Aging and Rejuvenation with Fractional Derivatives

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We discuss a dynamic procedure that makes the fractional derivatives emerge in the time asymptotic limit of non-Poisson processes. We find that two-state fluctuations, with an inverse power-law distribution of waiting times, finite first moment and divergent second moment, namely with the power index µ in the interval 2 < µ < 3, yields a generalized master equation equivalent to the sum of an ordinary Markov contribution and of a fractional derivative term. We show that the order of the fractional derivative depends on the age of the process under study. If the system is infinitely old, the order of the fractional derivative, ord, is given by ord = 3 − µ. A brand new system is characterized by the degree ord = µ − 2. If the system is prepared at time −t₀ < 0 and the observation begins at time t = 0, we derive the following scenario. For times 0 < t << t₀ the system is satisfactorily described by the fractional derivative with ord = µ − 2. Upon time increase the system undergoes a rejuvenation process that in the time limit t >> t₀ yields ord = µ − 2. The intermediate time regime is probably incompatible with a picture based on fractional derivatives, or, at least, with a mono-order fractional derivative.

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I. INTRODUCTION

The fractional calculus has recently received a great deal of attention in the physics literature, through the publications of books [12], review articles [3, 4], as well as an ever increasing number of research papers, some of which are quoted here [5, 6, 7, 8, 9, 10, 11, 12]. The blossoming interest in the fractional calculus is due, in part, to the fact it provides one of the foundational frameworks for fractal stochastic processes [2, 3]. The adoption of the fractional calculus by the physics community was inhibited historically because there was no clear experimental evidence for its need. The disciplines of statistical physics and thermodynamics were thought to be sufficient for describing complex physical phenomena solely with the use and modifications of analytic functions. This view was supported by the successes of such physicists as Lars Onsager, who through the use of simple physical arguments was able to relate apparently independent transport processes to one another, even though these processes are associated with quite different physical phenomena [13]. His general arguments rested on three assumptions: 1) microscopic dynamics have time-reversal symmetry; 2) fluctuations of the heat bath decay at the same rate as do macroscopic deviations from equilibrium and 3) physical systems are aged. We refer to assumption 2 as the Onsager Principle and show that it is tied up with assumption 3.

Onsager’s arguments focused on a system that is in contact with a heat bath sufficiently long that the bath has come to thermal equilibrium and consequently the system is aged. In statistical physics we know that the bath is responsible for both fluctuations and dissipation, and if the fluctuations are white the regression of per-turbations of the bath to equilibrium is instantaneous. This means that the energy absorbed from the system of interest by the bath, through macroscopic dissipation, is distributed over the bath degrees of freedom on a very much shorter time scale than the relaxation time of the system. This property is summarized in the well known fluctuation-dissipation theorem, which has even been generalized to the case where the fluctuations in the bath do not regress instantaneously [14].

The dynamics of the physical variables to which the Onsager Principle apply are described by two different kinds of equations: 1) the Langevin equation, a stochastic differential equation for the dynamical variable and 2) the phase space equation for the probability density. Two distinct methods have been developed to describe the phase space evolution of the probability density: the master equation introduced by Pauli and the continuous time random walk (CTRW) approach of Montroll and Weiss [15]. The CTRW formalism describes a random walk in which the walker pauses after each jump for a sojourn specified by a waiting time distribution function. It was shown by Bedeaux et al. [16] that the Markov master equation is equivalent to CTRW if the waiting time distribution is Poissonian. However, when the waiting time distribution is not exponential, the case we consider here, the equivalence between the two approaches is only maintained by generalizing to the non-Markov master equation, the so-called GME [17]. Recently, Metzler [18] argued that the GME unifies the fractional calculus and CTRW.

Allegrini et al. [19] have shown that to create a master equation compatible with the Onsager Principle requires that the system be entangled with the heat bath in such a way that the bath does not regress to equilibrium infinitely fast. The system-bath entanglement is the result
of a rearrangement process that may take infinitely long to complete, leading to the generalized master equation (GME) of Kenkre et al. [17]. Allegreni et al. [19] were concerned with how to make the GME stationary and therefore compatible with the Onsager Principle. Herein, we extend that discussion to include the connection with both the fractional calculus and the nonstationary condition.

For simplicity we restrict our discussion to the case of a two-site system coupled to a heat bath, a problem closely related to the quantum problem of decoherence of a qubit, due to coupling to the environment. The connection of the CTRW, a two-state non-Markov master equation and the fractional calculus has been explored by Sokolov and Metzler [12]. Herein we go beyond their discussion and investigate the relationships among the fractional calculus, a particular generalization of the Onsager Principle, and one concept of aging. We also show that the result of Sokolov and Metzler, which refers to the renewal theory relation

\[ \psi(t) = \int_0^\infty \psi(t') dt'. \]

where \( \psi(t) \) is the waiting time distribution function and the memory kernel can be related to one another by taking the Laplace transform of the GME (1) and the CTRW (2). This comparison, after some algebra [19], yields

\[ \hat{\Phi}(u)K = \frac{u\hat{\psi}(u)}{1 - \hat{\psi}(u)}(M - I), \]

where \( I \) is the \( m \times m \) unit matrix and the Laplace transform of the function \( f(t) \) is \( \hat{f}(u) \). Here, as in Allegreni et al. [19], we limit our discussion to the two-state case where

\[ M = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \]

and

\[ K = \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}, \]

thereby reducing (5) to

\[ \hat{\Phi}(u) = \frac{u\hat{\psi}(u)}{1 - \hat{\psi}(u)}. \]

This relation between the Laplace transform of the memory kernel and the Laplace transform of the waiting time distribution function was first obtained by Kenkre et al. [17] and is reviewed by Montroll and West [20].

