ESF PESC EXPLORATORY WORKSHOP
on

Crackling noise

SCIENTIFIC REPORT

Istituto Nazione di Ricerca Metrologica (I.N.Ri.M)
Torino, Italy
24 -27 may 2006

Convened by:
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Executive summary

The ESF Exploratory workshop on 'Crackling noise' was held in Torino, Italy at the Istituto Nazionale di Ricerca Metrologia (INRiM), from May 24 to May 27, 2006. It has seen the participation of 22 invited speakers, together with the 2 convenors, coming from 11 European countries - Finland (1), Ireland (1), Spain (3), Switzerland (1), France (5), Hungary (1), Norway (1), Belgium (1), Netherlands (1), UK (1), Italy (3) - and non-European - Israel (1) and USA (2). Other local participants and a few students attended the meeting, and appreciated the proposed talks and the living discussions. The meeting has been held in one of the conference rooms in the central building of the INRiM, equipped with a recording system allowing to record all the talks to be inserted in a CD together with all the electronic files of the presentations. Coffee breaks and lunches have been provided in a neighbor room of the same building, while internet connections, both cabled and wireless, have been provided for all the participants.

The reduced number of participants, when compared to usual attendance at conferences, has been ideal to really make this workshop a useful place for discussion and exchange of idea. This was particularly important as the participants come from several different scientific communities, and hardly have the opportunity to meet other researchers and listen talks over a large interdisciplinary fields.

This ESF workshop on 'Crackling noise' has been promoted as a starting opportunity to create a new – highly interdisciplinary – scientific community which could explore the exciting topic of complexity in natural systems within a common framework and approach to problem solving. In fact, a wide variety of slowly driven systems in nature show very similar properties, as they all respond to external perturbations by impulsive events of widely distributed amplitudes. These impulsive events are usually detected as a crackling noise. These systems are really widespread and common, but even if the signal itself has different origin (electrical, magnetic, acoustic, etc.), its statistical features are often similar, being characterized by power law distributions and $1/f$-type spectra.

Probably the most common and familiar example is the occurrence of earthquakes in a particular seismic zone, where the event amplitudes span from the smallest imperceptible vibration of the crust, detectable only with proper instruments, to the largest destructive catastrophic events. As said, many other systems show a similar dynamics, usually with events not occurring on such a large timescale (months or years), but at the same time spanning many order of magnitudes (from fraction of milliseconds to seconds, for instance). Examples are abundant especially in materials science: magnetic Barkhausen noise in ferromagnetic and ferroelectric materials, acoustic emission in fracture and plasticity, martensitic transformation, voltage or resistance noise in semiconductors and superconductors, to name a few.

It is clear that understanding the nature of crackling noise is of practical importance for various applications, from non-destructive material testing to failure evaluation. For instance, magnetic Barkhausen noise and acoustic emission are commonly employed to scrutinize the internal damage present in a material. Resistance noise in electromigration is a valuable tool for microelectronic reliability. The noise can be viewed as a signature of the occurrence of a widely fluctuating internal activity in the material. In recent years similar “dynamical heterogeneities” have been observed in the response of soft matter and glasses and are though to reflect the complex internal energy landscape.

From the theoretical point of view, crackling noise is an indirect measure of the internal complexity of the materials dynamics. The presence of avalanches fluctuating over a wide range of timescales is often the result of many interacting degrees of freedom. Crackling noise thus emerges as a cooperative effect, reflecting both the system complexity and the fundamental interactions. Despite the large differences

between different systems, the noise statistical properties are surprisingly similar, as said. This suggests a general behavior independent of microscopic and macroscopic details. This behavior reminds the universal properties of systems at the second order critical transition, where the system details are irrelevant and only a few general properties, such as the system dimensionality and the range of relevant interactions, are needed to describe the critical transition.

