Out-of-plane magnetoresistivity for fields parallel to the c axis in single-crystalline $(La_{1-x}Sr_x)_2CuO_4$

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The c-axis magnetoresistivity as a function of temperature T and field H for fields parallel to the c axis is experimentally investigated for single-crystalline $(La_{1-x}Sr_x)_2CuO_4$ (x=0.068). It is argued that the observed Lorentz force free magnetoresistive phenomena cannot be accounted for by previously considered mechanisms. By contrast, they can be explained by the extended Josephson coupling model, which takes into account both effective thermal energy and anisotropy. Based on this extended model, it is shown that all the magnetoresistivity curves obtained in $H//I//c$ at various constant temperatures could be nicely scaled onto a single curve without any adjustable parameter in a wide transition region.

I. INTRODUCTION

Compared to conventional type-II superconductors, the following two features are unique to the high-temperature superconductors (HTSCs). One is their intrinsic layered crystalline structures, which contain superconducting Cu-O layers separated by some nonsuperconducting materials. Therefore, even in a perfect single crystal the amplitude of the superconducting order parameter should vary strongly between the layers. This situation leads to the idea, that the c-axis conduction could be viewed as a series stack of Josephson coupled junctions along the c axis.[1] Experimental evidence for such a picture arises from direct measurements of both dc and ac Josephson effects with currents flowing along the c axis in zero field or in fields parallel to the superconducting layers for various HTSCs.[2] The other is the existence of the irreversibility (or depinning) line in this kind of material. Although its origin has been an issue of controversy, it is often noted that various unusual phenomena occur just above this line. A typical example is that a real superconducting state of zero resistivity is realized only below this line.[3,4] Above this line, the high-T_c materials show an unusual Lorentz force free resistive dissipation, which is typically observed in a Lorentz force free configuration of $H//I//c$.

A lot of dissipation models have been proposed to explain the observed Lorentz force free dissipation in HTSCs, including superconducting order-parameter fluctuations,[5,6] vortex glass,[7,8] one-dimensional phase slippage,[9] and interlayer Josephson coupling;[1,10] however, they fail to provide quantitatively a consistent explanation of the experimental observations in a wider temperature and field transition region. To better understand the origin of the Lorentz force free dissipation, we here study the out-of-plane magnetoresistivity as a function of T and H in a typical Lorentz force free configuration of $H//I//c$ for single-crystalline $(La_{1-x}Sr_x)_2CuO_4$ (x=0.068). We argue that the observed phenomena cannot be accounted for by previously considered mechanisms. By contrast, the extended Josephson coupling model,[11–13] which was recently developed by accounting both for the effective energy k_B $(T-T_{irr})$ (here T_{irr} being the irreversibility temperature) and the anisotropic parameter γ in the conventional Josephson coupling model,[14] is able to explain the observed experimental phenomena. As an indication of this argument, we show that all the observed curves are nicely scaled onto a single curve without any adjustable parameters in a wide transition region.

II. EXPERIMENT

The sample used in the present study is a $(La_{1-x}Sr_x)_2CuO_4$ single crystal with the nominal Sr content of x=0.068, close to that (x=0.075) with the highest T_c in this family, which was grown by the traveling solvent floating-zone method at the University of Tokyo (Japan). The longest edge (of size ~3 mm) is along the c axis, which allows us to perform resistivity measurements directly by applying a current along the direction perpendicular to the superconducting layers in terms of standard either dc or ac four-probe methods. The magnetoresistivity measurement was performed at the National Research Institute for Metals (Japan). In zero field, the out-of-plane superconducting transition temperature T_c is 35.7 K (corresponding to a resistive transition at $\rho_c=0.9\rho_n$) and the transition width is about 2 K (10%–90%). The temperature dependence of the c-axis normal-state resistivity exhibits a quasisemiconductive behavior and can be empirically approximated by $\rho_n=0.153+0.025\exp(53.3/T)$ (Ω cm), which is obtained by fitting the corresponding data in zero field at T>40 K. Before the measurement of magnetoresistivity, the angular dependence of the resistivity was first investigated at various fixed temperatures by slowly varying the field orientation

