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Precursory Activity
A Physical Approach

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PRECURSORY ACTIVITY
A PHYSICAL APPROACH

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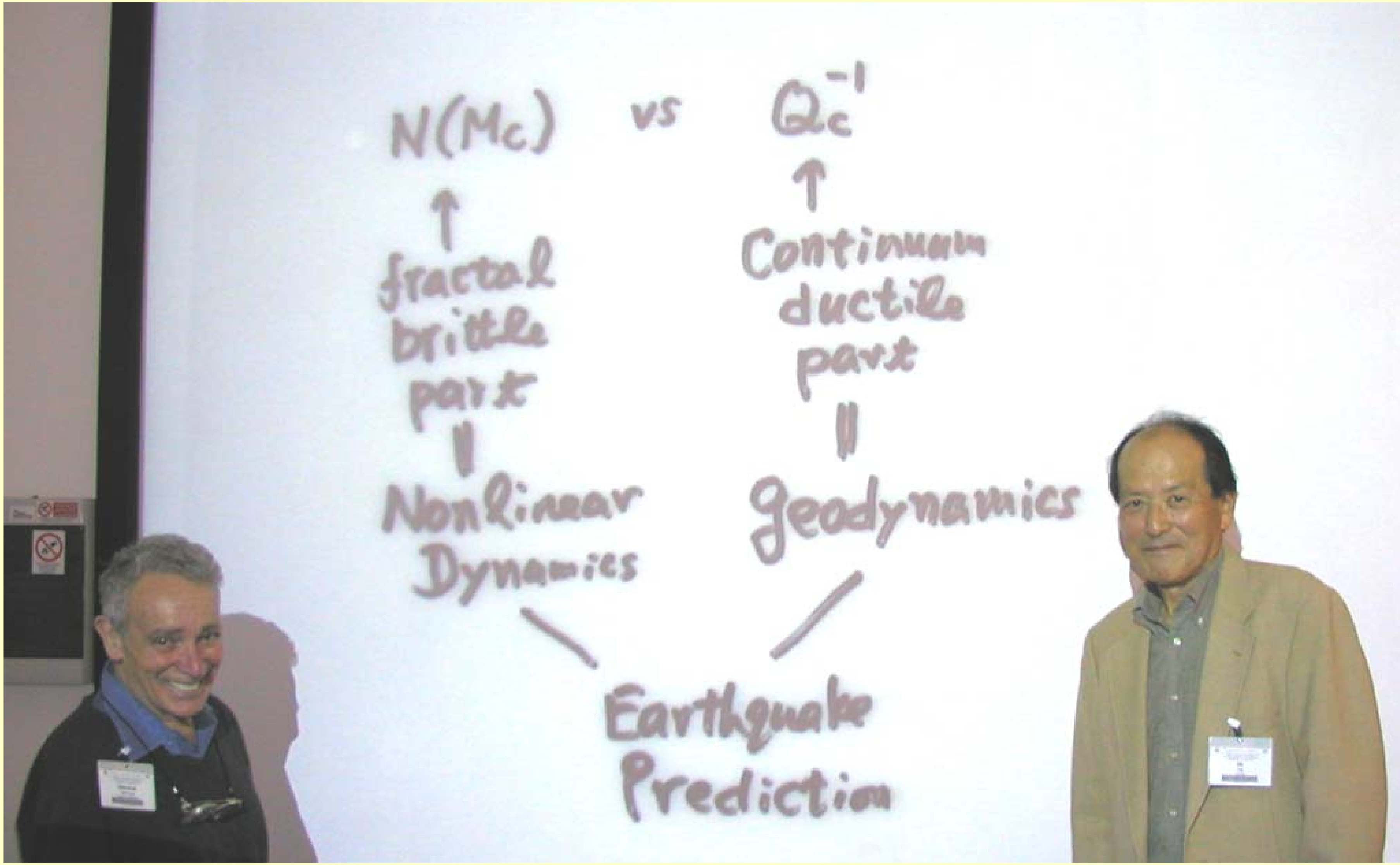
PREDICTION OF NATURAL HAZARDS

Predicting natural hazards resembles the game of croquet in *Alice in Wonderland*, where the ball was a live hedgehog who would not stand still or go where the players intended. We can make statistics about the habits of hedgehogs, but we are still far from understanding the rules of the game.

(Cinna Lomnitz)

Abdus Salam ICTP, Trieste, October 2003



V. Keilis-Borok K. Aki

EARTHQUAKES AS CATASTROPES

- From a mathematical point of view, an earthquake may be associated to a **catastrophe**, a sudden change that appears as the response of a system to a smooth change in the external conditions (Arnold, 1984).
- The sudden change that appear in some parameters can be modeled as a step transition, a discontinuity or a bifurcation.
- We can also talk about a volcanic eruption as a **catastrophic event**, due to the looses it may cause. Here the need for its **forecasting**.

EARTHQUAKE OCCURRENCE AS CRITICAL PHENOMENA

The term **critical phenomena** refers to the peculiar behavior of a system when it is at or near the point of a continuous-phase transition, known as critical point. A continuous phase transition, in turn, may be defined as a point at which the system changes from one state to another without a discontinuity or jump of a given property (the density in the liquid/vapor phase change or the stress/friction in earthquakes).

On a generic way we may consider the occurrence of an earthquake as a continuous phase transition order/disorder, the system in a constrained state to an unconstrained one. The critical point would be the threshold “accumulated stress = resistance of the material”.

Critical phenomena are characterized by scaling (power law behavior) and (very often) universality.

SELF-ORGANIZATION

If we accept earthquake occurrence as critical phenomena, we should formulate the evolution of the system in terms of the order parameter and the correlation length.

As the correlation length grows, the patches self-organize in several geometrical and dynamical structures.

The paradigmatic example of self organization is Rayleigh-Benard convection (elastic rebound point of view)

THE THRESHOLD OF TURBULENCE AS A PHASE TRANSITION

For a constant heating, the cell structures are stationary. However, if heat grows the structure of the cells evolves is continuously evolving towards a more complex structures until the threshold of turbulence is reached. The transition from convective to turbulent regimes can again be viewed as a phase transition.

Two critical points can thus be defined:

1. The beginning of convection with the meaning of the **emergence of self-organization**, defining a bifurcation point

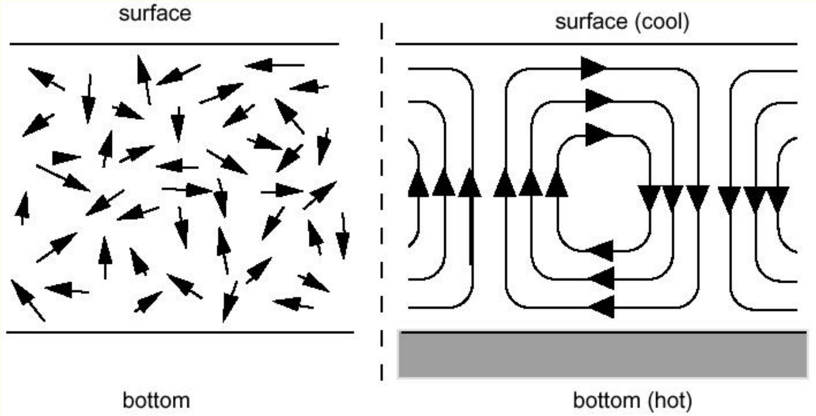
2. The transition from convection to turbulence that can be assimilated to a **phase transition order/disorder**.

