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A Physical Scenario for Earthquake Prediction

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PHYSICAL BASES FOR EARTHQUAKE PREDICTION

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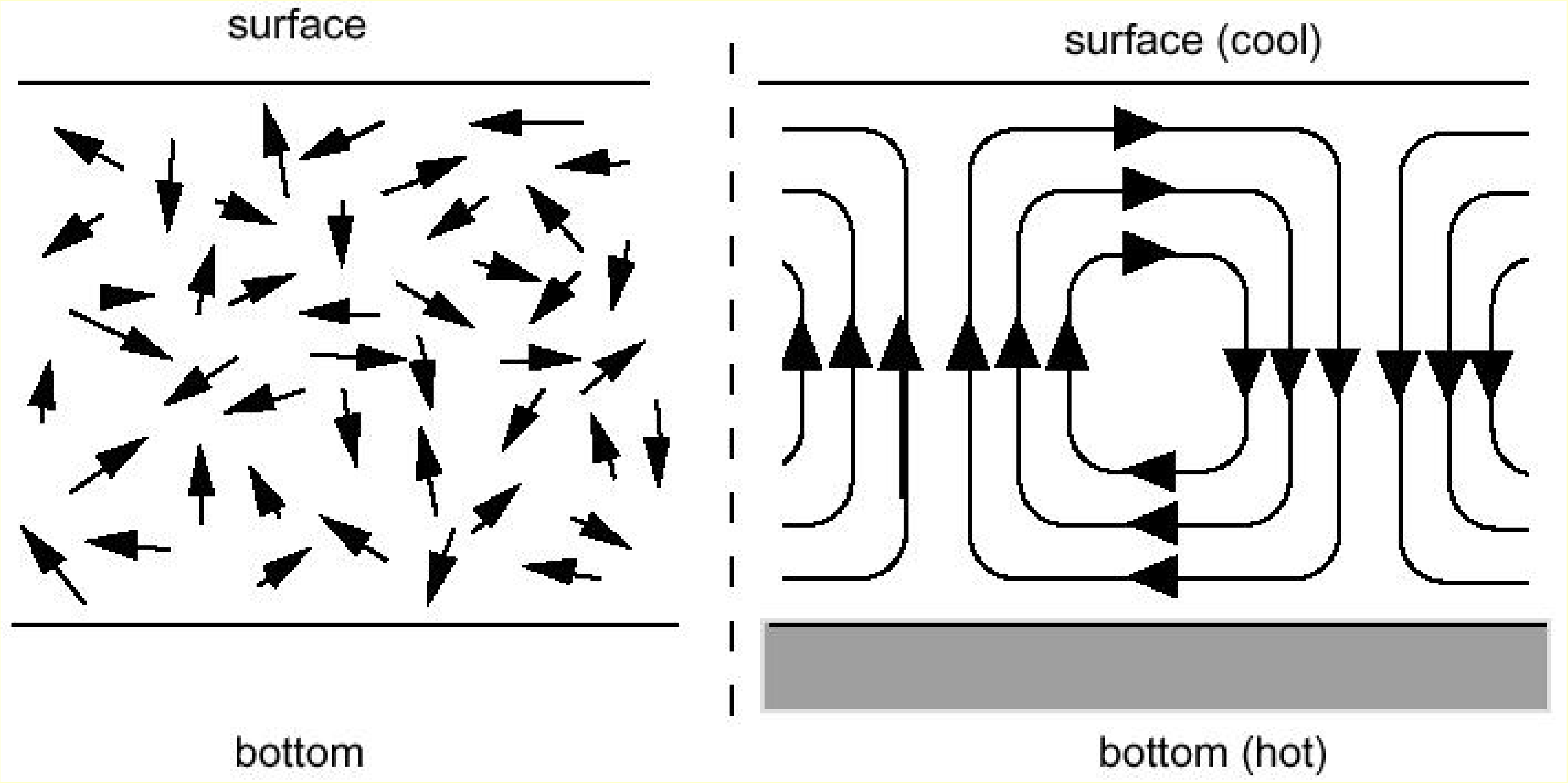
EARTHQUAKES AS CATASTROPES

- 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**.

