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Are There Pre-Seismic Electromagnetic Precursors? A Multidisciplinary Approach

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1. Introduction

In recent years, the wind prevailing in the scientific community does not appear to be favourable for earthquake (EQ) prediction research, in particular for the research of short term prediction [1]. Sometimes the arguments were extended to the extreme claim that any precursory activity is impossible [2]. Considering the difficulties associated with such factors as the highly complex nature, rarity of large EQs and subtleties of possible preseismic signatures, the present negative views are not groundless. It is difficult to prove associations between any two events (possible precursor and EQ) separated in time. To a certain extent, the aforementioned negative views were due to the fact that in the last decades the study of seismic precursors was expected to lead in a relatively short period of time to EQ prediction. However, the EQs are nothing but physical phenomena, and science should have some predictive power on their future behaviour of any physical system. In spite of this scepticism of the scientific community, the research towards the possible prediction of EQs in the future continues. This is attempted now with a more critical view taking into account new ideas and performing detailed theoretical, laboratory, field, and numerical investigations. Significant progress has been made in the research of precursory pattern changes of seismicity (e. g., Wyss and Martirosyan,[3]; Huang et al. [4]; Huang [5]) and the intermediate-term prediction of large EQs world-wide is already in the statistically proven stage (e g., Kossobokov et al. [6]). More recently, even the efforts to shorten the lead time to the "short-term" range are being made (e. g., Keilis-Borok et al.[7]). Some significant new waves have been rising in EQ science!

An EQ is a sudden mechanical failure in the Earth's crust, which has heterogeneous structures. The use of basic principles of fracture mechanics is a challenging field for understanding the EQ preparation process. A key fundamental question in strength considerations of materials is: *when does it fail?* Thus, a vital problem in material science and in geophysics is the identification of precursors of macroscopic defects or shocks. It is reasonable to expect that EQ's preparatory process has various facets which may be observed before the final catastrophe. *The science of EQ prediction should, from the start, be multidisciplinary!*

The present contribution focuses on fracture induced electromagnetic (EM) fields, which allow a real-time monitoring of damage evolution in materials during mechanical loading. Crack propagation is the basic mechanism of material failure. EM emissions in a wide frequency spectrum ranging from kHz to MHz are produced by opening cracks, which can be considered as the so-called precursors of general fracture. The radiated EM precursors are detectable both at a laboratory [8-16] and geological scale [17-37].

Data collection: Since 1994, a station has been installed and operated at a mountainous site of Zante island $(37.76^o N - 20.76^o E)$ in the Ionian Sea (western Greece). The main aim of this station is the detection of kHz-MHz EM precursors. Six loop antennas detect the three components (EW, NS, and vertical) of the variations of the magnetic field at 3 kHz and 10 kHz respectively; three vertical $\lambda/2$ electric dipoles detect the electric field variations at 41, 54 MHz, and 135 MHz respectively. These frequencies were selected in order to minimize the effects of the sources of man-made noise in the mountain area of the Zante Island. Moreover, two *Short Thin Wire Antennas*, oriented at EW and NS directions of length of 100 m, respectively, have been also installed. The aim of the last installation is the detection of ultra-low-frequency $(< \ 1Hz)$ EM precursors rooted in a preseismic lithosphere-atmosphere-ionosphere-coupling. All the EM time series were sampled at 1 Hz. Such an experimental setup helps to specify not only whether or not a single EM anomaly is preseismic in itself, but also whether a sequence of EM disturbances at different frequencies, which are emerged one after the other in a short time period, could be characterized as preseismic one. Clear such EM precursors have been detected over periods ranging from approximately a week to a few hours prior to catastrophic EQs that occurred in Greece or Italy (e.g., [21,22,25-37]). We emphasize that the detected precursors were associated with EQs: (i) occurred in land (or near coast-line); (ii) were strong, i.e., with magnitude 6 or larger; and (iii) were shallow. Recent results indicate that the recorded EM precursors contain information characteristic of an ensuing seismic event (e.g., [21,22,25-37]).

An important feature, observed both at laboratory and geophysical scale, is that it the MHz radiation precedes the kHz one [25,27-29,35,36]. Studies on the small (laboratory) scale reveal that the kHz EM emission is launched in the tail of pre-fracture EM emission from 97% up to 100% of the corresponding failure strength [25 and references therein]. At the geophysical scale the kHz EM precursors are emerged from a few days up to a few hours before the EQ occurrence. The association of MHz, kHz EM precursors with the last stages of EQ generation is justified.

The origin of EM emissions. The origin of EM emissions from fracture is not completely clear, and different attempts have been made in order to explain it [8, 32 and references therein]. A relevant attempt is related to the "capacitor model" [32]. In many materials, emission of photons, electrons, ions and neutral particles are observed during the formation of new surface. The rupture of inter-atomic (ionic) bonds also leads to intense charge separation, which is the origin of the electric charge between the micro-crack faces. On the faces of a newly created micro-crack the electric charges constitute an electric dipole or a more complicated system. The motion of a crack has been shown to be governed by a dynamical instability causing oscillations in its velocity and structure of the fractured surfaces. It is worth mentioning that laboratory experiments show that more intense fracto-emissions are observed during the unstable crack growth. Due to the crack strong wall vibration, in the stage of the micro-branching instability, it behaves as an efficient EM emitter [32].

Are there credible EM earthquake precursors? This is also a question debated in the science community. Despite fairly abundant circumstantial evidence, EM precursors have not been adequately accepted as real physical quantities [1]. There may be legitimate reasons for the critical views. The degree to which we can predict a phenomenon is often measured by how well we understand it. However, many questions about fracture processes remain standing. Especially, many aspects of EQ generation still escape our full understanding. Kossobokov [38] states that *"No scientific prediction is possible without exact definition of the anticipated phenomenon and the rules, which define clearly in advance of it whether the prediction is confirmed or not"*. We bear in mind that whether EM precursors to EQ exist is an important question not only for EQ prediction but also for understanding the physical processes of EQ generation. The comprehensive understanding of EM precursors in terms of physics is a path to achieve more sufficient knowledge of the last stages of the EQ preparation process and thus more sufficient short-term EQ prediction. A *seismic* shift in thinking towards basic science will lead to a renaissance of strict definitions and systematic experiments in the field of EQ prediction.

2. A proposed strategy for the study of MHz and kHz EM precursors

This chapter concentrates, in an appropriately critical spirit, on asking 3 crucial questions:

(i) How can we recognize an EM observation as a pre-seismic one?
(ii) How can we link an individual EM precursor with a distinctive stage of the earthquake preparation?
(iii) How can we identify precursory symptoms in EM observations which signify that the occurrence of the prepared EQ is unavoidable?

We shall attempt to approach the above mentioned questions in the simplest and most intuitive way, rather than emphasize mathematical rigor. In any case, the readers should be aware that this attempt refers to a *snap-shot* of a rapidly moving field.

One wonders whether necessary and sufficient criteria, have yet been established, that permit the characterization of an EM anomaly as a real EM precursor. One of the main purposes of this contribution is to suggest a procedure for the designation of observed kHz / MHz EM anomalies as seismogenic ones.

As it is said, an important feature, observed both at laboratory and geophysical scale, is that the MHz radiation precedes the kHz one [25, 28, 29 and references therein]. The remarkable asynchronous appearance of these precursors indicates that they refer to different stages of EQ preparation process. Moreover, it implies a different mechanism for their origin. Scientists ought to attempt to link the available various EM observations, which appear one after the other, to the consecutive processes occurring in Earth's crust.

The following *two stage model of EQ generation by means of pre-fracture EM activities* has been proposed: The pre-seismic MHz EM emission is thought to be due to the fracture of the highly heterogeneous system that surrounds the family of large high-strength entities distributed along the fault sustaining the system, while the kHz EM radiation is due to the fracture of the aforementioned large high-strength entities themselves [e.g.,28-30,32-36,39]. In the frame of the above mentioned two stage model, the identification of MHz and kHz EM precursors requires different methods of analysis.

