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16. Summary/Notes

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PERIODICITIES IN THE INTERPLANETARY MAGNETIC FIELD POLARITY

by

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ABSTRACT

A spectrum analysis for daily values of the interplanetary magnetic field polarity observed and inferred from 1947 to 1976 shows a dominant peak with a period of about that of the solar rotation indicating that sector patterns live long enough for this modulation to occur. From a subsequent annual analysis of the data we conclude that two-sector patterns are frequently observed during time intervals around solar maximum whereas a four-sector structure can become dominant during smaller intervals at solar minimum. The occurrence of two sectors around solar maximum covers a time interval (within one solar cycle) larger than that covered by the four sectors at solar minimum. Therefore, when one takes sets of data for reasonably long periods of time, one may find a general predominance of two sectors. The possible origin of these structures is discussed in terms of a combined "tilted-warped" interplanetary current sheet model.

INTRODUCTION

A recurrent pattern in the polarity of the interplanetary magnetic field was proposed by Wilcox and Gonzalez (1971). From a superposed epoch analysis of the observed field polarity from 1963 to 1968, they found a 26.875 ± 0.003 days recurrence pattern with the field polarity predominantly towards the Sun (negative) during approximately one half of the period and away from the Sun (positive) during the other half. According to them, in addition to the two basic polarity intervals per period, there would be a structure of four polarity changes per period responsible for the modulation observed in the resulting curve of their superposed epoch analysis.

The aim of the present work is to improve statistically the results obtained by Wilcox and Gonzalez. The search for possible periodicities in the interplanetary magnetic field polarity was done by using power spectrum analysis. In addition, the examined data wer extended to a longer time interval by including the ground inferred magnetic field polarity previous to the satellite era. The data were taken from Svalgaard (1975, 1976) who gives the polarity of the interplanetary magnetic field for each day of the interval between January 1, 1947 to December 31, 1975. The data were subjected to spectral analysis and the possible periods were obtained to a 95% confidence level. The analysis shows that the fundamental peak, with period of about 27.5 days, has the largest power indicating that, in general, any sector pattern lives long enough so that the solar rotation can actually modulate its power spectrum. A subsequent analysis was done dividing the data annualy and including also the preliminary data for 1976 given by Scherrer et al. (1977). It shows that a two-sector structure seems to be a frequent feature in the interplanetary magnetic field for time intervals around solar maximum whereas a four-sector structure may become dominant for smaller intervals at solar minimum. The occurrence of two sectors arounds solar maximum covers a time interval (within one solar cycle) larger than that covered by the four sectors at solar minimum. Therefore, when one takes stes of data for reasonably long periods of time, as in the work of Wilcox and Gonzalez (1971) or in our analysis for the whole set of data (1947 - 1975), one may find a general predominance of two sectors. The possible origin of these structures is discussed in terms of the following combined "tilted-warped" interplanetary current sheet model (Rosenberg 1970, Schulz 1973, Svalgaard and Wilcox 1976, Svalgaard and Wilcox 1976, Smith et al 1978).

In general, both the dipole and quadrupole components of the solar magnetic field, associated to the two and four sectors, respectively, seem to be present al all times. However, around solar maximum the tilt of the dipole seems to dominate the effect of the current sheet-warp due to the quadrupole component and two sectors are basically observed at Earth. At solar minimum, the tilt decreases and the basically warped sheet gives rise to the observed four sectors. During field reversal, the tilt attains 90^{0} and the resulting two gross "sectors" can be observed at Earth, although one could also expect large contributions from the other components.

SPECTRUM ANALYSIS

The power spectrum analysis allows the detections of all the periodicities present in a temporal series, and it can be shown that this technique has great advantages in comparison to other statistical methods, like superposed epoch analysis (see, for instance, Hauska et al. 1972). The estimation of power spectrum can be done in two basic ways. One is through the direct Fourier transform of the sample function (via, for instance, the fast Fourier algorithm). Alternatively, it can be calculated by applying the Fourier transform to the autocovariace function. The latter method has the advantage of showing the autocovariance function as an intermediate result, as well as allowing the incorporation of a lag window, which has the property of performing a predeterminated ammount of smoothing on the spectral estimate (Jenkins and Watts 1968; Black 1970; Armstrong and Gough 1978).

A detailed treatment of power spectrum analysis from the computation of the autocovariance function is given by Jenkins and Watts (1968), who also describe the different lag windows used for smoothing the spectrum.

Applying the so called window closing technique one has the possibility of varying the resolution of the spectrum by changing the bandwidth of the window. The latter is a function of the "truncation point" of the window, which is the maximum lag considered in the weighting process used for smoothing. As a consequence, the increase of the truncation point produces an increase in the fidelity of the spectrum and at the same time a decrease in its stability. Therefore, a compromise must be adopted in order to choose the most convenient value of the truncation point. Finally, for a given lag window, the confidence interval to a chosen level of significance may also be evaluated for each frequency (*). Using a logarithmic scale for the power, this interval is independent of the frequency and can be represented by a single bar.

In the present work the spectral analysis was done using the "Hanning-Tukey" window. The data were considered all together, in a set of 10592 points, as well as in shorter subintervals. In each case the "null spectrum" for Markov red noise was also computed in the way described by Mitchell et al. (1966). For the complete series, the autocorrelation function was computed up to a maximum lag of 3000 days. Then, the spectral analysis was carried out for values of the truncation point of the Hanning-Tukey window of 50, 100, 200, 500, 1000 and 3000, the resulting bandwidths varying between 0.0667 and 4×10^{-4} cycles per day. Figure 1 shows the logarithm of the power as a function of the frequency for a truncation point equal to 500. In this figure we also plot the bandwidth of the window, which gives an idea of the detail that can be resolved in the spectrum, as well as the confidence bars for 80% and 95% significance levels. For the subsequent analysis of smaller subintervals of the data, truncation points of 50 and 100 were used.

The maximum entropy method (Burg 1967) has also been used with results similar to those described below.

(*) As a matter of fact, confidence intervals derived on the assumption of continuous Gaussian noise are questionable for this kind of data and more careful interpretation of the results should be done. This problem is considered by Avara and Blackman (1975).