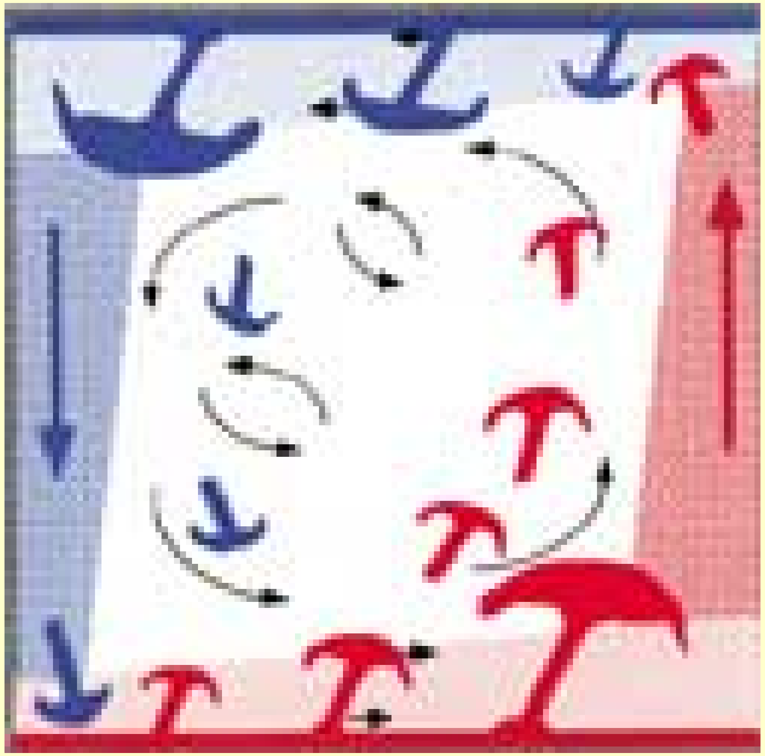
The occurrence of earthquakes can be assumed to be a temporal point-process with respect to the characteristic timed scale of stress accumulation. Hence, we can talk about the occurrence of events as an instantaneous phase transition.

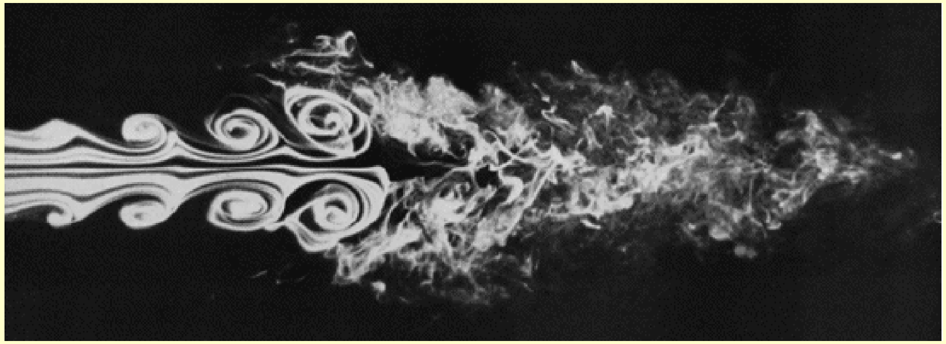
TURBULENT CONVECTION

- Turbulence is associated to transport of energy by means of a cascading process, direct and inverse. In this process all structures, at all scales, interact non-linearly.
- When a phase transition is reached, energy is liberated. Part of this energy is emitted as elastic waves, part is absorbed by the medium and part is used to account for a process of adaptation/self-organization of the system (the stress field) to a new environment.
- Is precisely this adaptive/self-organizing process that could manifest as a precursory activity.

TURBULENT CONVECTION







STRESS ACCUMULATION. 1

Since the beginning of the stress accumulation until its failure (earthquake occurrence), two different process can be distinguished (Bernard, 1999):

i. the generation of crustal instabilities (transients)

ii. the appearance of precursory activity (self-organizing process)

Relevant observations of crustal instabilities:

1) Silent and slow earthquakes
2) Fluid migration instabilities in the crust
3) Seismicity is not a Poisson process
4) Earthquake sizes have power law distributions
5) Size and roughness of fault segment follow power law distributions
6) Continuous or transient aseismic fault slips

STRESS ACCUMULATION. 2

According to the previous observations, two different physical models can be defined, that would act sequentially:

1. **Preparation-zone paradigm in seismogenesis**. Process reported in 1) to 4), and their subsequent effects (such as ground deformation and electromagnetic effects) can sometimes be recognized as being precursors to large earthquakes.
2. **Observations 5) and 6)** provides the basis for **self-organized critical models for the crust** (**SOC**), or similar models leading to a chaotic system with a large degree of freedom, in which earthquakes are inherently unpredictable in size, space and time (such as cascade or avalanche process).

Models **1** and **2** not necessarily are incompatible. At the contrary, they could be merged in a general SOC model.

However, there is no general agreement in accepting both models.

SELF-ORGANIZED CRITICALITY MODELS?

There are several important observational arguments against the applicability of SOC to the earthquake problem (Knopoff, 1999).

1. Seismicity at almost all scales is absent from most faults, before any large earthquake on that fault.
2. There is no evidence for long-range correlations of the stress field before large earthquakes.
3. Some doubts arise on the universality of power law laws for observed seismicity.
4. Faults and fault systems are inhomogeneous, and may present several scale sizes.

PRECURSORY ACTIVITY

The main problem with precursory activity is that there is no 'universal precursor'. Some precursors have been detected in seismic catalogs and in model simulations, but up to now is the whole set of observations and processes that can provide some indication (probabilistic forecasting) on the future occurrence of a large earthquake. This is the base of **'pattern recognition methods'** (Keilis-Borok and Soboliev, 2003), which are based on the analysis of fluctuations in the rates of occurrence of intermediate-magnitude earthquakes. Up to now, the developed prediction techniques are successful at about 80% level, and present an improvement over poisonian estimates of the order of 3:1.

UNIVERSAL LAWS

(generally accepted) basic and robust facts of earthquake phenomenology:

- Gutenberg-Richter law

$$\log \dot{N}(m) = -bm + \log \dot{a}$$

- Omori's law

$$\dot{n}(t) = \frac{k}{(t+c)^p}$$

HOWEVER …

- Two significantly different branches in the scaling relation have been reported in the literature:

- Knopoff (PNAS, 97 (2000)11880), M ~ 4.8
- Kanamori & Heaton (Geophys. Mon. 120 (2000) 147), $M_W > 4.5$ and $M_W < 2$.
- Ben-Zion & Zhu (Geophys. J. Int., 148(2002), F1-F5). $M_L \sim 3.5$.