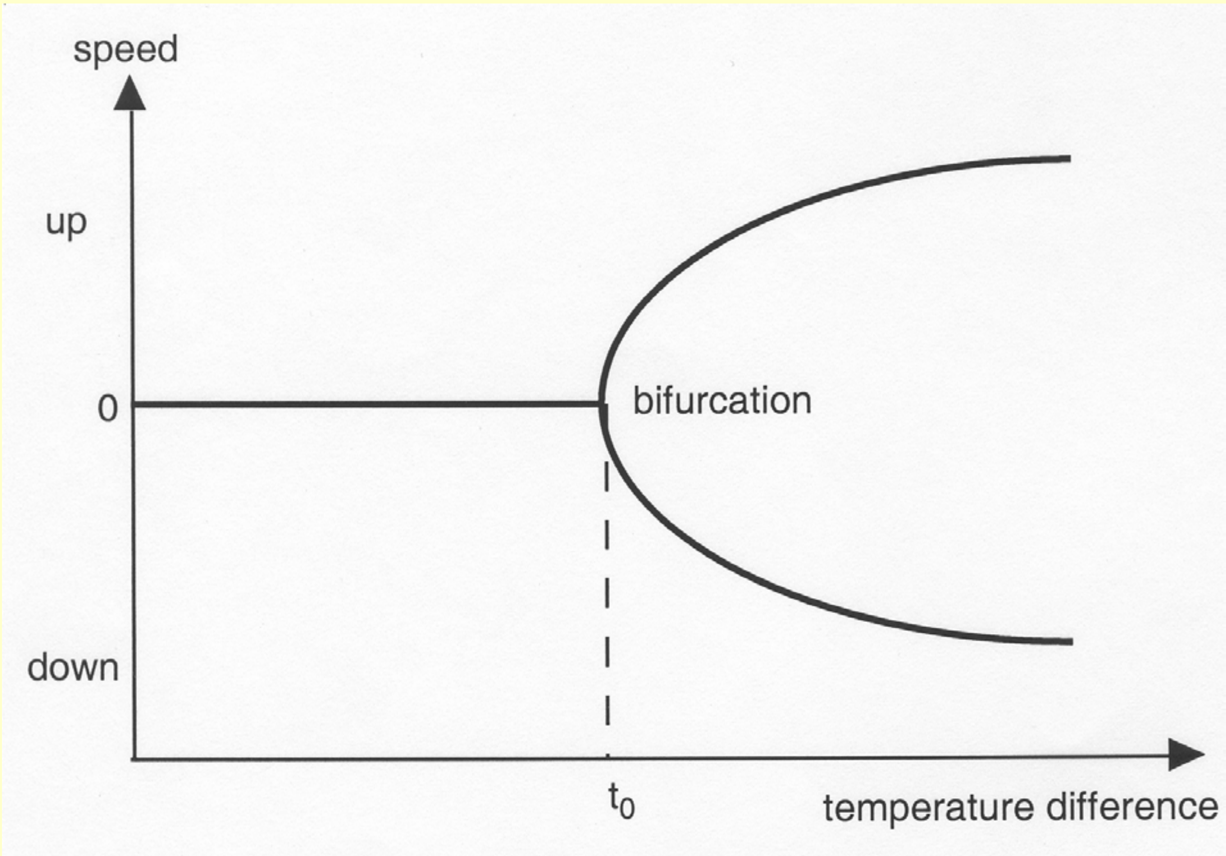
PHYSICAL SCENARIO

- Plate Tectonics provides a mechanism to explain earthquake occurrence as a **recurrent phenomenon**, defining cycles.
- The physical scenario of earthquake occurrence is that of a **dissipative complex system**, with an input (at a variable rate) of energy, that is suddenly released (*failure*). This process repeats again and again, defining earthquake cycles.
- The framework of earthquake processes is that of **far from equilibrium systems**.

