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# ON A POSSIBLE CONNECTION OF NON-CRITICAL STRINGS TO CERTAIN ASPECTS OF QUANTUM BRAIN FUNCTION

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ABSTRACT

We review certain aspects of brain function which could be associated with non-critical (Liouville) string theory. In particular we simulate the physics of brain microtubules (MT) by using a (completely integrable) non-critical string, we discuss the collapse of the wave function as a result of quantum gravity effects due to abrupt conformational changes of the MT protein dimers, and we propose a new mechanism for memory coding.

## 1 Introduction

The interior of living cells is structurally and dynamically organized by *cytoskeletons*, i.e. networks of protein polymers. Of these structures, *MicroTubules* (MT) appear to be [1] the most fundamental. Their dynamics has been studied recently by a number of authors in connection with the mechanism responsible for dissipation-free energy transfer. Recently, Hameroff and Penrose [2] have conjectured another fundamental rôle for the MT, namely being responsible for *quantum computations* in the human brain, and, thus, related to consciousness. The latter is argued to be associated with certain aspects of quantum theory [3] that are believed to occur in the cytoskeleton MT, in particular quantum superposition and subsequent collapse of the wave function of coherent MT networks. While quantum superposition is a well-established and well-understood property of quantum physics, the collapse of the wave function has been always enigmatic. We review here one recent proposal [4, 5] to use an explicit string-derived mechanism - in one *interpretation* of non-critical string theory - for the collapse of the wave function[6], involving quantum gravity in an essential way and solidifying previous intuitively plausible suggestions[7, 8]. It is an amazing surprise that quantum gravity effects, of order of magnitude $G_N^{1/2} m_p \sim 10^{-19}$, with $G_N$ Newton's gravitational constant and $m_p$ the proton mass, can play a rôle in such low energies as the $eV$ scales of the typical energy transfer that occurs in cytoskeleta. However, the fine details of the MT characteristic structure indicate that not only is this conceivable, but such a picture leads to order of magnitude estimates for the time scales entering *conscious perception* that are close enough to those conjectured/"observed" by neuroscientists, based on completely different grounds.

To understand how quantum space-time effects can affect conscious perception, we mention that it has long been suspected [9] that large scale quantum coherent phenomena can occur in the interior of biological cells, as a result of the existence of ordered water molecules (lattice). Quantum mechanical vibrations of the latter are responsible for the appearance of 'phonons' similar in nature to those associated with superconductivity. In fact there is a close analogy between superconductivity and energy transfer in biological cells. In the former phenomenon electric current is transferred without dissipation in the surface of the superconductor. In biological cells, as we shall discuss later on, energy is transferred through the cell without *loss*, despite the existence of frictional forces that represent the interaction of basic cell constituents with the surrounding water molecules [10]. Such large scale quantum coherent states can maintain themselves for up to $\mathcal{O}(1\,\text{sec})$, without significant environmental entanglement. After that time, the state undergoes self-collapse, probably due to quantum gravity effects. Due to quantum transitions between the different states of the quantum system of MT in certain parts of the human brain, a sufficient distortion of the surrounding space-time occurs, so that a microscopic (Planck size) black hole is formed. Then collapse is induced, with a collapse time that depends on the order of magnitude of the number $N$ of coherent microtubulins. It is estimated that, with an $N = O[10^{12}]$, the collapse time of $\mathcal{O}(1\,\text{sec})$, which appears to be a typical time scale of conscious events, is achieved. Taking into account that experiments have shown that there exist $N = 10^8$ tubulins per neuron, and that there are $10^{11}$ neurons in the brain, it follows that that this order of magnitude for $N$ refers to a fraction $10^{-7}$ of the human brain, which is very close to the fraction believed responsible for human perception.

The self-collapse of the MT coherent state wave function is an essential step for the operation of the MT network as a quantum computer. In the past it has been suggested that MT networks processed information in a way similar to classical cellular automata (CCA) [11]. These are described by interacting Ising spin chains on the spatial plane obtained by fileting open and flattening the MT cylindrical surface. Distortions in the configurations of individual parts of the spin chain can be influenced by the environmental spins, leading to information processing. In view of the suggestion [2] on viewing the conscious parts of the human mind as quantum computers, one might extend the concept of the CCA to a quantum cellular automaton (QCA), undergoing wave function self-collapses due to (quantum gravity) enviromental entanglement.

An interesting and basic issue that arises in connection with the above rôle of the brain as a quantum computer is the emergence of a direction in the flow of time (arrow). The latter could be the result of succesive self-collapses of the system's wave function. In a recent series of papers [6] we have suggested a rather detailed mechanism by which an *irreversible* time variable has emerged in certain models of string quantum gravity. The model utilized string particles propagating in singular space-time backgrounds with event horizons. Consistency of the string approach requires conformal invariance of the associated $\sigma$-model, which in turn implies a coupling of the backgrounds for the propagating string modes to an infinity of global (quasi-topological) delocalized modes at higher (massive) string levels. The existence of such couplings is necessitated by specific coherence-preserving target space gauge symmetries that mix the string levels [6].

