IN-51-CR

AIAA-95-1053

Microgravity and Charge Transfer in the Neuronal Membrane: Implications for Computational Neurobiology

R. Wallace
University of Central Florida
Orlando, FL

Life Sciences and Space Medicine Conference
April 3-5, 1995 / Houston, TX

MICROGRAVITY AND CHARGE TRANSFER IN THE NEURONAL MEMBRANE: IMPLICATIONS FOR COMPUTATIONAL NEUROBIOLOGY

Ron Wallace, Ph.D.
Department of Sociology and Anthropology
University of Central Florida
Orlando, Florida 32816

Abstract

Evidence from natural and artificial membranes indicates that the neural membrane is a liquid crystal. A liquid-to-gel phase transition caused by the application of superposed electromagnetic fields to the outer membrane surface releases spin-correlated electron pairs which propagate through a charge transfer complex. The propagation generates Rydberg atoms in the lipid bilayer lattice. In the present model, charge density configurations in promoted orbitals interact as cellular automata and perform computations in Hilbert space. Due to the small binding energies of promoted orbitals, their automata are highly sensitive to microgravitational perturbations. It is proposed that spacetime is classical on the Rydberg scale, but formed of contiguous moving segments, each of which displays topological equivalence. This stochasticity is reflected in randomized Riemannian tensor values. Spacetime segments interact with charge automata as components of a computational process. At the termination of the algorithm, an orbital of high probability density is embedded in a more stabilized microscopic spacetime. This state permits the opening of an ion channel and the conversion of a quantum algorithm into a macroscopic frequency code.

Nomenclature

a_0	Bohr radius
CQM	Copenhagen interpretation of quantum mechanics
CTC	charge transfer complex
FMM	fluid mosaic membrane model
GR	General Relativity
HOMO	highest occupied molecular orbital
LCM	liquid crystal membrane model
LUMO	lowest unoccupied molecular orbital
n	principal quantum number
QGM	quantum gravity model
$\mathcal{T}$	Riemannian tensor
USG	Unturbe-Sanchez-Gomez model

I. Background

The nerve cell membrane is an amphiphilic bilayer composed of a phospholipid lattice and embedded proteins.[1] Hydrophilic phosphorus head groups define the outer surfaces of the exterior and interior membrane leaflet, while the hydrophobic interior is comprised of hydrocarbon diacyl chains. The embedded proteins have a spanning domain ranging from a single α-helical polypeptide to several structured strands of amino acids.

According to FMM, the membrane bilayer is a homogeneous 2-dimensional liquid with considerable lateral mobility.[2] The liquid state is due to positional and orientational randomness of the constituent phospholipids. Due to the membrane's stochastic nature, computational properties of nerve cells in FMM are attributed to embedded-protein dynamics (i.e., ion channel activity). The lipid bilayer serves as a semipermeable barrier separating aqueous compartments and as an "anchoring site" for the proteins.

X-ray crystallographic studies indicate that the stochasticity emphasized in FMM is inaccurate, and that LCM has stronger empirical support.[3,4,5] In the alternative model, the membrane bilayer is a molecular lattice which displays phase transitions between liquid and gel states. These transitions

occur on a time scale as brief as 100-190 ps and a length of 100-1000 Å. They are associated with membrane permeability to Na+, cholesterol, and other ionic and molecular species, and hydration-layer formation on the outer membrane surface which influences transmitter and other ligand binding. Because several of these features are significant in neural communication, it is useful to examine their possible microscopic basis.

II. Membrane Charge Transfer

Molecular theory predicts that 1-2 electrons introduced at one end of a metastable lattice characterized by orbital overlap will propagate as a soliton through the system.[6] This is a CTC of the form:

$$\Psi_{CTC} = C_1\Psi_{AD} + C_2\Psi_{A\text{-}D+} \qquad (1)$$

where Ψ_{AD} is the wave function, without taking into account the charge transfer, of two molecules, A and D, and $\Psi_{A\text{-}D+}$ is electron transfer from donor D to acceptor A. Energy transfer in CTC is HOMO $\mapsto$ LUMO, generating excited states with 10^{-10} sec lifetimes. These protocols are consistent with experimental evidence for membrane charge-transfer activity immediately prior to depolarization at a voltage-gated ion channel.