PARADIGMATIC EXAMPLE OF FAR FROM EQUILIBRIUM SYSTEMS: RAYLEIGH-BENARD CONVECTION



CONVECTION THRESHOLD: A BIFURCATION POINT



EQUILIBRIUM SYSTEMS: ISING MODEL

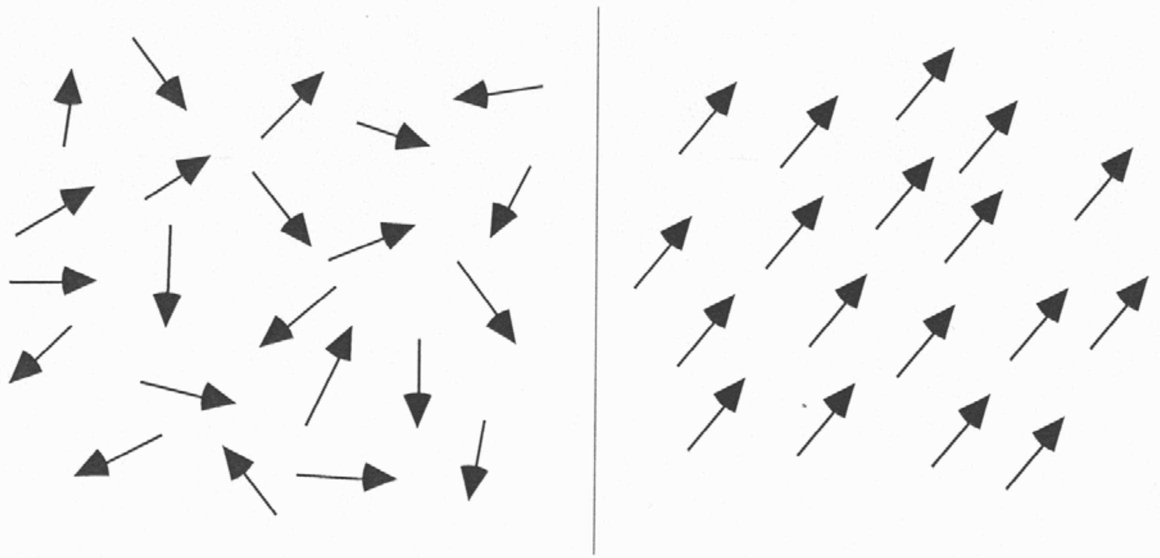
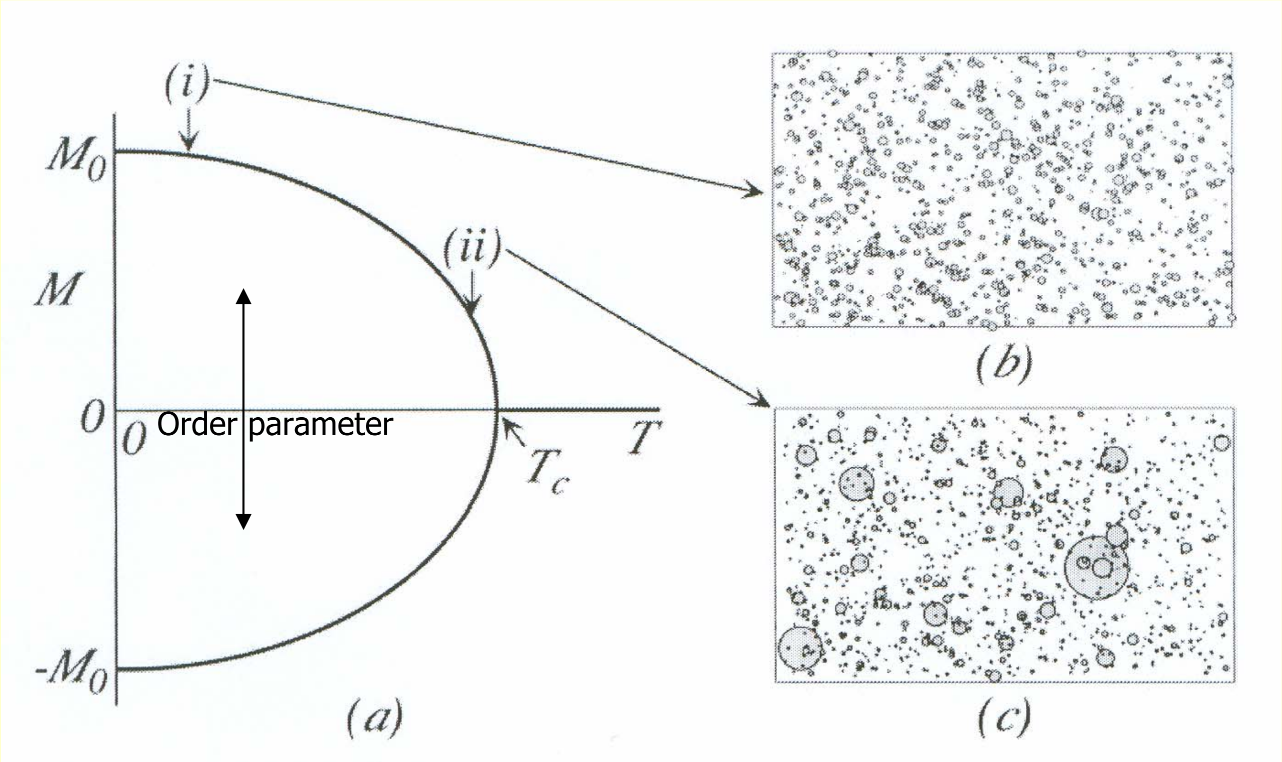


Figure 1: two arrangement of spins: disordered (left) and ordered (right)

