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ScienceDirect
Physica A 387 (2008) 1161–1172
PHYSICA A
www.elsevier.com/locate/physa

Dynamical complexity detection in pre-seismic emissions using nonadditive Tsallis entropy

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Received 14 August 2007; received in revised form 15 October 2007
Available online 20 November 2007

Abstract

We investigate, within the framework of nonextensive Tsallis entropy, particular aspects of the relation between signal analysis and signals originating in a very special nonlinear system: the focal area of an impending earthquake. The Tsallis-like time-dependent entropy is shown to be a rather powerful tool for providing a novel quantitative strategy for monitoring the focal area states just before the earthquake occurrence.

Keywords: Tsallis entropy; Hurst exponent; Time series analysis

1. Introduction

Earthquakes (EQs) are large-scale fracture phenomena. Despite the large amount of experimental data and the considerable effort that has been undertaken by material scientists, many questions about fracture processes remain standing. Especially, many aspects of EQ generation still escape our full understanding.

Fracture-induced physical fields allow a real-time monitoring of damage evolution in materials during mechanical loading. Electromagnetic (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. These precursors are detectable both at a laboratory and a geophysical scale [1–10]. Being non-destructive, monitoring techniques based on these fracture-induced fields are a basis for a fundamental understanding of fracture mechanism and for developing consecutive models of rock/focal area behavior [1].

Our main observational tool is the monitoring of the fractures which occur in the focal area before the final break-up by recording their kHz–MHz EM emissions. Recent studies imply that these pre-seismic EM signals not only contain information characteristic of an ensuing EQ but also yield clues regarding the underlying fracture dynamics [1–10]. It is crucial to point out that the pre-fracture MHz EM radiation appears earlier than the kHz one both in the laboratory and geophysical scale [6].

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0378-4371/$ - see front matter
doi:10.1016/j.physa.2007.10.053

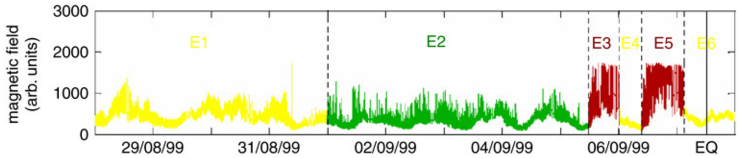

Fig. 1. View of the candidate pre-seismic EM emission included in the time series of the 10 kHz (East–West) magnetic field strength. The vertical line indicates the time of the Athens EQ occurrence. The initial phase of the precursor follows the anti-persistent fBm model (green section), while the final epoch follows the persistent fBm model (red section). The EM background (noise) follows the fractional Gaussian (yellow sections). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An important challenge in this field of research is to distinguish characteristic epochs in the evolution of precursory EM activity and identify them with the equivalent last stages in the EQ preparation process. Recently, we attempted to approach this challenge bringing together experimental pre-seismic EM data and aspects having their roots in statistical physics [3]. Our model of the focal area consists of: (i) a backbone of strong and large asperities distributed along the fault that sustains the system; (ii) a strongly heterogeneous material that surrounds the family of asperities. Analyses by means of critical phenomena have been applied to pre-seismic MHz–kHz EM fluctuations indicating a possible two stage transition from the normal state to the catastrophic seismic event [2,3]. The first epoch, which includes the initially emerged MHz part, originates during cracking in the heterogeneous component of the focal area, while the underlying fracto-electromagnetic mechanism can be described as a generalized continuous phase transition [3]. The abrupt emergence of strong impulsive kHz EM activity in the tail of the precursory activity is thought to be due to the fracture of the family of main asperities that sustain the system. The kHz EM radiation evolves as a phase transition far from equilibrium [3].

Herein we focus on the finally emerged kHz EM emission: we study whether novel signatures further indicate the transition to the last stage of the EQ preparation process, namely the fracture of the main asperities. A time-dependent Tsallis entropy is employed to characterize the level of precursory “crust injury”. The analysis reveals that this entropy detects the pattern of alterations in pre-seismic kHz EM signals and is able to discriminate between the “injury levels” of the focal area. We compare the results of the aforementioned analysis with ones resulting from a fractal spectral analysis performed in terms of wavelets. The results suggest that a significant increase of the degree of organization coupled with appearance of persistency can be confirmed at the tail of the detected pre-seismic kHz EM emission. We claim that this feature might be used as diagnostic tools for the fracture of the backbone of strong and large asperities that sustain the system.

2. Candidate precursory EM anomalies

In this work, we concentrate on the candidate kHz EM precursors associated with the Athens and Kozani–Grevena EQs. We mainly focus on the precursor of the Athens EQ, for the following reasons. (i) It has a rather long duration, thus it provides sufficient data for a valuable statistical analysis; the data have been recorded with a sampling rate of 1 sample/s while the duration of the candidate EM precursor is more than six days. (ii) A multidisciplinary analysis in terms of fault modelling, laboratory experiments, scaling similarities of multiple fracturing of solid materials, fractal electrodynamics, criticality, complexity, universality, and mesomechanics seems to validate the association of the detected pre-seismic EM emission with the fracturing process in the focal area of the impending EQ [2–10].

Pre-seismic EM anomalies at MHz and kHz frequency bands emerged during the last days prior to the Athens EQ that occurred on September 7, 1999, with a magnitude $M = 5.9$; the MHz EM candidate precursor appeared earlier than the kHz one [2,3,5]. In Fig. 1 the green and red segments of time series show the candidate precursor which is embedded in a long duration quiescence period concerning the detection of EM disturbances at the kHz frequency band [4,7].

On May 13, 1995 the Kozani–Grevena EQ with magnitude $M = 6.5$ occurred. At the tail of the MHz anomalies strong multi-peaked EM fluctuation simultaneously emerged at 3 and 10 kHz which ceased almost one hour before the EQ [2,3,6]. Fig. 2 shows the candidate precursor at 3 kHz.