The specific model of ref. [6] is a completely integrable string theory, in the sense of being characterised by an infinity of conserved charges. This can be intuitively understood by the fact that the model is a $(1+1)$-dimensional Liouville string, and as such it can be mapped to a theory of essentially free fermions on a discretized world sheet (matrix model approach [12]). A system of free fermions in $(1+1)$ dimensions is trivially completely integrable, the infinity of the conserved charges being provided by appropriate moments of the fermion energies above the Fermi surface. Of course, formally, the precise symmetries of the model used in ref. [6] are much more complicated [13], but the idea behind the model's integrability is essentially the above. It is our belief that this quantum integrability is a very important feature of theories of space-time associated with the time arrow. In its presence, theories with singular backgrounds appear consistent as far as maintainance of quantum coherence is concerned. This is due to the fact that the phase-space density of the field theory associated with the matter degrees of freedom evolves with time according to the conventional Liouville theorem[6]

$$\partial_t \rho = -\{\rho, H\}_{PB} \tag{1}$$

as a consequence of phase-space volume-preserving symmetries. In the two-dimensional example of ref. [6], these symmetries are known as $W_\infty$, and are associated with higher spin target-space states[13]. They are responsible for string-level mixing, and hence they are broken in any low-energy approximation. If the concept of 'measurement by local scattering experiments' is introduced [6], it becomes clear that the observable background cannot contain such global modes. The latter have to be integrated out in any effective low-energy theory. The result of this integration is a non-critical string theory, based on the propagating modes only. Its conformal invariance on the world sheet is restored by dressing the matter backgrounds by the Liouville mode $\phi$, which plays the role of the time coordinate. The $\phi$ mode is a dynamical local world-sheet scale [6], flowing irreversibly as a result of certain theorems of the renormalization group of unitary $\sigma$-models [14]. In this way time in target space has a natural arrow for very specific *stringy reasons*. Eq. (1) is now replaced by a modified Liouville equation with non-Hamiltonian correction terms

$$\partial_t \rho = -\{\rho, H\}_{PB} + \beta^i G_{ij} \frac{\partial}{\partial p_j} \rho \tag{2}$$

where $t = ln\phi$ plays the rôle of target time, under the conditions specified in ref. [6], $\beta^i$ is the world-sheet Renormalization Group $\beta$ function of the (not exactly marginal) coupling $g^i$/field mode in target space, $p_i$ is its canonical momentum, and $G_{ij}$ is a 'metric' in the (infinite-dimensional) space of couplings [14]. Upon formulating string theory in higher-genus-resummed world-sheets, quantization of the couplings/fields $g^i$ is implied. It turns out that canonical quantization in the space $\{g^i\}$ is possible in this generalized non-quantum-mechanical setting [15].

Given the suggestion of ref. [2] that space-time environmental entanglement could be responsible for conscious brain function, it is natural to examine the conditions under which our theory [6] can be applied. Our approach [4, 5] utilizes extra degrees of freedom, the $W_\infty$ global string modes, which are not directly accessible to local scattering 'experiments' that make use of *propagating* modes only. Such degrees of freedom carry information, in a similar spirit to the information loss suggested by Hawking[16] for the quantum-black-hole case. For us, such degrees of freedom are not exotic, as suggested in ref. [17], but appear *already* in the non-critical String Universe [6, 4], and as such they are considered as 'purely stringy'. In this respect, we believe that the suggested model of consciousness [4, 5], based on the non-critical-string formalism of ref. [6], is physically more *concrete*. The idea of using string theory instead of point-like quantum gravity is primarily associated with the fact that a *consistent* quantization of gravity is at present possible *only* within the framework of string theory, so far. However, there are additional reasons that make advantageous a string formalism. These include the possibility of construction of a completely integrable model for $MTs$, and the Hamiltonian representation of dynamical problems with friction involved in the physics of MTs. This leads to the possibility of a consistent (*mean field*) *quantization* of certain soliton solutions associated with the energy transfer mechanism in biologcal cells.

According to our previous discussion emphasizing the importance of strings, it is imperative that we try to identify the completely integrable system underlying MT networks. This will allow the identification of the analogue of the (stringy) propagating degrees of freedom, which eventually couple to quantum (stringy) gravity and to global environmental modes. As we have discussed in detail in ref. [5] the relevant basic building blocks of the human brain are one-dimensional Ising spin chains, interacting among themselves in a way so as to create a large scale quantum coherent state, believed to be responsible for preconscious behaviour [2]. The system can be described in a world-sheet conformal invariant way and is unitary. Coupling it to gravity generates deviations from conformal invariance which lead to time-dependences, by identifying time with the Liouville field (local renormalization group scale) on the world sheet. The situation is similar to the environemtnal entanglement of ref. [18, 19]. Due to this entanglement, the system of the propagating modes opens up as in Markov processes [20]. This leads to a dynamical self-collapse of the wave function of the MT quantum coherent network. In this way, the part of the human brain associated with consciousness generates, through successive collapses, an arrow of time. The interaction among the Ising spin chains, then, provides a mechanism for quantum computation, resembling a planar cellular automaton. Such operations sustain the irreversible flow of time.