2.1 Focus on MHz EM precursors

Fracture process in heterogeneous materials *can be attributed to phase transition of second order* [40,41,42]. This crucial property should be hidden in a seismogenic MHz EM activity [28,29,34,39]. The temporal evolution of a MHz EM precursor, which behaves as a second order phase transition, reveals transition from the phase from non-directional almost symmetrical cracking distribution to a directional localized cracking zone that includes the backbone of strong asperities (*symmetry breaking*) [29]. The identification of the time interval where the *symmetry breaking* is completed indicates that the fracture of heterogeneous system in the focal area has been obstructed along the backbone of asperities that sustain the system: *The siege of strong asperities begins [29]. However, the prepared EQ will occur if and when the local stress exceeds fracture stresses of asperities*. Consequently, the appearance of a really seismogenic MHz EM anomaly does not mean that the EQ is unavoidable (see Section 3).

2.2 Focus on kHz EM precursors

It has been suggested that the lounge of the kHz EM activity shows the fracture of asperities sustaining the fault [28,29,32-36]. This fracture is characterised by a non-equilibrium instability, thus acquiring a self-regulating character and to a great degree the property of irreversibility. The latter, is one of the most important components of prediction reliability. An associated fracto-EM precursor should show persistent behaviour and evolve as a phase transition far from equilibrium without any footprint of an equilibrium phase transition. Two questions effortlessly arise:

(i) *How can we recognize an observed kHz EM anomaly as a seismogenic one?*
(ii) *How does it indicate that the impending EQ is unavoidable?*

What follows concentrates on the above aforementioned two questions.

2.2.1 Statistical analysis of the kHz candidate EM precursors

An anomaly in a recorded time series is defined as a deviation from normal (background) behaviour. Concerning the development of a quantitative identification of kHz EM precursors, tools of information theory and concepts of entropy rooted in extensive and nonextensive statistical mechanics can be used in order to identify changes in the statistical pattern. A significant change is expected in the time series of the EM precursor, namely the appearance of entropy “drops” or information “peaks”, revealing that the underlying fracto-EM mechanism is characterized by a high order of organization. The catastrophic fracture of asperities should be also characterized by a positive feedback mechanism. This means that the kHz EM precursors should show persistent behaviour (see Section 5.2.1).

2.2.2 Analysis in terms of universal structural patterns of fracture and faulting

From the early work of Mandelbrot [43], the aspect of self-affine nature of faulting and fracture is widely documented from field observations, laboratory experiments, and studies of failure precursors on the small (laboratory) and large (EQ) scale. The activation of a single fault should behave as a “reduced image” of the regional seismicity, and a “magnified image” of the laboratory seismicity. Moreover, fracture surfaces were found to be self-affine following the fractional Brownian motion (fBm) model over a wide range of length scales, while, the spatial roughness of fracture surfaces has been interpreted as a universal indicator of surface fracture, weakly dependent on the nature of the material and on the failure mode [27-30,35,36 and references therein]. Such universal structural patterns of fracture and faulting process should be included into an EM precursor which is rooted in the activation of a single fault. Therefore, an important pursuit is to examine whether universal patterns of fracture and faulting are hidden in the observed candidate kHz EM precursors (see Section 5).

2.2.3 Analysis by means of fractal electrodynamics

EQ's occur on a fractal structure of faults. An active crack or rupture, can be simulated by a "radiating element" [32]. The idea is that a fractal geo-antenna can be formed as an array of line elements having a fractal distribution on the focal area as the critical point is approached. The recently introduced Fractal Electrodynamics [44, 45], which combines fractal geometry with Maxwell's equations, offers a new possibility for the exploration of the kHz EM anomalies (see Section 7).

2.2.4 The science of EQ prediction should, from the start, be multi-disciplinary

EQ's preparatory process has various facets which may be observed before the final catastrophe. The science of EQ prediction should, from the start, be multidisciplinary. A candidate preseismic kHz-MHz EM activity should be consistent with other EM precursors (SES [46], EM precursors rooted in lithosphere-atmosphere-ionosphere coupling [47]) and precursors which are imposed by data from other disciplines such as: Seismology, Infrared Remote Sensing [48], Synthetic Aperture Radars Interferometry [49]. The sequential appearance of different precursors in a relative short time interval supports the seismogenic origin of each of them, increases the probability that a significant EQ is coming, and leads to higher estimation accuracy of its parameters, namely, magnitude, time and position (see Section 8). The EQ generation is a cooperative phenomenon and its prediction needs the cooperation of scientists!

2.2.5 Analysis in terms of complex systems

The field of study of complex systems holds that their dynamics is founded on universal principles that may be used to describe various crises [50,51]. The presence of common pathological symptoms in candidate kHz EM precursors on one hand and other catastrophic events (e.g., epileptic seizures, magnetic storms and solar flares), which clearly distinguish the catastrophic event from the corresponding normal state, strongly supports the seismogenic origin of the detected kHz EM anomalies (see Section 8.4).

The burden of this section was to describe a plausible scenario for the study of kHz EM precursors, without obvious internal inconsistencies and without violating the laws of physics. In the next sections we present results gained from previous studies applying the framework of analysis described above.

3. The precursory MHz EM activity as a second order phase transition phenomenon

In natural rocks at large length scales there are long-range anti-correlations, in the sense that a high value of a rock property, e.g. threshold for breaking, is followed by a low value and vice versa. Failure nucleation begins to occur at a region where the resistance to rupture growth has the minimum value. An EM event is emitted during this fracture. The fracture process continues in the same weak region until a much stronger region is encountered in its neighborhood. When this happens, fracture stops, and thus the emitted EM emission ceases. The stresses are redistributed, while the applied stress in the focal area increases. A new population of cracks nucleates in the weaker of the unbroken regions, and thus a new EM event appears, and so on. Therefore, the associated precursory MHz EM activity should be characterized by antipersistent behaviour and the interplay between the heterogeneities and the stress field should be responsible for this behaviour. This crucial feature is included in the recorded MHz EM precursors.

Physically, the presence of anti-persistency implies a set of EM fluctuations tending to induce stability to the system, essentially the existence of a non-linear negative feedback mechanism that “kicks" the opening rate of cracks away from extremes. The existence of such a mechanism leads to the next step: it has been proposed that the fracture of heterogeneous materials can be described in analogy with a continuous second order phase transition in equilibrium [40,41]. Thus, a seismogenic MHz EM activity, which is rooted in the fracture of the highly heterogeneous system that surrounds the family of large high-strength asperities, should be described as critical phenomenon. This critical signature is also hidden in the recorded MHz EM precursors [28-29,34-36,39]. The relevant analysis is based on the recently introduced Method of Critical Fluctuations (MCF) [52,53].

3.1 The method of critical fluctuations

The MCF, which constitutes a statistical method of analysis for the critical fluctuations in systems that undergo a continuous phase transition at equilibrium, has been recently introduced [52,53]. The authors have shown that the fluctuations of the order parameter ϕ, obey a dynamical law of intermittency which can be described in terms of a 1-d nonlinear map. The invariant density $\rho(\phi)$ for such a map is characterized by a plateau which decays in a super-exponential way (see Fig. 1 in [52]). For small values of ϕ, this critical map can be approximated as

$$\phi_{n+1} = \phi_n + u\phi_n^z + \epsilon_n \tag{1}$$

The shift parameter ϵ_n introduces a non-universal stochastic noise: each physical system has its characteristic “noise”, which is expressed through the shift parameter ϵ_n. For thermal systems the exponent z is introduced, which is related to the isothermal critical exponent δ by $z = \delta + 1$.

The plateau region of the invariant density $\rho(\phi)$ corresponds to the laminar region of the critical map where fully correlated dynamics take place [29 and references therein]. The laminar region ends when the second term in Eq. (1) becomes relevant. However, due to the fact that the dynamical law (1) changes continuously with ϕ, the end of the laminar region cannot be easily defined based on a strictly quantitative criterion. Thus, the end of the laminar region should be generally treated as a variable parameter.

Based on the foregoing description of the critical fluctuations, the MCF develops an algorithm permitting the extraction of the critical fluctuations, if any, in a recorded time series. The important observation in this approach is the fact that the distribution $P(l)$ of the laminar lengths l of the intermittent map (1) in the limit $\epsilon_n \to 0$ is given by the power law [53]

$$P(l) \sim l^{-p_l} \tag{2}$$

where the exponent p_l is connected with the exponent z via $p_l = \frac{z}{z-1}$. Therefore the exponent p_l is related to the isothermal exponent δ by

$$p_l = 1 + \frac{1}{\delta} \tag{3}$$

with $\delta > 0$.

