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Similarities in precursory features in seismic shocks and epileptic seizures

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Abstract. – Theoretical studies suggest that the final earthquake (EQ) and neural-seizure dynamics should have many similar features and could be analyzed within similar mathematical frameworks. Herein, by monitoring the temporal evolution of the fractal spectral characteristics in EEG time series and pre-seismic electromagnetic (EM) time series we show that many similar distinctive symptoms (including common alterations in associated scaling parameters) emerge as epileptic seizures (ES) and EQs are approaching. These alterations reveal a gradual reduction of complexity as the catastrophic events approach. The transition from anti-persistent to persistent behaviour may indicate that the onset of a severe crisis is imminent. The observations find a unifying explanation within the school of the "Intermittent Criticality".

Introduction. – Both EQ and ES involve interacting threshold elements. A large event, *i.e.* a seismic shock or an epileptic seizure, is the result of repeated nonlinear interactions among the respective sub-units, namely, opening cracks (that emit EM emission) or firing neurons. A common hallmark of these out-of-equilibrium phenomena is their extraordinary complexity. Complex systems self-organise their internal structure and their dynamics showing novel and surprising macroscopic properties including coherent large-scale collective behaviours. A basic reason for our interest in complexity is the striking similarity in behaviour close to irreversible phase transitions among systems that are otherwise quite different in nature [1–3]. Recent studies have demonstrated that a large variety of complex processes, including EQs [4, 5], forest fires [6], heartbeats [7], human coordination [8], neuronal dynamics [9–11], exhibits statistical similarities, most commonly the power law scaling behaviour of a particular observable. The strong analogies between the dynamics of the "self-organized–criticality" (SOC) model for EQs and that of neurobiology have been realized by numerous of authors, *e.g.* [12–15]. Interestingly, authors have suggested that EQ dynamics and neurodynamics should have many similar features and could be analyzed within similar mathematical frameworks [9–11]. Here, we attempt to verify this hypothesis.

† Deceased.

Method of analysis. – A way to examine transient phenomena is to divide the measurements into time windows and analyze these windows. If this analysis yields different results for some precursory time intervals, then a transient behaviour can be extracted. On the other hand, complexity manifests itself in linkages between space and time, generally producing patterns on many scales and the emergence of fractal structure close to irreversible phase transitions. The emergence of a scale-free behaviour is generally named "criticality" [16]. Based on these concepts, recently, a fractal spectral statistical analysis under the critical-point hypothesis has been applied to EM signals emitted before EQs [17–19]. More precisely, the analysis shows that the pre-seismic EM time series are fractals, that is, have a power spectrum $S(f)$ of the form $f^{-\beta}$. This reveals that the system shows interesting ordering phenomena as the opening cracks simultaneously change their behaviour to a common fractal pattern. Particularly, we focus on the way in which an individual unit's activity is dominated by its neighbours and these new properties appear. In this direction, dividing the series into sub-series, and studying how both the exponent β and the correlation coefficient (that measures the goodness of the data which can be fitted by a power law) evolve as we go from one sub-series to another, we claim that characteristic footprints emerge as the global failure is approached, which could be used as diagnostic tools for Earth's crust failure. Herein, based on this new method, we concentrate on the question whether many similar distinguishing symptoms (including similar alterations in associated scaling parameters) emerge as epileptic seizures and EQs are approaching. For this purpose, we analyse both i) an electroencephalogram (EEG) including Sprague-Dawley rat epileptic seizure (fig. 1a) and ii) a pre-seismic EM signal, which is associated with the Athens EQ ($M = 5.9$, 7 September 1999) [18–20] (fig. 1a′).