## 2 Physical Description of the Microtubules and their representation as a non-critical string model

Microtubules (MT) are hollow cylinders comprised of an exterior surface (of cross-section diameter 25 $nm$) with 13 arrays (protofilaments) of protein dimers called tubulins. The interior of the cylinder (of cross-section diameter 14 $nm$) contains ordered water molecules, which implies the existence of an electric dipole moment and an electric field. Ordered water molecules exist also in the exterior of the MT cylinders, and their presence, together with the ones in the interior of the MT, is associated with providing a sort of dissipation. This dissipation turns out to be quite crucial for an energy-loss-free trasfer through the MT. The arrangement of the dimers is such that, if one ignores their size, they resemble triangular lattices on the MT surface. Each dimer consists of two hydrophobic protein pockets, and has an electron. There are two possible positions of the electron, called $\alpha$ and $\beta$ *conformations*. When the electron is in the $\beta$-conformation there is a $29^o$ distortion of the electric dipole moment as compared to the $\alpha$ conformation.

In standard models for the simulation of the MT dynamics, the 'physical' degree of freedom - relevant for the description of the energy transfer - is the projection of the dimer electric dipole moment on the longitudinal symmetry axis (x-axis) of the MT cylinder. The $29^o$ distortion of the $\beta$-conformation leads to a displacement $u_n$ along the $x$-axis, which is thus the relevant physical degree of freedom. This way, the effective system is one-dimensional (spatial), and one has a first indication that quantum integrability might appear.

Let $u_n$ be the displacement field of the $n$-th dimer in a MT chain. The continuous approximation proves sufficient for the study of phenomena associated with energy transfer in biological cells, and this implies that one can make the replacement

$$u_n \rightarrow u(x,t) \qquad (3)$$

with $x$ a spatial coordinate along the longitudinal symmetry axis of the MT. There is a time variable $t$ due to fluctuations of the displacements $u(x)$ as a result of the dipole oscillations in the dimers. At this stage, $t$ is viewed as a reversible variable.

The effects of the neighboring dimers (including neighboring chains) can be phenomenologically accounted for by an effective double-well potential of the form suitable for spontaneous symmetry breakdown [21]. The effects of the surrounding water molecules can be summarized by a viscous force term that damps out the dimer oscillations. This friction should be viewed as an environmental effect, which however does not lead to energy dissipation, as a result of the non-trivial solitonic structure of the ground-state and the non-zero constant force due to the electric field along the MT longitudinal axis. This is a well known result, directly relevant to energy transfer in biological systems [10]. The solution of the dissipative equations of motion acquires the form of a travelling wave, and can be most easily exhibited by defining a normalized displacement field

$$\psi(\xi) \propto u(x - vt) \tag{4}$$

with $v$ a propagation velocity determined appropriately by the parameters of the model [21, 5]. In terms of the $\psi(\xi)$ variable, the equation of motion of the displacement field acquires the form of the equation of motion of an anharmonic oscillator in a frictional environment

$$\begin{aligned} \psi'' &+ \rho\psi' - \psi^3 + \psi + \sigma = 0 \\ \rho &\equiv \gamma v \sqrt{M|A|(v^2 - v_0^2)^{-\frac{1}{2}}}, \\ \sigma &= q\sqrt{B}|A|^{-3/2}E \end{aligned} \tag{5}$$

with $v_0$ the sound velocity, and the various other parameters are explained in ref. [21, 5]. This has a *unique* bounded solution [21]

$$\psi(\xi) = a + \frac{b-a}{1 + e^{\frac{b-a}{\sqrt{2}}\xi}} \tag{6}$$

with the parameters $b, a$ and $d$ satisfying:

$$(\psi - a)(\psi - b)(\psi - d) = \psi^3 - \psi - \left(\frac{q\sqrt{B}}{|A|^{3/2}}E\right) \tag{7}$$

Notice that the kink function (6) also appears in neural network models, but here it is derived in a dynamical way. The kink propagates along the protofilament axis with fixed velocity

$$v = v_0[1 + \frac{2\gamma}{9d^2 M v_0^2}]^{-\frac{1}{2}} \tag{8}$$

with $v_0$ the sound velocity. This velocity depends on the strength of the electric field $E$ through the dependence of $d$ on $E$ via (7). Notice that, due to friction, $v \neq v_0$, and this is essential for a non-trivial second derivative term in (5), necessary for wave propagation. For realistic biological systems $v \simeq 2m/sec$. With a velocity of this order, the travelling waves of kink-like excitations of the displacment field $\psi(\xi)$ transfer energy along a moderately long microtubule of length $L = 10^{-6}m$ in about

$$t_T = 5 \times 10^{-7} sec \tag{9}$$

This time is very close to Frohlich's time for coherent phonons in biological system. In realistic biological models for MT, the effective mass, whose movement might cause distortion in the surrounding spacetime [2, 4, 5], is [21] of order $5 \times 10^{-27} kg$, which is about the proton mass ($1GeV$) (!). As we discussed in ref. [4, 5], these values are essential in yielding the correct estimates for the time of collapse of the '*preconscious*' state due to our quantum gravity environmental entanglement.