Artificial membrane studies (Langmuir-Blodgett preparations) indicate that bonding between ethylenic p orbitals of carbon atoms 9 and 10 in adjacent hydrocarbon diacyls can be further stabilized by 1 or 2 additional electrons.[7] The sequential release of spin-correlated electron pairs into the system is accomplished by cyclical electrochemical events at the outer membrane surface. Spatially and/or temporally summed afferent impulses produce a surge of Na+ causing phospholipids to become deprotonated. The deprotonation temporarily dissociates a phospholipid-cholesterol complex, releasing 2 spin-correlated electrons that move longitudinally through a conduction pathway created by the overlapping ethylenic orbitals.

Quasi-particles passing through a thin sample of condensed matter produce a form of absorbtion spectroscopy using electrons instead of light. In a neural membrane conduction system, ethylenic p orbitals, which have a low excitation threshhold, would be promoted to metastable levels. Movement of successive electron pairs through the system would deform the p orbitals into a series of topologically equivalent hypershapes. The time interval between deformations based on the absorbtion/emission interval in biomembrane fluorescence depolarization probes $\approx 10^{-8}$ sec.[8]

The major constraints on interactions between and within deformed orbitals are hypersurface and charge. Units with dipolar, complementary hypersurfaces combine to form larger units. The process continues until configurations settle into a stable high energy arrangement of high probability density Ψ^2. Time estimates for this process based on hexadecane simulation of diacyl-chain carbon reorientations during increasing membrane viscosity $\approx$ 100 picosec or 10^{-10} sec.[9] The estimate is compatible with lifetimes ($\approx 2 \times 10^{-10}$ sec) of highly localized reconstituted Rydberg wave packets or fractional revivals which may function as automata.[10,11] This possibility merits further investigation.

Viewed from a computational standpoint, the superposition postulate in CQM implies massive parallelism for microscopic cellular automata.[12,13,14] Highly intractable combinatorial problems involving temperature, pH, osmolarity, metabolite and hormone binding as well as sensory, autonomic and emotional data integration (in more neurologically complex species) can be microscopically solved at near optimality in polynomial time. Coulombic attraction between high probability density of self-assembled Rydberg automata and positively charged arginine and lysine residues of an adjacent ion channel regulate channel opening and the conversion of microscopic solutions into classical frequency codes.[15,16,17]

"Learning" in the neural CTC is accomplished by mesoscopic interaction between membrane and cytoskeleton. Electrotonic conduction of the spike frequency pattern from a voltage-gated channel to a ligand-gated Ca++ channel at the NMDA receptor produces a complex chemical reaction which modifies the

cytoskeleton.[18,19,20,21,22,23] Conformational changes in cytoskeletal protein tubulin dimers produce gross structural modifications in the attached membrane, including formation of dendritic spines at synapses. The modified synaptic structure in turn affects phase relations of subsequent afferent pulses at the outer membrane surface. Because these pulses generate the Na+ surge which indirectly activates the release of spin-correlated electrons into CTC, any modification of the interval or spatial extent of Na+ dissociation incrementally modifies iterations of Rydberg automata. This would constitute directional change or an "arrow of time" for the quantum wave function in a neural membrane mesoscopic computational system. This exception to the principle of strong Poincaré Recurrence in CQM permits quantum adaptation to combinatorially complex macroscopic environments.[24]

III. The Role of Microgravity in CTC.

It is known that energy eigenstates of hydrogenlike (Rydberg) atoms are sensitive to gravitational perturbations on an atomic scale due to their high principal quantum numbers n (typical n = 10-100) or high macroscopic distance r of the electron from the nucleus ($r >> a_0$, where a_0 is the Bohr radius).[25,26,27,28] In a neural CTC, topological fluctuations in Rydberg automata during the course of the algorithm are physically identical with energy eigenstates. It follows that microgravity (i.e., spacetime on the atomic scale $\approx a_0$) may have a significant effect on charge density interactions in neural membrane computations.

