Self-Organized Criticality in the Model of Biological Evolution Describing Interaction of "Coenophilous" and " Coenophobous" Species

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The modification of the model of P.Bak and K.Sneppen of the self-organized biological evolution is proposed on the basis of a formalization of the scheme of the biosphere evolution suggested by O.V.Kovalev. This scheme is regarded as one approximating the realistic model of the ecosystem evolution. The fundamental difference between "coenophilous" species and "coenophobous" ones in respect to their reaction on the external environment is represented. The dynamics of the modified model as well as that of the model of P.Bak and K. Sneppen possesses the most important features of selforganized criticality: the avalanche-like processes and the punctuated equilibrium. The results obtained by using the numerical experiment for the study of these phenomena are presented.

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Introduction - Recently, the considerable attention has been focussed on the studies of the phenomena of the self-organized criticality (SOC) in dynamical systems. The main characteristic feature of this type of the critical dynamics is its occurrence without a special fine tuning of the system parameters. Since only the most fundamental properties of interactions manifest itself in a critical dynamics there is a good reason to believe that as the SOC phenomena are the same in a number of real situations they could be described in the framework of the universal theoretical models. The well studied model of such a kind is the "sand pile" model [1]. A very interesting line of the SOC investigations is arisen on the basis of the model of self-organized biological evolution suggested by P.Bak and K.Sneppen [2].

This model describes the dynamics of the ecosystem of interacting species governed by the processes of mutation and natural selection. The SOC type in the Bak-Sneppen model (BSM) has the main specific features of real biological evolution considered in the framework of the Gould and Eldredge "punctuated equilibrium" conception [3]. The "punctuated equilibrium" manifests itself in the BSM critical dynamics as alternating quasistable states and avalanche-like processes of the balance disturbance. This model makes it possible to explain nonuniform race and uneven character of the biological evolution. The scale invariance of extinction events exposed with help of analysis of paleontological data is in a good agreement with criticality of BSM dynamics.

The interactions of species, mutations and a natural selection are taken into account in the BSM. However, the factors of external environment are not represented in an explicit form and the specific of their influence on the trend of biological evolution is ignored. In this paper we propose the modification of the BSM involving consideration of the environments effects.

It is constructed as formal mathematical modelling of important mechanisms of evolution processes on the basis of "the model of evolution of biosphere" proposed recently [4].

Simple model of environment influence on the self-organization of biological evolution- In the BSM framework, the species as an element of the ecosystem has only one characteristic. It is its average probability for survival in the population called barrier, as it is interpreted also as mutation stability. The state of the ecosystem of N species is considered to be given at the time t if the barriers $b_i(t)$,$i = 1, 2, ..., N$ are defined for all its species. The barrier $b_i(t)$ of the i-th species is the function of a discrete time t with values belonging to the interval $[0,1]$: $0 \leq b_i(t) \leq 1$. The BSM dynamics is formulated as follows. Initially, each barrier is set to a randomly chosen value. At each time step the barrier with minimal value of the "weakest" species and the barriers of all species interacting with it (neighbors) are being replaced by new values. In the random neighbor model (R) the neighbors of "weakest" species are chosen at random. In the local or nearest neighbors model (L) the interaction structure of the species is time independent. Generally for its definition the species are correlated with the sites of the D dimensional lattice and the species corresponding to nearest neighbors on the lattice are considered as the interacting ones. A new variable in our modification of the BSM is the time dependent external environment factor (EEF) $f(t)$. We suggest that $0 \leq f(t) \leq 1$. The EEF influences the evolution processes of the species. For to take it into account we introduce the characteristic which will be called the type of reaction on the influence of the environment (TRIE). There are two alternative cases. The barrier transformation of the species is determined only by the EEF and not influenced by barriers of other species or the barriers of other species are also essential for this process. By definition, the first TRIE of the species is caenophobous (Cpb) and the second TRIE will be called caenophilous (Cpl).

