On the relation between solar activity and seismicity

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Abstract — Much attention is recently paid to the role of extraterrestrial factors in terrestrial seismicity, and to the possibility to assess the seismic risk. Seven centuries of records of ancient earthquakes in the Mediterranean region show that the century-scale variations in the number of strong earthquakes closely follow the secular cycle of solar activity. Two well expressed maxima in the global yearly number of earthquakes are seen in the 11-year sunspot cycle – one coinciding with sunspot maximum, and the other on the descending phase of solar activity. A day to day study of the number of earthquakes worldwide reveals that the arrival to the Earh of high speed solar streams is related to significantly greater probability of earthquake occurrence. The possible mechanism includes deposition of solar wind energy into the polar ionosphere where it drives ionospheric convection and auroral electrojets, generating in turn atmospheric gravity waves that interact with neutral winds and deposit their momentum in the neutral atmosphere, increasing the transfer of air masses and disturbing of the pressure balance on tectonic plates. The main sources of high speed solar streams are the solar coronal mass ejections which have a maximum in the sunspot maximum, and the coronal holes with a maximum on the descending phase of solar activity. Both coronal holes and CMEs are monitored by satellite-borne and ground-based instruments, which makes possible to predict periods of enhanced seismic risk. The geoeffectiveness of solar wind from a coronal hole only depends on the position of the hole relative to the Earth, and for the CMEs an additional factor is their speed. It has been recently found that a useful tool in identifying the population of geoeffective CMEs is the detection of long-wavelength (decameter-hectometer) type II solar radio bursts, as the CMEs associated with them are much faster and wider than average.

INTRODUCTION

Many authors have studied the role of extraterrestrial factors in terrestrial seismicity [1-5]. Different elements of solar activity have been proposed as triggers or seismic activity: solar proton fluxes [6], solar and lunar tides [7], high speed solar wind [8], earthward movement of the magnetopause as a result of increased solar wind dynamic pressure [9]. However, the problem remains controversial.

LONG-TERM EFFECTS

The Catalogue of Ancient Earthquakes in the Mediterranean Area [10] compiles information gathered from ancient books and chronicles about earthquakes from 760 BC to 995 AD. The longest set of solar activity data is based on the estimations of Schove [11] from records about auroras and sunspot groups visible with naked eye, where the years of minima and maxima of the 11-year solar activity cycles are given together with the approximate values of the maxima. Schove's data set covers the period from 649 B.C. to present, however the set is continuous only since 296 AD, so we have data for both earthquakes and solar activity from 296 to 995 AD. This period covers several secular (so-called Gleissberg) solar cycles.

For each 11-year sunspot cycle, we have compared the estimated value of the maximum of the cycle to the number of earthquakes in this cycle (*Fig.1*). The variations of solar activity statistically account for 47% of the variations in the number of earthquakes, with $p<0.01$. Fig.1 demonstrates that, on time-scales of the order of centuries, seismic activity follows solar activity.

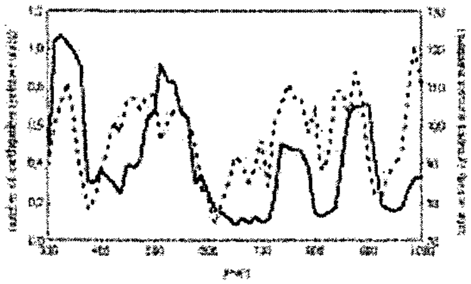

Fig.1: Number of earthquakes in the Mediterranean area summed over the 11-year solar cycles (solid line) and solar activity in the maxima of the solar cycles (broken line) in the period 296-1000; 3-point running means.

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THE 11-YEAR SOLAR CYCLE

The statistics about the numbers of earthquakes are most reliable since the beginning of the 20th century, so the global number of strong (with magnitude 7 or greater) earthquakes per year is studied, provided by the National Earthquake Information Center, World Data Center A for Seismology (http://neic.usgs.gov/neis/eqlists/7up.html). The expected effects are small because the variations in the yearly number of earthquakes as a result of variations in solar activity are much smaller than the average yearly number of earthquakes which are randomly distributed. In cases like this, when looking for a relatively small effect on the background of other variabilities, widely used in solar-terrestrial physics is the superposed epochs method [12, 13]. There are nine 11-year solar cycles in the period 1900-1999. As a reference (zero) year we take the year of sunspot maximum and calculate the average number of earthquakes in the 9 sunspot maximum years. For year (-1) the average number of earthquakes is calculated in the 9 years preceding the sunspot maximum by one year, for year (+1) – the average number of earthquakes in the 9 years following the sunspot maximum, and so on. Fig. 2 shows the distribution of the number of earthquakes in the 11-year solar cycle as derived is this way.