In the case when the lattice has only two sites, a left and a right site, the random walker corresponds to a dichotomous signal \( \xi \), with the values \( \xi(0) = -1 \), for the left site, and \( \xi(0) = 1 \), for the right site. For the sake of simplicity, we assume the two states to have the same statistical weight. Also in the two-state CTRW, if we adopt a discrete time representation, the motion of the random walker corresponds to a symbolic sequence \( \{ \xi \} \), with the form

\[ + + + + + - + - + + + - - - - - - - - - - - - - ... \]

which shows a significant persistence of both states. The waiting time distribution \( \psi(t) \) is the distribution of the patches filled with either +’s or -’s. We assume symmetry between the two states and a finite first moment of \( \psi(t) \) making it possible for us to define the autocorrelation function for the fluctuations \( \xi(t) \)

\[ \Phi_\xi(t) = \frac{<\xi(0)\xi(t)>}{<\xi^2>}, \]
because the process is stationary in time $21$.

In his original work Onsager considered the case of a macroscopic fluctuation that regresses to equilibrium through the phenomenological equations of motion. Here we adopt an extension of the Onsager Principle made by Allegrini et al. $14$ to the case of two states, using the probability of the random walker being in state $i = 1, 2, p_i(t)$, at time $t$,

$$\Phi_\xi(t) = \frac{p_1(t) - p_2(t)}{p_1(0) - p_2(0)}.$$  \hfill (10)

The GME cannot provide information about the auto-correlation function of the fluctuations, but only about the probability of occupying a given state $i = 1, 2, p_i(t)$, at time $t$. Thus, given that the state is initially out of equilibrium $p_1(0) - p_2(0) \neq 0$, the generalized Onsager Principle given by (10) is the only way to relate the bath auto-correlation function to the dynamics of the system. Assuming a regression to equilibrium in such a way as the retain $10$ we obtain from the GME $11$ using the coupling matrix $7$:

$$\frac{d\Phi_\xi(t)}{dt} = -2 \int_0^t \Phi(t - t') \Phi_\xi(t') dt'.$$  \hfill (11)

The authors of Ref. $19$ studied the problem of establishing a complete correspondence between the GME and renewal theory, characterized by the waiting time distribution

$$\psi(t) = (\mu - 1) \frac{T^{\mu-1}}{(T + t)^\mu},$$  \hfill (13)

with $\mu > 2$ to fit the stationary condition. These authors determined that this problem could be solved by expressing the CTRW in stationary form, resulting in the GME memory kernel:

$$\hat{\Phi}(u) = \frac{u (1 + \psi(u))}{-2 (1 - \psi(u)) + u (1 + \psi(u))}.$$  \hfill (14)

The form of the memory kernel given by (14) is consistent with the equation of motion for the auto-correlation function (11), and consequently, Eq. (15) is equivalent to

$$\hat{\Phi}(u) = \frac{1}{2} \left( \frac{1}{\Phi_\xi(u)} - u \right).$$  \hfill (16)

We have to remind the reader that the stationary auto-correlation function of $\xi$ is not related directly to $\psi(t)$. Zumofen and Klafter $22$ provided a prescription for deriving the corresponding equilibrium auto-correlation function of $\xi$ from $\psi(t)$. Their result rests on the observation that $\psi(t)$ is an experimental function, evaluated by observing the time duration of the two states. The connection with renewal theory is established by assuming that the time duration of a state is determined by two processes, one is the extraction of a random number from a theoretical inverse power law distribution, $\psi^*(\tau)$, with the same power index $\mu$, and the other is a coin tossing procedure that determines the sign of this laminar region. Thus, a given experimental sojourn time in one of the two states may correspond to an arbitrarily large number of drawings and coin tossings. Renewal theory is used to relate the auto-correlation function $\Phi_\xi(t)$ to the waiting time distribution function $\psi^*(t)$. In fact, from the renewal theory $21$ we obtain the following important result:

$$\Phi_\xi(t) = \frac{1}{\tau^*} \int_t^\infty (t' - t) \psi^*(t') dt',$$  \hfill (17)

where $\tau^*$ is the mean waiting time of the $\psi^*(t)$-distribution density. It is interesting to notice that this equation implies that the second derivative of the auto-correlation function is proportional to $\psi^*(t)$,

$$\frac{d^2}{dt^2} \Phi_\xi(t) = \frac{\psi^*(t)}{\tau^*}.$$  \hfill (18)

In Section 2 the departure point of our calculations is given by the auto-correlation function $\Phi_\xi(t)$ of Eq. (17). In this case is convenient to assign to this equilibrium auto-correlation function a simple analytical form. This is done as follows. We assign the form of Eq. (13) to $\psi^*(t)$, thereby writing

$$\psi^*(t) = (\mu - 1) \frac{T^{\mu-1}}{(t + T^*)^\mu}.$$  \hfill (19)

This makes it possible for us to write $\tau^*$ as follows

$$\tau^* = \int_0^\infty t \psi^*(t) \, dt = \frac{T^*}{\mu - 2}.$$  \hfill (20)

With the choice of Eq. (19) for $\psi^*(t)$, the autocorrelation function $\Phi_\xi(t)$ of Eq. (17) gets the attractive analytical form

$$\Phi_\xi(t) = \frac{T^{\mu\beta}}{(T^* + t)^\beta},$$  \hfill (21)
where

$$\beta \equiv \mu - 2. \quad (22)$$

Thus, in the case $\mu < 3$, the auto-correlation function of the fluctuations is not integrable.