AFTERSHOCK TIME SERIES

- The geometrical structure of the aftershock time series is composed of a **relaxation process** (Omori's potential law) and **fluctuations,** that can be positive (accelerations) or negative (decelerations).
- A possible pattern could emerge: in the observed aftershock time series, positive fluctuations dominate over the negative ones.

HOWEVER …

- Fluctuations are too large
- Model parameters are time dependent (back to equilibrium?)

BUT ...

Bak *et al.* (2002) attempted an explanation of **interevent time** of earthquake occurrence by unifying the observations on

- statistics of earthquakes,
- the geometrical fractal structure of hypocentral locations
- the fractal structure displayed by faults, considered all of them as a result of a dynamical process.

The underlying philosophy was (Corral, 2004)

- Do not bother about the tectonic environment.
- Do not bother about aftershocks and foreshocks, all are equally treated.
- Do not bother about temporal heterogeneity.

THE END OF SEISMIC CYCLE?

The abandon of the ingrained concept (in many seismologists' mind) of the distintion between foreshocks, aftershocks and mainshocks is an important step toward a simplification and toward an understanding of the mechanism underlying earthquake sequence.

(*Helmstetter & Sornette, 2003*)

GLOBAL SCALING LAWS. 1

Bak et al. (2002) carried out a spatiotemporal analysis over a region with a grid with cells of dimension L x L and defined the waiting time (interevent time) as the time interval of two successive events.

The distribution of waiting times T was measured between earthquakes occurring within a range L, whose magnitude are greater that **$m = m_c = \log(S)$,** S being the fault surface related to the energy as **$S \sim E^{2/3}$.**

The PDF **$P_{S,L}(T)$** of waiting times **T** can be displayed in a log-log plot in the rescaled coordinates **$x = TS^{-b}L^{df}$, $y = T^{\alpha}P_{S,L}(T)$.**

GLOBAL SCALING LAWS. 2

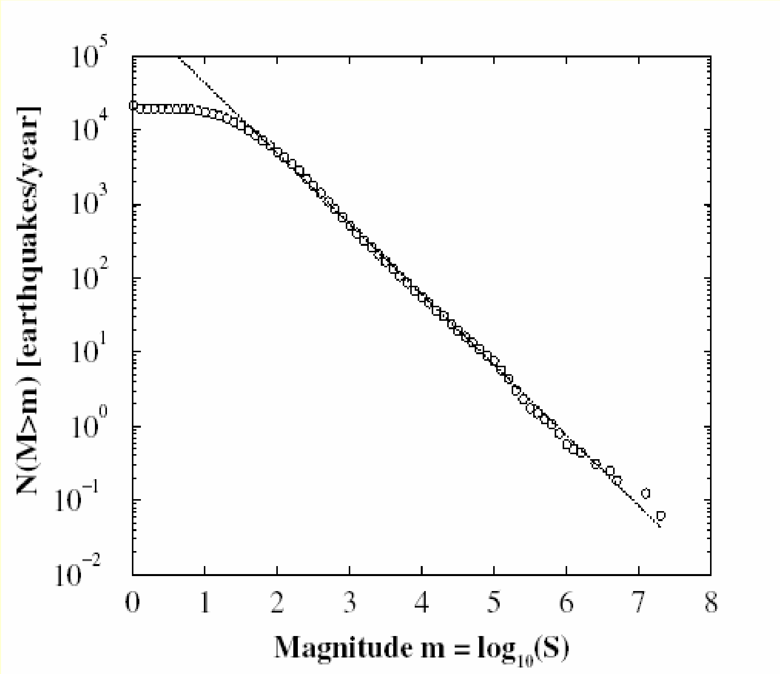
For a suitable choice on the interval exponent α, the magnitude exponent b, and the spatial dimension d_f, all the data collapse onto a single well-defined curve f(x), that is

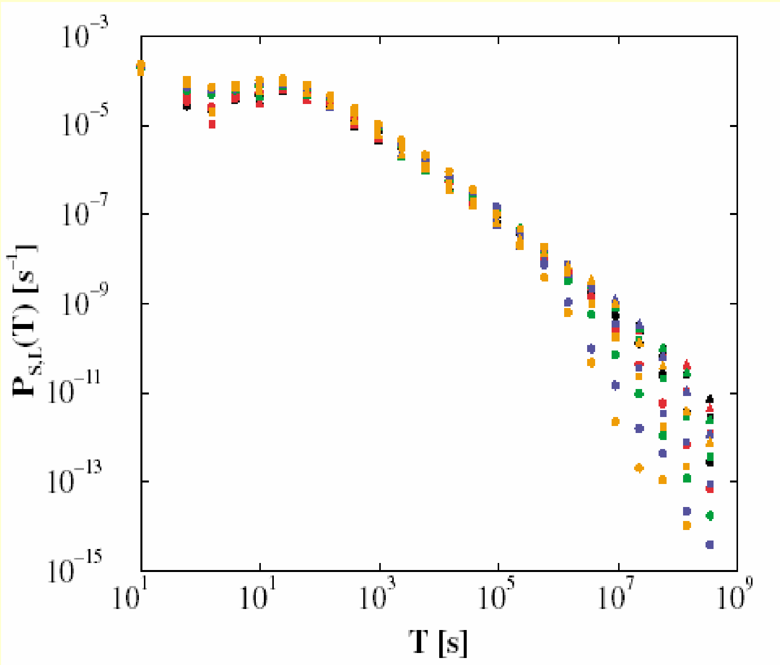
$$\mathbf{T^{\alpha}P_{S,L}(T) = f(TS^{-b}L^{df})}$$