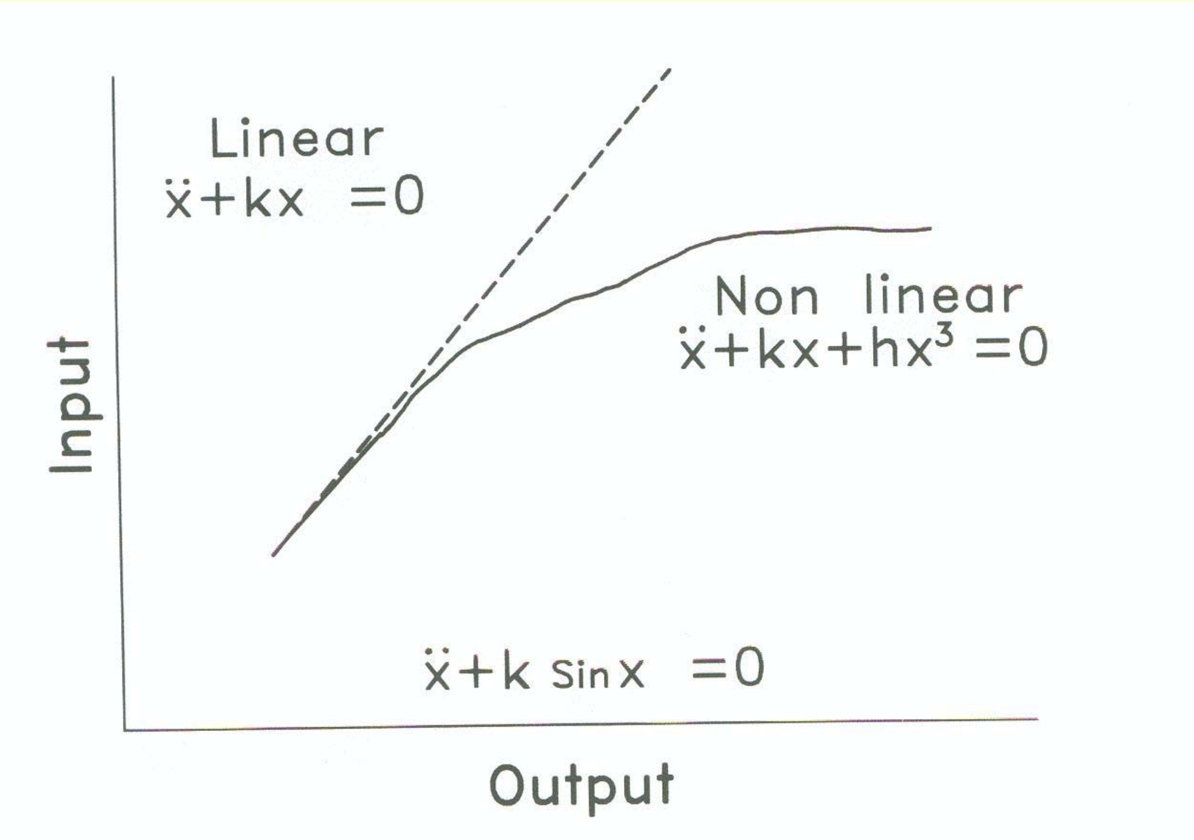
2nd. ORDER PHASE TRANSITION



Order (or control) parameter: a measure of the 'fight' between **order** (interactions between the constituent of the system) and **disorder** (noise or thermal fluctuations).

correlation length: grows in approaching the critical point, following as power law.

NON-LINEAR SYSTEMS



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.

⟶ **NOT YET EXPLORED!**

The Real Ginzburg-Landau Equation

Amplitude equation near the threshold of an instability

$$\frac{\partial \mathbf{A}}{\partial \mathbf{t}} = \frac{\partial^2 \mathbf{A}}{\partial \mathbf{x}^2} + \varepsilon \mathbf{A} - |\mathbf{A}|^2 \mathbf{A}$$