We focus on the statistics of the fluctuations in the EEG (or pre-seismic time series) with respect to their amplitude, let us say $A(t_i)$. If the time series $A(t_i)$ is a temporal fractal, that series cannot have a characteristic frequency. The only possibility is then that the power spectrum $S(f)$ has a scaling form:

$$S(f) \sim f^{-\beta}, \tag{1}$$

where f is the frequency of the Fourier transform. In a $\log S(f)$-$\log f$ representation, the power spectrum is a line with spectral slope β. The linear correlation coefficient, r, is a measure of the goodness of fit to the power law (1). The nonstationary character of pre-seismic records requires the application of methods that can appropriately treat such nonstationarities. In practice, the condition of stationarity for nonstationary signals can be satisfied by dividing the signal into blocks of short, pseudo-stationary segments [21]. We divide the signals into successive segments of 1024 samples each, in order to study not only the presence of a power law $S(f) \sim f^{-\beta}$ but, mainly, the temporal evolution of the associated parameters β and r. On the other hand, recent studies show that the wavelet transform can remove effects due to nonstationarities present in time series [22]. The wavelet transform has been found particularly useful for signal analysis because of its ability to localise in both time and frequency (see figs. 1f, f′). The "global wavelet spectrum" is used in order to provide an unbiased and consistent estimation of the true power spectrum of the time series. The continuous wavelet transform based on the Morlet wavelet makes the calculation.

Footprint of clustering in more compact fractal structures with time. – Figure 1b (or fig. 1b′) exhibits the temporal evolution of r. We observe a gradual increase of r values. At the tail of the precursory activity the fit to the power law is excellent: a region with r close to 1 is approached. The fact that the data follow the power law (1) implies that the pre-seizure (or pre-seismic activity) could be ascribed to a multi-time-scale cooperative activity of numerous activated firing neurons (or opening cracks) in which an individual unit's activity is dominated by its neighbours so that all units simultaneously alter their behaviour to a common pattern.