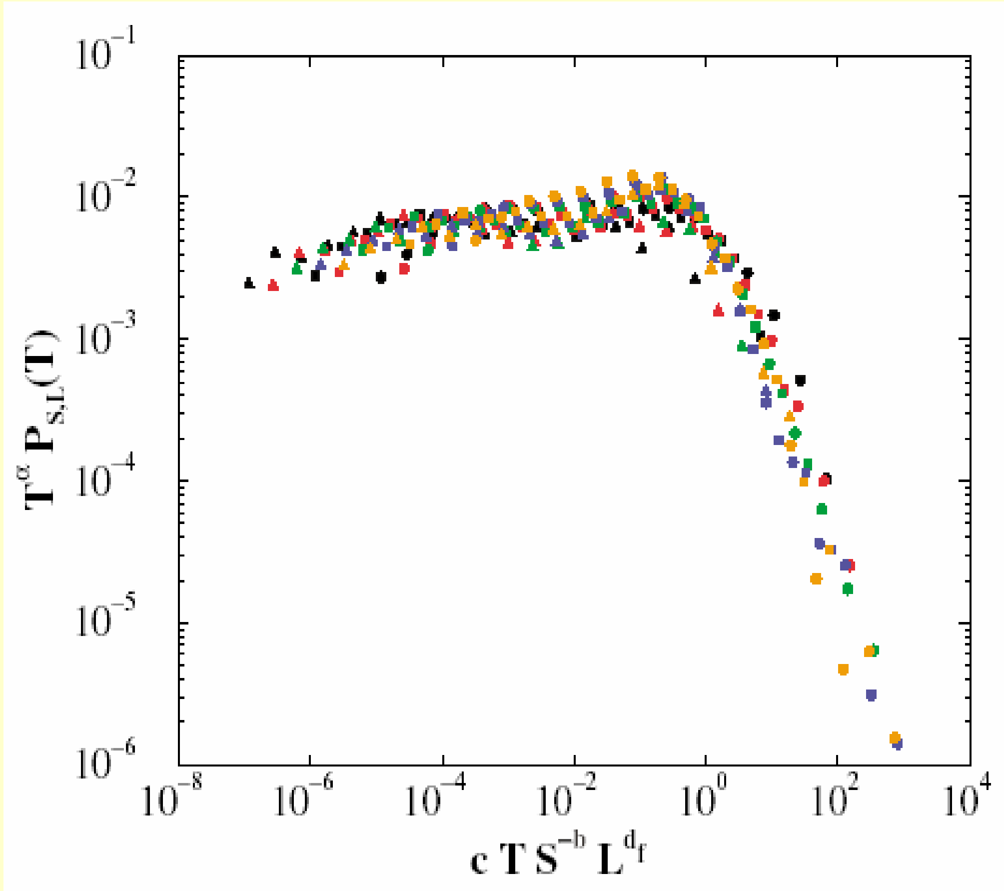
This equation expreses the **unified scaling law for earthquakes**, and consists on a constant part and a decaying part, separated by a sharp kink.

The index α ~ 1 can be identified as the **Omori-law exponent**, b ≈ 1 is the b value in the **Gutenberg-Richter law**, and $\mathbf{d_f}$ describes the 2d **fractal dimension of the epicentral distribution.**

Due to the fact that the variable $\mathbf{x = TS^{-b}L^{df}}$ has no absolute meaning, **there is no unique way of characterizing earthquakes as aftershocks or main shocks**.







The data with T > 38 s (left top) replotted with $T^{\alpha}P_{S,L}L^{df}$ as a function of the variable $x = cTS^{-b}L^{df}$, $c = 10^{-4}$. The data collapse implies a <u>unified law</u> for earthquakes. The Omori law exponent a = 1, Gutenberg-Richter value b = 1, and fractal dimension df = 1.2 have been used in order to <u>collapse all the data onto a single, unique curve *f(x)*.</u> The estimated uncertainty in the exponents is less than 0.2.

PROBABILITY DISTRIBUTION FUNCTION. 1

Write $D(\tau, mc, L) \equiv P_{S,L}(T)$, $\tau \equiv T = t_i - t_{i-1}$. It has been found:

- $D(\tau, m_c, L)$ behaves as $1/\tau$ for short times
- $D(\tau, m_c, L)$ displays a faster decay for longer times, with a dependence also on L and m_c.

After rescaling by S^b/L^{df}, the PDF reads

$$D(\tau, m_c, L) \simeq \frac{L^{d_f}}{S^b} F\left(\frac{L^{d_f}}{S^b}\tau\right) = \frac{1}{\tau} G\left(\frac{L^{d_f}}{S^b}\tau\right)$$

PROBABILITY DISTRIBUTION FUNCTION. 2

For short times, the function G shows a slow variation not affecting the power law ($1/\tau$) behavior.

For long times a fast decay is obtained, which could be consistent with an exponential distribution and therefore with a Poisson process.

This PDF is relevant because

- shows a spatiotemporal occurrence of earthquakes (as in critical phenomena)
- relates interevent times with the G-R law and the epicentral distribution of earthquakes
- is valid for all kind of events (foreshocks, mainshock, aftershocks)
- the power law tells us that immediately after an earthquake there is a high probability of return, probability that decreases in time.

GLOBAL SCALING LAWS. 3

The scaling function f can be represented mathematically as

$$f(\theta) = \frac{C|\delta|}{a\Gamma(\gamma/\delta)} \left(\frac{\theta}{a}\right)^{\gamma-1} \mathrm{e}^{-(\theta/a)^{\delta}}$$

Where $\theta \equiv R_{xy}\tau$ is a dimensionless time, γ and δ controls the shape of the PDF, a is a scale parameter and C a normalization correction.

OBSERVED PDF D(τ) FOR THE INTEREVENT TIME

594 Á. Corral / Physica A 340 (2004) 590–597

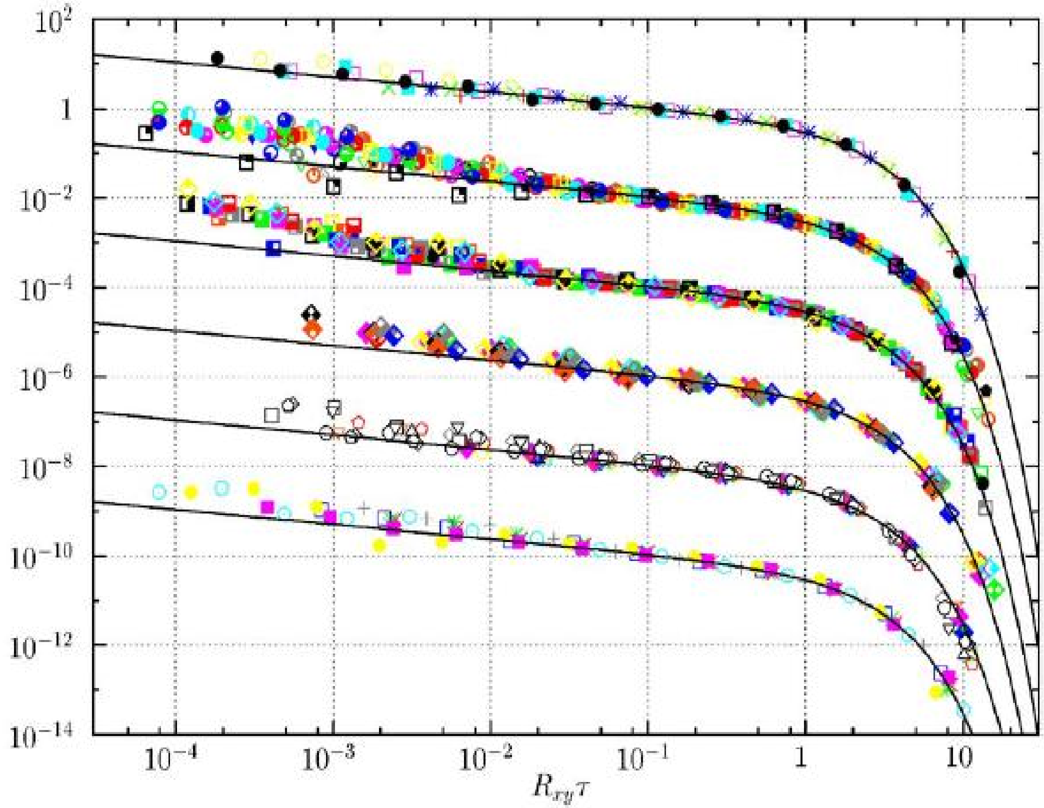


Fig. 1. Single-region recurrence-time probability densities, D_{xy}, after rescaling with the rate R_{xy}.