Zumofen and Klafter \cite{22}, in addition to explaining with clear physical arguments the connection between $\psi(t)$ and $\psi^*(t)$, established that the Laplace transforms of the two functions are related one to the other by

$$\hat{\psi}^*(u) = \frac{2\hat{\psi}(u)}{1 + \hat{\psi}(u)}. \quad (23)$$

This important relation allows us to establish a connection between $\tau$ and $\tau^*$, which turns out to be

$$\tau = 2\tau^*. \quad (24)$$

The equivalence between Eq. (23) and Eq. (24) rests on the key property of Eq. (23). We note that if we make the choice of Eq. (23) then the waiting time distribution $\psi^*$ loses the simple analytical form of Eq. (19), and vice versa. On the same token, the choice of the analytical form of Eq. (23) for $\psi(t)$ makes the auto-correlation function $\Phi_\xi(t)$ lose the analytical form of Eq. (21). However, using the property of Eq. (23), it is straightforward to prove that $\psi(t)$ with the form of (23) yields, for the auto-correlation function $\Phi_\xi(t)$, the following time asymptotic behavior:

$$\Phi_\xi(t) \sim \frac{1}{t^\beta}, \quad (25)$$

Thus, whatever choice is made, either the analytical form of Eq. (23) or the analytical form of Eq. (23), in both cases the two waiting time distributions maintain the same time asymptotic behavior, with the same $\mu$. So do the two different expressions for the equilibrium auto-autocorrelation functions, the time asymptotic equivalence being the property that matters to study the emergence of fractional derivative.

Herein, using the inverse Laplace transform of (23) we determine the unknown memory kernel $\Phi(t)$, making it possible to discuss how to express the GME in terms of fractional derivatives. The case where $2 < \mu < 3$ is compared to the recent work of Sokolov and Metzler \cite{12}. We find that the index of the fractional derivative is $3 - \mu$, rather than $\mu - 2$, as predicted by Sokolov and Metzler. We prove that this difference in index is due to the fact that we adopt a stationary condition, while Sokolov and Metzler do not. We also prove that in the case of a finite, rather than infinite age, our GME makes a transition from the $(3 - \mu)$-th to the $(\mu - 2)$-th order. The stationary case becomes stable only in the limiting case of infinite age. Thus, on the one hand we shed light on the meaning of the work of Allegrini \textit{et al.} \cite{19}, which is proven to be a subordination to a Markov master equation through the stationary distribution of first exit times. On the other hand, we extend the approach to systems of any age and reveal the phenomenon of a continuous time random walk with rejuvenation. To accomplish this dual role we rely heavily on the results recently obtained by Barkai \cite{23} and, to a lesser extent, the results of Allegrini \textit{et al.} \cite{19}. However, this allows us to reveal some aspects of aging and rejuvenation dependent on the order of fractional derivatives, which were not previously identified.

## II. THE INVERSE LAPLACE TRANSFORM OF THE MEMORY KERNEL

To establish the form of the unknown memory kernel $\Phi(t)$, we make a few preliminary observations. First of all, we note that through Eq. (23) we establish a direct connection with the correlation function $\Phi_\xi(t)$ and that this correlation function is, in turn, directly related to the waiting time distribution $\psi^*(t)$, through Eq. (17). Thus, with no loss of generality for the reasons illustrated in Section 1, it is convenient to refer ourselves to $\psi^*(t)$ rather than to $\psi(t)$. For simplicity, we set $T^* = 1$ throughout the section. Thus, the Laplace transform of the autocorrelation function is (24):

$$\hat{\Phi}_\xi(u) = \frac{\Gamma(1 - \beta)}{u^{1 - \beta}} \left(e^u - E_{\beta - 1}^u\right), \quad (26)$$

where $0 < \beta < 1$, given the fact that we are considering $2 < \mu < 3$, and $E_{\beta - 1}^u$ is the generalized exponential function \cite{2}. Thus, $\hat{\Phi}_\xi(u)$ diverges as $u \to 0$ and Eq. (23) yields $\hat{\Phi}(0) = 0$. We explore the opposite limit, $u \to \infty$ using Eq. (14), which yields $\hat{\Phi}(u) = \frac{1}{u} = \frac{1}{\tau^*}$. In the time representation, the latter limit is equivalent to $\Phi(t) \approx \frac{\delta(t)}{\tau^*}$ for $t \to 0$. Therefore, we segment the Laplace transform of the GME memory kernel into two parts as follows

$$\hat{\Phi}(u) = \frac{1}{2\tau^*} + \hat{\Phi}_a(u). \quad (27)$$

The first term models the short-time limit, while the second term is responsible for the long-time behavior. In the time representation we have

$$\Phi(t) = \frac{\delta(t)}{2\tau^*} + \Phi_a(t). \quad (28)$$

Note that this division of the memory kernel into a white-noise contribution and a slow term corresponds to a similar partition made by Fuliński \cite{25}.