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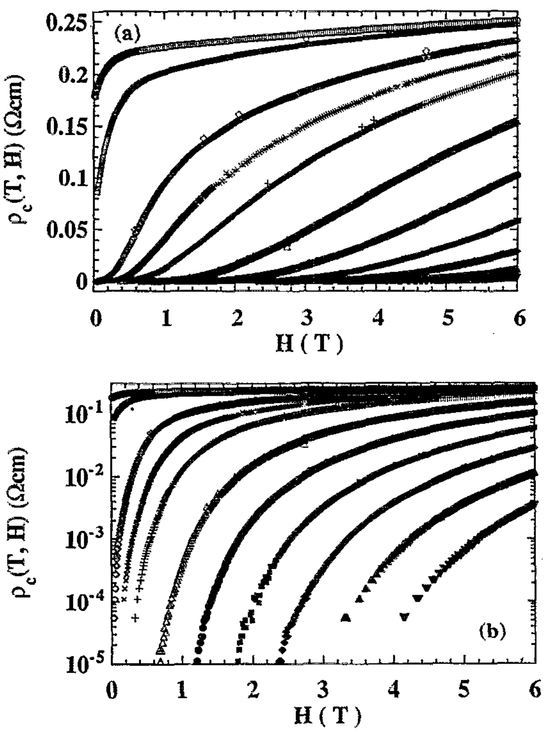

FIG. 1. The experimental c-axis magnetoresistivity $\rho_c(T,H)$ in single-crystalline $(La_{1-x}Sr_x)_2CuO_4$ ($x=0.068$) for fields parallel to the c axis at constant temperatures T=34.723 K (○), 33.744 K (□), 31.776 K (◇), 30.785 K (×), 29.785 K (+), 27.813 K (△), 25.832 K (●), 23.855 K (■), 21.784 K (♦), 19.895 K (▲), and 17.914 K (▼): (a) lin-lin plots and (b) log-lin plots.

from the a-b plane to the c axis while keeping the field constant. In this way, the orientation of the field with respect to the c axis of the single crystal was precisely determined with a deviation angle smaller than 0.001° between H and the c axis. The measurement of the c-axis magnetoresistivity was performed in fields up to 6 T parallel to the c axis with an increasing rate of about 0.1 T/min in a constant temperature regulated within ±0.005 K.

III. RESULTS AND DISCUSSION

Figure 1(a) displays the magnetoresistivity $\rho_c(T,H)$ data obtained in a typical Lorentz force free configuration of $H//I//c$ at various constant temperatures ranging between ~17.9 and ~34.7 K for single-crystalline $(La_{1-x}Sr_x)_2CuO_4$ ($x=0.068$). To see the behavior at low resistivity, the data shown in Fig. 1(a) are replotted in Fig. 1(b) on a semilogarithmic scale. As seen in Fig. 1(a), the ρ_c-H curves have concave behavior at lower temperatures (e.g., at T=25.832 K) and convex behavior at higher temperatures (e.g., at T=33.744 K). At intermediate temperatures (e.g., at T=30.785 K), the curve varies smoothly from concave at lower fields to convex at higher fields. Similar behavior is also observed in single-crystalline $Bi_2Sr_2CaCu_2O_8$.[15]

We argue that the observed c-axis magnetoresistive phenomena for fields parallel to the c axis cannot be accounted for by previously considered mechanisms. First, one should note the lack of a macroscopic Lorentz force in the present experimental configuration for ρ_c. A Lorentz force is needed to drive vortices in any flux creep or flux-flow scenario. It has been suggested that a nonzero Lorentz force might be generated through some sort of misalignment between the field H and the transport current; however, misalignment due to random microscopic inhomogeneities in the current distribution will average to zero. Similarly, the Lorentz force on a randomly bent vortex (threading the sample parallel to the c axis) should also average to zero; therefore, to explain the observed experimental phenomena, the problem must be argued within the framework of the Lorentz force free dissipation model.

Among various Lorentz force free models, both superconducting order-parameter fluctuations[5,6] and vortex glass[7,8] models are generally thought to be reasonable for the HTSCs. Although the effects of the order-parameter fluctuations are commonly thought to play an important role in dominating various physical properties, the expression for the resistivity[5] developed by Ikeda and co-workers on the basis of the order-parameter fluctuation theory, as shown by themselves,[6] can work well only in a narrow transition region near T_c. In the vortex glass model proposed by Fisher and co-workers,[7,8] an observable resistive dissipation in a vortex fluid regime for arbitrarily small applied currents is explained to be a consequence of the fact that the phase of the local superconducting order parameter varies with the Brownian motion of the vortices. While this model is intellectually attractive, it has not yielded mathematical descriptions to which experimental data may be readily compared.