The recent renewal of interest in synthesizing GR with CQM has produced several competing models of microscopic gravity. The majority of these, however, are QGM models which apply at the Planck length ($\approx 10^{-33}$ cm), a scale many orders of magnitude smaller than that of the Rydberg atom. An exception is USG which postulates a stochastic form of the spacetime metric as a major explanatory feature of wave function reduction $\mathbf{R}\ \Psi(X,t)$.[29] The model (similar to that of Károlyházy, Frenkel and Lukás) assumes a classical but stochastic Gaussian metric in which the wave function is embedded. $\mathbf{R}\ \Psi(X,t)$ is construed as an interaction between matter and the fluctuating metric such that Ψ becomes increasingly localized, with corresponding decoherence of superposition, in a more stabilized spacetime metric with highly localized curvature values. In USG the threshhold between microscopic and macroscopic systems occurs at transitional mass M^{tr} ($\approx 10^{-14}$ g). Masses $m << M^{tr}$ (i.e., elementary particles) display quantum behavior while macroscopic masses $m >> M^{tr}$ behave classically. Unlike alternative attempts to synthesize CQM and GR, USG is consistent wtih the stochastic character of nature and does not require a Relative State ("Many-Worlds") interpretation of $\mathbf{R}\ \Psi(X,t)$.

For Rydberg atoms in a neural-membrane CTC, the stochastic spacetime of USG may be expressed in computational terms. The metric M_{USG} is mathematically definable as a set of fluctuating tensor values

$$d\mathbf{T}_i\Psi = d(g_{\mu\nu})_i\Psi\ , \qquad (2)$$

where $d(g_{\mu\nu})$ is a derivative representing an instantaneous rate of change in the Riemannian coefficient $g_{\mu\nu}$ of GR. In accordance with USG, $d\mathbf{T}_i\Psi$ describes the rate of curvature change in a microscopic and mobile spacetime segment contiguous with other such segments and displaying topological equivalence. From a computational standpoint, $d\mathbf{T}_1\Psi$, $d\mathbf{T}_2\Psi$, $d\mathbf{T}_3\Psi ... d\mathbf{T}_N\Psi$ are mathematical objects representing physically real spacetime cellular automata interacting systemically with one another and with charge density configurations in a promoted orbital. Increased probability density of self-assembled charge configurations generates increasing stability of spacetime automata approximating the manifold of classical GR. Reciprocally, the increasing stabilization of spacetime automata increases the localization of charge density configurations.

The algorithm converges at an end state S of {**S**} defined in terms of phospholipid molecular probability density and stochasticity of microscopic spacetime. Subsequent Coulombic attraction between the phospholipid orbital envelope and

positively charged arginine and lysine residues of an adjacent ion channel permit channel opening and neural membrane depolarization.

Regulation of field strength responsible for ion channel activation is the specialized role of self-assembled $d\mathcal{T}_i\Psi$ automata. In macroscopic GR, Newtonian "action at a distance" $\mathbf{G}(M_1 M_2)$ was reformulated by Einstein as a propagated change in local spacetime curvature[30,31]:

$$\mathbf{G}(M_1, M_2) = \Delta\mathcal{T}_1 \mapsto \Delta\mathcal{T}_2 \mapsto \Delta\mathcal{T}_3 \ldots \Delta\mathcal{T}_N. \quad (3)$$

In a quantum regime as described in USG, curvature propagation is randomized in proportion to the mobility of the contiguous $d\mathcal{T}_i\Psi$ segments comprising microscopic spacetime. It follows that Coulombic interaction (between phospholipid envelope and ion-channel amino residues) essential for membrane depolarization is determined by $d\mathcal{T}_i\Psi$ distribution at the end state S of {**S**} of the quantum algorithm.