Thus in the proposed BSM modification the state of the species is given by its TRIE and its barrier. We define the controlled by EEF dynamics of this community of the species in following way. The initial state is to be chosen at random. The EEF is to be given at every time step. At each time step, the state of the Cpb species remains unchanged if the EEF is less then its barrier. If the EEF is greater then the Cpb barrier then we have to assign the new random barrier value for this species and to change its TRIE from the Cpb to the Cpl, if this new barrier value will still less then the EEF.

As to the Cpl, we have at first to define their interaction matrix and to fix through it which species are interacting with the given one. In principle the Cpl can also interact with the Cpb but in this paper we restrict ourselves by the case with the only Cpl mutual interaction. In analogy with the BSM we will consider two types of interaction matrix: with the random neighbors and with the nearest neighbors we will refer on these two type of our model as MR and ML respectively. At each time step we have to find the Cpl species with the lowest barrier value, to assign the new random barrier values for this species and for the species which are interacting with it and to change also the TRIE from the Cpl to the Cpb, if this new species barrier value will less then the EEF.

If in accordance with our rules we are changing the TRIE from the Cpb to Cpl we put this species at the random place in the Cpl community both for MR and ML types of our model. Respectively if we are changing the TRIE from the Cpl to Cpb we extract this species from its place in the Cpl community. Correspondingly we have to change the interaction matrix in these two cases. Note that in the case of ML model this alters the definition of the nearest neighbors in the vicinity of the species with changing TRIE.

Results of numerical experiments- If the function $f(t)$ representing the TRIE is constant, the system arrives the stable state (for the number of the time steps comparable with the number of the species). All the species become Cpb with the uniformly distributed on the interval $[f, 1]$ barriers. If $f(t) = 0$, there are the stable Cpb subsystem of the species having initial barriers and the Cpl subsystem evolving as the corresponding (random or linear) BSM. For $f = 1$ the dynamics of the Cpl subsystem is as follows: on each time step the equal number of species leaves the subsystem and is introduced in it. As the species are introduced on the random sites of the Cpl subsystem, for $f = 1$ the dynamical behavior of the MR and ML systems is practically the same and coincides with the case R of the BSM.

The dynamics with the stochastic EEF was investigated for the $f(t)$ uniformly distributed on the interval $[0, 1]$. It has the following characteristic features. After starting avalanche-like processes the greatest part of the species became Cpl. Then the number of Cpb species obtains the stable tendency to increase. The common "punctuated equilibrium"-like processes take place in the system. It can be considered as a quasistable Cpl ecosystem (community) interacting by exchanging of the species with the Cpb environment. Only the "weak" species are involving in the exchange process. They are mainly "young", i.e. not long ago leaving the Cpl ecosystem. The "strong" caenofobous species having high barriers are "in general situation" not introduced in the caenophilous ecosystem (it could be called the "non-caenophilisation" trend of the evolution). The most of the "strong" Cpb species are "old", i.e. they evolve long ago in the "non-caenophilisation" kind. The "exchange interaction" influences the "punctuated equilibrium" dynamics of the Cpl ecosystem (community), and results in its disintegration and in the increase of the number of the "old", "strong" Cpb species. The disintegration processes are $10^2 - -10^3$ times slower than the processes of the reaching of "the punctuated equilibrium".

On the Fig.1 and Fig.2 the results of numerical simulations are shown for the distributions of the barriers (”right” curves) and the minimal barrier (”link” curves). In the Fig.1 (Fig.2), ones are presented for the ML(MR)-model for the cases: $f = 0$ (stars), $f = 1$ (crosses), the stochastic f (squares). As it was mentioned above, the ”$f = 0$”-curves present the common BSM distributions respectively for the cases L(R). The ”$f = 1$”-curves of ML and MR models coincide practically with each other and with the R case of the corresponding BSM distributions. For the stochastic case, the very similar curves have been obtained for the MR and ML models, i.e. for the random EEF the behavior of the systems is practically universal and independent on detail properties of the interactions. It is interesting that the curve for the ”stochastic” minimal barrier distribution have an clearly expressed maximum at $b \neq 0$, whereas the distribution functions for the minimal barrier are monophonically decreasing in the BSM (the cases $f = 0$ and $f = 1$).

