Properties of the interfaces generated by the competition between stable and unstable growth models

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Two different growing mechanisms, given by the Eden model (EM) and the unstable Eden model (UEM), are used to numerically explore the properties of the interface generated by a competitive dynamic process in which particles are aggregated according to the rules of the EM with probability $(1-p)$ and following the UEM with probability p. Based on extensive numerical simulations, it is shown that the interface width exhibits a growing regime that at time t_{x2} crosses over to a saturation state such that the width (W_{sat}) remains stationary. It is shown that W_{sat} and t_{x2} depend on both the lattice size L and the probability p. This behavior can be rationalized by proposing new scaling relationships, which are tested numerically. Furthermore, the relevant exponents are determined showing that the instabilities of the UEM dominate the dynamics of the growing process.

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I. INTRODUCTION

The study of the morphology, structure, and other physical and chemical properties of growing interfaces has recently become a very active field of research [1–4]. This interest is due to the fact that evolving interfaces appear in a great variety of physical, chemical, and biological systems. For example, it is well known that mechanical problems concerning wear, friction, and adhesion show a crucial dependence on the smoothness of the surfaces that come into contact. Also, the surface roughness modifies the electrical, magnetic, and optical properties of thin films. The development of better controlled surface growth techniques is an important line of research with technological applications, and these techniques generally show the existence of growth regimes with common spatiotemporal features, such as scale invariance [1]. Also, natural processes such as the propagation of forest fires and the growth of bacterial colonies show interfacial scale invariant behavior [1]. Scale invariance is revealed by scaling exponents and functions that have to be measured in order to classify the growth processes into universality classes.

Models of growing interfaces may be defined and studied by means of both continuous equations and discrete lattices. Continuous equations focus on macroscopic aspects of surface roughness that are expected to be universal. The main idea behind this approach is to follow the evolution of coarse-grained variables such as the interface location. The most popular approaches are the Edwards-Wilkinson (EW) [5] and the Kardar-Parisi-Zhang (KPZ) equations [6]. On the other hand, discrete models are defined by a set of rules that provide a detailed microscopic description of the evolution of the surface. Some very well known discrete models are random deposition (RD), random deposition with surface relaxation (RDSR), and ballistic deposition (BD) [1–4]. In these models the interface is described by a discrete set $h(i,t)$ that represents the height of site i at time t. The interface has L^d sites, where L is the linear size and d is the dimensionality of the substrate. The interface of the aggregate is characterized by the scaling of the interface width

$$W(L,t) \equiv \sqrt{1/L^d \sum_{i=1}^{L^d} [h(i,t) - \langle h(t) \rangle]^2}, \tag{1}$$

where $\langle h(t) \rangle$ is the average height of the surface at time t and is defined as

$$\langle h(t) \rangle = \frac{1}{L^d} \sum_i h(i,t). \tag{2}$$

The Family-Vicsek phenomenological scaling approach [7] provides a very successful way to describe the dynamic evolution of growing interfaces. Accordingly, it may be expected that $W(L,t)$ would show the spatiotemporal scaling behavior given by [7]: $W_{sat}(L) \propto L^{\alpha}$ for $t \gg t_c$ and $W(t) \propto t^{\beta}$ for $t \ll t_c$, where $t_c \propto L^z$ is the crossover time between these two regimes. The scaling exponents α, β, and $z = \alpha/\beta$ are called roughness, growth, and dynamic exponents, respectively. The above concepts can be summarized by means of the following scaling ansatz [7]:

$$W(t) \propto L^{\alpha} F(t/L^z), \tag{3}$$

where $F(x) \equiv \text{const}$ for $x \gg 1$ and $F(x) \propto x^{\beta}$ for $x \to 0$.