RESULTS

Figure 1 shows the power spectrum of the whole set of data and four peaks are significant to a 95% confidence level with respect to the null spectrum. They correspond to periods of about 27.5, 13.5, 9.1 and 6.8 days. Similar results are obtained for other truncation points and are shown in Table I, where the periods are given in days. The small number at the right corner of each box in this table gives the power for the corresponding peak and the numbers in brackets are the uncertainties due to the discreteness of points in the computed spectrum. The results obtained for a truncation point equal to 3000 are not shown in this table due to the spurious splitting produced in the peaks by the large instability observed in this case.

The results of the analysis done for the data divided annually are shown in Figure 2, where the vertical axis (in logarithmic scale) gives the power for the fundamental peak (heavy line) with period of about 27.5 days and for the second peak (dashed line) with period of about 13.5 days. The truncation point is equal to 100. The other two peaks shown in Figure 1 have smaller powers and are not plotted in Figure 2. The full and dashed arrows at the middle of the vertical axis of Figure 2 indicate the estimated 80% confidence limit for each curve, such that only those points above them are significant at that level of condidence. In this figure as well as in Figures 3 and 4, the results obtained from preliminary data for the interplanetary magnetic field polarity of 1976 (Scherrer et al. 1977) are also included. Notice that for each year there are two points on Figure 2. This is because the annual analysis was carried out twice, dividing the data in annual groups which started on January 1 and then in annual groups which started on July 1, in order to smooth the curve with the resulting overlap. At the bottom of Figure 2, the relative sunspot number averaged for each year is also plotted. The annual variation of the period (given in days) corresponding to the first peak of the spectrum is shown in Figure 3, also for a truncation point of 100. The dashed and discontinuous portions of the curve correspond to values below the 80% confidence limit (see Figure 3). The average period obtained from Figure 4 for the fundamental peak is about

27.5 days. A tendency for a longer period basically around solar maximum is in agreement with results discussed by Svalgaard and Wilcox (1975).

The ratio of the power of the fundamental peak over that of the second one, as obtained from the annual analysis, is given at the top of Figure 4. The little horizontal bars with the adjacent numbers 2 or 4 show, respectively, the occurrence of two or four sectors as indicated by a visual inspection of the data used in our analysis (Svalgaard 1975, 1976). The length of these bars give an idea of the duration of the respective occurrences. It is found from this plot, as well as form that of Figure 2, that the first peak dominates the second one for most of the years and this predominance becomes more pronounced at those intervals for which the two-sector structure is also cleary observed in the data On the other hand, for the two occasions in which the four-sector structure is well defined in the data, the relative power becomes less than one, showing a clear predominance of the second peak over the first one. A discussion of these features and their implications are given below, after the following considerations.

As it is known, a symmetric square wave has a Fourier spectrum with a maximum at the fundamental frequenty and subsequent peaks at frequencies that are odd multiples of it, whose amplitude go asymptotically to zero. Therefore, for a symmetric two-sector structure model with period of say 27 days, one should expect a power spectrum with a prodominant peak at the fundamental frequency of (27 days)$^{-1}$ followed by the odd harmonics, decreasing in amplitude, at frequencies of about (9 days)$^{-1}$, (5.4 days)$^{-1}$ and so on. On the other hand, a symmetric four-sector model would generate a power spectrum with a fundamental peak at (13.5 days)$^{-1}$ and harmonics at frequencies of about (4.5 days)$^{-1}$, (2.7 days)$^{-1}$ and so on. However, for a non symmetric pattern all the harmonics can be present in general, as shown in the examples of Figures 5 and 6,where the spectra of a non symmetric two and four-sector pattern, respectively,are simulated. Notice from Figure 6 that a non symmetric recurrent four-sector pattern can also contribute to the fundamental peak.

From the above arguments and Figure 4,it becomes apparent that there is not a unique pattern to represent the whole set of the analysed data. However, as expected from the analysis shown in Figures 1 and 2, the existence of a generally well defined period, approximately equal to that of a solar rotation and with the highest power for most of the time, gives an evidence that, in general, any sector pattern lives long enough, so that the solar rotation can actually modulate its power spectrum. In addition to this global behaviour, a reasonably well defined two-sector structure seems to show up with certain frequency during intervals of time around solar maximum, while intervals with marked four-sector structure are observed at solar minimum. Between those intervals more complex structures may also be present.

The occurrence of two sectors around solar maximum covers a time interval (within one solar cycle) larger than that covered by the four sectors at solar minimum. Therefore, when one takes sets of data for reasonably long intervals of time, as in the work of Wilcox and Gonzalez (1971) or in our analysis for the whole set of data (shown in Figure 1), one may find a general predominance of two sectors and the highest power of the fundamental peak in the spectrum analysis could well have a strong contribution from physically existing two sectors. For this to occur, the two sectors should in general be equally divided within a solar rotation (almost symmetrical pattern) since, when the symmetry diminishes, the contribution to the power of the fundamental peak becomes weaker, as it is shown by the simulated two sector patterns of Figure 5.

As observed from Figure 2 and 4, the year 1964 was characterized by a notable contribution of the second peak over the fundamental one. The power spectrum for this particular year is shown on Figure 7. An approximation of the recurrent pattern observed for it is that given on Figure 6, where the ocorresponding spectrum obtained by applying the fast Fourier transform algorithm to a numeric simulation with 2^{14} points is also shown. As it is seen, a good agreement exists between the simulated and the actual spectrum, except for a scale factor. Therefore, the year 1964 is a nice example of a four-sector pattern in the interplanetary magnetic field. By coincidence, it was during this year that the first observation of the interplanetary magnetic field organized in sectors was made with the Satellite IMP-1 (Wilcox and Ness, 1965).

It would be appropriate to extend the present analysis to previous solar cycles and to find out, in particular, whether there is some kind of periodicity in the recurrence of well defined intervals with two and four sectors and their relationship to solar activity. For the years studied in the present analysis, shown in Figure 4, there seems to be an indication of one main interval with a well defined four-sector structure around solar minima and two or three main intervals with well defined two-sectors during a larger portion of the solar cycle around solar maxima. Furthermore, it is interesting to see from this figure that the two-sector structure seems to become less developed during intervals of strong solar activity, as observed in the correlation with peaks of solar proton events (Hakura 1974). A more detailed discussion on this point is given below.

DISCUSSION

As shown in Figure 4, a two-sector structure seems to be a frequent feature in the interplanetary magnetic field, especially for time intervals around solar maximum. Similarly, at solar minimum there seems to be a tendency for a dominance of a four-sector pattern. These correlations with the solar cycle have been already pointed out by several authors (Rosenberg and Coleman 1969, Schulz 1973, Svalgaard and Wilcox 1975).