In the Fig.3 the distribution for the space correlations of the minimal barrier in the Cpl community of the ML-model is shown for $f = 0$ (stars), $f = 1$ (crosses) and the stochastic f (squares). For $f = 0$ it coincides with the space correlations distribution for the L case of the BSM. For $f = 1$ the distribution is uniform as it must be for the R case of the BSM. For the random f one sees that there are only ”short-range” space correlation in the ”punctuated equilibrium”.

To obtain the distribution function of the Cpb species one needs the longer time period of numerical simulations. The point is that at the first stages of dynamical processes their portion in the whole community is very small. Our numerical experiments show that for the sufficiently large time t the barrier distribution $P(t, b)$ can be approximated as follows:

$$P(t, b) = \frac{\alpha(t)}{(1 - b)^{1-\alpha(t)}},$$

where $\alpha(t) > 0$ is universal for the MR and ML models and becomes very small for the large t. Thus the average value of the Cpb barriers is very high, i.e. as it was mentioned above, the most species of the Cpb community are ”strong” and ”old” and the exchange interaction between Cpb and Cpl communities involves few number of the ”weak” and ”young” species.

Conclusion- Summing up, one can draw the following inferences. In our BSM modification the type of the interspecies interaction essentially manifest itself only in the case, when the influence of the EEF is not strong enough.

The greater is the role of EEF in the evolution processes the less role plays the interacting type in the dynamics of the Cpl community. One can note the following peculiarities of the behavior of this community in MR and ML models with respect to original RBSM and LBSM models. The intensification of the EEF influence on the evolution process decreases the average barrier value in the ML model: for $f = 0$ the average barrier is greatest, for $f = 1$ it is the lowest, for the stochastic case the average barrier is intermediate. The situation is a very different for the MR-model: the average barrier is lower for $f = 1$ (maximal effect of the EEF on dynamics) and $f = 0$ (the EEF does not influence on dynamics) whereas for the random f (the intermediate effect) the average barrier is greater, i.e. the random EEF increases the average survival probability of the Cpl species in the system with random interaction.

In conclusion, we discuss the biological ideas which have stimulated constructing of the considered model. The BSM was elaborated on the basis of the Gould-Eldredge "punctuated equilibrium model", in which the EEF role in ecosystem evolution was not considered. However, there is the reason to believe that it is impossible to model biological processes regardless the external factors. The community evolution is controlled by the climate evolution and the climate transformations are the integral reflection of several geological, geophysical and cosmical processes [4]. Influenced by the climate transformations (the EEF in our model) the succession processes form in the nature the consequences of the community series from the quasisteady to stable states. The importance of the difference between the "caenophilous"- and "caenophobous"-like species for the evolution process is in a good agreement with the MacArthur's theory of "K"- and "r"-selection [5] and with the Krasilov's "ecosystem theory of evolution" [6]. In the framework of MacArthur's conception the "r-selection" is dominating for the fecundity and colonizing and the "K-selection" ensures the efficiency and adaptiveness [5],[7]. In Krasilov's approach [6] the model of "coherent" and "non-coherent" trends of evolution is elaborated. At a period when the ecosystems decay (the non-coherent phase of evolution) the "pioneer" ("caenophobous") species become the active colonisators quickly capturing niches under conditions of the weak concurrence. In the "model of the evolution of biosphere" [4], "caenophobous" species or "philogenetically advanced juvenil taxa" have in virtue of low caenotic intensity the advantage of the genom structure: activity of the mobile genetic elements, poliplody, parthenogenesis et.c. This is why in the processes of permanently changing "external factor" of climate genesis, the key events of evolution process are the interrelations between "caenophobous" and "caenophilous" species.