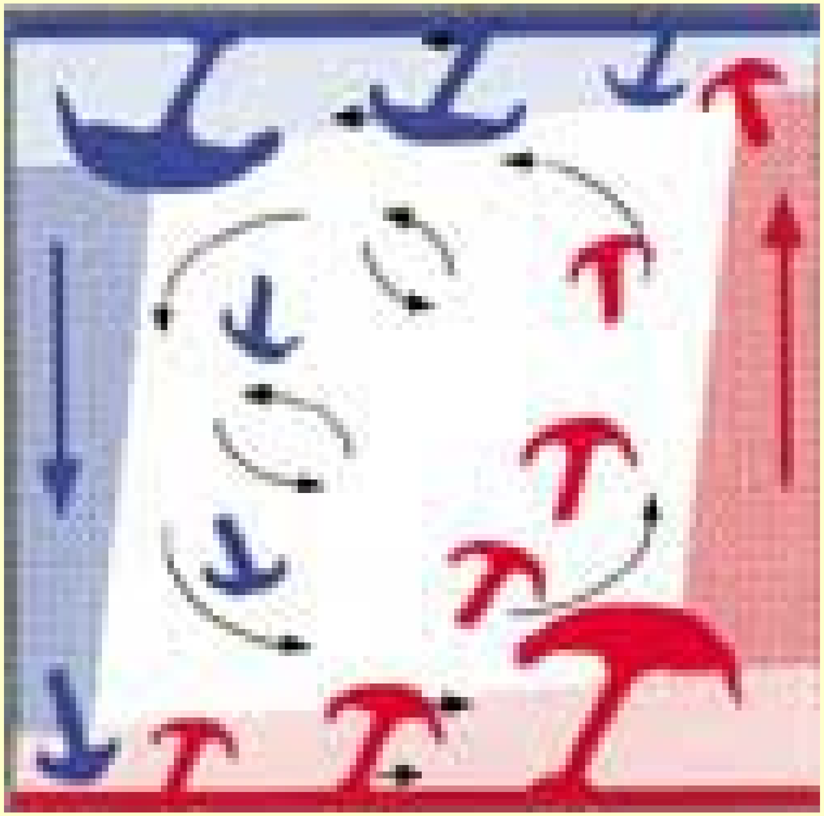
Where **A**(x,t) is the complex amplitude or envelope of the relevant field close to threshold:

$$\textit{Physical field} \sim A(x,t)^{ikx} + c.c. + h.o.t.$$

Turbulent Convection. 1

- Turbulence is associated to **energy transport** through cascades, direct and inverse. During this process, structures at all scales interact nonlinearly.
- When a structure is destroyed (*i.e.*, an episode in a volcanic process), part of the energy may be released, and part is used in a process of **adaptation/self-organization** of the system (*i.e.,* the stress field) to a new environment, created by the occurrence of the episode.
- This adaptation process should be reflected as observable patterns: the **precursory activity** or **premonitory phenomena**.

Turbulent Convection. 2



(Kadanoff , Physics Today, August 2001, p.34)

The Complex Ginzburg-Landau Eq. 1

Amplitude equation for a traveling wave near the threshold of instability.

In this case:

$$Physical\ field \sim A(x,t)^{-i(\Omega t + kx)} + c.c. + h.o.t.$$

The corresponding amplitude equation reads

$$\frac{\partial A}{\partial t} = (1 + ic_1)\frac{\partial^2 A}{\partial x^2} + \varepsilon A - (1 - ic_3)|A|^2 A.$$

The Complex Ginzburg-Landau 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**.

Hallmarks of Self-organization

	convection	earthquake occ.
Control parameter	Temperature	Strain
Order parameter	Amplitude of fluctuation (displacement, velocity)	Rate of released energy
Threshold	Gradient of temperature	Gradient of deformation
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)

PREDICTION. 1

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)

PREDICTION. 2

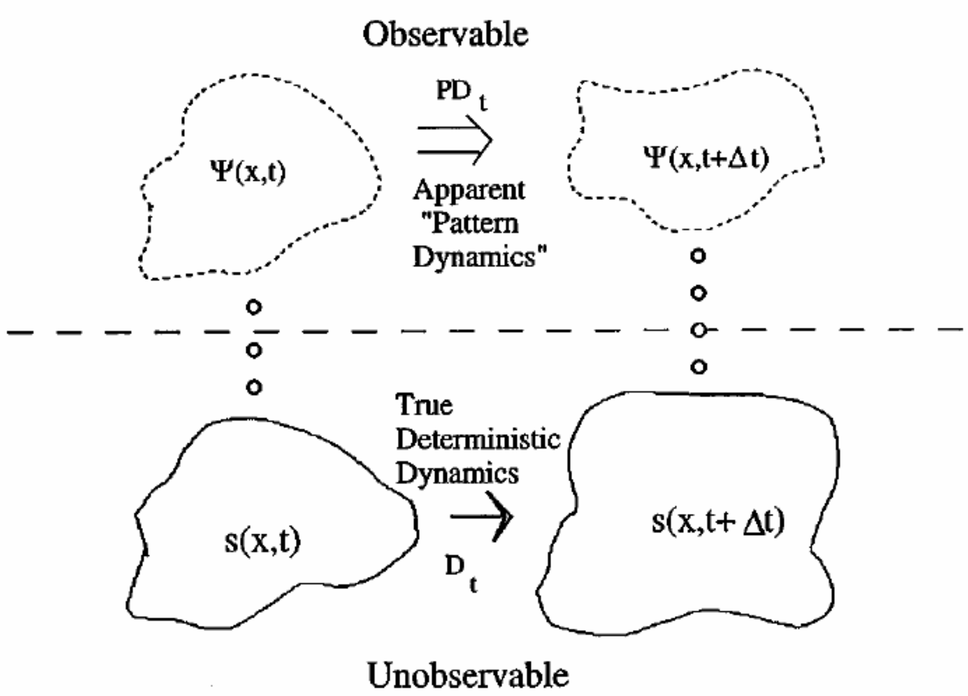
- When will occur the next solar eclipse, visible from Barcelona? (On 3 October 2005. It will be partial and will begin at 7 h 41 m 07 s, UT).
- Which will be the weather for New Year? (It can be sunny or unpleasant. We will not be able to be more precise until a few days before).
- Will I succeed in my job? (The conditions are favorable, but the vision of a cat can spoil it all).

