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ΑΣΤΡΟΝΟΜΙΑ.—**Possible periodicities of the annually released planetary seismic energy (M ⩾ 7.8) during the period 1898-1977,** *by John Xanthakis**.

ABSTRACT

In the present paper a global study of the annually released planetary seismic energy E_s ($M \geqslant 7.8$) is made. Corresponding M magnitudes were taken from the catalogues published by Duda (1965) and by Bath and Duda (1965). Periodicities of 180, 25, 12.5 and 4-years were used to express analytically the annual values of the released planetary seismic energy E_s, during the period 1898-1977.

1. INTRODUCTION

In a recent paper Kalinin et al (1978) studied the values of E for the period 1820 - 1960 with the aim to detect a correlation between the variable quantity E and the solar activity expressed by the Zürich relative sunspot numbers R_z.

Kalinin et al (1978) used annual amounts of released seismic energy E as the characteristic of planetary activity because as it is well known the greater part of annual seismic energy is released when earthquakes of great magnitude occur ($M = 7.9$ corresponds to $E = 5 \times 10^{16}$ Joule). Figure 1 shows the changes of planetary seismic energy for the time interval 1800 to 1971. From this figure we can see that the year-to-year changes of the parameter E are not regular and probably random, but there are also long-time variations.

* Ι. ΞΑΝΘΑΚΗ, **Πιθαναὶ περιοδικότητες τῆς ἐκλυομένης ἐτησίας σεισμικῆς ἐνεργείας τῆς Γῆς (M ⩾ 7.8) κατὰ τὴν χρονικὴν περίοδον 1898 - 1977.**

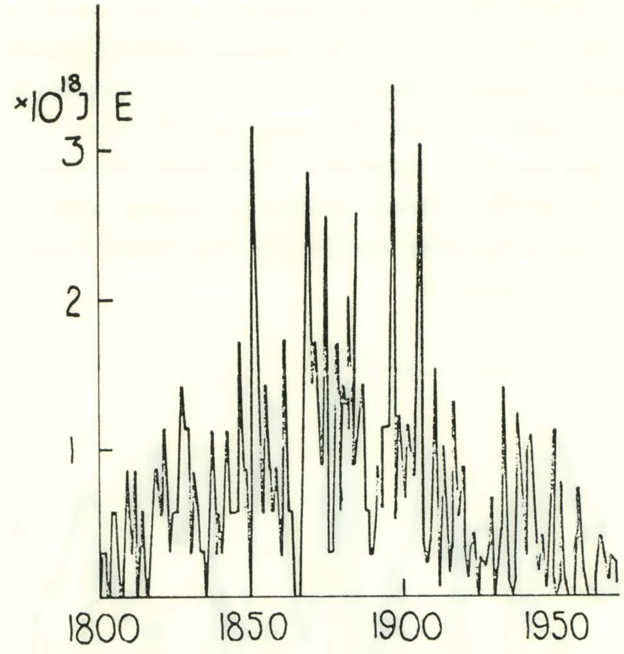

Fig. 1. Changes of annual values of released seismic energy in 10^{18} J for 1800 - 1974 (after Kalinin et al.).

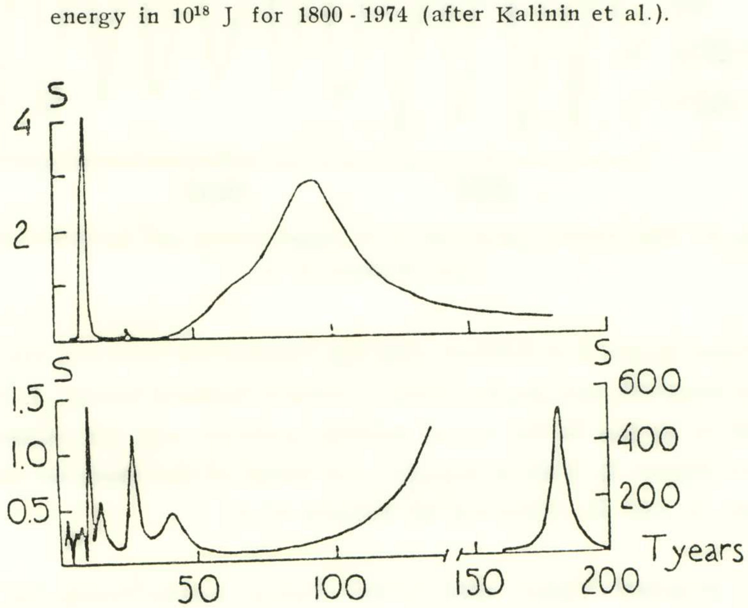

Fig. 2. Power spectra of relative sunspot numbers (R_z) and of released seismic energy (lower curve). The scale of peak of the long-term variation of E is placed to the right in figure (after Kalinin et al.).