In the last two decades, many researches explored this possibility to provide a general mechanism to explain individual systems. A notorious example is provided by the ideas of self-organized criticality, where it is assumed that the system is always spontaneously close to a critical transition, giving a quite convincing general mechanism for the large occurrence of crackling noise. This concept has stimulated an intense debate in the past, and a large series of both experimental and theoretical studies. In particular, theoretical simple models have been suggested, giving the possibility to further exploring the scaling properties of the complex systems.

If from a theoretical point of view, a general conceptual frame is well established, much work remains to model the large variety of real systems, and describe with accuracy the experimental data. While, for instance, significant results have been obtained in condensed matter, other systems appear more difficult to tackle, as, for instance, in geophysics, to name the field which can have the highest impact on society as long as a proper description together with earthquake forecast would be available.

This ESF workshop has been intended to be a starting point, at least at European level, in this important and exciting field. As a matter of fact, all the participants have realized the importance of this effort, and have shown their enthusiasm to take part of the project. This means the onset of new collaborations, while there is already an agreement for the preparation of new proposals (COST actions, 7th European Framework, ect). In addition, because of the high degree of interdisciplinary of the topic, all have accepted to prepare an introductory paper which could help the others and that we are planning to publish in the near future as a 'Lecture notes on physics' by Springer. This text book will be useful not only for whose who are active in the project, but also for a wider audience, both of students and researchers who are interested in this field.

Scientific content of the event

The scientific program ESF exploratory workshop on “Crackling Noise” was divided into 9 topical sessions, covering various aspects of the problem in different physical systems, and included as well two tutorial sessions on theoretical and experimental approaches, held by two distinguished scientists from USA: J. P. Sethna (Cornell) and M. Weissmann (Urbana-Champaign).

The meeting started in the afternoon of May 24, with the welcome address given by the president of the INRiM, Prof. E. Bava and by some short remarks of the organizers, G. Durin and S. Zapperi. Next we had the first tutorial session by J. P. Sethna, who summarized the key points of the theoretical approaches devoted in the past to crackling noise and introduced the ensuing discussion. To this end, after a brief summary of the program he highlighted the common aspects to be seen in different talks. This introduction was very helpful to put the topic of workshop rapidly into a common framework. In addition, a coherent view of the topics was useful anticipate possible points of discussion. Among these, the questions that stimulated most interest were: (i) the most efficient way to define inter-event correlation in a noisy sequence; (ii) the search for new indicators for the noise statistics, such as the pulse shape; (iii) the introduction of new spatio-temporal visualization methods for avalanches. The tutorial talk was followed by a short talk by M. J.

Alava, discussing the relation between the spectral properties of the noise and the internal correlation of the avalanches. This point was mentioned already in the tutorial and was then explored in more depth by Alava, who presented results of computer simulations of sandpile models and a dislocation dynamics model. The first conference day ended with an experimental talk by E. Vives on martensitic transformation. The crackling noise there arises as the acoustic emission measured during the transformation. The key questions discussed concerned the universality of the distributions and the reproducibility of the noise.

The second day of the workshop started with the second tutorial, on experimental aspects, held by M. B. Weissman. The talk clarified the difference between non-equilibrium crackling noise and equilibrium 1/f noise, that has a completely different origin and phenomenology. There was then an introduction to the main experimental problems in the measurement and interpretation of the Barkhausen noise in ferromagnetic and ferroelectric materials. In particular, it was shown how high order spectra can provide detailed information on the underlying microscopic dynamics, helping to discriminate between theoretical models.
The program continued with a session on crackling noise in electronic properties, including superconductors, ferroelectrics and electromigration. G. Jung discussed voltage noise in the transport properties of superconductors. The noise is measured when an electrical current flows in a type II superconductor and is due to the erratic motion of the magnetic vortices. It was shown that a possible source of the noise was the edge contamination mechanism: vortices enter into the sample in a disordered state and then order as they move inside the sample. Another aspect of vortex avalanches was discussed by R. J. Wijngaarden who showed experimental results on the penetration of magnetic flux in a type II supercondutor. By magneto-optical method it is possible to have direct access to the statistics of flux avalanches, which are found to be power law distributed. It was also shown how to connect the crack roughness to the avalanche statistics and the role of disorder on these quantity was clearly discussed. D. Corcoran next discussed resistance fluctuations during electromigration in metals. This problem of important practical relevance has intriguing analogy with other crackling systems, since the resistance noise shows a power law distribution of amplitudes. Finally, D. Damjanovic presented a broad introduction to the phenomenology of ferroelectric materials, with particular emphasis on hysteresis and noise. It was shown that while Barkhausen noise was repeatedly measured in these materials, there has not been so far a coherent statistical treatment of these fluctuations. New activities in analogy with other phenomena discussed in the present workshop could help fill this gap.