To make plausible a consistent study of such effects, at a quantum level, we showed in ref. [5] that the equations of motion (5) can be derived from an appropriately constructed $(1+1)$-dimensional (target space) non-critical string model. Such a representation turns out to be quite crucial, as it allows for a consistent quantum treatment of possible gravitational effects, including induced collapse of the coherent wavefunction of a MT netork [6, 4, 5].

Abrupt conformational changes of the tubulin dimers, due to quantum effects (pulses), lead [5] to a formation of *virtual* 'black holes' in the effective target two-dimensional space time. Such black hole solutions can be thought of either as being associated with real quantum gravitational effects, or as representing displacement-field-pulse collapse due to abrupt distortion of the surrounding environment. It should be noted that in the former case, one can calculate the time required for an induced collapse of the wave function of a network of MT consisting of $10^{12}$ dimers. Such quantities constitute the part of the brain believed to be responsible for *conscious* perception. The collapse time is found to be of order $\mathcal{O}(1sec)$ which is in excellent agreement with observations based on completely different (biological) methods. This supports the idea that realistic quantum gravity effects might play an important rôle in conscious brain functioning.

The possibility that a (quantum) theory as weak as gravity affects the physics of low-energy systems, like MT networks, does not seem so remote, if we recall some recent *experimental* indications [22] about an appreciable sensitivity exhibited by MT structures to classical gravity effects, and more general to weak external fields. In such experiments, gravity effects can lead to a sort of symmetry breaking and pattern formation in assemblies of MT. Although theoretically the sistuation is still very vague, however the above phenomena appear consistent with predictions based on reaction-diffucion theories [23], involving out-of-equilibrium chemical reactions coupled to gravity. As we have argued in ref.

[6] quantum gravity in non-critical string theory can be viewed as such an out-of-equilibrium theory, resulting in an irreversible flow of time and entropy production at a fundamental (string) energy scale. Whether MT systems, whose (quantum) physics scale is that of electroweak effects, are senstitive to *quantum* gravity effects, as opposed to classical ones, still remains to be seen. However the idea does not seem so absurd if we draw an analogy with what happens in the neutral kaon system discussed in this meeting [24]. There, violations of quantum mechanics, associated with quantum gravity effects of order $O[G_N^{\frac{1}{2}} m_K] \simeq 10^{-19}$, could be on the verge of being observed experimentally in $CPLEAR$ or $DA\phi NE$ facilities.

However we should bear in mind that in the case of systems pertaining to the function of the brain things are by no means simple. The simple fact that the collapse time, calculated on the basis of string quantum gravity [4, 5] or conventional quantum gravity [2] (provided that the latter exists as a mathematical theory), is in agreement with estimates of conscious perception time obtained by quite different methods, although a pleasant indication, however it by no means constitutes a proof of the relevance of quantum mechanics or quantum gravity on brain function. From our point of view [5], such a proof could come from observations of fluctuations ('quantum jumps') of the length of isolated microtubules. This is supported by the fact that the Liouville approach to time in string theory leads [6, 5] to a stochastic growth, a kind of saw-tooth behaviour of the length of a MT assembly, which notably is observed experimentally [25]. When applied to an individual MT this approach may lead to instabilities that could predict fluctuations of the tip of MT due to quantum gravity entanglement [26, 5].

Whether experiments can be devised, which are sensitive enough to capture such microscopic fluctuations of isolated (cold) MT, is not known to us. We believe, however, that if they could be devised, they would constitute the best proof of the relevance of quantum (gravity) effects for brain functioning, provided of course that any other conventional source of mechanical instabilities [27] is excluded. For instance, the stochastic/diffusive nature of Liouville gravity, advocated in ref. [5], encourages a comparison with the situation of ref. [22] and, in general, with experiments testing predictions of reaction-difusion theories. One is tempted to conjecture that the quantum fluctuations of the tip of MT structures, predicted in ref. [5] in the framework of Liouville theory, might also be seen in the pattern formation of the experiments of ref. [22], provided that the latter are repeated in 'cold' environment so as to minimize noise due to (thermal) dissipation or other mechanical instabilities [27], that could interfere with pure quantum gravity effects. Whether this is possible, or even conceivable as an idea for future research, is unknown to us at present, but we believe that such speculations deserve closer attention.

