

Nonequilibrium spin glass dynamics with Janus

F. Belletti^{*}, A. Cruz^{†,**}, L.A. Fernandez^{‡,***}, A. Gordillo-Guerrero^{§,**},
 M. Guidetti^{*}, A. Maiorano^{*,**}, F. Mantovani^{*}, E. Marinari[¶],
 V. Martin-Mayor^{‡,***}, A. Muñoz Sudupe[‡], D. Navarro^{||}, G. Parisi[¶],
 S. Perez-Gaviro^{**}, J. J. Ruiz-Lorenzo^{§,***}, S.F. Schifano^{*}, D. Sciretti^{**},
 A. Tarancon^{†,**}, R. Tripiccione^{*} and D. Yllanes^{‡,***}

^{*}*Dipartimento di Fisica Università di Ferrara and INFN - Sezione di Ferrara, Ferrara, Italy.*

[†]*Departamento de Física Teórica, Universidad de Zaragoza, 50009 Zaragoza, Spain.*

^{**}*Instituto de Biocomputación y Física de Sistemas Complejos (BIFI), Zaragoza, Spain.*

[‡]*Departamento de Física Teórica I, Universidad Complutense, 28040 Madrid, Spain.*

[§]*Departamento de Física, Universidad de Extremadura, 06071 Badajoz, Spain.*

[¶]*Dipartimento di Fisica, INFN and INFN, Università di Roma "La Sapienza", 00185 Roma, Italy.*

^{||}*D. de Ingeniería, Electrónica y Comunicaciones and I3A, U. de Zaragoza, Zaragoza, Spain.*

Abstract. The out of equilibrium evolution for an Edwards-Anderson spin glass is followed for a tenth of a second, a long enough time to let us make safe predictions about the behaviour at experimental scales. This work has been made possible by Janus, an FPGA based special purpose computer. We have thoroughly studied the spin glass correlation functions and the growth of the coherence length for $L=80$ lattices in 3D. Our main conclusion is that these spin glasses follow noncoarsening dynamics, at least up to the experimentally relevant time scales.

Keywords: Spin glass, nonequilibrium, coarsening dynamics, replica symmetry breaking

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THE EDWARDS-ANDERSON SPIN GLASS

Experiments on Spin Glasses [1] (SG) focus on nonequilibrium dynamics. Typically, the system is cooled to a subcritical working temperature $T < T_c$, where it is let to evolve for a waiting time t_w and probed at a time $t + t_w$. The main feature of these systems is the extremely slow dynamics, characterised by the growth of the coherence length $\xi(t_w)$.

In order to analyse these experiments, theorists rely to a large extent on numerical work. There is a problem, however, with this approach. A typical experiment takes place on time scales of about 50 s– 10^4 s, while conventional computers are only able to reach times of about 10 μ s. In the simulation we are going to describe here [2], the use of the custom built Janus computer [3] has allowed us to reach times of tenths of a second.

We shall work with the Edwards-Anderson model for the Ising spin glass,

$$\mathcal{H} = - \sum_{\langle \mathbf{x}, \mathbf{y} \rangle} J_{\mathbf{x}, \mathbf{y}} \sigma_{\mathbf{x}} \sigma_{\mathbf{y}}, \quad P(J_{\mathbf{x}, \mathbf{y}}^2) = \delta(J_{\mathbf{x}, \mathbf{y}}^2 - 1), \quad (1)$$

(the $\langle \dots \rangle$ denotes that the summation is restricted to nearest neighbours). This model experiences a SG transition [4], with a critical temperature of $T_c = 1.101(5)$ [5].

We are going to work at subcritical temperatures of $T = 0.6, 0.7$ and 0.8 , in each case simulating ~ 100 samples. We follow the system for 10^{11} Monte Carlo steps (~ 0.1 s).

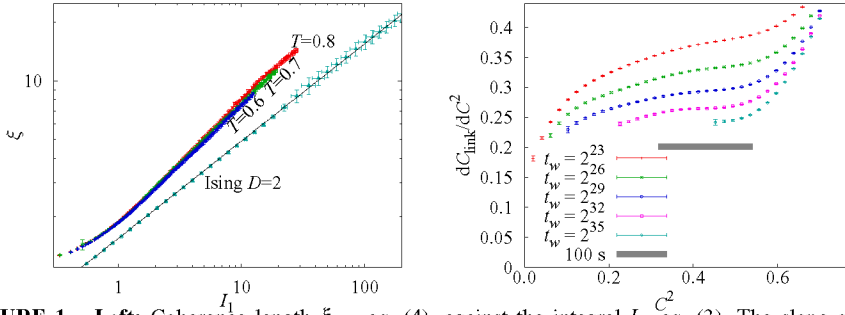


FIGURE 1. Left: Coherence length $\xi_{1,2}$, eq. (4), against the integral I_1 , eq. (3). The slope of this logarithmic plot equals $2 - a$ and is clearly incompatible with the $a = 0$ value for coarsening dynamics (exemplified here with an analogous plot for the Ising model). **Right:** Slope of the function $C_{\text{lmk}}(C^2, t_w)$ for several values of t_w at $T = 0.6$. Our extrapolation for 100 s (the thickness of the line indicates our uncertainty interval) is incompatible with the vanishing value for coarsening dynamics.

