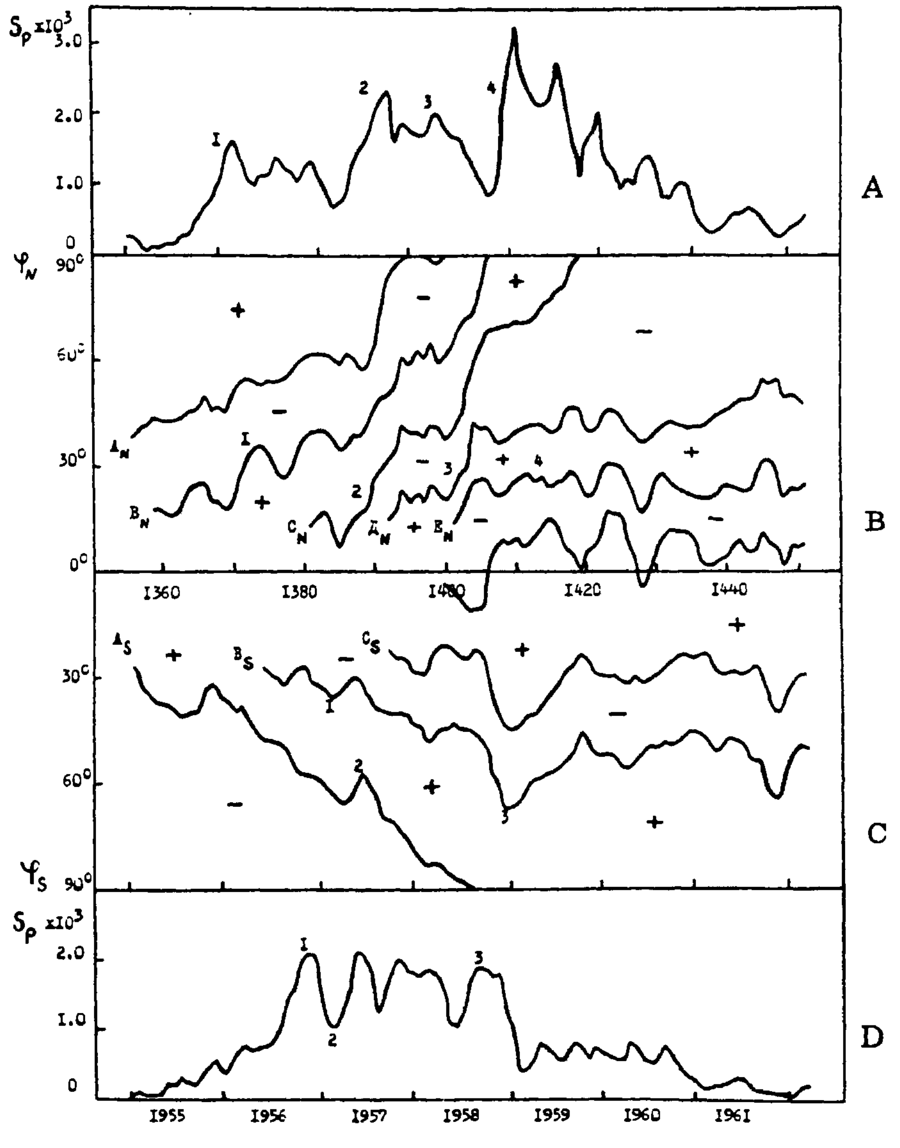

Figure 4. Detail of the migration process of neutral lines during the 19 cycle (1954-1962). A and D show the variation of the sunspot area for the N and S hemispheres separately; neutal lines distribution is shown on parts B and C. Notice the 3-fold polar reversal on the N hemisphere and the one-fold one in the S hemisphere which coincide with the occurence of a large N-S asymmetry of the sunspot activity.

10830 HeI points in the chromosphere and corona and also both bipolar and unipolar ephemeral magnetic regions. This activity has been known for a long time thanks to the observations of the green line coronal emission of Fe XIV, see for example Trellis, 1956, Koutchmy et al. 1974, Leroy and Noens, 1983 and R. Altrock, 1987. Special magnetic field measurements at Mount Wilson and at Crimean Observatories have shown in years (1972-77) an enhanced magnetic field activity at both the solar poles (no activity was observed in 1968-72); during this period the chromospheric network registered at 13.5mm was also greatly enhanced by 1400K in brightness temperature.

a. Polar Faculae (see Figure 5).