EARTQUAKE OCCURRENCE AS A SELF-ORGANIZING PROCESS

TABLE I. HALLMARKS OF SELF-ORGANIZATION

Parameters

Parameters	**Convection**	**Seismogenesis**
Control parameter	Gradient of temperature	Strain
Order parameter	Amplitude of fluctuation (displacement, velocity)	Rate of released energy
Threshold	Gradient of temperature	Gradient of deformation

TABLE I. HALLMARKS OF SELF-ORGANIZATION

Dynamics

Physical Process	Convection	Seismogenesis
Phase transition	Onset of convection (bifurcation point)	Onset of intermittency (bursts of energy release)
Self-organization	Convective cells Turbulent convection	Emergence of Spatio-temporal patterns
Phase transition	Onset of turbulence	Failure (earthquake)

OBSERVABLES

Our goal is to infer the occurrence time, location and magnitude of the next event from observations made during the self-organizing process along with a good body of theory.

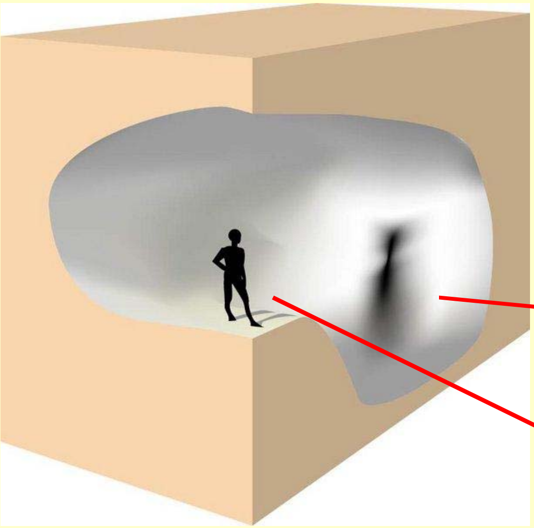
We should emphasize that the main **observables** will be the **time variations of the structures**.

This is what we term **precursory activity**. As the underlying physics of earthquake occurrence is very elusive, the planned problem is: **which are the precursors we have to look for, where and when?**

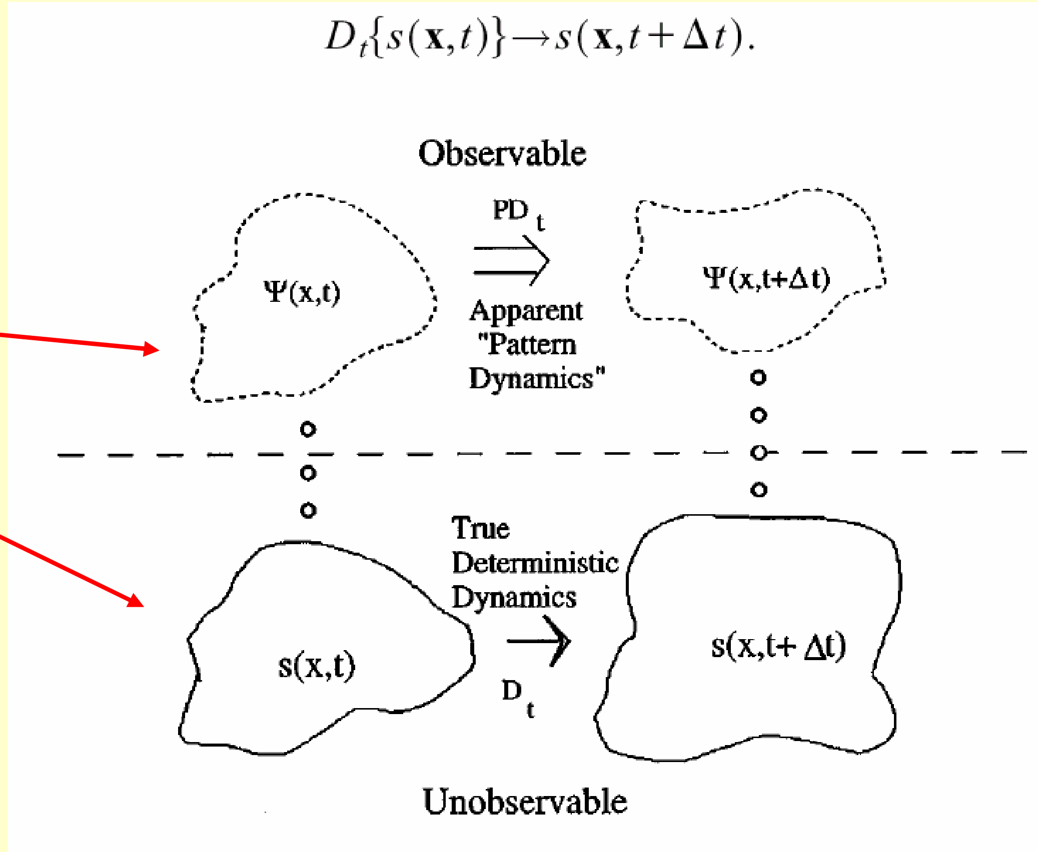
Similarly to **turbulent convection**, we are dealing with a physical system characterized by a **continuous aport of energy**. The deformation potential will be continuously increasing, and because of medium inhomogeneities the energy will be primarily released at the weakest zones.

Hence, the most promising observable is the **evolution of seismicity**.