PREDICTION. 3

- Deterministic prediction (individual events, based on –linear- physical models).
- Probabilistic prediction or forecasting (evolution of a physical system, based on -non-linear- physical models).
- Oracles (not scientific)

OBSERVABLE PATTERNS

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



(Rundle *et al.*, 2000)

PATTERN DYNAMICS

The analysis and quantification of the apparent **Pattern Dynamics** (the observables), that will bring us with the possibility of forecasting (*predicting*) future earthquakes, relies on the correct identification of precursory activity, *i.e.*, on the identification of true **precursors**.

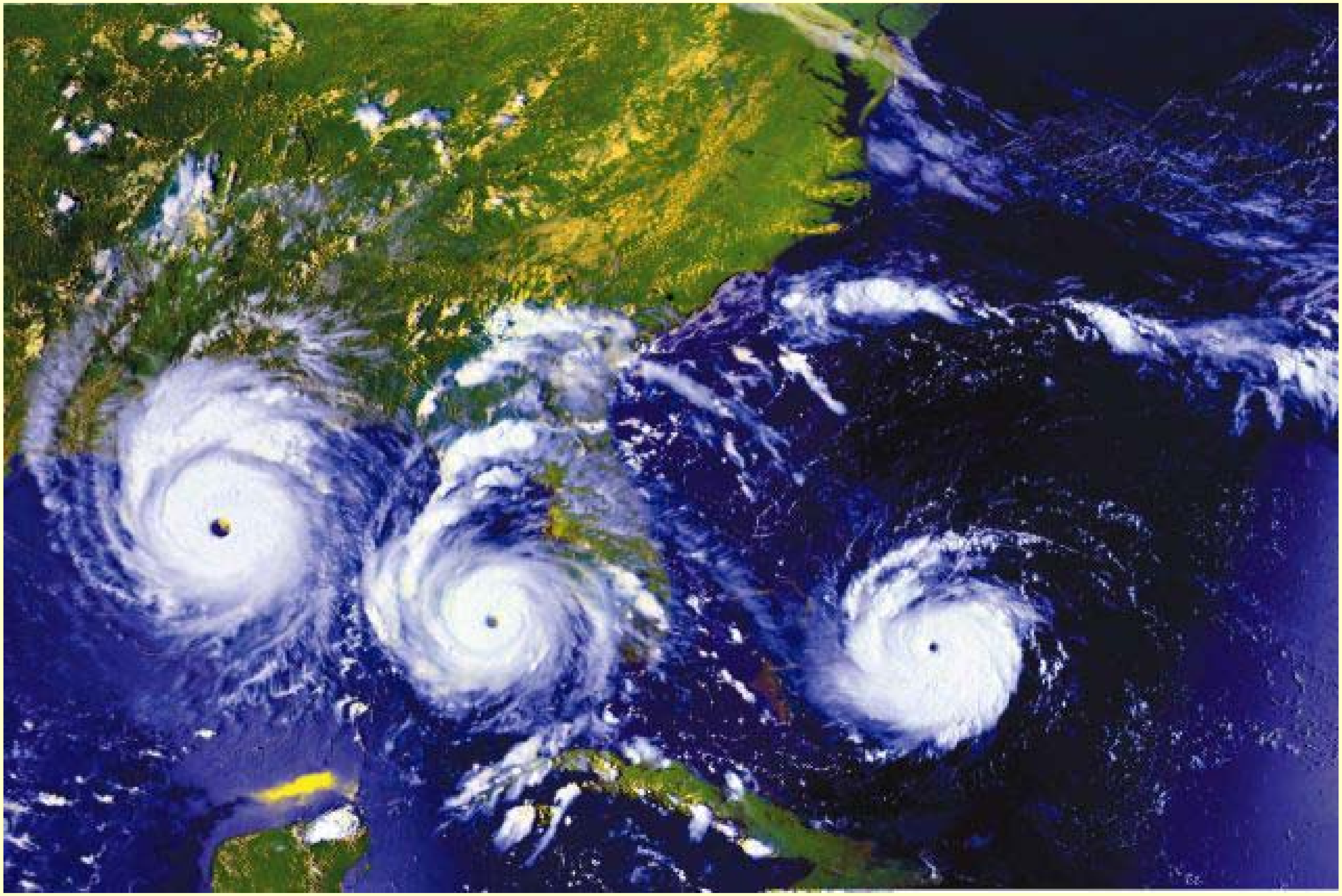
PRECURSORS. 1

- **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.

HURRICANES: NATURAL ORGANIZED SYSTEMS



TORNADOS: NATURAL ORGANIZED SYSTEMS

Figure 1-8

A Galaxy

This spectacular galaxy contains several hundred billion stars. The galaxy's spiral arms are outlined by many nebulae, which are sites of active star formation. This galaxy, with a diameter of about 130,000 light-years, is about 65 million light-years from Earth. (Anglo-Australian Observatory)

Figure 1-5

A Thermonuclear Explosion

Understanding the Sun's source of energy has given humanity the ability to build thermonuclear weapons. The hydrogen bomb and the thermonuclear reactions at the Sun's center both operate under the same basic physical principle: the conversion of matter into energy. This thermonuclear detonation on October 31, 1952, had an energy output, or "yield," equivalent to 10.4 million tons of TNT. (Defense Nuclear Agency)

PRECURSORS. 2

- A precursor must be understood as the manifestation of the evolution of patterns or s*tructures,* defined as a *collectivity of events*, not as individual events.
- From another point of view, a precursor must be viewed not as a local observable, but as a global one: as an emergent structure that develops during a self-organizing process.

PRECURSORY ACTIVITY
(a possible example)

A physical process that gives rise to a precursory structure is the time evolution of the deformation field. In approaching the failure, the temporal evolution of the deformation organizes as a power law in time:

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

where Ω(t) is the cumulative deformation.

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

Universal Laws

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

- Gutenberg-Richter law

- Omori's law

Break down of scale invariance?