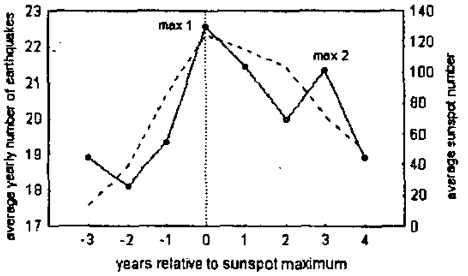

Fig.2: Average number of earthquakes (solid line, left scale) and solar activity (broken line, right scale) in the 11-year solar cycle for the period 1900-1999.

Two maxima in the average yearly number of earthquakes are seen – one labelled in Fig.2 as "max 1" (with an average yearly number of earthquakes 22.6 and a standard deviation S=8.0, n=9) coinciding with sunspot maximum (year 0), and a second one labelled "max 2" (21.3 earthquakes with S=9.08, n=9) on the descending phase of the sunspot cycle. The means of the number of earthquakes in these two maxima are compared to the overall mean yearly number of earthquakes with M≥7 in the 100 year period studied (20.05 with S=7.23, n=100) and to the average yearly number of earthquakes in the 10 years of sunspot minimum (19.0 with S=7.15, n=10). To evaluate the significance of the difference, we use the modified Student's t-test for small samples:

$$t_1 = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{S_1^2 n_1 + S_2^2 n_2}{n_1 + n_2 - 2} \frac{n_1 + n_2}{n_1 n_2}}} .$$

Even if we apply the harder criterion and compare the average number of earthquakes in the years of sunspot maximum to the average number of earthquakes in all years studied (n=100), this gives t_1=2.64 and p<0.05. The maximum in year (+3) is less significant when compared to the 100-year average (p<0.1) but is well pronounced and is still highly significant (p<0.05) when compared to the average number of earthquakes in solar cycle minimum. There results confirm the hypothesis about the effects on earthquake occurrence of solar activity.

HIGH SPEED SOLAR WIND

In sunspot maximum there is a maximum of solar flares, and on the descending phase of sunspot cycle – a maximum of the solar coronal holes. Both solar flares and solar coronal holes are regions of open magnetic flux and sources of high speed solar wind. To study the relation between seismic activity and high speed solar wind, we use data for the whole period of direct measurements of solar wind parameters – January 1973 – May 2000 (http://nssdc.gsfc.nasa.gov/omniweb/). We define the days of arrival to the Earth of high speed solar wind as days with an abrupt increase in the solar wind velocity (to no less than 500 km/sec by at least 100 km/s in no more than a day) accompanied by a drop in solar wind density and increase in the temperature. Fig.3 is an example of two such cases – on 14 and on 18 December 1976.

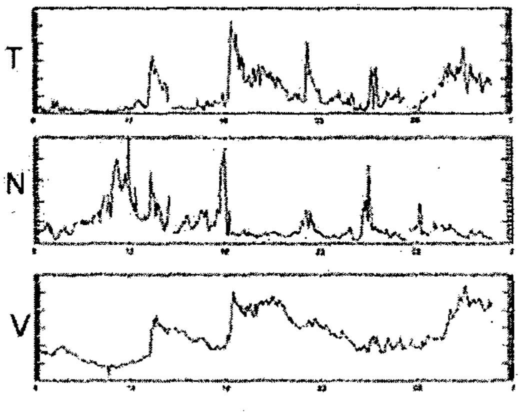

Fig.3: Parameters of near-Earth solar wind for 2 cases of high-speed flow; from top to bottom: plasma temperature, K; ion density, cm^{-3}, flow speed, km/s.