Inversely, the existence of a power law such as relation (2), accompanied by a plateau form of the corresponding density $\rho(\phi)$, is a signature of underlying correlated dynamics similar to critical behavior [52,53].

We emphasize that it is possible in the framework of universality, which is characteristic of critical phenomena, to give meaning to the exponent p_l beyond the thermal phase transitions [53].

The MCF is directly applied to time series or to segments of time series which appear to have a cumulative stationary behaviour. The main aim of the MCF is to estimate the exponent p_l. The distribution of the laminar lengths, l, of fluctuations included in a stationary window is fitted by the relation:

$$P(l) \sim l^{-p_2} e^{-p_3 l} \tag{4}$$

If p_3 is zero, then p_2 is equal to p_l. Practically, as p_3 approaches zero, then p_2 approaches p_l and the laminar lengths tend to follow a power-law type distribution. So, we expect a good fit to Eq. (4) with $p_2 > 1$ and $p_3 \approx 0$ if the system is in a critical state [50]. In terms of physics this behaviour means that the system is characterized by a "strong criticality", e.g., the laminar lengths tend to follow a power-law type distribution: during this critical time window the opening cracks (EM-emitters) are well correlated even at large distances [50].

We stress that when the exponent p_2 is smaller than one, then, independently of the p_3-value, the system is not in a critical state. Generally, the exponents p_2, p_3 have a competitive character, namely, when the exponent p_2 decreases the associated exponent p_3 increases (they are mirror images of each other). To be more precise, as the exponent p_2 ($p_2 < 1$) is close to 1 and simultaneously the exponent p_3 is close to zero, then the system is in a sub-critical state. As the system moves away from the critical state, then the exponent p_2 further decreases while simultaneously p_3 increases, reinforcing in this way the exponential character of the laminar length distribution: the EM fluctuations show short range correlations. In this way, we can identify the deviation from the critical state [50,52,53].

3.2 Application of the MCF method

On 13 May 1995 (8:47:13 UT) the Kozani-Grevena EQ (40.17°N, 21.68°E) occurred with magnitude $M = 6.6$. Fig. 1 shows the associated 41 MHz EM time series [25,28,29]. The data are sampled at 1 Hz.

A critical window (CW) has been identified including 23000 points (Fig. 1a) starting almost 11 hours before the time of the EQ occurrence. The corresponding distribution of the amplitude $P(\psi)$ of the emerged EM pulses in this CW is shown in Fig. (1c). It is characteristic the appearance of the plateau region in the top of distribution, as it is provided for the invariant density of critical map [52]. The laminar lengths l follow a power-law distribution $P(l)$. This feature indicated that the underlying fracture mechanism is characterized by fluctuations which are extended at many different time scales as well as the presence of long-range correlations. We note that the amplitude ψ_i of the preseismic MHz EM time series behaves as a kind of the order parameter [29]. Therefore, in the CW the fluctuations of the amplitude ψ_i of the recorded EM time series have an intermittent behaviour similar to the dynamics of the order parameter's fluctuations of a thermal critical system at the critical point. It is for this reason that this window is characterized as *critical window*.

A thermal phase transition is associated with a *symmetry breaking*. To gain inside into the temporal evolution of fracture, as the EQ is approaching, we elucidate the evolution of the *symmetry breaking* with time by making an analogy to a thermal continuous phase transition [29]. In the latter, the distribution of the fluctuations of the order parameter with temperature reveals the progress of the *symmetry breaking*. This distribution is almost a δ function at high temperature and evolves to a Gaussian with mean value zero as the system approaches the critical point. At the critical point, a characteristic plateau in the distribution appears, and the *symmetry breaking* emerges as the temperature further decreases. Below the critical temperature the distribution becomes again Gaussian, but its mean shifts to higher values associated with the *symmetry breaking*. As temperature approaches to $0^{\circ} K$, where the *symmetry breaking* is completed, it becomes a δ function again. We look for these characteristic features in the preseismic time series, with stress taking on the role of temperature [29].

Let us look specifically at the precursor under study. Figs. (1b-1e) exhibit the distribution of the recorded EM fluctuations in successive time windows. As is was mentioned, the distribution of the amplitude (order parameter) in Fig. (1c) indicates the appearance of the CW. Fig. (1b) shows the distribution before the emergence of CW: the laminar lengths, l, do not follow a power-law-type distribution $P(l)$. The system is characterized by a spare almost symmetrical distributed in space random cracking with short-range correlations.

During the CW the sort-range correlation evolve to long-range; the corresponding distribution (Fig. 1c) might be considered as a precursor of the impending *symmetry breaking*. The *symmetry breaking* is readily observable in the subsequent time interval (Fig. 1d). The cracking is restricted in the narrow zone that includes the backbone of strong asperities distributed along the activated fault sustaining the system [29]. The distribution of the order parameter in Fig. (1e) is very similar to that of Fig. (1b). However, here there is an upward shift of the values to the range of the second lobe of the distribution in Fig. (1d). The laminar lengths does not follow a power-law distribution $P(l)$. The appearance of this window indicates that the *symmetry breaking* in the underlying fracto-EM process has been almost completed [29]. *The siege of strong asperities begins* [29]. However, the prepared EQ will occur if and when the local stress exceeds fracture stresses of asperities. The lounge of the kHz EM activity shows the fracture of asperities sustaining the fault [28,29,32-36]. Indeed, a very strong kHz EM burst appeared a few hours later and after that face the EQ occurred [29].

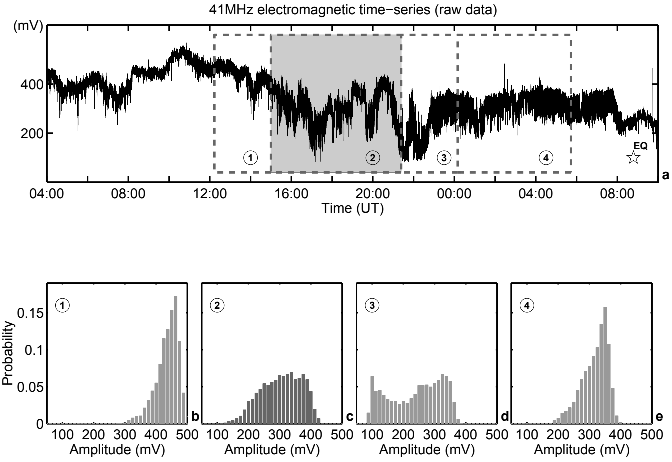

Fig. 1. The upper part shows the 41 MHz EM time series associated with the Kozani-Grevena EQ. The lower part elucidates the evolution of symmetry breaking with time.

4. How can we recognize a kHz EM anomaly as a pre-seismic one?

An anomaly in a recorded time series is defined as a deviation from normal (background) behaviour. In order to develop a quantitative identification of EM precursors, tools of information theory and concepts of entropy are used in order to identify statistical patterns. Entropy and information are seen to be complementary quantities, in a sense: entropy “drops” have as a counterpart information “peaks” in a more ordered state. The seismicity is a critical phenomenon [41,54] , thus, it is expected that a significant change in the statistical pattern, namely the appearance of entropy “drops” or information “peaks”, represents a deviation from normal behaviour, revealing the presence of an EM anomaly.

It is important to note that one cannot find an optimum organization or complexity measure. Thus, a combination of some such quantities which refer to different aspects, such as structural or dynamical properties, is the most promising way.

Several well-known techniques have been applied to extract EM precursors hidden in kHz EM time series:

(i) *T*-entropy: It is based on the intellectual economy one makes when rewriting a string according to some rule [55].

(ii) Approximate entropy: It provides a measure of the degree of irregularity or randomness within a series of data. More precisely, this examines the presence of similar epochs in time series; more similar and more frequent epochs lead to lower values of approximate entropy [35 and references therein].

(iii) Fisher Information: It represents the amount of information that can be extracted from a set of measurements [56].

(iv) Correlation Dimension: It measures the probability that two points chosen at random will be within a certain distance of each other, and examines how this probability changes as the distance is increased [57].

(v) R/S analysis: It provides a direct estimation of the Hurst Exponent which is a precious indicator of the state of randomness of a time-series [58].

