Self-Organized Criticality and Turbulence

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Abstract

Nonlinear systems exhibiting self-organized criticality (SOC) are observed in astrophysics, magnetospheric physics, geophysics, human activities (stock market, city sizes), and in natural hazards (earthquakes, avalanches, forest fires). The theoretical concept of SOC has been pioneered since Bak in 1987 and simulated with cellular automaton models, but a comprehensive universal theory is still lacking. It is timely now to take stock of large new databases of space observations and geophysics records over the last half century. The aim of this workshop at ISSI with a balanced interdisciplinary team is to cross-compare observations (from space physics and other databases), to discuss SOC and SOC-related (such as turbulence) theoretical models, and to define a diagnostic metrics between observations and theoretical models that yields new physical insights into SOC phenomena and complexity in nature.

1 Scientific Rationale

How can the universe start with a few types of elementary particles at the big bang, and end up with life, history, economics, and literature? The question is screaming out to be answered but it is seldom even asked. Why did the big bang not form a simple gas of particles, or condense into one big crystal? (Bak 1966). The answer to this fundamental question lies in the tendency of the universal evolution towards complexity, which is a property of many nonlinear energy dissipation processes. Dissipative nonlinear systems generally have a source of free energy, which can be partially dissipated whenever an instability occurs that triggers an avalanche-like energy dissipation event above some threshold level. Such nonlinear processes are observed in astrophysics, magnetospheric physics, geophysics, physical laboratories, material sciences, human activities (stock market, city sizes, internet, brain activity), and in natural hazards and catastrophes (earthquakes, snow avalanches, forest fires), see Table 1 and Figure 1 for specific examples.

A prominent theory that explains such nonlinear energy dissipation events is the so-called *Self-organized criticality (SOC)* concept, first pioneered by Bak et al. (1987, 1988) and simulated with cellular automaton models, which mimic next-neighbour interactions leading to complex patterns. The topic of SOC is reviewed in recent reviews, textbooks, and monographs (e.g., Bak 1996; Jensen 1998; Turcotte 1999; Charbonneau et al. 2001; Hergarten 2002; Sornette 2004; Aschwanden 2011; Crosby 2011; Pruessner 2012). SOC can be considered as a basic physics phenomenon - universally occurring in systems with many coupled degrees of freedom in the limit of infinitesimal external forcing. This theory assumes a critical state that is robust in the sense that it is self-organizing, like a critical slope of a sandpile is maintained unter the steady (but random) dropping of new sand grains on top of the pile. Individual avalanches occur with unpredictable sizes, uncorrelated to the disturbances produced by the input. Sandpile avalanches are a paradigm of the SOC theory, which has the following characteristics: (1) Individual events are statistically independent, spatially and temporally (resulting into an exponential waiting time distribution between subsequent events); (2) The size or occurrence frequency distribution is scale-free and can be characterized by a powerlaw function over some size range (i.e., the inertial range); (3) The detailed spatial and temporal evolution is complex and involves a fractal geometry and stochastically fluctuating time characteristics (sometimes modeled with 1/f-noise, white, pink, red, or black noise). There are some related physical processes that share some of these characteristics, and thus are difficult to discriminate from a SOC process, such as turbulence, Brownian motion, percolation, or chaotic systems. A universal SOC theory that makes quantitative predictions of the powerlaw-like occurrence frequency and waiting time distributions is still lacking. Thus, it is most timely now to study large new databases of space observations and geophysics records that are now available over at least a half century, to obtain unprecented statistics of SOC phenomena. Such large datasets will provide the necessary statistics that is needed to constrain and test the existing SOC theories and models, and to discriminate SOC models from other nonlinear dissipative processes (e.g., MHD turbulence). The aim of an interdisciplinary approach is to cross-compare observations in different fields, to establish common statistical properties in different physical systems, to stimulate and cross-fertilize theoretical modeling, and to improve forecasting of extreme events.

Table 1: Examples of physical processes with SOC behavior.