With respect to the interplanetary magnetic current sheet model discussed in the literature (Rosenberg 1970, Schulz 1973, Svalgaard and Wilcox 1976, Smith et al. 1978), the two and four-sector structures implied by the present analysis could be related as follows. The two-sector structure can be nicely explained by the magnetic current sheet, somewhat "tilted" with respect to the ecliptic plane, discussed by Smith et al. (1978), since for each rotation of the Sun, an observer at the Earth would see each polarity approximately half of the time. However, this current sheet, governed mainly by the strength of the polar fields at the Sun, has also to explain the four-sector structure and sometimes more complex structures, which are also observed at the Earth specially during periods of solar minimum. In this direction, Svalgaard et al. (1975) have studied the influence of the low latitude solar photospheric sector structure on the interplanetary current sheet giving rise to a "warped" current sheet model,and have shown that the demarcation "line" between adjacent sectores rotates from 90^{o} at the solar photosphere to approximately 15^{o} at the Earth. Scherrer et al. (1977) also showed that there is a good corespondence between the interplanetary sector structures and those observed at the solar photosphere. From the present analysis,we also support this correspondence,since the interplanetary magnetic sector structures seem to live long enough,so that the solar rotation can modulate the spectrum (high power at about 27.5 days) even when a two-sector structure is not well developed. Alternatively, the simple current sheet, discussed by Schulz (1973) and Smith et al. (1978) following previous unpublished comments by Alfvēn, may develop kinks and folds giving rise to four sectors and more complex patterns in the interplanetary field. However, these kinks and folds might not live long enough and a correspondence with the photospheric field of the type observed by Scherrer et al. (1977) would not necessarely occur, unless the folds and kinks are somehow originated in the photospheric sector structure at low latitudes on the Sun and, in that case, both models would become basically the same.

Svalgaard and Wilcox (1976) have studied the latitudinal heliographic extension of the influence of the low latitude photospheric sector structure in the interplanetary field and have shown that at solar minimum the latitudinal extension is smaller as compared to that at solar maximum. The fact that at the Earth one can observe four sectors mainly at solar minimum and two sectors around solar maximum might be related to that influence and have the following implications. The tilt of the interplanetary current sheet would have to be small enough for the Earth to stay always withing heliographic latitudes containing the warped current sheet, crossing the extended photospheric four-sector structure of solar minimum. Otherwise, it could leave the thin warped current sheet and one would observe basically two sectors, which is not the case. On the other hand, around solar maximum, the tilt of the sheet should be considerably larger such that the effect of any warping due to the quadrupole component of the solar magnetic field may be regarded as relatively negligible. During field reversal, the tilt of the sheet attains 90^0 and the resulting gross regions with two polarities can be observed regardless of heliographic latitude, although one could also expect large contributions from the other components.

This combined "tilted - warped" current sheet model is idealized in Figure 8, where the dynamic evolution in heliographic latitude of the tilted sheet is drawn for one magnetic cycle. The numbers 4 or 2 indicate the expected four or two sectors, respectively. This model is supported by studies on the heliographic latitudinal extension of the interplanetary current sheet as function of solar-cycle phase (Svalgaard and Wilcox, 1976) and also by the Pioneer 11 observations (Swith et al., 1978) obtained for most of the year 1976 and at heliographic latitude of about 16^0N, which show the existance of basically one polarity in the interplanetary magnetic field expected for intervals at solar minimum and at reasonably high heliographic latitudes. However, there are not yet similar satellite observations for intervals around solar maximum and at field reversal in order to see how the implications of our hipothesis could actually occur for that part of the solar cycle. For instance, one could distinguish the period between solar minimum and solar maximum (which we have been referring to as the period "around solar maximum") from that at field reversal (solar maximum) by satellite crossings at middle heliographic latitudes, which would show for the former period either magnetic polarity and changes from one to the other, whereas for the latter period only one polarity would be observed. At solar minimum, satellite observations at low latitudes would show the existence of four sectors and simultaneous observations at higher latitudes would indicate the presence of two sectors. All these simple arguments can be obtained from an inspection of Figure 8 and by imagining the Earth crossing the extended tilted sheet and satellites orbiting the Earth or the Sun at different heliographic latitudes.

The occurrence of more intense solar proton events (Hakura 1974) during intervals when the interplanetary two-sector patterns becomes less dominant, as shown in Figure 4, might be one aspect of the important influence of solar activity on the coupling between the photospheric and interplanetary magnetic fields. During those intervals, which occur basically around solar maximum, the general magnetic structure at the Sun may become more complex and the extension of the whole structure to the interplanetary medium may become less evident. This type of influence, as well as the more continuous one produced by the solar wind, represent some of the critical problems which will have to be solved first, before a clear undrstanding of the origin and dynamics of the interplanetary magnetic field sector structure can be obtained. Some progress in this direction has been obtained by Pneuman and Kopp (1971), Schulz (1973) and Schulz et al. (1978).

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Table I - Periodicities in the Interplanetary Magnetic Field Polarity for the Time interval January 1947 - December 1975. The periods (in days) derived from the peaks in the power spectrum, which are significant to a 95% level of confidence, are given for different values of the truncation point. The bandwith of the spectral window for each case is also indicated. The number in brackets which is shown together with each period is the uncertainty due to the discreteness of the points in the curve. The italic numbers at the upper corners represent the powers for each peak.

TABLE I

Truncation Point	Bandwidth (cycles/day)	Period (days)			
		Peak 1	Peak 2	Peak 3	Peak 4
50	0.0267	27.4(±.2) *14.7*	13.70(±.05) *8.3*	9.13(±.02) *3.0*	6.86(±.02) *1.9*
100	0.0133	27.8(±.2) *26.1*	13.61(±.05) *13.7*	9.09(±.02) *4.1*	6.79(±.02) *2.3*
200	0.0067	27.8(±.2) *43.8*	13.61(±.05) *21.5*	9.05(±.02) *5.5*	6.78(±.02) *2.7*
500	0.0027	27.5(±.1) *66.3*	13.51(±.03) *34.1*	9.07(±.01) *7.0*	6.77(±.01) *3.2*
1000	0.0013	complex	13.55(± 02) *40.2*	9.09(±.01) *7.6*	complex

FIGURE CAPTIONS

Figure 1 - Smoothed spectral power (logarithm of the power) for the whole set of data (1947 - 1975). The truncation point used for the Tukey - Hanning lag window is 500.