(vi) Detrended Fluctuation Analysis: It has been proven useful in revealing the extent of long-range correlations in time series [59, 60].

(vii) Shannon n-block entropies (conditional entropy, entropy of the source, Kolmogorov-Sinai entropy): They measure the uncertainty of predicting a state in the future, provided a history of the present state and the previous states [61-65].

(viii) Tsallis entopy: One of the crucial properties of the Boltzmann-Gibbs entropy in the context of classical thermodynamics is extensivity, namely proportionality with the number of elements of the system. The Boltzmann-Gibbs (B-G) entropy satisfies this prescription if the subsystems are statistically (quasi-) independent, or typically if the correlations within the system are essentially local. In such cases the energy of the system is typically extensive and the entropy is additive. In general, however, the situation is not of this type and correlations may be far from negligible at all scales. Inspired by multifractals concepts, Tsallis [66, 67] has proposed a generalization of the B-G statistical mechanics. He introduced an entropic index q which leads to a nonextensive statistics. The value of q is a measure of the nonextensivity of the system: $q = 1$ corresponds to the standard, extensive, B-G statistics. The order of organization of the nonextensive systems is measured by the Tsallis entropy.

The application of all the above mentioned multidisciplinary statistical procedure [30,33,35,36,68-71] sensitively recognizes and discriminates the candidate EM precursors from the EM background: they are characterized by significantly higher organization in respect to that of the EM noise in the region of the station. However, we should keep in mind that though a sledge hammer may be wonderful for breaking rock, it is a poor choice for driving a tack into a picture frame!

5. Focus on the possible seismogenic origin of the detected kHz EM anomaly by means of universally holding scaling laws of fracture

As it is mentioned in the previous Section, all the applied techniques reveal that the kHz EM anomaly is characterized by a significant lower complexity (or higher organization). Importantly this anomaly is also characterized by strong persistency [28,29]. The simultaneous appearance of both these two crucial characteristics implies that the underlying fracture process is governed by a positive feedback mechanism which is consistent with an anomaly being a precursor of an ensuing catastrophic event.

However, we suggest that any multidisciplinary statistical analysis by itself is not sufficient to characterize an emerged kHz EM anomaly as a pre-earthquake one. Much remains to be done to tackle systematically real pre-seismic EM precursors.

As it is mentioned in Section 2.2, the Earth's crust is extremely complex. However, despite its complexity, there are several universally holding scaling relations. Such universal structural patterns of fracture and faulting process should be included into an EM precursor which is rooted in the activation of a single fault. Therefore an important pursuit is to investigate whether universal features of fractures and faulting are included in the recorded kHz EM precursors.

5.1 The activation of a single fault as a self-affine image of the regional and laboratory seismicity

The self-affine nature of faulting and fracture predicts that the activation of a single fault is a reduced / magnified image of the regional/ laboratory seismicity, correspondingly (see Section 2.2.2). A fracto-EM precursor rooted in the activation of a single fault should be consistent with the above mentioned requirement.

5.1.1 The activation of a single fault as a "reduced self-affine image" of the regional seismicity

A model for EQ dynamics coming from a non-extensive Tsallis formulation [66,67] has been recently introduced by Sotolongo-Costa and Posadas, [72]. Silva et al. [73] have revised this model. The authors assume that the mechanism of relative displacement of fault plates is the main cause of EQs. The space between fault planes is filled with the residues of the breakage of the tectonic plates, from where the faults have originated. The motion of the fault planes can be hindered not only by the overlapping of two irregularities of the profiles, but also by the eventual relative position of several fragments. Thus, the mechanism of triggering EQs is established through the combination of the irregularities of the fault planes on one hand and the fragments between them on the other hand. This nonextensive approach leads to a Gutenberg-Ricter (G-R) type law for the magnitude distribution of EQs:

$$\log(N_{>m}) = \log N + \left(\frac{2-q}{1-q}\right) \log\left[1 - \left(\frac{1-q}{2-q}\right)\left(\frac{10^{2m}}{\alpha^{2/3}}\right)\right] \tag{5}$$

where N is the total number of EQs, $N(> m)$ the number of EQs with magnitude larger than m. Parameter α is the constant of proportionality between the EQ energy, ε and the size of fragment. The entropic index q describes the deviation of Tsallis entropy from the traditional Shannon one. The proposed non-extensive G-R type law (5) provides an excellent fit to seismicities generated in various large geographic areas, each of them covering many geological faults. We emphasize that the q-values are restricted in the narrow region from 1.6 to 1.8 [72-74]. Notice, the magnitude-frequency relationship for EQs do not say anything about a specific activated fault (EQ). A kHz EM precursors refers to the activation of a specific fault. Thus, we examine whether the kHz EM activity also follows the Eq. (5).

Definition of the "Electromagnetic earthquake": We regard as amplitude A of a candidate "fracto-EM fluctuation" the difference $A_{fem}(t_i) = A(t_i) - A_{noise}$, where A_{noise} is the background (noise) level of the EM time series. We consider that a sequence of k successively emerged "fracto-EM fluctuations" $A_{fem}(t_i), i = 1, \ldots, k$ represents the EM energy released, ε, during the damage of a fragment. We shall refer to this as an "electromagnetic earthquake" (EM-EQ). Since the squared amplitude of the fracto-EM emissions is proportional to their energy, the magnitude m of the candidate "EM-EQ" is given by the relation

$$m = \log \varepsilon \sim \log\left(\sum \left[A_{fem}(t_i)\right]^2\right) \tag{6}$$

The Eq. (5) provides an excellent fit to the pre-seismic kHz EM experimental data incorporating the characteristics of nonextensivity statistics into the distribution of the detected precursory “EM-EQs” [32,33,36,75]. Herein, $N(> m)$ is the number of “EM-EQs” with magnitude larger than m, $P(> m) = N(> m)/N$ is the relative cumulative number of “EM-EQs” with magnitude larger than m, and α is the constant of proportionality between the EM energy released and the size of fragment. The best-fit q parameter for this analysis has been estimated to be approximately 1.8 [32,33,36,75].

It is very interesting to observe the similarity in the q-values associated with the non-extensive Eq. (5) for: (i) seismicities generated in various large geographic areas, and (ii) the precursory sequence of “EM-EQs”. This finding indicates that the statistics of regional seismicity could be merely a macroscopic reflection of the physical processes in the EQ source, as it has been suggested by Huang and Turcotte [76].

5.1.2 The activation of a single fault as a “magnified self-affine image” of the laboratory seismicity

Rabinovitch et al. [77] have studied the fractal nature of EM radiation induced in rock fracture. The analysis of the prefracture EM time series reveals that the cumulative distribution of the amplitudes also follows a power law with exponent $b = 0.62$. A similar statistical analysis of kHz EM precursor associated with the Athens EQ reveals that this also follows the power law $N(> A) \sim A^{-b}$, where $b = 0.62$ [78].

In seismology, a well known scaling relation between magnitude and the number of EQs is given by the Gutenberg-Richter (G-R) relationship:

$$\log N(> M) = \alpha - bm \tag{7}$$

where, $N(> M)$ is the cumulative number of EQs with a magnitude greater than M occurring in a specified area and time and b and α are constants.

Importantly, the Gutemberg-Ricther law also holds for acoustic emission events in rock samples [79]. Laboratory experiments by means of acoustic emissions also show a significant decrease in the level of the observed b-values immediately before the global fracture [79]. Characteristically, Ponomarev et al. [80] have reported a significant fall of the observed b-values from ~ 1 to ~ 0.6 just before the global rupture. Recently, Lei and Satoh [81], based on acoustic emission events recorded during the catastrophic fracture of typical rock samples under differential compression, suggest that the pre-failure damage evolution is characterized by a dramatic decrease in b-value from ~ 1.5 to ~ 0.5 for hard rocks. There are increasing reports on premonitory decrease of b-value before EQs: foreshock sequences and main shocks are characterized by a much smaller exponent compared to aftershocks [82]. We emphasise the sequence of kHz EM-EQs associated with the Athens EQ also follows the Gutenberg-Richter law with $b = 0.51$ [32].

The above mentioned results verify that the activation of a single fault behaves as a magnified self-affine image of the laboratory seismicity and reduced image of the regional seismicity.