In the interval January 1973 – May 2000 we have identified 307 cases of high-speed solar wind. The seismic activity for the same period is evaluated by the number of earthquakes worldwide with magnitude 5.5 or greater, provided by the National Earthquake Information Center (http://quake.geo.berkeley.edu/cnss/). As an illustration, the average daily number of earthquakes is presented in Fig.4 on the days of arrival of high-speed solar wind (day 0), one day before and after the arrival of the high-speed solar wind (day -1 and +1, respectively), etc. A well pronounced maximum in the number of earthquakes is seen on the day of arrival of high speed solar wind and one day after it.

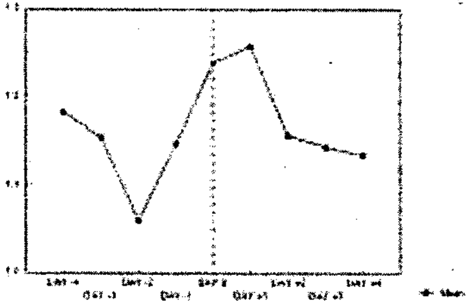

Fig.4: Average daily number of earthquakes on the day of arrival of high speed solar wind (day 0), one day before and after the arrival of high speed solar wind (day –1 and +1, respectively), etc.

The statistical significance of the difference between the occurrence of earthquakes on different days relative to the days of arrival of high speed solar wind is evaluated by the means of the Factor Analysis (Statistica for Windows, StatSoft, Inc.). The main applications of factor analytic techniques are: (1) to reduce the number of variables and (2) to detect a structure in the relationships between variables, that is to classify variables. Therefore, factor analysis is applied as a data reduction or structure detection method. Factor analysis allows us to find the dimensionality of the set of observations and to locate the variables in these dimensions. To do this we use the Principal Components Analysis. This analysis gives us the main axes of elipsoid of the observations. If two variables are grouped in one factor this means that they lie in one dimension, or that they are described by one, unobserved, variable. This variable is supposed to be independent from the variables which represent the other factors. So we can conclude that the variables in different factors are significantly different.

The data-set we use is the daily number of earthquakes with M≥5.5 in the period 1973-2000. We divide this data-set into four variables. The first variable is the number of earthquakes on days of arrival of high-speed solar wind ("SW"). The second variable is the number of earthquakes on the days following the arrival of high-speed solar wind ("SW+1"). As Sytinskii (1997) has found that in the period 1976-1982, more earthquakes tend to occur one day before the day of the maximum of solar wind speed, our third variable is the number of earthquakes on the day before the arrival of high speed solar wind ("SW-1"). And in the forth variable we include all the remaining days ("RANDOM"). Table 1 demonstrates that two factors are extracted accounting for 55.40% of the observations., and the factor loadings, after Varimax raw rotation, are presented in Table 2.

Table 1: Principal components extraction

	Eigenval.	% of total Variance	Cumul. Eigenval.	Cumul. %
1	1.180441	29.51103	1.180441	29.5110
2	1.035755	25.89386	2.216196	55.4049
3	0.980620	24.51550	3.196816	79.9204
4	0.803184	20.07961	4.000000	100.0000

Table 2: Factor loadings for the two factors with eigenvalues greater than 1

	Factor 1	Factor 2
RANDOM	-0.116919	0.458458
SW-	0.049259	0.834281
SW	0.798448	0.230324
SW+	0.712816	-0.308571

"SW" and "SW+" (the day of arrival of high speed solar wind and the following day) are in one factor, and the day before the solar day arrival ("SW-") and all other days ("RANDOM") – in another factor. The clear differentiation between the distribution of the variables in the two factors is demonstrated in Fig.5.

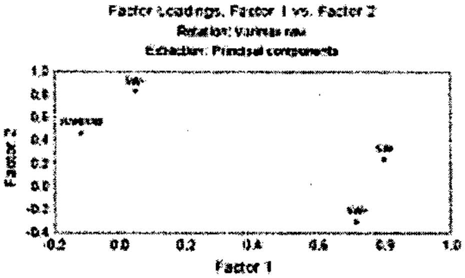

Fig.5: Factor loadings for the variables SW, SW+, SW- and RANDOM (see text).

This means that the day of arrival of high speed solar wind and the day following right after it are "special" concerning the earthquake appearance, they are significantly different from all other days. On the other hand, the day before the arrival of high speed solar wind does not differ in any way from all other days.