Thus, for the time evolution equation of the correlation function of $\xi(t)$, we derive the following equation

$$\frac{d\Phi_\xi(t)}{dt} = -\frac{1}{\tau^*}\Phi_\xi(t) - 2 \int_0^t \Phi_a(t - t') \Phi_\xi(t') dt'. \quad (29)$$
Using Eq. (32) and substituting into it the explicit expression of $r^*$ as a function of $\mu$, after some algebra, we obtain

$$\left(\frac{T}{t+T}\right)^{\beta t} \frac{\beta t}{T(t+T)} = \Phi_\xi(t) \frac{\beta t}{T(t+T)} = -2 \int_0^t \Phi_\alpha(t-t') \Phi_\xi(t') \, dt'.$$

The two terms on the left-hand side Eq. (33) are positive. Due to the negative sign on the right-hand term of this equation we conclude that it might well be that $\Phi_\alpha(t)$ is always negative.

Let us concentrate on the case $\beta < 1$: using the autocorrelation function $\Phi_\xi(t)$ of Eq. (21) (with $T^* = 1$) and using the change of time variable $t' + 1 \rightarrow t'$, we rewrite Eq. (30) in the form:

$$-2 \int_0^{t+1} \Phi_\alpha(t+1-t') \frac{1}{t^{\beta t}} \, dt' + 2 \int_0^t \Phi_\alpha(t+1-t') \frac{1}{t^{\beta t}} \, dt' = \frac{\beta t}{(t+1)^{\beta+1}}. \quad (31)$$

In the limiting case $t \rightarrow \infty$ we neglect the second term on the left-hand side of this equation. This is a natural consequence of the assumption that the memory kernel must tend to zero with a negative tail, as an inverse power law. With this assumption it is straightforward to prove that the modulus of the first term becomes much larger than that of the second term on left-hand side of this equation. The consequences of this crucial assumption are supported by the numerical results depicted in Fig. (1). With this assumption Eq. (31) simplifies to

$$-2 \int_0^t \Phi_\alpha(t-t') \frac{1}{t^{\beta t}} \, dt' = \frac{\beta t}{(t+1)^{\beta+1}}, \quad (32)$$

which can be solved by means of the fractional calculus. We use the Riemann-Liouville (RL) definition of the fractional integral

$$D_t^{-q} [f(t)] = \frac{1}{\Gamma(q)} \int_0^t \frac{f(t') \, dt'}{(t-t')^{1-q}}, \quad (33)$$

which is the anti-derivative of the fractional derivative with order $q$, with $q < 1$. Consequently for $\beta < 1$ we can express (32) in terms of the RL fractional integral

$$D_t^{-\beta} \Phi_\alpha(t) = -\frac{1}{2\Gamma(1-\beta)} \frac{\beta t}{(t+1)^{\beta+1}}. \quad (34)$$

so that inverting this equation we have the formal expression for the slow part of the memory kernel

$$\Phi_\alpha(t) = -\frac{1}{2\Gamma(1-\beta)} D_t^{1-\beta} \left[ \frac{\beta t}{(t+1)^{\beta+1}} \right] = -\frac{1}{2\Gamma(1-\beta)} D_t^{1-\beta} [\beta \Phi_{\xi,\beta+1}(t)]. \quad (34)$$

We denote the correlation function with the inverse power $(\beta+1)$ by the symbol $\Phi_{\xi,\beta+1}(t)$. Carrying out the required calculations on the right-hand side of (34), we obtain, see for example pg.90 of West et al. [2],

$$\Phi_\alpha(t) = -\frac{\beta}{2\Gamma(1-\beta)\Gamma(1+\beta)} \frac{t^\beta}{(t+1)^{2}}, \quad \beta < 1 \quad (35)$$

A comparison with a numerical inversion of the kernel is shown in Fig. (1).

For the sake of completeness, it is worth noticing that we can proceed in a similar way also in the case $\beta > 1$. In this case we find, for the contribution $\Phi_\alpha(t)$ of the GME, the following time asymptotic behavior

$$\Phi_\alpha(t) = -\frac{\beta (\beta-1)}{2} \frac{t^\beta}{(t+1)^{\beta+1}}, \quad \beta > 1. \quad (36)$$

III. THE EMERGENCE OF FRACTIONAL OPERATORS

In this section we show that in the two-site case we are discussing, the GME has the form of a transport equation, with two terms on the right-hand side. The first has the form afforded by the ordinary master equation and consequently satisfies the Onsager Principle, giving a relaxation dependent on the average waiting time of CTRW. The second term corresponds to a fractional derivative in time, and extends the Onsager Principle to
the case of a relaxation with a fat tail. To obtain these results, we use what we have learned in the preceding section.

First of all, since we are dealing with the two-site case, using the form of \( M \) and \( K \) matrices, with \( z = x = -1 \) and \( y = 1 \), we rewrite Eq. (11) in the following form:

\[
\frac{d}{dt} p_1(t) = \int_0^t \Phi(t - \tau) (p_2(\tau) - p_1(\tau)) d\tau, \quad (37)
\]

\[
\frac{d}{dt} p_2(t) = \int_0^t \Phi(t - \tau) (p_1(\tau) - p_2(\tau)) d\tau. \quad (38)
\]

The memory kernel \( \Phi \) is related to the autocorrelation function of the dichotomous variable \( \Phi \) through Eq. (16). Inserting Eq. (16) into the Laplace transform of the set of the two-site dynamical equations, solving the resulting set of equations, and taking the corresponding inverse Laplace transforms yields the solution

\[
p_1(t) = \frac{1}{2} [1 - \Phi_\ast(t) (p_1(0) - p_1(0))] \quad (39)
\]

\[
p_2(t) = \frac{1}{2} [1 + \Phi_\ast(t) (p_2(0) - p_1(0))] \quad (40)
\]

Note that these solutions can be combined to yield the generalized Onsager Principle given by (10) in terms of the difference in the probabilities.