5.2 Signatures of fractional-Brownian-motion nature of faulting and fracture in the candidate kHz EM precursor

Fracture surfaces were found to be self-affine following the fractional Brownian motion model (see Section 2.2.2) [27-30,35,36 and references therein]. This universal feature should be included into an kHz EM precursor. If a time series is a temporal fractal then a power-law of the form $S(f) \propto f^{-\beta}$ is obeyed, with $S(f)$ the power spectral density and f the frequency. The spectral scaling exponent β is a measure of the strength of time correlations. The goodness of the power-law fit to a time series is represented by a linear correlation coefficient, r. Based on a fractal spectral analysis, which has been performed by means of wavelets, it has been shown [27-30,35,36] that the emergent strong kHz EM precursors follow the law $S(f) \propto f^{-\beta}$; the coefficient r takes values very close to 1, i.e., the fit to the power-law is excellent. This result shows the fractal character of the underlying processes and structures.

The β exponent takes high values, i.e., between 2 and 3. This finding reveals that:

(i) The EM bursts have long-range temporal correlations, i.e. strong memory: the current value of the precursory signal is correlated not only with its most recent values but also with its long-term history in a scale-invariant, fractal manner.

(ii) The spectrum manifests more power at lower frequencies than at high frequencies. The enhancement of lower frequency power physically reveals a predominance of larger fracture events. This footprint is also in harmony with the final step of EQ preparation.

(iii) Two classes of signal have been widely used to model stochastic fractal time series, fractional Gaussian (fGn) and fractional Brownian motion (fBm) model [83]. The fGn-model the scaling exponent β lies between -1 and 1, while the fBm regime is indicated by β values from 1 to 3. The estimated β exponent successfully distinguishes the candidate precursory activities from the EM noise [27-31,35,36]. Indeed, the β values in the EM background are between 1 and 2 indicating that the time profile of the EM series during the quiet periods is qualitatively analogous to the fGn class. On the contrary, the β values in the candidate EM precursors are between 2 and 3, suggesting that they belong to the fBm class.

In summary, the fBm nature of faulting and fracture is included in the kHz EM precursors.

5.2.1 Persistent behaviour of the detected kHz EM precursors

The β exponent is related to the Hurst exponent H by the formula [83, 84]:

$$\beta = 2H + 1 \tag{8}$$

with $0 < H < 1$ ($1 < \beta < 3$) for the fractional Brownian motion (fBm) model. The exponent H characterizes the persistent / anti-persistent properties of the signal. The range $0.5 < H < 1$ ($2 < \beta < 3$) indicates persistency, which means that if the amplitude of the fluctuations increases in a time interval it is likely to continue increasing in the next interval. We recall that we found β values in the candidate EM precursors to lie between 2 and 3. The H values are close to 0.7 in the strong segments of the kHz EM activity [27-31,35,36]. This means that the EM fluctuations are positively correlated: the underlying dynamics is governed by a positive feedback mechanism. External influences would then tend to lead the system out of equilibrium. The system acquires a self-regulating character and, to a great extent, the property of irreversibility, one of the important components of prediction reliability. Sammis and Sornette [85] have recently presented the most important positive feedback mechanisms.

It is expected that a positive feedback mechanism results in a finite-time singularity. The kHz EM time series under study shows such a behaviour by means of the "cumulative Benioff type EM energy release". A clear finite-time singularity of this type has been reported in [27,28,78].

Remark: The estimated Hurst exponents through the R/S analysis are in harmony with those estimated from the fractal spectral analysis via the hypothesis that the time series follows the fBm-model [35,36]. This fact supports the hypothesis that the profile of kHz EM precursors follow the persistent fBm-model. The last hypothesis has been further verified by a DFA-analysis [35,36].

5.3 Footprints of universal roughness value of fracture surfaces in the kHz EM activity

The Hurst exponent, H, specifies the strength of the irregularity ("roughness") of the fBm surface topography: the fractal dimension is calculated from the relation $D = (2 - H)$ [83].

The Hurst exponent $H \sim 0.7$ has been interpreted as a universal indicator of surface fracture, weakly dependent on the nature of the material and on the failure mode [86-90]. Importantly, the surface roughness of a recently exhumed strike-slip fault plane has been measured by three independent 3D portable laser scanners [91]. Statistical scaling analyses show that the striated fault surface exhibits self-affine scaling invariance that can be described by a scaling roughness exponent, $H_1 = 0.7$ in the direction of slip. In Section 5.2.1 we showed that the "roughness" of the profile of the kHz EM precursors, as it is represented by the Hurst exponent, is distributed around the value 0.7. This result has been verified by means of both fractal spectral analysis and R/S analysis [35,36]. Thus, the universal spatial roughness of fracture surfaces nicely coincides with the roughness of the temporal profile of the recorded kHz EM precursors.

6. Interpretation of precursory kHz EM activity in terms of Intermittent Criticality

The Intermittent Criticality (IC)-viewpoint of EQ dynamics is based on the hypothesis that a large regional EQ is the end result of a process in which the stress field becomes correlated over increasingly long scale-lengths, which set the size of the largest EQ that can be expected at any given time. The largest event on the fault network cannot occur until regional criticality has been achieved and stress is consequently correlated at all length scales up to the size of the region. The growth of the spatial correlation length obeys a power law with a singularity in the critical point [92-102]. This large event destroys, after its occurrence, the criticality on its associated network, creating a period of relative quiescence, after which the process repeats by rebuilding correlation lengths towards criticality and the next large event. In contrast to self-organized criticality, in which the system is always at or near criticality, intermittent criticality implies time-dependent variations in the activity during a seismic cycle. Before the large EQ, the growing correlation length manifests itself as an increase in the frequency of intermediate-magnitude earthquakes. This is commonly referred to as the "accelerating moment release model", and has been discussed by a number of authors [97,98]. Briefly, IC-approach includes self-organized criticality, growing spatial correlation length, and accelerating energy release.

A kHz EM anomaly can be interpreted as an EM confirmation of the IC-hypothesis. Indeed, a power-law type increase in the rate of EM energy release as the global instability approaches is observed [27,28,78]. The recorded acceleration of the EM emission leading up to EM large event and "EM shadow" following this is in harmony with the IC-hypothesis. Notice, the rate of seismic energy release computed around the epicenter of the EQ follows a similar power-law type increase [27,28,78]. This experimental fact supports the hypothesis that both the seismicity and the preseismic EM activity represent two cuts in the same underlying fracture mechanism. Moreover, the spectral scaling exponent β (see Section 5.2) is a measure of the strength of time correlations. The β-values are significantly shifted to higher values as the EQ is approaching [27,28,78], namely, the correlation length in the time series increases as the catastrophic event approaches. Consequently, the two basic signatures predicted by the IC-model are included in the candidate kHz EM precursors.

7. Interpretation of MHz-kHz EM precursors in terms of fractal electrodynamics

Recently, the research area known as "fractal electrodynamics" has been established. This term was first suggested by Jaggard [44,45] to identify the newly emerging branch of research, which combines fractal geometry with Maxwel's theory of electrodynamics. From the laboratory scale to the geophysical scale, fault displacements, fault and fracture trace length, and fracture apertures follow a power-law distribution. Thus a fault shows a fractal pattern: a network of line elements having a fractal distribution in space is formed as the event approaches. However, an active crack or rupture can be simulated as a radiating element. The idea is that a *Fractal EM Geo-Antenna* can be formed as an array of line elements having a fractal distribution on the ground surface as the significant EQ is approached. This idea has been tested in [27]: the precursors are governed by characteristics (e.g., scaling laws, temporal evolution of the spectrum content, broad-band spectrum region, and accelerating emission rate) predicted by fractal electrodynamics. Notice, the fractal tortuous structure can significantly increase the radiated power density, as compared to a single dipole antenna. The tortuous path increases the effective dipole moment, since the path length along the emission is now longer than the Euclidean distance, and thus the possibility to capture these preseismic radiations by aerial antennas.

The fractal dimension of the *fractal EM geo-antenna* associated with the Athens EQ is $D = 1.2$ [27]. Seismological measurements as well as theoretical studies [101,102 and references therein] suggest that a surface trace of a single major fault might be characterized by $D = 1.2$. We clarify that the exponent D does not describe the geometrical setting of the rupture faults but it only gives the distribution of rupture fault lengths irrespective of their positions. More information is needed for a full geometrical interpretation of the faults, e.g. the position of the rupture centers.