Polar faculae are observed in both white light or chromospheric lines like K CA II. They occur in bright points of 700 to 3500 Km horizontal extension or in "couples" or "pairs" with extension up to 7000 Km or again in "chain" of bright points extending up to 30,000 Km and in more diffuse formation of 7000 up to 20,000 Km or more.

They show a cyclic variation with a period near 11 years (Sheeley, 1976), the first polar faculae appearing 1 or 2 months after the polar reversal; their maximum corresponds roughly to the minimum of sunspot activity. The migration of polar faculae toward the poles corresponds to an apparent proper motion of 0.5 m sec^{-1} which is one order of magnitude smaller than the motion of neutral lines. They appear at the beginning at latitudes 40 to 70° and during the final process, at latitude 70 to 80°.

b. Latitude Distribution of Polar Faculae

We used high contrast photo heliograms obtained at Kislovodsk with
λ eff = 410 nm. A comparison with K CaII spectroheliograms made at Kodaikanal for periods of the last sunspot minima (1964;1975;1985) permits us to find polar faculae-like structures at all latitudes. We counted a number near 10^3 during these periods; half of them being at latitudes between 0° and 40 and half at latitudes between 40° and 90° which means that the occurence of polar faculae at polar latitudes per unit of area is 2 times higher. Nearly 8 polar faculae structures are then observed per 3 x 10^{10} Km^2 corresponding to the surface of 5 supergranules.

c. More than half of polar faculae appear in pairs, suggesting a bi-polar structure following the rule of Hale, with polarities reversed when poles are compared. For latitudes more than 40°, the polarity of the leading (westward) faculae coincide with

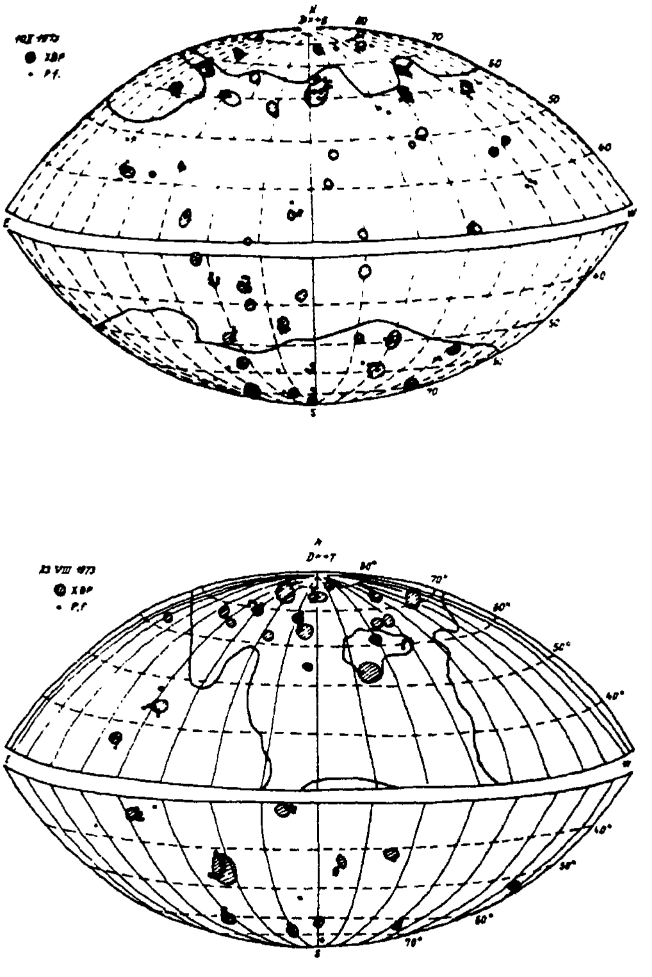

Figure 5. Comparison of the location of X-ray bright points observec with the ATM X-ray telescope on SkyLab on Oct. 10, 1973 anc Aug. 23, 1973, with the location of W.L. polar faculae observed at Kislovodsk; the best coincidence is found witl couple or pair of polar faculae.