- Two significantly different branches in the scaling relation have been lately 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. 1

- 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 seem to emerge: positive fluctuations dominate over the negative ones.

Aftershock time series. 2

- A lot of mean field models have been constructed to deal with aftershock, some of them based on physical grounds (Yamashita (2003), GJI, 152, 20-33) and some other, based on the validity of universal laws of O and G-R (Helmstetter & Sornette (2003), 107(B10), 2237, doi: 10.1029/2001JB001580, 2002). None of them, however, account for fluctuations or time variation of model parameters.
- Moreover, every model is able to explain some specific features, but not other.

Aftershock time series. 3

- In some way, aftershocks are similar to precursors:

  - not always appear
  - not always repeat

Break down of Omori's law?

- Fluctuations too large
- Time dependent model parameters

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 et al. 2003*)

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 …)

TIME OF INCREASED PROBABILITY. 1

- **Physical basis**: the dynamics of the lithosphere viewed as a non-linear hierarchical dynamical system.
- **Observational basis**: the seismic activity in a wide magnitude range.
- **Methodology**: that of critical phenomena, for which prediction of complex systems requires a holistic approach *from the whole to details,* in consecutive approximations, starting with the most robust coarse-graining of the process considered..

TIME OF INCREASED PROBABILITY. 2

- **Prediction algorithms**: based on the hypothesis that prediction is as pattern recognition problem of infrequent events.
- **Major features of the patterns**: long range correlations and similarity.
- **Validation of predictive methods**: rigorous analysis of successful predictions, false alarms and failure to predict.
- The **probabilistic side of prediction** is reflected in the rates of errors, evaluated as error diagrams.

BASIC TYPES OF PREMONITORY PHENOMENA

The approach of a strong earthquake is indicated by the following **changes in the basic characteristics of seismicity**:

(i) Rise of seismic activity.

(ii) Rise of earthquake clustering in space and time.

(iii) Rise of the earthquake correlation range.

(iv) Transformation of magnitude distribution.

(v) Rise of irregularity in space and time.

(vi) Reversal of territorial distribution of seismicity.

(vii) Rise of correlation between different components decrease of dimensionality).

(viii) Rise of response to excitation.