THE MITH OF THE CAVERN & THE SEISMIC OBSERVABLES



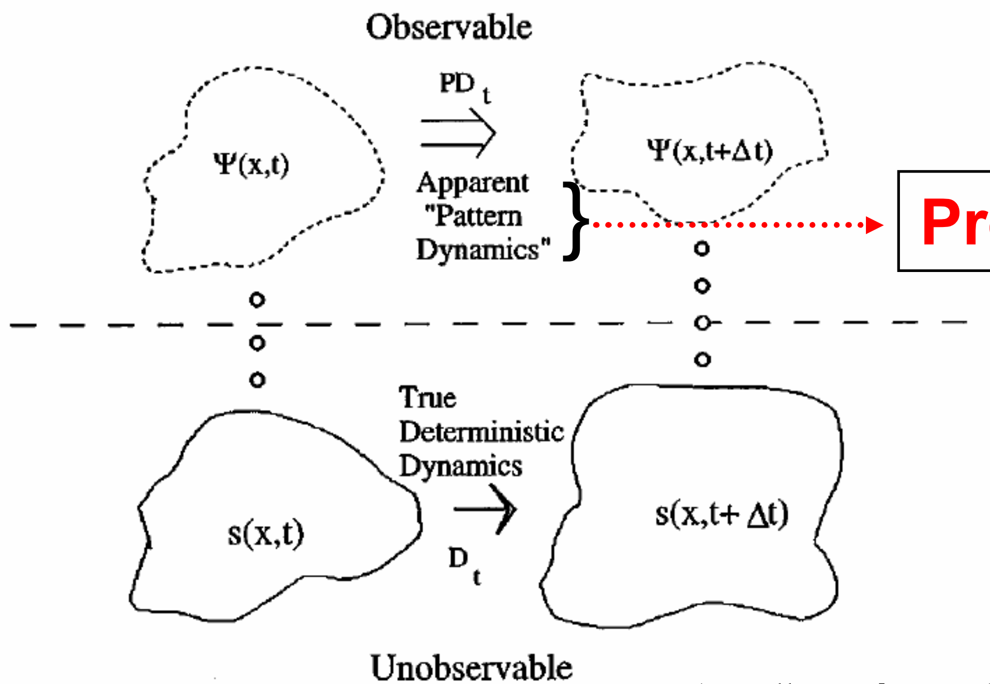
Plato, Myth of the Cavern



FORECASING OF EARTHQUAKES

Let D_t be an (unknown) operator that describes the evolution of the system, at a given fixed point x, from a time t to a time t+Δt. The dynamics of the real system is not an observable: the only ***observable*** will be its projection PD_t.

$$D_t\{s(\mathbf{x},t)\}\rightarrow s(\mathbf{x},t+\Delta t).$$



(Rundle *et al.*, 2000)

Which manifestations?

Precursory activity

They should be determined from:

- theoretical approaches
- observations

PREDICTION

The aim on any scientist is to advance the future evolution of the system under study. Three different kinds of prediction can be distinguished:

- **Deterministic prediction** (individual events, based on linear-physical models): when will occur the next solar eclipse, visible from Reus (Spain)? (On 12 August 2026. It will be total, withm magnitude 1.0035 and will begin at 17h, 35m, 26.0 UT).
- **Probabilistic prediction or forecasting** (evolution of a physical system, based on -non-linear- physical models): which will be the weather for New Year? (It can be sunny or unpleasant. We will not be able to be more precise until a few days before).
- **Oracles** (not scientific): will I succeed in my job? (The conditions are favorable, but the vision of a black cat over the left shoulder can spoil it all).

PRECURSORS

IASPEI Preliminary List of Significant Precursors

Only five possible precursors, out of the forty proposed, seem to deserve further study *(Wyss, 1997)*:

- one based on ground water chemistry
- one based on deformation of the crust
- three based on **seismicity patterns**

GENERALIZATION OF THE CONCEPT OF PRECURSOR

Precursors: (dynamical) self-organized pattern in observables, generated when the system approaches a critical state.

● **Observational difficulty of precursors:**

- the time series associated to natural phenomena are non-stationary and/or intermittent.

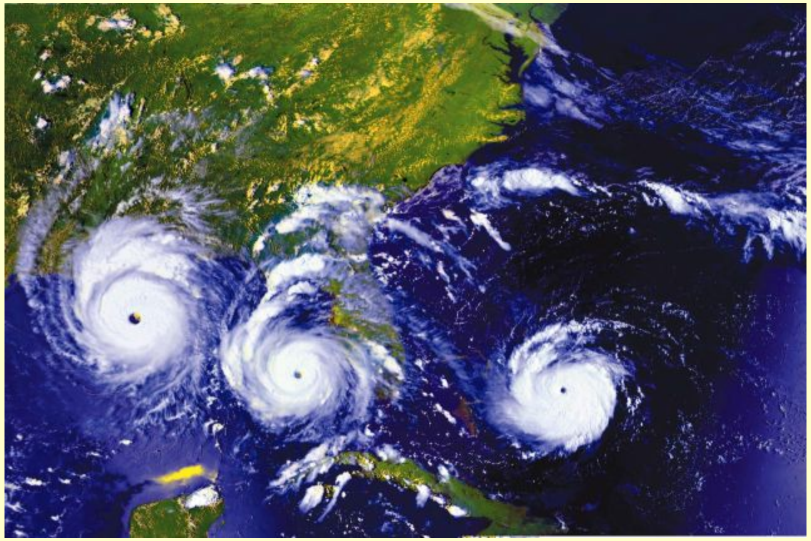
  and/or

- there are some in the data, but we haven't found them yet.
- there are some, but not in the data currently available.
- there aren't any.

● **Complex systems:** for some spacio-temporal scales, natural phenomena are highly organized.

NATURAL & MAN-MADE ORGANIZED SYSTEMS

hurricanes



tornados

galaxy

thermonuclear explosion

TIME TO FAILURE: A PRECURSOR?

An example of a self-organizing dynamical pattern is the time evolution of the deformation field. In approaching the failure (earthquake), the temporal evolution of the deformation (sometimes) organizes as a power law in time:

$$\Omega(t) = A + B(t_f - t)^m$$

where $\Omega(t)$ is the cumulative deformation.

The deformation field $\Omega(t)$ can be estimated in terms of direct measurement of the deformation, the released seismic energy or the rate of seismicity.

Time to failure is not a universal feature

(No any single precursor is a universal feature!)

UNIVERSAL PATTERNS: AN ILLUSION?

UP TO NOW, NO UNQUESTIONED UNIVERSAL BEHAVIOR (PRECURSORY PATTERN) HAS BEEN DETECTED. DO THEY REALLY EXIST ?

The idea of universality appears in the theory of critical phenomena. Close to the critical point the observables self-organize as power laws, with the same value of the exponents for different phenomena. Is in this context that we can talk about **universality**.

Different instabilities may drive the system to failure (the critical point), and no one predominates over the others. Which one will select the system will depend on the initial conditions. Hence, we cannot pretend that the precursory patterns will repeat in some pre-established way. Indeed, a premonitory phenomenon may have different manifestations in different timescales, geographical regions and magnitude ranges.

THE UNIVERSAL BEHAVIOR HAS TO BE UNDERSTOOD IN THE SENSE OF THE BEHAVIOR OF THE WHOLE SET OF OBSERVABLES.