the polarity of the background field. The tilt angle of the corresponding dipole with respect to the E-W direction changes from + to - $\Pi/2$. Apparently, the direction of magnetic field lines of the polar faculae dipole coincides with the one of the following sunspot cycle; we think this reveals the behaviour of the toroidal component of the magnetic field of the solar dynamo.

d. Polar Faculae and X-ray Bright Points (X-BP)

To identify polar faculae with X-BP we used 12 published X-ray pictures of the SkyLab epoch (1973); and 2 more pictures obtained in 1976. We determined the coordinates of 335 polar faculae and those of 420 XBP. Some difficulties arise because of the rather diffuse appearance of XBP (overall appearance up to 20,000 Km in diameter). This analysis shows for selected days a coincidence ratio up to 85% at latitudes more than 40°; both dimension and position are coincident. In average (for 14 days) the coincidence is 66%. Some days show up to half of XBP non coincidental with polar faculae, due to the delay of observations (up to 12 hours!) and also, due to the difficulty of identification of XBP (their number growing by an order of magnitude when exposure time is changed from 4 sec to 64 sec). The main conclusion from this analysis (see also Makarov and Makarova, 1987) is illustrated on figure 5: the XBP coincide the best with polar faculae showing a bi-polar structure .

e. Polar Faculae and Ephemeral Active Regions (EAR).

Ephemeral active regions were analyzed for the first time in the literature by Mrs. Dodson as early as 1953, using K CaII; they correspond to bright point like structures. Further, J. Harvey used the Kitt Peak magnetograms with the best resolution to show EAR correspond to bi-polar fields with a flux in order of 3×10^{19} Mx and lifetime of 1 day; he observed simultaneously on the Sun 8×10^2 up to 10^3 EAR. Furthermore, the polarity of an EAR bipole is found to correspond to the polarity of sunspot regions of the following sunspot cycle; the same is observed for EAR in polar regions. It was also shown that a good correspondence between EAR and XBP exists although a one to one correspondence is missing. Another very important property of these structures characterized by an intensity brightening, is their large phase lag (indeed almost an anticorrelation) with respect to the phase of the sunspot cycle. We conclude from Harvey's analysis that they are a form of activity which belongs to a definitely different and new form of solar activity. When comparison is made with the sunspot activity we noticed: anti-phase; start of the cycle exactly after the polar reversal; form of activity over the whole surface of the Sun with a maximum at latitude near 60°, see figure 6.