The workshop continued in the afternoon with two sessions on geophysical applications and soft-matter. The occurrence of crackling noise in the geophysical context was discussed in detail by J. R. Grasso, that reported examples from seismic signals, avalanches, rockfalls and volcanic activity. The talk provided an interesting overview and indicated the main modeling strategies taken in the geophysics community. The ensuing discussion signaled the need for a more microscopic derivation of widely used phenomenological laws. The following talk by A. Corral, discussed a refined treatment of the inter-event distribution of earthquakes, showing the importance of scaling laws inspired by the renormalization group for critical phenomena. Finally, J. Weiss discussed the rheology of the ice cover in the artic see, proposing the concept of “solid turbulence” to describe the diffusion of tracers on the ice cover.

In the session on soft-condensed matter, F. Ramos discussed the shear melting of columnar crystals, pointing out the interesting analogies with vortices in type II superconductors and the role of dislocations in the melting process. He was followed by P. Hebraud who reported the result of an experiment on the coagulation of a colloidal suspension. The dynamics of the system was characterized as a series of rapid bursts, separated by quiescent periods, another clean example of crackling noise.

The following day started with a session on fracture, starting with the talk of L. Vanel. He reported experimental measurements of the acoustic emissions (AE) during the rupture of vitreous polymer foams and

compared the results with numerical simulations of the thermal random fuse model. Next, K. J. Maloy reported the result of an experiment of planar crack propagation in plexiglas. Thanks to a careful visualization analysis it was possible to follow step by step the dynamics of the crack front, characterizing its avalanche statistics. It emerged an interesting picture with several scaling exponents that are still to be interpreted theoretically. In the following talk, M. J. Alava, discussed a series of AE experiments in paper fracture, in tensile and peel modes. Both experiments display power law scaling for inter-event times and pulse energies. It was noticed that the peel experiment appears to yield the same exponent as in the experiment by Maloy.

The next session was on magnetic Barkhausen noise and was started by the talk of F. Colaiori. She discussed the properties of a single degree of freedom model which allows to recover most experimental results, including the asymmetry of the pulse shape, which is due to eddy current propagation. Next, E. Puppin summarized the results obtained by his group on magnetic thin films, analyzed by magneto-optical methods. The last talk of the session was given by F. Kun and represented an interesting link between fracture and magnetic noise. He showed that the statistics of the Barkhausen noise can be used to distinguish between brittle and ductile fracture in steel, providing a useful application of crackling noise to practical problems.

The session on plasticity was started by M.-C. Miguel who discussed about crackling noise in dislocation assemblies, in crystalline materials and vortex matter in type II superconductors. The results of numerical simulations were compared with experiments, in particular with the results on micro-size samples, published the very same day on Science by the group of Dimiduk. The discussion continued naturally with the talk by M. Zaiser, who discussed of the avalanche behavior in terms of continuum models of plasticity. He introduced the concept of the yielding transition, that can be used as a general framework for crackling in plasticity. Experimental evidence for this phenomenon was provided in the following talk by J. Weiss, reporting about AE measurements in plastically deforming crystals, in ice and in metals.