As we have seen, there are the similar dynamics features in our model. At a period when the EEF are changing weakly ($f \approx const, f \neq 0, f \neq 1$), the avalanche-like increase of the Cpb species number happens. Correspondingly the number of Cpl species quickly decreases, what can be interpreted as the decay of the Cpl ecosystem and capturing of empty ecological niches by the Cpb species. The repeating sharp EEF changes result in the Cpl species prevalation over the Cpb ones due to the domination of the coherent evolution processes under this EEF. So it seems to us that the main dynamical properties of our model reflect the specific features of the real biological evolution which can not be described in the framework of the more simple BSM.

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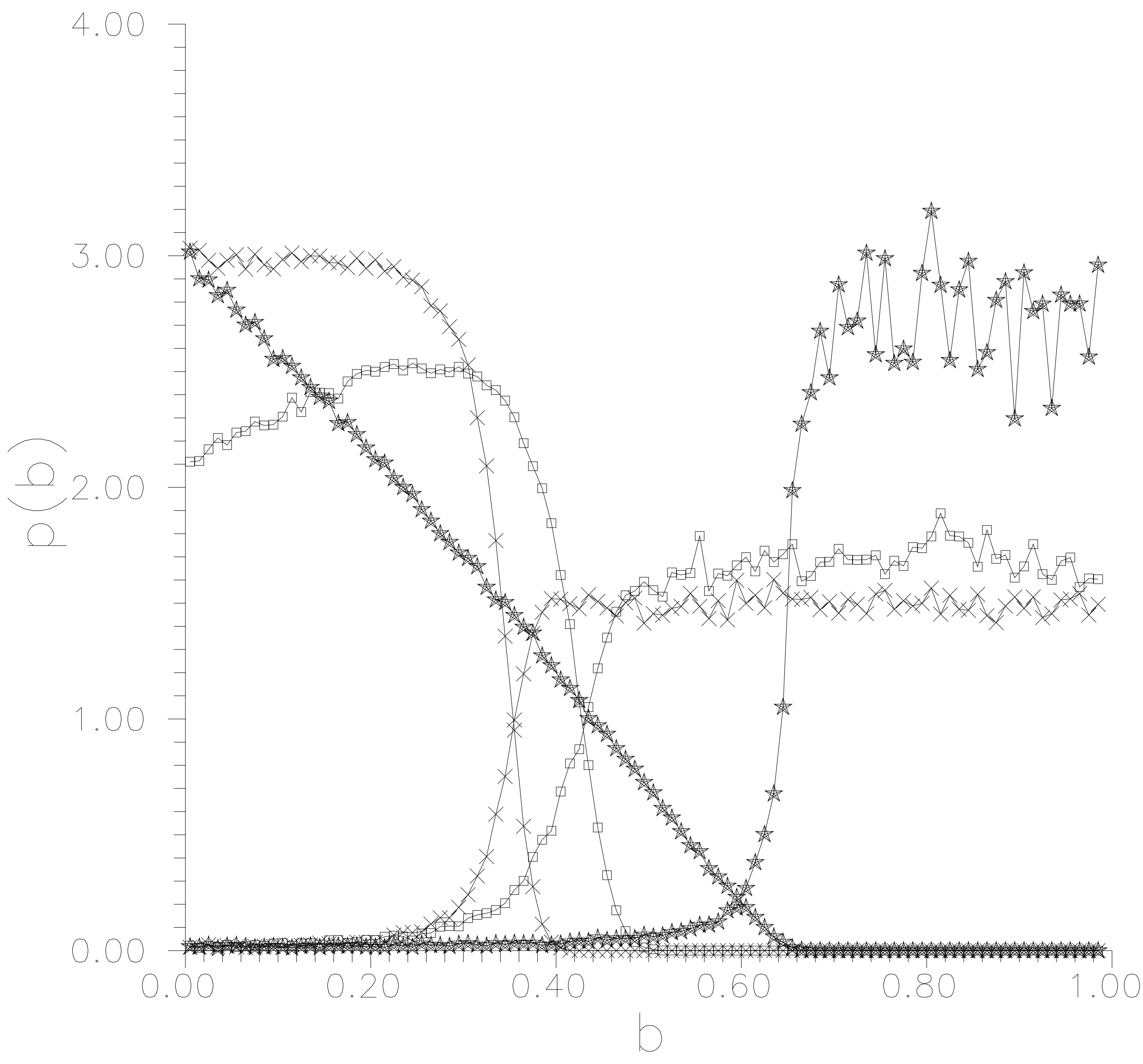