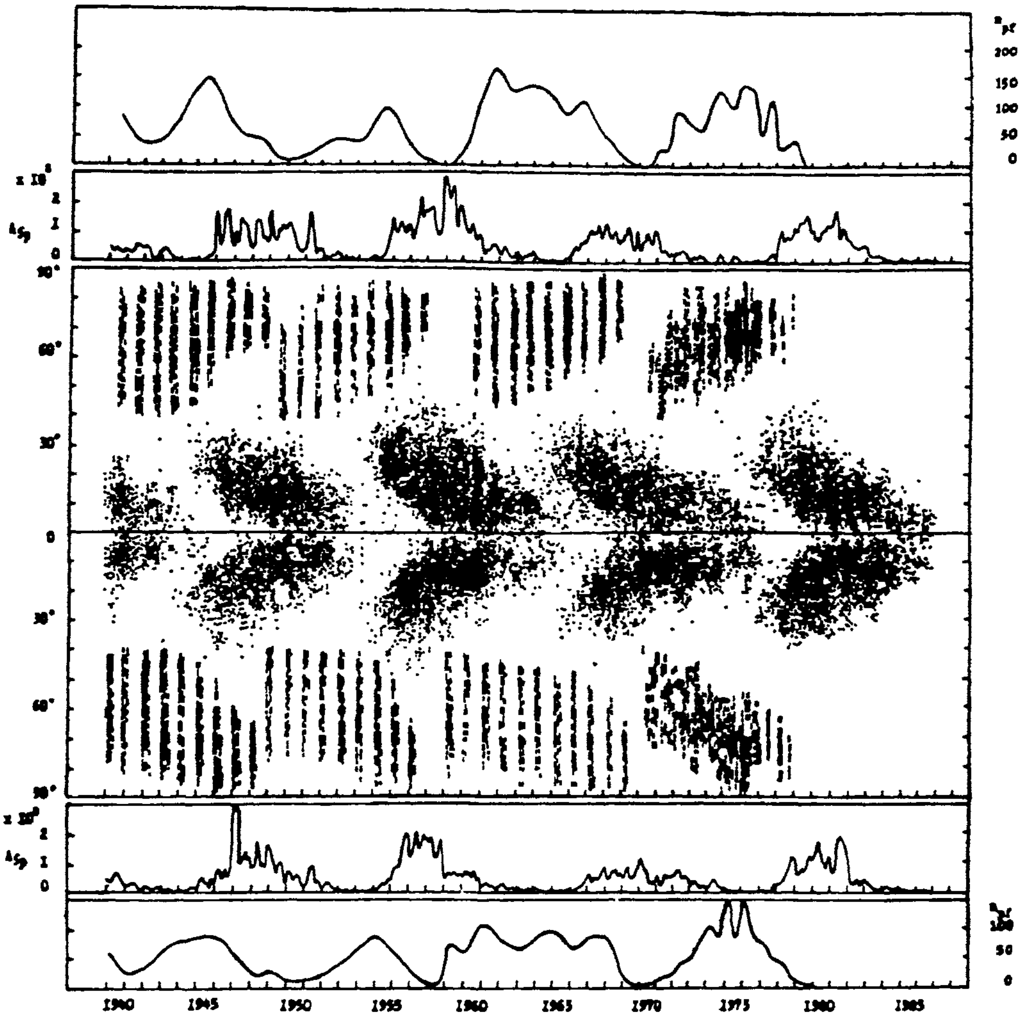

Figure 6. Diagram showing the latitude distribution of sunspots and polar faculae from 1940 to 1985. Upper and lower curves show the corresponding average per month sunspots and faculae number. Note the occurence of 2 out of phase cycles of activity corresponding the equatorial (sunspot) and polar (polar faculae) regions.