## 3 Memory Coding and Capacity of the brain as a (non-critical string) dissipative system

Irrespective of the possibility of proving experimentally the possible effects of quantum gravity on brain function, the conjecture of ref. [5] that MT dynamics stems from one-dimensional Ising spin chains in the brain, that can be represented as a (completely integrable) non-critical string model admitting space-time singularities, implies certain peculiar but highly interesting properties of brain functioning, associated with non-equilibrium (dissipative) temporal evolution. The latter implies an irreversible arrow ot time, evolution of pure states into mixed ones, and, more generally, what a particle field theorist would call $CPT$ violation [5].

In this respect, our model has many things in common with dissipative (local field theory) models of ref. [28, 29] in an attempt to construct realistic models for memory capacity. Below we shall briefly review such models, and discuss the possible advantages of our (non-critical string) approach over such local field theory approaches to brain function.

In conventional brain models [28], based on local field theories, the kind of symmetry assumed is that of rotational electric dipole symmetry. The quantum numbers associated with the latter constitute a certain class of code numbers. If the brain lies on a specific ground state, which implies spontaneous breaking of the dipole rotational symmetry, in order to reach any other ground state corresponding to a new code number it would require a sequence of phase transitions that would destroy the previously stored information, a procedure known as *overprinting* [28, 29].

A way out of this problem of *memory capacity* would be to increase the symmetry of the problem to the one with huge dimensions [30]. In a local field theory this cannot be done without destroying the practical use of the model. The problem is analogous to that of how to incorporate the huge entropy of a macroscopic black hole in an information theory framework within a local field theory setting. This again would require an enormous amount of black hole degrees of freedom to account for the macroscopic entropy, which would be hard, if not impossible, to reconciliate with the finite number of degrees of freedom existing in a local field theory.

String theory seems to provide a way out of these problems [6] due to the infinite-dimensional gauge stringy symmetries that mix the various levels. In the black hole model of ref. [31], which is used to simulate the physics of the MT [5], there is an undelrying world-sheet $SL(2,R)$ symmetry of the $\sigma$-model, according to which the various stringy states are classified. The various states of the model, including global string modes characterised by discrete values of (target) energy and momenta, are classified by the non-compact isospin $j$ and its third component $m$, which - unlike the compact isospin $SU(2)$ case - is not restricted by the value of $j$. Thus, for a given $j$, which in the case of string states plays the role of energy, one can have an *infinity* of states labelled by the value of the third isospin component $m$. All such states are characterised by a $W_{1+\infty}$ symmetry, in target space. As we mentioned above, this symmetry is responsible for the maintenance of *quantum coherence* in the presence of a black hole background [6], in the sense of an area-preserving diffeomorphism in a matter phase-space of the two-dimensional target space theory. It should be noted that such area-preserving symmetries, as spectrum generating algebras, also appear in connection with the excitations of planar quantum Hall systems having non-degenerate ground states [32]. So, it should not be considered as a surprise that such symmetries appear in our two-dimensional spin chain model for the brain MT. In the particular case of two-dimensional string black holes there is even a formal analogy with quantum Hall models, as argued in ref. [33].

In ref. [6] it has been argued that such symmetries are responsible for an 'infinite-dimensional' quantum hair ($W$-hair) of the two-dimensional black hole, which consists of (conserved) quantum (global) charges, characterising a black hole space-time even asymptotically, i.e. after evaporation. Such a hair would induce a huge degeneracy in the ground state of the system that could lead to the solution of the problem of memory capacity. From a formal point of view, the rigorous existence proof of such conserved charges would be the explicit construction of exactly marginal deformations that correspond to turning on the above charges. The exaclty marginal character of the deformations is required in order to maintain conformal invariance of the world-sheet $\sigma$-model and thus stable ground state of the string.

At present, within the black hole model of ref. [31], used to simulate also the physics of the MT dynamics [5], it became possible to construct [34] the exactly marginal deformation corresponding only to the lowest non-trivial charge, which is the $ADM$ mass of the black hole. From a $W_\infty$ symmetry point of view, this would be the charge associated with the spin-two part of the target space spectrum, i.e. the stress-energy tensor of the black hole. There is a huge degeneracy of the ground state of the system which is due to the existence of known exactly marginal deformations that are responsible for changing continuously the $ADM$ mass of the black hole. In the notation of ref. [34], such deformations are denoted by $L_0^2\overline{L}_0^2$, and their coupling constant (which is a *free* parameter of the model) shifts the $ADM$ mass of the black hole space time. The above operator turns on only backgrounds corresponding to the (discrete) higher-level string states that do not propagate in space-time. The ground state of such models consists of turning on backgrounds corresponding to matter propagating states. Such backgrounds are turned on by another exactly marginal deformation $L_0^1\overline{L}_0^1$, which mixes the propagating states (belonging to the lowest string level) with an infinity of higher-level string global states. Both operators $L_0^1$ and $L_0^2$ owe their existence to the target space $W_{1+\infty}$-spectrum-generating algebra of the black hole space-time [6, 34]. The latter is broken explicitly by 'measurement' by local scattering experiments or in general by operations that are performed within localised regions of space-time, such as those taking place in the conscious part of the brain.