We now want to find a formal equation of evolution for the probabilities involving fractional operators. We know from the preceding section that:

\[
\Phi(t) = \frac{\delta(t)}{2\tau^*} + \Phi_\ast(t) \quad (41)
\]

with \( \tau^* = \frac{T^*}{\mu - 2} = \frac{1}{\beta} \), thanks to the fact that we set \( T^* = 1 \). Substituting the decomposition of the memory kernel into Eq. (57), we obtain

\[
\frac{dp_1(t)}{dt} = \frac{p_2(t) - p_1(t)}{2\tau^*} + \int_0^t \Phi_\ast(t - \tau) (p_2(\tau) - p_1(\tau)) d\tau. \quad (42)
\]

Writing \( \Phi_\ast(t) \) as the derivative of an as yet unspecified function \( f(t) \), and using the property

\[
\frac{d}{dt} \int_0^t f(t - \tau) g(\tau) d\tau = f(0) g(t) + \int_0^t f'(t - \tau) g(\tau) d\tau \quad (43)
\]

with \( f'(t) = \frac{d}{dt} f(t) \), we obtain

\[
\frac{dp_1(t)}{dt} = \frac{p_2(t) - p_1(t)}{2\tau^*} - f(0) (p_2(t) - p_1(t)) \quad (44)
\]

Also we found that in the case \( 0 < \beta < 1 \) the asymptotic behavior of the memory kernel is expressed by

\[
\Phi_\ast(t) \approx -\frac{\beta}{2\Gamma(1 - \beta) \Gamma(1 + \beta)} t^{\beta - 2} \quad (45)
\]

\[
\approx -\frac{\beta}{2\Gamma(1 - \beta) \Gamma(1 + \beta)} t^{\beta - 2} \quad t \to \infty, \ T^* = 1.
\]

Rewriting Eq. (10) as:

\[
\Phi_\ast(t) \approx -\frac{1}{2\Gamma(1 - \beta) \Gamma(1 + \beta)} \frac{d}{dt} t^{\beta - 1}, \quad (46)
\]

we identify \( f(t) \) with \( \frac{1}{2\Gamma(1 - \beta) \Gamma(1 + \beta)} t^{\beta - 1} \) for \( t \to \infty \).

Choosing \( f(0) = 0 \) and using the properties of the gamma function, we assign to the time asymptotic equation of motion the following form

\[
\frac{dp_1(t)}{dt} = -\frac{p_1(t) - p_2(t)}{2\tau^*} + \frac{1}{2\Gamma(2 - \beta)} D_{t\to\infty}^{1 - \beta} [p_1(t) - p_2(t)]. \quad (47)
\]

The same procedure applied to the equation of motion for \( p_2(t) \) yields,

\[
\frac{dp_2(t)}{dt} = -\frac{p_2(t) - p_1(t)}{2\tau^*} + \frac{1}{2\Gamma(2 - \beta)} D_{t\to\infty}^{1 - \beta} [p_1(t) - p_2(t)]. \quad (48)
\]

The difference between these two equations yields

\[
\frac{d}{dt} [p_1(t) - p_2(t)] = -\frac{p_1(t) - p_2(t)}{\tau^*} - \frac{1}{\Gamma(2 - \beta)} D_{t\to\infty}^{1 - \beta} [p_1(t) - p_2(t)] \quad (50)
\]

clearly showing the two kinds of contributions to the generalized Onsager Principle. The first term gives the relaxation of the perturbation away from equilibrium at the macroscopic rate required by Onsager. The second term gives the additional slow relaxation in the form of the fractional integral.

**IV. AGING ORDER**

We have to remark that the condition of Eq. (12) refers to the stationary condition explicitly considered by Klafter and Zumofen [206]. In this section we prove that there is a connection between a system’s age and the order of the fractional derivative in the relaxation process.
A sign of the dependence of the fractional derivative order on age is given by the discrepancy between the result of Section 3 and Ref. 12. Let us compare Eq. (15) to Eq. (16) of Ref. 12. We obtain the fractional index $1 - \beta$ rather than $\beta$ as in the work of Sokolov and Metzler. In Appendix 1 we prove that our time asymptotic approach to fractional derivatives, in the non-stationary case studied by Sokolov and Metzler yields the same index as they obtain 12. Thus, the discrepancy between our prediction and the prediction of Sokolov and Metzler depends on the fact that we consider a condition consistent with the Onsager principle, whereas Sokolov and Metzler do not. Furthermore, if the system is not infinitely aged, a sort of rejuvenation process is expected to take place that will lead to the fractional order of Sokolov and Metzler.

To support our remarks concerning the relation between aging and the order of fractional operator, here we discuss how to define a waiting time distribution of any age. The authors of Ref. 19 have shown that the waiting time distribution $\psi(t)$ of Eq. (13) is obtained from the following dynamic model. A particle moves in an the interval $I \equiv [0, 1]$ driven by the equation of motion

$$\frac{dy}{dt} = \alpha y^z,$$

with $z > 1$. When the particle reaches the border $y = 1$, it is injected back to an initial condition between $y = 0$ and $y = 1$ with uniform probability. The age of the CTRW is determined by the distribution of first exit times. The ordinary CTRW rests on identifying this distribution with $\psi(t)$. This means that the CTRW is equivalent to assuming that the system is prepared in a flat distribution at $t = 0$, which coincides with the beginning of the observation process.