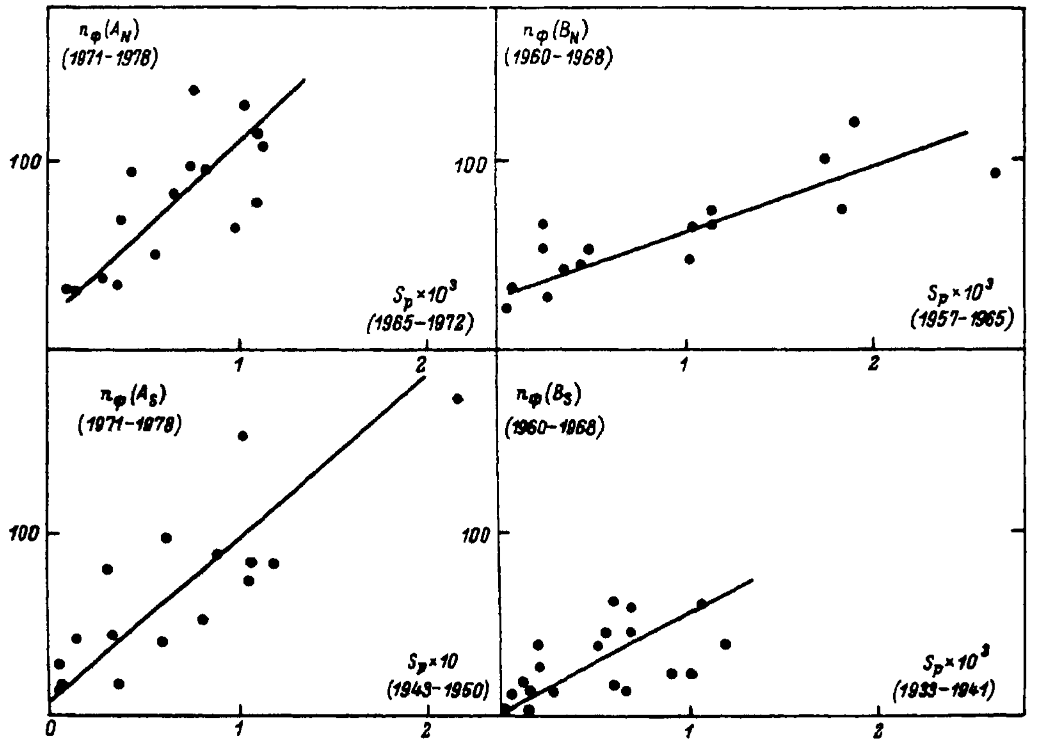

Figure 7. Correlograms polar faculae over sunspot number for selected periods of cycles when each hemisphere is considered and different shifts of phase are introduced.