Figure 2 - Smoothed spectral power (in logarithmic scale) for the annual analysis. The full and dashed curves give the power for the fundamental and second peak,.respectively. The truncation point used was 100. The full and dashed arrows at the middle of the vertical axis, indicate the estimated 80% confidence limit for each curve. At the bottom, the relative sunspot number averaged for each year is plotted for reference.

Figure 3 - Annual variation of the period(in days)corresponding to the fundamental peak obtained from the annual spectrum analysis. The dashed and discontinuous portions of the curve correspond to values below the 80% confidence limit (see Figure 2).

Figure 4 - At the top, the relative power of the fundamental to the second peak is shown from the annual analysis. The little horizontal bars with the adjacent numbers 2 on 4 indicated the periods of time for which one can identify in the data continuous two and four sector patterns, respectively. At the middle, the number of solar proton events is shown for most of the studied time interval (Hakura 1974). At the bottom, the relative sunspot number averaged for each year is plotted.

Figure 5 - Simulation of a non symmetrical two sector pattern and spectrograms of its reccurrence for three values of the parameter a/T.

Figure 6 - Simulation of a non symmetrical four sector pattern and spectrograms based on the data for 1964.

Figure 7 - Smoothed spectral power (logarithm of power) for the year 1964. The truncation point used was 50.

Figure 8 - Variation in heliographic latitude of the tilted interplanetary current sheet for one magnetic solar cycle.

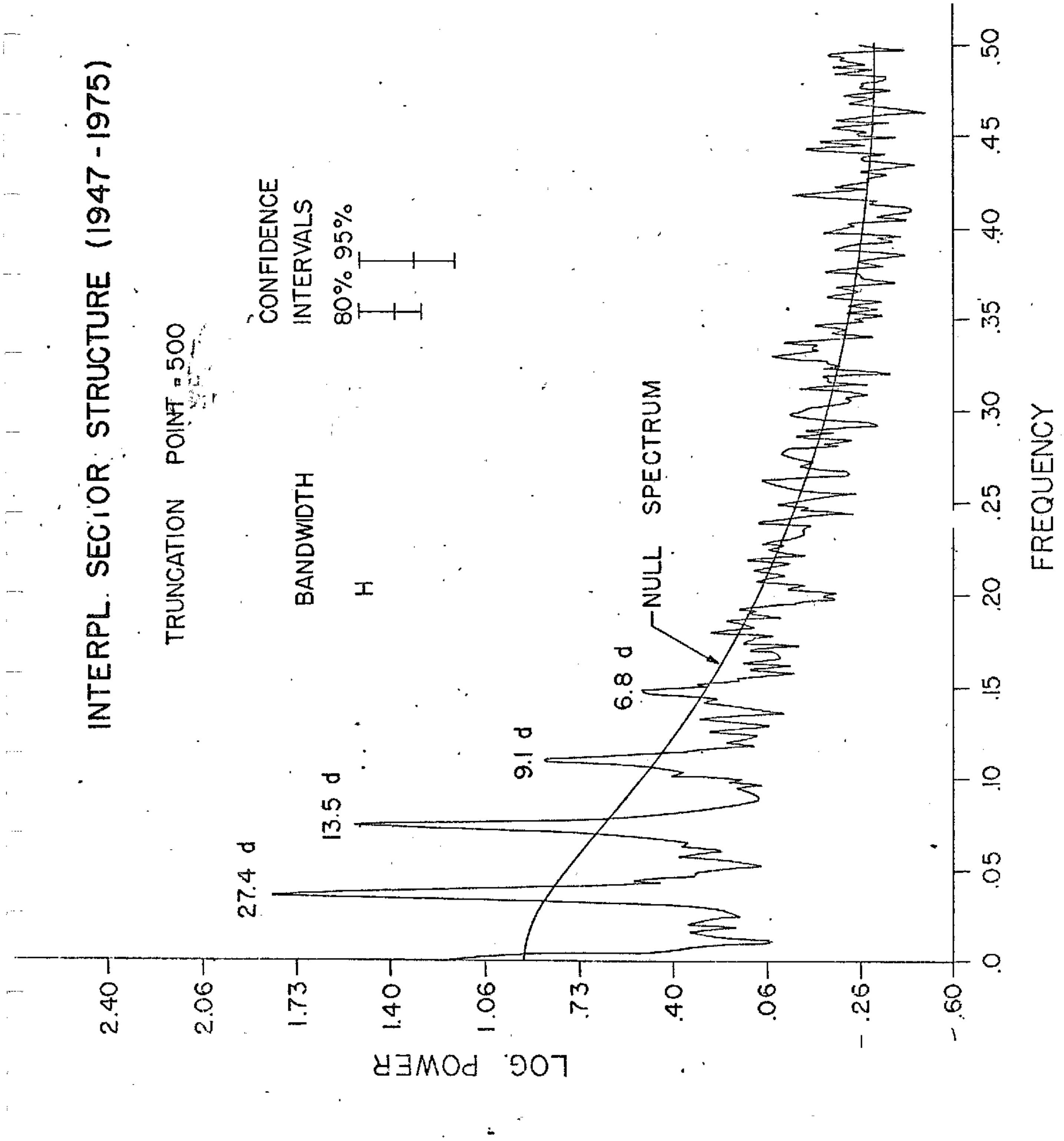

INTERPL. SECTOR STRUCTURE (1947 - 1975)
TRUNCATION POINT = 500
BANDWIDTH
CONFIDENCE INTERVALS
80% 95%
NULL SPECTRUM
27.4 d
13.5 d
9.1 d
6.8 d
LOG POWER
2.40
2.06
1.73
1.40
1.06
.73
.40
.06
-.26
-.60
FREQUENCY
0.
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