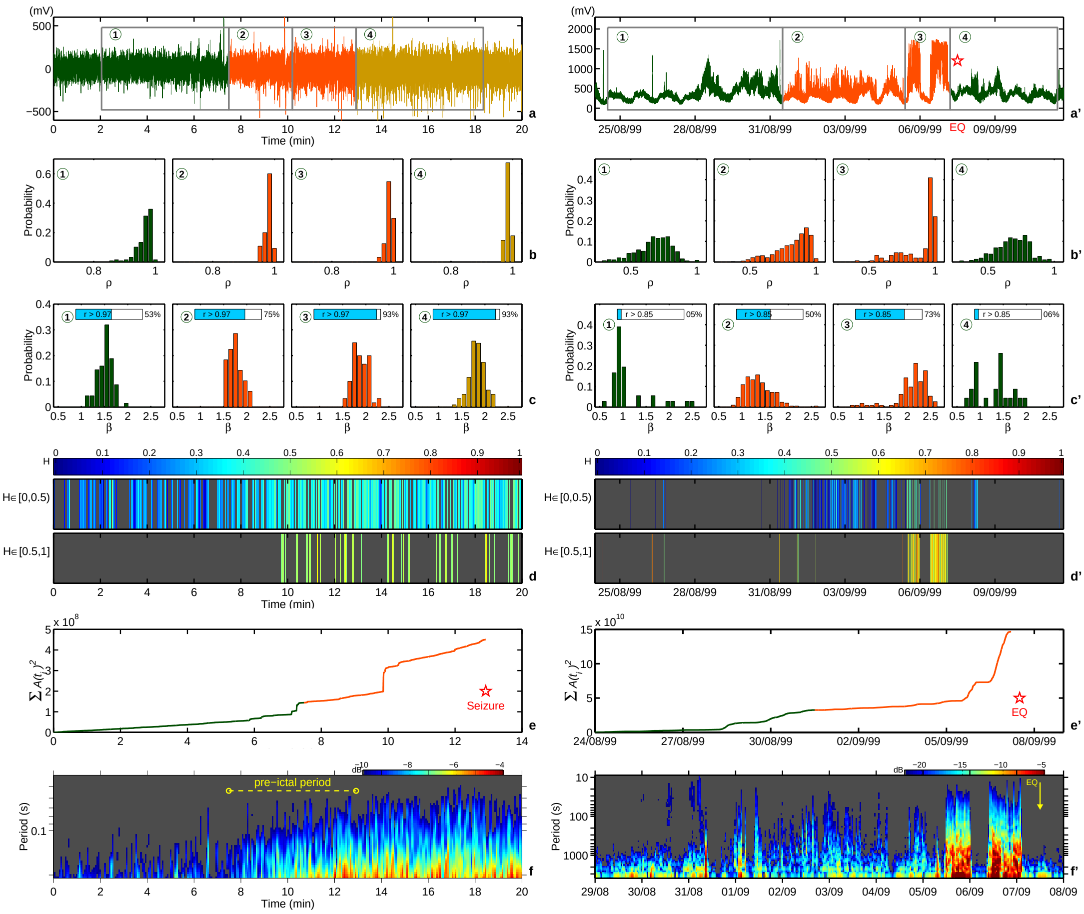

Fig. 1 – (a) Rat EEG time series. The sampling rate was 200 Hz. Bicuculline i.p. injection was used to induce the rat epileptic seizures. The green, red and ochre epochs show the normal state, the pre-epileptic phase, and the stage of the epileptic seizure, respectively. (a′) EM anomalies recorded at magnetic loop antennas during the last days before the Athens EQ. The consecutive green, red and green epochs show the normal state, the pre-seismic phase, and the aftershock state (new normal state), respectively. The sampling rate was 1 Hz. (b)/(b′) Histograms of probability distribution of the correlation coefficient r calculated on 1024 measurements segments for the four consecutive time intervals marked in (a)/(a′). (c)/(c′) Histograms of probability distribution of the exponent β calculated on 1024 measurements segments for the four consecutive time intervals marked in (a)/(a′). The insets show the percentage of segments with $r > 0.97$ and $r > 0.85$, respectively. (d)/(d′) Decomposition of time series into sub-sets, each characterized by a different local Hurst exponent H. The behaviour of the pre-ictal/pre-seismic signal becomes persistent in the tail of the precursory phase. (e)/(e′) depict the cumulative energy release, in arbitrary units, as a function of time. (f)/(f′) The wavelet power spectrum of the time series. The intensity scale on the top shows colours corresponding to the values of the square spectral amplitudes in arbitrary units.

The gradual increase of r-values with time suggests that the fractal character of the underlying processes and structures becomes clearer with time.

Signatures indicating the approach to the global instability. – The β-exponent lies between 1 and 3 during the precursory epochs (red epochs in figs. 1a, a′). This evidence implies that the associated time series follow the fractional Brownian motion (fBm) random field model [23,24], which is a generalization of the normal Brownian motion. The distribution of β-exponents is also shifted to higher values (fig. 1c or c′) during the pre-ictal (or pre-seismic) period. This shift reveals several features of the underlying mechanism.

As the β-exponent increases, the spatial correlation in the time series also increases. This behaviour indicates a gradual increase of the memory, and thus a gradual loss of complexity. In a geometrical sense, the β-exponent specifies the strength of the signal's irregularity as well. Indeed, the fractal dimension d is calculated from the relation $d = (5-\beta)/2$ in the frame of the fBm model [24], which, after considering the shift of the β-exponent to higher values, leads to a decrease of the fractal dimension as the epileptic (or seismic) crisis approaches. The decrease of d with time may reflect that the action of anisotropy inherent to the system leads to the appearance of preferred directions of elementary activities just before the main shock, thus the network of firing neurons (or opening cracks) becomes less ramified. Concerning the fracture, theoretical and experimental evidence strongly support the former hypothesis [18,19]. On the other hand, the characteristic abnormalities associated with ESs include simplification of the dendrite tree [25]. This may justify a significant decrease of d just as the ES is approached. The above findings suggest that the ES (or EQ) onset may represent a gradual transition from a less orderly state to a more orderly state.

The colour-type behaviour of the power spectrum density ($\beta > 0$) means that the spectrum manifests more power at low frequencies than at high frequencies. The increase in the spectrum slope β with time indicates the gradual enhancement of lower frequency fluctuations. *This behaviour may indicate that the activated neurons (or cracks) interact and coalesce to form larger fractal structures, i.e., the events are initiated at the lowest level of the hierarchy, with the smallest elements merging in turn to form larger and larger ones.*