It should be noticed that most studies, reported up to now and performed using both continuous equations and/or discrete models, usually involve a single kind of particle. In contrast, less attention has been drawn to the study of the dynamics of competitive processes, even when these processes are significant to the growth of real materials in at least two different situations: (a) in growing processes involving two or more types of particles and (b) considering the deposition of a single kind of particle that may undergo

either a deposition-evaporation process or is subjected to different growing mechanisms. One example of case (a) arises during the deposition of alloys or single-component systems contaminated with impurities; see Refs. [8–13] and references therein. In this case, there may be different interactions among different kinds of particles causing the growing mechanisms to change [8–13]. Based on these ideas, Cerdeira and co-workers [8–11] have studied models for binary systems involving competitive randomlike and ballisticlike deposition.

Also, deposition of a single kind of particle in a competitive process arises upon the growth of polycrystalline films [14]. In this case, particles deposited in the central area of small crystals undergo restricted diffusion, while particles deposited close to the intercrystalline gaps may experience intercrystalline diffusion and consequently different adsorption-diffusion mechanisms have to be considered [14]. Also, Shapir *et al.* [15] have reported experimental results for the surface roughness of interfaces obtained during cyclic electrodeposition and dissolution of silver. They found that the roughness exhibits a power-law dependence with the number of cycles, a result that is consistent with a scaling description developed by using continuous equations and renormalization group techniques [15].

In this context, two of us have previously studied two competitive models [16,17]. In the first discrete growth model—namely, the RDSR-RD model—particles of a single kind have been aggregated according to the rules of RDSR with probability p and according to the rules of RD with probability $(1-p)$ [16]. In the second discrete growth model—namely, the BD-RD model—particles have been aggregated according to the rules of BD with probability p and according to the rules of RD with probability $(1-p)$ [17]. Our main results can be summarized as follows: in both models, three different regimes and the corresponding crossovers can easily be observed. For short times—say, $t<t_{x1}$—the RD process dominates and the random growth of the interface is observed. At this stage, correlations have not been developed yet and $W(t)\propto t^{\beta_{\mathrm{RD}}}$ $(t<t_{x1})$ holds. During an intermediate-time regime—say, $t_{x1}<t<t_{x2}$—correlations develop since the RDSR (BD) process now dominates leading to $W(t)\propto t^{\beta_{\mathrm{RDSR}}}$ $(W(t)\propto t^{\beta_{\mathrm{BD}}})$. At a later stage, for $t>t_{x2}$, correlations can no longer grow due to the geometrical constraint of the lattice size and saturation is observed. The saturation width $W_{sat}(L,p)$ and the characteristic crossover time t_{x2} behave as [16,17]

$$W_{sat}(L,p)\propto L^{\alpha_X}p^{-\delta} \quad (p>0) \tag{4}$$

and

$$t_{x2}(L,p)\propto L^{z_X}p^{-y} \quad (p>0), \tag{5}$$

where δ and y are exponents and $X\equiv$RDSR, BD depending on the model. For $t_{x1}<t<t_{x2}$ one has

$$W(t,p)\propto t^{\beta_X}p^{-\gamma}, \tag{6}$$

where γ is also a characteristic exponent.

The exponents γ, δ, and y are not independent. Using a phenomenological dynamic scaling ansatz it has been shown that the following relationship between exponents holds [16,17]:

$$y\beta_X-\delta+\gamma=0. \tag{7}$$

For the RDSR-RD model in $d=(1+1)$ dimensions, the conjectured exact values are $y\equiv 2$, $\delta\equiv 1$, and $\gamma\equiv\frac{1}{2}$. Also, for the BD-RD model in the same dimension one has $y\equiv 1$, $\delta\equiv\frac{1}{2}$, and $\gamma\equiv\frac{1}{6}$.

It is worth mentioning that from these results it follows that the saturation value W_{sat} depends sensitively on p: saturation takes place at longer times for smaller values of p, while W_{sat} decreases as p increases. This is because in both competitive models the lack of correlations among particles deposited according to RD produces a delay in the development of correlations along the direction parallel to the interface.