Fig. 1

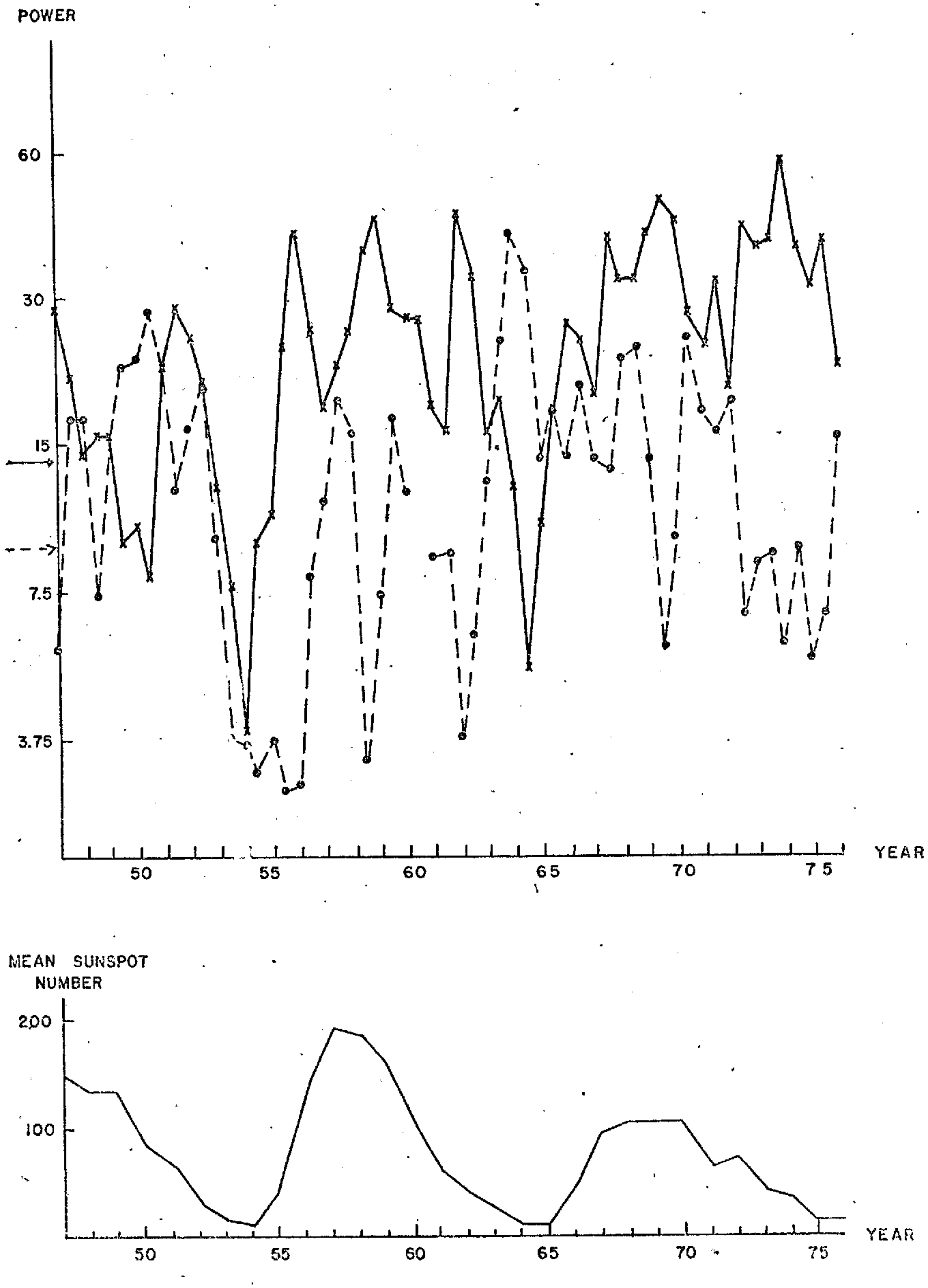

POWER
60
30
15
7.5
3.75
YEAR
50
55
60
65
70
75
MEAN SUNSPOT NUMBER
200
100
YEAR
50
55
60
65
70
75

Fig. 2

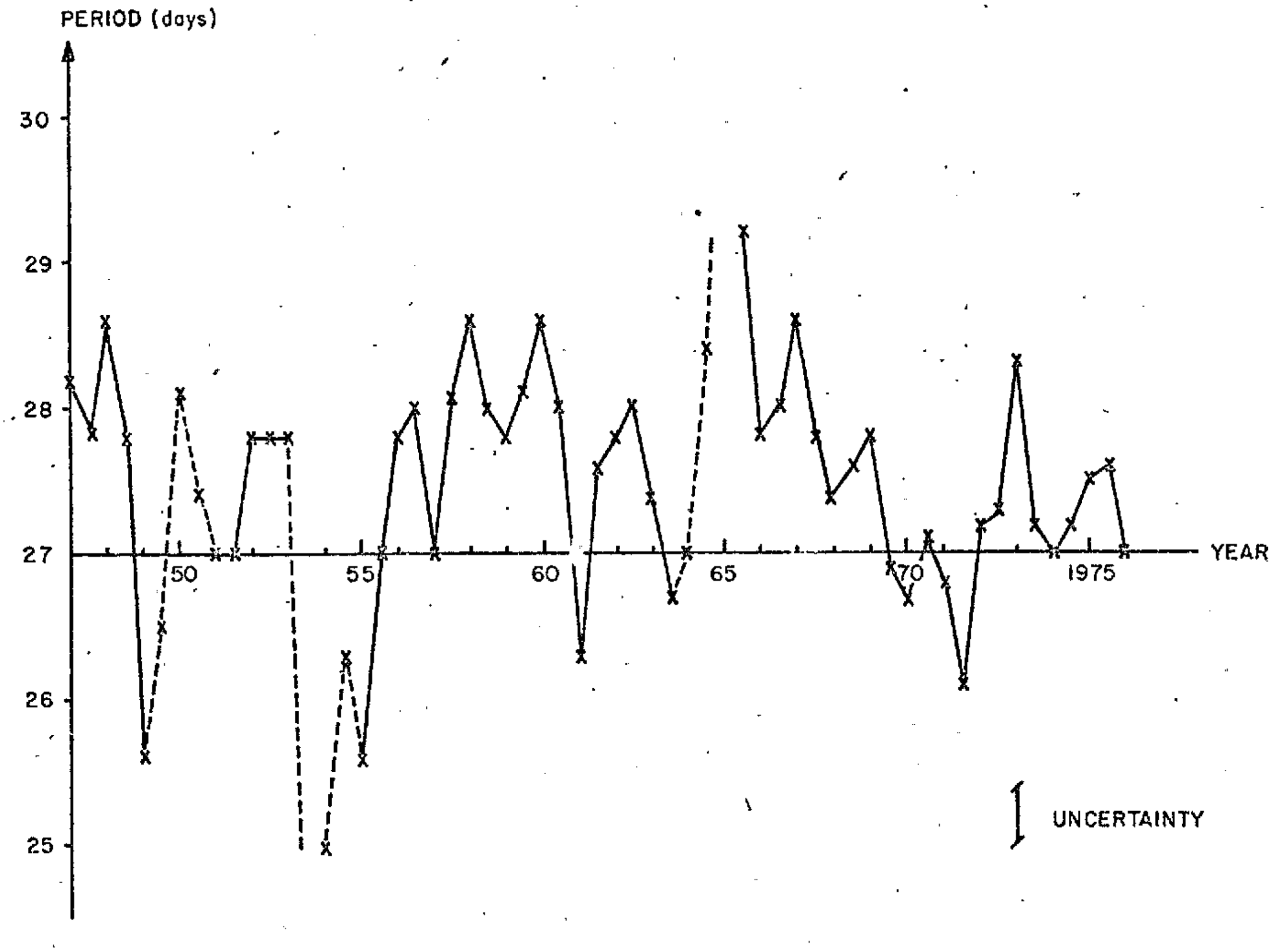

PERIOD (days)
30
29
28
27
26
25
50
55
60
65
70
1975
