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A new model of mass extinctions

K. Sznajd-Weron^{a,*}, Rafał Weron^b

^a*Institute of Theoretical Physics, University of Wrocław, pl. Maxa Borna 9, 50-204 Wrocław, Poland*

^b*Hugo Steinhaus Center for Stochastic Methods, Wrocław University of Technology,
50-370 Wrocław, Poland*

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Abstract

Distribution of extinction sizes constructed from original fossil records exhibits not a single, but a double power-law, with tail exponents being roughly the same in different scales, i.e., for species, families and orders. Moreover, time correlations of extinction sizes decrease with a power-law suggesting long range dependence and/or criticality in extinction events. A thorough analysis of paleobiological data is followed by an introduction of a model, which describes the behavior of complex systems with random interactions and uniquely leads to a double power-law observed in extinctions data. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Our planet has been shaken by five major extinctions in the four billion year history of life [1,2]. The first, some 450 million years ago, occurred shortly after the evolution of the first land-based plants and 100 million years after the Cambrian Explosion of marine life. The second extinction wave came over 350 million years ago, causing the formation of coal forests. Then the Earth experienced two mass extinctions during the Triassic period, between 250 and 200 million years ago. The fifth mass extinction – probably caused by a collision with a giant meteorite – occurred 65 million years ago, at the end of the Cretaceous period. This ended the reptilian dominance of the Earth and led to the current mammalian domination. Are we to experience the sixth extinction?

* Corresponding author.

E-mail address: kweron@ift.uni.wroc.pl (K. Sznajd-Weron).

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When is it coming? And what may be its cause? These and similar questions are bothering paleobiologists nowadays [3].

Is there something physicists can do to help solve these problems? Well, yes. Methods originating in statistical physics have already been proven useful in diverse branches of science, including economy, biology and sociology (for a review see Refs. [4–7]). This inspired us to model mass extinction events by a method originally developed to explain dielectric relaxation in dipolar materials [8–10] and recently successfully applied to financial markets [11]. More specifically, we use the conditionally exponential decay (CED) approach and treat the ecosystem as a complex stochastic system.

2. Fossil records

Paleontologists have focused a great deal of attention on episodes of mass extinctions and the physical factors that might have led to them. Fig. 1 shows the record of extinction events for marine species over the last 600 million years as recorded by Sepkoski [12]. Similar patterns of extinction for The Fossil Record 2 of Benton [13,14] are shown in Figs. 2 and 3, where records of extinction events for higher taxa – continental families and orders, respectively – are presented.

Biologists have long known that the smaller the population, the more susceptible it is to extinction from various causes. Models of demographic stochasticity [15] have identified densities below which populations risk rapid extinction, even in a constant environment. In the theory developed by Lynch and Lande [16] extinction of small populations (demes) was treated as an essentially deterministic process.

It is much more difficult, however, to understand the extinction of whole species, families or orders. Higher taxa form more complex systems. For example, species interact through the predator–prey relationship, food chain or competition. Yet, each

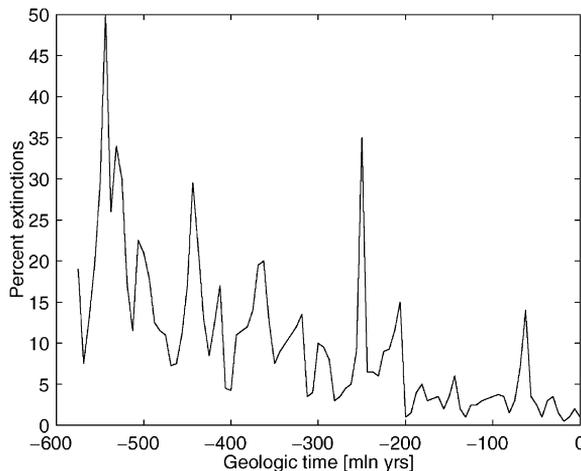


Fig. 1. Percent extinctions of marine species over the last 600 million years (after Sepkoski [12]).