It should be noted that with increasing the magnitude of the earthquakes studied (i.e. by reducing the data sample), the statistical significance of the result decreases. Besides, no clear relation was found between different manifestations of solar activity and the energy released in earthquakes. This confirms the assertion of Vidale et al. [14] that all earthquakes start in a similar fashion, but some grow bigger than other. As the energy released is an exponential function of the magnitude, log E = 1.5 M + 11.8 [15], a much higher weight is attributed to the few strongest earthquakes in the total energy than to the numerous smaller arthquakes, so studying the total energy released rather than the total number of earthquakes above a certain magnitude is equivalent to reducing the data set to only the strongest earthquakes.

SUMMARY AND DISCUSSION

Most of the studies devoted to the extraterrestrial factors influencing seismicity deal with tidal forces resulting from gravitational interaction between the Earth, Moon and Sun [1, 4, 16, 17]. Attempts to explain earthquake triggering by astronomical tides have been continuing even after the paper of Vidale et al. [14] showing the lack of earthquake correlation with tides [18, 19].

Sytinskii [3], based on the case study of several strong earthquakes, suggested that the triggering mechanism for earthquake occurrence is not the tidal force but the solar induced change in atmospheric circulation expressed in large-scale reorganization of baric fields, and showed that the energy of these disturbances is at least 3 orders of magnitude greater than the energy of an earthquake. Ludmany and Baranyi [20] argued that the high speed plasma streams would lead to the modification of the global atmospheric circulation. Further, Prikryl et al. [21] studied the response of atmospheric circulation to the high speed solar wind as mediated by auroral electrojet, ionospheric convection and atmospheric gravity waves. Their case study and superposed method analysis of the variations of the high-level clouds which have been shown to be a good representation of mid-latitude cyclones, confirm that gravity waves generated by pulsed ionospheric convection (auroral electrojet) as a result of high speed solar wind MHD wave coupling to the magnetosphere-ionosphere system, are transmitted to the lower atmosphere and alter the atmospheric circulation.

To check the relation between the atmospheric circulation and seismic activity, we have compared the long-term changes of the strength of zonal circulation expressed by the temperature contrast between the equatorial and polar regions, anomalies with respect to the period 1961-1990, and the number of earthquakes with M≥7 in the last century (Fig.6). The strengthening of western winds (i.e. increased transfer of air masses from East to West) is accompanied by an increase in the number of earthquakes. Studying the list of earthquakes, it can be seen that often an earthquake in the course of several hours to one day is followed by one or more earthquakes at almost the same latitude and a substantially higher longitude.

Therefore, the possible mechanism of solar activity influences on seismic activity could include the following elements: high-speed solar wind streams – strengthening of auroral electrojet – generation of atmospheric gravity waves – changes in atmospheric circulation – disrupting the pressure balance on tectonic plates – earthquake triggering.

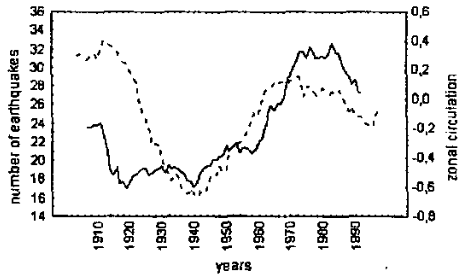

Fig.6: Yearly number of earthquakes with M≥7 in the period 1900-1997 (solid line) and intensity of zonal circulation (broken line).

The main source of high-speed solar wind are solar coronal holes and coronal mass ejections (CMEs). They are both regularly monitored by satellite and ground-based instruments, which makes it possible to forecast periods of enhanced seismic risk. To be geoeffective, the solar wind from a coronal hole or from a CME has to first arrive at the Earth, so the geoeffectiveness of solar wind from a both coronal hole and from a CME mainly depends on their position relative to the Earth. For the CMEs an additional factor is their size and speed. Faster and wider CMEs are more geoeffective. It has been recently found [22] that a useful tool in identifying the population of geoeffective CMEs is the detection of long-wavelength (decameter-hectometer) type II solar radio bursts, as the CMEs associated with them are much faster and wider than average. However, much further study is needed before the enhanced seismic risk related to solar activity can be reliably evaluated.

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