YEAR
UNCERTAINTY

Fig. 3

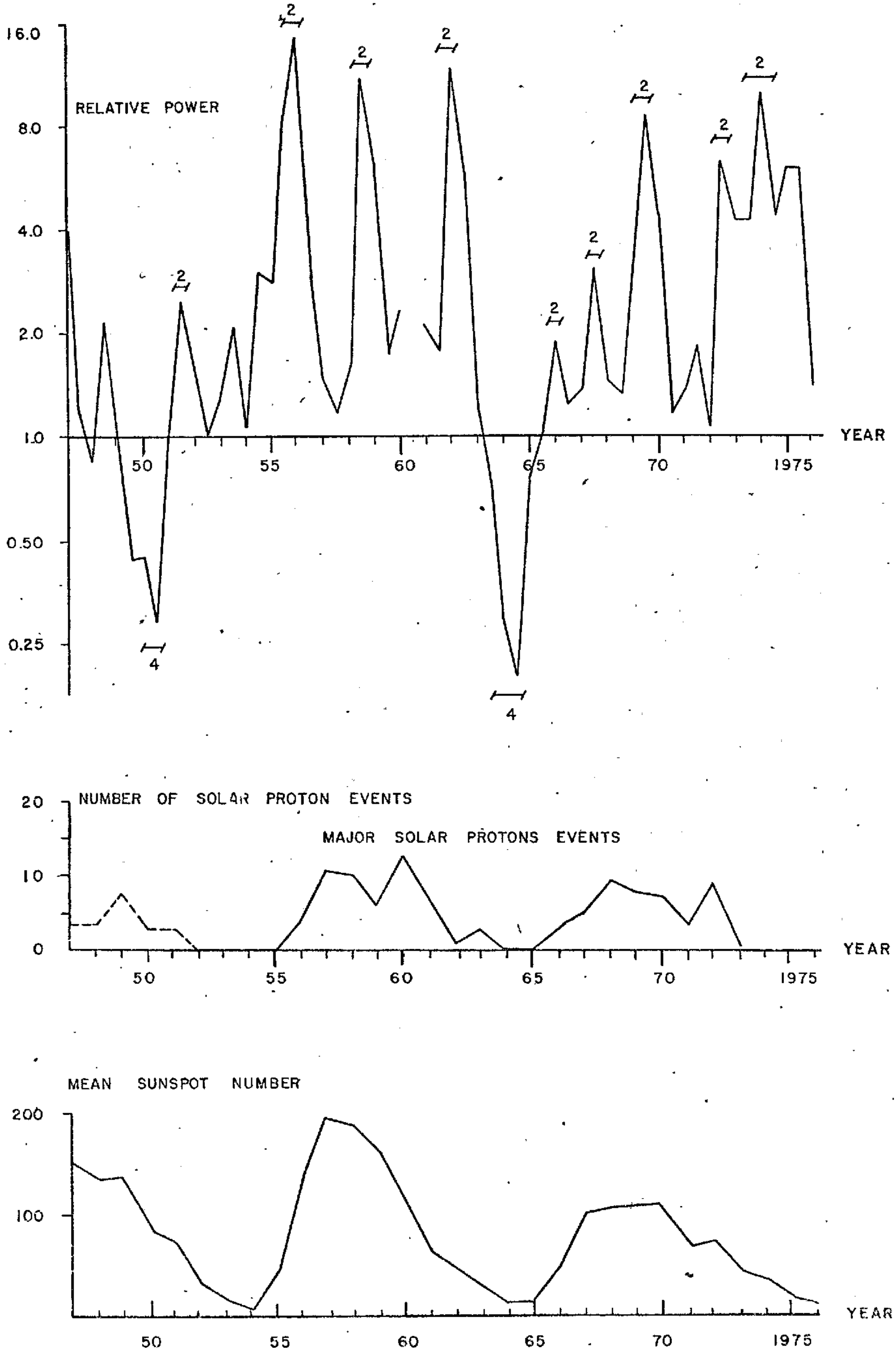

RELATIVE POWER
16.0
8.0
4.0
2.0
1.0
0.50
0.25
YEAR
50
55
60
65
70
1975
2
4
NUMBER OF SOLAR PROTON EVENTS
MAJOR SOLAR PROTONS EVENTS
20
10
0
YEAR
MEAN SUNSPOT NUMBER
200
100
YEAR