SEISMICITY PATTERNS

Premonitory phenomena of each type are depicted by different seismicity patterns:

1. Measures of seismic activity.
2. Measures of earthquake clustering.
3. Measures of earthquake correlation range.
4. The measures of irregularity.
5. The measures of premonitory transformation of magnitude distribution.

NUMERICAL ALGORITHMS

Several algorithms have been devised for the quantification of the above seismicity patterns and its future evolution, *i.e.*, the prediction of the next strong earthquake. The more widely used are Algorithms M8, MSc, CN and SSE.

In all cases, prediction is aimed at earthquakes of magnitude M_0 or higher, and uses all available earthquakes of a seismic catalog with aftershocks removed. Several running averages are computed for the sequence of earthquakes for a given time window and magnitude range:

- **Seven functions** are calculated with different characteristics, and as a result the earthquake sequence is given a robust averaged description.

- **Very large** values are identified for each function from the condition that they exceed Q percentiles.

- An **alarm** or a **TIP**, time of increased probability, is declared for a give n period of time when at least six out of seven functions become "very large" within a narrow time window.

PHASE DYNAMICS. 1

- As in the case op TIP, the starting point is the variety of **spatial and temporal patterns** associated to strong earthquakes.
- **Main hypothesis**: seismic activity is highly correlated across many space scales and tim3escales within large volumes of the Earth's crust.
- **Observational fact**: earthquake main shock occur at quasiperiodic intervals and, for some parts of the world, average recurrence intervals are well defined.
- **Goal**: identify basis patterns for all possible space-time seismicity configurations.
- **Methodology**: the patterns are defined by the eigenstates and eigenvalues of one of an appropriately constructed family of correlation operators.

PHASE DYNAMICS. 2

- The s**eismicity** (**firing patterns**) are emergent processes that develop from the underlying structures, parameters, and dynamics of a multidimensional nonlinear system. It can be located in both space and time with considerable accuracy.
- The firing activity, Ψ(x,t), can be represented as a set of time series at all positions x, where Ψ(x,t) = 1 if an event occurs in the time interval between t and t+Δt, and Ψ(x,t) = 0 otherwise.
- The classical Karuhunen-Loeve expansion technique is extended to include the construction of pattern states that can be used to forecast events in time.
- The above procedure Involves constructing a correlation operator $C(x_i , x_j)$ for the sites that contains the spatial relationship of slip events over time. $C(x_i , x_j)$ is decomposed into the orthonormal spatial eigenmodes and their associated time series.

PHASE DYNAMICS. 3

- The presence of both large- and small-scale correlations in the data, prompts a study of the change in these modes for each year and allows the identification of modes which consistently appear over some identifiable time period prior to an event.
- A complex rate correlation operator $K(\mathbf{x}_i , \mathbf{x}_j)$ can be used to compute the probability of future events on a fault patch model.
- In this method there is no fitting, smoothing, windowing or declustering performed on the data; and no *a priori* knowledge of the location or extend of the activity/quiescence area is required.
- The method is a coarse-grained measure of the spatio-temporal variations in seismicity performed on the regional historic catalog that quantifies the change through time of a unit vector over the entire space.
- Changes in phase angle of the basic activity rate function $S(x, t_b, t)$ are then the physically meaningful quantities, rather than changes in the norm or variance. Here the name *phase dynamics*.

PHASE DYNAMICS. 4

- There are no free parameters to be determined by fits to data.
- The method cannot predict magnitudes. Up to the present, the method can forecast seismic activity for earthquakes of magnitude equal or greater to a given threshold, and this can be accomplished through the linear dimension of the greed. For example, to forecast earthquakes of magnitude $m \geq 6$ the linear size of the3 greed is selected to be $\Delta L \sim 10$ km.

PROBABILISTIC PREDICTION. 1

Rikitake's approach (Rikitake, 1999):

- The starting point is a seismic catalog of characteristic earthquakes.
- Assume the validity of the *seismic gap*.
- Main hypothesis: *the rupture time of characteristic earthquakes follow a Weibull distribution.*
- This hypothesis permits the estimation of the **expected time** of the next earthquake along with its **standard deviation**.

PROBABILISTIC PREDICTION. 2

The method (Jackson and Kagan, 1999; Kagan and Jackson, 2000) refers to the long term and short term forecast for magnitude 5.8 and larger earthquakes.

- The forecast applies to the ensemble of earthquakes during a previously established test period and it is not meant to predict any single earthquake.
- The short term forecast is based on a specific stochastic model of earthquake occurrence. Considers temporal clustering of the sort that causes foreshock-main shock- aftershock sequences.
- The long term forecast is essentially an empirical description of observed spatial clustering, a le to estimate the probabilistic structure of future earthquakes. Temporal clustering is ignored.

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