Such a procedure will integrate out the global degrees of freedom, leaving only an effective (string) theory of propagating degrees of freedom in a black hole background space time. For each matter ground state of a propagating degree of freedom, say the zero mode of the massless field corresponding to the static "tachyon" background of ref. [31], with $SL(2,R)$ quantum numbers $j=-\frac{1}{2}, m=0$, there will be an infinite degeneracy corresponding to a continuum of black hole space-time backgrounds with different $ADM$ masses. These backgrounds are essentially generated by adding various constants to the configuration of the dilaton field in this two-dimensional string theory [31, 34]. It should be noted here that the infinity of propagating "tachyon" states (lowest string mass-level (massless) states), corresponding to other values of $m$, for continuous representations of $j$, constitute *excitations* about the ground state(s), and, thus, they should not be considered as contributing to the ground state degeneracy. In principle, there may be an additional infinity of quantum numbers corresponding to higher-level $W$-hair charges of the black hole space time which are believed [6] responsible for quantum coherence at the full string theory level.

Taking into account the conjecture of ref. [5], that formation of virtual black holes can occur in brain MT models, which would correspond to different modes of collapse of pulses of the displacement field $\psi$ defined in (4) [5], one obtains a system of *coding* that is capable to solve in principle the problem of memory capacity. Information is stored in the brain in the following sense: every time there is an external stimulus that brings the brain out of equilibrium, one can imagine an abrupt conformational change of the MT dimers, leading to a collapse of the pulse pertaining to the displacement field. Then a (virtual) black hole is formed leading to a spontaneous collapse of the MT network to a ground state characterised by say a special configuration of the displacement field $(j, m)$. This ground state will be conformally invariant, and therefore a true vacuum of the string, only after complete evaporation of the black hole, which however would keep memory of the particular collapse mode in the 'value' of the constant added to the dilaton field, or other $W$-charges. This reflects the existence of additional exactly marginal deformations, consisting of global modes only, that are not direclty accessible by local scattering experiments, in the context of the low energy theory of propagating modes (displacement field configurations $\psi$ in the model of ref. [5]). In such a case, the resulting ground state will be infinitely degenerate, which would solve the problem of *memory capacity*. Breaking of this degeneracy would correspond to selecting a given set of expectation values for the dilaton field ant the remaining $W$-hair charges, which we believe corresponds to the *memory printing* process, i.e. storage of information by a selection of a given ground state. A new information would then choose a different value of the dilaton field or other $W$-hair charges etc. This provides a new and satisfactory mechanism of *memory recall* in the following sense: if a new pulse happens to correspond to the same set of (conserved) $W$-hair moduli configurations [6], then the associated virtual black hole will be characterised by the same set of quantum hair, and then the same memory state is reached *asymptotically* (recall). The irreversible arrow of time, endemic in Liouville string theory [6] explains naturally why "only the past can be recalled" [29]. Indeed, as we mentioned above, in the presence of a space-time foamy environment, characterised by the virtual appearence and evaporation of black holes, there is a coupling of global modes to the propagating modes. The environmental global modes match in a special way with the propagating mode $j = -\frac{1}{2}$ $m = 0$, which is the zero mode of the (massles) tachyon corresponding to the tachyon background of a two dimensional black hole which constitutes the *ground* state or *memory* state of our system. This coupling is necessary so as to form *exactly* marginal deformations [6, 34]. This is a *special coding* which were it not for the infinte degeneracy of the black hole space time would lead to a restricted memory capacity[1]. However, the importance of this coupling lies on the fact that it leads to a time arrow in the way explained briefly above and in detail in ref. [6]. A fuller account of these considerations will be given in a forthcoming publication of ours [35]. We cannot resist in pointing out that the existence of such coded situations in memory cells bears an interesting resemblence with DNA coding, with the important difference, however, that here it occurs in the model's state space.

At this point we would like to draw an analogy of our approach to dissipative models for brain function, within local field theory framework, advocated in ref. [29]. As observed in ref. [29] the doubling of degrees of freedom which appears necessary for a canonical quantization of an open system [28], is essential in yielding [36] a *non-compact* $SU(1,1)$ symmetry for the system of damped harmonic oscillators, used as a toy example for simulating quantum brain physics. The quantum numbers of such a system are the $SU(1,1)$ isospin and its third component, $j \in Z_{\frac{1}{2}}, m \geq |j|$. The memory (ground) state corresponds to $j = 0$ and there is a huge degeneracy characterised by the various coexisting (infinite) eigenestates of the Casimir operator for the $SU(1,1)$ isospin. The open-character of the system introduces a time arrow which is associated with the *memory printing* process and is compatible with the 'observation' that 'only the past can be recalled' [29]. The crucial difference of our string case is that the ground state of the string system, which is conformally invariant, is actually a state with given quantum numbers $j = -\frac{1}{2}, m = 0$ of the $SL(2,R)$ isospin in the asymptotically flat space time case. The degeneracy occurs, as we have already mentioned, as a result of the 'existence of an environment' of global modes, inaccessible by local scattering operations of the brain, which lead to exactly marginal deformations shifting the ground state value of the dilaton field, or in general leading to an infinity of $W$-hair charges.