SOC Phenomenon	Source of free energy or physical mechanism	Instability or trigger of SOC event
Galaxy formation	gravity, rotation	density fluctuations
Star formation	gravity, rotation	gravitational collapse
Blazars	gravity, magnetic field	relativistic jets
Soft gamma ray repeaters	magnetic field	star crust fractures
Pulsar glitches	rotation	Magnus force
Blackhole objects	gravity, rotation	accretion disk instability
Cosmic rays	magnetic field, shocks	particle acceleration
Solar/stellar dynamo	magnetofriction in tachocline	magnetic buoyancy
Solar/stellar flares	magnetic stressing	magnetic reconnection
Nuclear burning	atomic energy	chain reaction
Saturn rings	kinetic energy	collisions
Asteroid belt	kinetic energy	collisions
Lunar craters	lunar gravity	meteroid impact
Magnetospheric substorms	electric currents, solar wind	magnetic reconnection
Earthquakes	continental drift	tectonic slipping
Snow avalanches	gravity	temperature increase
Sandpile avalanches	gravity	super-critical slope
Forest fire	heat capacity of wood	lightening, campfire
Lightening	electrostatic potential	discharge
Traffic collisions	kinetic energy of cars	driver distraction, ice
Stockmarket crash	economic capital, profit	political event, speculation
Lottery win	optimistic buyers	random drawing system

2 Proposed Work and Goals

Our proposal has three main foci: (1) Data analysis of statistical datasets of SOC phenomena, using new and enhanced older datasets (see Table 2), (2) quantitative modeling and fitting of the obtained statistical distributions in terms or powerlaw and modified powerlaw functions, and (3) dicussion of the interpretation in terms of SOC theories and/or related non-SOC theories, with the goal to discriminate SOC and non-SOC processes (see Figure 2) and to obtain a deeper physical understanding of the involved nonlinear energy dissipation processes. We strive for a good balance between observations (space data already observed), theory/modeling, and simulations. Our combined observational/modeling/theoretical effort aims to provide physical insights into SOC systems beyond mathematical models and numerical simulations. Our assembled team consists of a very broad range of representatives from different nonlinear physics disciplines that cover alternate approaches (SOC, turbulence, chaos theory). A more specific outline of the various data analysis and SOC modeling approaches is given in the following, which contains a subset of the work, projects, questions, and problems that are proposed by this ISSI team to be studied and addressed in the ISSI meetings:

1. Black hole objects: Using data from blackhole objects (e.g., from FERMI) to explore what is the origin of light fluctuations from accreting objects (white dwarfs and black holes). Can MHD turbulence and/or magnetic flares account for the observations (Ohsuga and Mineshige 2011; Dobrotka et al. 2012).

2. Stellar flares: The Kepler mission provides white-light light curves of flares in $\approx 23,000$ cool dwarfs in Quarter 1 long cadence data (Walkowicz et al. 2011). Do stellar flares have the same occurrence frequency distribution as solar flares? Or do they exhibit powerlaw slopes steeper than the critical value of $\alpha = 2$ that would indicate that there is more energy in nanoflares, which possibly could domninate coronal heating (Audard et al. 2000).

3. Solar flares: Extend the occurrence frequency distribution over 8 orders of magnitude with flare statistics from the same instrument (AIA/SDO) in 6 different wavelengths. Can it be fitted with a single powerlaw slope over the entire range? Does the powerlaw slope vary during the solar cycle (Asachwanden 2011a), and what is the explanation for it (Aschwanden 2011b)? Are the slopes of the flare durations, peak rates, and total fluences consistent with the