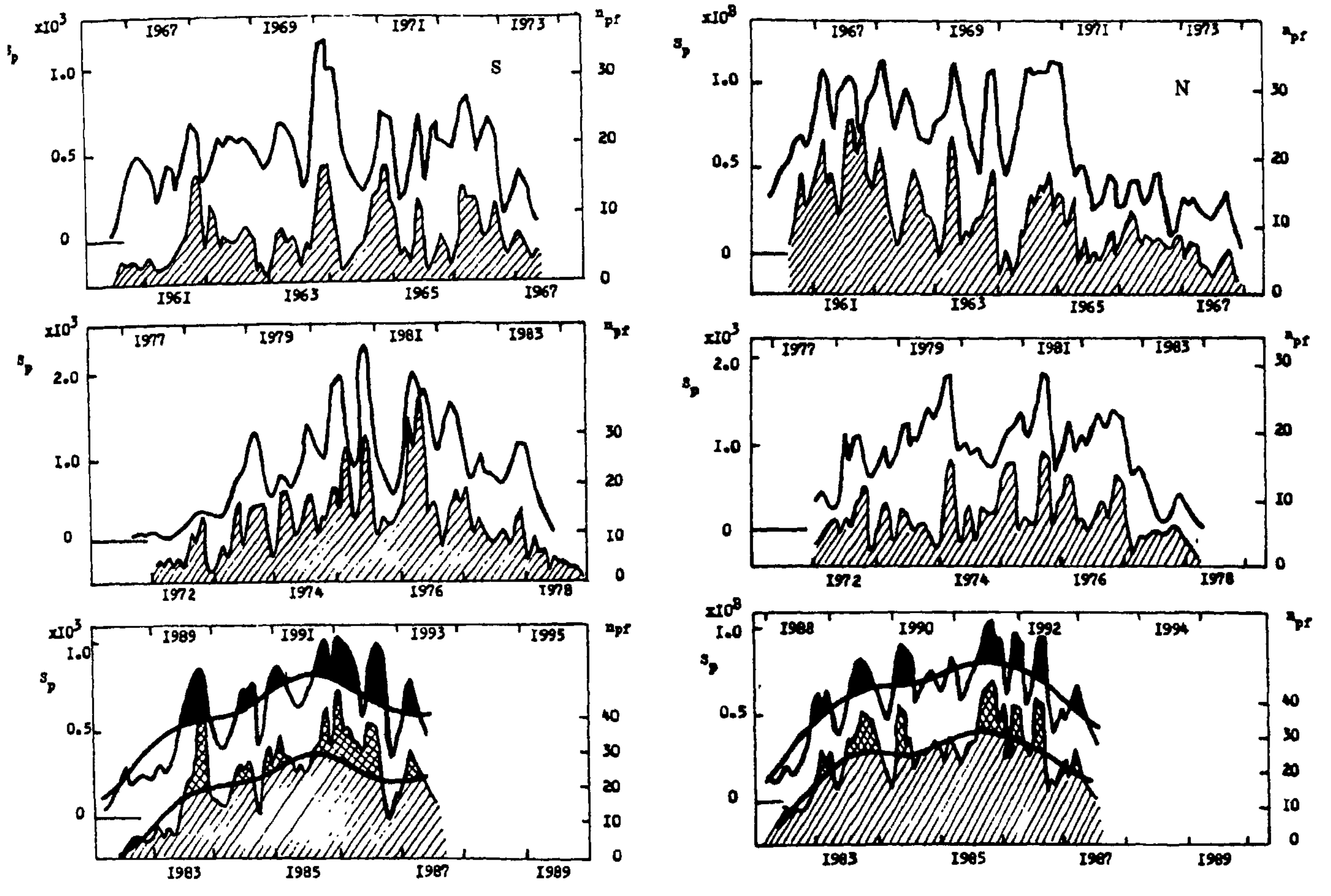

Figure 8. Superposed curves of variation of the monthly averaged sunspot number (lower curve and right-side scale) and of the polar faculae number when a shift in time of 5.8 to 6.2 years is introduced. The lower diagrams (a-southern hemisphere; b-northern hemisphere) are predictions for the next 22 solar cycles.

4 DISCUSSION AND CONCLUSIONS

From the analysis of the behavior of magnetic neutral lines and especially from the analysis of polar faculae and their comparison with other forms of small scale solar activity (XBP; EAR), we hypothesize the existance of 2 "waves" of solar activity to explain global processes going on the Sun. The start of the cycle would occur right after the polar reversal, in the form of small scale regions reaching a maximum density at latitudes near 60°. Then the 2nd wave of activity begins in the form of sunspots appearing at latitude ± 40° with a maximum occuring at latitude 15°. So the global process of solar activity can be described by a 2-wave (out of phase) phenomenon with a period of 11 years, see also Legrand and Simon, 1981, Leroy and Noens, 1983, Koutchmy et al. 1984, the overall length of the global process being 17 to 18 years.

It is tempting to look more carefully at the relations between these 2 waves in order to understand and hopefully, to predict the level of the solar activity, including the possible relation between the sunspot and the facular cycles, see for example Charentenay and Koutchmy, 1985. As a first step we looked at the correlations between the number of recorded polar faculae during several years and the sunspot number of the current cycle, the preceeding one and the following one. Sheeley, 1976 has sought for a relation between the current cycle and polar faculae as a consequence of the dispersion (random-walk process described for the first time by Leighton) of magnetic fields from sunspot regions toward the poles and their interactions with the polar field newly appearing. Figure 8 illustrates the typical result we got, including a prediction for the forthcoming 22 sunspot cycle. It shows an apparent "duality" in the behaviour of the polar faculae number and the sunspot number, when the two solar hemispheres and shifts of 5.8 to 6.2 years, are considered. The correlation reaches 0.8. These rather speculative results will be tested thanks to the curves we are showing for the next cycle. It is, however, clear that more analysis and especially, more observations of the solar activity, are needed to understand the details of the mechanism of the solar dynamo.

References:

Altrock, R., 1987, this volume (Sac Peak Coronal Workshop)
Charentenay, Ch. and Koutchmy, S. 1985, CRAS, **301**, 151.
Koutchmy, S., Bareau, C. and Stellmacher, G. 1974, CRAS, **278**, 873.
Koutchmy, S. Loucif, M. and Koutchmy, O., 1984, Solar-Terrestrial Predictions; Meudon Obs., Proceedings, Simon et al, ed., 67.
Legrand, J.P. and Simon, P.A. 1981, Solar Physics, **70**, 173.
Leroy, J.L. and Noens, J.C., 1983, A.Ap. Letters, **120**, L1.
Lockyer, W.J.S., 1931 MNRAS, **41**, 7, 801.
Makarov, V.I. and Sivaraman, K.R. 1983, Solar Physics, **85**, 227
Makarov, V.I. et al: 1984, Solneshnye Dannye, **9**, 52
1985, Solneshnye Dannye, **8**, 53
1986, Solneshnye Dannye, **7**, 113
1986, Solneshnye Dannye, **9**, 64
1987, Solneshnye Dannye, 3, 62
Makarov, V.I. and Makarova, V.V. 1986, J. of Astrophys. Astr. **7** 113.
McIntosh, P.S., 1972, Rev. Geophys. Space Physics **10**, 837.
Scheeley, N.R., 1976, J.G.R. **81**, 3462.
Stenflo, J.O. and Weisenhorn, A.L. , 1987, Solar Physics, **108**, 205.
Trellis, M., 1956, Thesis, Paris Univ. A-2950, 3822.
Wilson, P.R. 1987, Solar Physics, **110**, 1.