The environmental entanglement of the global modes, the non-equilibrium (in target space) nature of the temporal evolution and inevitably its stochastic nature [15], as well as the fact that an irreversible time arrow arises in our stringy approach [6], makes our non-critical string model of brain function qualitatively similar to the dis-

[1] It should be noted at this stage that the various other (infinite) states corresponding to continuous representations of the $SL(2,R)$ symmetry that pertain to various tachyon modes do not constitute memory states, because, as mentioned earlier, they are just *excitations* about the ground state.

sipative approach of ref. [29]. However, in our system *energy* is conserved on the average, as a result of the renormalizability of the world-sheet $\sigma$-model, unlike the generic dissipative system case. Thus this feature of our model is more likely to correspond [5] to realistic biological systems which are believed to transfer energy without dissipation [10]. Moreover our non-critical stringy approach is capable of analysing real quantum gravity effects that might be responsible for certain aspects of *conscious* quantum brain function, according to the ideas of ref. [2, 4, 5]. Our model incorporates naturally an *arrow* of time, at a *microscopic* level, resulting from integrating out delocalised global (string) states that cannot be accessible by local scattering experiments. The associated collapse of the wave function, as a result of quantum gravity effects, that couple the global modes to the low-energy (observable) world, makes a connection of this microscopic - and thereby macroscopic and biological - time arrow, to a *conscious* time arrow generated by *successive* collapses in the MT cellular networks.

It should be noted, however, that despite the appealing features encompassed by the above ideas, very little is known about the actual mechanisms of energy transfer in brain cells, and therefore any claims about a theoretical understanding of *conscious* perception would be inappropriate at this stage. However, we believe that daring of putting down some modest attempts to simulate some apsects of the physics of the brain by capturing (at least in a *qualitative* way) certain *key* features of model brain systems, such as quantum *integrability* as advocated in ref. [5], is worthy and deserves further quantitative investigations. We hope to come back to these issues in the near future.

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## References

[1] P. Dustin, *MicroTubules* (Springer, Berlin 1984);

Y. Engleborghs, *Nanobiology* 1 (1992), 97.

[2] R. Penrose and S. Hameroff, *Orchestrated Reduction of Quantum Coherence in Brain Microtubules: a Model of Consciousness*, to appear.

[3] R. Penrose, *The Emperor's New Mind* (Oxford Univ. Press 1989); *Shadows of the Mind* (Oxford Univ. Press 1994).

[4] D.V. Nanopoulos, *Theory of Brain Function, Quantum Mechanincs and Superstrings*, ACT-08/95,CERN-TH/95-128,CTP-TAMU-22/95, hep-ph/9505374, based on talk presented at the "XV Brazilian National Meeting on Particles and Fields", Angra dos Reis, Brazil (October 4-8 1994).

[5] N.E. Mavromatos and D.V. Nanopoulos, preprint ACT-09/95, CTP-TAMU-24/95, ENSLAPP-A-524/95.

[6] J. Ellis, N.E. Mavromatos and D.V. Nanopoulos, Phys. Lett. B293 (1992), 37;

Mod. Phys. Lett. A10 (1995), 425;

CERN-TH.6897/93, ENS-LAPP-A427-93, CTP-TAMU-30/93; ACT-10/93 (1993); hep-th/9305117;

CERN-TH.7195/94, ENS-LAPP-A-463/94, ACT-5/94, CTP-TAMU-13/94, *lectures presented at the Erice Summer School, 31st Course: From Supersymmetry to the Origin of Space-Time*, Ettore Majorana Centre, Erice, July 4-12 1993 ; hep-th/9403133, to be published in the proceedings (World Sci. ) ;

For a pedagogical review of this approach see: D.V. Nanopoulos, Riv. Nuov. Cim. Vol. 17, No. 10 (1994), 1.

[7] J. Ellis, J.S. Hagelin, D.V. Nanopoulos and M. Srednicki, Nucl. Phys. B241 (1984), 381.

[8] J. Ellis, S. Mohanty and D.V. Nanopoulos, Phys. Lett. B221 (1989), 113.

[9] H. Fröhlich, *Bioelectrochemistry*, ed. by F. Guttman and H. Keyzer (Plenum, New York 1986).

[10] P. Lal, Physics Letters 111A (1985), 389.