Numerical work is needed to make several conflicting theoretical pictures for the SG phase quantitative and to determine which one best describes the physics.

On the one hand we have the droplets picture [6], according to which only two equilibrium states exist, related by a global spin reversal. Droplets' is an example of coarsening dynamics, characterised by the growth of compact domains where the order parameter takes one of its two equilibrium values $q = \pm q_{\text{EA}}$.

On the other hand we have the Replica Symmetry Breaking theory [7], where q has a nontrivial probability distribution in $[-q_{\text{EA}}, q_{\text{EA}}]$. There also is the intermediate TNT picture [8], which agrees with RSB in a nontrivial distribution for q . It also agrees with droplets in that the largest thermally activated domains have a vanishing surface to volume ratio in the thermodynamic limit, while in RSB excitations are space filling.

THE COHERENCE LENGTH

The first observable we are going to study is the autocorrelation of the overlap field,

$$C_4(\mathbf{r}, t_w) = \overline{L^{-3} \sum_{\mathbf{x}} q_{\mathbf{x}}(t_w) q_{\mathbf{x}+\mathbf{r}}(t_w)}, \quad q_{\mathbf{x}}(t_w) = \sigma_{\mathbf{x}}^{(1)}(t_w) \sigma_{\mathbf{x}}^{(2)}(t_w) \quad (2)$$

This function has been found [7] to decay as $C_4(\mathbf{r}, t_w) \sim r^{-a} \exp[-(r/\xi(t_w))^b]$, $a \approx 0.4$, $b \approx 1.5$. This asymptotic expression is characterised by the coherence length $\xi(t_w)$ and by an exponent a . An $a = 0$ would indicate coarsening dynamics, while $a > 0$ is consistent with RSB. Here we intend to give a very precise determination of a .

In order to do this we are not going to use an explicit asymptotic formula for C_4 . Instead, we are going to consider the integrals

$$I_k(t_w) = \int_0^\infty dr r^k C_4(r, t_w). \quad (3)$$

If C_4 is well described (at long r) by the scaling form $C_4(r, t_w) \sim r^{-a} f[r/\xi(t_w)]$, then

$$\xi_{k,k+1}(t_w) = \frac{I_{k+1}}{I_k} \propto \xi(t_w). \quad (4)$$

We have ascertained that $\xi_{k,k+1}$ are valid coherence lengths by checking that they are proportional to one another and to the (much noisier) second moment estimate.

Using this definition, and noticing that $I_1 \propto \xi_{k,k+1}^{2-a}$, we have been able to obtain the following values for the exponent a : $a(T = 0.6) = 0.359(13)$, $a(T = 0.7) = 0.355(15)$, $a(T = 0.8) = 0.442(11)$ (Fig. 1, left).

THE LINK AND SPIN CORRELATION FUNCTIONS

We are now interested in the following correlation functions

$$C(t, t_w) = L^{-3} \overline{\sum_{\mathbf{x}} \sigma_{\mathbf{x}}^{t_w} \sigma_{\mathbf{x}}^{t+t_w}}, \quad C_{\text{link}}(t, t_w) = \overline{(3L^{-3}) \sum_{\langle \mathbf{x}, \mathbf{y} \rangle} \sigma_{\mathbf{x}}^{t_w} \sigma_{\mathbf{x}}^{t+t_w} \sigma_{\mathbf{y}}^{t_w} \sigma_{\mathbf{y}}^{t+t_w}}. \quad (5)$$

We are going to eliminate t as an independent variable and study $C_{\text{link}}(C^2, t_w)$. This function has a very different look depending on the dynamics. Indeed, its slope for $C^2 < q_{\text{EA}}^2$ would vanish for a coarsening system, but not for an RSB one. The derivative of this function for the EA SG is depicted in Fig. 1, right. Even for experimental time scales, the slope is clearly nonzero and hence incompatible with coarsening dynamics.

We have presented evidence for the noncoarsening dynamics of the Ising SG, made available to us by the use of the Janus machine. Other aspects of this work, untouched upon here, are the study of critical dynamics, aging and overlap equivalence (see [2]).

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