Let us stress that all these previous studies involve the competition between growing mechanisms leading to the development of stable interfaces with $\beta<1/2$. So, in order to further contribute to the understanding of competitive processes, the aim of the present work is to study the properties of the interface generated by a competitive dynamic process involving both stable and unstable growing mechanisms. For this purpose the Eden model (EM) [18,19] and the unstable Eden model (UEM) [20] have been used. According to Ref. [19] three different versions of the EM can be implemented. We have used the version A in which the new particle is added equiprobably on any unoccupied site of the perimeter (see Sec. II). Since unstable interfaces are not described by means of the standard Family-Vicsek ansatz [Eq. (3)], the present work is also aimed at contributing to the development of more general dynamic scaling approaches. The paper is organized as follows: the competitive model is introduced in Sec. II. In Sec. III our numerical results are presented and discussed and, finally, our conclusions are stated in Sec. IV.

II. DESCRIPTION OF THE MODEL

The Eden Model was earlier introduced by Eden as a growth model of tumor cells [18]. In this paper, the EM is defined in the square lattice of width L and length M in $(1+1)$ dimensions. The sites of the lattice are labeled by indexes (i,j) such that $1\leqslant i\leqslant L$ and $1\leqslant j\leqslant M$. The growing process starts from a row of occupied sites at $j=1$ $(\forall i)$ while the remaining sites of the lattice are left vacant. Eden clusters grow by adding new particles to perimeter sites—i.e., those empty sites that are nearest neighbors of already occupied sites. Specifically, the EM assumes that all perimeter (or growing) sites have the same probability of becoming occupied. This version of the EM corresponds to that called version A in Ref. [19] and exhibits strong finite-size effects [21]. Because of these effects, the determination of the β exponent becomes difficult and the use of very large lattice sizes is necessary. In the present work we reach the asymptotic limit for the largest lattice size that we used and we show that our conclusions are valid in this limit.

It is well known that Eden clusters are compact objects with a self-affine interface characterized, in 1+1 dimensions, by exponents $\beta_{EM}=1/3$ and $\alpha_{EM}=1/2$ and, consequently, $z_{EM}=\alpha_{EM}/\beta_{EM}=3/2$ [1]. The EM belongs to the KPZ universality class [1].

In the unstable Eden model [20] the growing sites have a probability $P(j-\langle h\rangle)$ of becoming occupied, such that

$$P(j-\langle h\rangle)=C|j-\langle h\rangle|^{\Delta}, \tag{8}$$

where Δ is an exponent that can be tuned as an external parameter and $\langle h\rangle$ is the average height of the interface at time t, which is given by Eq. (2). It should be noticed that after each deposition event the growing probability of all perimeter sites has to be evaluated, such that the normalization constant becomes $C=1/\Sigma_{allsites}P(j-\langle h\rangle)$. It is also clear that for $\Delta=0$ the UEM gives the classical EM. The UEM is inspired by the experimental observation of the growth of unstable interfaces upon both chemical vapor deposition of SiO_2 [22] and electrodeposition of Cu [23]. In fact, these experiments show that due to the preferential deposition of atoms in some regions of the sample, one observes the development of protrusions surrounded by deep valleys and the growth of the interface becomes unstable during a transient period. The UEM was numerically studied for several values of Δ [20], and it was established that for $\Delta>0$ the critical exponents become independent of Δ with $\beta_{UEM}=2/3$ and $\alpha_{UEM}=1$. These values were numerically determined by simulating the UEM in lattices of $L\leqslant 1536$. Assuming the validity of the Family-Vicsek scaling relation, the value $z_{UEM}=\alpha_{UEM}/\beta_{UEM}=3/2$ should be expected. Our preliminary estimation was $z_{UEM}=1.35\pm0.20$, while for the purpose of the present work a more accurate value has been determined, performing exhaustive simulations so that $z_{UEM}=1.05\pm0.05$. This result is not surprising since unstable models with $1/2<\beta\leqslant 1$ depart from the standard Family-Vicsek scaling approach. It is also worth mentioning that models with $\alpha>1$ exhibit superroughening since the density of sites of the interface diverges in the thermodynamic limit [24,25]. So, the UEM with $\alpha_{UEM}\cong 1$ may be marginally superrough. Also, as was shown in Ref. [20], the UEM lacks self-affinity.