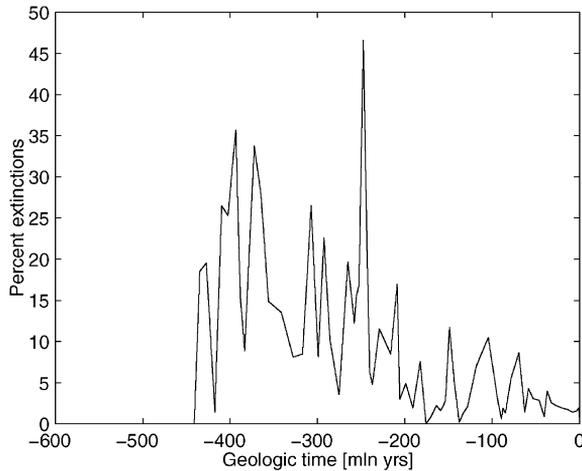


Fig. 2. Percent extinctions of continental families over the last 600 million years (after Benton [13]).

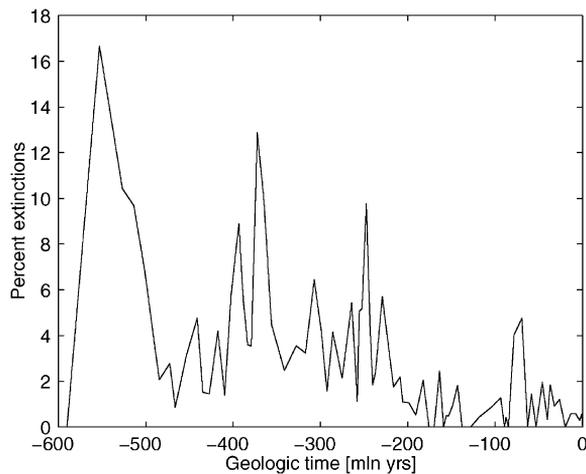


Fig. 3. Percent extinctions of orders (marine and continental) over the last 600 million years (after Benton [13]).

species consists of many demes that also interact with each other (through competition and/or gene flow). All those inter- and intra-species relations are random and very complex. For these reasons it seems impossible to determine the behavior of a whole ecosystem having information only about the behavior of demes.

In 1993, Bak and Sneppen [17] proposed to model biological evolution through self-organized criticality (the BS model). Two years later Bak and Paczuski [18] observed that the histogram of extinction sizes for marine species, originally produced by Raup [19], can be approximated by a power law with an exponent $\tau \in (1, 2)$ (for a review of power-law models for mass extinction see [20]). They applied the BS model and obtained similar results. This led to the conclusion that biological systems self

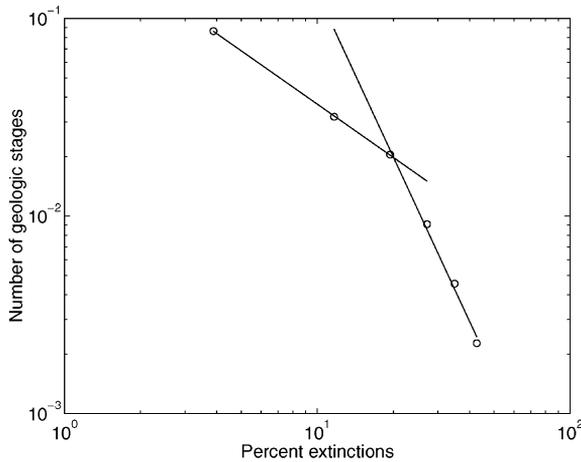


Fig. 4. Two power-laws of the empirical density for continental families (see Fig. 2).

organize into a critical state. However, it is not obvious that extinction sizes should be modeled by a power law in the first place.

Analysis of fossil records presented in Figs. 1–3 reveals the fact that small and large extinction events follow two different power-laws, see Fig. 4 and table below. The density of extinction sizes (percent extinctions) can be quite well approximated by

$$f(x) \propto \begin{cases} x^{\alpha_1} & \text{for small } x, \\ x^{\alpha_2} & \text{for large } x, \end{cases} \quad (1)$$

with exponents α_1 and α_2 estimated from the data as

	α_1	α_2
Marine species	−0.51	−2.58
Continental families	−0.90	−2.76
Orders (marine & continental)	−0.97	−2.63

Notice that large extinctions are described by roughly the same tail exponent α_2 for each scale (taking as units species, families and orders). This may indicate that extinction phenomena have a fractal nature.