Figure 2 shows the spectrum analysis of the seismic energy calculated by Kalinin, using the maximum entropy method (Smylie et al. 1973). From this figure it appears that the parameter E presents 3 periodicities with periods of about 11 years, 25 years, and 180 years.

Finally, Kalinin et al concluded that there was some evidence for solar dependence of the seismic activity variations with 11 and 25-year periodicities. The correlation coefficient was found equal to 0.59. This is clearly shown in figure 3.

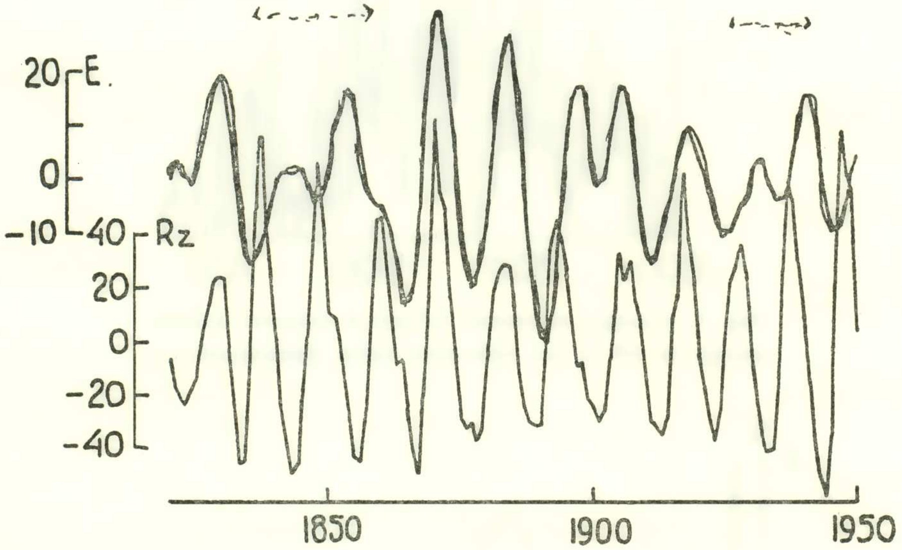

Fig. 3. The 11-year variations of E (upper curve) and R_z (lower curve) (after Kalinin et al.).

From figure 3 it follows that the correlation between the Relative Sunspot numbers and the Released Planetary Seismic Energy E (hereafter referred to as E_s) is for some periods positive and for other periods negative (figure 4). This is probably the cause of the unstable correlation between R_z and E_s observed by Kalinin et al.

2. SCHORT-TERM AND LONG-TERM VARIATIONS OF E_s

In view of these results we decided to analyze all the available data with the aim to express analytically the annual values of the released planetary seismic energy E_s.

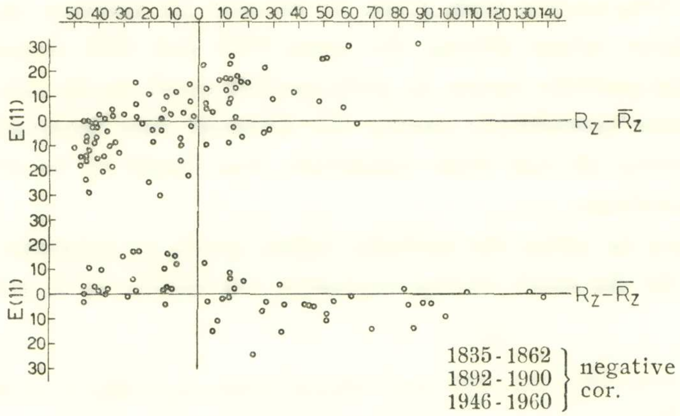

Fig. 4. Positive and negative correlation between the relative sunspot numbers and the released seismic energy E_s.