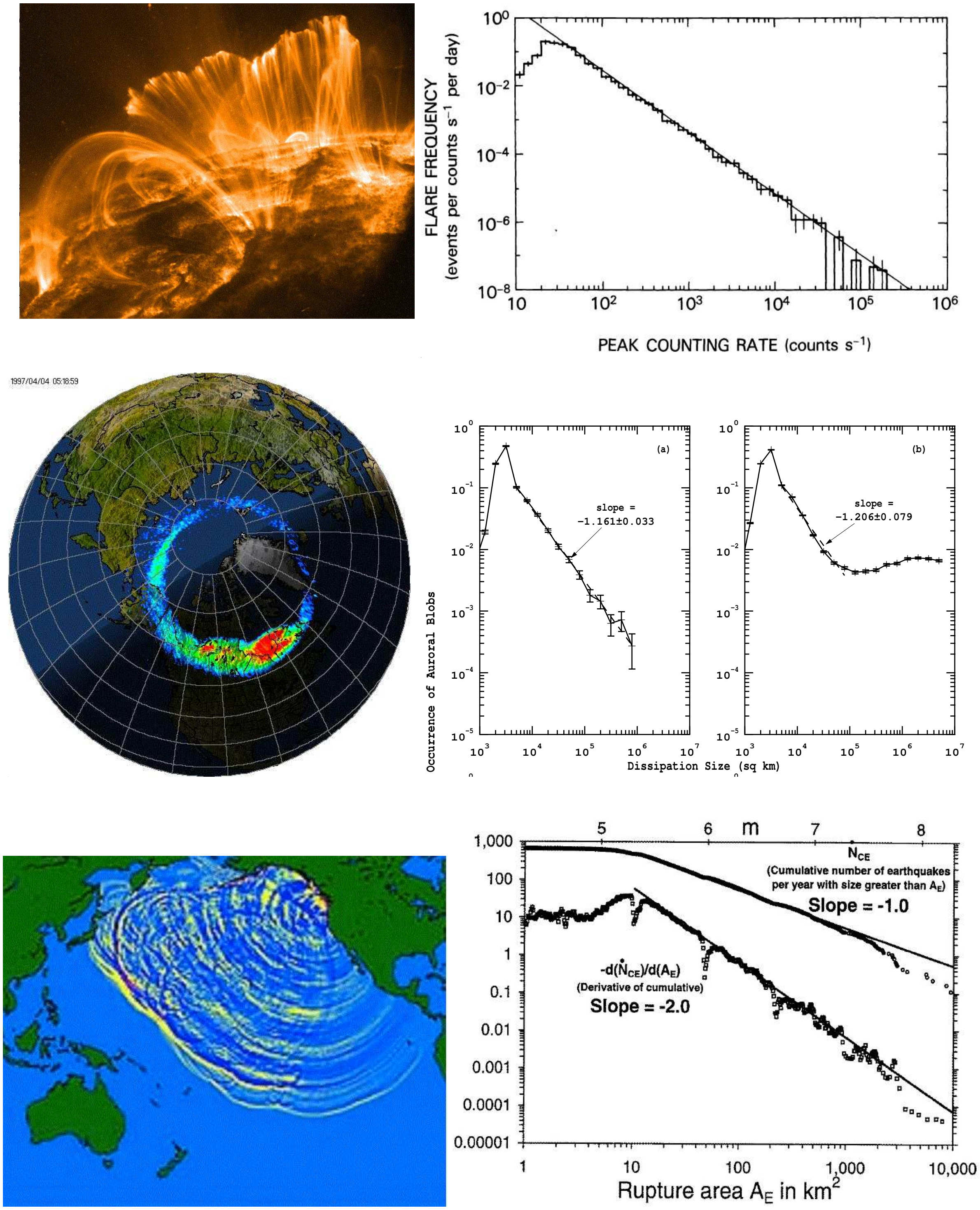

Figure 1: *Top left:* The solar flare of 2001 April 15, observed with the TRACE spacecraft in 171 Å. *Top right:* Occurrence frequency distribution of the peak count rate of solar flare hard X-ray count rates recorded with HXRBS/SMM (Dennis 1985). *Middle left:* The auroral oval observed with the NASA satellite Polar/UVI on 1997 April 4, 0519 UT. *Middle right:* Occurrence frequency distribution of auroral blobs during quiet (left) and substorm time intervals (right). *Bottom left:* Satellite recording of tsunami waves produced by one of the 10 largest earthquakes, originating in North America. *Bottom right:* World-wide cumulative (slope $= -1$) and differential frequency distribution (slope $= -2$) of earthquakes per year as a function of the rupture area A_E during 1977-1994. The Gutenberg-Richter magnitude m is indicated on the top axis (Turcotte 1999).

Table 2: Statistical Datasets used and proposed by the ISSI Team to study SOC phenomena.