Fig. 4

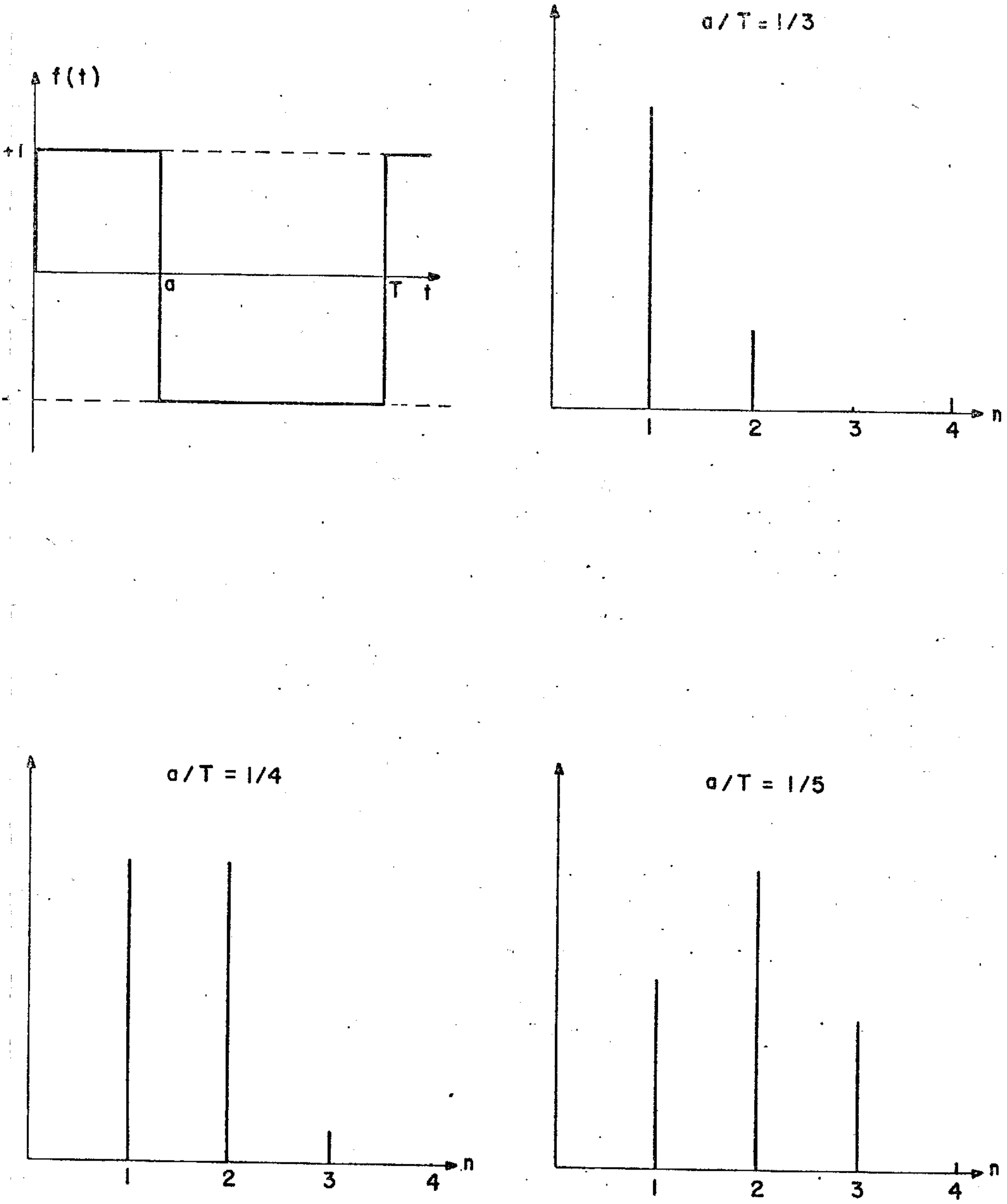


Fig. 5

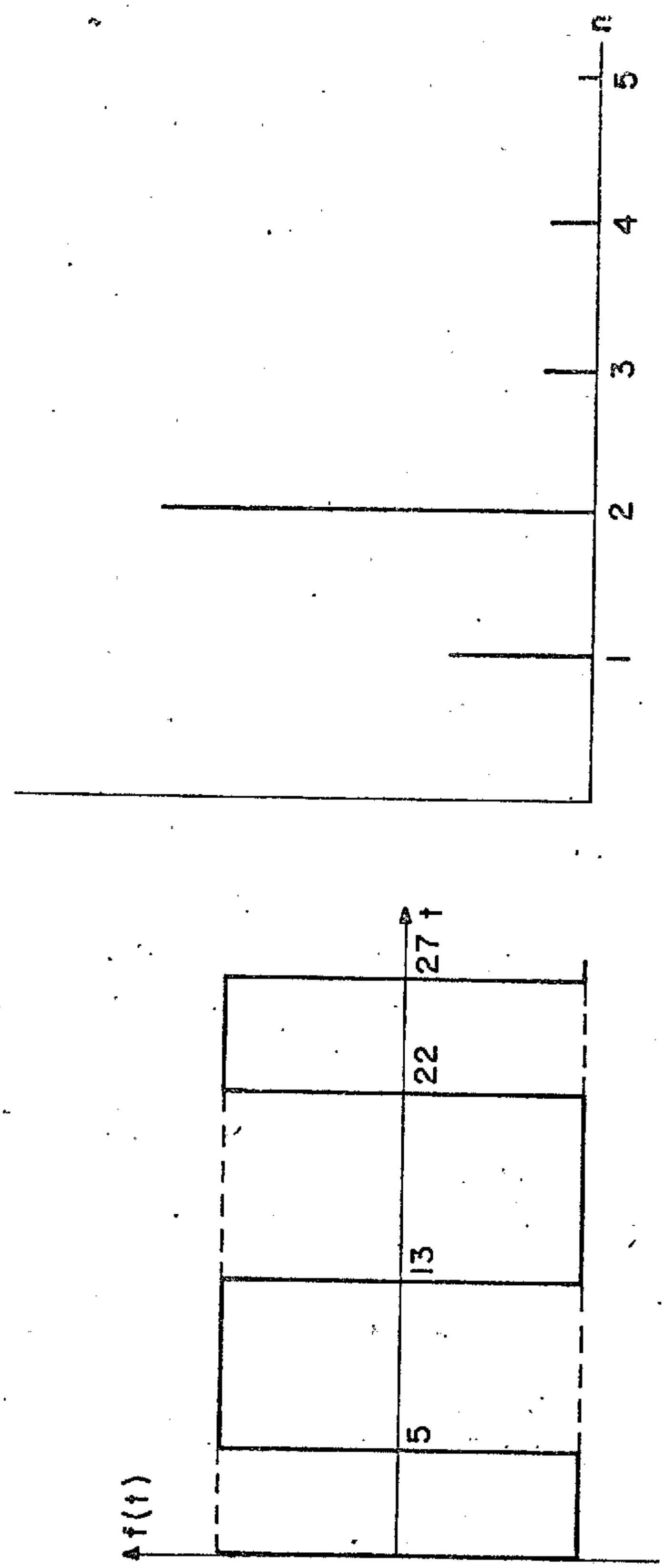
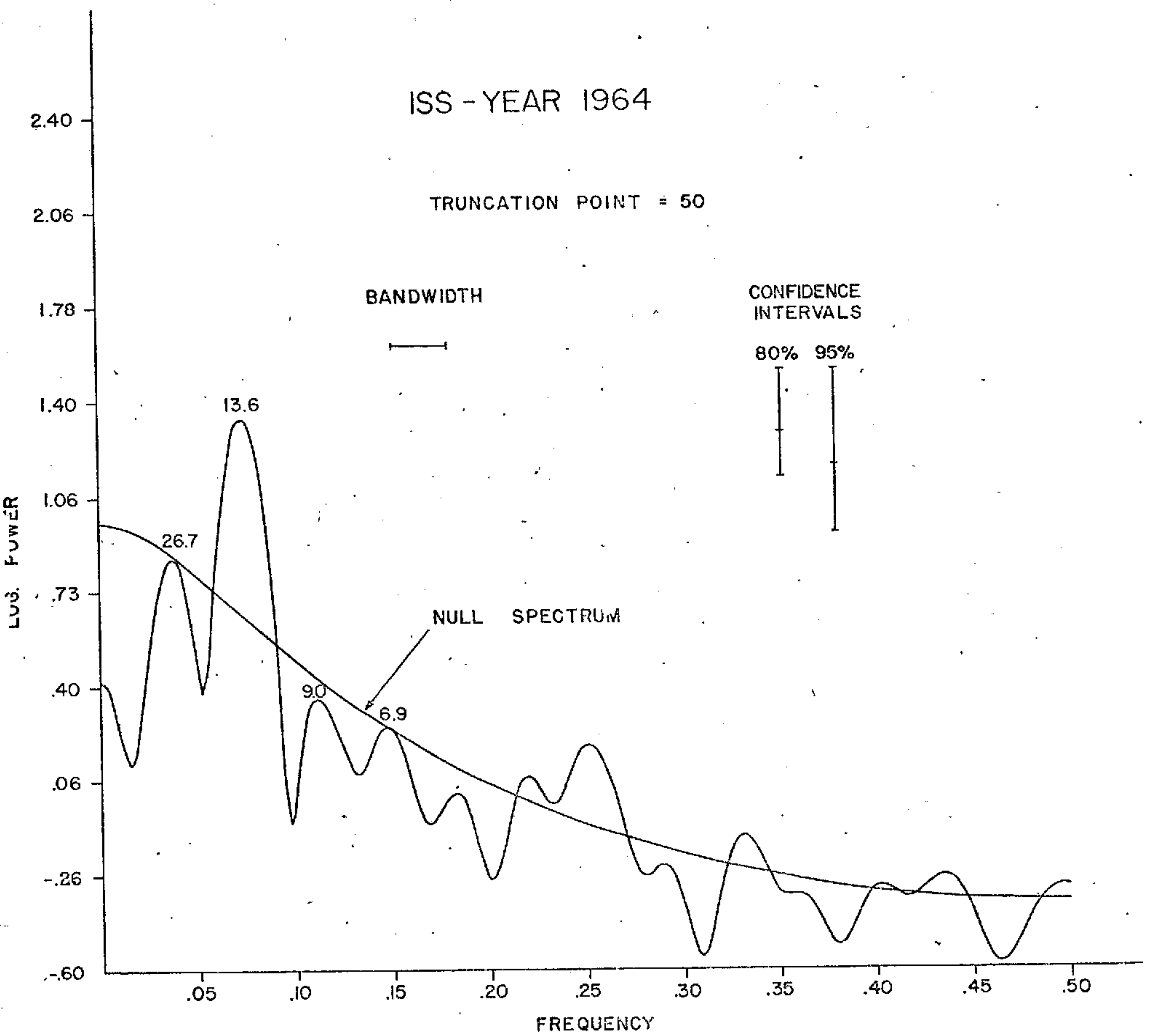


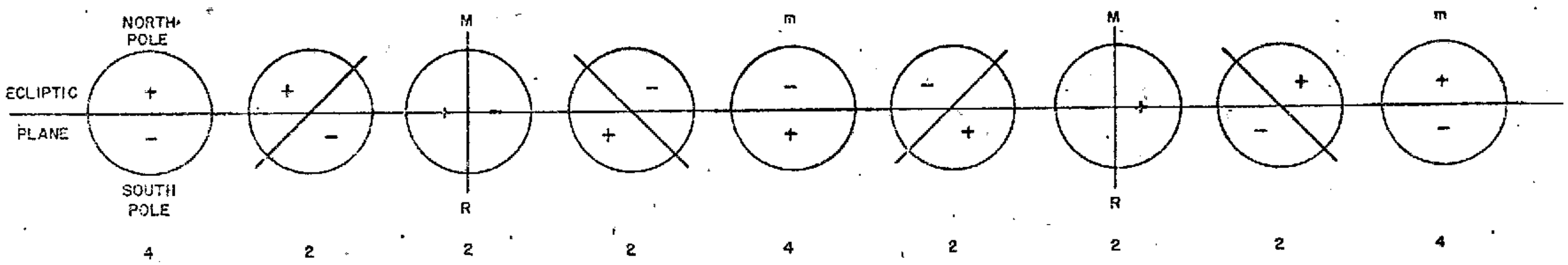
Fig. 6



ISS - YEAR 1964
TRUNCATION POINT = 50
BANDWIDTH
CONFIDENCE INTERVALS
80% 95%
13.6
26.7
9.0
6.9
NULL SPECTRUM
LOG. POWER
2.40
2.06
1.78
1.40
1.06
.73
.40
.06
-.26
-.60
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
FREQUENCY

Fig. 7

(8)



+ : POSITIVE MAGNETIC POLARITY

− : NEGATIVE MAGNETIC POLARITY

R : REVERSAL OF MAGNETIC POLARITY

m : SOLAR MINIMUM (ACTIVITY)

M : SOLAR MAXIMUM (ACTIVITY)

4 : FOUR SECTORS OBSERVED AT EARTH (MAINLY WARPED CURRENT SHEET)

2 : TWO SECTORS OBSERVED AT EARTH (MAINLY TILTED CURRENT SHEET)

Fig. 8