Let us discuss now the consequence of beginning the observation a significant time after the preparation. Let us imagine that the system is prepared in a flat distribution at a time $t = -t_a < 0$, and that the observation begins at $t = 0$. This means that the flat distribution begins producing a sequence of time intervals of size $\tau$, according to the distribution of Eq. (13); more precisely, the time interval $\tau_1$ beginning at $t = -t_a$ and ending at $t = -t_a + \tau_1$, the time interval $\tau_2$ beginning at $t = -t_a + \tau_1$ and ending at $t = -t_a + \tau_1 + \tau_2$, and so on. The waiting time distribution of age $t_a$, denoted by $\psi_{t_a}(t)$, is determined by the first of these time intervals overlapping with $t > 0$. The time length of that overlap is the time length whose distribution determines $\psi_{t_a}(t)$. We make the assumption that the beginning of the first time interval overlapping with $t > 0$ occurs with equal probability at any point between $t = -t_a$ and $t = 0$. The validity of this assumption is discussed in Appendix 2, which establishes that this assumption is very good for $t_a \to 0$ and $t_a \to \infty$. In between the asymptotic limits the resulting prediction is not exact. However, since it yields simple analytical formulas, we adopt this simplifying assumption for any age. Thus, we have that

$$\psi_{t_a}(t) = \int_0^{t_a} \psi(t+y)dy/g(t_a),$$

where $g(t_a)$ is the normalization factor defined by

$$g(t_a) = \int_0^{t_a} \Psi(t')dt',$$

and $\Psi(t)$ is the probability that no event occurs throughout the time interval of length $t$. Using for $\psi(t)$ the explicit form of Eq. (13), it is easy to prove that Eq. (15) can be written under the form

$$\psi_{t_a}(t) = (\mu - 2)(t + T)^{(1-\mu)} - (t + T + t_a)^{(1-\mu)}
/T^{(2-\mu)} - (t_a + T)^{(2-\mu)}.$$

This formula proves that for $t << t_a$ the index of the distribution is $\mu - 1$, whereas for $t >> t_a$ the index becomes $\mu$. This result for the age-dependent waiting time distribution function agrees with the predictions by Barkai 22 and by the authors of Ref. 19. Notice that the formula Eq. (15) is equivalent to drawing the initial condition for $y$ from an aged distribution of this variable.

Here, we are in a position to evaluate the waiting time index at a generic time, where, we write $\psi_{t_a}(t)$, as

$$\psi_{t_a}(t) = \frac{A(T, t_a)}{(t + T)^{\mu_{eff}(t)}},$$

Using Eq. (14) we arrive at the following formula for the time dependence of the effective power-law index

$$\mu_{eff}(t) = \frac{\ln[(t + T)^{(1-\mu)} - (t + t_a)^{(1-\mu)}]}{\ln[t + T]}.$$

FIG. 2: The effective power index $\mu_{eff}(t)$ as a function of time, for $\mu = 2.3$. The curves refer, from top to bottom, to $t_a = 100, 1000, 10000$. Fig. 2 illustrates the regression of the effective power-law age. This for-
it is possible to build a GME that at short times follows the prescription of our GME and at long times moves into the basin of attraction of Sokolov and Metzler. This is certainly the case, if \( t_a > -\infty \).

This aspect is important and needs a more exhaustive illustration. We note that the approach of Ref. [10] can be easily extended to the case where the distribution of first exit times has a finite age. It is enough to follow the procedure of Ref. [10] and to replace the first exit time distribution with \( \psi_{t_a}(t) \) rather than with \( \psi_{\infty}(t) \equiv \psi_{t_a=-\infty}(t) \), as done in Ref. [10]. The result of this procedure yields for the GME the following form for the Laplace transform of the memory kernel

\[
\hat{\Phi}_{t_a}(u) = \frac{u\hat{\psi}_{t_a}(u)}{1 + \psi(u) - \hat{\psi}_{t_a}(u) u}.
\]

It straightforward to prove that for \( t_a = 0 \) \[57\] reduces to

\[
\hat{\Phi}_{t_a=0}(u) = \frac{u\hat{\psi}(u)}{1 - \psi(u)}.
\]

In fact, the general prescription of Eq. \[52\] immediately yields \( \psi_{t_a}(t) = \psi(t) \) for \( t_a = 0 \). To derive the memory kernel corresponding to the infinitely aged condition of Eq. \[71\] we have to notice first that Eq. \[52\] yields, in accordance with Refs. \[22\] and \[16\],

\[
\psi_{\infty}(t) = \psi_{t_a=-\infty}(t) = \frac{1}{\tau} \int_{t}^{\infty} dt' \psi(t').
\]

To illustrate the change of the memory kernel with time, notice that the Laplace transform of Eq. \[53\] is:

\[
\hat{\psi}_{t_a}(u) = \hat{\Psi}(u)(1 - e^{ut_a}) + e^{ut_a} \int_{0}^{t_a} e^{-uy} \Psi(y) dy
\]

that is:

\[
\hat{\psi}_{t_a}(u) = \left(1 - \hat{\psi}(u)(1 - e^{ut_a}) + u e^{ut_a} \int_{0}^{t_a} e^{-uy} \Psi(y) dy\right)
\]

\[
ug(t_a).
\]

Let us substitute \[51\] into Eq. \[57\], from which we obtain the Laplace transform of the memory kernel for an arbitrary age. In Fig. \[3\] we show the Laplace transform of the memory kernel corresponding to a number of different ages. Moving from the top to the bottom curve the age increases from the brand new kernel \( (t_a = 0) \) to the infinitely aged, or stationary kernel \( (t_a = \infty) \).