Thus, the values of the quantity E_s ($M \geqslant 7.8$) were computed according to the formula $\log E_s = 11.8 + 1.5\,M$ (Richter, 1958) from the values of M given by Duda (1965) and Bath and Duda (1965) and for the period 1898 - 1977.

In the present we will use the periodicities found by Kalinin et al but we will restrict ourselves to the study of the values E_s given in Table 1 (column 4) for the period 1898 - 1977. These values have been determined with the help of instrumental records exclusively as opposed to part of the values used by Kalinin et al and, therefore, are more reliable.

Table 1 (column 1) gives the 11-years sliding means of the values E_s, which will be denoted by $E_s(11)$. These values which can be considered as giving the mean variation of the annually released planetary seismic energy during the period 1900 - 1971 can be represented by the following relation:

$$E_s(11) = 50 + 33\cos\frac{2\pi}{180}(T - 1885) + L_t \qquad (1)$$

where L_t represents the sum of periodic terms with periods equal to 25 and 12.5 years:

$$L_t = -40\sin\frac{2\pi}{25}t - 20\sin\frac{2\pi}{25}t + 20\sin\frac{2\pi}{12.5}t + 10\sin\frac{2\pi}{12.5}t + 10\sin\frac{2\pi}{12.5}t \qquad (2)$$

t :	1882 - 1908	1887 - 1902	1902 - 1927	1909 - 1922	1944 - 1963
		1922 - 1947			1958 - 1963

The long-period term given by relation (1) assumes its maximum and minimum values during the years 1885 and 1975 respectively. As regards the periodic terms L_t with periods equal to 25 and 12.5 years, these appear sporadically during the different time intervals indicated below relation (2) and their amplitude was found to be 40, 20 and 10 units respectively.

Figure 5a gives the periodic terms given by relations (1) and (2). In figure 5b the small circles represent the values of E_s (11) given in

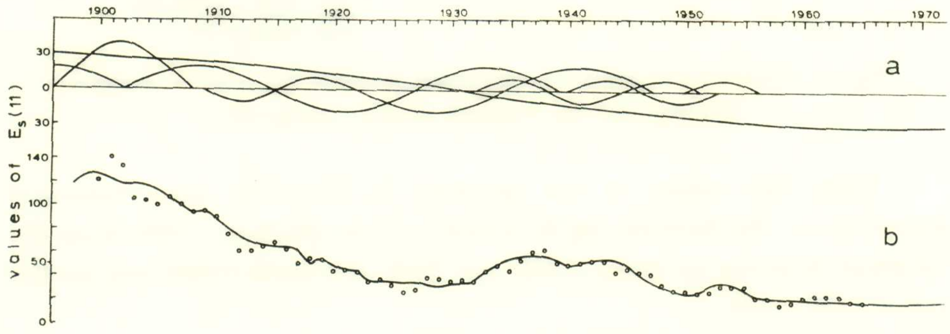

Fig. 5. Figure 5a gives the periodic terms given by relations (1) and (2). In figure 5b the small circles represent the values of E_s (11) given in Table 1 (column 1) while the continuous line gives the values of E_s (11) computed with the help of relations (1) and (2).

Table 1 (column 1) while the continuous line gives the values of the same quantity computed by relations (1) and (2), which are also given in Table 1 (column 2). From this figure we see that relations (1) and (2) represent satisfactorily the values of E_s (11) for the period 1900 - 1975. The corresponding value of the standard deviation is

$$\sigma = \sqrt{\frac{\left[E_s^{obs}(11) - E_s^{com}(11)\right]^2}{N-1}} = \pm 6.5 \times 10^{23} \text{ erg or } 12\%.$$

The spectral analysis of the quantity $E_s - E_s(11)$ reveals that this quantity shows only one periodicity with a period equal to 4 years and a confidence level above 99%. The amplitude and the time interval of appearance of this periodicity have been graphically determined, and are represented in figure 6. In this figure the small circles represent the values of the difference $E_s - E_s(11)$ while the continuous lines give the periodic term with period equal to 4 years and amplitude varying between 10 and 120 units. These periodic terms can be represented by the formula:

$$W = \sum C_n \sin \frac{2\pi}{4} t. \qquad (3)$$

C_n	t	C_n	t
− 10	1930 - 1934, 1938 - 1942, 1958 - 1964, 1960 - 1964	+ 40	1909 - 1913, 1939 - 1945, 1940 - 1944
+ 10	1896 - 1900, 1921 - 1927, 1923 - 1927, 1943 - 1947, 1945 - 1949	+ 50	1907 - 1911, 1934 - 1940, 1951 - 1957, 1953 - 1959, 1963 - 1969
+ 15	1908 - 1912, 1910 - 1916	− 50	1948 - 1954
+ 20	1970 - 1974	− 60	1900 - 1904
− 20	1952 - 1956, 1954 - 1958	+ 70	1895 - 1899, 1937 - 1941
− 30	1904 - 1908, 1911 - 1919, 1917 - 1923, 1922 - 1930, 1924 - 1928, 1946 - 1950	− 70	1908 - 1912, 1914 - 1918
		− 80	1903 - 1907
		+ 90	1932 - 1936, 1941 - 1951
+ 30	1942 - 1946, 1965 - 1971, 1967 - 1973	− 90	1945 - 1949
		− 100	1902 - 1908
− 40	1899 - 1903, 1901 - 1905, 1920 - 1924, 1963 - 1967	+ 120	1905 - 1909

The values of the periodic term W are given in Table 1 (column 3). From the above discussion we see that the values E_s can be represented analytically by the relation:

$$E_s = 50 + 33 \cos \frac{2\pi}{180} (T - 1885) + L_t + W. \qquad (4)$$

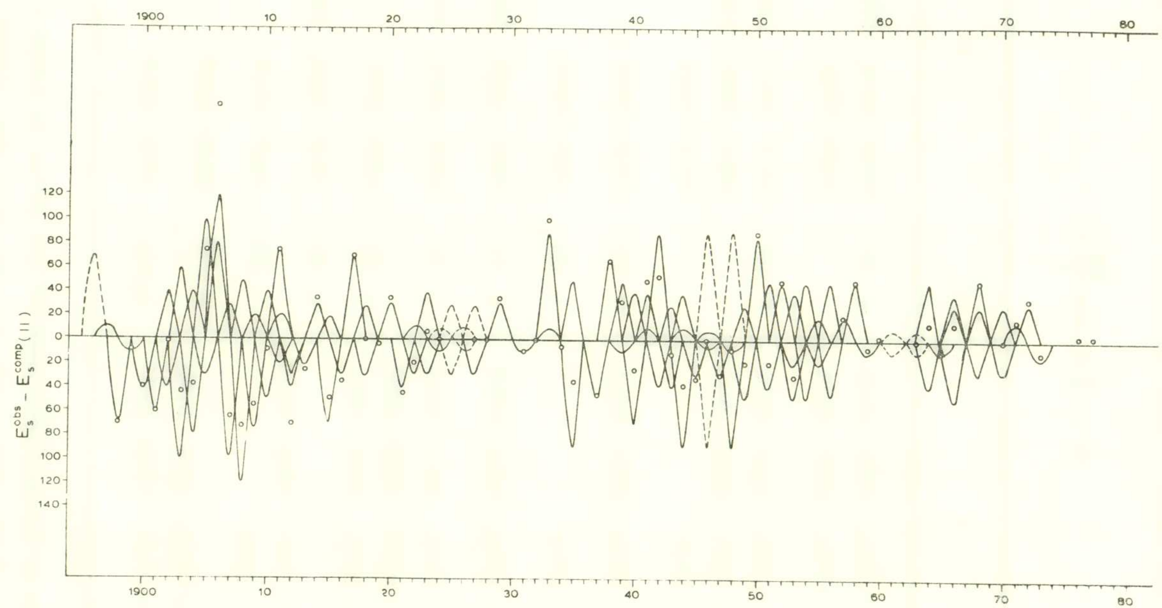

Fig. 6. The small circles represent the differences $E_s^{obs} - E_s^{com}(11)$. The continuous lines give the periodic term with period equal to 4 years and amplitude varying between 10 and 120 units.

Where L_t and W are given by relations (2) and (3).

Table 1 (columns 4 and 5) gives the observed values of E_s (Duda, 1965, and Bath and Duda, 1965) as well as the values of this quantity computed according to equation (4). From this table we see that equation (4) represents the observational data very satisfactorily.

The corresponding standard deviation is equal to $\sigma = \pm 3.3 \times 10^{23}$ erg.

The agreement between the observed and the computed values of E_s can be clearly seen in Figure 7b, where the continuous line gives the observed values of E_s given in Table 1 (column 4), while the dashed line gives the values of E_s computed from relation (4) which are also given in Table 1 (column 5).