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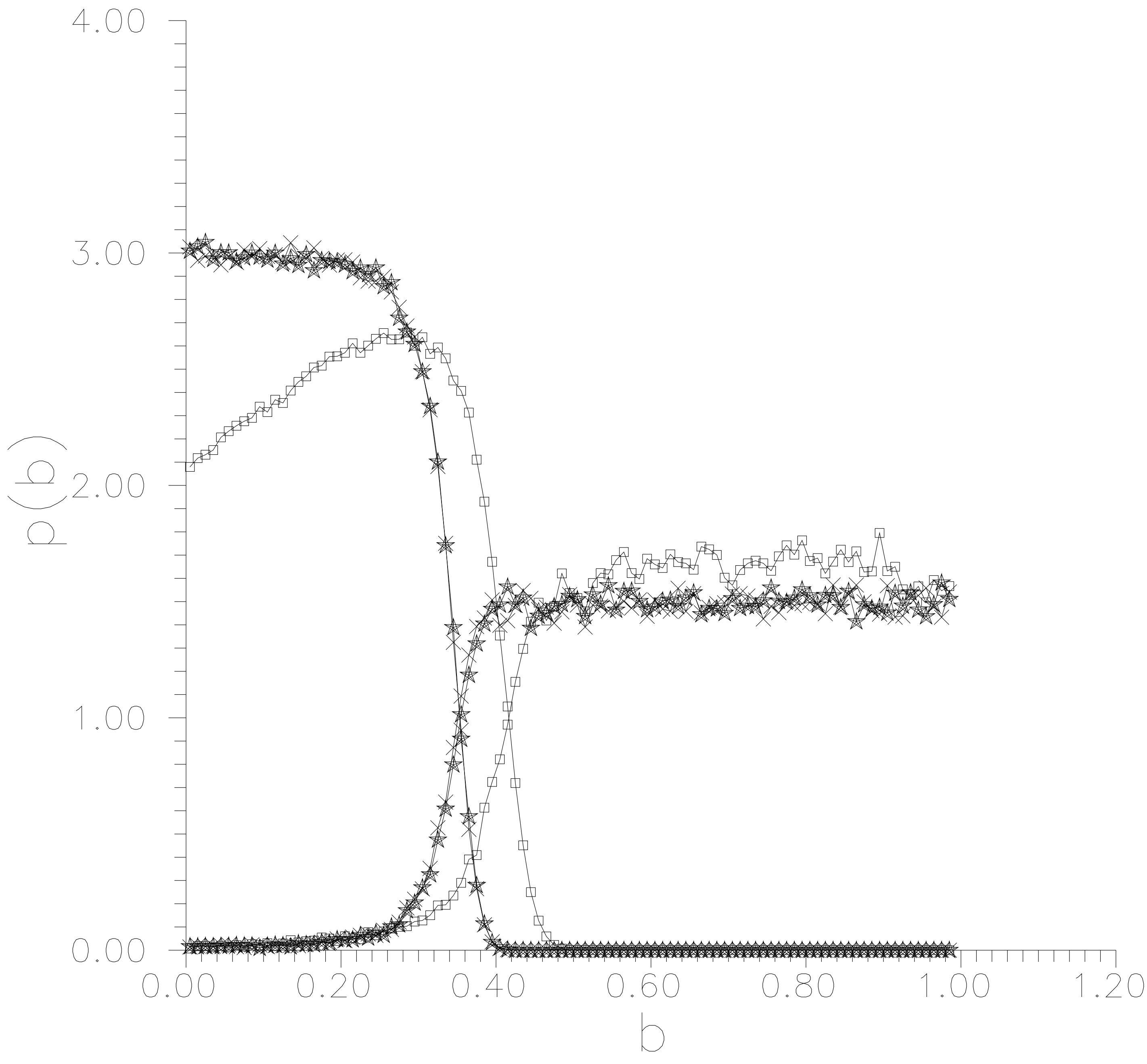