It is interesting to examine the phase slippage model, which contains thermal activation and also is independent of the presence of the Lorentz force. This model was first developed for conventional Josephson junctions in zero field by Ambegaokar and Halperin (AH).[14] In their model, an essential quantity is $x(T)$ [$\equiv E_j(T)/k_BT$], the ratio between the Josephson coupling energy $E_j(T)$ [$\propto I_c(T)$, here $I_c(T)$ is the maximum Josephson currents in zero field without thermal noise], and the thermal energy k_BT. Some authors[9,10,16] have extended this model to the case of applying the field normal to the superconducting layers in order to explain the Lorentz force free dissipation observed for $H//c$ in HTSCs. Although the origin of phase slippage is different among them, they develop similar expressions for the resistivity for $H//c$ within the framework of the AH model.[14] Their models could be summarized by considering a quantity $x(T,H)$, the ratio between the Josephson coupling energy $E_j(T,H)$ [$\propto I_c(T,H)$] and the thermal energy k_BT. Assuming $I_c(T,H)=I_c(T)/(1+C_0H)$, where C_0 is constant, and neglecting the T- and H-independent constants, the quantity $x(T,H)$ could be expressed as

$$x(T,H)=E_j(T,H)/k_BT=[I_c(T)/T]/(1+C_0H). \qquad (1)$$

For instance: (1) letting $C_0=A_0/\phi_0$ (A_0 being the effective phase-coherent area), Eq. (1) reduces to the case presented by Kim and co-workers;[10] (2) in the case of $C_0H\gg1$, Eq. (1) returns to Tinkham's model[16] by assuming $I_c(T)/T\propto(1-T/T_c)^{3/2}$; (3) similarly, the model proposed by Briceno and co-workers[9] is also obtained by assuming $I_c(T)\propto(1-T/T_c)^{3/2}$ and $C_0H\gg1$. As is well known, according to the AH theory,[14] in the limit of zero measuring current

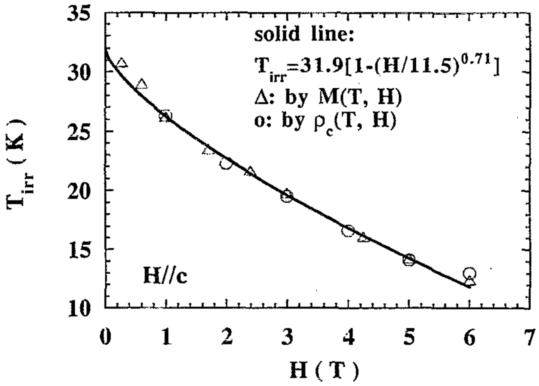

FIG. 2. The field dependence of the irreversibility temperature T_{irr}: (O) determined from the ρ_c-T measurement for $H//I//c$ by using $\rho_c=10^{-6}\rho_n$ as a criterion of zero resistivity; (Δ) obtained by measuring magnetization $M(T,H)$ for $H//c$, corresponding to a kink in $M(T,H)$; and (solid line) a fit to the experimental $T_{irr}(H)$ data by $T_{irr}=31.9[1-(H/11.5)^{0.71}]$ (K) (H in T).

there is only one variable, i.e., $x(T)$ or $x(T,H)$, in the expression of the normalized resistivity. This means that if their models[9,10,16] were appropriate for HTSCs, the observed normalized resistivity as a function of T and H for $H//c$ should be consistently scaled onto a single curve by using $x(T,H)$ as a scaling variable. Our analysis shows that it is impossible to make such a scaling for the data shown in Fig. 1. Therefore, it is concluded that a model, which is developed simply by extending the conventional Josephson coupling theory,[14] is unable to yield a reasonable explanation of the observed Lorentz force free magnetoresistive phenomena at least for the present system.