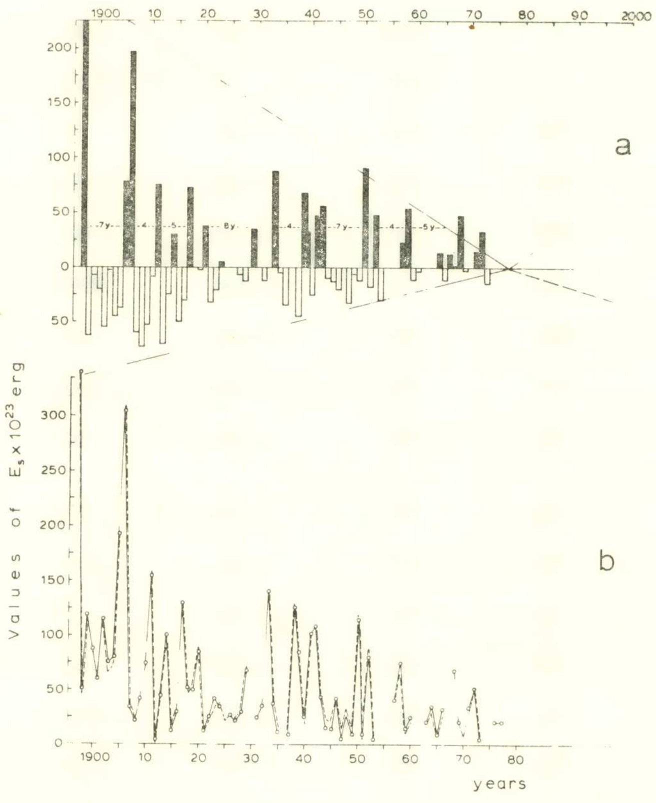

Fig. 7. a. The values of the differences $E_s^{obs} - E_s^{com}$ (11).
b. The continuous line gives the observed values of Es (Table 1, col. 4) while the dashed line gives the values of Es computed by relation 4 (Table 1, col. 5).

TABLE 1.

Values of E_s (11), W and E_s.

Date	E_s (11)		W	E_s	
	1 obs	2 comp	3	4 obs	5 comp
1898		118	— 70	52	48
99		127	— 10	120	117
1900		126	— 40	87	86
01		122	— 60	61	62
02		116	0	115	116
03	133	118	— 40	74	78
04	104	116	— 40	80	76
05	103	113	+ 70	183	183
06	99	106	+200	306	307
07	105	98	— 70	36	28
08	100	92	— 70	22	22
09	94	93	— 50	42	43
1910	96	85	— 10	75	75
11	90	77	+ 70	156	147
12	75	71	— 70	4	1
13	60	66	— 20	44	46
14	61	65	+ 30	101	95
15	65	63	— 50	13	13
16	62	62	— 30	29	32
17	63	60	+ 70	130	130

Table 1 (continued)

Date	E_s (11)		W	E_s	
	1 obs	2 comp	3	4 obs	5 comp
1918	51	48	0	53	48
19	54	53	0	52	53
1920	44	48	+ 40	86	88
21	45	43	− 30	13	13
22	44	43	− 20	25	23
23	36	36	+ 10	43	46
24	37	37	0	36	37
25	33	32	0	—	—
26	26	26	0	27	26
27	28	35	− 10	22	25
28	31	31	0	31	31
29	31	31	+ 30	68	61
1930	36	32	0	—	—
31	36	34	− 10	22	26
32	35	36	0	36	36
33	44	40	+100	141	140
34	49	43	0	38	43
35	45	47	− 40	13	17
36	54	50	0	—	—
37	69	54	− 50	9	4

Table 1 (continued)

Date	E_s (11)		W	E_s	
	1 obs	2 comp	3	4 obs	5 comp
1938	68	58	+ 70	125	128
39	52	55	+ 30	86	85
1940	50	50	— 30	25	20
41	52	53	+ 50	102	103
42	54	55	+ 50	108	105
43	55	57	— 10	45	47
44	45	56	— 40	18	16
45	48	59	— 40	18	19
46	45	43	0	43	43
47	43	37	— 30	4	7
48	34	33	— 10	27	23
49	30	29	— 20	9	9
1950	28	27	+ 90	115	117
51	28	— 28	— 20	9	8
52	27	33	+ 50	80	83
53	37	36	— 30	6	6
54	32	36	0	—	—
55	33	31	0	—	—
56	23	23	0	—	—
57	22	23	+ 20	42	43