Moreover, if we consider the correlation function of the extinction time series and plot it on a log–log scale we can observe that it decreases with a power-law, see Fig. 5. We can interpret this phenomenon in the following way: mass extinctions that took place millions of years ago have influence on today’s environment and may be one of the sources of the sixth major extinction, which – as is often suggested [3] – is taking place right now. On the other hand, the power-law decrease of the correlation function may indicate a critical behavior of the extinction process.

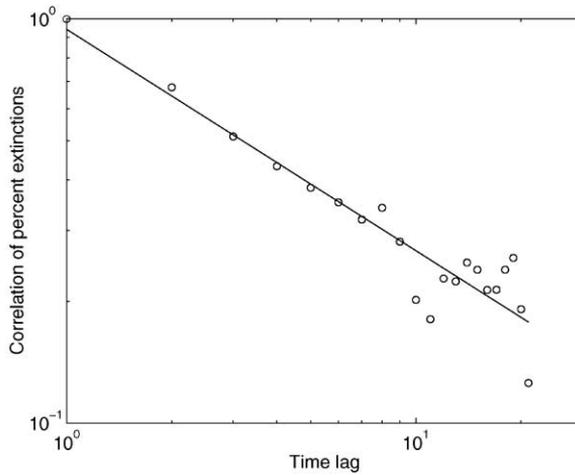


Fig. 5. Correlation function for extinction sizes of marine species (see Fig. 1).

3. The model

The conditionally exponential decay (CED) approach provides a rigorous mathematical framework for analysis of complex systems [21]. It uniquely leads to a double power-law and explains the origins of mass extinctions. To see this, notice that we can interpret the ecosystem as a complex stochastic system with short-range (in the sense of phylogenetic distance) and long-range interactions.

As a sample setup for the model let us take the species level. By no means are we restricted to this level. The same reasoning may be used for higher taxa, such as orders or families.

It is well known by biologists [22] that species are not homogeneous units, but consist of many demes. In this model each i th deme is related to a species, which is the set of many demes interacting with each other. Short-range interactions are relations between demes belonging to the same species, whereas long-range interactions – between demes belonging to different species (which can also be interpreted as a relationship between species themselves).

Each deme is characterized by its fitness F_i , which can be defined as a measure of capacity to survive and reproduce [23]. Natural selection resulting from temporal changes of the environment reduces the population size [16], but the magnitude of the extinction (E_i) depends on demes' fitness. Interactions of the long-range type are represented by random factors B_j^i for all $j \neq i$. They reflect how strongly the i th deme depends on other species (through a predator–prey relationship, food-chain, etc.), see Fig. 6.

The basic result which allows us to see the structure of distributions describing extinction size is the following. If the global behavior of the ecosystem is given by the probability that the magnitudes of extinction (E_i) for all individual species will be

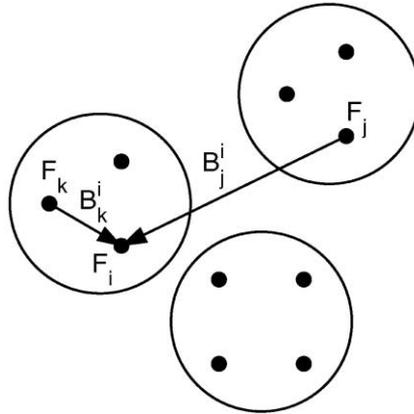


Fig. 6. Inter- and intra-species relations. Black dots represent demes, circles – species. Each deme is characterized by its fitness F_i . B_j^i and B_k^i are random factors which reflect how strongly the i th deme depends on demes j and k , respectively.

no less than a certain value e ,

$$\phi(e) = \mathbf{P} \left(\lim_{N \rightarrow \infty} e_N \min(E_1, \dots, E_N) \geq e \right), \tag{2}$$

where e_N is a suitable, positive normalizing constant, than it can be shown [21] that the probability density of the global extinction $f(e) = -d\phi(e)/de$ exhibits the double power-law property

$$f(e) \propto \begin{cases} (\lambda e)^{\alpha-1} & \text{for } \lambda e \ll 1, \\ (\lambda e)^{-\frac{\alpha}{k}-1} & \text{for } \lambda e \gg 1, \end{cases} \tag{3}$$

where the parameters $\alpha, \lambda, k > 0$ are determined by the limiting procedure in (2).