8. The science of EQ prediction should, from the start, be multi-disciplinary

As it was mentioned in Introduction, EQ's preparatory process has various facets which may be observed before the final catastrophe, thus, a candidate preseismic EM activity should be consistent with other EM precursors or precursors that are imposed by data from other disciplines (Seismology, Infrared Remote Sensing, Synthetic Aperture Radars Interferometry e.t.c.).

8.1 Seismic electric signals

A well documented type of precursory signals is the so-called seismic electric signals (SES) [103]. They are transient low frequency $(< 1Hz)$ electric signals and are consistent with the "pressure stimulated currents model", which suggests that, upon a gradual variation of the pressure (stress) on a solid, transient electric signals are emitted, from the reorientation of electric dipoles formed due to disorder in the focal area, when approaching a critical pressure. Field and laboratory experience coincide to the point that the transient SES tend to appear earlier in respect to the MHz-kHz EM precursors. In a recent paper, Varotsos et al. [54] report that the occurrence time of a main shock is specified in advance by analyzing in "natural time" the seismicity subsequent to the initiation of the SES activity. This analysis identifies the time when the seismicity approaches the critical state. The authors conclude that, from the time of that critical state, "the main shock was found empirically to follow usually within a few days up to one week". It is important to note that: (i) MHz / kHz EM precursors are emerged from approximately a week up to a few hours before the EQ occurence, namely, when the earth crust is in critical state by means of seismicity. (ii) MHz EM precursors can also be attributed to a phase transition of second order, as it happens for the seismicity preceding main shocks. Bear in mind that, in the frame of the proposed two stage model, MHz EM precursors are rooted in fracture of heterogeneous regime which surrounds the activated fault. The finally emerged kHz EM precursors indicate that the occurrence of the prepared EQ is unavoidable. This scheme, namely, the appearance of SES following by kHz-MHz EM precursory radiations, has been reported before EQs that occurred in Greece [21,25,30,104]. We note that, using Fisher Information and entropy metrics, it has been found that both the organization of the seismicity around the activated fault and the organization of the kHz EM precursors significantly increase as the EQ approaches [105].

8.2 EM anomalies rooted in preseismic LAI-coupling

A class of precursors is rooted in anomalous propagation of EM signals over epicentral regions due to a pre-seismic Lithosphere-Atmosphere-Ionosphere (LAI)coupling [1 and references therein]. During quiet periods, the daily EM data present a main bay-like behaviour. The records refer to the Earth-ionosphere waveguide propagation of natural EM emissions. Any change in the lower ionosphere due to an induced pre-seismic LAI-coupling may result in significant changes in the signal propagation-received at a station. Therefore, the emergence of an ionospheric EM anomaly is recognized by a strong perturbation of the characteristic bay-like morphology in the chain of daily data. Pulinets et al. [106] have reported that ionospheric precursors within 5 days before the seismic shock are registered in 100% of the cases for EQs with magnitude 6 or larger. Such anomalies have been recorded in Greece [21, 27, 104]. *Importantly, these anomalies were followed by well documented preseismic sequence of MHz and kHz EM activities, while SES appeared earlier*. The EM precursors sourced in the preseismic LAI-coupling and the MHz/kHz EM precursors appear during the last days before the main shock, namely, when the earth crust was in critical state by means of seismicity.

8.3 Precursors imposed by data from other disciplines

As it was emphasized in Introduction, EQ's preparatory process has various facets which may be observed before the final catastrophe. On September 7, 1999 the catastrophic Athens (Greece) EQ with a magnitude $M_w = 5.9$ occurred. The following sequence of well documented different precursors have been observed [26,29,30,104]:

1. A clear SES activity was recorded.

2. MHz EM anomalies were simultaneously recorded at 41, 54, and 135 MHz on August 29, 1999. These anomalies can be attributed to a phase transition of second order by means of the analysis reported in Section 3.

3. Two stong burst-like EM anomalies at 3 and 10 kHz were simultaneously recorded before the EQ occurrence. The first and second anomaly lasted for 12 and 17 hours, respectively, with a cessation of 9 hours. The second anomaly ceased about 9 hours before the EQ. This preseismic activity obeys all the requirements of the Section 2.2.

4. Infrared remote sensing makes use of satellite infrared sensors to detect infrared radiation emitted from the Earth's surface before EQs. A clear increase in the thermal infrared radiation (TIR) over the area around the Athen's EQ epicentre recorded during the last days before the EQ. The appearance of TIR emissions enhances the consideration that the fracture process has been extended up to the surface layers of the crust in the case of this EQ.

5. Synthetic aperture radars (SAR) are space-borne instruments that emit EM radiation and then record the strength and time delay of the returning signal to produce images of the ground. By combining two or more SAR images of the same area, it is possible to generate elevation maps and surface change maps with unprecedented precision and resolution. This technique is called SAR interferometry. SAR interferometry is becoming a new tool for active tectonics by providing both mm-precision surface change maps spanning periods of days to years and m-precision, high-resolution topographic maps for measuring crustal strain accumulated over longer periods of time. The fault modelling of the Athens EQ, based on information obtained by radar interferometry (ERS-2 satellite), predicts two faults: the main fault segment is responsible for 80% of the total energy released, with the secondary fault segment for the remaining 20%. A recent seismic data analysis carried out by Kikuchi, using the now standard methodology, also indicates that a two-event solution for the Athens EQ is more likely than a single event solution. According to Kikuchi, there was probably a subsequent ($M = 5.5$) EQ after about 3.5 s of the main event ($M = 5.8$). On the other hand, two strong impulsive kHz EM bursts were emerged in the tail of the preseismic EM emission. The first burst contains approximately 20% of the total EM energy received during the emergence of the two bursts, and the second the remaining 80%. The aforementioned surprising correlation in the energy domain between the two strong preseismic kHz EM signals and two faults activated, strongly supports beyond any analysis the hypothesis that the two strong EM bursts reveal the nucleation of the impending EQ.

6. A precursory power-law-type acceleration of the seismic energy release has been observed in the case of Athens EQ. The apparent onset of precipitous power-law behaviour began approximately 20 days before the EQ and culminated with the main event appearance, disappearing soon afterward.

The aforementioned observed phenomena, support the proposal that *"the science of EQ prediction should, from the start, be multi-disciplinary!"*

8.4 Universality among various geophysical and biological catastrophic events

In the last 20 years, the study of complex systems has emerged as a recognized field in its own right, although, a good definition of what a complex system is has proven elusive. Is there a common factor in the seemingly diverse complex phenomena? The answer is yes-they happens in systems consisting of many similar units interacting in a relatively well-defined manner; the field of study of complex systems holds that their dynamics is founded on universal principles that may be used to describe phenomena that are otherwise quite different in nature. When one considers a phenomenon or a thing that is "complex", one generally associates it with something that is *hard to separate, analyze or to solve*. Instead, we refer to a complex system as one whose phenomenological laws, which describe the global behaviour of the system, are not necessarily directly related to the microscopic laws that regulate the evolution of its elementary parts. The main features of this collective bahaviour are that an individual unit's action is dominated by the influence of its neighbours, the unit behaves differently from the way it would behave on its own; and such systems show ordering phenomena as the units simultaneously change their behaviour to a common pattern [107-109]. Generally, topological disorder within the complex system introduces new, surprising effects, the laws that describe their behaviour are qualitatively different from those that governs its units. Therefore, the description of the entire system's behaviour requires a qualitatively new theory. Interesting principles have been proposed in an attempt to provide such a unified theory. These include self-organization, intermittent criticality, simultaneous existence of many degrees of freedom, self-adaption, rugged energy landscapes, and scaling (for example, power-law dependence) of the parameters and the underlying network of connections.