PREDICTION

Basically there are two methods for the forecasting of future activity:

- **Pattern Recognition**
  - Time of increased probability, **TIP** (Keilis-Borok and Soboliev, 2003)
  - Phase Dynamics (Rundle et al., 2000)
- **Probabilistic**
  - Previous activity + some *reasonable* assumption (Rikitake, 1976; Kagan and Jackson, 2000; and a lot more …)

BASIC TYPES OF PREMONITORY PHENOMENA

The approach of a strong earthquake is indicated by (some of) the following

changes in the basic characteristics of seismicity:

a. Rise of seismic activity.

b. Rise of irregularity in space and time.

c. Reversal of territorial distribution of seismicity.

d. Transformation of magnitude distribution.

e. Rise of earthquake clustering in space and time.

f. Rise of the earthquake correlation range.

g. Accelerated stress-release

EQUIVALENCE TO TURBULENT CONVECTION

a. Rise of seismic activity

development of convective cells

b. Rise of irregularity in space and time

c. Reversal of territorial distribution of seismicity

turbulent convection

d. Transformation of magnitude distribution

approach to critical point

e. Rise of earthquake clustering in space and time

f. Rise of the earthquake correlation range

g. Accelerated stress-release

close to critical point

A POSSIBLE STRATEGY FOR THE STUDY OF PRECURSORY ACTIVITY (pattern formation)

Why is there Something instead of Nothing? (Leibniz)

Homogeneous (amorphous) vs. inhomogeneous (structured)

Actors
and
spectators
(N. Bohr)

THE CUBIC GINZBURG-LANDAU EQUATION

The cubic Ginzburg-Landau equation is one of the most studied nonlinear equations. It describes on qualitative, and often in a quantitative, level a vast variety of phenomena, from nonlinear waves to second-order phase transitions, from Rayleygh-Benard convection to pattern formation, apart of others in condensed matter physics. It is specially addressed to the study of non-equilibrium phenomena in spatially extended systems.

THE COMPLEX G-L EQ. 1

The Equation is given by

$$\partial_t A = A + \left(1 + ib\right) \Delta A - \left(1 + ic\right) \left|A\right|^2 A$$

where *A* is a complex function of (scaled) time t and space **x** and the real parameters b and c characterize linear and nonlinear dispersion. This equation arises as a “modulational” (or “envelope” or “amplitude”) equation. In analogy with phase transition, A is often called an ***order parameter***.

The physical quantities **u**(t,r) (temperature, velocities, densities, *etc*.) are given in the form

$$\vec{u} = A' \exp\left[i \left(q_c . x - \omega_c t \right) \right] U_l(z) + c.c. + h.o.t.$$

U_l is an eigenvector of the linear approximation, and ω_c and $\mathbf{q}_c$ the corresponding eigenvalues.

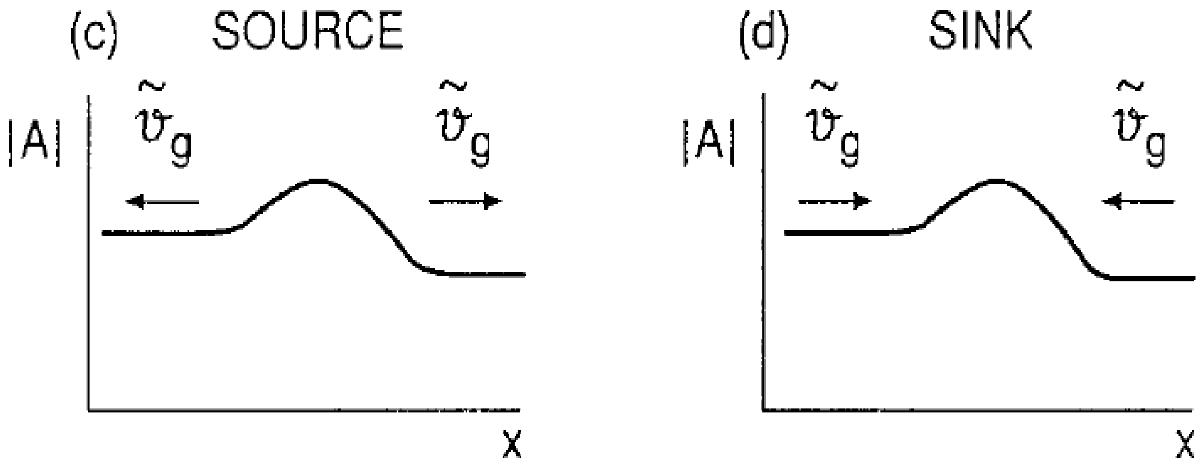
THE COMPLEX G-L EQ. 2

- This equation has regimes where the behavior is intrinsically chaotic, and is often studied as a prototype equation for ***spatio-temporal chaos*** and ***pattern-formation***.
- This equation can generate a large variety of ***coherent structures***. The most interesting are ***front***, ***pulse***, ***source*** and ***sink***. The precursory seismic activity would be associated to the generation and evolution of these structures, *i.e.*, to the process of **self-organization**.

Coherent Structures

sources and sinks

parting travelling waves — colliding travelling waves



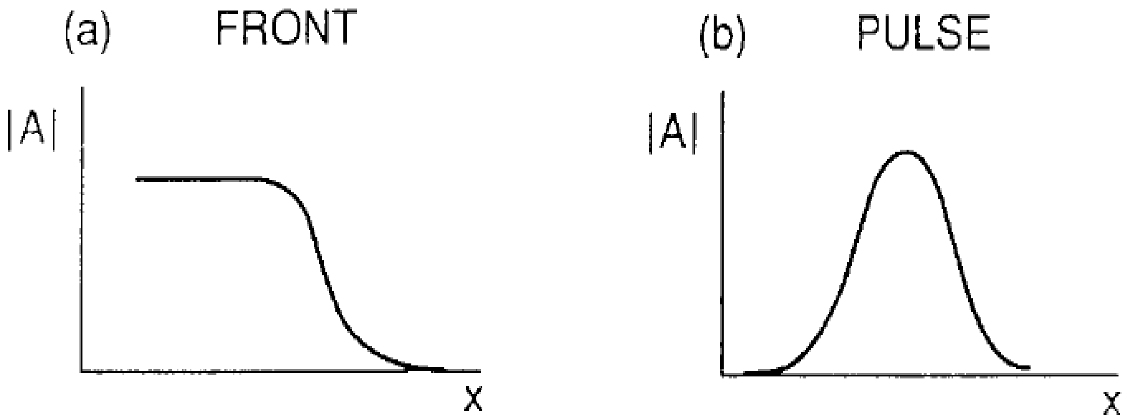
$$\tilde{v}_g := v_{\text{group}} - v_{\text{structure}}$$