In the present work, a discrete growth model—namely, the EM-UEM model—where particles are aggregated according to the rules of the EM with probability $(1-p)$ and according to the rules of the UEM with probability (p), is studied by means of Monte Carlo simulations. These simulations are performed in the square lattice of width L and length M, in 1+1 dimensions, assuming periodic boundary conditions along the L direction. One Monte Carlo time step (MCS) involves the deposition of L particles.

III. RESULTS AND DISCUSSION

Figure 1(a) shows plots of W versus t obtained for the EM-UEM model using different values of p and taking $L=512$. It is found that the saturation of the interface width (W_{sat}) depends sensitively on p, with values ranging between both models—i.e., the EM with $p=0$ and the UEM with $p=1$. As follows from Fig. 1(a), for the selected lattice size, the growing regime of the EM does not reach the asymptotic slope with $\beta_{EM}=1/3$, but a smaller slope is observed. This is, of course, a typical finite-size effect, and the use of noise-reduction techniques (or a large lattice size) is necessary in order to obtain a reliable estimation of β_{EM} [1]. For $p>0$ one observes the departure from the growing regime of the EM. This regime becomes clearly dominated by the UEM for $0.08\leqslant p\leqslant 0.64$.

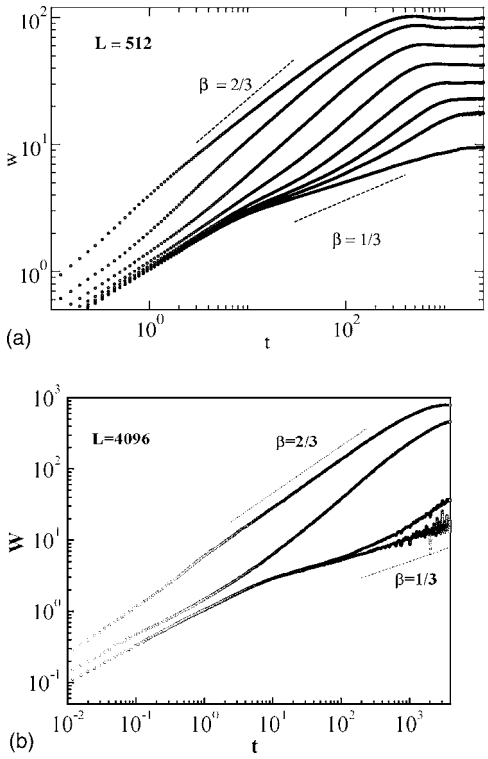

FIG. 1. Log-log plots of the interface width (W) versus time (t) for the EM-UEM model. (a) Data obtained taking $L=512$ and different values of p, which are, from bottom to top, $p=0$, 0.02, 0.04, 0.08, 0.16, 0.32, 0.64, and 1.00. (b) Data obtained taking $L=4096$ and different values of p, which are, from bottom to top, $p=0$, 0.01, 0.32, and 1.00. Also, for the UEM ($p=1$) and EM ($p=0$) dashed lines with slopes $\beta_{UEM}=2/3$ and $\beta_{EM}=1/3$ have been drawn for the sake of comparison.

Because the scaling regimes for the EM and UEM were not reached in these simulations, one wonders if similar conclusions can be drawn even in the asymptotic limit. Figure 1(b) shows plots of W versus t for different values of p for $L=4096$. The asymptotic regime for the EM and UEM is reached for $p=0$ and $p=1$, respectively (we have measured $\beta_{EM}=0.329\pm0.004$ and $\beta_{UEM}=0.666\pm0.001$). Though due to the so large lattice size used the saturation regime could not be reached and therefore W_{sat} (and t_{x2}) cannot be determined, it can be seen that for $p>0$ the growing regime departs from the EM become clearly unstable. Therefore, we conclude that the UEM dominates even in the asymptotic behavior.