[11] S. Hameroff, S. A. Smith, R.C. Watt, Ann. N.Y. Acad. Sci. 466 (1986), 949;

S. Hameroff, *Ultimate Computing* (Elsevier North-Holland, Amsterdam 1987).

[12] E. Brézin and V.A. Kazakov, Phys. Lett. B236 (1990), 144;

M. Douglas and A. Shenker, Nucl. Phys. B335 (1990), 635;

D. Gross and A.A. Migdal, Phys. Rev. Lett. 64 (1990), 127;

For a review see, e.g., I. Klebanov, in *String Theory and Quantum Gravity*, Proc. Trieste Spring School 1991, ed. by J. Harvey et al. (World Scientific, Singapore, 1991), and references therein.

[13] I. Bakas and E. Kiritsis, Int . J. Mod. Phys. A7 (Suppl. 1A) (1992), 55.

[14] A.B. Zamolodchikov, JETP Lett. 43 (1986), 730; Sov. J. Nucl. Phys. 46 (1987), 1090.

[15] J. Ellis, N.E. Mavromatos and D.V. Nanopoulos, preprint ACT-03/95, CERN-TH.7480/94, CTP-TAMU-12/95, ENSLAPP-A-492/94, hep-th/9503162; Mod. Phys. Lett. A10 (1995), 1685.

[16] S. Hawking, Phys. Rev. D14 (1976), 2460.

[17] D. Page, *Information Loss in Black Hole and/or Conscious Beings ?*, Alberta preprint, hepth/9411193, to be published in *Heat Kernel Techniques and Quantum Gravity*, eds. S.A. Fulling (Texas A& M University (1995)).

[18] R.P. Feynman and F.L. Vernon Jr., Ann. Phys. (NY) 94 (1963), 118.

[19] A.O. Caldeira and A.J. Leggett, Ann. Phys. 149 (1983), 374.

[20] Y.R. Shen, Phys. Rev. 155 (1967), 921;

A.S. Davydov and A. A. Serikov, Phys. Stat. Sol. B51 (1972), 57;

B.Ya. Zel'dovich, A.M. Perelomov, and V.S. Popov, Sov. Phys. JETP 28 (1969), 308;

For a review see : V. Gorini *et al.*, Rep. Math. Phys. Vol. 13 (1978), 149.

[21] M.V. Satarić, J.A. Tuszyński, R.B. Zakula, Phys. Rev. E48 (1993), 589.

[22] J. Tabony and D. Job, Proc. Nat. Acad. Sci. (USA), Vo. 89 (1992), 6948.

[23] P. Glandsdorff and I. Prigogine, *Thermodynamic Theory of Structure, Stability and Fluctuation* (Wiley, New York 1971);

G. Nikolis and I. Prigogine, *Self Organization in non-equilibrium systems* (Wiley, New York 1977);

A. Babloyantz, *Molecules, Dynamics and Life* (Wiley, New York 1986);

C. Vidal and H. Lemarchand, *La Réaction Créatrice* (Hermann, Paris 1988).

[24] J. Ellis, N.E. Mavromatos and D.V. Nanopoulos, Phys. Lett. B293 (1992), 142;

see also N. Mavromatos's talk in these proceedings and references therein.

[25] T. Mitchison and M.W. Kirschner, Nature (London) 312 (1984), 232; *ibid* 237;

M. Dogterom and S. Leibler, Phys. Rev. Lett. 70 (1993), 1347.

[26] H. Rosu, IFUG-19-1994 Guanajato U. preprint, bulletin gr-qc:9409007, and also at *Pedestrian Notes in Quantum Fundamentals* Guanajato U. preprint, IFUG-24-1994, bulletin gr-qc: 9411035 (revised May 1995).

[27] B.G. Sumpter and D.W. Noid, J. Chem. Phys. 102 (1995), 6619.

[28] L.M. Ricciardi and H. Umezawa, *Kibernetik* 4, (1967) 44.

[29] G. Vitiello, Salerno Univ. preprint, to appear in Int. J. Mod. Phys. B9 (1995).

[30] C.I.J. Stuart, Y. Takahashi and H. Umezawa, J. Theor. Biol. 71 (1978) 605; Found. Phys. 9 (1979) 301.

[31] E. Witten, Phys. Rev. D44 (1991), 344.

[32] A. Cappelli, C. Trugenberger and G. Zemba, Nucl. Phys. B396 (1993), 465;

S. Iso, D. Karabali and B. Sakita, Phys. Lett. B296 (1992), 143.

[33] J. Ellis, N.E. Mavromatos and D.V. Nanopoulos, Phys. Lett. B296 (1992), 40.

[34] S. Chaudhuri and J. Lykken, Nucl. Phys B396 (1993), 270.

[35] N.E. Mavromatos and D.V. Nanopoulos, to appear.

[36] E. Celeghini, M. Rasetti and G. Vitiello, Ann. Phys. (N.Y.) 215 (1992), 156.