SOC Phenomena	Statistical Datasets
Black hole objects	FERMI
Stellar flares	Kepler
Solar flares hard X-rays	HXRBS/SMM, BATSE/CGRO, RHESSI, AIA/SDO, FERMI
Solar flares, soft X-rays	NOAA/GOES,
Solar nanoflares, EUV	AIA/SDO, Hinode
Solar magnetic field	Hinode/SOT, SDO/MDI, SOLIS
Transition region/corona	STEREO/EUVI, SDO/AIA
Solar wind	WIND, ACE, CLUSTER, ULYSSES
Magnetospheric events	Supermag
Magnetic Confinement Fusion	MAST, JET
Neural brain activity	fMRI (functional Magnetic Resonance Imaging)

predictions of the fractal-diffusive SOC model (Aschwanden 2012)? How do the powerlaw slopes vary for different wavelengths and can they be explained by physical scaling laws of radiative loss in different wavelengths? Is there more energy in large flares than in nanoflares possibly accounting for coronal heating?

4. Solar prominences and eruptions: Using Hinode/SOT to study turbulence on spatial scales of $0.1'' - 100''$ and temporal scales of 17 s -4.5 hrs, multifractal scale invariance, powerlaw spectra, scaling of higher-order moments, structure functions, non-Gaussian statistics (Leonardis et al. 2012). At the larger scales, finite-size effects can be quantified. Can we distinguish between SOC and turbulence or other processes that show the same scaling? What do we need to measure beyond powerlaws and exponents? (Chapman) Do eruptive and non-eruptive active regions, filaments, and prominences have different SOC characteristics? (Dimitropoulou et al. 2009, 2011; Georgoulis 2012). Are solar active regions with major flares more fractal, multifractal, or turbulent than others (Georgoulis 2012).

5. Solar wind: Study finite range of spatial scales in turbulence in the solar wind, using ULYSSES, WIND, ACE, and CLUSTER data. Are the turbulence spectra invariant or sensitive to plasma conditions, for instance during the solar cycle maximum and the current extremely low minimum? (Chapman and Nicol 2009). Can we distinguish between SOC and Kolmogorov turbulence, based on bursty transport control parameters? (Chapman et al. 2009; Chapman and Watkins 2009; Watkins et al. 2009; Uritsky et al. 2007).

6. Solar cycle and total solar irradiance: Study time series of sunspot numbers, solar flare inex, and total solar irradiance with Hurst analysis for long-range persistentce and memory (Rypdal and Rypdal 2011a). Can the temporal fluctations and avalanche exponents of various SOC systems (including the Bak-Tang-Wiesenfeld sandpile model) be self-conistently modeled (Rypdal and Rypdal 2008a,b).

7. Magnetospheric physics: Can we model the outer radiation belt as a complex system in a self-organized critical state (Crosby et al. 2005, 2011). Can the bursty and intermittent dynamics of magnetospheric substorms, previously modeled with cellular automata models, be described in terms of thermodynamics large deviations of rare events (Lavenda and Florio 1992; Lavenda 1995, 1997), providing a nonequilibrium thermodynamic description of avalanching systems? (Consolini and Kretschmar 2007; Touchette 2009; Frisch and Sornette 1997).

8. Neural brain activity: Using fMRI (functional Magnetic Resonance Imaging) from the imaging laboratory at ICL to analyse bursts of activities. High levels of neural activity spread across the brain like SOC avalanches. Multi-level dynamics will be explored: How do avalanches of bursts of collective activity at one level of a hierarchical structured complex system relate to the activity at lower levels? How can information processing be carried in the form of avalanche activity with a very broad (potentially powerlaw) size distribution? (Jensen). Predictive information can be defined as the mutual information between the past and the future of a time series, which links predictability, complexity, and learning (Bialek et al. 2001), complexity, contingency, and criticality (Bak and Paczuski 1995), and natural complexity (Watkins and Freeman 2008).