Figure 2 shows plots of W versus t obtained using lattices of different size but keeping $p=0.32$ constant. Three different regimes and the corresponding crossovers can be observed. For short times—say, $t<t_{x1}$—the growth proceeds

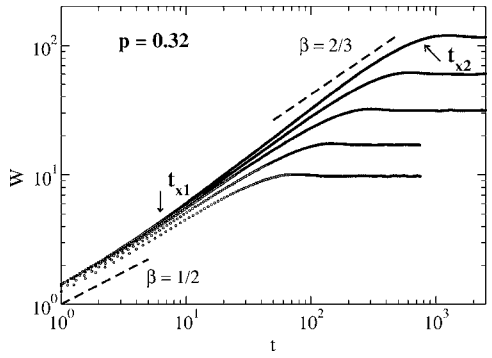

FIG. 2. Log-log plots of the interface width (W) versus time (t) for the EM-UEM model. Data obtained keeping $p=0.32$ constant and using lattices of different size, which are, from bottom to top, $L=64$, 128, 256, 512, and 1024. The arrows show the location of t_{x1} and t_{x2} for the data corresponding to $L=1024$. Also, the dashed lines have slopes $\beta_{\mathrm{UEM}}=2/3$ and $\beta_{\mathrm{RD}}=1/2$, and have been drawn for the sake of comparison. More details in the text.

essentially at random, so it follows that $W(t) \propto t^{\beta_{\mathrm{RD}}}$, $t < t_{x1}$, where $\beta=1/2$ is the growing exponent of the RD model. During an intermediate-time regime—say, $t_{x1} < t < t_{x2}$—the UEM process starts to dominate and finally, for $t > t_{x2}$, correlations can no longer develop due to the geometrical constraint of the lattice size, and therefore the saturation of the interface width is observed.

In order to outline a phenomenological dynamic scaling approach and based on Eqs. (4) and (5), we propose the following ansatz for the saturation value of the interface width $W_{sat}(L,p)$,

$$W_{sat}(L,p) \propto L^{\alpha_{\mathrm{UEM}}} p^{-\delta} \quad (p > 0), \tag{9}$$

and the crossover time t_{x2},

$$t_{x2}(L,p) \propto L^{z_{\mathrm{UEM}}} p^{-y} \quad (p > 0), \tag{10}$$

where δ and y are exponents. It is worth mentioning that only the exponent of the UEM, but not those of the EM, enter into Eqs. (9) and (10). So the confirmation of the proposed scaling ansatz will be clear evidence that the growth mechanism of the UEM is dominant, while the growth mechanism of the EM becomes irrelevant.

Figure 3 shows log-log plots of $W_{sat}/L^{\alpha_{\mathrm{UEM}}}$ versus p obtained for $L=128$, 256, 512, and 1024. A systematic approach of the data to a straight line behavior is observed when the lattice size is increased, in agreement with Eq. (9). The best fit of the data corresponding to $L=1024$ gives the slope $\delta \cong -0.48 \pm 0.03$. The systematic deviation of the data for low values of p may be due to the partial stabilization of the interface caused by the stable growth mode of the EM, which is expected to become important in the $p \to 0$ limit and for small lattices.

Figure 4 shows log-log plots of $t_{x2}/L^{z_{\mathrm{UEM}}}$ versus p obtained using lattices of size $L=128$, 256, 512, and 1024. Again, a rather small systematic deviation of the data for low values of p can be seen, but this deviation becomes negligible when the size of the samples is increased. This effect is in agreement with the fact that the EM growing regime becomes irrelevant even for small p when the lattices are large enough. The best collapse is found using $z_{\mathrm{UEM}}=1.05$, in agreement with our previous estimation and the fact that $z_{\mathrm{UEM}} \neq \alpha_{\mathrm{UEM}}/\beta_{\mathrm{UEM}}$ as expected when the Family-Vicsek ansatz [Eq. (3)] is no longer valid. The observed straight line is in agreement with Eq. (10), and the best fit of the data gives the slope $y \cong 0.47 \pm 0.04$.