Quite recently, an extended Josephson coupling model[11–13] has been developed for the resistive dissipation in $H//I//c$ for HTSCs by accounting for the following two essential facts: One is the intrinsic layered structures in HTSCs, which urges us to consider the c-axis conduction to be that of a series stack of Josephson tunnel junctions between well-coupled units consisting of superconducting Cu-O layers. A similar picture has been proposed by Gray and Kim.[1] The other is that the resistive dissipation becomes observable only when the temperature is higher than the irreversibility temperature T_{irr}. To emphasize this, in Fig. 2 we plot the field dependence of both T_{irr} and T_c ($\rho_c=0$) for $H//c$ for the present sample. They are determined by measuring magnetization $M(T,H)$ [corresponding to a "kink" in $M(T,H)$] and the c-axis resistivity (using $\rho_c/\rho_n=10^{-6}$ as a criterion of zero resistivity), respectively. It can be found that for $H//c$ both $T_{irr}(H)$ and $T_c(H)$ determined by different methods are very close to each other. A similar conclusion has also been reported for other high-T_c systems such as $YBa_2Cu_3O_{7-\delta}$,[3] $Bi_2Sr_2CaCu_2O_{8+\delta}$,[4] etc. This suggests that the thermal energy k_BT in the conventional AH theory[14] should be replaced with the effective thermal energy, $k_BT(1-T_{irr}/T)=k_B\Delta T$, where $\Delta T=T-T_{irr}$. The term $(1-T_{irr}/T)$ reflects the effective contribution to the thermal energy, which is expected to observe actually in experiments. Then, the extended Josephson coupling model is summarized by a quantity $x'(T,H)$, the ratio between the Josephson coupling energy $E_j(T,H)$, and the effective thermal energy $k_B\Delta T$. Neglecting all the constant factors, the quantity $x'(T,H)$ in the present case becomes

$$x'(T,H)=E_j/k_B\Delta T=J_c(T,H)/\Delta T, \tag{2}$$

where $J_c(T,H)=I_c(T,H)/A_0$ is the maximum Josephson coupling current density in the absence of thermal noise and A_0 is the junction area in zero field.

A key problem is left, i.e., how to determine $J_c(T,H)$ for $H//c$. Its exact determination requires detailed knowledge of vortex dynamics in HTSCs, which is unavailable yet for the HTSCs at present. Because of this reason, we here adopt a rather general argument to describe the possible behavior of $J_c(T,H)$. According to the Lawrence–Doniach model,[17,18] which describes Josephson-coupled superconducting layers of thickness d and stacking periodicity length s, the maximum Josephson current density $J_{c0}(T)$ in zero field could be expressed as $J_{c0}(T)=a_0/s\lambda_c^2$, where a_0 is constant and λ_c is the penetration depth parallel to the layers. On the other hand, the penetration depth λ_{ab} normal to the layers[18] is $\lambda_{ab}=\lambda_s(s/d)^{1/2}$, where λ_s is the intrinsic bulk penetration depth. Therefore, one has

$$J_{c0}(T)=a_0/s\lambda_c^2=a_0/s(\gamma_0\lambda_{ab})^2\propto 1/(\lambda_s\gamma_0)^2,$$

where $\gamma_0=\lambda_c/\lambda_{ab}$ is the intrinsic anisotropic parameter. For $H//c$, such a dependence in its functional form is still assumed to be formally held for HTSCs, i.e., $J_c(T,H)\propto 1/(\lambda_s\gamma)^2$, where γ is the anisotropic parameter of the HTSCs that expects to be experimentally observed. By such a simple argument, one then obtains

$$J_c(T,H)=J_{c0}(T)(\gamma_0/\gamma)^2. \tag{3}$$

Note that the unusual behavior in the HTSCs has been accounted for by introducing γ. According to conventional theory for anisotropic type-II superconductors, the γ is a temperature-independent parameter. In the case of HTSCs, however, this parameter strongly depends on temperature. For instance, the reported γ value[19] for $(La_{1-x}Sr_x)_2CuO_4$ varies from ~10 at T~34 K to ~20 at T~32 K. On the other hand, such an unusual temperature dependence is expected to be observed only at $T>T_{irr}$ suggesting that the γ should also be a function of T_{irr}. Taking into account the facts that the γ becomes substantially large as $T\rightarrow T_{irr}^+$ and returns to its usual value at $T\rightarrow T_c$, the γ as a function of both T and T_{irr} at $T>T_{irr}$ has been argued[20] to be

$$\gamma=\gamma_0[(T_c-T_{irr})/(T-T_{irr})]^b, \tag{4}$$

where b is a material constant between 0 and 1. Although Eq. (4) is proposed by a rather rough argument, by inserting it into the scaling rule for the resistivity developed by Hao and Clem,[21] it has been shown[20] that the resistivity as a function of field and its orientation measured at various constant temperatures could be consistently scaled onto a series of single curves for each given temperatures by using γ_0 and b as adjustable parameters.