V. CONCLUDING REMARKS

In this paper we establish that an infinitely old system, with the power-law index in the interval \( 2 \leq \mu \leq 3 \), yields the fractional order \( 1 - \beta = 3 - \mu \). The prediction of Ref. \[12\], on the other hand, yields the fractional order \( \mu - 2 \), corresponding to the brand new condition. If the system is not infinitely aged, namely \( t_a < \infty \), the short-time behavior of the system, for \( t << t_a \) is expected to be that of an aged system. At large observation times, \( t >> t_a \), rejuvenation begins. This can be explained using the dynamical model of Eq. \[51\].

FIG. 3: The Laplace transform of the \( t_a \)-old memory kernel \( \Phi_{t_a}(t) \), \( \Phi_{t_a}(u) \) as a function of \( u \), for \( \mu = 2.3 \). The curves refer, from top to bottom, to \( t_a = 0, \ 0.1, \ 1, \ 10, \ \infty \).
the order $3 - \mu$ to the order $\mu - 2$. In conclusion, the fractional operator, and its order, reflects a stable condition, of a brand new or infinitely old system. The regime of transition from the dynamic to any of these two thermodynamic regimes, and the regime of transition from the earlier to the latter thermodynamic regime is not yet a fully understood physical condition, an issue calling for further investigation.

It is interesting to notice that, even if we select $\mu > 2$, and consequently we adopt a condition compatible with the stationary condition, the effective index of the first exit distribution is located in the non-stationary region, if $\beta < 1$. This is probably the reason why the memory kernel seems to share the same properties as those adopted by Ref. [6, 10, 28] to produce sub-diffusion. Notice that the baths used by Lutz [6] and Pottier [28] have properties quite different from the subordination perspective of Ref. [10], even the relaxation process stemming from subordination is quite similar to that produced by the non-ohmic baths of Lutz and Pottier. We hope that the present work might help understanding the connection between the two perspectives. This is another subject for future research.

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APPENDIX I

In this Appendix we show how to obtain the order of the fractional operator in the GME for $1 < \mu < 3$, using the Laplace transform form for $\Phi(t)$ given by Eq. (A-5). We are referring ourselves to $\psi(t)$ rather than $\psi^*(t)$. Thus, for the reasons pointed out in Section 2, we adopt the analytical expression of Eq. (A-5).

We note that for $u \to \infty$ we get a finite value: $\hat{\Phi}(\infty) = \frac{2}{\Gamma(\mu - 1)}$ corresponding to $\psi(0)$ in $t$-space. As done in Section 2, we separate the kernel into two contributions: $\Phi(t) = \frac{u}{\Gamma(\mu - 1)} \delta(t) + \Phi_a(t)$, and insert the Laplace transform of separation into Eq. (A-5), to write:

$$\hat{\Phi}_a(u) = \frac{u \hat{\psi}(u) - (\mu - 1) + (\mu - 1) \hat{\psi}(u)}{1 - \hat{\psi}(u)}, \quad (A-1)$$

We introduce $\hat{\psi}_D(u)$ is the Laplace transform of the distribution’s derivative $\psi'(t) = -\mu(\mu - 1) \frac{t^{\mu - 1}}{(t + 1)^{\mu}}$; using the Laplace transform of an inverse power law and substituting it into Eq. (A-1) we have:

$$\hat{\Phi}_a(u) = \frac{(\mu - 1)^2 \Gamma(1 - \mu)(e^u - E_{\mu-1}^u)}{u^{\mu - 1} - (\mu - 1) \Gamma(1 - \mu)(e^u - E_{\mu-1}^u)} - \frac{\mu(\mu - 1) \Gamma(-\mu) u (e^u - E_{\mu-1}^u)}{u^{\mu - 1} - (\mu - 1) \Gamma(1 - \mu)(e^u - E_{\mu-1}^u)}, \quad (A-2)$$

where, as usual, for simplicity we have set $T = 1$. Anticipating the convolution form of the solution we cross-multiply to obtain:

$$[u^{\mu - 1} - (\mu - 1) \Gamma(1 - \mu)(e^u - E_{\mu-1}^u)] \hat{\Phi}_a(u) = (\mu - 1) ((\mu - 1) \Gamma(1 - \mu)(e^u - E_{\mu-1}^u) - \mu \Gamma(-\mu) u (e^u - E_{\mu}^u)) \quad (A-3)$$

Using the following relation [2]

$$\int_0^\infty \frac{tx^{\alpha}}{t^\alpha + 1} \exp[-ut] dt = \int_0^\infty \frac{\pi a^{\alpha}}{\sin \pi \alpha} (E_{\alpha}^u - e^{ua}) \alpha > -1 \quad (A-4)$$

and setting $\alpha = \mu - 1$ we construct

$$R(t) = \frac{1}{\Gamma(\mu - 1)} \int_0^t t^{\mu - 2} \Phi_a(t - t') dt' \quad (A-5)$$

$$= \frac{\sin \pi \mu}{\pi} (\mu - 1) \Gamma(1 - \mu) \int_0^t \frac{t^{\mu - 1}}{t' + 1} \Phi_a(t - t') dt',$$

where $R(t)$ is the inverse Laplace transform of right side of Eq. (A-3). Using the well known recurrence relation of Gamma function, we can combine terms in Eq. (A-5) to obtain

$$R(t) = \frac{1}{\Gamma(\mu - 1)} \int_0^t t^{\mu - 2} \left(1 - \frac{t'}{t' + 1}\right) \Phi_a(t - t') dt'$$

$$= \frac{1}{\Gamma(\mu - 1)} \int_0^t \frac{t^{\mu - 2} \Phi_a(t - t') dt'}{t' + 1}.$$ (A-6)