The final day was devoted to granular media, with two talks. In the first talk, N. Vandewalle discussed about the complex dynamics of granular media including fluctuations, hysteresis, aging and compaction. He also reported an interesting experiment measuring resistance fluctuations associated to a granular medium. Finally, A. Petri reported the result of a stick-slip experiment of a sheared granular bed. He proposed an interpretation of the results in term of a model derived from the Barkhausen effect, in particular the one discussed in the talk by F. Colaiori.

All the abstracts, together with the pdf files of presentation and recordings of the given talks are available on http://bknoise.ien.it/ESF/.

ASSESSMENT OF THE RESULTS AND FUTURE DIRECTIONS

The workshop was very helpful because it provided a unique opportunity to meet for people working in crackling noise from different scientific fields. All talks were followed by lively discussions that mostly tried to establish connections and similarity between different topics. The workshop allowed thus to establish clearly the state of the art of the field and propose future directions. A set of common statistical tools are now emerging and could lead to progress in different fields. For instance, the pulse shape scaling, originally introduced in the context of the Barkhausen noise has been recently applied to earthquakes, and as seen in the workshop also to dislocation dynamics. It was then proposed to perform a similar study for martenistic transformations. Similarly, the connection between spectral properties and avalanche scaling proposed by Sethna appears to be applicable to many different cases. The need to harmonize the

measurements of waiting time distributions emerged clearly during the workshop, since up to now different definitions were used in different systems. The discussions in the workshop was useful to suggest future pathways for investigation, like a complete statistical analysis of Barkhausen noise in ferroelectric materials. Several experiments, still needing a quantitative theoretical explanation, were presented during the workshop. Among them, the most intriguing questions relate to the universality class of flux front propagation and of planar cracks. Both these example show robust scaling behavior that is not captured by simple models.

The workshop allowed also to discuss possible instruments to tackle the scientific problems through a joint european effort. It was unanimously decided to propose a COST action on crackling noise. It was believed that this could be a useful instrument to coordinate the activity at european level, attracting further researchers working on similar topics and allowing for exchanges that are particularly needing in such an interdisciplinary topic. A pre-proposal was rapidly set up and submitted soon after the workshop. In addition, it was noticed that it would be very useful to set a common framework in a joint publication that should summarize methods, ideas and results obtained in different fields where crackling noise is observed. The idea was to write together a book in the form of lecture notes, that could be useful for graduate students and researchers dealing with crackling noise. Contact will be taken with editors to put forward this proposal.

Final program

Wednesday 24 May 2006		
16:00	Welcome address (Elio Bava, president of INRIM), Presentation of the European Science Foundation (ESF) (Andreas Alexandrou, Standing Committee for Physical and Engineering Sciences)	
	CRACKLING MODELS	
16:30	James P. Sethna	Crackling noise theories: beyond critical exponents (Tutorial)
17:30	Mikko Alava	Crackling noise in avalanching systems
	CRACKLING AEMISSION	
17:50	Eduard Vives	Acoustic emission in martensitic transitions: avalanches, hysteresis and learning
18:30	Practical information	
19:00	Welcome party	

Thursday 25 May 2006		
	CRACKLING EXPERIMENTS	
9:00	Michael B. Weissman	Tutorial on Crackling noise: Experimental aspects
	CRACKLING (SUPER)ELECTRONS	
10:00	Grzegorz Jung	Non-gaussian Noise in Superconductors
10:20	Coffee break	
11:00	Rinke J. Wijngaarden	Avalanches in superconductors
11:40	David Corcoran	Complex Abrupt Resistance Changes in Electromigration
12:20	Dragan Damjanovic	Ferroelectric materials: Experimental studies of domain wall displacement, Barkhausen noise and related phenomena
13:00	Lunch	
	CRACKLING EARTH	
14:30	Jean Robert Grasso	Seismic noise before earth crust instabilities
15:10	Alvaro Corral	Scaling law for earthquake waiting times and invariance under renormalization-group transformations
15:50	Jerome Weiss	Solid turbulence in the fracture of the arctic sea ice cover
16:10	Coffee break	
	CRACKLING SOFTNESS	
16:30	Laurence Ramos	Creep, flow and shear-melting of a soft hexagonal columnar crystal
17:10	Pascal Hébraud	Intermittent dynamics of a coagulating suspension
18:00	Discussion	
20:30	Dinner (Porto di Savona, center of Turin)	
Friday 26 May 2006		
	CRACKLING FRACTURES	
9:00	Loic Vanel	Acoustic emissions in rupture of heterogeneous materials: Experiments and Numerical Model