Inserting Eqs. (3) and (4) into Eq. (2), the quantity $x'(T,H)$ in the case of $H//I//c$ for HTSCs could be rewritten as

$$x'(T,H) = (1 - T/T_c)[(T - T_{irr})/(T_c - T_{irr})]^{2b}/(T - T_{irr}), \quad (2')$$

where $J_c(T)$ has been assumed to be $J_c(T) = (1 - T/T_c)$, and $T_{irr} = T_{irr}(H)$. Both T_c and T_{irr} can be directly experimentally determined. The parameter b can be obtained by a scaling for the angular dependence of the resistivity.[20] Therefore, there is no adjustable parameter involved in Eq. (2′) for the present problem. Similar to the above argument, one suggests again that if such a model were appropriate for the HTSCs, the normalized resistivity as a function of T and H measured in $H//I//c$ should consistently map onto a single curve by using $x'(T,H)$ as a scaling variable, which is important for supporting this extended Josephson coupling model.

To make sure of the above extended Josephson coupling model, we now make a scaling to the data shown in Fig. 1. For the present sample, its T_c is given to be 35.7 K, corresponding to a transition temperature at $\rho_c = 0.9\rho_n$ in zero field. Its T_{irr} is approximated by

$$T_{irr} = 31.9[1 - (H/11.5)^{0.71}] \text{ (K)}$$

(H in T), which is obtained by fitting to the $T_{irr}(H)$ data Δ shown in Fig. 2. The parameter b is estimated to be ~1/3 by making a scaling for resistivity as a function of T, H, and θ according to the extended scaling rule recently developed for HTSCs.[20] Using these values, it is possible to make a consistent scaling for the data shown in Fig. 1 by using $x'(T,H)$ as shown in Fig. 2 as a scaling variable. The thus scaled results are shown in Figs. 3(a) and 3(b) for two different plots. It can be seen that all the curves shown in Fig. 1 have been consistently scaled onto a single curve quite nicely in the whole selected temperature and field region, which strongly supports the above extended Josephson coupling model.

Finally, we would like to argue the following three points.

(1) In our case the parameter b is given by a scaling for the angular dependence of resistivity according to the extended scaling rule;[20] however, the exact measurement of the angular dependence is unavailable in most laboratories. In this case, one could use b as an adjustable parameter. Therefore, this actually suggests a new method to determine the normalized anisotropic parameter γ/γ_0 as a function of T and T_{irr}. In other words, the parameter b (hence γ/γ_0) could be determined by scaling the resistivity as a function of T and H measured in $H//I//c$ onto a single curve by using $x'(T,H)$ shown in Eq. (2′) as a scaling variable.

(2) In this article we only account for the c-axis magnetoresistivity for $H//c$. In fact, Eq. (2′) is easily extended to the general case, i.e., the field oriented at angle θ with respect to the c axis, by replacing H in Eq. (2′) with the reduced field h, where $T_{irr} = T_{irr}(h)$ and $h = H(\sin^2\theta/\gamma^2 + \cos^2\theta)^{1/2}$. In this way, all the c-axis resistivity $\rho_c(T,H,\theta)$ data could be nicely scaled onto a single curve by using $x'(T,h)$ as a scaling variable. Details will be reported elsewhere.[22]