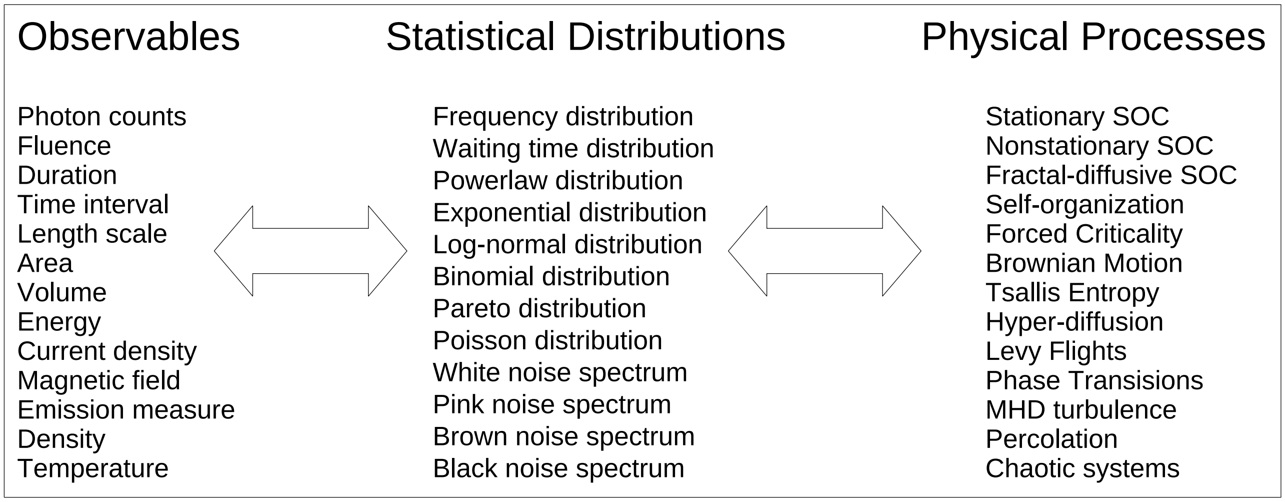

Figure 2: Metrics of observables, statistical distributions, and physical models that need to be defined in order to discriminate SOC from non-SOC processes.

We envision to make significant progress in a number of fundamental questions about SOC systems. One critical issue is that powerlaw distributions cannot be taken as an unambiguous diagnostics of SOC mechanisms (Stumpf and Porter 2012), in particular in the case of small statistics, which restricts the powerlaw to a small inertial range. Other questions are: (1) How to identify scaling and universality in experimental and computational data; (2) How to identify and characterize the underlying critical phenomenon (if it extists); (3) What are the SOC mechanisms at work; (4) How can we discriminate between SOC and non-SOC mechanism? (Figure 2). (5) What part of SOC phenomena is captured by lattice models and is there a route to basic theories and first-principle equations? In summary, one specific final goal of this workshop is to come up with a metrics as outlined in Figure 2, where the observables are characterized/fitted with specific mathematical distributions, which then help in the identification of specific physical processes and in the interpretation of the observed phenomena. The metrics given in Figure 2 can also be read from right to left, which means that a theoretical model of a nonlinear process predicts a specific distribution, which can then be tested with measured observables.

3 Time Schedule of Project and ISSI Support

We plan to meet two times with a team of 9-12 funded ISSI team members plus some young scientists, and invite self-supporting experts in addition (at no cost to the ISSI grant). The two meetings may be chosen with a one-year interval inbetween, say in fall 2012 and 2013. In the first meeting all participants will present the best available data (from new missions and databases if possible) in each interdisciplinary field, and discuss theoretical models and interpretations, new methods and avenues for future data analysis and collaborations, and define a metrics between observables and physical models. During the intervening year, the participants will then conduct tests which datasets and theoretical models fit together and quantify the relationships in the metrics of Figure 2 (between observables and theoretical models) to the extent possible. The results will then be discussed in the second meeting and a series of publications on the results will be planned with specific author teams, which should be published within a year time frame, say in fall 2014.

The support of ISSI for this planned team work is extremely useful, which probably could not be conducted by other means. The main benefits of such an ISSI team project are: (1) A well-balanced, interdisciplinary, international team from fields as diverse as astrophysics, magnetospheric physics, geophysics, and biophysics can jointly tackle a common problem in nonlinear physics and complexity; (2) Each participant has access to unprecedented rich and large state-of-art databases in space physics and laboratories; (3) The joint discussions will enforce that we use a common scientific vocabulary that is important to understand each others progress in any field of science; (4) Young scientists will be trained during these meetings and they will bring new thinking to our problems; and (5) Observational/phenomenological, numerical computer simulations, and analytical/theoretical/modeling approaches will be combined to reach a deeper physical understanding of SOC and related non-SOC processes.

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