Is the evolution towards global instability unavoidable? – A question that scientists in these fields ought to address is as follows: Is the evolution towards global instability unavoidable after the appearance of distinguishing features in the time series? We focus on this question. The β-exponent is related to the Hurst exponent, H, by the formula

$$\beta = 2H + 1 \qquad \text{with } 0 < H < 1 \tag{2}$$

for the fBm model. The exponent H characterizes the persistence/anti-persistence properties of the signal [18]. The range $0 < H < 0.5$ ($1 < \beta < 2$) during the normal period (figs. 1c, c′ and figs. 1d, d′) indicates an anti-persistency, reflecting that increases in the value of a time series are likely to be followed by decreases and conversely. Physically, this implies a set of fluctuations tending to induce a stability to the system, namely a nonlinear feedback system that "kicks" the firing/opening rate away from extremes. The observed systematic increase of the H-exponent during the pre-epileptic (or pre-seismic) stage indicates that the fluctuations become less anti-correlated with time. This implies that the nonlinear negative feedback mechanism gradually loses its ability to "kick" the system away from extremes. Finally, the time series show persistent properties, $0.5 < H < 1$ ($2 < \beta < 3$), at the tail of the precursory phase (figs. 1d, d′). This means that increases in the value of a time series are likely to be followed by further increases, namely the system has been starting to self-organize by a positive feedback process. The systems seem to acquire to a great degree the property of irreversibility. Thus, the launch of the persistence activity could give a significant hint of a considerable probability for a forthcoming significant epileptic (or seismic) event.

Figures 1e, e′ reveal an accelerating energy release as the main shock approaches. This shows that during this epoch the brain (or pre-focal area) is not only near the "critical point" in the sense of having power law correlations, but also in terms of exhibiting high susceptibility

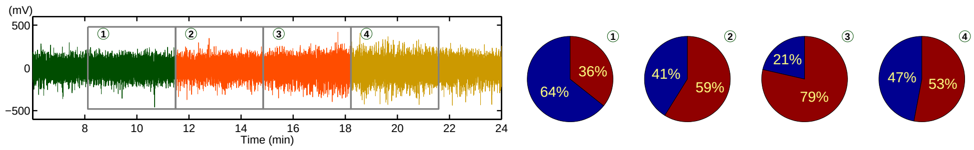

Fig. 2 – The blue and red sectors demonstrate the percentage of segments exhibiting anti-persistent and persistent behaviour respectively. For this representation we use the segments that follow a power law spectrum $S(f) \sim f^{-\beta}$ with an excellent regression ($r \geq 0.98$). This figure verifies that the appearance of fBm persistent behaviour with sufficient duration can be a candidate precursory symptom of an impending epileptic seizure.

to perturbations. This finding further indicates the last stage of the shock preparation, when due to the high level of the clustering of firing neurons (or opening cracks) even a new small cluster, if it connects large clusters, may generate a significant event. The simultaneous appearance of persistent properties at the tail of the pre-ictal (or pre-seismic) activity further supports this consideration. Figures 1f, f′ also reveal that progressively new higher emission rates emerge, while the amplitudes in each emission rate increase too. This further indicates the approach to the global instability.

Common footprints distinguish the dynamics in brain and pre-focal area close to their instability. – To conclude, a unified method to assess the approach to the global instability in biological and geological systems has been applied. We monitor step-by-step the evolution of fractal characteristics of pre-epileptic and pre-seismic time series toward the "critical point" in consecutive time windows. This analysis reveals: *i) Emergence of long-range correlations, i.e., appearance of memory effects. This implies a multi-time-scale cooperative activity of numerous activated sub-units. ii) Increase of the spatial correlation in the time series with time. This indicates a gradual transition from a less orderly state to a more orderly state. iii) Decrease of the fractal dimension in the time series with time. This suggests the appearance of preferred directions in elementary activities. iv) Gradual increase of number of time intervals with "critical characteristic". This signals that the "quality" of the underlying fractal structures increases. v) Gradual predominance of large events as the main shock is approached. This shows that the events are initiated at the lowest level of the hierarchy, with the smallest elements merging in turn to form larger and larger ones. vi) Decrease of the anti-persistent behaviour with time. It implies that the nonlinear negative feedback mechanism gradually loses its ability to "kick" the system away from extremes. This also may predict the launch of the persistent epoch. vii) Appearance of persistent properties in the "tail" of the precursors. This may inform that the system acquires to a great degree the property of irreversibility. viii) Significant divergence of the energy release with time. This reveals that the system exhibits high susceptibility even to small perturbations.* The aforementioned footprints distinguish the dynamics in a complex system close to its final instability. The emergence of persistent properties, the increase of susceptibility of the system, the predominance of large events, the coherent fluctuations of all scales, may indicate that the generation of an extreme event becomes, indeed, unavoidable.