Empirical evidence has been mounting that supports the possibility that a number of systems arising in disciplines as diverse as physics, biology, engineering, and economics may have certain quantitative features that are intriguingly similar. Picoli et. al. [110] reported similarities between the dynamics of geomagnetic signals and heartbeat intervals. de Arcangelis et al. [111] presented evidence for universality in solar flare and earthquake occurrence. Kossobokov and Keilis-Borok [112] have explored similarities of multiple fracturing on a neutron star and on the Earth, including power-law energy distributions, clustering, and the symptoms of transition to a major rupture. Sornette and Helmstetter [113] have presented occurrence of finite-time singularities in epidemic models of rupture, EQs, and starquakes. Abe and Suzuki [114] have shown that internet shares with EQs common scale-invariant features in its temporal behaviours. Peters et al. [115] have shown that the rain events are analogous to a variety of nonequilibrium relaxation processes in nature such as EQs and avalanches. Fukuda et al. [116] have shown similarities between communication dynamics in the Internet and the automatic nervous system.

A corollary in the study in terms of complexity is that transferring ideas and results from investigators in hitherto disparate areas will cross-fertilize and lead to important new results. Considering the rarity of large surface EQs which occurs on land and subtleties of possible preseismic EM signatures, the study of EM precursors by means of complexity offers new possibilities for their exploration.

Importantly, the strong analogies between the dynamics of EQ and neurobiology have been realized by numerous authors [117-123]. In general, authors have suggested that EQ's dynamics and neurodynamics can be analyzed within similar mathematical frameworks [117-127]. Characteristically, driven systems of interconnected blocks with stick-slip friction capture the main features of EQ process. These models, in addition to simulating the aspects of EQs may also represent the dynamics of neurological networks [117 and references therein]. Hopfield [118] proposed a model for a network of N integrate-and-fire neurons. In this model, the dynamical equation of k^{th} neuron equation 28 in [118] is based on the Hodgekin-Huxley model for neurodynamics and represents the same kind of mean field limit that has been examined in [123], in connection with EQs.

Recently, it has been shown that a unified approach to catastrophic events-from the normal state of earth / brain to EQ by means of preseismic kHz EM emission/epileptic seizure exists.

The appearance of common “pathological” symptoms, i.e, high organization, persistency, and acceleratin energy release accompanies the emergence of kHz EM precursors and seizures [124-126]. More recently, Osorio et al. [127] have shown that a dynamical analogy supported by five scale-free statistics , namely, the Gutenberg-Richter distribution of event sizes, the distribution of interevent intervals, the Omori and inverse Omori laws, and the conditional waiting time until the next event, is shown to exist between seizures and EQs.

Strong analogies between the dynamics of kHz EM precursors and that and magnetic storms have been realized. The appearance of common “pathological” symptoms, i.e, high organization, persistency, and accelerating energy release accompanies the emergence of these two crises [128-131]. Moreover, the Tsallis-based energy distribution function (Eq. 5) is able to describe solar events and magnetic storms, as well. The best-fit for this analysis is given by a q-parameter value equal 1.82 and 1.84, correspondingly [131]. It is very interesting to observe the similarity in the q-values for: (i) seismicities generated in various large geographic areas, (ii) the precursory sequence of “EM-EQs” associated with the activation of a single fault,(iii) solar flares, and (iv) magnetic storms. This experimental evidence could be considered as an indication of universality among various geophysical processes. A unified theory may exist for the ways in which the above mentioned different systems organize themselves to produce a large geological or biological crisis.

9. Conclusions

As mentioned in Introduction, a key question debated in the scientific community is: Are there credible EM earthquake precursors? Despite fairly abundant circumstantial evidence, EM precursors have not been adequately accepted as real physical quantities, and there may be legitimate reasons for the critical views. In this contribution we propose a strategy for the study of MHz and kHz EM precursors which concentrates in an appropriately critical spirit, on asking 3 crucial questions:

(i) How can we recognize an EM observation as a pre-seismic one?

An anomaly in a recorded time series is defined as a deviation from normal (background) behaviour. In order to develop a quantitative identification of EM precursors, tools of information theory and concepts of entropy are used in order to identify statistical patterns. Entropy and information are seen to be complementary quantities, in a sense: entropy “drops” have as a counterpart information “peaks” in a more ordered state. The seismicity is a critical phenomenon [41,54], thus, it is expected that a significant change in the statistical pattern, namely the appearance of entropy “drops” or information “peaks”, represents a deviation from normal behaviour, revealing the presence of an EM anomaly. Several well-known techniques have been applied to extract EM precursors hidden in kHz EM time series: T-entropy, Approximate entropy, Fisher Information, Correlation Dimension, R/S analysis, Detrended Fluctuation Analysis, Shannon n-block entropies (conditional entropy, entropy of the source, Kolmogorov-Sinai entropy), Tsallis entopy. It is important to note that one cannot find an optimum organization or complexity measure. Thus, a combination of some such quantities which refer to different aspects, such as structural or dynamical properties, is the most promising way. The application of all the above mentioned multidisciplinary statistical procedure [30,33,35,36,69-71] sensitively recognizes and discriminates the candidate kHz EM precursors from the EM background: they are characterized by significantly higher organization / lower complexity in respect to that of the EM noise in the region of the station. Importantly this pre-seismic EM emission is also characterized by strong persistency [28,29]. The simultaneous appearance of both these two crucial characteristics, i.e., higher organization and persistency, implies that the underlying fracture process is governed by a positive feedback mechanism which is consistent with an anomaly being a precursor of an ensuing catastrophic event.

However, we suggest that any multidisciplinary statistical analysis by itself is not sufficient to characterize an emerged kHz EM anomaly as a pre-earthquake one. Much remains to be done to recognise systematically real pre-seismic EM precursors. The Earth's crust is clearly extremely complex. However, despite its complexity, there are several universally valid scaling relations. From the early work of Mandelbrot, much effort has been put to statistically characterise the resulting fractal surfaces in fracture processes. Fracture surfaces were found to be self-affine following the fractional Brownian motion (fBm) model over a wide range of length scales. Moreover, the spatial roughness of fracture surfaces has been interpreted as a universal indicator of surface fracture, weakly dependent on the nature of the material and on the failure mode. The Hurst Exponent H specifies the strength of the irregularity ("roughness") of the surface topography and the value of $H \sim 0.7$ has been interpreted as a universal indicator of surface fracture, weakly dependent on the nature of the material and the failure mode. Therefore, an important pursuit is to make a quantitative comparison between fractal patterns possibly hidden in an emergent kHz EM anomaly on one hand and universal fractal patterns of fracture surfaces on the other hand: an EM precursor associated with the last stage of EQ generation should behave as a persistent fBm temporal fractal, while the "roughness" of its profile, as it is represented by the Hurst exponent, should be characterized by the value $H \sim 0.7$. These two universal features of fracture are hidden in the recorded kHz EM precursors (see Section 5).

The self-affine nature of faulting and fracture predicts that the activation of a single fault is a reduced / magnified image of the regional/laboratory seismicity, correspondingly [76]. A fracto-EM precursor rooted in the activation of a single fault should be consistent with the above mentioned requirement. The sequence of kHz "electromagnetic earthquakes" rooted in the activation of a single fault satisfies the aforementioned requirement.

(ii) How can we link an individual EM precursor with a distinctive stage of the earthquake preparation?

An important feature, observed both at laboratory and geophysical scale, is that the MHz radiation precedes the kHz one. The remarkable asynchronous appearance of these precursors indicates that they refer to different stages of EQ preparation process. Moreover, it implies a different mechanism for their origin. Scientists ought to attempt to link the available various EM observations, which appear one after the other, to the consecutive processes occurring in Earth's crust.

The following *two stage model of EQ generation by means of pre-fracture EM activities* has been proposed: The pre-seismic MHz EM emission is thought to be due to the fracture of the highly heterogeneous system that surrounds the family of large high-strength entities distributed along the fault sustaining the system, while the kHz EM radiation is due to the fracture of the aforementioned large high-strength entities themselves [e.g.,28,29,31,34,39].

The temporal evolution of a MHz EM precursor, which behaves as a phase transition of second order (see Section 3), reveals transition from the phase from non-directional almost symmetrical cracking distribution to a directional localized cracking zone that includes the backbone of strong asperities (*symmetry breaking*). The identification of the time interval where the *symmetry breaking* is completed indicates that the fracture of heterogeneous system in the focal area has been obstructed along the backbone of asperities that sustain the system: *The siege of strong asperities begins*. However, the prepared EQ will occur if and when the local stress exceeds fracture stresses of asperities. As it is mentioned, the lounge of the kHz EM activity shows the fracture of asperities sustaining the fault.