IV. Discussion.

The purpose of this article has been to suggest in an admittedly schematic way the role of microgravity in neural communication. While certain features of the model will probably not be testable for some time to come, the general properties of a Rydberg atom in a regime of fluctuating macroscopic spacetime curvature may be derivable experimentally. Perturbation of different energy levels in a gravitational field varying over the dimension of the atom (ie., tidal forces) is theoretically a function of the local macroscopic Riemannian curvature tensor $\mathcal{T}$. This condition may be observed as frequency shifts of Rydberg atoms with high lifetimes near neutron stars and black holes[32]. The lifetimes are generally greater than those of Rydberg atoms generated in an Earth laboratory. In terms of USG, the energy shifts are induced by the propagation of curvature change from the classical GR manifold to the $d\mathcal{T}_i\Psi$ automata. Consequent movements and curvature changes in the segmented spacetime automata in turn produce a changed distribution of charge density configurations. If the USG model is correct, the frequency shifts should be highly randomized, reflecting the stochasticity of spacetime and charge density on the atomic scale. The astronomical data set, when combined with models of charge transfer and excitation in biomembranes, may generate more detailed models (possibly of the cellular automata family) of microgravity in subneural systems. As a consequence, the means by which neurons routinely compute near-optimal solutions to highly complex problems of physiology and cognition will be better understood.

V. Acknowledgements.

I wish to gratefully acknowledge the comments and constructive criticism of Ralph Llewellyn, Department of Physics, University of Central Florida. Responsibility for any errors of fact or interpretation is entirely my own.

References

[1] Gennis, R.B., *Biomembranes: Molecular Structure and Function,* Springer-Verlag. New York,1989, pp. 36-84.

[2] Singer, S. and Nicolson, G., " The fluid mosaic model of the structure of cell membranes," *Science*, Vol. 173, 1972, pp. 720-731.

[3] Mouritsen, O.G. and Jørgensen, K., "Dynamic lipid-bilayer heterogeneity: a mesoscopic vehicle for membrane function?" *BioEssays*, Vol.14, 1992, pp. 129-136.

[4] Kinnunen, P.K.and Virtanen, J.A., "A qualitative, molecular model of the nerve impulse: conductive properties of unsaturated lyotropic liquid crystals,"*Modern Bioelectrochemistry* Edited by F.Gutman, and H Keyzer, Plenum Press, New York,1986, pp. 457-479.

[5] Chistyakov, I.G., "Liquid crystals," *Soviet Physics* ,Vol. 9, 1967, pp. 551-573.

[6] Ladik, J.J., "Charge-transfer reactions in biomolecules," *Biophysics*, edited by W. Hoppe, W. Lohmann, H. Markl, and H. Ziegler, Springer-Verlag, New York,1983, pp. 230-233.

[7] Kinnunen, P.K.and Virtanen, J.A., "A qualitative, molecular model of the nerve impulse: conductive properties of unsaturated lyotropic liquid crystals," *Modern Bioelectrochemistry* Edited by F.Gutman, and H Keyzer, Plenum Press, New York,1986, pp. 457-479.

[8]Gennis, R.B., *Biomembranes: Molecular Structure and Function,* Springer-Verlag. New York,1989, p.175.

[9]Venable, R. , Zhang, Y, Hardy, B., and Pastor, R., " Molecular dynamics simulations of a lipid bilayer and of hexadecane: an investigation of membrane fluidity,"*Science* Vol. 262, 1993, pp. 223-226.

[10]Yeazell, J.A. and Stroud, C.R., "Observation of fractional revivals in the evolution of a Rydberg atomic wave packet," *Physical Review A* , Vol. 43, 1991, pp. 5153-5156.

[11]Parker, J. and Stroud, C.R., "Coherence and decay of Rydberg wave packets," *Physical Review Letters* , Vol. 56, 1986, pp. 716-719.

[12]Wallace, R., "Cognitive mapping and algorithmic complexity: is there a role for quantum processes in the evolution of human consciousness?" *Behavioral and Brain Sciences,* Vol. 16,1993, pp. 614-615.