van Saarlos

27

Coherent Structures

fronts and pulses



occur in quintic CGLE

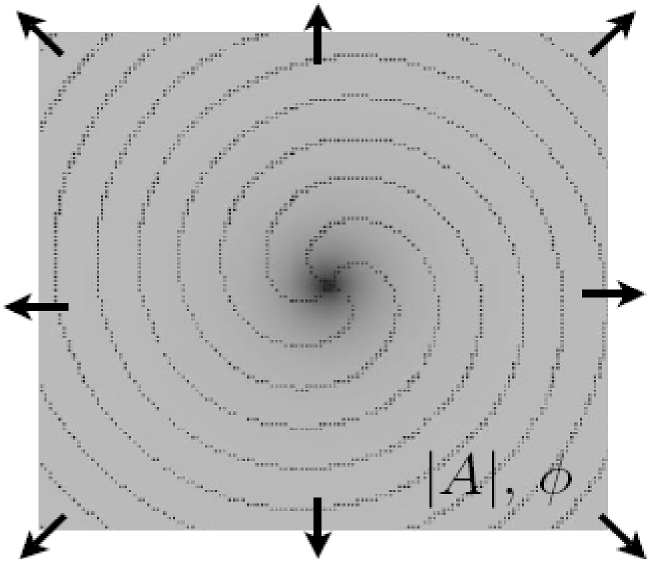
Aranson & Kramer

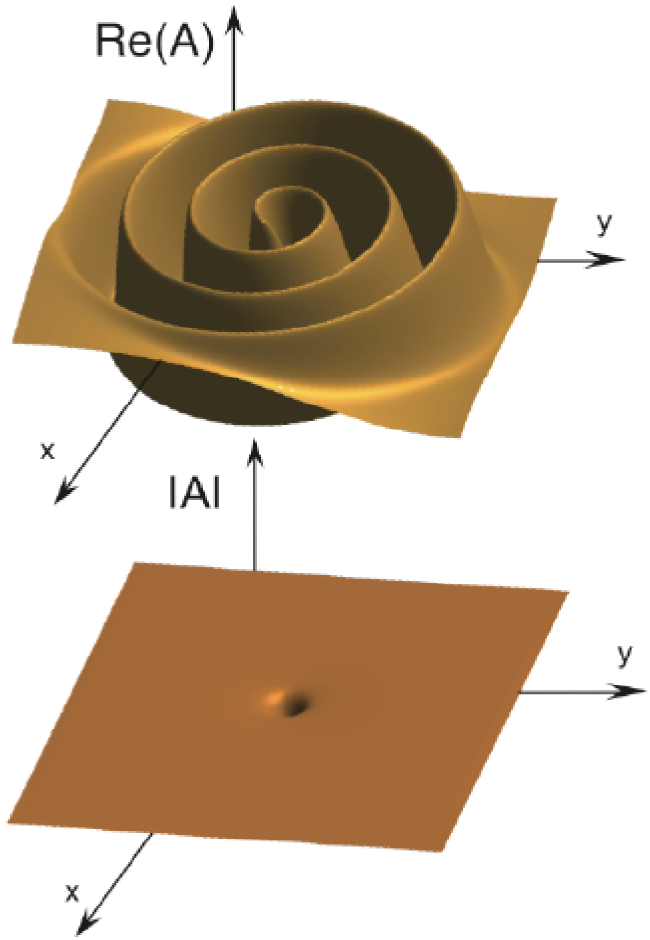
28

Two-dimensional Phenomena

spiral waves

$$A(r,\theta,t) = F(r)\mathrm{e}^{\mathrm{i}[-\omega t + m\theta + \psi(r)]}$$

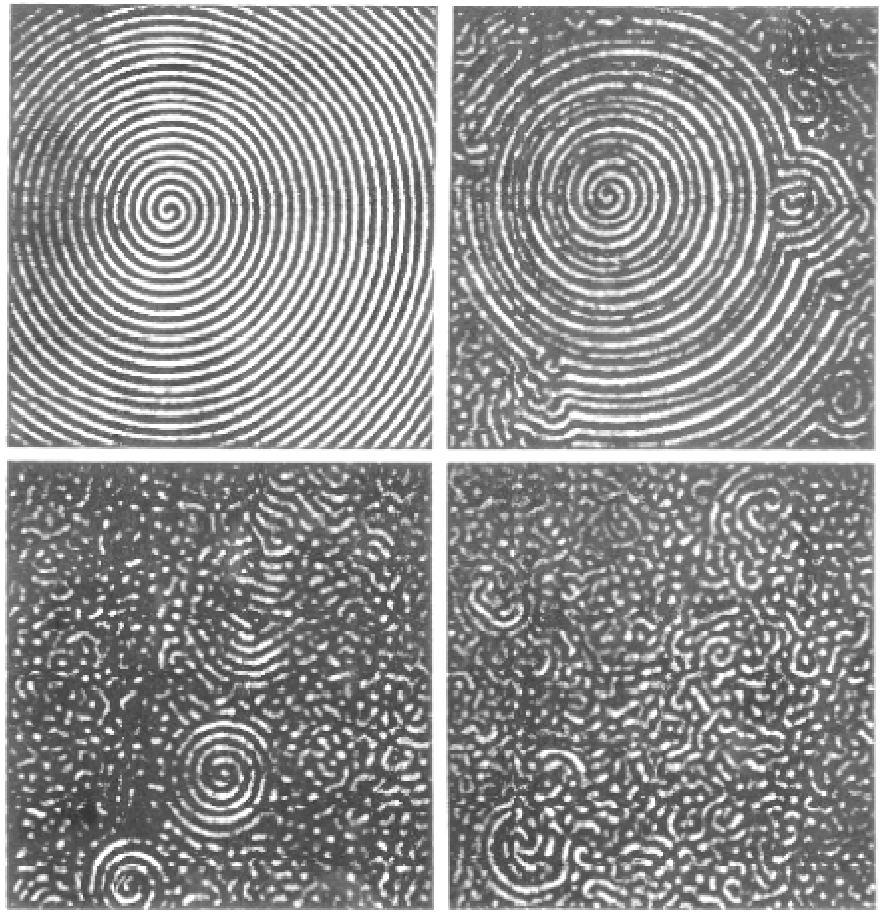




emitting plane waves with

$$Q_{\mathrm{asympt}} = \partial_r \psi \big|_{r\to\infty}$$

Aranson & Kramer (edited)
created by P. Collet, courtesy of Lorenz Kramer



different parameters

Kauffman, S.: *Der Öltropfen im Wasser*. Piper Verlag, München 1996
Oyang, Flessels in *Nature*, 379 (1996)

THE COMPLEX G-L EQ. 3

i. **$\omega_c = 0$, $q_c \neq 0$** define stationary periodic instabilities, and the complex Ginzburg-Landau equation reduces to the real one

$$\partial_t A = A + \Delta A - |A|^2 A$$

also known as the *Complex Nonlinear Diffusion Equation* by analogy with the Nonlinear Schroedinger Equation. This is the case of the Rayleigh-Benard convection.

ii. **$\omega_c \neq 0$, $q_c = 0$** represent oscillatoriy uniform instabilities.

iii. **$\omega_c \neq 0$, $q_c \neq 0$** represent propagating instabilities.

These different possibilities agree with the observed seismicity patterns.

EQUIVALENCE TO TURBULENT CONVECTION

a. Rise of seismic activity

development of convective cells ($\omega_c = 0, q_c \neq 0$)

b. Rise of irregularity in space and time

c. Reversal of territorial distribution of seismicity

turbulent convection ($\omega_c \neq 0, q_c = 0$)

d. Transformation of magnitude distribution

approach to critical point

e. Rise of earthquake clustering in space and time

f. Rise of the earthquake correlation range

g. Accelerated stress-release

close to critical point ($\omega_c \neq 0, q_c \neq 0$)

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