9:40	Knut Jørgen Maloy	Local waiting time in inplane fracture
10:20	Mikko Alava	Acoustic emission in (paper) fracture
10:40	Coffee break	
	CRACKLING MAGNETS	
11:10	Francesca Colaiori	Crackling noise in ferromagnetic materials: Barkhausen effect and asymmetry in the pulse shape
11:50	Ezio Puppin	Temperature and Barkhausen noise in 2D ferromagnets
12:30	Ferenc Kun	Magnetic noise in dynamic fracture
13:10	Lunch	
	CRACKLING PLASTICITY	
15:00	M. Carmen Miguel	Crackling Noise in Dislocation Assemblies
15:40	Michael Zaiser	Yielding, plastic deformation and crackling noise in crystals: discrete dislocations and continuum models
16:20	Jerome Weiss	Crackling noise in plasticity
16:50	Coffee break	
17:20	Debate: "The future of crackling people" (Chairs: Gianfranco Durin, Stefano Zapperi)	
20:30	Dinner (Bel doit, Superga)	

Saturday, May 27		
	CRACKLING GRAINS	
9:00	Nicolas Vandewalle	Granular materials: complex reorganisation dynamics and unusual electrical properties
9:40	Alberto Petri	Granular shearing and Barkhausen noise
10:20	Coffee break	
11:10	Closing remarks	
12:00	Closure	

Participants

Surname	*Name*	*Gender*	*Country of work*	*25-35*	*36-45*	*46-55*
Alava	Mikko	M	Finland		X	
Colaiori	Francesca	F	Italy		X	
Corcoran	David	M	Ireland		X	
Corral	Alvaro	M	Spain		X	
Damianovic	Dragan	M	Switzerland			X
Durin	Gianfranco	M	Italy		X	
Grasso	Jean Robert	M	France			X
Hebraud	Pascal	M	France		X	
Jung	Grzegorz	M	Israel			X
Kun	Ferenc	M	Hungary		X	
Maloy	Knut Jørgen	M	Norway			X
Miguel	M. Carmen	F	Spain		X	
Petri	Alberto	M	Italy			X
Puppin	Ezio	M	Italy			X
Ramos	Laurence	F	France		X	
Sethna	James P.	M	USA			X
Vandewalle	Nicolas	M	Belgium		X	
Vanel	Loic	M	France	X		
Vives	Eduard	M	Spain		X	
Weiss	Jerome	M	France		X	
Weissman	Michael B.	M	USA			X
Wijngaarden	Rinke J.	M	Netherlands			X
Zaiser	Michael	M	U.K.		X	
Zapperi	Stefano	M	Italy		X	
Cerruti	Benedetta	F	Italy	X		
Boato	Valentina	F	Italy	X		
Pugno	Nicola	M	Italy		X	
Lacidonia	Giuseppe	M	Italy		X	
Paggi	Marco	M	Italy		X	
Niccolini	Gianni	M	Italy	X		
Manuello-Bertetto	Amedeo	M	Italy		X	
Carpinteri	Alberto	M	Italy			X
Total				4	18	10

Age	***25-35***	***36-45***	***46-55***
	4	18	10
%	12	57	31

Country of work	***Invited***	***Auditors***
Finland	1	-
Italy	5	8
Ireland	1	-
Spain	3	-
Switzerland	1	-
France	5	-
Israel	1	-
Hungary	1	-
Norway	1	-
USA	2	-
Belgium	1	-
Netherlands	1	-
U.K.	1	-

Gender	***Invited***	***Auditors***
Female	3	2
Male	21	6
Total	24	8

Final list of participants

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