[13]Conrad, M., "Emergent computation through self-assembly," *Nanobiology,* Vol. 2, 1993, pp. 5-30.

[14]Deutsch, D., " Quantum theory, the Church-Turing principle and the universal quantum computer," *Proceedings of the Royal Society of London A* , Vol. 400, 1985, pp. 97-117.

[15]Leuchtag, H.R., "Long-range interactions, voltage sensitivity, and ion conduction in S4 voltage segments of excitable channels," *Biophysical Journal* , Vol.66, 1994, pp. 217-224.

[16]Stühmer, W., Conti, F., Suzuki, H., Wang, X., Noda, W., Yahagi, N., Kubo, H. and Numa, S., "Structural parts involved in activation and inactivation of the sodium channel," *Nature* , Vol. 339, 1989, pp. 597-603.

[17]Catterall, W., "Structure and function of voltage-sensitive ion channels,"*Science* , Vol.242, 1988, pp. 50-61.

[18]Malgaroli, A. and Tsien, R.W., "Glutamate-induced long-term potentiation of the frequency of miniature synaptic currents in cultured hippocampal neurons," *Nature,* Vol. 357,1992, pp.134-139.

[19]Kelso, S.R., Ganong, A.H., and Brown, T.H., "Hebbian synapses in the hippocampus," *Proceedings of the National Academy of Sciences USA* , Vol. 83,1986, pp.5326-5330.

[20]Baudry, M. and Lynch, G., "Glutamate receptor regulation and the substrates of memory," *Neurobiology of Learning and Memory.* Edited by G.Lynch, J.L. McGaugh, and N.M. Weinberger, The Guilford Press, New York, 1984, pp. 431-447.

[21]Hameroff, S.R., "Quantum conformational automata in the cytoskeleton: nanoscale cognition in protein connectionist networks," Abisko, Sweden Conference on *Toward a material basis for cognition* , May 10-14, 1993.

[22]Hameroff, S., Dayhoff, J., Lahoz-Beltra, R., Samsonovich, A. and Rasmussen, S., "Conformational automata in the cytoskeleton: models for molecular computation,"*IEEE Computer* , Vol. 25, 1992, pp. 30-39.

[23]Desmond, N. and Levy, W., "Synaptic correlates of associative potentiation/depression: an ultrastructural study in the hippocampus," *Brain Research,* Vol. 265,1983, pp. 21-30.

[24]Wallace, R. "The mesoscopic neuron and Poincaré recurrence: can a quantum system 'learn'?" *Social Neuroscience Bulletin,* 1995, Forthcoming.

[25]Fischer, U., "Transition probabilities for a Rydberg atom in the field of a gravitational wave," *Classical and Quantum Gravity* , Vol.11, 1994, pp. 463-474.

[26]Pinto, F., "Rydberg atoms in curved space-time," *Physical Review Letters,* Vol. 70, 1993, pp. 3839-3843.

[27]Gill, E., Wunner, G., Soffel, M., and Ruder, H., "On hydrogen-like atoms in strong gravitational fields," *Classical and Quantum Gravity,* Vol. 4, 1987, pp. 1031-1042.

[28]Parker, L., "One-electron atom as a probe of spacetime curvature," *Physical Review D,* Vol. 22, 1980, pp. 1922-1934.

[29]Unturbe, J. and Sánchez-Gómez, J.L., "On the role of gravitation in the possible breakdown of the quantum superposition principle for macroscopic systems," *Il Nuovo Cimento,* Vol. 107B, 1992, pp. 211-237.

[30]Skinner, R., *Relativity,* Blaisdell, Waltham, MA, 1969, pp. 283-321.

[31]Taylor, E., and Wheeler, J., *Spacetime Physics,* W.H. Freeman, New York, 1992, pp. 284-

287.

[32]Gill, E., Wunner, G., Soffel, M., and Ruder, H., "On hydrogen-like atoms in strong gravitational fields," *Classical and Quantum Gravity,* Vol. 4, 1987, p.1042.