(iii) How can we identify precursory symptoms in EM observations which signify that the occurrence of the prepared EQ is unavoidable?

This is a crucial question. Our results suggest that the appearance of a really seismogenic MHz EM anomaly does not mean that the EQ is unavoidable [28, 29]. The interplay between the heterogeneities and the stress field could be responsible for the observed antipersistent pattern of the precursory MHz EM time series [28, 29]. Indeed, in natural rock at large length scales there are long-range anticorrelations, in the sense that a high value of a rock property, e.g., threshold for breaking is followed by a low value and vice versa. The antipersistent character of the MHz EM time series may reflect the fact that in heterogeneous media, volumes with a low threshold for breaking alternate with much stronger volumes. Crack growth in a heterogeneous medium continues until a much stronger region is encountered. When this happens, crack growth stops while another crack nucleates in a weaker region and so on. Antipersistent behavior implies a set of fluctuations tending to induce stability within the system, i.e., a nonlinear negative feedback, which "kicks" the opening cracks away from extremes. Consequently, heterogeneity could account for the appearance of a stationary-like behavior in the antipersistent MHz part of the prefracture EM time series and thus enable the fracture in highly heterogeneous systems to be described via an analogy with thermal continuous phase transition of second order (see Section 3).

On the contrary, the lounge of the kHz EM activity is the sign of EQ generation. Accumulated evidence support the hypothesis that the kHz EM emission is originated during the fracture of asperities distributed along the activated fault sustaining the system (see Sections 4-7).

The burden of this contribution was to describe a plausible scenario for the study of EM precursors which includes a rather strict set of criteria for characterizing a sequence of MHz - kHz EM emissions as a seismogenic one. We emphasize that this scenario has already been applied to precursors associated with significant, i.e., EQs with magnitude larger than 6, surface EQs that occurred on land or near the coast-line in Greece and Italy. It seems to provide a coherent framework which ties together the observed phenomenology of MHz and kHz EM precursors, without obvious internal inconsistencies and without violating the laws of physics.

It might be difficult for someone to accept that such anomalies are indeed seismogenic. However it is even more difficult to prove that they are not. How possible would it be to find a non seismogenic EM emission that meets the criteria for such a multidisciplinary scheme?

One of the largest controversial issues of the materials science community is the interpretation of scaling laws on material strength. In particular, an important open question is whether the spatial and temporal complexity of earthquake and fault structures emerges from geometry or from the chaotic behaviour inherent to the nonlinear equations governing the dynamics of these phenomena. The observed scaling laws associated with EQs have led a variety of researchers to the conclusion that these events can be regarded as a type of generalized phase transition, similar to the nucleation and critical phenomena that are observed in thermal and magnetic systems [132]. In spite of this prevailing view, other scientists propose a different argument, purely based on geometry. They conclude that as happened for relativity, geometry could again hold an unexpected and fundamental role [133].

Our analysis suggests that we should discriminate two distinct cases: (i) The scaling laws associated with the fracture of the backbone of asperities of a single fault could be a product of the fractal scaling of asperities. Geometry holds a fundamental role of the emergence of fractal scaling laws in phenomena associated with the fracture of asperities. The observed precursory kHz EM emission is such a phenomenon. (ii) The scaling laws associated with the fracture of highly heterogeneous component that surrounds the family of asperities could be attributed to a phase transition of second order. Recent results support the concept that seismicity which preceeds of a significant seismic event is a critical phenomenon, it can be attributed to a phase transition of second order [134]. Moreover, it has been found empirically that main shocks occur a few days up to one week after the appearance of criticality. We recall that the MHz EM precursors also behave as a phase transition of second order, and also emerge from approximately one week up to a few hours before the EQ occurrence. These findings verify that the seismicity and the precursory MHz EM activity are two faces of the same coin. Notice, the persistent kHz EM emission, which is emerged in the tail of the preseismic preseismic EM activity, is a nonequilibrium process without any footprint of an equilibrium thermal phase transition. This process indicates that the system acquires a self-regulating character and to a great degree the property of irreversibility, which is one of the important components of predictive capability. The above mentioned findings suggest reconsidering the interpretation of scaling laws on material strength.

The absence of any EM activity during the EQ occurrence and aftersocks period constitutes a puzzling feature in the study of seismogenic EM precursors. A catastrophic decrease in the elastic modulus just before the final rupture is expected. The appearance of an EM gap in all the frequency bands just before the EQ occurrence might be considered as a hallmark that the expected decrease in the elastic modulus has occurred [28, 29]. So, the existence of a quiescent period may constitute the last clue that a significant seismic event is forthcoming with a considerable probability. On the basis of our study, drawing on both field observations and laboratory experiments on rock fracture, we make the following suggestion concerning the initial and final times for the crucial last stage of the EQ preparation process. The initial point corresponds to the appearance of persistent kHz EM emission. The final point corresponds to the onset of a quiescent period when all precursory EM activities cease. This analysis may point to a possible way of estimating the time to global failure. Certainly, further work in this direction is needed.

Irreversible deformation of rocks is accompanied by the Kaizer effect: if the heterogeneous material is loaded, then unloaded before fracture, and loaded again, only a small number of micro-fractures are detected before attaining the previous load. Micro-fracturing activity increases dramatically as soon as the largest previously experienced stress level are exceeded indicating the beginning of further damage in rocks. The existence of Kaiser effect in geological scale can justify the systematically observed absence of EM emission during the aftershocks period. The stress during the aftershocks period does not exceed the maximum previously reached stress level associated with the main shock occurrence.

The described here results seem to be tolerable, whether the presented ideas will prove to be corrects or disappear as others have remain for the future. However, if we accept the presented suggestions, the absence of EME after the EQ occurrence supports the hypothesis that the launched EQ was the main shock. In any case, the complexity of EQ preparation process is enormous, and thus a huge amount of research is needed before we begin to understand it. There are many outstanding answers that we do not know. Yet it is certain that we have begun to place most of the right questions. And this is perhaps a sign of a latent solution. The Greek poet and Nobel Laureate George Seferis has referred to what the ancient Greek spirit is all about:

"The birthplace of this idea is found at the dawn of Greek history. Aeschylus, the ancient Greek playwright, formulated it once and for all: He who steps beyond moderation is a hubrist, i.e. arrogant, and hubris is the greatest evil that can fall upon us. Greek Tragedy throughout is full of symbols of this idea. And the symbol that moves me above all others, this symbol I find in the Persians. Xerxes, the old legend tells us, was defeated because he was a hubrist; because he committed this extraordinary deed: he lashed at the sea...".

For the purpose of this chapter, it would mean committing hubris for scientists who have dedicated themselves to the prognosis of earthquakes to think that they can defeat "Eggelados".

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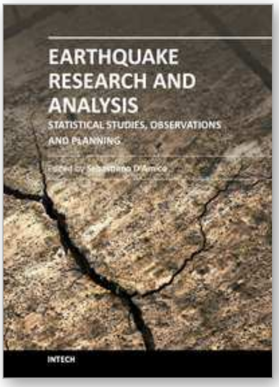

Earthquake Research and Analysis - Statistical Studies, Observations and Planning
Edited by Dr Sebastiano D'Amico

ISBN 978-953-51-0134-5
Hard cover, 460 pages
Publisher InTech

Published in print edition March, 2012

The study of earthquakes plays a key role in order to minimize human and material losses when they inevitably occur. Chapters in this book will be devoted to various aspects of earthquake research and analysis. The different sections present in the book span from statistical seismology studies, the latest techniques and advances on earthquake precursors and forecasting, as well as, new methods for early detection, data acquisition and interpretation. The topics are tackled from theoretical advances to practical applications.

Konstantinos Eftaxias (2012). Are There Pre-Seismic Electromagnetic Precursors? A Multidisciplinary Approach, Earthquake Research and Analysis - Statistical Studies, Observations and Planning, Dr Sebastiano D'Amico (Ed.), ISBN: 978-953-51-0134-5, InTech, Available from: http://www.intechopen.com/books/earthquake-research-and-analysis-statistical-studies-observations-and-planning/are-there-pre-seismic-electromagnetic-precursors-a-multidisciplinary-approach-

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