We note that all the aforementioned precursory symptoms are also hidden in the EM activity observed before the 13 May 1995 Kozani-Grevena (Greece) with $M_s = 6.6$ [18,19]. On the other hand, fig. 2 verifies that the appearance of fBm persistent behaviour with sufficient duration can be a candidate precursory symptom of an impending ES.

A possible common scenario. – The experimental results might be indicating the following common scenario for epilepsy and EQ generation. In the first phase of the precursory stage, the brain (or the pre-focal area) is in a self-organized anti-persistent complexity, with a restricted and systematically fluctuating correlation length. During the pre-ictal (or pre-seismic) epoch, the long-range correlations gradually build up through local interactions until they extend throughout the entire system. The small events are the agents by which larger correlations are established. A population of small events will advance the correlation length by an amount depending on its magnitude and system's state, triggering catastrophic events only if the conditions are right. In the strong anti-persistent regime, with a restricted correlation length, a population of small events leads to a decaying activity, always dying out. In the strong persistent state, with long-range correlations, a population of events is just able to continue "indefinitely". This naturally explains why not every event can induce a shock. Consequently, the final shock is the end result of a process in which the pathological spiking neurons (or opening cracks) become persistently correlated over increasing long scale lengths. *The scale over which the interacting units are correlated sets the size of the largest event that can be expected at that time.* A large epileptic (or seismic) event destroys criticality on its associated network, creating a period of normal state after which the process repeats by re-building correlation lengths toward criticality and the next large event. Thus, a large shock may act as a sort of "critical point" dividing the epileptic (or seismic) cycle into a period of growing correlations before the great event and a relatively uncorrelated phase after.

Pure SOC models imply a system perpertually near global failure [4], hence reducing the degree of predictability of individual events. The above-mentioned evolution may be characterized overall as "Intermittent Criticality" [26–29] that predicts a time-dependent variation in the activity as the "critical point" is approached, implying, in contrast to SOC, a degree of predictability. As is mentioned, the analogies between the dynamics of the SOC model for EQs and that of neurobiology have been realized by numerous authors. The present study suggests that it is important to distinguish between SOC and "Intermittent Criticality" not only in the study of the seismic cycle but even in the study of the epileptic cycle.

A proper recognition and understanding of tuning parameters may lead to the development of improved algorithms having higher performance reliability. One of the main features of complex systems is the role that the topological disorder plays in such systems [30, 31]. The range of size scales characterizing heterogeneities of the thresholds may act as a tuning parameter of the underlying final EQ dynamics and neural-seizure dynamics.

Conclusions. – Understanding a complex phenomenon is usually achieved by relating it to less complex ones. Characteristically, Fukuda *et al.* [2] suggest that the understanding of the mechanism underlying the "human-made" Internet could help to understand the natural network that controls the heart. The hypothesis that the fracture in the disordered systems may provide another useful "model-system" to investigate the mechanism responsible for the dynamics of the nervous system that controls involuntarily the epilepsy generation cannot be excluded. In principle, it is difficult to prove associations between events separated in time, such as earthquakes and their EM precursors. The present state of research in this area requires a refined definition of a possible pre-seismic anomaly, and also the development of more objective methods of distinguishing seismogenic emissions from nonseismic EM events. EEG time series provide a window through which the dynamics of shock preparation can be investigated in the absence of noise. Consequently, the analysis of a pure pre-catastrophic time series may help in establishing a collection of criteria to indicate the approach to the shock. The existence of pre-seismic features is still in discussion, and the analogy between activated cracks and firing neurons is not totally accepted. However, the herein observed similarities further support the hypothesis that the detected EM anomaly could have originated during the preparation of the Athens EQ [17–20].

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