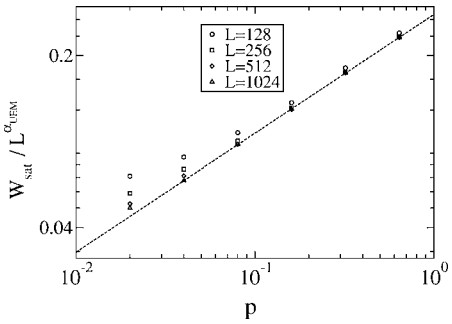

FIG. 3. Log-log plots of $W_{sat}/L^{\alpha_{\mathrm{UEM}}}$ versus p obtained for lattices of different size, as indicated in the figure. The best fit of the data, according to Eq. (9), has slope $\delta=-0.48$ and corresponds to the dashed line.

These results lead us to conjecture the following exact (rational) values for the new exponents of the EM and UEM:

$$\delta \equiv -\frac{1}{2}(-0.48 \pm 0.03), \quad y \equiv \frac{1}{2}(0.47 \pm 0.04), \tag{11}$$

where the values between brackets are our numerical estimations.

Table I summarizes the values of the exponents δ and y obtained for competitive growth models. It follows that for the competition between mechanisms leading to stable interfaces one has $\delta > 0$, in agreement with the fact that the rougher interface of the RD model becomes smoother when p is increased, due to the increasing influence of either the BD or the RDSR growth mechanisms. However, in the case of the EM and UEM one has $\delta < 0$ because the smoother interface of the EM with roughness of the order of $W_{sat} \propto L^{\alpha_{\mathrm{EM}}}$ ($\alpha_{\mathrm{EM}}=1/2$) is further roughened by the operation of

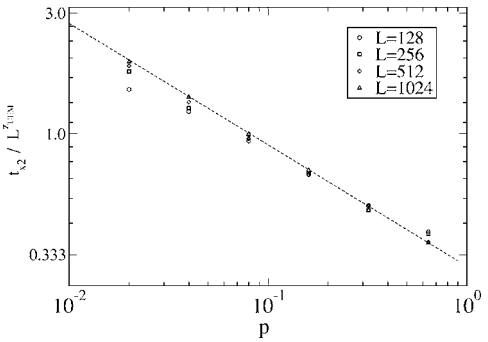

FIG. 4. Log-log plots of $t_{x2}/L^{z_{\mathrm{UEM}}}$ versus p obtained for lattices of different size, as indicated in the figure and taking $z_{\mathrm{UEM}}=1.05$. The dashed line has slope $y=0.47$ and corresponds to the best fit of the data according to Eq. (10). More details are given in the text.

TABLE I. Scaling exponents δ and y determined for different competitive growth processes. RD≡random deposition, RDSR ≡random deposition with surface relaxation, BD≡ballistic deposition, EM≡Eden model, UEM≡unstable Eden model, and PW ≡present work. More details are given in the text.

Model	δ	y	Reference
RD-RDSR	1	2	[20]
RD-BD	1/2	1	[20]
EM-UEM	−1/2	1/2	PW

the UEM mechanism with $W_{sat} \propto L^{\alpha_{\mathrm{UEM}}}$ ($\alpha_{\mathrm{UEM}}=1$) when p is increased, as shown in Fig. 1.

It is also worth mentioning that the crossover time of the EM ($p=0$) and the UEM ($p=1$) behaves according to $t_{x2} \propto L^{z_{\mathrm{EM}}}$ ($z_{\mathrm{EM}}=3/2$) and $t_{x2} \propto L^{z_{\mathrm{UEM}}}$ ($z_{\mathrm{UEM}}=1$), respectively. So one has that for the EM and UEM t_{x2} decreases when p is increased, as is also shown in Fig. 1 and in agreement with the exponent $y=1/2$ reported in Table I.

IV. CONCLUSIONS

In the present work a competitive dynamic process involving two different growing mechanisms having different lateral correlations—namely, the EM and UEM—has been studied numerically. In this discrete model, particles are aggregated according to the rules of the EM with probability $(1-p)$ and according to the rules of the UEM with probability (p). We have found that the saturation width W_{sat} and the crossover time t_{x2} depend on both the lattice size L and the probability p. New scale behaviors are proposed and the corresponding exponents are numerically determined, according to Eqs. (9)–(11). It is found that the unstable growth mechanism dominates the dynamics of the system. This finding may simply be a particular characteristic of the selected competing mechanisms or it may reflect a deeper physical behavior. This open question is relevant for the search of suitable stabilization mechanisms for highly disordered surfaces.