Table 1 (continued)

Date	E_s (11)		W	E_s	
	1 obs	2 comp	3	4 obs	5 comp
1958	17	23	+50	75	73
59	19	22	−10	15	12
1960	20	21	0	24	21
61	28	21	0	—	—
62	23	20	0	—	—
63	25	20	0	—	—
64	20	20	+10	18	20
65	18	19	−10	9	9
66	19	19	+20	32	39
67	24	18	0	—	—
68	25	18	+50	67	68
69	23	18	0	18	18
1970	20	18	0	—	—
71	21	17	+15	34	32
72	20	17	+30	53	47
73		17	−15	6	2
74		17	0	—	—
75		17	0	—	—
76		17	0	22	22
77		17	0	22	22

3. CONCLUSIONS

From the above discussion we see that it is not possible to predict with satisfactory accuracy the annually released planetary seismic energy E_s. Besides the term with period equal to 180 years, the quantity E_s does depend also on the periodic terms with periods equal to 25 and 12.5 years, which are not always present, as well as on the periodic term with a period equal to 4 years, and amplitude varying between 10 and 120 units. The observational data available so far do not allow a prediction of the time of appearance of these terms. Very difficult is also the prediction of the values of the «mean variation» E_s (11) (11-year sliding means) which assumes its minimum value during the year 1975, when the long-period (180 years) term becomes also minimum. Starting with the year 1975, however, the values of E_s (11) will show an increase for a long period of time (90 years), with some fluctuations due to the probable appearance of the 25 and 12.5 years periodicities.

The amplitude of the term of the 4-years periodicities shows considerable fluctuations (figure 6). Thus, during the period 1897 - 1921 the amplitude of this term is very large, during the period 1922 - 1932 becomes smaller, during the period 1933 - 1958 assumes again large values, and then becomes again very low during the years 1959 - 1977 (with the exception of the year 1968).

If these fluctuations continue in the same way, then we must expect that the amplitude of the 4-year term will assume again large values during the period 1978 - 2000 i.e. we will have strong seismic activity, with great deviations of the values of E_s from the corresponding values of the mean variation E_s (11).

According to Benioff (Richter, 1958 p. 369) intervals of high seismicity are separated by intervals of lower activity, but the totals reached in the active periods successively decrease.

Analogous results we get when we study the values of the differences $E_s^{obs} - E_s^{com}$ (11). Figure 7a represents the values of the differences $E_s^{obs} - E_s^{com}$ (11). From this figure we see that the differences $E_s^{obs} - E_s^{com}$ (11) continuously decrease from 1897 until 1975. The positive values of this difference (full bars) which correspond to periods of intensive release of planetary seismic activity are separated by periods with a duration of 4 - 8 years, during which lower seismic actiyity prevails i. e. $E_s^{obs} - E_s^{com}(11) \leqslant 0$ (empty bars). This decrease of the value of $E_s^{obs} - E_s^{com}(11)$ continues until the year 1975, during which both $E_s(11)$ and the long period (180 years) term become minimum.

This phenomenon together with the fluctuations of the amplitude of the 4 year term lead to the hypothesis that after the year 1975 the values of the differences $E_s^{obs} - E_s^{com}(11)$ will probably follow the inverse trend for an interval of time of about 90 years.

All the above results are clearly shown in figures 5, 6 and 7.

The possible causes of the detected periodicities are an interesting subject for further observational and theoretical investigation.

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ΠΕΡΙΛΗΨΙΣ

Εἰς τὴν παροῦσαν ἐργασίαν μελετῶνται αἱ μεταβολαὶ τῶν ἐτησίων τιμῶν τῆς πλανητικῆς σεισμικῆς ἐνεργείας E_s διὰ σεισμοὺς εἰς τὴν κλίμακα Richter $M \geqslant 7.8$. Ἡ μελέτη καλύπτει τὴν χρονικὴν περίοδον 1898 - 1977. Αἱ τιμαὶ E_s ὑπελογίσθησαν σύμφωνα μὲ τὴν σχέσιν $\log E_s = 11.8 + 1.5 M$. Αἱ ἀντίστοιχοι τιμαὶ M ἐλήφθησαν ἐκ τῶν καταλόγων τοῦ Duda (Tectonophysics, 1965) καὶ Bath καὶ Duda (Monograph, 1965).