The above result can be derived if we assume that the distribution excess ϕ_i of the i th deme’s extinction size (conditioned on its fitness F_i and the most important information from the ecosystem: $\max_{j \neq i} B_j^i$) is given by an exponential decay with a breakdown at some critical point. This assumption can be justified by the following two facts: 1° large extinction events are less probable than small ones; 2° if character of demes that interact with the i th deme reaches some critical value (e.g. critical density, fitness, etc.) then the extinction structure is disrupted and it is likely that a large percent of the i th deme will die. It is obvious that the death of a prey can cause extinction of its predator. Yet, the opposite can happen as well. For the population of herbivores the existence of predators is necessary, because it controls the number and quality of the former. An uncontrolled growth of the herbivore population can, in some extreme cases, lead to its total extinction.

4. Conclusions

The main result (3) is in agreement with the analyzed fossil records. The observed double power-law emerges as a natural description of the model, thus allowing us to

conclude that mass extinctions take place because of the complex nature of interactions in the ecosystem and need not be caused by global external events. Similar results were obtained by Paczuski et al. [24] for the SOC (self-organizing criticality) model. However, it should be noted that extinctions on the demes' level, which in turn are the source of structural changes of higher taxa, are caused by natural selection (i.e., small environmental changes [16]). This is similar to the domino effect, where one falling piece makes all other pieces fall. But “someone” has to make the first move!

References

- [1] S.M. Stanley, *Extinction*, Scientific American Books, New York, 1987.
- [2] D. Raup, *Extinction, Bad Genes or Bad Luck*, W.W. Norton, New York, 1991.
- [3] R. Leakey, R. Lewin, *The Sixth Extinction*, Doubleday, New York, 1995.
- [4] R.N. Mantegna, H.E. Stanley, *An Introduction to Econophysics: Correlations and Complexity in Finance*, Cambridge University Press, Cambridge, 1999.
- [5] S. Moss de Oliveira, P.M.C. de Oliveira, D. Stauffer, *Evolution, Money, War and Computers*, Teubner, Leipzig, 1999.
- [6] S. Cebrat, M.R. Dudek (Eds.), *Statistical physics in biology*, Proceedings of the XIIIth Max Born Symposium, *Physica A* 273 (1999).
- [7] A. Pełkalski, K. Sznajd-Weron (Eds.), *Exotic statistical physics*, Proceedings of the 36th Karpacz Winter School, *Physica A* 285 (2000).
- [8] K. Weron, *J. Phys.: Condens. Matter* 3 (1991) 9151.
- [9] K. Weron, A. Jurlewicz, *J. Phys. A* 26 (1993) 395.
- [10] A.K. Jonscher, *Universal Relaxation Law*, Chelsea Dielectrics, London, 1996.
- [11] Sz. Mercik, R. Weron, *Physica A* 267 (1999) 239.
- [12] J.J. Sepkoski Jr., *Paleobiology* 19 (1993) 43.
- [13] M.J. Benton, *The Fossil Record* 2, Chapman & Hall, London, 1993.
- [14] M.J. Benton, *Science* 268 (1995) 52.
- [15] R. Lande, *Amer. Naturalist* 142 (1993) 911.
- [16] R. Bürger, M. Lynch, *Evolution* 49 (1995) 151.
- [17] P. Bak, K. Sneppen, *Phys. Rev. Lett.* 71 (1993) 4083.
- [18] P. Bak, M. Paczuski, *Proc. Nat. Acad. Sci. USA* 92 (1995) 6689.
- [19] D.M. Raup, *Science* 231 (1986) 1528.
- [20] M.E.J. Newman, *J. Theoret. Biol.* 189 (1997) 235.
- [21] A. Jurlewicz, A. Weron, K. Weron, *Appl. Math.* 23 (1996) 379 see <http://www.im.pwr.wroc.pl/~hugo/Publications.html>.
- [22] E. Mayr, *Populations, Species, and Evolution*, Harvard University Press, Cambridge, MA, 1970.
- [23] R. Dawkins, *The Extended Phenotype*, Freeman and Co., Oxford, 1982.
- [24] M. Paczuski, S. Maslov, P. Bak, *Europhys. Lett.* 72 (1994) 97.