We expect that this numerical calculations may stimulate further work, both experimental and theoretical, since competitive processes appear in many physical, chemical, and biological systems.

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[1] A. L. Barabasi and H. E. Stanley, *Fractal Concepts in Surface Growth* (Cambridge University Press, Cambridge, England, 1995).
[2] *Kinetics of Aggregation and Gelation*, edited by F. Family and D. Landau (North-Holland, Amsterdam, 1984).
[3] *Fractals and Disordered Systems*, edited by A. Bunde and S. Havlin (Springer-Verlag, Berlin, 1992), p. 229.
[4] F. Family, in *Rough Surfaces: Scaling Theory and Universality*, edited by R. Jullien, L. Peliti, R. Rammal, and N. Boccara, Springer Proceedings in Physics, Vol. 32 (Springer-Verlag, Berlin, 1988), p. 193.
[5] S. F. Edwards and D. R. Wilkinson, Proc. R. Soc. London, Ser. A **381**, 17 (1982).
[6] M. Kardar, G. Parisi, and Y.-C. Zhang, Phys. Rev. Lett. **56**, 889 (1986).
[7] F. Family and T. Vicsek, J. Phys. A **18**, L75 (1985); F. Family, *ibid.* **19**, L441 (1986).
[8] W. Wang and H. A. Cerdeira, Phys. Rev. E **47**, 3357 (1993).
[9] W. Wang and H. A. Cerdeira, Phys. Rev. E **52**, 6308 (1995).
[10] H. F. El-Nashar, W. Wang, and H. Cerdeira, J. Phys.: Condens. Matter **8**, 3271 (1996).
[11] H. F. El-Nashar and H. A. Cerdeira, Phys. Rev. E **61**, 6149 (2000).
[12] B. Drossel and M. Kardar, Phys. Rev. Lett. **85**, 614 (2000).
[13] M. Kotrla, F. Slanina, and M. Predota, Phys. Rev. B **58**, 10003 (1998); M. Kotrla, M. Predota, and F. Slanina, Surf. Sci. **402-404**, 249 (1998).
[14] E. V. Albano, R. C. Salvarezza, L. Vázquez, and A. J. Arvia, Phys. Rev. B **59**, 7354 (1999).
[15] Y. Shapir, S. Raychaudhuri, D. G. Foster, and J. Jorne, Phys. Rev. Lett. **84**, 3029 (2000).
[16] C. M. Horowitz, R. A. Monetti, and E. V. Albano, Phys. Rev. E **63**, 066132 (2001).
[17] C. Horowitz and E. V. Albano, J. Phys. A **34**, 357 (2001).
[18] M. Eden, *Proceedings of the Symposium on Information Theory in Biology*, edited by H. P. Yockey (Pergamon Press, New York, 1958).
[19] R. Jullien and R. Botet, Phys. Rev. Lett. **54**, 2055 (1985).
[20] E. V. Albano and I. M. Irurzun, J. Phys. A **34**, 9631 (2001).
[21] M. Plischke and Z. Racz, Phys. Rev. Lett. **53**, 415 (1984).
[22] F. Ojeda, R. Cuerno, R. Salvarezza, and L. Vázquez, Phys. Rev. Lett. **84**, 3125 (2000).
[23] P. Schilardi, S. Méndez, R. Salvareza, and A. Arvia, Langmuir **14**, 4308 (1998).
[24] N. N. Pang and W. J. Tzeng, Phys. Rev. E **61**, 3559 (2000).
[25] P. Meakin, in *Fractals, Scaling and Growth Far From Equilibrium*, edited by B. Chirikov, P. Cvitanovic, F. Moss, and H. Swinney (Cambridge University Press, Cambridge, England, 1998).