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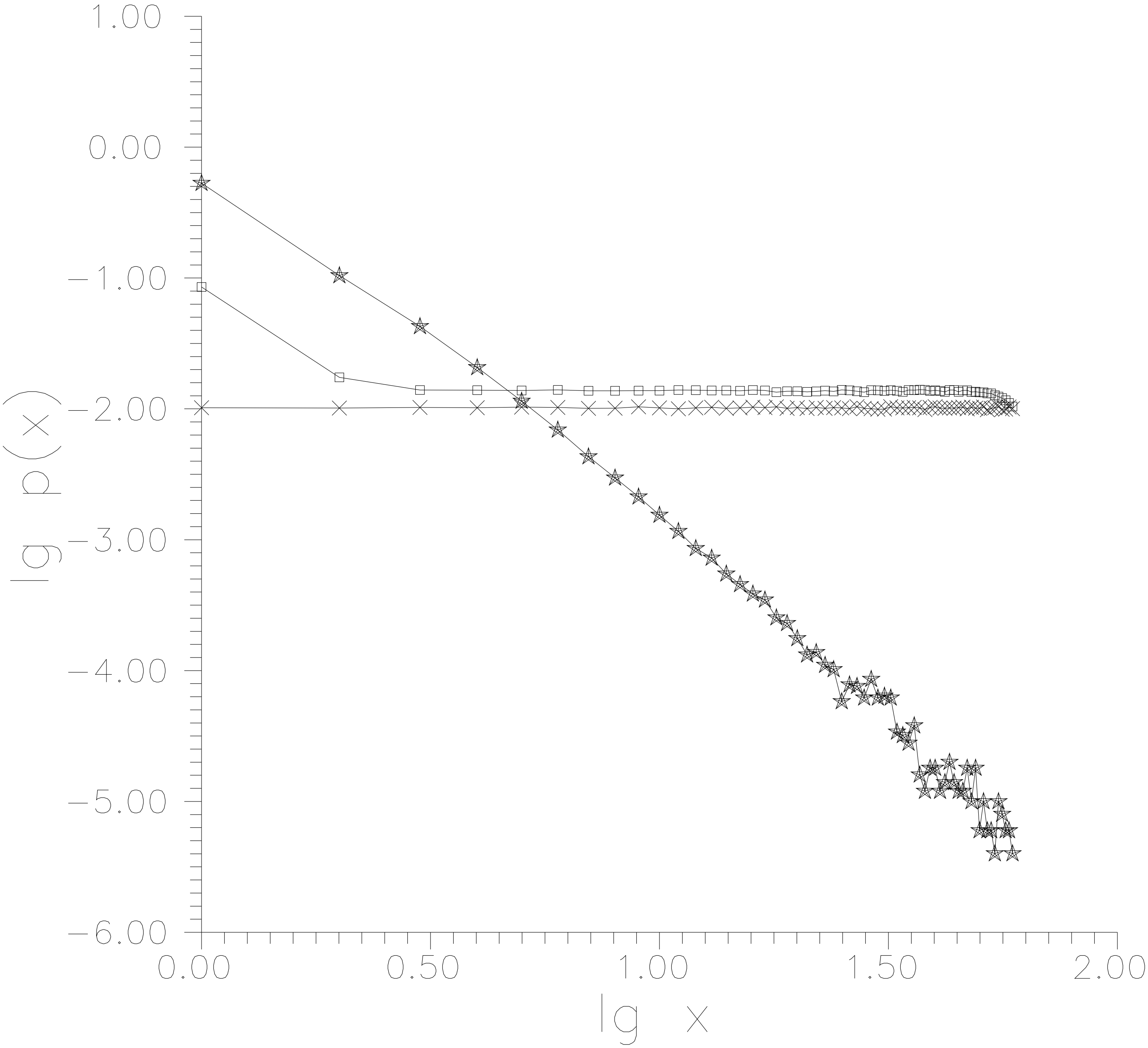

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