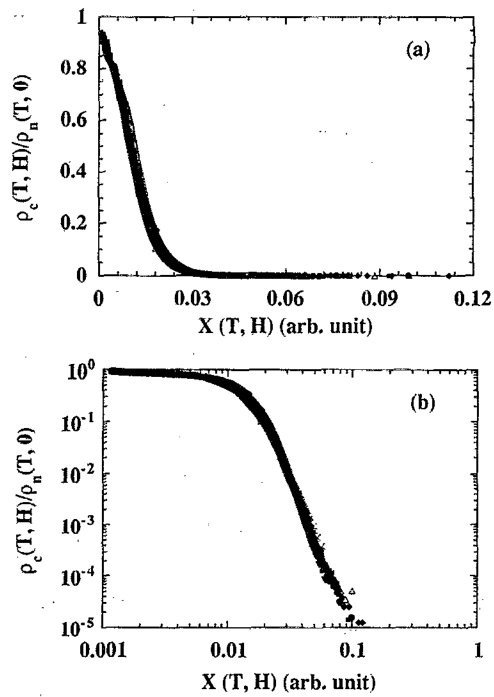

FIG. 3. Scaling for the data shown in Fig. 1 by using $x'(T,H)$ as a scaling variable for (a) lin-lin and (b) log-log plots: T=34.723 K (○), 33.744 K (□), 31.776 K (◇), 30.785 K (×), 29.785 K (+), 27.813 K (△), 25.832 K (●), 23.855 K (■), 21.784 K (◆), 19.895 K (▲), and 17.914 K (▼), where $\rho_n(T,0) = 0.153 + 0.025\exp(53.3/T)$ (Ω cm), $x'(T,H) = (1 - T/T_c)[(T - T_{irr})/(T_c - T_{irr})]^{2/3}/(T - T_{irr})$, T_c=35.7 K, and $T_{irr} = 31.9[1 - (H/11.5)^{0.71}]$ (K) (H in T).

(3) The present scaling approach is appropriate only for the resistivity measured in the case of $I//c$. In the case of the in-plane resistivity, one could not use $x'(T,H)$ shown in Eq. (2′) as a scaling variable, since Eq. (3) is proposed only for the case of measuring current applied along the c axis.

IV. SUMMARY

We have experimentally investigated the Lorentz force free magnetoresistive phenomena in $H//I//c$ for single-crystalline $(La_{1-x}Sr_x)_2CuO_4$ (x=0.068). We argue that the observed phenomena cannot be accounted for by previously proposed mechanisms. By contrast, the extended Josephson coupling model is able to provide a consistent explanation of the observed Lorentz force free magnetoresistive phenomena. As an indication of this argument, we have nicely shown that all the magnetoresistivity curves obtained in $H//I//c$ for the present system could be consistently scaled onto a single curve quite satisfactorily without any adjustable parameter in the whole selected temperature and field region.

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[20] S. L. Yuan, K. Kadowaki, Z. J. Yang, H. Takeya, T. Kimura, and K. Kishio (unpublished). Based on the anisotropic Ginzburg–Landau theory, Hao and Clem (HC) proposed the scaling rule (Ref. 21) for resistivity of HTSCs as $\rho(T,H,\theta)=\rho[T,\epsilon(\theta,\gamma)H]$, where $\epsilon(\theta,\gamma)=(\sin^2\theta/\gamma^2+\cos^2\theta)^{1/2}$ and θ is an angle between H and c axis. Our analysis shows that it is impossible to make a consistent scaling for $\rho(T,H,\theta)$ of HTSCs according to the HC rule. To give a consistent scaling, an extended scaling rule was recently developed by replacing γ in the HC rule with $\gamma(T,T_{\rm irr})$ shown in Eq. (4) of this article, where $T_{\rm irr}=T_{\rm irr}[\epsilon(\theta,\gamma)H]$. Note that γ is hidden in the expression of $T_{\rm irr}$. To the first order, one can approximate γ by γ_0 in the actual calculation of $T_{\rm irr}$. The extended scaling rule is then expressed by $\rho(T,H,\theta)=\rho[T,\epsilon(\theta,\gamma)H]$ and $\gamma=\gamma_0(\{T_c-T_{\rm irr}[\epsilon(\theta,\gamma_0)H]\}/\{T-T_{\rm irr}[\epsilon(\theta,\gamma_0)H]\})^b$. Based on this extended rule, it has been shown that the $\rho(T,H,\theta)$ obtained in $(La_{1-x}Sr_x)_2CuO_4$ could be consistently scaled on a series of single curves for each given temperature. By this scaling, both material parameters are estimated to be $\gamma_0=12.5$ and $b=1/3$ for this system.
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