Ἐκ τῆς γενομένης φασματικῆς ἀναλύσεως ἀπεκαλύφθησαν περιοδικότητες τῆς τάξεως τῶν 180, 25, 12,5 καὶ 4 ἐτῶν. Τῇ βοηθείᾳ τούτων τῶν περιοδικοτή-

των κατέστη δυνατὸν νὰ ἐκφρασθοῦν ἀναλυτικῶς αἱ ἐτήσιοι τιμαὶ τῆς ἐκλυομένης πλανητικῆς σεισμικῆς ἐνεργείας E_s μὲ ἐξαιρετικὴν ἀκρίβειαν.

Τὰ ἐξαχθέντα συμπεράσματα δύνανται νὰ συνοψισθοῦν ὡς κάτωθι:

1) Ἡ ἀνάλυσις δεικνύει ὅτι δὲν εἶναι δυνατὸν νὰ προβλέψωμεν μὲ ἱκανοποιητικὴν ἀκρίβειαν τὰς ἐτησίας τιμὰς τῆς πλανητικῆς σεισμικῆς ἐνεργείας E_s. Ἡ μεταβλητὴ αὕτη ἐξαρτᾶται ἀπὸ περιοδικοὺς ὅρους 180, 25, 12,5 ἐτῶν ποὺ δὲν ἐμφανίζονται κατὰ τρόπον συνεχῆ, καθὼς καὶ ἀπὸ ὅρους βραχυτέρας περιόδου 4 ἐτῶν οἱ ὁποῖοι ἀλληλοπροστιθέμενοι, ἐμφανίζονται ὑπὸ μορφὴν πλέγματος περιοδικοτήτων μὲ εὖρος κυμαινόμενον μεταξὺ 10 καὶ 120 μονάδων.

Τὰ μέχρι τοῦδε δεδομένα δὲν μᾶς ἐπιτρέπουν μίαν πιθανὴν πρόβλεψιν εἰς τὴν ἀλληλοδιαδοχὴν τῶν περιοδικῶν τούτων ὅρων.

2) Ἡ μέση πορεία τῶν τιμῶν τῆς μεταβλητῆς E_s (11) (11ετεῖς κινητοὶ μέσοι ὅροι) φαίνεται νὰ λαμβάνῃ τὴν μικροτέραν τιμήν της κατὰ τὸ ἔτος 1975, ὅπου καὶ ὁ ὅρος μακρᾶς περιόδου (180 ἐτῶν) λαμβάνει πιθανῶς τὴν μικροτέραν τιμήν του. Ἀπὸ τὸ ἔτος 1975 ὅμως ἡ μέση πορεία E_s (11) θὰ βαίνῃ αὐξανομένη ἐπὶ μακρὰν σειρὰν ἐτῶν (90 ἔτη) μὲ αἰσθητὰς αὐξομειώσεις ἐκ τῆς πιθανῆς ἐμφανίσεως τῶν περιοδικοτήτων τῶν 25 ἐτῶν.

3) Τὸ σύμπλεγμα τῶν περιοδικοτήτων τῶν 4 ἐτῶν παρουσιάζει διαδοχικῶς λίαν αἰσθητὰς αὐξομειώσεις. Ἐὰν ὑποτεθῇ ὅτι ἡ αὐξομείωσις αὕτη συνεχίζεται κατὰ τὴν αὐτὴν τάξιν, ὡς δεικνύεται εἰς τὴν εἰκόνα 6 τότε δέον νὰ ἀναμένωμεν ἔντονον σεισμικὴν δραστηριότητα κατὰ τὴν περίοδον 1978 - 2000.

4) Ἐκ τῆς μελέτης τῶν διαφορῶν $E_s^{obs} - E_s^{com}$ (11) ἤτοι τῶν διαφορῶν τῶν τιμῶν τῆς ἐτησίας ἐκλυομένης πλανητικῆς ἐνεργείας E_s ἀπὸ τῆς μέσης πορείας E_s (11) καταλήγομεν εἰς ἀνάλογον πρὸς τὸ προηγούμενον συμπέρασμα. Τοῦτο δεικνύεται ὑπὸ τῆς εἰκόνος 7.