Let us consider first the case $\mu > 2$, where, in the limit of $t \gg 1$ (equivalent to $t \gg T$), we can write Eq. (A-6) to a good approximation

$$R(t) = \frac{1}{\Gamma(\mu - 1)} \int_0^t t^{\mu - 3} \Phi_a(t - t') dt' = R(t). \quad (A-7)$$

$$R(t) = \frac{1}{\Gamma(\mu - 1)} \int_0^t t^{\mu - 3} \Phi_a(t - t') dt' = R(t). \quad (A-7)$$
Going back to the Laplace transform representation, we obtain the simpler expression

\[ \frac{\Gamma(\mu - 2)}{\Gamma(\mu - 1)} \hat{\Phi}_a(u) = (\mu - 1)^2 \Gamma(1 - \mu) \left( e^u - E^u_{\mu - 1} \right) - \mu(\mu - 1) \Gamma(-\mu) \left( e^u - E^u_{\mu} \right), \]

which after a little algebra yields for \( \hat{\Phi}_a(u) \):

\[ \hat{\Phi}_a(u) = (\mu - 1)(\mu - 2) \cdot \left[ (\mu - 1) \Gamma(1 - \mu) \frac{1}{u} \left( e^u - E^u_{\mu - 1} \right) \right] - \mu \Gamma(-\mu) \frac{1}{u} \left( e^u - E^u_{\mu} \right). \]

(A-8)

So that using the inverse Laplace transforms we obtain the corresponding expression in the time representation:

\[ \Phi_a(t) = (\mu - 1)(\mu - 2) \left[ \frac{1}{(1 + t)^\mu} - \frac{1}{(1 + t)^{\mu - 1}} \right]. \]

(A-9)

In the time asymptotic limit we get

\[ \Phi_a(t) \propto \frac{1}{\mu^\mu - 1}, \]

(A-10)

corresponding to fractional operator of index \( \beta = \mu - 2 \).

For the sake of completeness, we also give the expression for the GME kernel in the case \( \mu < 2 \). Proceeding as done earlier we obtain:

\[ \Phi(t) \approx \frac{-\sin \pi \mu}{\pi} \frac{\mu^{\mu - 2}}{(t + 1)^2} \left[ \mu - 1 + (\mu - 2) t \right]. \]

(A-11)

Finally, we want to point out that the expressions we are proposing refer to values of \( \mu \) which are not integer. We are exploring the interval [1,3]. Thus the the expressions we are proposing become questionable for \( \mu = 2 \). To get the proper expression for \( \mu = 2 \) we have to apply to study expressions like those of Eq. (A-1) and (A-8) at \( \mu = 2 + \epsilon \), do a Taylor series expansion around \( \mu = 2 \), and assign to \( \mu = 2 \) the limiting values reached for \( \epsilon \to 0 \).

**APPENDIX II**

This Appendix is devoted to establishing the accuracy of Eq. (B-2), and consequently the validity of the assumption that the beginning of the first laminar region overlapping with \( t > 0 \) is uniformly distributed between \( t = -t_a \) and \( t = 0 \). Let us set \( t_a = 0 \).

The exact expression for \( \psi_{t_a}(t) \) is

\[ \psi_{t_a}(t) = \int_0^{t_a} dx G(t_a - x) \psi(t + x), \]

(B-1)

where

\[ G(t) \equiv \delta(t) + \psi(t) + \sum_{n=2}^{\infty} \int_0^t d\tau_1 \psi(\tau_1) \cdot \int_{\tau_1}^t d\tau_2 \psi(\tau_2 - \tau_1) ... \int_{\tau_{n-2}}^t d\tau_{n-1} \psi(t - \tau_{n-1}). \]

(B-2)

![FIG. 4: The waiting time distribution \( \psi_{t_a}(t) \) as a function of time \( t \). The dots denote the exact values, and the lines the prediction of Eq. (B-4) for \( \mu = 2.3, T = 1 \). Moving from bottom to top in the right-hand portion of the \( t_a = 0.01, 1, 10, 100 \).

It is straightforward to find the Laplace transform of \( G(t) \). This is given by

\[ \hat{G}(u) = \sum_{n=0}^{\infty} \hat{\psi}(u)^n = \frac{1}{1 - \hat{\psi}(u)}. \]

(B-3)

Thus, the Laplace transform of \( \psi_{t_a}(t) \) respect to \( t_a \) reads:

\[ \psi_{t_a}(t) = \frac{1}{1 - \psi(s_a) e^{-s_a t}} \left[ \psi(s_a) - \int_0^t e^{-s_a y} \psi(y) dy \right]. \]

(B-4)

By the numerical anti-Laplace transforming Eq. (B-4) we evaluate the time dependence of the exact waiting time distribution of age \( t_a \), Eq. (B-1). In Fig. we compare the exact prediction, evaluated numerically, to the heuristic expression of Eq. (B-2). We find that at short and large values of \( t_a \) these two expressions coincide. In the intermediate region they do not. Nevertheless, we think the agreement between the two expressions is satisfactory enough for the purpose of this paper.
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